# Acoustic Propagation Variation with Temperature Profile in Water Filled Steel Pipes at Pressure 

John Eugene Hough

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# Acoustic Propagation Variation with Temperature Profile in Water Filled Steel Pipes at Pressure. 

John Eugene Hough

Supervisors:
Professor Cheng Lu
Dr Ajit Godbole

This thesis is presented as part of the requirement for the conferral of the degree: Doctor of Philosophy

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School of Mechanical, Materials, Mechatronic and Biomedical Engineering Faculty of Engineering and Information Sciences

University of Wollongong


#### Abstract

Conventional pressure leak testing of buried pipelines compares measurements of pressure with pipe wall temperature. An alternative proposed method uses acoustic velocity measurements to replace pipe wall temperature measurements. Early experiments using this method identified anomalous results of rising acoustic velocities thought to be caused by air solution.

This research investigated the anomalous acoustic velocity measurements by evaluation of acoustic velocity variation with pressure, temperature and air solution. Quiescent air solution rate experiments were carried out in water filled pipes. Computer modelling of the air bubble shape variation with pipe diameter was found to agree with bubble and drop experiments over the pipe diameter range from 100 mm to 1000 mm . Bubbles were found to maintain constant width over a large volume range confirmed by experiments and modelling.

Multi-sensor temperature probes were developed and manufactured with some used for measuring internal water filled pipe temperatures at high pressure and the others for measuring below ground soil temperatures and diffusivities. The internal probes were used in above ground experiments and the 435 mm diameter below ground tank experiment. External pipe wall temperature sensors supplemented these temperature measurements with pressure also recorded using data loggers. One ground probe located next to the buried tank evidenced good correlation between sensor temperatures and the tank pressure over an annual seasonal cycle. The buried tank and soil data highlighted the significant contribution from earlier weather based changes of the order of a week which may enable prediction of below ground temperatures ahead of pressure tests and assist test scheduling. There was indirect evidence that the external pipe wall and central vertical internal temperature data was incomplete. Computational Fluid Dynamic, CFD, research previously carried out at the University was scaled to cover pipe diameters from 250 mm to 1000 mm and included soil thermal diffusivity variation. Field data was supplemented by the CFD results as thermal gradient input to a Matlab based computer model of acoustic ray propagation inside a pipe. The model demonstrated a reduction in acoustic velocity when thermal gradients were present and the extent of the change was dependent on the thermal gradient shape and distribution. For inclined pipe there was a more significant nonlinear reduction in acoustic velocity dependent both on thermal gradient and pipe topographical incline.

Acoustic velocity field measurements were reviewed based on the Matlab computer model and the field temperature measurements. Also used in the review were computer generated below ground temperature predictions based on weather bureau data. The model was able to account for a proportion of the acoustic anomalies but could not be directly linked as the cause. A proposed anomaly solution was based on a combination of spring-summer period, rugged terrain, inclined pipe and lack of thermal stability resulting


from prior water movement through the test section and particularly the movement disturbance of the pressurising water.

The acoustic based pressure test methodology appears already suitable for use with both above and below ground pipes and for mixed above/below ground pipes which are difficult to test using conventional methods of temperature measurement. Extending the leak test duration may be sufficient to achieve leak test acceptance for the worst anomaly cases (or lack of thermal stability). Use in pipeline pressure test situations where it is difficult to measure temperatures such as water-crossings, shore-approaches and offshore should be considered. High latitude pressure test situations may benefit from using the method where rapid one point acoustic measurements would complement pressure measurements from the same location.

## ACKNOWLEDGMENTS

Most of the field data used in this Thesis has been accumulated while working with the international pipeline construction company SAIPEM, an ENI subsidiary. Opportunities and generous support for experimentation and improvements are gratefully acknowledged with initial support from Lino Palmitessa and Emiglio Grandi and particular long term support from Claudio Savini.

Early field acoustic experiments were carried out with the generous assistance of other Pipeline Contractors in Australia who provided access to their pipelines under construction for acoustic measurements and access to relevant field data.

Kyungmin Baik on this author's behalf kindly carried out modifications of his Matlab programs to extend the solutions to the Baik and Leighton equations [1-4] to low frequency regions that they had never previously addressed. He provided attenuation and phase velocity results for multiple pipe diameters and wall thicknesses at these low frequencies. In addition he found a way to extend Kinsler and Frey's [5] linear attenuation results to frequencies below their cutoff.

One individual in particular, Vito Martinello, started my learning experience of pipeline hydrotesting from 1975 and continued for many years of interaction and discussion of unusual occurrences and ways to improve the process.

My wife Tanya was a continual support in the background during extensive foreign consignments performing my assigned work and collecting measurements on the side. Many nights spent machining, designing and coding were tolerated.

Sandro Cantaffio was generous with his support, guidance and company at the Companies' Moorebank Depot while I carried out experimental measurements on a pipe section and machined the large transmitter.

At Dubbo North, my sister Rita and Michael provided accommodation, company, locations and help to install diffusivity probes and eventually burial and recovery of the DN 435 tank.

Sent home from Sakhalin Island Russia late 2005 with leukaemia and never expected back. Returned with generous help of the Australian Government's Pharmaceutical Benefits Scheme. This document is partial thanks.

## CERTIFICATION

I, John Eugene Hough, declare that this thesis submitted in fulfilment of the requirements for the conferral of the degree Doctor of Philosophy, from the University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualifications at any other academic institution.

John Eugene Hough
Date 29 ${ }^{\text {th }}$ August 2023

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## LIST OF NAMES OR ABBREVIATIONS

Associations and Companies

| ANSYS | Company supplying computer software including CFX and FEA |
| :---: | :---: |
| APGA | Australian Pipeline and Gas Association. |
| APIA | Australian Pipeline Industry Association, now known as APGA |
| AS | Australian Standard |
| BOM | Bureau of Meteorology (Australia) |
| BV | Bureau Veritas - Certifying body. |
| CRC | Cooperative Research Centre (Australia) |
| CSIRO | Commonwealth Scientific and Industrial Research Organisation |
| DT | Model prefix for Data Electronics or Data Taker loggers (now part of Thermo Fisher Scientific). |
| DNV | Det Norske Veritas - Offshore pipeline testing code and certifier. |
| ENI | Italian abbreviation for National Group for Hydrocarbons. |
| IAPS | Predecessor to IAPWS. |
| IAPWS | International Association for the Properties of Water and Steam. |
| IUPAC | International Union of Pure and Applied Chemistry. |
| KOPP | name of German specialist hydrotest contractor (no longer exists). |
| OMAE | Offshore Mechanics and Arctic Engineering. |
| SAIPEM | Italian abbreviation for Drilling and Construction Company. |
| UOW | University of Wollongong |
| Technical Terms |  |
| BSP | British Standard Pipe (thread) |
| BSPT | British Standard Pipe Taper |
| CFD | Computational Fluid Dynamics |
| CFX | ANSYS abbreviation for CFD |
| DN | Nominal Diameter (usually metric in mm) |
| DWT | Dead Weight Tester |
| ETB | Engineering Toolbox (website for Engineering) |
| FEA | Finite Element Analysis |
| FFT | Fast Fourier Transform |
| ID | Inside Diameter |
| IFFT | Inverse Fast Fourier Transform |
| KP | Kilometre Post |
| MLV | Mainline Valve |
| MOC | Method of Characteristics |
| NDT | Non Destructive Testing |
| NPT | National Pipe Thread |


| OD | Outside Diameter |
| :--- | :--- |
| PMMMA | Poly Methyl MethAcrylate |
| PMV | Partial Molar Volume |
| RTC | Room Temperature Creep |
| SMYS | Specified Minimum Yield Stress (usually in MPa or thousands of psi) |
| SPT | Scaled Particle Theory |
| WT | Wall Thickness (relating to pipe) |

## UNITS

Where duplicates occur, the context will determine which meaning and terms apply.
Length

| km | kilo metre |
| :--- | :--- |
| m | metre |
| mm | milli metre |
| $\mu \mathrm{m}$ | micro metre |
| $"$ | inch Imperial unit of length |
| inch | Imperial unit of length |
| Diameter | mm, metre or imperial inch (") |

Area

| $\mathrm{m}^{2}$ | square metres |
| :--- | :--- |
| $\mathrm{mm}^{2}$ | square millimetres |

Volume

| I | litre |
| :--- | :--- |
| ml | millilitre |
| $\mathrm{m}^{3}$ | cubic metre |


| Mass |  |
| :--- | :--- |
| mg | milligram |
| g | gram |
| kg | kilogram |

Density
$\mathrm{kg} / \mathrm{m}^{3} \quad$ kilogram per cubic metre
$\mathrm{g} / \mathrm{ml} \quad$ grams per millilitre
g/cc grams per cubic centimetre

Flow rate
I/s litres per second
cc/s cubic centimetres per second
$\mathrm{ml} / \mathrm{s} \quad$ milli litres per second
$\mathrm{m}^{2} / \mathrm{s} \quad$ unit of gas diffusion or diffusivity
$\mathrm{mm}^{2} / \mathrm{s} \quad$ unit of gas diffusion or diffusivity
Time

| $s$ | seconds |
| :--- | :--- |
| $m$ | minutes |


| m | month |
| :---: | :---: |
| h | hours |
| d | day |
| y | year |
| Pressure |  |
| Pa | Pascal - unit of pressure |
| kPa | kilo Pascal - unit of pressure |
| MPa | mega Pascal - unit of pressure |
| bar | equivalent to 100 kPa - unit of pressure |
| bara | absolute version of Bar - unit of pressure |
| barg | relative to atmospheric pressure (gauge) - unit of pressure |
| atm | atmosphere of pressure equivalent to standard atmospheric pressure. |
| mbar | milli bar - unit of vacuum pressure, 0.001 bar |
| mm Hg | millimetres of mercury in a manometer - vacuum unit of pressure. |
| psig | pounds per square inch (gauge) $=6.8948 \mathrm{kPag}$ |
| psia | pounds per square inch (absolute) |
| Stress (same units as pressure) |  |
| MPa | Mega Pascal |
| GPa | Giga Pascal |
| $\mathrm{N} / \mathrm{mm}^{2}$ | Newton per square millimetre $=1 \mathrm{MPa}$ |
| Force |  |
| N | Newton or kg.m/sec ${ }^{2}$ |
| kgf | kilogram force - gravitational force exerted by a weight of one kilogram. |
| lbf | pound force - gravitational force exerted by a weight of one pound |
| Wavelength |  |
| m | metres |
| Velocity |  |
| $\mathrm{m} / \mathrm{s}$ | metres per second |
| $\mathrm{mm} / \mathrm{s}$ | millimetres per second |
| $\mathrm{m} / \mathrm{d}$ | metres per day |
| Frequency |  |
| Hz | Hertz or cycles per second |
| rad/s | radians per second |
| $\mathrm{c} / \mathrm{s}$ | cycles per second |

c/d cycles per day

## Attenuation

Neper/m Neper per metre - ratio of natural logarithms of source and echo amplitudes divided by the distance travelled between them in metres.
$\mathrm{dB} / \mathrm{m} \quad$ decibels per metre $=8.7$ Neper $/ \mathrm{m}=20 \times$ ratio of log10 of source and echo amplitudes divided by the distance travelled in metres between them.

Viscosity
Poise unit of viscosity
Centipoise unit of viscosity (=Poise/100)
Pa.s $/ \mathrm{m}^{2} \quad$ Pascal-second per square metre

## Temperature

| ${ }^{\circ} \mathrm{C}$ | degree Celsius |
| :--- | :--- |
| ${ }^{\circ} \mathrm{K}$ | degree Kelvin |
| mK | milli Kelvin, $0.001^{\circ} \mathrm{K}$ or $0.001^{\circ} \mathrm{C}$ (interchangeable) |
| ${ }^{\circ} \mathrm{F}$ | degree Fahrenheit $=0.555^{\circ} \mathrm{C}$. |

Energy

| J | Joule |
| :--- | :--- |
| kJ | kilojoule |
| MJ | Mega joule |

Work (same as Energy)
Power

| W | Watts or Joules/second |
| :--- | :--- |
| kW | kilowatt |
| MW | Megawatt |
| J/s | Joules per second |

Heat

| $\mathrm{W} / \mathrm{m} . \mathrm{K}$ | unit of thermal conductivity |
| :--- | :--- |
| $\mathrm{J} / \mathrm{kg} \cdot \mathrm{K}$ | unit of specific heat |
| $\mathrm{m}^{2} / \mathrm{s}$ | unit of diffusivity |
| $\mathrm{mm}^{2} / \mathrm{s}$ | unit of diffusivity |
| $\mathrm{cm}^{2} / \mathrm{s}$ | unit of diffusivity |

Electrical

| A | Ampere |
| :--- | :--- |
| mA | milliampere |
| V | Volt |
| mV | millivolt |
| $\Omega$ | Ohms |

## LIST OF MATHEMATICAL SYMBOLS

## Axes

X
Y
Z

Coordinates
$x$ axial coordinate

Other
$\emptyset_{i} \quad$ angle of the incident ray relative to the surface normal
$\emptyset_{r}$
$v_{i}$
$v_{r}$
a
b
B
$B_{A}$
BI
C
C
$C_{p} \quad$ phase velocity of sound in pipe
c velocity of sound in the pipe
$\mathrm{C}_{\mathrm{m}} \quad$ sound velocity in the medium
$C_{p} \quad$ specific heat at constant pressure of the medium.
$C_{p} \quad$ specific heat at constant pressure.
$\mathrm{C}_{\mathrm{s}} \quad$ speed of sound in steel
$c_{w} \quad$ speed of sound in open water
D outside pipe diameter.
dT temperature change,
$\mathrm{dV} / \mathrm{dP} \quad$ change in volume of the same specific mass for a change in pressure under constant temperature conditions.

## MATH SYMBOLS (Ctd)

Young's Modulus of elasticity (for steel, $2.06 \times 10^{8} \mathrm{kPa}$ ).
frequency $(\mathrm{Hz})$
wall thickness
Bessel function of the first order
Bessel function of the second order.
isothermal bulk modulus of the water
thermal conductivity of the heat transmitting medium
thermal conductivity of the medium
wave number or the angular frequency, $\omega$, divided by the velocity $c$
adiabatic compressibility
Isentropic compressibility
T isothermal compressibility.
pressure
pressure, kPa
pipe internal radius

R
pipe wall thickness
temperature, Celsius, C.

V

元
$\Delta a \quad c h a n g e ~ i n ~ a c o u s t i c ~ v e l o c i t y ~ i n s i d e ~ t h e ~ p i p e, ~ m / s . ~$
$\Delta p \quad$ change in pressure, kPa .
$\Delta T \quad$ change in temperature, $C$.
$\Delta V \quad$ change in pipeline internal volume, $\mathrm{m}^{3}$.
$\eta \quad$ coefficient of dynamic shear viscosity
$\theta \quad$ angle the vector makes with the pipe axis in the vertical direction,
$\theta$ temperature
$\mu \quad$ Poisson's ratio
$\mu \quad$ Poisson's ratio for steel, 0.27, (as used in AS2885.5 all editions).
$\rho \quad$ density of the medium
$\rho_{\mathrm{s}} \quad$ steel density
$\rho_{w} \quad$ water density
$\Phi \quad$ angle the vector makes with the pipe axis in the horizontal direction.
$\omega \quad$ angular frequency
$\omega_{w} \quad$ absorption coefficient between the medium and the pipe wall.

## Lame's Constants:

G
$\lambda$

## Subscripts

S normally used for isentropic processes.
r
A
R
U unrestrained.
0 ambient or reference conditions such as STP or NTP

## Superscripts

S normally used for isentropic processes.
r stress and strain). no meaning. Its usefulness will appear in the equations below which include it. used for reflected, with small I for incident. adiabatic with large or small I for isothermal. restrained. used for reflected, with small I for incident.
shear modulus is the ratio of shear stress to shear strain (like Young's modulus for tensile

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## CHAPTER 1 INTRODUCTION

### 1.1 BACKGROUND

The topic of this research relates to acoustic velocity variation with temperature profile inside pipes. What is missing from the brief topic expression are the circumstances in which such measurements are relevant and useful. Following pipeline construction, sections are subjected to a pressure test to confirm they have sufficient strength and are free of leaks. Such leak tests compare pressure changes with temperature changes of the water/pipe system and if the changes in both are comparable within a pre-agreed margin are considered leak free. Conventional temperature measurements involved excavation of locations along the section and installing temperature measuring systems with means of data recovery for comparison with pressure. The author first experienced primitive buried pipe wall temperature measurements using liquid filled sensors connected to chart recorders which proved to be good recorders of ambient influence but of no use for the pipe wall. This was the first field experience following graduation in Mechanical Engineering in 1975 and provided the impetus to find improved temperature measuring techniques during a subsequent half decade engaged in Acoustics and enrolled part time in a Master of Science in Acoustics degree.

On returning to pipeline construction in 1982, the author developed and trialled the use of electronic pipewall temperature measurements which subsequently became the standard method in Australia for the pipeline construction industry but required multiple temperature probes installed along a test section and then means for data recovery. As a more convenient alternative to such temperature measurements, the author proposed an acoustic technique consisting of generating pressure surge like signals which travelled the length of the section and back. An Australian Patent was granted for the acoustic technique for testing pipelines [6]. Australian Patents were also granted for the transmitter method and variants [7, 8]. Initial short pipe experiments and subsequent field trials were encouraging and confirmed the expected direct correlation between acoustic velocity measurements (a proxy of temperature) and pressure. Other results appeared anomalous and commenced with an inconsistent rapid rise followed by a more gradual rise of overall exponential-like shape over time with an inverted relationship between velocity and pressure. Many explanations were considered but one dominated in that such an exponential-like rise could result from air solution which was proposed at the time. Other possible factors needed to be considered such as strain rate and relaxation or creep relating to the pipe steel and effects on pressure which needed to be characterised to see whether their effects were responsible for the anomaly.

While this author has also been involved in offshore pipeline pressure testing, the only acoustic measurements carried out were for the location of obstructions where subsea noise was encountered which could affect the application of the acoustic hydrotesting technique offshore if such sources were present. Knowledge of the average temperature was needed in such cases to estimate Obstruction locations.

## CHAPTER 1 - INTRODUCTION

While acting as the Pipeline Industry Advisor to the University of Wollongong Computational Fluid Dynamic (CFD) study of pipeline leak test uncertainty, this author became aware of the predicted vertical thermal gradient that ultimately developed in the pipe and took time to dissipate following the pressurisation and associated adiabatic heating. This potentially was another possible explanation of the anomaly.

This document details the research attempting to resolve the anomalous acoustic velocity results. While the research topic specifically mentions steel and water it is also applicable to other metals and liquids including hydrocarbons and water/antifreeze mixtures with appropriate property changes.

This Chapter provides further details relevant to both the pipeline pressure testing and acoustic techniques to assist the unfamiliar reader.

Chapter 2 covers published literature and for some topics extends the published findings to areas relevant to the research topic of this document.

Chapter 3 is in effect an externsion to Chapter 2 to address the important and highly relevant findings from the CFD studies at the University of Wollongong. It is separated from Chapter 2 to better enable extension of the findings to the research topic of this document.

Chapter 4 may appear a strange inclusion in a study on acoustic velocity since it addresses air solution rate and its pipeline diameter based scaling. The research was essential in that there was negligible research in the field and what limited research there was did not address air trapped inside horizontal pipes nor the effect of pressure and especialy the scaling with pipe diameter. The effect of localised air pockets on overall velocity have been briefly studied very recently without conclusion. The present study has been able to hopefully resolve this problem.

Chapter 5 provides a strange mixture of above and below ground temperature measurements of water filled short pipes and ambient effects on soil at depth to provide field data to support computer modelling of thermal gradients in Chapter 7 and to also provide support data to Chapter 6 on field acoustic velocity measurements.

Chapter 8 attempts to bring together the research in Chapters 3 to 7 so that the research findings can be used in future research and by Industry.

NOTE: Abbreviations are listed near the beginning of the document following the Table of Contents. A detailed glossary is included at the end of this document to aid readers. Symbols and Units follow the Abbreviations with some symbols reused for different entities which can be resolved by the context.

### 1.2 PIPELINE HYDROSTATIC TESTS

During the construction phase of cross-country buried pipelines it is normal practice to pressuretest with water (hydrotest) the pipe in section lengths from many kilometres to occasionally a few hundred metres. Access to pipeline pressure tests is difficult both due to rarity, relatively short duration and inherent safety concerns so that data is difficult to obtain. The detail in this section is intended to assist the reader's understanding of the contributors to the thermal layering within the pipe during pressure testing.

## CHAPTER 1 - INTRODUCTION

### 1.2.1 Purpose

Pipeline pressure tests have two main functions - to confirm that:

1) The pipe is capable of working at the design pressure with the required safety factor;
2) There are no leaks in each test section as identified by a temperature-corrected pressure not changing beyond a predetermined margin over a specified time period (usually 24 hours or multiples thereof).

### 1.2.2 Method

Figure 1-1 shows the pipeline construction activity sequence to aid the reader in understanding the activities needed prior to and after the hydrotest activities. In Figure 1-1, only the blocks in salmon colour represent the pressure test specific activities. The activities shown in light blue are performed by other specialist crews such as welding, joint coating, lowering-in, backfill and possibly clean-up. Pressure test support activities (orange) are performed by the pressure test crew. Multiple interactions with the welding crew, for installation and removal of different headers, requires coordination and notice. The peripheral activities around the pressure test are wholly dependent on the completion of the works by other pipeline crews not under the control of the pressure test (hydrotest) crew.


Figure 1-1 - Related Sequential Pipeline Construction Activities with Pressure Test Activities highlighted in light red and Related Activities by the Pressure Test Crew highlighted in orange. Other construction activities such as clear and grade, trenching, stringing and final clean up are not shown.

The high pressure headers are shown in the following Figure 1-2 with the necessary overlap to ensure that once welded together (tied-in) there is continuous pipe that has been subjected to a pressure test.


Figure 1-2 - $\quad$ Test Headers on adjoining test sections ensuring overlap for weld Tie-In. Fill hose is shown upper centre connecting to a pipe which bypasses the Main Line Valve shown top right corner in gravelled area. Foreground orange box is connected to temperature probe under pipe ready for pressure test and has radio modem to relay data to the test cabin at the opposite end of the test section. Pipe section connected to Main Line Valve tested separately due to pressure limits and to minimise contamination from filling water debris (if any). Pump station location is some 50 to 60 km to the upper right of the photo. Header connected to Main Line Valve differs from the Mainline test header in number of branch valves and fittings.

The following Figure 1-3 attempts a brief summary of possible temperature influences associated with pipeline construction and pressure test-related activities detailed in Figure 1-1.


Figure 1-3 - Construction Related Factors affecting Pressure Test Water Temperature. Factors are split into three groups; Backfill effect (prior to water filling), Water Fill effect, Pressurisation Water effect (excluding ambient-related effects).

The first box in Figure 1-3 relates to influences on the ground temperature prior to water filling. The second relates to the fill process and the last to the testing process.

## Stabilisation Following Filling

Normally a time delay is maintained between the end of filling and the start of the pressure test to enable the water temperature inside the pipe to approach the ground temperature. This is referred to as a period for "thermal stabilisation". A study by Arfiadi et al. [9] addressed this issue and will be addressed in the following Chapter but in essence effectively addressed the first two groups in Figure 1-3. The last group is more complex and is best understood in relation to Figure 1-4.

### 1.2.3 Steel Effects on Pressure and Pressure Test Thermal History

Figure 1-4 shows the different stages in terms of pressure changes for most pipeline pressure tests with the details based on pressure testing in Australia in accordance with the Australian Standard for pipeline pressure testing AS2885.5:2020 [10].


Figure 1-4 - Major Pressure Phases during Pipeline Pressure Testing. Depressurisation is the last stage (not numbered but 6.). Curvature during pressurisation implies air present. Repeated
pressure decays during the strength test implies pipe yielding with the dashed line indicative of the pressure trend when repressurisation did not occur. Approximate 10\% pressure drop at the end of the strength test is not always applicable. The leak test pressure decay has been exaggerated to show the usual gradual reduction in pressure drop over time. The curvature of depressurisation has assumed that undissolved air remains.

The above Figure 1-4 (originally provided by this author) taken from Godbole [11] summarises graphically the following major pressure phases of pipeline pressure testing.

## (3) Pressurisation

The quantity of water needed to pressurise a typical pipeline test section is around $1 \%$ of the section volume. This $1 \%$ additional volume of water acts like a slug behind a piston and displaces the previous water by a distance of $1 \%$ of the test section length. This water can be at a different temperature and cause significant disturbance. Each location along the section will have reached some level of thermal stabilisation prior to such movement. Moving water tens of metres can result in differences between the ground and water. This pressurising water can disturb thermal stabilisation and cause time delays in the pressure leak test.

Another contribution is that of heating of the pressurising water as it passes through the diesel driven high pressure pump with additional frictional heating through the hoses or pipes.

Increasing the pressure causes all the water to increase in temperature (adiabatic temperature rise) while the steel pipe reduces in temperature resulting in a net rise of the order of $0.3^{\circ} \mathrm{C}$ but dependent on the pressure change and water thermal properties. Depressurisation has the reverse effect. This adiabatic temperature change was behind the CFD research detailed in Chapter 3 which demonstrated resulting thermal gradients.

If the displacement effect of $1 \%$ had a temperature change of $3^{\circ} \mathrm{C}$ for that $1 \%$, the effect on the whole test section would be $0.03^{\circ} \mathrm{C}$, whereas the adiabatic effect applied to the whole section could result in say a $0.3^{\circ} \mathrm{C}$ change which is an order of magnitude higher.

The pressurising process normally consists of pressure readings at uniform intervals of pressure together with the volume of water injected at that pressure, both accumulative and differential, in order to plot the pressure rise against the injected volume to assess the process and to identify any anomalous behaviour of the pipe or the operation. Normally the slope of the plot of pressure vs. injected volume follows a nearly straight line, consistent with theoretical calculations of $\mathrm{dP} / \mathrm{dV}$ or $\mathrm{dV} / \mathrm{dP}$ (the pressure-volume characteristic). Curvature at low pressures with centre of curvature above the curve implies that air pockets are present in the pipeline. The pressure and volume measurements can be used to determine the quantity but not the location of the air which is then assumed to be at the high points. Opposite curvature at high pressures is usually indicative of pipe yielding and plastic deformation.

The pressurising process is usually conducted at a steady rate to avoid pressure surges and to permit reliable pressure and volume measurements. Once the required pressure has been reached, the pumps are stopped, usually abruptly, generating pressure surges in the process.

## CHAPTER 1 - INTRODUCTION

If the pressure is close to or above uni-axial yield stress of the pipe material, there may be criteria required to determine whether to stop pumping. For cold expanded pipe, what is called 'half slope' of the pressure-volume curve (double added volume for same pressure change) is a recommended cutoff criterion. Any pipe yielding can result in thermal heating of the pipe and subsequent additional net heating of the water/pipe system.

If pipe yielding and plastic deformation take place, temperature changes of the steel can be of similar order to the thermoelastic effect but in the opposite direction with heating of the deformed steel.

## Pressure change between Strength and Leak Test.

With a pressure drop of $5 \%$ to $10 \%$ after the strength test, the disturbances highlighted in the previous section will still apply but in the opposite direction and with an order of magnitude lower effect.

## (4) Strength Test

When the required pressure has been reached the pressure is maintained within the specified range for a specified time, typically 2 to 4 hours, in what is called the strength test. If the test pressure is close to or even above the uni-axial yield stress, it is often necessary to repeatedly add water using the pressurising pumps to compensate for stretching or plastic deformation of the pipe. The volumes added are commonly measured together with the pressure changes over time. Such volumes can be used to determine the plastic deformation of the pipe, if any. If the pressure is likely to rise above the upper limit then drainage is carried out. There may be other factors such as temperature changes and air solution taking place which affect the pressure. These are generally ignored during the strength test which is essentially a confirmation that the pipe has sufficient strength to maintain the pressure within the specified time without failure while permitting water to be added or removed to maintain the required pressure range.

At the end of the strength test the pressure is usually dropped around 5 to $10 \%$ to move the pressure range away from that which could cause continuing plastic deformation, creep or relaxation. Water is removed and may or may not be measured as this can be estimated from the pressure drop. This is then the start of the leak test.

## (5) Leak Test

When the required leak test pressure has been reached it is common to then isolate pressure pump connections and seal off the test section other than for pressure monitoring. Since the leak test is for the purpose of determining whether the test section is free of leaks (within acceptance criteria) and the pipe functions as an exquisitely sensitive thermometer with pressure as the indicator, then it is necessary to assess whether the pressure changes are caused by temperature or by leakage.

Leakage sensitivity can be enhanced by:

- reducing the section length and volume;
- increasing the time duration of the leak test;
- improving the resolution of temperature measuring instrumentation;
- improving the resolution of the pressure measuring instrumentation;
- Increasing the number of temperature probes measuring buried pipe wall temperatures;
- measuring the temperature of any exposed pipe;

Almost all of these factors will have been addressed prior to the start of the test and the selection of test sections and instrumentation. The supervising test person will have selected locations for temperature measurements based on his experience and expectations of contributions from respective pipe locations.

Most of the present research is focussed on the leak test and any prior phases which can impact on measured temperature or affect pressure.

## (6) Depressurisation

Once the pipe section has been accepted as leak-free, the section is partially or completely depressurised to static head as required by subsequent operations. If leakage is detected or declared then appropriate action is taken, usually with the pressure lowered so that it no longer poses a potential hazard if left unattended.

### 1.2.4 Pressure Measuring Instruments

In the past, the use of dead weight testers to measure the test pressure was common due to their being mechanical, reliable, robust, accurate and reasonably capable of resolutions of the order of 10 kPa or better while measuring pressures of $20,000 \mathrm{kPa}$ with minimal temperature coefficient due solely to the thermal expansion of the piston with known characteristics. One problem with such instruments is the time taken to perform each measurement. This is of the order of ten seconds or more, depending on the number and range of weights used. The other problem is that the pressure measured is dependent on the local gravitational constant since the weights divided by the piston area balance the pressure, with the weight varying with gravity. It is only in the past decade that electronic pressure measuring instruments with accuracy and temperature coefficients to match the best dead weight testers have become available at prices below that of the comparable dead weight tester. These electronic instruments have the advantage of measuring pressure without gravitational effects and at order of magnitude faster speeds and with logging and communication capabilities. It is very important for such electronic instruments that they have temperature coefficients comparable to or better than dead weight testers. They are not simple pressure transducers but specialised instruments commonly used for calibration purposes. High quality dead weight testers and electronic equivalents are capable of resolutions of 1 kPa while measuring 30,000 or more kPa with effective resolutions of 30 parts per million (ppm).


Figure 1-5 - Test Cabin With four Pressure instruments - Dead Weight Tester left foreground, Pressure recorder behind weights on DWT, Digital Pressure instrument on bench between laptop and external monitor and Pressure Gauge top just left of blue curtain. Digital Pressure instrument displaying pipeline pressure on left and barometric pressure on right of its display. External monitor mimic screen connected to DT80 data logger hidden behind the laptop and copying multiple instrument readings of pressure, temperature and pressurising flow.

Pressure instruments are located at one end of the pipeline section (same as pump location) and measure the static head pressure at that location. All other locations along the pipeline can be estimated from that pressure and the elevation difference.

The only non-temperature related effects on pressure are air solution and those due to steel plastic deformation in the form of creep or relaxation.

All other problems with leak testing relate to temperature effects on pressure and hence the importance of resolving temperature issues affecting pressure tests.

### 1.2.5 Flow Measuring Instruments

The water added during pressurisation needs to be measured with resolution at least of the order of $0.1 \%$ of the volume needed to pressurise so that the resolution of the pressure-volume graph is of that order. Higher quality commercial instruments are available which can satisfy such requirements.

## CHAPTER 1 - INTRODUCTION

Data obtained using such instruments assist in checking the pressure/volume factor $\mathrm{dP} / \mathrm{dV}$ and any air content, both of which ultimately can indirectly influence the leak test assessment.

It had been a tradition in the U.S.A. to use the number of piston pump strokes as a convenient measure of the volume of water pumped. From AS1978-1977 [12] onwards there has been a statement in the document not to use pump strokes due to the difficulty of verification. This author's experience with use of stroke counts includes strokes being counted without flow due to cavitation on the suction stroke. A flowmeter is not subject to such problems and is able to highlight them.

An alternative used in the U.S.A. for air volume checking is to reach test pressure and then decant some water into a measuring container while measuring the pressure drop to establish the pressurevolume characteristic at pressure which differs when air is present. Pressure surges can affect such measurements.

### 1.2.6 Temperature Measuring Instruments

The following is based on pressure tests on long cross-country pipelines which present the most difficult conditions and have the most stringent requirements for temperature measurements.

For an average water temperature of $20^{\circ} \mathrm{C}$ inside a typical pipe to be tested, the equivalent average temperature measurement resolution should be of the order of $0.01^{\circ} \mathrm{C}$ or 10 milli Kelvin (mK) together with minimal or no interference from ambient temperatures on the total measurement system. This is needed to match the high quality pressure measurement resolution mentioned above. For higher temperatures, the resolution needs to increase and for lower temperatures a decrease down to around $4^{\circ} \mathrm{C}$ at which temperature measurements would be unnecessary other than for freezing protection.

The highest resolution instruments are required to measure buried pipe wall temperatures which may only change by a few hundredths of a degree Celsius over 24 hours but the readout device is subject to ambient changes of the order of 10 to 20 degrees Celsius over the same time period. This is opposite to normal laboratory quality instruments which are housed in temperature controlled conditions to within say 1 degree Celsius while measuring large ranges of temperature of many degrees. Few commercial instruments are suitable for buried pipe wall temperature measurements.

For exposed pipe measurements the requirements are an order of magnitude less stringent and commercial instruments are suitable. Similar requirements exist for any ambient temperature measurements.

Ultimately a single average temperature is needed. The problem is how to obtain such a value for a long cross-country pipeline many kilometres in length over variable terrain and ground conditions. The following tries to address factors contributing to the problem.

### 1.2.7 Temperature measurement methodology

Temperature measurements of buried pipe, exposed pipe, ambient and ground are needed and their unique requirements were detailed below.

## Ambient Temperature Measurements

The general practice is to measure the ambient temperature when taking pressure measurements. This has advantages when the pipe is not buried and fully exposed to solar radiation and ambient temperature changes. There are difficulties in determining any correspondence between ambient temperature and pressure measurements. Other than in exceptional cases such as a short section of buried pipe, ambient temperature measurements are generally ignored but still reported.

## Soil Temperature Measurements

Backfill soil temperatures are not normally considered during pressure tests. The Australian Standards have recommended that soil temperatures be used for an assessment of stabilisation of temperatures in the pipe/soil system. The general practice in Australia is to install ground temperature probes near each end of the pipeline test section and near the pipe wall temperature probes. The recommended location of the soil temperature sensor is at the edge of the backfill away from the pipe and at the pipe centre height. The results of the soil or ground measurements are generally ignored and not included in the numerical assessment process which only considers the pressure and average pipe wall temperature changes over the required test period.

## Exposed Pipe Temperature Measurements.

Exposed pipe generally follows ambient temperature changes with the top of the pipe exposed to direct sunlight and the remainder exposed to the ambient air in contact with the pipe. Sometimes part of the pipe is in water or mud in the trench while pressure attachment and water transfer fittings and valves are on top of the pipe out of such inaccessible locations. For very long pipe test sections of the order of 50 km , the normal length of exposed pipe has little effect on the average pipe temperature with the pressure showing only slight ambient-like fluctuation. For short sections of a few hundred metres, exposed pipe contributions are most important as evidenced by the dramatic ambient-related pressure changes. Judgement of the pressure tester determines the need and location of exposed pipe temperature probes with the preferred location on the underside of the exposed pipe where no direct solar heating occurs and measurements appear better related to pressure changes.

Expected changes over a 24 -hour period for exposed pipe can match and sometimes exceed ambient changes for small diameter pipes, but are a fraction of such changes for large diameter pipe. Nevertheless the changes are in degrees, not milli K, so that the requirement for the temperature sensor and measurement system is far less stringent than for buried pipe or ground probes. Links from the exposed pipe probe to the test cabin can facilitate measurements at the pressure instrument end but with greater difficulty at the opposite end.

The external monitor in the test cabin shown in Figure 1-5 displays the exposed pipe wall temperature of the header nearest the test cabin along with the ambient temperature.

## Buried Pipe Temperature Measurements

Most high quality temperature measurement systems are designed for use in temperaturecontrolled laboratories, with maximum changes of the order of one or two degrees, while measuring large temperature changes. Pipe temperature probes have the opposite requirement to measure changes of the order of 0.001 K while they are expected to achieve such performance under ambient temperature changes of the order of $10-20^{\circ} \mathrm{C}$. This requirement is difficult to achieve with the best commercial instruments. This author experimented with, manufactured and introduced electronic measuring systems capable of such measurements forty years ago. An example of current state of the art is shown in the following Figure 1-6 and Figure 1-7.


Figure 1-6 - Below Ground Pipe wall Temperature probe shown in foreground with tapered orange fibreglass tube inside DN 50 PVC tube. Cable from probe connected to DT80 datalogger inside bright orange box with radio modem and transmitter. Radio aerial mounted on front left corner of box and relaying data back to Test Cabin. Solar panel at rear of box for recharging battery inside box.


Figure 1-7 - Temperature Probe Radio Modem and DT80 Logger with Battery and support modules. Radio modem left bottom, DT80 Logger bottom right of centre, Probe RS232 converter to DT80 bottom far right, partly hidden right of battery is 3V3 supply for Probe. Top left is solar cell battery charger module. Battery must power Modem, DT80 and Probe.

Most probes are installed with their sensor tip in contact with the coated top of the pipe as in the above Figure 1-6. Some are installed after manual excavation or a combination of water jetting and vacuum excavation techniques, others via a PVC tube around 40 to 50 mm diameter preinstalled during construction with the probe installed when needed. The process is time-consuming and often difficult due to limited access on the completed pipeline right of way, including having to negotiate multiple fences and gates. This makes manual data recovery a slow and tedious operation usually lasting a couple of hours and repeated multiple times during a pressure test.

According to the Australian Standard for pipeline pressure tests AS2885.5:2020 [10], temperature probe installation should be at least 48 hours prior to the start of the pressure test.

Usually livestock are not restricted along test sections. Cattle tend to enjoy the novelty of a rodlike device protruding from the ground which can be used for rubbing, scratching and kicking, if too low. This can subsequently dislodge the sensor from contact with the pipe. Their other pastime is experimental chewing and salivating on anything that looks different, especially electrical cables and instrument enclosures. Expected temperature results are sometimes never achieved, or are faulty due to such disturbance. Theft can also be an issue but with two legged animals responsible.

## Internal Temperature Probes

Commercial fittings are available that insert into pipe fittings and valves with an internal hollow to allow for the insertion of a small diameter temperature sensor. Such fittings are known as thermowells and are common in oil and gas plants and facilities. Such fittings are in contact with the water inside the pipe and interfere with the movement of pigs. To install such devices after filling (to avoid
obstructing pigs) requires special valves and devices if the location is under pressure. For the buried pipe section such installation is avoided. Some pipelines in Australia in the 1980s have been tested with internal probes installed in the buried section with very good pressure test results. The subsequent issue is ensuring that such fittings are not causes of leaks in service or of corrosion. Special corrosion protection is needed after removal, together with careful backfill. Currently the practice is avoided.

### 1.2.8 Temperature Assessment

Since pressure instruments provide a single value at a single point in time, for comparison a similar single average temperature for the whole pipeline test section is required for that instant in time. This is generally achieved by producing a weighted average of all the functioning temperature probes along the test section. Experience has suggested that for the exposed pipe its contribution is in accordance with the actual exposed length as a fraction of the test section length. The buried pipe probe contributions are shared over the remaining portion. At the discretion of the pressure tester, sometimes the weighting may be changed to reflect unusual contributions such as that from a river, pond or lake overlying the pipe, difficult terrain and other unusual features based on prior experience.

The important temperature averages are those at the start and end of the mandatory test period. However it is recommended that there should be consistency in measurements and that unusual and favourable measurements be critically evaluated. Ultimately a decision has to be made that the correspondence between pressure changes and average temperature changes fits within the acceptance range and with the trend of the fit improving over time so that if the test was extended the results would progressively improve.

### 1.3 ACOUSTIC HYDROTESTING TECHNIQUE

The acoustic technique essentially replaces the temperature measurements detailed above without changing the pressure and flow measurements nor the different stages of the pipeline pressure test. The greatest advantage is obtaining temperature measurements at the same end as the pressure and eliminating all of the activities, instruments and communications systems needed to efficiently obtain the external pipewall measurements. As the CFD results in Chapter 3 will highlight, the pipewall temperature measurements are not representative of the bulk water temperature changes and provide a distorted estimate of the pipeline temperatures whereas the acoustic measurements are only of the water inside the pipe. This research study aims to resolve abovementioned anomalies in acoustic measurements and identify the circumstances or conditions necessary to enable it to replace the current conventional external multi probe system.

### 1.3.1 Principles and Methods

Results reported at the APIA Cairns Conference [13] used a small electromagnetic transmitter attached via a valve to the test header similar but smaller in size than that shown in Figure 1-8 below. On the opposite end of the transmitter from the pipe was a pressure accumulator.

The following Figure 1-8 shows the larger double acting electromagnetic transmitter with two litre pressure accumulator installed on a DN 900 test header at the start of a 375 metre long above ground pipe section. The small transmitter had a single coil on the piston of outer diameter 35 mm while the large transmitter had two coils in series on the same piston with outer diameter 50 mm . Pistons were immersed in high pressure water and drove the slug of water between the test header branch connection and the accumulator bladder. The bladder of the hydraulic accumulator had to be precharged with nitrogen or air at a pressure below the expected measurement pressure so that when leak test pressure was reached the bladder was lifted off its seat and functioned as a high pressure air spring at the end of the water slug driven by the piston.


Figure 1-8- DN 900 pipe showing Large transmitter (left of centre) mounted on 1" (DN 25) valve with 4 litre pressure accumulator on top. To the left of transmitter is the transducer mounted above another 1" (DN 25) valve with cable to the combination power supply and pre-amplifier loosely sitting on top of test header. Main 6" (DN 150) fill valve shown right of centre. High pressure hose for pressure measurement connected to another valve to the left of the photo. Electrical power cable to transmitter shown. Test trailer with computer and instruments many metres to the left.

The outgoing signal was generated by a portable Compaq computer with expansion chassis in which was mounted an Analog Devices combination analog-to-digital and digital-to-analog converter circuit board RTI-815 with programmable gain as shown in the following schematic Figure 1-9. The

Compaq laptop was later replaced by an IBM Thinkpad laptop with expansion chassis and ultimately the expansion chassis was discarded when National Instruments produced compact A/D D/A systems which could directly attach externally to a laptop computer and had better 16 bit resolution and more generous memory.


Figure 1-9 - Schematic for Signal Generation and Receipt. Software in red. Computer with electrical instrumentation and equipment in orange. Bottom row - signal output to pipeline. Upper row - signal input from pipeline.

The digital signal generated by the computer was passed to the circuit board digital-to-analog converter and thence to a large twin channel concert type power amplifier set up in bridge mode to enhance the power output from the nominal 600 watts per channel to at least double that value of acoustic power into a 2 or 4 ohm piston coil in the transmitter. Resultant pressure signal was of the order of 10 to 100 kPa dependent on the pipeline diameter with pressure reduced for larger diameter pipelines. A Piezotronics piezoelectric pressure transducer was attached to a nearby valve with its output and power supply provided by a Bruel and Kjaer charge amplifier 2635 (alternatively a Piezotronics combination transducer power supply and pre-amplifier). These transducers were capable of withstanding pressure of the order of $20,000 \mathrm{kPa}$ while sensitive to changes of the order of 1 Pa but special care was required when connecting to the pipeline to ensure the rate of pressure change was within the manufacturer's recommended limits. They had limited signal operating range of the order of 100 kPa . Frequency range was from fractions of Hz (dependent on pre- amplifier) to tens of kHz . This analog signal was returned to the circuit board for conversion to digital form for logging on the computer.

Software was written in Turbo Pascal to produce the initial signal, to control the circuit board and store the return data. Later migrated to Embarcadero Delphi Pascal. Gain on the circuit board was changed part way through the recording to allow for the low amplitude of the echo compared with the
high amplitude output signal. Readings were repeated every few minutes when time permitted while carrying out the conventional pressure test involving the dead weight tester pressure measurements. Data loggers were used to record the temperature probe data but required repeated trips along each section to download the data at intervals during the pressure test. Sometimes two sections were tested simultaneously with acoustic measurements carried out only on one section but with double the requirements for other test activities.

Collected acoustic data records were generally checked for presence of suitable data without excessive noise. If needed, corrections were made to settings of the respective instruments or of the computer program inputs and sometimes to the computer programs. The resolution of the analog-todigital converter was only 12 bit or 1 part in 4,000 within which allowance had to be made to avoid overloading and to allow sufficient resolution of the attenuated echo. Each measurement used two bytes of data. Records were limited by the circuit board to a maximum of 32,767 samples of data per run which limited the best time and velocity resolution to around 1 part in 10,000 but were also dependent on the signal frequency used and the attenuation together with extraneous noise. This circuit board had the highest resolution and features available at the time of first use.

## CHAPTER 2 LITERATURE REVIEW

Some relevant research findings in references are viewed and reassessed in terms of the applicability to pipeline pressure tests which sometimes takes the form of extending their findings and at other times points out overlooked features and applications that only someone with experience in the pipeline hydrotest industry can appreciate and use. One example is that of steel creep at high stress which has been suspected by the Pipeline Hydrotest Industry but was difficult to confirm and apply. This approach has the advantage of avoiding the need to later refer back to the same documents. It has the disadvantage of increasing the size of the literature review but hopefully allows for a better flow and structure in the document.

The term 'acoustic velocity' is frequently used and may raise concerns with some readers. An alternative expression could be sound speed, which is used often in the acoustics field, but the signals used are rarely at frequencies which can be heard and hence are more like infrasound. Some higher frequencies are used but for typical long pipelines the infrasound region is preferred. The term velocity in Engineering normally denotes speed with direction. Inside a long pipeline the only surviving signals are those that travel along the pipe with wave fronts generally normal to the pipe axis and so essentially in one direction or its reverse on reflection.

### 2.1 PIPELINE HYDROSTATIC TESTS

Most oil and gas pipelines are constructed in accordance with National Standards or standards adopted from other countries. Some National Standards also address the pressure testing following construction. In Australia, Standards Australia has published such standards commencing with AS1978-1977 [12] with the last published as AS2885.5:2020 [10], with respective State Governments requiring that pressure tests be carried out in accordance with these standards. Other countries such as Germany, Canada and the Russian Federation have detailed standards, while some major oil and gas companies such as Shell have their own specifications which are often used when Government or Country standards are not available or are not sufficiently comprehensive. These National Standards and Company Standards are some of the very few sources of information on the topic.

There are negligible books relating to hydrostatic pressure testing of pipelines. One commonly referenced book on pipeline construction titled "Pipeline Rules of Thumb" edited by McCallister [14] has a chapter on the subject with a total of 13 pages of which less than 5 (including figures) describe the process and the balance are appendices, charts, forms or calculations. Harnell's "Hydrostatic Testing of Pipelines" [15] devotes 8 pages to the hydrostatic test while the remainder of the 132 page book includes details of the necessary peripheral activities such as filling, dewatering and drying with emphasis overall on compliance with the requirements of the Australian Standard for Pipeline Pressure Testing AS2885.5 [10] for which Harnell was the Standards Committee Chairman and this author was a member and significant contributor.

Proposals have been made by Kirkwood and Cosham [16] to dispense with pressure tests and to rely solely on Quality Control (QC) documentation commencing at the Pipe Production Facility (or Mill) through to the Non Destructive Testing (NDT) of each pipe weld joint. They recommend more stringent

Mill testing, attention to pipe support during transport, rigorous NDT of girth welds and internal intelligent pig runs to locate detrimental features in the pipe. While some pipelines have been put into operation using such support instead of a pressure test, the pressure test is able to uncover errors in such documentation which otherwise could be catastrophic once oil or gas product is introduced. This author has been involved in projects carried out with Quality Control to International Standards, only to have a failure occur during pressure test due to incorrect documentation and even missing weld joints. Leaks and failures have also occurred as a result of transportation-induced fatigue cracks (ship and road). These are not addressed in QC documentation which normally relies on the factory test and field welding Non Destructive Testing but nothing in between. A pressure test is the ultimate validation to support Quality Control documentation, even if it is only used to identify and eliminate construction or documentation mistakes.

### 2.1.1 Basic Pressure Test Equations

AS2885.5:2020 [10] provides a complete differential equation relating volume, pressure and temperature in a form which is modified and condensed as follows:

$$
\begin{equation*}
d V=\frac{d V}{d p} d p+\frac{d V}{d T} d T \tag{2.1.1}
\end{equation*}
$$

which is re-expressed in the following form (with minor adjustments by this author);

$$
\begin{equation*}
d V=V_{0}\left(\frac{C_{1} D}{E t}+\frac{1}{B_{I}}\right) d p+V_{0}\left(\beta-C_{2} \alpha\right) d T \tag{2.1.2}
\end{equation*}
$$

or alternatively:

$$
\begin{equation*}
d V=V_{0} \frac{1}{B_{I}}\left(\frac{C_{1} B_{I} D}{E t}+1\right) d p+V_{0}\left(\beta-C_{2} \alpha\right) d T \tag{2.1.3}
\end{equation*}
$$

where

| Vo | pipe internal volume |
| :---: | :---: |
| dV | volume change (litres) |
| dp | pressure change ( kPa ) |
| dT | temperature change ( ${ }^{\circ} \mathrm{C}$ ) |
| D | internal diameter of the pipe (mm) |
| t | wall thickness (mm) |
| E | Young's Modulus for steel, $2.06 \times 10^{8} \mathrm{kPa}$ (as used in AS2885.5:2020 [10]) |
| BI | Isothermal bulk modulus (kPa) (varies with temperature and pressure) |
| $\beta$ | water thermal expansion coefficient (varies with temperature and pressure) |
| a | pipe thermal expansion coefficient, $11.7 \times 10^{-6} /{ }^{\circ} \mathrm{C}$. |
| $\mathrm{C}_{1}$ | pipe bulk modulus factor based on pipe restraint conditions and including Poisson's ratio, diameter and radius. |
| $\mathrm{C}_{2}$ | Pipe expansion factor based on pipe restraint conditions and including Poisson's ratio. |

Pipe above ground and allowed to freely move longitudinally is referred to as unrestrained. Buried pipe is prevented from longitudinal movement and is referred to as restrained. Above-ground pipe on rigid supports with pipe clamps preventing longitudinal movement is also referred to as restrained. Other intermediate forms of restraint occur in water pipelines but rarely in oil and gas pipelines and the $C$ factors make provision for such restraint conditions. Also affecting the $C$ factors is the pipe diameter to thickness ratio which is simple for thin wall pipes but needs to incorporate the pipe parameters for thick wall pipe (see Wylie and Streeter [17]).

Table 2-1 - Restraint-based Factors for Hydrotest and Acoustic Calculations

| Restraint-based factors used in hydrotest calculations |  |  |  |
| :---: | :---: | :---: | :---: |
| Restraint Condition | Diameter/thickness ratio | $\mathrm{C}_{1}$ factor for pressure factor | $\mathrm{C}_{2}$ factor for pipe thermal expansion |
| Restrained | large (thin wall pipe) | $1-\mu^{2}=0.9271$ | $2(1+\mu)=2.54$ |
| Unrestrained | large | $5 / 4-\mu=0.98$ | 3 |
| Restrained | small (thick wall pipe) | $\frac{2 t}{D}(1+\mu)+\frac{D\left(1-\mu^{2}\right)}{D+t}$ | $2(1+\mu)=2.54$ |
| Unrestrained | small (thick wall pipe) | $\frac{2 t}{D}(1+\mu)+\frac{D\left(\frac{5}{4}-\mu\right)}{D+t}$ | 3 |

Table Note: Wylie and Streeter [17] recommended use of the thick wall pipe pressure factors, $\mathrm{C}_{1}$, when the D/t ratio is less than approximately 25 . The unrestrained version differs from theirs which is based on one end anchored. The thick wall versions revert to the thin wall versions for large $\mathrm{D} / \mathrm{t}$ ratios typical of many oil and gas pipelines. They did not consider temperature effects.

With constant temperature the above equation (2.1.2) provides the $\mathrm{dV} / \mathrm{dp}$ ratio:

$$
\begin{equation*}
\frac{d V}{d p}=V_{0}\left(\frac{C_{1} D}{E t}+\frac{1}{B_{I}}\right)=V_{0} \frac{1}{B_{I}}\left(\frac{C_{1} B_{I} D}{E t}+1\right) \tag{2.1.4}
\end{equation*}
$$

while constant volume provides the dp/dT ratio:

$$
\begin{equation*}
\frac{d p}{d T}=-\frac{\left(\beta-C_{2} \alpha\right)}{\left(\frac{C_{1} D}{E t}+\frac{1}{B_{I}}\right)}=-\frac{B_{I}\left(\beta-C_{2} \alpha\right)}{\left(\frac{C_{1} B_{I} D}{E t}+1\right)} \tag{2.1.5}
\end{equation*}
$$

In the last equation, the multiplier of the bracket term $\left(\beta-C_{2} \alpha\right)$ is equivalent to a combined pipewater bulk modulus, $B_{P I}$, which can be expressed as:

$$
\begin{equation*}
B_{P I}=\frac{B_{I}}{\left(\frac{C_{1} B_{I} D}{E t}+1\right)} \tag{2.1.6}
\end{equation*}
$$

While the above equations use the isothermal water bulk modulus, in cases where the pressure change takes place relatively quickly (as in acoustic propagation) the adiabatic or isentropic water bulk modulus, $\mathrm{B}_{\mathrm{A}}$, can be used and the combined bulk modulus, BPA, expressed as:

$$
\begin{equation*}
B_{P A}=\frac{B_{A}}{\left(\frac{C_{1} B_{A} D}{E t}+1\right)} \tag{2.1.7}
\end{equation*}
$$

The adiabatic bulk modulus is related to the isothermal version by the ratio of specific heats, $\gamma$, as follows:

$$
\begin{equation*}
B_{A}=\gamma B_{I} \tag{2.1.8}
\end{equation*}
$$

If liquid mixtures are used then an equivalent bulk modulus can be determined from the components. Suspended solids such as colloidal particles in water can be treated in a similar manner as can be suspended bubbles of gases. To combine bulk moduli the following form is needed:

$$
\begin{equation*}
\frac{1}{B_{C}}=\frac{x_{1}}{B_{1}}+\frac{x_{2}}{B_{2}}+\frac{x_{3}}{B_{3}}+\cdots \tag{2.1.9}
\end{equation*}
$$

where
$B_{C} \quad$ is the combined value
$B_{1,2,3} \quad$ are component values
$x_{1,2,3} \quad$ Volume fractions of respective components
It is sometimes easier to use the compressibility, K , which is the inverse of the bulk modulus for such combinations.

Variants and different combinations of the above isothermal equations are used by others e.g. Matta [18]. Values of essential water bulk modulus, thermal expansion coefficients, ratio of specific heats and other properties (where relevant) will be addressed later.

AS2885.5:2020 [10] indirectly provides equations for dV/dP but the appendix on air measurement provides an equation for the effect of free air on the $\mathrm{dV} / \mathrm{dP}$ factor together with worked examples. However it does not provide an equation for the dP/dT factor affected by free air.

A recent U.S. Conference paper by Zhang [19] presented a series of equations which effectively reproduce in a different format the above equations based on AS2885.5 [10]. What was different in his approach is the splitting of the exposed and buried pipe sections within a test section, assessing each independently, combining their results for assessing the temperature effect on pressure, and then comparing the discrepancy between measured pressure change and temperature-based pressure change with a reference pressure change based on a reference temperature change such as $0.25^{\circ} \mathrm{F}\left(0.14^{\circ} \mathrm{C}\right)$. His suggested location for pipe wall only temperature measurements was the bottom of the pipe for both buried and exposed pipe with a recommended period of 24 hours between the probe installation and the start of the test. If the bottom of the pipe was inaccessible then the side only was the preferred alternative. Protection was applied to the sensor to minimise soil influence and the excavation backfill compacted. The number of temperature probes used in his examples were only two or three for the buried section and two for the exposed. He stated that the use of a reference
temperature change as the basis for test acceptance had been used by the company Phillips 66 and its predecessors for three decades. In Australia since the mid-1980s a similar criterion has been used with $0.1^{\circ} \mathrm{C}$ together with a pressure of 10 kPa to allow for pressure measurement instrument uncertainty which is very similar to that of the Phillips 66 company. European Companies and National pipeline authorities took similar approaches and were the initiating influence for incorporation into the first Australian Standard AS1978-1977 [12] for pressure testing of pipelines.

### 2.1.2 Pressure Test Challenges

Pressure can be measured to 1 kPa which then equates to a temperature change of a few thousandths of a degree Celsius with this sensitivity independent of pipe volume and length. The main purpose of the Leak Test is confirmation of leak free status or identification of leaks for which volume change (leak) sensitivity is most important. For a typical cross country pipeline pressure test at 15,000 kPa with a pressure resolution of again 1 kPa , volume sensitivity is limited to around 1:1,500,000 ( $15000 \times 100$ ) which is 1 litre in a section volume of 1,500 cubic metres. For a DN 1200 pipe of approximately 1000 litres volume per metre this limits the section length to 1500 metres. Smaller diameters can have much larger lengths with 6,000 metres for DN 600 and 24,000 metres for DN 300. Leak sensitivity is the starting point from which the maximum pipeline volume is selected to match available pressure sensitivity. Then pressure sensitivity determines average temperature sensitivity. The major challenge with pressure testing is that of obtaining the average temperature measurements of the water inside the pipe. Current methodology is satisfactory but subject to problems raised above including the problem of finding below ground temperature probes (or temperature measurement system) capable of matching required pressure sensitivity. Test duration can be extended to effectively improve instrument sensitivity but with normal test duration of 24 hours to minimise diurnal temperature effects extended duration needs to be in multiples of 24 hours.

Below ground temperature instruments are normally installed only a day or so prior to the pressure test so that no little to no indication of below ground and pipe temperatures is usually available.

Pipeline pressure testing is mostly on what is called the "critical path" of construction schedules with any prior construction delays putting increased time constraints on completing the pressure test as soon as possible with minimal delay. Such focus is challenging in that the pressure test process is not well understood by the remaining construction crews and management. The need for time to stabilise fill temperatures prior to pressurisation and any delays resulting from adverse temperature measurements during testing are not appreciated and often challenged by management. Any need to extend test duration to improve instrument sensitivity would be severely criticised.

### 2.2 ACOUSTIC HYDROTESTING TECHNIQUE

This author proposed an acoustic technique for replacing multiple external pipe wall temperature measurements which consisted of sending from the same end as used for pressure measurements, acoustic signals and measuring the echo time for the returned signal which enables the average internal temperature to be obtained. The technique had been awarded an Australian Patent [6] and the signal generation method and particular variants also [7, 8].

### 2.2.1 Known Literature

The Australian Patent [6] proposing the technique had a filing date of January 1988 following development of suitable transmitters and extensive field trials. The International Patent search report only mentioned one existing patent application in Germany by Hermann Rosen that could affect the Australian Patent. No known development work or field testing had been carried out by Rosen. The Australian Patent was granted. An International Patent was not pursued.

The technique and methodology based on field experiments on buried pipelines during hydrostatic tests was first published in a paper presented at the Offshore Mechanics and Arctic Engineering (OMAE) Conference in Houston Texas, USA titled "Leak Testing of Pipelines using Pressure and Acoustic Velocity", paper No. 88-882 [20].

Subsequent detailed experiments on an above-ground DN200 pipe were reported in an article in the Oil and Gas Journal [21], which showed a direct correspondence between pressure and acoustic velocity. Also revealed were variations of the external pipe wall temperatures indicative of thermal convection activity within the pipe based on temperature sensors located on the top, bottom, sunny and shade sides of the pipe.

Following extensive field experiments during the pressure testing of the Roma to Gladstone DN300 gas pipeline, a paper was presented at the (then) Australian Pipeline Industry Association Conference in Cairns, Queensland, Australia [13]. Observed anomalies mentioned in that paper led to a protracted search for the causes thought at the time to be due to air solution effects on the acoustic velocity. This Thesis is the latest effort at resolution. In that paper was mention of detection of wall thickness changes at road crossings together with acoustic-based estimates of length of the heavier wall pipe. Such locations were many kilometres away from the instrument location.

### 2.2.2 Literature search using Scopus

A search using Scopus available via the University of Wollongong Library was made using the title of the Oil and Gas Journal Article [21]. 24 papers had referenced it while none had referenced the OMAE Conference paper [20]. Of these 24 papers, the only one to mention a layered medium was the paper by Ih et al. [22] who modelled a 31 metre long horizontal PVC DN100 pipe as a layered medium to address leak detection. However, their concept of a layered medium was for different sections in the longitudinal direction representing changed acoustic impedance due to leaks. It had nothing to do with vertical thermal layering. Furthermore, the fluid inside the pipe was gas. The remaining papers or articles addressed leak detection in gas or liquid pipelines, focussing on detection and location of the leak using a range of techniques. None of them address thermal effects since in almost all cases of leak detection in operating pipelines, there is flow of fluid inside the pipeline which then disturbs any convection-based temperature distribution. The only internal acoustic technique mentioned was a neutrally buoyant spherical acoustic combined leak sensor and logging device which was propelled along the inside of the pipe by liquid flow (Fletcher [23, 24]). A similar technique using a different device with similar function but equipped with odometer wheels was used to successfully detect leaks in a few hundred kilometre-long subsea buried Chinese pipeline in 1998-9. The problem with such techniques is correctly locating the detected acoustic leak signal with the position along the
pipe, especially when buried subsea. One paper [25] used ground penetrating radar and infrared camera images to locate water leakage in a buried pipeline based on the changed thermal and radar characteristics of the affected soil. This is the only other mention of thermal effects.

Another Scopus search was carried out using the following text:
pressure AND test OR hydrotest OR leak AND test AND water AND pipeline AND t emperature

This Scopus search resulted in 456 hits. The abstracts or summaries of these were evaluated and around $90 \%$ discarded including a large number of Conference proceedings where individual abstracts or summaries were not available. Of the remaining ones only one paper by Botros et al. [26] specifically addressed internal water temperatures affecting hydrotests but none addressed acoustic techniques for measuring the internal water temperature. One of the papers (Gajdos et al. [27, 28]) addressed creep-related pressure drop following pressurisation at stresses below yield.

Adding the words "acoustic velocity" returned only 4 results. Three of these were conferences in 2013 relating to measurement, sensors and related fields, without identification of specific papers which relate to the search criteria. The fourth paper within Conference proceedings was about subsea hydrotesting of oil and gas pipelines and a communication system capable of transmitting data acoustically from the subsea measuring devices to the surface with recording. This then enables the redeployment of the expensive support vessel (typically diving) otherwise needed to monitor the accumulation of data over many days. Only a summary was available without access to the full text via the University.

Changing the Scopus search words "acoustic velocity" to "sound speed" resulted again in four hits with the same first three and the last relating to pipeline rupture and topic unrelated to the Thesis.

A single paper by Bracken et al. [29] measured acoustic velocities of water-filled fibre-reinforced concrete pipe sections between sensors to determine the average internal condition of the pipe. Deterioration in the pipe condition results in acoustic velocity changes as the wall thickness is a major determinant of the acoustic velocity. The section lengths used were from around 100 to 300 metres and selected on the basis of access to branch fittings for signal generation. They used vibration sensors to detect the acoustic signal which was generated by releasing water or tapping on a valve of fitting. They gave results for measurements in pipe from DN150 to DN600. No mention was made of temperature effects. Since they essentially monitor for changes in subsections of a longer pipe section, relative changes in acoustic velocity between sections are more important than absolute velocity values which are dependent on temperature. They would have had the opportunity for measuring water temperature at the access locations but this was not indicated. While the paper does not address steel pipe, it provides more recent evidence of the successful use of acoustic techniques to assess internal pipe condition.

Other references applied to specific factors and were addressed accordingly.

### 2.2.3 Pressure Surges

Figure 1-4 showed the phases in pipeline pressure testing with an exaggerated indication of pressure changes. In the strength test it showed repeated pressurisations. At the end of the first stage
of pressurisation it showed towards the end a smooth slope terminated by a gradual decline before the first strength test repressurisation. What it did not show were pressure surges generated by every sudden change in water flow into and from the test section and especially the end of the initial pressurisation which is shown poorly in the following pressure chart record Figure 2-1 from a DN 650 pipeline pressure test with section length of around 35 km .


Figure 2-1 - Pressure Surge - DN 650 Buried Pipeline - 35.4 km - end of pressurisation major time scale 30 seconds (horizontal). End of pressurisation marked by arrow with pressure of 12425 kPa when flow from high pressure pump stopped. Subsequent trace shows the pressure surge, initially as a sudden drop almost half of the subsequent drop followed by a gradual rise over a period of around 60 seconds followed by a sudden drop double the initial. (Pressure scale unavailable. time scale of 30 seconds per major vertical line).

The overall pattern of the pressure surge is a saw tooth shaped pressure wave with the pattern repeating every 61.15 seconds which for 35.424 km length indicates a velocity of $1158 \mathrm{~m} / \mathrm{s}$. The poor resolution was a result of copying a small area 19 mm wide from a 150 mm wide chart record. Such record of the end of pressurisation is difficult to catch and as the pressure rose required continuous adjustment of the pressure scale while simultaneously checking the dead weight tester for the final pressure. Occasional spikes interfering with the pattern were caused by checking the dead weight tester which was connected to the same manifold as the pressure transducer. The information on repetition time was based on the chart once the time scale was changed to 10 seconds per centimetre and the pressure scale enlarged.

The information in the above Figure 2-1 is rarely observed. The important points to note are:

- The end of pressurisation (at 12425 kPa )
- Initial surge start is the pressure drop of half the final surge height
- Surge generally follows the incline of the pressure rise at the end of pressurisation
- The average height of the surge is the initial pipeline pressure ( 12425 kPa in this case). A line drawn from the end of pressurisation through the average of the saw tooth waveforms plots the base pressure on which the surge is superimposed.
- Pressure measurement in the presence of surges is best taken at the centre of the rise.
- The start of the sudden drop at the end of the first surge rise has the same shape as the end of the pressurisation.
- The end of the sudden drop is curved and differs from the start of the drop.
- The start of the sudden drops best provides the timing used to determine surge velocity.
- The sharp drop results from high frequencies travelling with higher velocity.
- The rounded termination of the drop results from the slower velocity of lower frequencies.
- The saw tooth initial shape eventually changes to a reduced amplitude sinusoidal shape with time and still able to be detected an hour or more after the start dependent on pressure measurement sensitivity.
- Gauge and absolute based pressure transducers capable of measuring the whole range from zero pressure to the test pressure are needed for such observations.
- Piezoelectric transducers with low frequency cut off are not suitable for such observations but are better suited to monitor high frequency changes and to detect the sudden changes used to determine the velocity.
- Amplitude of the surge depends on the pressurisation slope (pump rate and section volume) and the surge time period.
The following Figure 2-2 is from an offshore pipeline more than ten times the length of the above pipeline and of smaller diameter and shows only the time period after the start of the surge. It shows the change from saw tooth towards sinusoidal and the slow attenuation after one hour with an amplitude of more than 0.2 bar ( 20 kPa ) and implies that the surge will be present at reduced amplitude hours afterwards.


Figure 2-2 - DN 350 Offshore Pipeline - Pressure Surge after Pumps stopped- 365 km Long - digitised from pressure chart - velocity $1304 \mathrm{~m} / \mathrm{s}$.

The frequency of the final sinusoid for the above signal would be 0.00035 Hz for a period of 47 minutes and may not be detected by transducers with a low frequency cut-off. For a long pipeline of 365 km length it would be necessary to use low frequency signals to ensure propagation.


Figure 2-3- DN 350 Offshore Pipeline, Oil Filled, Surge at end of pressurisation. Oil as the fluid medium significantly increases attenuation (data provided by others)u.

Figure 2-3 highlights the features mentioned below Figure 2-1 except for a different pressure. This raises a quandry since the pressure drop immediately following cessation of pumping is almost half of that of the first echo. Subsequent echoes reduce the amplitude of the first echo drop and the first few drops are either higher or similar to the initial drop. The quandry relates to the source pressure signal used in the acoustic technique. Should the source pressure signal be doubled relative to all subsequent echoes? This quandry requires resolution which is not provided by books on pressure surges.

Figure 2-3 from 40 seconds to 150 seconds looks similar to Figure 2-2 whereas the time interval in the latter is one hour or 3600 seconds, more than 20 times and highlights the difference between seawater and oil as propagating fluids for the acoustic signals.

Kinsler et al. [5] has a figure showing the consequences of attenuation on propagating sawtooth waveforms. The following Figure 2-4 was generated by Matlab using a uniform saw waveform source as shown in light red and the attenuated versions after travelling the equivalent of the first echo and then the third echo. This Figure 2-4 closely approximates the Figure in Kinsler et al. [5]. What is of note is that the start of any of the three waveforms has an amost instantaneous rise as expected by the highest frequencies travelling fastest. Such sudden rise has been used in the location of stuck objects inside pipelines with the source generated by sudden opening of a branch valve for a short period. The shape of the saw wave is opposite to that in Figures 2-2 and 2-3 but inverting Figure 2-4 produces similar shapes except for the change in waveform over time.


Figure 2-4 - Theoretical Attenuation of Saw Wave showing Source, First Echo and Third Echo for 990 metre long pipe length.

Figure 2-4 type waveforms can only be observed when pressure transducers operate in DC mode. When Piezoelectric pressure transducers are used, as was the case with most waveforms for the current study, the response is AC and the recorded waveform shape changes significantly as shown in the following Figure 2-5 which applied a high pass filter to the waveforms in Figure 2-4.


Figure 2-5 - Application of High Pass Filter to the Saw Wave Signals from Previous Figure.
To achieve high resolution, especially when attenuation is high, use of Piezoelectric pressure transducers is necessary with the attendant modification of waveform shape as highlighted by the differences between Figures 2-4 and Figure 2-5. Hence the need for an understanding of pressure surges and the effects of type and characteristics of pressure transducer. It is possible to reverse the
filtering effect of the recorded Piezoelectric based waveforms but this has limitations when noise is present. A combination of DC and AC based pressure transducers would allow for better reconstruction of the waveforms with the Piezoelectric transducer providing the fine detail while the DC based transducers provided background corrections.

Transmitter design used for the acoustic measurements is based on generation of pressure surges with current lower limitation of around 1 Hz based on amplitude limits associated with the available piston travel and low frequency power limits of conventional Acoustic Power Amplifiers. The AM1600 Power Amplifier used for many of the recorded waveforms in this document was specially factory modified to permit DC operation since the normal low frequency -3dB rolloff was around 8 Hz . This ability was enabled with a switch.

### 2.2.4 Noise

The above examples of pressure surges represent noise for any acoustic measurements taken during the time that the surges remain. Added to the above surges following pressurisation will be surges resulting from any repressurisation during the strength test and reduction to the leak test pressure which add to the noise.

Ground vibration flexes and ovalises the pipe resulting in pressure signals inside the pipe. This author has had to suspend acoustic velocity measurements when earthmoving equipment was operating nearby and also the movement of a grader almost 30 km away next to the pipeline. While such noise disturbs measurements, it propagates the same as pressure surges and has repetitive patterns in cycles equivalent to the fundamental cycle of surges. It can be used to measure the acoustic velocity and attenuation in the pipeline section using correlation based signal analysis of data collected over multiple cycles.

For long offshore pipelines of similar length to the above example in Figure 2-2 it was often difficult to obtain measurements at onshore locations due to ground vibration noise produced by breaking waves and nearby habitation. At the opposite end on the offshore platform there was negligible locally produced noise as the pipe was vertical underwater and relatively impervious to wave related noise. Lower frequency noise from the shore area 340 km away reached the platform and interfered with measurements.

Such low frequency surge and ground vibration induced noise can be removed from data since it is repetitive and predictable, although attenuated in time, using the properties detailed later in this document.

### 2.2.5 Acoustic Technique Challenges

The technique was developed while the author was employed with an international pipeline construction company with access to pipelines under test and financial resources. Without access to pipelines and company resources it is difficult to obtain data and improve methodology.

The two transmitters mentioned in this document used ceramic magnets which had to be shipped overseas as dangerous goods (magnetic). They are not available commercially nor are suitable subassemblies available. While Neodymium Iron Boron (NdFeB) magnets would be a better alternative
to ceramic, investigations found that magnetising capability of suitable sized magnets could not be found in Australia including the relevant research division of the CSIRO. Such magnetising has to be carried out as a complete magnet circuit assembly so that already magnetised magnets should not be used. Countries such as China, USA and Germany can offer magnetising services which then requires the complete assembly to be shipped and then returned. Shipping of magnetised material is regulated under "Dangerous Goods" with strict restrictions.

The pressure accumulator required precharging at a pressure below the working pressure. What is needed is a self-regulating pneumatic charge system which can be discharged to enable air transport as pressurised vessels are subject to "Dangerous Goods" restrictions.

The 12-bit A/D conversion limitation made it necessary to use lower frequencies with poorer time resolution in order to overcome attenuation issues. A/D converters of at least 16 bit resolution are now available which improves the resolution from 1:4000 to 1:64,000, a 16 times improvement. The temperature coefficient of the timing crystals used in the A/D converter becomes more important as resolution increases. This can be addressed by careful selection or by measuring the crystal temperature and providing compensation. With encapsulated electronics such compensation becomes more difficult and may necessitate inclusion of delayed thermal response to any compensation.

It may be possible to supplement and help eliminate noise sources with additional instrumentation such as accelerometers, geophones, wrap around movement sensitive strips and other technologies.

With improved communications, it may be possible for a high sensitivity pressure transducer to be located at the remote end of the test section and transmit results to the test cabin enabling halving of the attenuation and possible additional use for leak detection and location.

The major challenge is resolving the cause of the acoustic velocity rise during the leak test reported in [13] which was the main purpose of the investigations in this document.

### 2.2.6 Benefits compared with other techniques

It is not possible to provide a direct comparison with the existing technique at this stage of research other than to indicate probable advantages, should the anomalies identified above be resolved. Measurements carried out so far have only been during the leak test phase.

The following can be considered benefits associated with using the acoustic technique instead of the traditional temperature measuring system of multiple probes installed along the test section to measure the buried pipe wall temperatures:

- All measurements are taken from the same end of the test section.
- Section length can be verified against supplied length.
- No need for
o Access along the test section right of way which can damage clean-up and affect environmental restoration efforts.
o Installation of temperature probes to measure below ground pipe wall temperatures.
o No risk of pipe damage while excavating to install temperature probes.
o Access along the right of way to monitor and recover data from below- ground pipe wall temperature probes with its risk to personnel in case of rupture.
o Removal of pipe wall temperature probes and data loggers after test.
o Communication systems between probe locations and test container.
- The average water temperature is measured and not anomalous pipe wall temperatures.
- Whole testing measurement system can be computerised.
- Thermal stability of the test section can be measured by the correlation between pressure and acoustic velocity.
- Measurements can be carried out following filling to track stabilisation progress.
- Measurements of pressure and acoustic velocity can be taken often and at the same time.
- Acoustic velocity measurements can be used to check theoretical hydrotest factors.
- Acoustic measurements can identify the location of air pockets (if any) and allow assessment of potential safety issues should such locations rupture.
- If significant undissolved air is present, the technique can quantify its effect.
- Acoustic measurements can check and confirm the presence of heavier wall pipe at crossing locations.
- Possible detection of vehicle and equipment intrusion or movement on the test section.


### 2.2.7 Additional Requirements or Activities

Sufficient electrical power is needed for the transmitter and computer used to carry out measurements. This may require an increase in capacity compared with the usual arrangement covering lighting, instrumentation, air conditioning or heating, refrigeration and refreshment appliances.

Additional branch valve connections may be required for the installation of the transmitter and special pressure transducer on the test header.

It may be necessary to install pipe wall temperature sensors on exposed pipe at the same end as the acoustic measurements and possibly at the opposite end should such pipe have influence on the pressure not measured by the acoustic technique.

A single below-ground pipe wall probe near the end where the acoustic measurements are made may be needed as a check on the acoustic temperature measurement.

### 2.2.8 Disadvantages compared with other techniques

By not accessing the test section right of way during the test the following are no longer applicable:

- Checking for presence of others or livestock in the restricted safety zone along the right of way.
- Confirming that no construction activity or equipment movements are taking place.
- No longer sampling the backfill material during probe installation.
- Obtaining confirmation as to actual below ground temperature measurements and their trends.

While the above are not really impediments, they are a tolerated feature of having to access buried pipe wall temperature probes and their loggers.

The following are adverse effects:

- Undissolved air content can affect ability of the acoustic technique to measure the temperature and correlate with pressure.
- Settlement of suspended solids such as clay colloids or precipitation of dissolved chemicals can affect measurements.
- Noise can interfere with the technique, especially ground vibration-based noise at low frequencies along the pipeline test section.
- Mains 'hum' or $50 / 60 \mathrm{~Hz}$ noise can be picked up by cabling from the test cabin to transmitter and from transducer preamplifier to test cabin.
- Any failure of one pipe wall probe can be permitted but failure of the acoustic equipment is similar to failure of the primary pressure instrument and needs replacement or spare.
- Transmitter and transducer are attached via valves to the test header and are subject to the same pressures as the pipe and represent pressure safety hazards during installation, use and removal which does not apply to pipe wall temperature probes.


### 2.3 FACTORS INFLUENCING ACOUSTIC MEASUREMENTS

The same pipe characteristics needed for conventional pressure testing are used to determine the expected acoustic velocities and their dependence on pressure and temperature:

- Test headers, valves, fittings, hoses, pumps, instruments etc.
- Pipe lengths of respective wall thickness and locations of such pipe.
- Pipe diameter(s)
- Pipe wall thicknesses.
- Pipe thermal expansion coefficient.
- Expected water isothermal compressibility or bulk modulus.
- Expected water thermal expansion.
- Expected test pressures for strength and leak tests.
- Frequency range of signals used.
- Expected acoustic velocity based on the above factors.

Additional water data requirements for acoustic measurements as against convenctional hydrotest measurements are as follows:

- Density
- Viscosity
- Adiabatic compressibility or bulk modulus.
- Water acoustic velocity in infinite medium.
- Ratio of specific heats.
- Specific heat at constant pressure.

These can be obtained from sources capable of providing those water factors needed for the conventional technique or dedicated computer programs written for the purpose and integrated into the software package running the acoustic measurements.

This section will address specific factors that affect the acoustic measurements that do not apply to conventional leak testing. The relevant equations are given.

### 2.3.1 Timing Accuracy of A/D Conversion

In order to measure velocities it is fundamentally important to have reliable time measurement. The signal commencing from the outgoing source signal until the last important returning echoes is digitised by the Analog to Digital A/D converter on the circuit board used for both generating the outgoing signal via the Digital to Analog D/A converter and digitising the received signals. On the same circuit board is a quartz crystal which provides the timing pulses which in turn control the A/D and D/A conversion. Such crystals are chosen for the required frequency but are subject to small changes due to temperature. They have timing tolerances which for the Crystek crystal used in the RTI815 circuit board from Analog Devices has a tolerance of $+/-50$ parts per million over the temperature range from -25 to $+70^{\circ} \mathrm{C}$. For the acoustic velocity measurements this translates to approximately $+/-0.05 \mathrm{~m} / \mathrm{s}$ over the whole range. The specification is compared with measurements in the following Figure 2-6 carried out on site over a limited temperature range but confirming the general compliance with standard specification.


Figure 2-6- A/D D/A Timing Crystal Typical and Measured Temperature Dependence
Since the crystal was on a circuit board which was installed in an expansion chassis without forced cooling in a mobile laboratory in remote areas with air conditioning but not always working, it was subject to temperature changes within the comfort range of the computer user. During a pressure test when measurements were carried out there could easily be 10 to 20 degree Celsius change in
temperature of the circuit board over the 24 hours of the leak test. Such range can result in time variation of up to 40 parts per million or +/- 20 parts per million which then translates to $+/-0.02 \mathrm{~m} / \mathrm{s}$ velocity variation and is less than the 12 bit resolution of 200 parts per million and not important.

The Crystek crystal temperature coefficient was investigated in order to eliminate timing error as a potential cause of the anomalous acoustic velocity results. During field velocity measurements the crystal and the mobile laboratory temperatures were not taken. Such measurements would be required should more precise velocities be needed.

### 2.3.2 Pipe Length in Test Section

Acoustic velocity depends on knowledge of distance and time. While time can be measured in milli to micro seconds the resultant velocity depends on the test section length. Pipe location is normally surveyed and the geographical coordinates and height of the top of the pipe recorded and incorporated into what is called the "As Built" drawings. The Eastings and Northings of the position are commonly used to determine the pipeline section length in plan view. What is not often provided is the true length which includes the contribution from the height which is mostly small but in rugged areas can be significant. This is referred to as the slope distance or slope chainage.

Usually along a pipeline route kilometre posts (KP) and marker pegs are installed by the surveyors which are then used by the construction crews in following the pipeline design detailed in the Alignment Sheets based on the KPs. During construction it is not uncommon for the route of the pipeline to be changed or modified as a consequence of newly discovered underground features, changes since the design was finalised, or agreement changes with property owners. These deviations from the original Alignment Sheets are referred to as reroutes but the original KPs are not changed so that there could be reductions or increases in the section length as a consequence.

Another source of length information is the "Pipe Book" which registers all the pipes in the pipeline together with their individual identification and measured length and the identification of all welds joining pipes. As with any detailed documentation, errors occur and are difficult to identify and correct. There is usually little comparison work between survey crew and weld inspection crews and often it is the Pressure Test Crew which has the unenviable task of resolving inconsistencies as it can affect their test section termination identification and of course the test section length which affects dP/dV calculations and checks during generation of the Pressure/Volume plot during pressurisation.

It can be difficult for the Pressure Test Crew to obtain the correct information on section length especially if they are a subcontractor with limited access to those with such information.

The acoustic velocity can be a valuable check on the survey-provided length, both in terms of gross errors and small deviations which the dP/dV measurements may not be able to detect. The acoustic technique can also detect the location of wall thickness changes and other features such as factory bends, branch fittings and valves which can then be checked and if their location is reliably known can be used to "calibrate" the acoustic velocity.

While best to have accurate length data, velocity changes are more important and an approximate length is sufficient for these.

### 2.3.3 Water Thermal and Acoustic Properties

The most comprehensive and accurate source of data on the following properties of pure and salt water in an infinite medium can be obtained using the equations and factors in the IAPWS publications, especially [30, 31] and for pure water and any variation between it and seawater [32, 33]. Unfortunately the method of calculation is complex and does not lend itself to simple equations. IAPWS and their predecessor group IAPS have also published equations for shear viscosity and thermal conductivity [34, 35]. These cover ranges of pressure and temperature.

The calculations can provide the following water properties relevant to this Thesis.

- Density
- Compressibility both isothermal and adiabatic.
- Bulk modulus both isothermal and adiabatic.
- Acoustic velocity
- Thermal expansion
- Specific heat at constant pressure
- Specific heat at constant volume
- Ratio of specific heats
- Shear viscosity
- Thermal conductivity

A program was developed in Excel to calculate the different properties and was later converted into Matlab. IAPWS provided selected tables of values against which to compare any numerical calculations and the above attempts were thus verified. Added to the above was the thermal diffusivity which is a combination of the above properties.

The Australian Standard for hydrotesting AS2885.5:2020 [10] includes simple equations for calculation of pure water compressibility (isothermal) and thermal expansion which are the only water properties needed for conventional hydrotests. The equation published for the restrained factor $B$ is in fact only the thermal expansion coefficient of water and is consistent with the IAPWS equations over the range 0 to 30000 kPa and 0 to $50^{\circ} \mathrm{C}$ but with slight variation due to the use of a single equation as compared with the far more numerous and complex IAPWS equations.

The A value given in the following equation is the isothermal compressibility which varies with both pressure and temperature with units of reciprocal kPa .

$$
\begin{gather*}
A=\left[0.003897 T^{2}-0.3133 T+50.65\right]\left[\frac{1-p}{411844}\right]  \tag{2.3.1}\\
\times 10^{-8}
\end{gather*}
$$

The water thermal expansion coefficient equation was based on IAPWS-95 and is a good approximation to it over the pressure range from 0 to 30000 kPa and temperature range from 5 to $40^{\circ} \mathrm{C}$ with a maximum error of $\pm 9 \times 10^{-6}$ at atmospheric pressure and reducing with higher pressure. Errors decrease further as the temperature is reduced below $40^{\circ} \mathrm{C}$ :

$$
\begin{align*}
& \alpha_{W} \\
& =\left[(3.102-0.07983 T) \frac{p}{1000} \sqrt{14872 T+175490}\right.  \tag{2.3.2}\\
& -483.3] \times 10^{-6}
\end{align*}
$$

Where

| A | the isothermal water compressibility |
| :--- | :--- |
| T | temperature in ${ }^{\circ} \mathrm{C}$ |
| p | pressure in kPa (gauge) |
| $\alpha_{W}$ | water thermal expansion coefficient. |

The international oil and gas company Shell has a Pressure Test Specification [36] which includes graphs showing the variation of the bulk modulus and thermal expansion for both pure water and sea water over the pressure range from 1 bar to 550 bar and temperature from 0 to 50 for fresh water and 0 to 40 for sea water. Only points at pressure intervals of 50 bar and temperature intervals of 10 or $15^{\circ} \mathrm{C}$ are provided making it necessary for interpolation for intermediate values. Countries in which Shell is the major Investor often use the same document. The values in the Shell charts are consistent with values calculated using the IAPWS equations. Other major European oil and gas companies and national authorities have tables covering typical pipeline temperatures and pressures for the same factors but usually in smaller intervals that those in the Shell Specification. The German Company KOPP (no longer existing) in the late 1970s and early 1980s used tables of compressibility and thermal expansion supplied by TÜV (Technischer Oberwachungs-Verein Bayern e. Y. Munchen) with temperatures at $1^{\circ} \mathrm{C}$ intervals and pressure at $10 \mathrm{Bar}(1000 \mathrm{kPa})$ intervals up to $300 \mathrm{Bar}(30000 \mathrm{kPa})$. The thermal expansion tables were a combination of the steel thermal expansion and the water thermal expansion based on the most common situation of restrained or buried conditions. The values in these tables were consistent with the later equations of IAPWS.

The most convenient are equations which can then be programmed together with the pipe characteristics to provide the required values and factors for hydrotests. Pressure Testing Contractors usually have their own software to provide the required water properties at the test temperature and pressure. Where more accurate values are needed then the equations based on IAPWS-95 and subsequent documents need to be used.

### 2.3.4 Other Liquid Thermal and Acoustic Properties

Operating oil and fuel pipelines need regulatory pressure testing and is normally carried out with product as water would create contamination and other problems.

## Hydrocarbon Fluids

AS2885.5:2020 [10] permits the use of hydrocarbon liquids for pressure testing. The calculations provided in Appendix $C$ of that document only provided for the compressibility and density at different
temperatures and pressures but not acoustic velocity. During this current study errors including missing equations for thermal expansion were identified which were originally published in AS2885.5:2002 [37] and continued unchanged to the present time.

## Effect of water/antifreeze mixtures on thermal and acoustic properties.

Botros et al. [26] reported on 50\% antifreeze properties based on available data but were unable to extend their work to other fractions due to lack of data. Properties of mixtures would assist in estimating these values. What is of particular interest to the current study is the effect of such mixtures on acoustic velocity and $\mathrm{dP} / \mathrm{dT}$, $\mathrm{dP} / \mathrm{da}$ and da/dT values to enable such liquids to be used during winter in high latitudes.

### 2.4 ACOUSTIC VELOCITY AND ATTENUATION IN LARGE BODIES

For the acoustic hydrotesting technique measurement of acoustic velocity is a primary measurement along with pressure. Hence predicting acoustic velocity and its variation with temperature, frequency and pressure is essential. To achieve such prediction it is essential to have good mathematical models of such acoustic velocity variation together with accurate fluid properties. This Section progresses through the mathematical expressions for acoustic velocity.

Acoustic velocity is dependent on factors noted in Section 2.3. Acoustic velocity in a large body of water or air is a fundamental property of the fluid which depends on temperature and pressure. When such fluid is enclosed within a pipe or tube the velocity generally is reduced due to the flexibility or elasticity of the pipe. Furthermore fluid viscosity and thermal characteristics influence the velocity in terms of frequency due to interaction between the fluid and the pipe wall. Generally the velocity reduces with reduction in frequency with such reduction generally referred to as dispersion which like many terms in Science has a technical meaning inconsistent with the English language meaning. Another influence is that of the nature of the soil or backfill surrounding the pipe and its water content if buried.

While the title of this document specifically mentions water, pressure tests can be carried out using high pressure compressed air especially where high gradient slopes occur in mountainous regions, such as the western slopes of the Andes in South America, because hydrotests are very difficult to carry out with test points at every 100 to 200 metre elevation change on high gradient slopes where access is extremely difficult. For this reason and for the fact that preliminary and subsequent activities to hydrotest involve compressed air it is considered useful to ensure that the following equations address both air and water.

Because of the multiple factors affecting velocity, these will be addressed progressively in the following sub sections.

### 2.4.1 Acoustic velocity in large bodies of water and air

Sound propagation in water and air takes place so rapidly that there is no time for the particles within the fluid to transfer heat so that the properties used need to be the adiabatic, isentropic or without heat transfer.

The basic acoustic velocity equation in a large body of air or water (which is equivalent to an infinite medium) is:

$$
\begin{equation*}
a_{0}=\sqrt{\frac{B_{A}}{\rho}}=\sqrt{\frac{\gamma B_{I}}{\rho}} \tag{2.4.1}
\end{equation*}
$$

where:

| $a_{0}$ | acoustic velocity in infinite medium |
| :--- | :--- |
| $\gamma$ | ratio of specific heats, |
| $\mathrm{B}_{\mathrm{I}}$ | isothermal bulk modulus |
| $\mathrm{B}_{\mathrm{A}}$ | adiabatic bulk modulus |
| $\rho$ | density. |

From the equation can be seen the need for the ratio of specific heats, $\gamma$, when the isothermal bulk modulus is used. Its reciprocal, isothermal compressibility is usually used for pressure test dP/dV calculations and should be available.

While pressure tests are carried out with water-filled pipes, air can sometimes be present and its effects need to be taken into consideration. Hence the equations have dual use and where differences occur for the different media these are highlighted and also provide an insight into the respective equations where differences occur.

Since the density and bulk modulus of air are directly proportional to pressure, the acoustic velocity in air does not change with pressure. For water, the effect of pressure on density and bulk modulus differ to such an extent that acoustic velocity reaches a peak around $76^{\circ} \mathrm{C}$ [38] but continues to drop below $4^{\circ} \mathrm{C}$, contrary to the minimum density at that value.

### 2.4.2 Bulk fluid attenuation in large bodies of air and water

For an unbounded fluid the attenuation due to viscous effects is of the form:

$$
\begin{equation*}
\alpha_{s}=\frac{\omega^{2}}{2 \rho_{0} c^{3}}\left[\frac{4}{3} \eta+\eta_{B}\right] \tag{2.4.2}
\end{equation*}
$$

Where:
$\eta \quad$ shear viscosity
$\eta_{B} \quad$ bulk viscosity which is generally zero with the exception of some fluids such as water with a value approxiately 3 times the shear viscosity $\eta$.

For the separate case of thermal effects on attenuation an equation similar to the above is given as:

$$
\begin{equation*}
\alpha_{K}=\frac{\omega^{2}}{2 \rho_{0} c^{3}}\left[\frac{(\gamma-1) K}{C_{p}}\right] \tag{2.4.3}
\end{equation*}
$$

These two equations can be added to provide the total absorption or attenuation coefficient:

$$
\begin{equation*}
\alpha=\alpha_{s}+\alpha_{K}=\frac{\omega^{2}}{2 \rho_{0} c^{3}}\left[\frac{4}{3} \eta+\eta_{B}+\frac{(\gamma-1) K}{C_{p}}\right] \tag{2.4.4}
\end{equation*}
$$

For a frequency of 100 Hz in water, this attenuation is of the order of $2.0 \mathrm{E}-6 \mathrm{~dB} / \mathrm{m}$ with the thermal term negligible. This is some three orders of magnitude smaller than the effects inside a cylinder or pipe and so can be neglected in the case of water.

For air, with lower velocity, the attenuation at the same frequency is approximately $1.4 \mathrm{E}-6 \mathrm{~dB} / \mathrm{m}$ with the thermal term of similar magnitude to the viscosity terms. This absorption or attenuation only applies without consideration of the effects of moisture. With dry air the attenuation is increased three orders of magnitude with increased humidity resulting is slightly lower attenuation but still two orders of magnitude higher than given by the above equation. At around 240 Hz the attenuation with moisture is almost three orders of magnitude higher from 0 to $100 \%$ humidity. Variation with frequency below 240 Hz is not linear (on a log scale) when moisture affects attenuation. Hence while the order of magnitude of classical absorption for both water and air using the above equation gives similar values, air by contrast is immensely affected by moisture. Only at very high ultrasonic frequencies does the above equation for absorption become significant as it increases as the square of frequency whereas in a fluid filled pipe, attenuation increases as the square root of the frequency. Temperature, but not pressure, affects viscosity and so the above attenuation is temperature dependent other than pressure effects on density so that as pressure increases there is an inverse attenuation due to density changes only.

Seawater has additional factors relating to boric acid and magnesium sulphate molecular effects on absorption which increases absorption approximately two orders of magnitude ( $\mathrm{on} \mathrm{dB} / \mathrm{m}$ scale).

### 2.5 ACOUSTIC VELOCITY AND ATTENUATION IN AIR FILLED PIPES

In air filled pipes, the presence of a pipe wall only affects the velocity and attenuation through viscous interaction between the fluid and the pipe wall. Pipe wall thickness has no bearing on either of these factors. Hence all equations for acoustic velocity and attenuation only include pipe internal radius without wall thickness. In addition, velocity is only dependent on fluid properties and independent of pressure since both density and bulk modulus both increase with pressure without the ratio changing. Attenuation however is highly dependent on density, shear viscosity and thermal characteristics but not with bulk modulus and consequently reduces with pressure.

Kirchhoff in the nineteenth century produced equations for velocity and attenuation in air filled pipes or tubes with his work translated into English by Rayleigh [39] later in the same century. Both provided approximations to the solutions which used Bessel Functions. Weston [40, 41] in the mid $20^{\text {th }}$ Century provided better approximations to the solutions by approaching a difficult frequency region from higher and lower frequencies which will be termed the Low Frequency and Ultra Low Frequency solutions respectively in this document to avoid confusing terminology used by Rayleigh and Weston. Weston obtained measurements of both phase velocity and attenuation bridging across this difficult frequency region which demonstrated the validity of his equation approximations on either side but leaving a gap only bridged by experimental results. Rayleigh's and much simplified versions of Weston's Low Frequency solution are found in current textbooks on acoustics. Equations based on

Weston's solution for air will later be used for water with further simplification but addition of pipe elasticity and wall thickness.

### 2.5.1 Weston's Acoustic Phase Velocity and Attenuation in Air Filled Pipes

The following Figure 2-7 plots Weston's [40] theoretical equations and experimental data for phase velocity against log scaled frequency as the $X$ axis. There is no overlap of the two equations and the "transition" zone between the two curves has spurious values. His experimental data bridges the two regions of Low Frequency on the right and Ultra Low Frequency on the left of the transition zone.


Figure 2-7- Graph using Weston's equations and digitised data for velocity variation with frequency for air with log scale. The Low Frequency region curve (right red) does not correctly extend to zero frequency which the Ultra Low Frequency (left blue) does. The transition zone is centred around 0.0001 Hz . The dashed line is based on the Tanh function to fit the curves and data.

Weston used scaled frequency for the $X$ axis based on the product of the pipe or tube internal radius multiplied by the square root of frequency. Figure $2-8$ and the subsequent figures have used an internal radius of 427 mm for DN900 pipe to enable comparisons with subsequent figures for this nominal diameter.


Figure 2-8 - Graph using Weston's equations and digitised data for velocity variation with frequency for air using a linear frequency scale. Equations and Weston's data for very small radius tubes has been adjusted for DN900 pipe. The Low Frequency region curve (red) does not extend to zero frequency whereas the Ultra Low Frequency curve (blue) does. The empirical Tanh function approximation is shown in the dashed green line.

Weston's equations for attenuation in air filled pipe are graphed in the following Figure 2-9 and Figure 2-10.


Figure 2-9- Weston's Scaled Attenuation (linear scale) plotted against scaled radius and frequency (log scaled) - Air filled Tubes. Added to the figure are Weston's experimental data and an empirical Tanh approximation by this author. The Low Frequency region (right red) and Ultra Low Frequency region (left blue) almost connect.

The above Figure 2-9 has been replotted with a log frequency scale for the $X$ axis and a log attenuation scale in dB/km for the vertical Y axis for a DN900 pipe.


Figure 2-10 - Linear Frequency version of Weston's two equation and Data. Added to the figure is the Empirical Tanh approximation as shown in the previous figure. A blue dashed line has been drawn below the attenuation curve to highlight the offset of the Ultra Low Frequency portion of the result. Weston's data has been modified for DN 900 pipe. The easily observed red and blue curves above the data points are spurious portions of Weston's two solution equations and are to be ignored. The changeover between the two solutions occurs around 0.0001 Hz which for air represents the fundamental frequency in a pipeline around 1700 km long, slightly longer than the current longest in the World.

From Figure 2-7 can be observed that the phase velocity above 0.001 Hz can be calculated using the Low Frequency equations and from Figure 2-10 attenuation can also be calculated similarly. Below such frequency it is necessary to consider the influence of the Ultra Low Frequency equations. For attenuation, the linear portion of Figure 2-10 only extends down to 0.1 Hz . Textbooks such as Kinsler et al. [5] only provide equations covering the linear portion of the attenuation curve in Figure 2-10.

The air properties used for the above figures were taken from Kinsler et al. [5] for $20^{\circ} \mathrm{C}$ and atmospheric pressure.

Weston's equations for the two regions are as follows:

## Weston's Low Frequency Region Equations

Weston's equations (3) and (44) to (46) in [40] for phase velocity and attenuation in the Low Frequency region take the following form:

$$
\begin{gather*}
c_{P}=c\left\{1-\frac{\gamma_{1}}{a \sqrt{(2 \omega)}}+\frac{\gamma_{1}{ }^{2}}{2 a^{2} \omega}-\frac{\left(\gamma_{3}+\frac{\gamma_{1}{ }^{3}}{2}\right)}{a^{3} \sqrt{\left(2 \omega^{3}\right)}}\right\}  \tag{2.5.1}\\
\alpha_{g}=\frac{\gamma_{1}}{a c} \sqrt{\left(\frac{\omega}{2}\right)}+\frac{\gamma_{2}}{a^{2} c}+\frac{\gamma_{3}}{a^{3} c \sqrt{(2 \omega)}} \tag{2.5.2}
\end{gather*}
$$

where the equations for $\gamma_{1}, \gamma_{2}$ and $\gamma_{3}$ are as follows:

$$
\begin{array}{r}
\gamma_{1}=\sqrt{\left(\frac{\eta}{\rho_{0}}\right)}+(\gamma-1) \sqrt{\left(\frac{K}{\rho_{0} C_{p}}\right)} \\
\gamma_{2}=\left(\frac{\eta}{\rho_{0}}\right)+(\gamma-1) \sqrt{\left(\frac{\eta}{\rho_{0}} \frac{K}{\rho_{0} C_{p}}\right)}-\frac{\gamma(\gamma-1)}{2}\left(\frac{K}{\rho_{0} C_{p}}\right) \\
\gamma_{3}=\frac{15}{8}\left(\frac{\eta}{\rho_{0}}\right)^{\frac{3}{2}}+4(\gamma-1) \frac{\eta}{\rho_{0}} \sqrt{\left(\frac{K}{\rho_{0} C_{p}}\right)} \\
+\frac{3(\gamma-1)(\gamma-2)}{2}\left(\frac{K}{\rho_{0} C_{p}}\right) \sqrt{\left(\frac{\eta}{\rho_{0}}\right)}  \tag{2.5.5}\\
+\frac{(\gamma-1)\left(4 \gamma^{2}-12 \gamma+7\right)}{8}\left(\frac{K}{\rho_{0} C_{p}}\right)^{\frac{3}{2}}
\end{array}
$$

where the symbols in the above equations are as follows:
a
$\omega$
$\eta \quad$ shear viscosity
$\rho$
K thermal conductivity
Y ratio of specific heats
$\mathrm{C}_{\mathrm{p}}$
$\alpha_{g} \quad$ attenuation in units of Nepers/metre
c velocity in boundless medium
Cv specific heat at constant volume
$\mathrm{Cp} \quad$ specific heat at constant pressure (not the phase velocity)
These equations have been modified slightly from Weston's in that Weston uses $\mathrm{C}_{v}$ and not $\mathrm{C}_{\mathrm{p}}$ so that the factor of $C_{p} / \gamma$ is used to replace $C_{v}$.

Substituting the values for air at $20^{\circ} \mathrm{C}$ and atmospheric pressure the three factors become:

$$
\begin{aligned}
& \gamma_{1}=6.12 E-03 \\
& \gamma_{2}=1.65 E-05
\end{aligned}
$$

## CHAPTER 2 - LITERATURE REVIEW

$$
\gamma_{3}=1.80 E-07
$$

Such values suggest that at least the $\gamma_{1}$ and $\gamma_{2}$ terms need to be included in calculations and $\gamma_{3}$ as the frequency becomes small in the case of air.

## Weston's Ultra Low Frequency Region Equations.

For the region down to zero frequency referred to by this author as the Ultra Low Frequency region, the following equations from Weston [40] apply (including typographical correction $\sqrt{ } 2$ to his equation (40)). The symbols are as for the Low Frequency region but with different equations for $\mathrm{y}_{2}$ and $\gamma_{3}$.

$$
\begin{gather*}
c_{P}=\frac{c a}{2} \sqrt{\frac{\omega \rho}{\eta \gamma}}\left\{1-\gamma_{2} a^{2} \omega+\left(\gamma_{3}+\gamma_{2}^{2}\right) a^{4} \omega^{2}\right\}  \tag{2.5.6}\\
\begin{array}{c}
\alpha_{g}=\frac{2}{c a} \sqrt{\frac{\omega \eta \gamma}{\rho}}\left\{1-\gamma_{2} a^{2} \omega\right. \\
\left.-\gamma_{3} a^{4} \omega^{2}\right\}
\end{array}
\end{gather*}
$$

Where $\gamma_{2}$ and $\gamma_{3}$ factors differ from the Low Frequency Region and are:

$$
\begin{gather*}
\gamma_{2}=\frac{1}{4}\left\{\frac{\rho_{0}}{3 \eta}-\frac{(\gamma-1)}{4} \frac{\rho_{0} C_{p}}{\gamma K}\right\}  \tag{2.5.8}\\
\gamma_{3}=\frac{1}{32}\left\{-\frac{1}{8}\left(\frac{\rho_{0}}{\eta}\right)^{2}-\frac{(\gamma-1)}{4} \frac{\rho_{0}}{\eta} \frac{\rho_{0} C_{p}}{\gamma K}\right. \\
\left.+\frac{(\gamma-1)(13 \gamma+3)}{48}\left(\frac{\rho_{0} C_{p}}{\gamma K}\right)^{2}\right\} \tag{2.5.9}
\end{gather*}
$$

For air at $20^{\circ} \mathrm{C}$ and atmospheric pressure the above constants in SI units are:

$$
\begin{gathered}
\gamma_{2}=4.62 E+03 \\
\gamma_{3}=-1.74 E+07
\end{gathered}
$$

### 2.5.2 Pressure consideration for attenuation in air filled pipe.

Angona [42] provided an equation for attenuation in the following form which addresses pressure for gases which was not addressed by Kinsler et al. [5] other than indirectly with the density term which must be adjusted for pressure:

$$
\begin{equation*}
\alpha=\sqrt{\pi \eta}\left[\frac{1}{\sqrt{\gamma}}+\frac{\gamma-1}{\gamma}\left(\frac{K}{C_{v} \eta}\right)^{\frac{1}{2}}\right] \frac{1}{r}\left(\frac{f}{p}\right)^{\frac{1}{2}} \tag{2.5.10}
\end{equation*}
$$

$$
\begin{equation*}
\alpha=\sqrt{\frac{\pi \rho_{0}}{\gamma}} \sqrt{\frac{\eta}{\rho_{0}}}\left[1+(\gamma-1) \sqrt{\left(\frac{K}{C_{P} \eta}\right)}\right] \frac{1}{r}\left(\frac{f}{p}\right)^{\frac{1}{2}}=\sqrt{\frac{\pi \rho_{0}}{\gamma}} \gamma_{1} \frac{1}{r}\left(\frac{f}{p}\right)^{\frac{1}{2}} \tag{2.5.11}
\end{equation*}
$$

Angona [42] states that "most investigators agree with the Kirchhoff formula as to radius and frequency dependence; however, there is a wide variation as to the actual magnitude of the attenuation".

Angona carried out experimental measurements and found that the attenuations were $4.5 \%$ higher than given by the above equation for dry air and dry nitrogen over the pressure range of 2 to 250 mm of Hg and from 2 to 10 kHz . The low pressures from almost vacuum to partial vacuum were especially intended to increase the attenuation in the 8.41 mm radius glass tube of 1.2 m length. Although he only used a limited frequency range from 2 to 10 kHz and larger pressure range from 2 to 250 mm Hg , this relationship enable him to obtain data from an extended range from 8 to $2000 \mathrm{kHz} / \mathrm{bar}$ range which normally is difficult to achieve. Rayleigh [39] had intimated that use of low pressures would emphasise attenuation. Angona corrected first for the classical gas attenuation. No mention was made of the thickness of the glass tube nor the phase velocities. Angona's experimental results for dry air confirm his equation over the experimental range with values $4.5 \%$ higher as indicated above.

So that by rearrangement of Angona's above equation:

$$
\begin{equation*}
\frac{\alpha r}{\sqrt{f}}=\sqrt{\pi \eta}\left[\frac{1}{\sqrt{\gamma}}+\frac{\gamma-1}{\gamma}\left(\frac{K}{C_{v} \eta}\right)^{\frac{1}{2}}\right]\left(\frac{1}{p}\right)^{\frac{1}{2}} \tag{2.5.12}
\end{equation*}
$$

Weston's [40] theoretical attenuation curves are reported in terms of the product of attenuation, radius and the inverse of the square root of frequency. These factors are the same as on the far left of the second version with the right side effectively a constant for the range of applicability of this equation times the pressure factor. However this assumes that pressure is at atmospheric pressure for all cases. Adding pressure requires the above equation to become:

$$
\begin{equation*}
\alpha r\left(\frac{p}{f}\right)^{\frac{1}{2}}=\alpha r\left(\frac{p}{f p_{0}}\right)^{\frac{1}{2}}=\sqrt{\pi \eta}\left[\frac{1}{\sqrt{\gamma}}+\frac{\gamma-1}{\gamma}\left(\frac{K}{C_{v} \eta}\right)^{\frac{1}{2}}\right] \tag{2.5.13}
\end{equation*}
$$

so that scaled attenuation should be reported as the product of attenuation, radius and the square root of the ratio of absolute pressure to frequency multiplied by the reference pressure (atmospheric pressure). The reference pressure is added to avoid scaling and unit issues. The above equations are in a form where all the terms relating to density have been rearranged, especially the viscosity terms.

### 2.6 ACOUSTIC PHASE VELOCITY AND ATTENUATION IN WATER FILLED PIPE

Excluding temperature effects, once water is contained within a pipe, its density and bulk modulus do not change but its bulk modulus is effectively reduced due to the pipe elasticity. As was the case for air inside pipes, there are further frequency based influences on phase velocity and attenuation associated with viscosity of the liquid in the pipe and its interaction with the pipe wall.

Jacobi [43] carried out measurements in a brass tube of 2" (DN50) internal diameter with $1 / 8$ " $(3.175 \mathrm{~mm})$ wall thickness with results shown in the following Figure 2-11.


Figure 2-11 - Figure from Jacobi of the phase velocity of water in DN 50 brass tube for the fundamental mode $(0,0)$ and the first mode $(0,1)$. Jacobi addressed pipe elasticity but only ideal liquids without viscosity although any experimental results could not exclude viscous effects other than by selecting frequencies where their effect was minimal.

Only the fundamental mode $(0,0)$ is of interest to this document. However the lack of experimental data between around 16 kHz and 21 kHz was due to energy diverted to the $(0,1)$ mode for higher frequencies. Of particular interest for the $(0,0)$ mode is the steady drop in phase velocity as the frequency increases from around 6 kHz to 16 kHz with a dip in the theoretical curve reaching a minimum around 21 kHz where the $(0,1)$ mode phase velocity data have their maximum values. There was no data below around 6 kHz . Jacobi did not report on attenuation.

Baik et al. [1-4] based their work on that of Elvira-Segura [44] and Lafleur and Shields [45] and identified typographical errors in the equations provided by both. They stated that their solution equation was the same as that of Elvira-Segura. Elvira-Segura considered Kirchhoff's theory and Weston's [40] work on different tube widths. They also made mention of Del Grosso [46] as did ElviraSegura however Del Grosso like Lafleur and Shields only addressed the inviscid (no viscosity) case. Baik et al. addressed both pipe elasticity and viscosity.

The following phase velocity Figure 2-12 from Baik et al. [1, 3] was based on theoretical calculations for a steel pipe of outside diameter 141.3 mm and wall thickness 6.55 mm and surprisingly for mercury as the liquid. However the infinite medium velocity for mercury is $1450 \mathrm{~m} / \mathrm{s}$ which is similar to that of water around $1490 \mathrm{~m} / \mathrm{s}$. Their other figures covered PMMA (poly methyl methacrylate) with water which has significantly different mechanical properties from steel pipe. Since PMMA is not relevant to this document it will not be addressed other than it caused a shift in response to lower frequencies and can be useful for limited pipe length experiments. The Baik et al. document also reported on water/aluminium results. The purpose behind the Baik et al. mercury based research and comprehensive equations was the establishment of a gas bubble free basis for then determining gas bubble based velocity reduction as a means of determining gas bubbles in nuclear reactor cooling systems.


Figure 2-12 - Baik et al. figure showing the phase velocity ratio plotted against the wave number pipe radius product for the first 7 modes of propagation.

What is of interest for this document is only the ETO mode which is poorly covered in the above figure showing the effects on the phase velocity dispersion. Previously LaFleur and Shields [45] addressed aluminium/ water together with PVC/ water but did not include the viscous and heat transfer effects and their experimental verification only extended down to around 8 kHz for the ETO mode even though the title of their paper was "Low-frequency propagation modes in a liquid-filled elastic tube waveguide". The effects of viscosity and heat transfer have little effect in the range of frequencies they addressed in experiments.

The Baik et al. [1, 3] figure for attenuation in pipes or tubes is shown in the following Figure 2-13.


Figure 2-13 - Baik et al. figure showing scaled attenuation plotted against wave number radius product for modes ETO to ET5.

The difficulty of solving the Baik et al. equations without their Matlab solution software in the public domain suggests that alternative approaches involving approximations may be necessary. The above graphs provide insufficient detail for the ETO or $(0,0)$ mode phase velocities and attenuation. Kyunmin Baik was requested by this author to provide solutions to their equations for specific pipe diameters and wall thicknesses. These are addressed in the subsequent Chapter.

### 2.6.1 Non-viscous Pipe Velocity Equations

Basic acoustic velocity in a large expanse of liquid was addressed in Secion 2.4.1 and required as input the fluid bulk modulus and density. When liquid is contained inside a pipe its effective bulk modulus is compromised by the pipe elasticity which appears as an additional term in the following equation only for liquids such as water but not for air:

$$
\begin{gather*}
a=\sqrt{\frac{B_{A}}{\rho\left(1+\frac{B_{A} D C}{E t}\right)}}=\frac{a_{0}}{\sqrt{\left(1+\frac{B_{A} D C}{E t}\right)}}  \tag{2.6.1}\\
=\frac{a_{0}}{\sqrt{\left(1+\frac{\gamma B_{I} D C}{E t}\right)}}
\end{gather*}
$$

Where:
a
acoustic velocity inside a liquid filled pipe ( $\mathrm{m} / \mathrm{s}$ )
ao acoustic velocity in large body of liquid
$\mathrm{BA}_{\mathrm{A}} \quad$ adiabatic bulk modulus, kPa
$\mathrm{B}_{\mathrm{I}} \quad$ isothermal bulk modulus, kPa
D internal diameter of the pipe in mm
C dimensionless factor based on pipe restraint conditions and including Poisson's ratio, diameter and wall thickness. See Table 2.1 for equations.
E Young's Modulus for steel, $2.06 \times 10^{8} \mathrm{kPa}$ (as used in AS2885.5:2020 [10])
t wall thickness in mm

In Weston's equations there was only internal pipe radius but no other pipe material properties. Baik et al. equations include all of the above pipe and water material factors plus viscous and thermal properties.

In the last variant in Equation (2.3.2), the isothermal bulk modulus, $B_{1}$, has been used together with the ratio of specific heats, $\gamma$, since the isothermal version of this square root term is used in the pressure test $\mathrm{dP} / \mathrm{dV}$ and $\mathrm{dP} / \mathrm{dT}$ calculations without the $\gamma$ term. Since for water the value of $\gamma$ is very close to 1 and can generally be ignored if accuracy to $1 \%$ is acceptable and temperatures are lower than $30^{\circ} \mathrm{C}$.

Using the previously mentioned combined bulk modulus, BPA (Eq. 2.1.7), the acoustic velocity equation in liquid-filled pipes becomes:

$$
\begin{equation*}
a=\sqrt{\frac{B_{P A}}{\rho}} \tag{2.6.2}
\end{equation*}
$$

The above equation does not address acoustic velocity changes due to contact with surrounding soil or pipe coating nor from the viscous and thermal properties of the liquid.

### 2.6.2 Combining Non-viscous Pipe Velocity and Weston's Low Frequency Equations

Firstly, Weston's Equations (2.5.1) to (2.5.5) use symbols inconsistent with the current document and need to have $a$ and $a_{0}$ changed to $c_{p}$ and $c_{0}$ and $a$ in Weston's equations changed to $r$, the internal radius. Weston's Low Frequency equations can be reduced for water due to the thermal terms being very small resulting in the following gamma values at $20^{\circ} \mathrm{C}$ for Equations (2.5.4) and (2.5.5):

$$
\begin{aligned}
& \gamma_{2}=1.003 E-06 \\
& \gamma_{3}=1.886 E-09
\end{aligned}
$$

which allows for Weston's equation to be simplified to a single equation (produced by this author):

$$
\begin{array}{r}
a_{P}=a\left[1-\frac{1}{r} \sqrt{\left(\frac{\eta}{2 \rho_{0} \omega}\right)}+\frac{1}{r^{2}} \frac{\eta}{2 \rho_{0} \omega}\right. \\
\left.-\frac{19}{8}\left(\frac{\eta}{\rho_{0}}\right)^{\frac{3}{2}} \frac{1}{r^{3} \sqrt{\left(2 \omega^{3}\right)}}\right] \tag{2.6.3}
\end{array}
$$

which cannot extend to zero frequency for obvious reasons of zero denominators and can only apply down to a frequency of 0.000005 Hz for DN900 pipe sufficient for all likely long length pipelines.

Replacing the velocity a, with Equation (2.6.1) the above equation becomes:

$$
\begin{gather*}
a_{P}=\frac{a_{0}}{\sqrt{\left(1+\frac{\gamma B_{I} D C}{E t}\right)}}\left[1-\frac{1}{r} \sqrt{\left(\frac{\eta}{2 \rho_{0} \omega}\right)}+\frac{1}{r^{2}} \frac{\eta}{2 \rho_{0} \omega}\right.  \tag{2.6.4}\\
\left.-\frac{19}{8}\left(\frac{\eta}{\rho_{0}}\right)^{\frac{3}{2}} \frac{1}{r^{3} \sqrt{\left(2 \omega^{3}\right)}}\right]
\end{gather*}
$$

which is then applicable to metal pipelines. Since the ratio of shear viscosity to density for water is of the order of $10^{-6}$ the last two terms with exponents of the ratio greater than one become negligible relative to the square root version resulting in the form of the equation generally expressed in textbooks such as Kinsler et al. [5] as:

$$
\begin{equation*}
a_{P}=a\left\{1-\frac{1}{r} \sqrt{\left(\frac{\eta}{2 \omega \rho_{0}}\right)}\right\} \tag{2.6.5}
\end{equation*}
$$

The attenuation equation (2.5.2) using the same approximations becomes:

$$
\begin{equation*}
\alpha_{g}=\frac{1}{r a} \sqrt{\left(\frac{\eta \omega}{2 \rho_{0}}\right)} \tag{2.6.6}
\end{equation*}
$$

These two simplified equations can be interconnected with the phase velocity expressed in terms of attenuation as:

$$
\begin{equation*}
a_{P}=a\left\{1-a \frac{\alpha_{g}}{\omega}\right\} \tag{2.6.7}
\end{equation*}
$$

This implies that phase velocity can be calculated from the attenuation and vice versa where the above approximations apply. As frequency increases, attenuation increases according to Equation (2.6.6) as the square root of the frequency while the denominator in Equation (2.6.7) increases at the unit power resulting in the phase velocity at higher frequencies approaching the viscous free pipeline velocity, a. Both equations (2.6.5) and (2.6.6) include the square root of the angular frequency, $\omega$, with both the attenuation and phase velocity increasing dependent on this factor.

### 2.6.3 Acoustic Versions of Pipeline Hydrotest Equations

The following equations are based on versions developed by this author [20] and detailed in Appendix $A$ of this document. They integrate the pipeline hydrotest equations from Section 2.1 .1 with the above non-viscous pipe acoustic velocity equations and ignore viscosity and its effects on attenuation and phase velocity.

A complete differential relating acoustic velocity to pressure and temperature is as follows:

$$
\begin{equation*}
d a=\frac{d a}{d p} d p+\frac{d a}{d T} d T \tag{2.6.8}
\end{equation*}
$$

where
da
is the change in acoustic velocity.
dp the pressure change.
dT the temperature change.
The differential da/dT is given by:

$$
\begin{equation*}
\frac{d a}{d T}=\frac{1}{2} \sqrt{\frac{\rho}{B_{P A}}}\left\{\frac{1}{\rho} \frac{d B_{P A}}{d T}-\frac{B_{P A}}{\rho^{2}} \frac{d \rho}{d T}\right\} \tag{2.6.9}
\end{equation*}
$$

Since the definition of the liquid thermal expansion coefficient, $\beta$, is:

$$
\begin{equation*}
\beta=\frac{1}{v} \frac{d v}{d T}=-\frac{1}{\rho} \frac{d \rho}{d T} \tag{2.6.10}
\end{equation*}
$$

The above equation can be rearranged and simplified to:

$$
\begin{equation*}
\frac{d a}{d T}=\frac{a}{2}\left\{\frac{1}{B_{P A}} \frac{d B_{P A}}{d T}+\beta\right\} \tag{2.6.11}
\end{equation*}
$$

An expansion of the differential in the brackets is needed and is as follows (see Appendix A for details):

$$
\begin{equation*}
\frac{d B_{P A}}{d T}=\frac{B_{P A}^{2}}{B_{A}^{2}} \frac{d B_{A}}{d T} \tag{2.6.12}
\end{equation*}
$$

Substituting results in:

$$
\begin{equation*}
\frac{d a}{d T}=\frac{a}{2}\left\{\frac{B_{P A}}{B_{A}{ }^{2}} \frac{d B_{A}}{d T}+\beta\right\} \tag{2.6.13}
\end{equation*}
$$

The differential da/dp given by:

$$
\begin{equation*}
\frac{d a}{d p}=-\frac{a}{2}\left\{\frac{\frac{1}{B_{A}{ }^{2}} \frac{d B_{A}}{d T}+\frac{\beta}{B_{P A}}}{\left(\beta-C_{2} \alpha\right)}\right\} \tag{2.6.14}
\end{equation*}
$$

and inverse by:

$$
\begin{equation*}
\frac{d p}{d a}=-\frac{2}{a}\left\{\frac{\left(\beta-C_{2} \alpha\right)}{\frac{1}{{B_{A}}^{2}} \frac{d B_{A}}{d T}+\frac{\beta}{B_{P A}}}\right\} \tag{2.6.15}
\end{equation*}
$$

The complete differential then becomes:

$$
\begin{array}{r}
d a=\frac{a}{2}\left\{\frac{1}{B_{A}{ }^{2}} \frac{d B_{A}}{d T}+\frac{\beta}{B_{P A}}\right\}\left\{B_{P A} d T\right.  \tag{2.6.16}\\
\left.-\frac{1}{\left(\beta-C_{2} \alpha\right)} d p\right\}
\end{array}
$$

The previous equations for $\mathrm{dp} / \mathrm{d} T$ and $\mathrm{dV} / \mathrm{dp}$ used the isothermal bulk modulus. For acoustic applications the adiabatic or isentropic bulk modulus are used so that $\mathrm{dp} / \mathrm{dT}$ and $\mathrm{dV} / \mathrm{dp}$ respectively become:

$$
\begin{gather*}
\frac{d p}{d T}=-B_{P A}\left(\beta-C_{2} \alpha\right)=-\rho a^{2}\left(\beta-C_{2} \alpha\right)  \tag{2.6.17}\\
\frac{d V}{d p}=V_{0} \frac{1}{B_{A}}\left(\frac{C_{1} B_{A} D}{E t}+1\right)=\frac{V_{0}}{B_{P A}}=\frac{V_{0}}{\rho a^{2}}  \tag{2.6.18}\\
=\frac{V_{0}}{B_{A}}\left(\frac{a_{0}}{a}\right)^{2}
\end{gather*}
$$

Since for water the adiabatic and isothermal bulk moduli are almost identical within approximately $1 \%$, these equations can be substituted for hydrotest requirements. Knowing the acoustic velocity in the pipe together with the above equations permits the $\mathrm{dp} / \mathrm{dT}$ and $\mathrm{dV} / \mathrm{dp}$ factors to be found or checked.

### 2.6.4 Effect of Backfill on Attenuation

Ovchinnikov and Lapshin [47] carried out experiments on a DN1200 oil pipe with signal generation by means of an external electromagnetic transmitter somehow attached to the pipe. Detection was by means of piezoelectric transducers mounted on the outside of the pipe (possibly accelerometers) and a velocity measuring geophone mounted on the ground surface. All measurements were within a distance of 173 metres. They measured attenuations of average $0.17 \mathrm{~dB} / \mathrm{m}$ at distances up to 143.5 m. Their signal had 4 peaks of 248 Hz at 29 m reducing to 127 Hz at 72.5 m and strangely 144 Hz at 98.5 m . They attributed the high attenuation to the dissipation in the soil which they confirmed by the geophone measurement with disappearance of the ground signal beyond 10 m from the pipe. The sketch of the experimental set up on a functioning oil line showed the transmitter mounted under the pipe. This would have generated vertical vibration in the pipe and contents which would have propagated also as the ground waves that were detected but only near the pipe centre line. The authors indicate that the additional attenuation due to the soil increases with pipe diameter. They also mentioned that the soil effect increases with frequency. For measurements so close together there would be other modes present especially since the input is from the bottom of the pipe. Modes higher than the ETO have higher attenuations.

A paper by Bernasconi et al. [48] included the following Figure 2-14 showing the pressure transducer measured attenuation variation with frequency for a DN400 buried oil pipeline with measuring distances of the order of 30 km . Their attenuation at 100 Hz is around $18 \mathrm{~dB} / \mathrm{km}$ an order of magnitude below that of Ovchinnikov et al. [47]. Model A in their figure is based on Elvira-Segura [44], Model B on Muggleton et al. [49] and Model C is their model. Muggleton et al. [49] did not include fluid viscosity effects but included soil while Elvira-Segura [44] included the fluid viscosity but not the soil. An unusual feature of the operating pipeline system discussed in the paper was the combination of acoustic transducers and vibration sensors mounted on the pipe with the combination used for detection of changes in pipeline operating conditions and detection of third party intrusion or damage.


Figure 2-14 - Figure from Bernasconi et al showing DN400 operating oil pipeline attenuation and comparison with Model A (no soil), Model B (non viscous liquid in soil) and their Model C.

Elvira-Segura [44] curve is similar to that based on Kinsler and Frey [5]. The data in the above Figure 2-14 has been replotted in Figure 2-15 which showed the deviation at higher frequencies of Bernasconi et al. [48] data from theoretical Elvira-Segura estimates without burial.


Figure 2-15 - Bernasconi et al data (red curve with red markers) was used to extract the effect of burial which is displayed in grey and compared with Elvira-Segura's (blue with markers). The burial
extract has a power exponent of 2.23 as against Elvira-Segura's 0.5. The burial extract at frequencies centred around 50 Hz appeared to merge with Elvira-Segura's line.

The difference between the two curves has been plotted as the set of grey points with a power trend line of slope 2.2 compared with Elvira-Segura slope of 0.5 consistent with Baik et al. [1, 3] slope. On this log frequency plot the two curves approach each other at low frequency but don't merge indicating some other contributing factor which could be the mass loading of the pipe by the external corrosion coating. Such contribution appears to be constant with increasing frequency.

The trend of the linear portion of the buried attenuation (red dots) should meet the theoretical curve at around 35 Hz .

This comparison of field data with theory is invaluable and helps to explain what appeared to be anomalous field measurements of attenuation obtained by the current author where attenuation slopes have varied from 0.5 to 2.0. It also pointed to a method of correction of theory for burial in that the difference in the above figure is in $\mathrm{dB} / \mathrm{km}$ which since dB values are logarithmic allows the addition of the burial dB component to the non-burial theory or the multiplication of the two attenuation factors. If there was a coating effect then this could be added as a simple $\mathrm{dB} / \mathrm{km}$ value independent of frequency.

Muggleton et al. [49] developed equations for attenuation for pipe surrounded by soil and in their later [50] paper carried out experiments on a 2 m long plastic pipe surrounded by air and a 34 m long buried 180 mm diameter plastic pipe. They reported that the results confirmed their theory. However results on plastic pipe cannot be applied to steel.

What was needed was additional burial attenuation information on pipe diameter, coating, soil type and soil water content.

### 2.7 AIR BUBBLE AFFECTED ACOUSTIC PHASE VELOCITY AND ATTENUATION IN WATER

Air is an unwanted intruder in hydrotests and generallly mostly removed or at least minimised by use of one or two tight sealing pigs or scrapers during water filling together with careful control of the filling process by use of "back pressure". The Australian Standard for hydrotesting [10] requires measurement of air content during pressurisation to Strength Test pressure. Such measurement only identifies approximate quantity of air and assumes that it only collects and exists at high points and is then subject to the pressure at that location. This section will show that small quantities of air have a significant influence on acoustic velocity. What is difficult to find in the literature is the effect on velocity on isolated air pockets as against evenly distributed air bubbles of which the latter is the main area of study and the former rarely addressed. The effect of isolated air pockets on acoustic velocity will be addressed by field examples where air content was known and acoustic velocity measurements taken.

### 2.7.1 Distributed Air Bubbles

Reeder et al. [51] referenced original work by Mallock [52] and later by Wood [53] and the equation for water with air bubbles in an infinite medium which he refers to as the "Mallock-Wood equation". Using symbols consistent with this document the equivalent equation is:

$$
\begin{equation*}
a_{a}=\sqrt{\frac{1}{\left(\rho_{l}(1-x)+\rho_{g} x\right)\left(K_{l}(1-x)+K_{g} x\right)}} \tag{2.7.1}
\end{equation*}
$$

where

| $a_{a}$ | acoustic velocity with air bubbles present and uniformly distributed |
| :--- | :--- |
| $x$ | is the volume fraction of air to combined volume |
| $\rho_{g}$ | air density |
| $\rho_{I}$ | liquid density |
| $\mathrm{K}_{1}$ | liquid compressibility |
| $\mathrm{K}_{g}$ | air or gas compressibility |

Using bulk moduli instead of compressibilities the following version results:

$$
\begin{equation*}
a_{a}=\sqrt{\frac{1}{\left(\rho_{l}(1-x)+\rho_{g} x\right)\left(\frac{(1-x)}{B_{l}}+\frac{x}{B_{g}}\right)}} \tag{2.7.2}
\end{equation*}
$$

where

| $\mathrm{B}_{\mathrm{g}}$ | air or gas bulk modulus |
| :--- | :--- |
| $\mathrm{B}_{\mathrm{I}}$ | liquid or water bulk modulus |

Reeder et al. [51] used such equations for coastal marine conditions and stated that the equation was limited to frequencies below bubble resonances ( $<1 \mathrm{kHz}$ ) with bubbles greater than $100 \mu \mathrm{~m}$ (micro metre or micron). They mentioned and used other references relating to the effect of bubble resonances on sound speed and its variation with frequency (dispersion) which has no relevance for the range of frequencies used in the acoustic pipeline technique.

Wilson [54] expressed the above equation in an alternative form which corresponds to Wood's [53] equation which Wilson [54] considered to apply to the low frequency propagation regime:

$$
\begin{equation*}
\frac{1}{a_{0}^{2}}=\left(\rho(1-x)+\rho_{g} x\right)\left(K_{l}(1-x)+K_{g} x\right) \tag{2.7.3}
\end{equation*}
$$

He then re-expresses it in the form of acoustic velocities as follows:

$$
\begin{equation*}
\frac{1}{a_{0}^{2}}=\frac{(1-x)^{2}}{a_{l}^{2}}+\frac{x^{2}}{a_{g l}^{2}}+x(1-x) \frac{\rho_{g}^{2} a_{g}^{2}+\rho_{l}^{2} a_{l}^{2}}{\rho_{g} \rho_{l} a_{g}^{2} a_{l}^{2}} \tag{2.7.4}
\end{equation*}
$$

He carried out experiments in a vertical PVC tube 0.6 m in length and 52 mm diameter (without any mention of thickness). The air or void fraction was estimated using a mechanical float on top connected to a pointer. The float system could resolve to 0.5 mm and the air fraction calculated from a simple relationship:

$$
\begin{equation*}
x=\frac{\Delta L}{L+\Delta L} \tag{2.7.5}
\end{equation*}
$$

where
$\mathrm{L} \quad$ is the tube air/water column height
$\Delta \mathrm{L} \quad$ is the change in height referred to zero air content.
His results compared with Wood's equation [53,55] are shown in the following Figure 2-16 (Wilson [54], based on his Fig A4.3):


Figure 2-16 - Comparison of Wilson's data for velocity variation with air volume and Wood's theoretical equation. Also shown is the effect of the air bubbled water inside a PVC vertical pipe (dashed line with orange markers).

Ruggles [56] also carried out experiments using vertical tubes with results shown using his figure as Figure 2-17 below and which was digitised based only on his best fit curve:


Figure 2-17 - $\quad$ Ruggles plot of data showing the need to change $C_{V M}$ values for his equation to match the data.

Silberman [57] much earlier summarised data at the time in the following Figure 2-18 together with lines using Wood's [53,55] and Spitzer's [58] equations. Superimposed on this Figure 2-18 are Wilson's and Ruggles' later data for comparison (Ruggles [56]). Spitzer's equation is only applicable for air fractions up to $3 \%$.


Figure 2-18 - Silberman's chart comparing theoretical equations by Wood and Spitzer with data. Also shown are Wilson's and Ruggles' data superimposed on Silberman's graph together with extended points for Spitzer's equation.

Wood's equation (used by Wilson for comparison purposes) only depends on the water and air properties. The modified Silberman [57] figure, Figure 2-18 (in ft/sec not $\mathrm{m} / \mathrm{s}$ and air fraction not $\%$ air fraction) and the general fit of experimental data for vertical tubes/pipes confirms both Spitzer's and Wood's equations over the range from: $0.027 \%$ for Silberman's data, $0.13 \%$ for Wilson and $0.6 \%$ for Ruggles to: $1 \%$ for Silberman's data, $2.45 \%$ for Wilson's data, $18 \%$ for Ruggles and $40 \%$ for Campbell and Pitcher data in Silberman's chart Figure 2-18.

Although Spitzer's calculation method is more complex than Woods, the curves are similar with Spitzer slightly higher in velocity. Using Spitzer's equations and assuming some bubble dimensions results in values similar to those of Wood for low frequencies.

The highest sound speed is around $550 \mathrm{~m} / \mathrm{s}$ at $0.027 \%$ for Silberman's data. He used 2 inch (DN50) and 3 inch (DN75) internal diameter pipes of stainless steel $1 / 4$ inch thick ( 6.35 mm ) and based his results on an absolute pressure of 15.8 psia ( $108.9 \mathrm{kPa}(\mathrm{abs})$ or 7.6 kPag ). Wilson used PVC pipe of nominal 2 inch (DN50) without mentioning thickness. Ruggles (1988) used a 63.5 mm internal diameter, 76.2 mm outside diameter stainless steel tube 2.0 metres long.

There was no mention of pipe diameter, wall thickness or pipe characteristics in the above equations but the results fit the Wood's and Spitzer equations. There is also no mention of pressure. Most of the research into the effect of bubbles is for marine and underwater use where pipes are irrelevant while pressure is important.

### 2.7.2 Effect of Pipe and Pressure

Karplus [59] specifically mentions pressure and the pressure dependence of his version of Wood's equation. He provided a graph of the effect of pressure on water with air bubbles up to 100 barg and for mass ratio, z, from zero to 0.001 . He also investigated whether the gas bubble compressibility was adiabatic of isothermal and supplied the following alternative equations for compressibility in terms of pressure:

$$
\begin{align*}
K_{g I} & =\frac{1}{p}  \tag{2.7.6}\\
K_{g A} & =\frac{1}{\gamma p} \tag{2.7.7}
\end{align*}
$$

where

| y | ratio of specific heats |
| :--- | :--- |
| p | pressure, absolute |
| $K_{g I}$ | gas compressibility, isothermal |
| $K_{g A}$ | gas compressibility, adiabatic |

He concludes that rapid heat exchange takes place with the bubbles so that the isothermal compressibility is to be used. His version of the equation is as follows:

$$
\begin{equation*}
\frac{1}{a_{0}^{2}}=\frac{x^{2} \gamma}{a_{g}^{2}}+\frac{1}{a_{l}^{2}}+x(1-x) \frac{\rho_{l}}{p} \tag{2.7.8}
\end{equation*}
$$

where

| $a_{1}$ | is the velocity of sound in pure liquid |
| :--- | :--- |
| $a_{g}$ | is the velocity of sound in gas under normal adiabatic conditions |
| $y$ | ratio of specific heats |

He includes the ratio of specific heats, $\gamma$, in only the first term of the above equation since $x=1$ for all air, the equation must match that for air.

He further supplies a simple approximation in the following form expressing the velocity in terms of pressure, liquid density and air volume ratio:

$$
\begin{equation*}
a_{0}=\frac{p}{\rho_{l}(1-x)} \text { for } 0.002<x<0.94 \tag{2.7.9}
\end{equation*}
$$

He simply refers to x as the ratio of air to total volume while not mentioning whether this ratio applies at the pressure or at a reference pressure such as atmospheric. His experimental work addressed the variation of velocity with frequency from around 250 Hz to around 1700 Hz and air content from $10 \%$ to $50 \%$.

In the previous Figure 2-17 of Ruggles [56] data he notes changes in the $\mathrm{C}_{\mathrm{Vm}}$ value progressively lowering to 0.5 at the lowest air fractions of $0.6 \%$ while a value of 0.7 was needed at $18 \%$ air fraction. $\mathrm{C}_{\mathrm{v}}$ is given by the following empirical equation:

$$
\begin{equation*}
C_{V M}=0.5\left(1+12\langle\alpha\rangle^{2}\right) \tag{2.7.10}
\end{equation*}
$$

where

| $\mathrm{C}_{V M}$ | is the virtual volume coefficient which is 0.5 for spherical bubbles |
| :--- | :--- |
| $\langle\alpha\rangle$ | is the global void fraction |

Ruggles (1988) plotted Cvm values against void fraction and made the comment that for bubble radii exceeding 1.5 mm were not spherical in his experiment. For the pipeline situation, only low air fractions are expected below $1 \%$ where such factors do not influence the results.

Ruggles measured attenuation and dispersion at low frequencies down to 20 Hz which was not the range of interest of most researchers. These results will be addressed later.

### 2.7.3 Pipe Effect

Wiley and Streeter [17] made reference to Kobori et al. [60], and Pearsall [61] in relation to the effects of air entrainment on pressure surges velocity with their equations and laboratory experiments as confirmation. Wiley and Streeter provided a figure which copied that of Kobori et Al. and their experimental data.

Wiley and Streeter's equation below was based on their work and approximates the density term of Wood's equation with the liquid density which is a reasonable approximation for air content below $1 \%$. It neglects the C factor for pipe restraint and avoids the use of air density and air fraction. It adds the KD/Et pipe term and correctly addresses pressure variation while differing from Kobori et Al., equation.

$$
\begin{equation*}
a=\sqrt{\frac{\frac{K_{l}}{\rho_{l}}}{\left\{1+\frac{K_{l} D}{E t}+\frac{m R T}{p}\left(\frac{K_{l}}{p}-1\right)\right\}}} \tag{2.7.11}
\end{equation*}
$$

Where

| $m$ | is the mass of free air per unit volume |
| :--- | :--- |
| $R$ | the universal gas constant |
| $T$ | the absolute temperature (Kelvin) |
| $\mathrm{K}_{I}$ | liquid bulk modulus |

Kobori et Al., developed and provided an equation of which the following is effectively the same (they used pressure units of $\mathrm{kg} / \mathrm{m} 2$ and so needed the gravitational constant, g , to achieve results in $\mathrm{m} / \mathrm{s}$ ).

$$
\begin{align*}
& \frac{1}{a^{2}} \\
& =\left(\rho_{l}-\left(\rho_{l}-\rho_{g}\right) \frac{V_{g}}{V}\right)\left\{\frac{1+\left(\frac{K_{l}}{K_{g}}-1\right) \frac{V_{g}}{V}+\frac{K_{l} D}{E t}}{K_{l}}\right\} \tag{2.7.12}
\end{align*}
$$

Their derivation of the above equation from the air free water hammer equation of Allievi [62,63] and by developing the equivalent mixture density expressed in the first bracket term and the equivalent bulk modulus in the second bracket term.

Using their equation, the following is equivalent but rearranged using air fraction terms $\mathrm{V}_{\mathrm{g}} / \mathrm{V}$;

$$
\begin{align*}
\frac{1}{a^{2}}=\left(\frac{V_{g}}{V} \rho_{g}+\right. & \left.\left(1-\frac{V_{g}}{V}\right) \rho_{l}\right)\left(\frac{1}{K_{g}} \frac{V_{g}}{V}+\left(1-\frac{V_{g}}{V}\right) \frac{1}{K_{l}}\right. \\
& \left.+\frac{D}{E t}\right) \tag{2.7.13}
\end{align*}
$$

where

| $\frac{V_{g}}{V}=x$ | is the air volume ratio |
| :--- | :--- |
| $V_{g}$ | is the gas or air volume |
| $V$ | is the combined volume of air and water |

Using the air volume ratio, x , the above equation with the addition of the C restraint factor becomes:

$$
\begin{align*}
\frac{1}{a_{a p}^{2}}=\frac{\rho_{m}}{B_{m}}= & \rho_{m} K_{m} \\
& =\left(x \rho_{g}+(1-x) \rho_{w}\right)\left(\frac{x}{B_{g}}\right.  \tag{2.7.14}\\
& \left.+\frac{(1-x)}{B_{A}}+\frac{C D}{E t}\right)
\end{align*}
$$

where

| $a_{a p}$ | is the velocity with air bubbles inside pipe |
| :--- | :--- |
| $\rho_{m}$ | is the water air mixture density |
| $B_{m}$ | the water air mixture bulk modulus |
| $K_{m}$ | the water air mixture compressibility |

Kobori et Al., expressed the adiabatic bulk modulus for air as:

$$
\begin{equation*}
K_{g}=\gamma p \tag{2.7.15}
\end{equation*}
$$

and density in the form:

$$
\begin{equation*}
\rho_{g}=0.01209 \times p \tag{2.7.16}
\end{equation*}
$$

where the pressure, p , is in units of kPa to result in density in $\mathrm{kg} / \mathrm{m}^{3}$.
The following equation incorporates such relationships and is similar in contents to Chaudhry [64]:

$$
\begin{align*}
\frac{1}{a_{a p}^{2}}=\left(x \rho_{g}\right. & \left.+\left(1-x \frac{p_{0}}{p}\right) \rho_{w}\right)\left(\frac{x p_{0}}{\gamma p^{2}}+\frac{\left(1-x \frac{p_{0}}{p}\right)}{B_{A}}\right. \\
& \left.+\frac{C D}{E t}\right) \tag{2.7.17}
\end{align*}
$$

where
$p_{0} \quad$ is the reference absolute pressure, normally atmospheric pressure $p \quad$ is the absolute pressure in the mixture (assumed uniform).
$x \quad$ must be the air volume ratio at atmospheric pressure, $\mathrm{p}_{0}$.
If $x_{p}$ is used to represent the value of air fraction at the pressure $p$ :

$$
\begin{equation*}
x_{p}=x \frac{p_{0}}{p}=\frac{V_{g} p_{0}}{V p} \tag{2.7.18}
\end{equation*}
$$

Then the above equation simplifies to:

$$
\begin{align*}
\frac{1}{a_{a p}^{2}}=\left(x_{p} \rho_{0 g}\right. & \left.+\left(1-x_{p}\right) \rho_{w}\right)\left(\frac{x_{p}}{p}+\frac{\left(1-x_{p}\right)}{B_{A}}\right.  \tag{2.7.19}\\
& \left.+\frac{C D}{E t}\right)
\end{align*}
$$

or with slight changes into a more familiar form:

$$
\begin{equation*}
a_{a p}=\frac{a_{0}}{\sqrt{\left(1+x_{p}\left(\frac{\rho_{0 g}}{\rho_{w}}-1\right)\right)\left(1+x_{p}\left(\frac{B_{A}}{p}-1\right)+\frac{C B_{A} D}{E t}\right)}} \tag{2.7.20}
\end{equation*}
$$

where
$\rho_{0 g} \quad$ is the density at reference or atmospheric pressure.
Pearsall's [61] version of the equation is essentially the same with the density ratio term removed as small compared with unity. These equations account for the effects of pressure in both the density (left) term and the bulk modulus (right) term. Chaudhry's version has $p_{0} \rho_{0 g}$ instead of $x_{p} \rho_{0 g}$ in the density term and is most likely missing other factors. Thorley [65] provided a similar equation and a figure showing the variation in wave speed with pressure and air content for a steel pipe D/t ratio of 30 which he attributed to Zhou et al. [66] however the figure could not be found in Zhou et al. unless it was in Zhou's Thesis of that year. It covered the air volume fractions from zero to $1 \%$ with pressures of 10,20 and 50 bar shown.

Silberman's and Ruggles' data were based on DN50 to DN75 stainless steel pipes of wall thickness 6.35 mm . The above CD/Et expression is negligible for small D/t ratio pipes except for air fractions below $0.03 \%$ where the velocity difference increases more than $1 \%$. In Wilson's case of PVC pipe of similar dimensions, the much lower Young's modulus of approximately 3.0 to 3.3 GPa is $1.5 \%$ of that for steel and results in a deviation more than $1 \%$ in velocity at air fractions below 3\%. A curve incorporating the above CD/ET effect is shown as the blue dashed line in the previous Figure 2-16 of Wilson's data. The data points at lower air contents no longer follow the theory curve. Scatter due to his difficulty in obtaining reliable measurements at low air content can be seen.

### 2.7.4 Horizontal pipes and air bubbles.

All the above experimental velocity measurements with air bubble content were with vertical pipes with the sole exception of Kobori et al. [60] Their data is unique in using essentially horizontal pipe and in another aspect that they used a pressure of 324 kPa absolute whereas all the others carried out their experiments with the top of the vertical pipe exposed to atmospheric pressure. Such data in addition to being unique is applicable to conventional pipelines in being horizontal or near horizontal whereas short vertical experiments are rarely if ever observed in pipelines. Their experiments were on a DN100 pipe 120 metres long with most horizontal and a final vertical rise and $U$ bend to discharge into an elevated tank. A valve was located at the discharge end to enable pressure containment and to initiate pressure surges. The paper was unique in those respects.

The following Figure 2-19 plots Kobori's data and the theoretical but also plots an exponential curve through the data with apparent good fit.


Figure 2-19 - Plot of Kobori et al. data with approximate fitted curve together with theoretical curves of Wood and Spitzer at atmospheric pressure. Also shown is Wood's curve at the pressure corresponding to Kobori et al. Ruggles' and Wilson's data also shown.

The data does not follow the theoretical for air fractions below 0.002 or $0.2 \%$ and deviates significantly which raises the obvious question. Fitting an exponential decay curve through the data doesn't help. They recorded air free velocity measurements of around $1270 \mathrm{~m} / \mathrm{s}$ which was used for the end point of the theoretical curve. Atmospheric pressure curves for Woods and Spritzer's equations are shown together with Ruggles' and Wilson's data which appear much lower on the chart due to the different pressure evidenced by the theoretical for Kobori et Al. pressure.

Kobori et Al., generated bubbles by attaching an inlet air hose to the pump suction supplying the DN100 pipe with a steady water flow and entrained air bubbles through venturi vacuum effect. They stated that they incorporated a transparent section temporarily which confirmed distribution of the bubbles but such section was not present during the experiments and may have been located near to the vertical end of the pipe where bubbles previously at the top of the pipe in the horizontal sections may have redistributed themselves. There was no mention of bubble sizes nor mention of attempts to measure them which would be of help in assessing terminal velocities.

Flow velocity in the pipe was around $1.5 \mathrm{~m} / \mathrm{s}$ for a travel distance of 120 m with a travel time of 80 seconds. There is a likelihood that the air bubbles slowly migrated towards the top of the pipe over the 80 second travel time. Analysis of rising bubble terminal velocities and with internal diameter 105 mm , bubbles must have been smaller in diameter than 0.05 mm to remain suspended in the mostly horizontal pipe for at least 105 metres of the pipe before it climbs vertically to the receiving tank. Such
small bubbles are likely very difficult to obtain using Kobori's method of bubble generation. Hence Kobori's data probably reflects pipe in which possibly most of the bubbles (assumed to be of larger diameter than 0.05 mm ) will have accumulated and amalgamated near the top of the pipe and would be dragged with the flow along the pipe and then redistributed in the flow in the final vertical section. There would have likely been a bubble density gradient inside the pipe changing with position along the horizontal section which in turn could have caused higher velocities to be measured for the same air content. Researchers would be reluctant to repeat such experiments due to the material and set up cost and their appears to be lack of supporting experimental evidence other than Wiley and Streeter's [17] indirect confirmation of such lack by continuing to publish Kobori et al.'s results in Editor Li's book published in 2000.


Figure 2-20 - Figure taken from Alexander et al. showing the approximate categories for two phase flow. Fluid and gas velocities are the axes.

Above Figure 2-20 was copied from Alexander [67]. Kobori et al. [60] water flow rate of $1.5 \mathrm{~m} / \mathrm{s}$ with entrained bubbles assumed to travel at the same rate fits into the region of elongated bubble flow merging with slug flow. This implies that if the Kobori et al. [60] bubbles drifted upwards they could be carried by slug flow.

Nazaroff and Alvarez-Cohen [68] included a figure (4.B.5) showing the terminal rising velocity of spherical particles of density $1.2 \mathrm{mg} / \mathrm{cm}^{3}$ and $2.5 \mathrm{mg} / \mathrm{cm}^{3}$ in water at $20^{\circ} \mathrm{C}$. This figure followed their detailing of Stoke's equation for terminal velocity. From it an equation can be derived for the velocity relative to diameter for spherical particles of density $1.2 \mathrm{mg} / \mathrm{cm}^{3}$ (same as air at atmospheric pressure) as follows:

$$
\begin{equation*}
v=5.6 \times 10^{-7} d^{2} \tag{2.7.21}
\end{equation*}
$$

where

| $v$ | is the velocity in $\mathrm{m} / \mathrm{s}$ |
| :--- | :--- |
| d | is the diameter in microns |

Their figure only covered the diameter range from 1 to 100 microns. For a bubble of diameter 0.05 mm or 50 microns the equation gives a velocity of $0.0014 \mathrm{~m} / \mathrm{s}$ which will travel 0.112 m in 80 seconds consistent with the internal diameter of Kobori et al. [60] pipe diameter of 105 mm . Ruggles smallest diameter was 0.56 mm or 560 microns which would travel the pipe diameter in less than 1 second. It would have been difficult for Kobori et al. [60] to achieve bubbles of 50 microns which in turn indicates that the bubbles would have settled and amalgamated well before the end of the pipe and would be moved by slug flow.

### 2.7.5 Air or vacuum pockets in pipelines

Some references to air or vacuum in horizontal pipes were for cases of partial or full vacuum generated by flow change induced pressure surges after reflection from a closed end. When negative pressure (vacuum) is generated under such circumstances, dissolved air can be released resulting in a partial vacuum containing water vapour and air. Since liquid flow is not present in pipeline pressure tests such circumstances are not applicable, nor are vacuum pockets, although air pockets are.

In Bergant et Al., water hammer and column separation review [69] they consider two cavity models; discrete vapour cavity model (DVCM) and discrete gas cavity model (DGCM). What is of relevance to the current study is that both models assume that the location of cavitation and/or gas pockets only is subject to reduced sound speed while the remainder of the pipe section are treated with the normal air free sound speed. Chaudhry [64] made the comment that experimental investigations by earlier researchers had shown that gas bubbles were dispersed either side of the column separation location cavity. However such situation only arises when sudden flow changes create the partial vacuum cavity with dissolved air likely to come out of solution either side of the cavity due to the reduced pressure until the static pressure head can prevent it. Also flow passed a cavity will likely generate gas bubbles. Neither situation applies to the pipeline pressure test situation and cavities without nearby bubbles is expected.

Ferriera et AI. [70] carried out experiments with a 15 m long 20 mm internal diameter 1 mm thick copper pipe with a branch tee pipe connection in line with the pipe and another tee connected to the top of the first tee with the run of the tee vertical, a pressure transducer mounted in the side branch and an acrylic clear dead end tube at the top end. The air pockets were visible in the end of the acrylic tube so that the branch contained a water volume in the branch under the air pocket. This configuration differs significantly from that of air trapped inside the pipe. What is interesting in their paper are the series of high speed photos of the air bubble showing it breaking apart or separating almost like boiling. Such may apply to in-line air bubbles under the same conditions of flow and pressure. Another point of interest is the use of a WIKA S-10 pressure transducer which is strain gauge based and operates to DC. Their branch configuration permits the pressure signal to travel completely through the tee without obstruction but is affected by the presence of the branch connection and the mass of the inline tee. Their results otherwise are not of relevant to the current study.

Alexander et Al., [67, 71-73] carried out experiments to distinguish between the effects on water hammer of branch air pockets and in line air pockets inside the pipe at high points. The slightly inclined experimental pipe was 41.6 m long with 22.25 mm internal diameter of 2 mm wall thickness and was
pressurised to a maximum of 300 kPa gauge ( 3.0 barg ) with 50 kPa increments used. They had provision for an intermediate high point in the shape of a double $S$ back to back or an omega shaped loop where air could be injected either directly into the pipe (in-line) or into a branch connection screwed into the same location. A side discharge valve fitted on top was used for the air injection with a PCB pressure transducer fitted at the same location. The PCB transducer has a low frequency cut off and does not have DC capability. No mention was made of the preamplifier used with it which determines the low frequency cut off and can change the DC response. The pressure pulse was generated by rapid opening and closing of a solenoid operated valve in around 6 ms with the measured air free wave speed $1348.5 \mathrm{~m} / \mathrm{s}$. The branch version of the experiments are not relevant to the present study except for the fact that the branch fitting caused attenuation of the order of $5 \%$ and highlights the effect of fittings. For the in-line experiments they used a syringe to inject and later remove air at the high point and found that within the time frame of a quarter of an hour the air volume had not changed so that air solution had not taken place. Volumes injected spread along the top of the curved pipe section of approximately constant bend radius of approximately 95 mm (not stated) with air volume varying between 2.9 ml and 40 ml at atmospheric pressure and below $0.25 \%$ of the pipe volume $(16,175 \mathrm{ml})$. They referred to the variable wave speed theory based on the air content distributed over the whole pipeline volume and stated that it was numerically stable only where the air fraction was extremely small ( $\leq 2 \times 10^{-6}$ or $\leq 0.0002 \%$ ). The downstream and low point end (opposite end to the solenoid activated valve) terminated in a receiver enabling pressure to be maintained as needed.

Their experiments complied with what they called the Courant condition (velocity $x \Delta t / \Delta x \leq 1$, with $\Delta t$ the time step of 0.1 ms for 10 kHz sampling and $\Delta x=0.23 \mathrm{~m}$ for 180 equal spatial nodes along the 41.6 m length) everywhere in the pipeline and assumedly in the in-line air pocket. The provided chart for the air pocket length implied that the longest air pocket was 0.083 mm which is $36 \%$ of the node separation.

The authors made mention of the possibility of air solution affecting the air volume and confirmed that it wasn't a problem by measuring the injected and removed volumes which were the same. They concluded that if any air dissolved that the volume dissolved would be negligible since approximately only $2 \%$ by volume can dissolve and their air volumes were well less than $2 \%$ of the total pipeline volume. The time duration of each experiment was of the order of 15 minutes which would have minimised any solution. There was no mention of or reference to solution rates of air in pipes.

One feature of these studies by Alexander et Al., was that they were all with no flow which is consistent with the conditions of a pipeline test section under pressure test.

### 2.7.6 Frequency Dependence of Velocity in Water with Air Bubbles

Wilson [54] produced the following Figure 2-21 using Ruggles' data compared with Wilson's equation and Wood's equation (indicated in the figure by the horizontal dashed line) and which shows the velocity variation with frequency (dispersion). It shows for the low frequency region that the velocity in water with air bubbles deceases with decrease in frequency. To match the Ruggles' data to the Wilson equation, Wilson slightly adjusted Ruggles' reported air fraction values, X , is given by:

## CHAPTER 2 - LITERATURE REVIEW

$$
\begin{equation*}
\chi=\frac{4}{3} \pi \bar{a}^{3} n \tag{2.7.22}
\end{equation*}
$$

where

| X | air fraction |
| :--- | :--- |
| $\overline{\mathrm{a}}$ | average bubble equilibrium radius between a and $\mathrm{a}+\mathrm{da}$ |
| n | number of bubbles of average radius $\overline{\mathrm{a}}$ per unit volume |



Figure 2-21 - Figure by Wilson showing Ruggles' data superimposed on Wilson's curves based on his equation 2.1 but with Ruggles' parameters changed slightly to fit. It shows the effect of frequency on the velocity but in the low frequency range away from any bubble resonance effects.

Wilson's equation 2.1 is given by:

$$
\begin{equation*}
\frac{1}{c_{m}^{2}}=\frac{1}{c_{\ell}^{2}}+\frac{4 \pi \bar{a} n}{\omega_{0}^{2}-\omega^{2}+2 i \delta \omega} \tag{2.7.23}
\end{equation*}
$$

## Where

$\mathrm{C}_{\mathrm{m}} \quad$ mixture sound speed
$\mathrm{Cl}_{\mathrm{I}} \quad$ is the liquid sound speed
$\omega_{0} \quad$ is the bubble resonant angular frequency
$\omega \quad$ is the angular frequency
$2 i \delta \omega \quad$ is two times $\sqrt{-1}$ times the delta function (relationship to $\omega$ not made clear by Wilson).

Wilson's [54] work did not extend below void fractions of $0.1 \%$ nor did Ruggles' [56] data due to difficulties obtaining such void fractions.

While Silberman [57] investigated the frequency effect on velocity with air bubbles, the graphed data covered a wide velocity range and consequently did not show detailed variation with frequency
for low air fractions whereas Ruggles [56] provided more detailed figures which have been copied and digitised as shown in Figure 2-22 below.

Ruggles' velocity variation with frequency for air fractions from $0.5 \%$ to $18 \%$ are covered in the following figure with varying values of bubble diameter.


Figure 2-22 - Ruggles data for velocity variation with frequency with air bubbles of different radii. The trend lines shown differ from Wilson's equation in the previous figure for frequencies below 20 Hz .

The digitised data trends have been plotted not the actual experimental points. The following Figure 2-23 is an example of one of the sets of data and the digitised data. The main concern of Ruggles [56] and predecessors such as Silberman [57] and Spitzer [58] were the effects at bubble resonance which occur at frequencies of the order of 1000 Hz and vary with bubble diameter. They had little interest in the low frequency region with low air content. In addition, difficulties in achieving uniform bubble distribution with low air content further limit experimental work in this area which is of most interest to pipelines.


Figure 2-23 - Ruggles data for velocity (vertical axis) variation with frequency (horizontal axis) for different air fractions and similar bubble radii for the highest air contents and lowest velocities.

This confirms that there is little scatter in his (Ruggles') data and that his trend lines well approximate the data within his error ranges.

## 2.8 <br> KNOWLEDGE GAPS RELATING TO FACTORS AFFECTING ACOUSTIC VELOCITY

Much research work has been carried out on acoustic velocity in water and air filled pipes. What does not appear to have been addressed in the literature is the effect of isolated air pockets on the resultant velocity through the pipeline containing such air pockets. The research by Alexander et Al., published in 2019, 2020 and 2021 [67, 71-73] highlighted the problem especially since their focus was on trying to get a model to work with the Method Of Characteristics traditionally used by engineers to solve water hammer problems.

The questions raised and most likely not answered by the literature are:

- Do air pockets only affect the length of pipe immediately below them?
- What is the effect on velocity of such air pockets?
- Are the equations used for uniformly distributed bubbles equally applicable for a concentrated air bubble on top of the pipe?
- If so how is the air content ratio determined and used?
- For typical tapering of the air pocket at both ends, what is the effect of such tapering on the velocity and the reflected signal?
- What is the difference between the signal reflected off the start of the air pocket and that from the end of the air pocket?
- What is the solution rate of air in pipes?
- What is the pressure/temperature or $\mathrm{dP} / \mathrm{dT}$ factor with free air?
- What is the $\mathrm{dP} / \mathrm{dT}$ factor with dissolved air?
- What is the $\mathrm{dP} / \mathrm{dT}$ factor with both free and dissolved air?
- How does combined free air and dissolved air affect velocity?
- Ruggles showed frequency dependence with free air. What is the effect of combined attenuation and dispersion for pipe and air content?


### 2.9 AIR SOLUTION

Physical Chemistry and Chemical Physics have accumulated extensive data and studies on the solubility of air in water from ambient to high pressures with extensive literature on the thermodynamics and modelling of the solution process such as Scaled Particle Theory (SPT) and others. Henry's law and Roule's laws provide equations for the relationship of maximum solubility with pressure and temperature. What is of interest to this Thesis is the solubility of air in water at varying temperatures and pressures. The maximum solubility is less of interest than the rate of solution which directly impacts the pressure changes during pressure testing of pipelines if large air quantities are present. This section will address solubility of air and its component gases and literature on solution rate. Also addressed is partial molar volume which is the physical volume of dissolved gas molecules in water as it impacts on some pressure test factors relating to dissolved air content and solution rate experiments. Air bubbles and pockets significantly affect the acoustic velocity in water.

### 2.9.1 Air component solubility in Water

Harvey et al. [74] provided the following mole fractions for the component gases in dry air for other purposes. The densities are from Bejan [75] at the temperatures noted except for Argon which is taken from the web-based Engineering Toolbox.

Table 2-2 - Air component Gases and Mole Fractions

| Component <br> Gas | Molar <br> mass <br> (grams) | Mole <br> fraction | Density of gas at <br> atm press (kg/m <br> or mg/ml) | Temperature |
| :---: | :---: | :---: | :---: | :---: |
| Oxygen | 31.9988 | 0.20940 | 1.301 | $27^{\circ} \mathrm{C}$ |
| Nitrogen | 28.0134 | 0.78103 | 1.138 | $27^{\circ} \mathrm{C}$ |
| Argon | 39.948 | 0.00917 | 1.661 | $20^{\circ} \mathrm{C}$ |
| Carbon di <br> Oxide | 44.010 | 0.00040 | 1.773 | $27^{\circ} \mathrm{C}$ |
| Air | 28.96 | 1.0000 | 1.293 | $0^{\circ} \mathrm{C}$ |
| Air | 28.96 | 1.0000 | 1.247 | $10^{\circ} \mathrm{C}$ |
| Air | 28.96 | 1.0000 | 1.205 | $20^{\circ} \mathrm{C}$ |
| Air | 28.96 | 1.0000 | 1.165 | $30^{\circ} \mathrm{C}$ |

Solubilities of air and component gases, except carbon di oxide, are given in the following Figure 2-24 in terms of parts per million by weight and taken from Dorsey [76] with the ET B oxygen taken from the web based Engineering ToolBox which closely matches Dorsey's values up to $30^{\circ} \mathrm{C}$.


Figure 2-24- Air, Nitrogen and Oxygen water solubility variation with temperature at atmospheric pressure

The component gas solubilities in this figure are based on their partial pressures in air with oxygen value close to 14.6 ppm at $0^{\circ} \mathrm{C}$. If pure oxygen were to dissolve in water the solubility would be around 5 times its partial pressure in air and close to 70 ppm .

A trend line through the air- 1 curve in Figure 2-24 is as follows with the temperature in ${ }^{\circ} \mathrm{C}$ and the air solubility in parts per million by mass and at atmospheric pressure (by this author):

$$
\begin{align*}
& \text { Air Solubility } \\
& \qquad \begin{aligned}
& 5.58 E-07 \times T^{4}-1.53 E \\
& -04 \times T^{3}+1.67 E-02 \times T^{2} \\
& -0.926 \times T+37.1
\end{aligned}
\end{align*}
$$

The gas densities in the above table for nitrogen, oxygen and air can be used with the above figure to approximate the volume ratios by multiplying the parts per million by approximately 830 at $20^{\circ} \mathrm{C}$ so that for air the solubility is around 20 parts per thousand or $2 \%$. At higher pressures the solubility increases directly with absolute pressure in accordance with Henry's law so that if the volume is considered at pressure then the volume solubility remains around $2 \%$ at $20^{\circ} \mathrm{C}$ which is typical of room temperatures and average ambient temperatures.

### 2.9.2 Air solution Rate Values in the Literature

The main reason for investigating the air solution rate was to assess the exponential like rise in some of the acoustic velocity field measurements reported in Hough [13] which was suspected at the time to be due to air solution. The exponential like rise in velocity was not unlike data presented in Dorsey [76] which ultimately came from Chappuis's [77] work in determining the solution rate of air into the water filled vessel used to very accurately determine water densities. Air solution affected his measurements and he needed to know the quantity dissolved over time to plan his experiments and make allowance for air solution.

Adeney [78, 79] carried out solution rate experiments with mixing and together with Richardson and Leonard [80] carried out quiescent experiments. The following Figure 2-25 shows the curve for Adeney's mixed solution rate experiments together with the quiescent experiments of Richardson et al., Chappuis and Adeney.


Figure 2-25 - Air solution with time data from Chappuis, Adeney and Richardson and Adeney. Adeney's mixed solution on upper (minute) time axis and remaining quiescent solution on lower (hour axis) with factor of 6000 difference between the two time axes.

Chappuis's measurements at $13.5^{\circ} \mathrm{C}$ are the orange dotted points through which a modified exponential (with time exponent) is plotted and extended for comparison. Richardson et al. only provided two points as marked on the blue line with the first corresponding to the initial air content after careful de-aeration and the second point after 27 days for a vertical pure water column 3.6 metres high and 0.03 m diameter. Chappuis's container was larger with depth similar to diameter. Adeney's quiescent data are the green points plotted on the hour axis. Adeney's mixed and quiescent data almost match but on scales different by a factor of 6000 demonstrating the significant difference between quiescent and mixed solution rates. Adeney's [81] quiescent experiments were carried out on 40 mm diameter vertical tubes of about 0.3 m length and quite different from the length of Richardson et al's [80].

Richardson et al. [80] repeated Adeney's [78, 79, 81] solution equation:

$$
\begin{equation*}
w=\left(1-w_{1}\right)\left(1-\exp \left(-f \frac{A}{V} t\right)\right) \tag{2.9.2}
\end{equation*}
$$

where
w is the fraction of saturation of dissolved air at time $t$,
$t \quad$ is the time
$\mathrm{w}_{1} \quad$ is the initial dissolved air fraction
f solution factor

A Surface area of contact between water and air
$V \quad$ Volume of water.
Richardson et al. [80] supplied only two values 27 days apart with the initial fraction of nitrogen saturation of $4.65 \%$ and after 27 days a gradient of nitrogen saturation percentage from the top to bottom of $40 \%$ to $13 \%$ with an average of $26.5 \%$. Values of $4.65 \%$ and $26.5 \%$ have been plotted but the equation (2.8.2) had to be changed to:

$$
\begin{equation*}
\left(1-w_{2}\right)=\left(1-w_{1}\right) \exp \left(-f \frac{A}{V}\left(t_{2}-t_{1}\right)\right) \tag{2.9.3}
\end{equation*}
$$

in order to find the time value corresponding to $\mathrm{w}_{1}$. Rearranging terms for finding fA/V or if known then initial time, $\mathrm{t}_{1}$, for $\mathrm{w}_{1}$ :

$$
\begin{equation*}
-f \frac{A}{V}\left(t_{2}-t_{1}\right)=\ln \left\{\frac{1-w_{2}}{1-w_{1}}\right\} \tag{2.9.4}
\end{equation*}
$$

These equations were used to determine the prior time interval ( $\mathrm{t}_{1}$ ) for Adeney's quiescent [81] first "de-aerated" value for $w_{1}$ of $13.8 \%$ of saturation.

Richardson et al. [80] were investigating so called "streaming" or the transferring of the dissolved air throughout the vertical container. Their explanation was that of evaporative cooling of the surface with resultant convection mixing, even though, as evidenced below, density with dissolved air is lower than for air free water. Thermal evaporative effects dominate air solution density issues. The nitrogen concentration variation over the 3.6 metres from $40 \%$ at the top to $13 \%$ at the bottom is an indication of the effects of depth and the streaming based mixing. Chappuis [77] had made the comment that in his container the dissolved air concentration was almost the same in 0.3 m depth.

Richardson et al. [80] water de-aeration was by distillation under vacuum but still resulted in $7 \%$ saturation of nitrogen. The rapid initial rise in all the curves in the above figure points to an initial affinity of air component gases to dissolve in the water surface with the overall curvature a consequence of the distribution process of this dissolved air into the remaining liquid.

Richardson et al. [80] also carried out experiments with sodium chloride salt in de-aerated distilled water and found the streaming effect more pronounced with less variation in nitrogen concentration over the height of the tubes. Adeney [81] also carried out quiescent solution rate experiments with sea water and found slightly faster solution.

The ratio in the above Equations (2.8.2), (2.8.3) and (2.8.4) of area divided by volume has dimensions of reciprocal length or for a vertical cylinder reciprocal depth. The above indicated effect of depth may suggest the need for addition of depth or other length scale in the numerator to make the factor dimensionless and especially independent of units leaving the factor to be the reciprocal of time only. Better still would be the incorporation of a velocity-like factor which would make the whole exponent dimensionless.

Adeney and Becker's [78,79] experiments consisted of an air bubble of constant size moving vertically up a long glass tube achieved by inverting a closed tube with air bubble at the top. Consequently the solution process once the tube was inverted has a moving gas bubble which contacts the water for the full tube length and essentially is mixed by a thin rapid movement of water
past the bubble so that in effect the water is squeezed into a thin annular ring as the bubble passes. This is different from Chappuis' [77] experiment which had quiescent solution. The difference between that of Chappuis [77] and Richardson et al. [80] could be due to the order of magnitude larger diameter and lower depth of Chappuis' container. Adeney's [81] quiescent data are similar to Chappuis's although Adeney's tubes were smaller than Chappuis' vessel but of similar height. Chappuis' container was in an enclosure and may have had some cover restriction.

Searching via Scopus with "solution rate of air in water" resulted in 6789 document results. Adding "pipe" reduced the count to 196. None of these appeared to address solution rate with the results most likely detecting the inclusion of the words "solution" and "rate". A comprehensive paper on the solution of gases in liquids by Rubin Battino [82] of almost 70 pages failed to mention solution rates. The extensive book "The Experimental Determination of Solubility" [83] also failed to mention experimental solubility rate determination.

## Small Bubble Solution Rate and Diffusion

Epstein and Plesset [84] published a paper on gas bubbles in liquid-gas solutions. Their theory essentially consisted of analysing the diffusion of the gas to and from the bubble into the solution and the stability conditions on bubble size.

Houghton et al. [85] used their theory to determine the diffusion coefficients of oxygen, nitrogen and helium into water and other liquids. Their maximum bubble diameter was 0.47 mm . Later Wise and Houghton [86] used bubbles of gas up to 0.4 mm to determine the diffusion coefficient for an extended range of gases over the temperature range of 10 to $60^{\circ} \mathrm{C}$. Krieger et al. [87] used bubbles up to 0.75 mm diameter for the same gases as Houghton et al. Later Ward et al. [88] investigated mathematically and experimentally the stability of small gas bubbles in a closed volume of liquid-gas solution with diameters up to 0.87 mm . All of the above experiments were at pressures close to atmospheric pressure. The fact that they could use such small bubbles to determine diffusion rates of gases in water with bubbles below 1 mm diameter meant that air solution inside pipes is ultimately limited by diffusion rates of the small bubbles. Their mathematics demonstrated that bubbles can enlarge and contract depending on the bubble diameter and gas-liquid solution concentration but always below 1 mm . All of the above bubble studies needed the bubbles stationary so that their diameters could be measured which need quiescent conditions. To view bubbles they had to be trapped against a clear surface or against fibres which is not unlike the situation for a residual bubble trapped at the top of a pipe. Ultimately final solution is by diffusion which is slow and further affected by surface tension.

A paper by Plesset [89] was the only to mention the effect of pressure with the comment "as the pressure is raised, the stable radius gets smaller to a minimum value. At higher pressures a stable bubble cannot be found."

Using the Young Laplace Equation (4.2.1) for small bubbles the pressure difference is as per the following Table $2-3$ for $25^{\circ} \mathrm{C}$ :

Table 2-3 - Pressure Difference across Air Bubble Surfaces using Young-Laplace Equation

| Pressure Difference across Air Bubble Surfaces |  |
| :--- | :---: |
| Bubble diameter (mm) | Pressure difference <br> $(\mathrm{kPa})$ |
| 1 | 0.14 |
| 0.4 | 0.36 |
| 0.1 | 1.44 |
| 0.01 | 14.4 |
| 0.001 (1 micron) | 144 (1.44 bar) |
| 0.0001 (0.1 micron) | 1440 (14.4 bar) |

Other than Plesset [89], surface tension had been ignored by the above authors as can be confirmed from this table since their bubbles were smaller than 1 mm in diameter which justified such assumption.

Some papers report on the solution rate of gas in bubbles used to determine the diffusion rates of these gases in water such as Houghton et al. [85], Wise and Houghton [86] and Krieger et al., [87]. The largest oxygen bubble diameter for Krieger et al. was 0.75 mm while Houghton et al. largest diameter was 0.46 mm again for oxygen while for air was 0.32 mm . All these bubble diameters occur in a pipe at the final stages of solution and such references are only of value at this extreme end of solution rates. Also for a tethered bubble the solution rate is quiescent. They do however provide a link between solution rate and diffusion at this very small bubble size and demonstrate that solution rate is generally faster than diffusion.

Houghton et al. [85] provided an equation to determine gas diffusivity as:

$$
\begin{equation*}
-\left(\frac{\partial c}{\partial r}\right)_{R}=\frac{\rho}{D_{L}} \frac{d R}{d t}=\left(c^{*}-c_{\infty}\right)\left[\frac{1}{R}+\frac{1}{\sqrt{\pi D_{L} t}}\right] \tag{2.9.5}
\end{equation*}
$$

where

| $c$ | is the concentration of the gas in the liquid (g mole/cc) |
| :--- | :--- |
| $c^{*}$ | is the saturation concentration of the gas in the liquid $(\mathrm{g} \mathrm{mole} / \mathrm{cc})$ |
| $C_{\infty}$ | concentration a large distance from the bubble (g mole/cc) |
| $R$ | the bubble radius $(\mathrm{mm})$ |
| $D_{L}$ | the diffusion coefficient $\left(\mathrm{cm}^{2} / \mathrm{sec}\right)$ |
| $t$ | time (sec) |
| $\rho$ | solvent density $\left(\mathrm{g} / \mathrm{cm}^{3}\right)$ |

This equation had been developed previously by Epstein and Plesset [84]. They refer to the second term in the square brackets as the transient term which after a short time becomes smaller than the first term and is then ignored so that the diffusion, $D_{L}$, then results from double integration and changing from radius to diameter, D , resulting in:

$$
\begin{equation*}
D^{2}-D_{0}^{2}=\frac{8 D_{L}\left(c^{*}-c_{\infty}\right) t}{\rho \ln 2} \tag{2.9.6}
\end{equation*}
$$

where
D is the measured diameter at time t
$\mathrm{D}_{0} \quad$ is the initial diameter at time zero.
$\mathrm{C}_{\infty} \quad$ is considered zero since the water had been degassed by boiling water for 45 minutes.

They measured the slope of the square of the diameter, D , with time from which they obtained the diffusion coefficient which was the whole purpose of their experiments and paper.

What is only of interest to this document is the transient term which becomes the dominant term for times in accordance with the following rearrangement of the square bracketed term:

$$
\begin{equation*}
t<-\frac{D^{2}}{4 \pi D_{L}} \tag{2.9.7}
\end{equation*}
$$

Using the diffusion coefficient for air in water determined by Houghton et al. [85] of $2.3 \times 10^{-5}$ $\mathrm{cm} 2 / \mathrm{sec}$ or $2.3 \times 10^{-7} \mathrm{~mm}^{2} / \mathrm{sec}$, times would be in accordance with the following Table 2-4.

Table 2-4 - Diffusion-based Times for Air Solution of Bubbles

| Diffusion based Times for Solution of Air Bubble |  |  |
| :---: | :---: | :---: |
| Bubble diameter (mm) | Maximum time (hours) | Maximum time (days) |
| 0.1 | 0.96 | 0.04 |
| 0.2 | 3.8 | 0.16 |
| 0.4 | 15.4 | 0.64 |
| 0.8 | 62 | 2.56 |
| 1.6 | 246 | 10.3 |
| 3.2 | 984 | 41 |
| 6.4 | 3936 | 164 |
| 12.8 | 15746 | 656 |

This table then implies that for solution rates with times of weeks, bubbles smaller than 1.6 mm diameter will dissolve by diffusion. What has been ignored in producing this table is the diffusion coefficient term multiplied by the dR/dt term.

Rearranging the Epstein and Plesset equation:

$$
\begin{equation*}
\frac{d R}{d t}=\frac{D_{L}\left(c^{*}-c_{\infty}\right)}{\rho}\left[\frac{1}{R}+\frac{1}{\sqrt{\pi D_{L} t}}\right] \tag{2.9.8}
\end{equation*}
$$

By ignoring the 1/R term in the square brackets by only considering larger bubble diameters:

$$
\begin{equation*}
d R=\sqrt{\frac{D_{L}}{\pi}} \frac{\left(c^{*}-c_{\infty}\right)}{\rho \sqrt{t}} d t \tag{2.9.9}
\end{equation*}
$$

Integrating:

$$
\begin{equation*}
R-R_{0}=2 \sqrt{\frac{D_{L} t}{\pi}} \frac{\left(c^{*}-c_{\infty}\right)}{\rho} \tag{2.9.10}
\end{equation*}
$$

Squaring both sides results in:

$$
\begin{equation*}
\left(R-R_{0}\right)^{2}=\frac{4 D_{L} t}{\pi}\left\{\frac{\left(c^{*}-c_{\infty}\right)}{\rho}\right\}^{2} \tag{2.9.11}
\end{equation*}
$$

Quiescent solution rate experiments of air in water filled pipes will be detailed later. The dissolved air molecules have a volume which can affect volume related properties of water and derived properties such as the $\mathrm{dP} / \mathrm{dV}$ and $\mathrm{dP} / \mathrm{dT}$ factors. The following section will briefly review relevant literature on dissolved molecular size or partial molar volume of dissolved gases.

### 2.10 PARTIAL MOLAR VOLUME

When a gas dissolves in a liquid the volume of the gas molecule significantly differs from the gaseous state and the liquid molar volume can also change when the gas molecule is added. For example when methanol liquid is added to water in a $50 \%$ mixture the water partial molar volume becomes $17.79 \mathrm{ml} / \mathrm{mole}$ while in water alone it is $18.05 \mathrm{ml} / \mathrm{mole}$. The added methanol has changed the water molar volume. When two or more different molecular species are present in a liquid their respective molar volumes are referred to as their partial molar volumes.

### 2.10.1 Partial Molar Volume at Atmospheric Pressure

The following discussion is based on atmospheric pressure without consideration of the effects of pressure which is addressed in the subsequent Section.

The complete differential of the volume containing two species $A$ and $B$ with respect to changes in the molar number of each is given by:

$$
\begin{equation*}
d V=\left(\frac{\partial V}{\partial n_{A}}\right)_{n_{B}} d n_{A}+\left(\frac{\partial V}{\partial n_{B}}\right)_{n_{A}} d n_{B} \tag{2.10.1}
\end{equation*}
$$

The differentials vary with the number of moles, n , and are referred to at the partial molar volumes so that:

$$
\begin{equation*}
V_{A}=\left(\frac{\partial V}{\partial n_{A}}\right)_{n_{B}} \approx\left(\frac{V_{1}-V_{2}}{n_{A 1}-n_{A 2}}\right)_{\text {per } 1 \mathrm{~mol} B} \tag{2.10.2}
\end{equation*}
$$

Where the indices 1 and 2 represent slightly different mixture conditions around the conditions required such as slight changes in concentration of the mixture. Similar equation holds for component $B$ with respect to $A$.

After integrating the complete differential the following relation results which applies to mixtures where the respective partial molar volumes are assumed constant:

$$
\begin{equation*}
V=n_{A} \overline{V_{A}}+n_{B} \bar{V}_{B} \tag{2.10.3}
\end{equation*}
$$

Where:
$V \quad$ volume of combined components $A$ and $B$.
$\mathrm{n}_{\mathrm{A}} \quad$ number of moles of component A
$n_{B} \quad$ number of moles of component $B$.
$\bar{V}_{A} \quad$ molar volume of $A$ (usually with a bar over the $V$ ).
$\bar{V}_{B} \quad$ molar volume of $B$ (usually with a bar over the $V$ ).
There is a long history of researchers attempting to determine the partial molar volumes (PMV) of dissolved gases especially the components of air. The partial molar volume has significance in the thermodynamics of gas solution in liquids (Hefter and Tomkins [83]). Hefter and Tomkins quoted Bignell's [90] water density results at $4^{\circ} \mathrm{C}$ with a difference between degassed and air-saturated water of 4.20 ppm with a standard deviation of 0.15 ppm based on 21 measurements and with temperature controlled to $+/-2 \mathrm{mK}$.

Harvey et al. [74] investigated the refractive index of water containing dissolved air at atmospheric pressure for which they needed the density. Their study of the effects of dissolved air on density was the most recent found and covers previous research. They investigated the work of Bignell [91] and Watanabe et al. [92] both of whom carried out high resolution measurements of water density and from it determined the partial molar volumes (PMV) of gases. Bignell used an extremely sensitive hydrometer like float while Watanabe et al. used high sensitivity densitometers. Both provided equations for PMV variation with temperature as detailed below.

Bignell's equations below were only for data from 3 to $21^{\circ} \mathrm{C}$. Units are in $\mathrm{cm}^{3} / \mathrm{mole}$.

$$
\begin{gather*}
O 2: V=31.729-0.0919 T+0.00267 T^{2}  \tag{2.10.4}\\
N 2: V=34.49-0.0082 T  \tag{2.10.5}\\
A r: V=32.676-0.06709 T \tag{2.10.6}
\end{gather*}
$$

Where the temperature, T , is in ${ }^{\circ} \mathrm{C}$.
The following table summarises the relative contributions for air and use Bignell's equations at 0 ${ }^{\circ} \mathrm{C}$.

Table 2-5 - Air component gases and properties - Bignell's molar volumes.

| Air Component Gases and Properties with Bignell's Molar Volumes |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
| Component Gas | Molar mass grams | Mole fraction | $0^{\circ} \mathrm{C}$ <br> Molar vol cm ${ }^{3}$ | $0^{\circ} \mathrm{C}$ density gm/cc |
| Oxygen | 32.00 | 0.2095 | 31.729 | 1.008 |
| Nitrogen | 28.01 | 0.7812 | 34.490 | 0.812 |
| Argon | 39.95 | 0.0093 | 32.676 | 1.223 |
| Air | 28.96 | 1.0000 | 33.895 | 0.857 |

Combining Bignell's equations based on the mole fractions in air as per the table above resulted in the following equation for the molar volume of air dissolved in water:

$$
\begin{equation*}
\text { Air: } V=33.895-0.0263 T+0.00056 T^{2} \tag{2.10.7}
\end{equation*}
$$

Watanabe and lizuka [92] have also determined partial molar volumes and have compared density changes with those of dissolved air over a range of concentrations at atmospheric pressure. They corrected their measurements for what they considered the air content in "air free" water which they determined using sensitive conductivity based measurements of oxygen content. Their equations are as follows over the range from 0 to $40^{\circ} \mathrm{C}$. Units are in $\mathrm{cm}^{3} / \mathrm{mole}$.

$$
\begin{align*}
& O 2: V=31.265-0.0285 T  \tag{2.10.8}\\
& N 2: V=35.359+0.0075 T  \tag{2.10.9}\\
& A r: V=30.092-0.0277 T  \tag{2.10.10}\\
& C O 2: V=35.520+0.0071 T \tag{2.10.11}
\end{align*}
$$

They make the comment that these equations can extend beyond 40 degrees C . The following Table 2-6 summarises the relative contributions for air and uses Watanabe and lizuka's values for 0 ${ }^{\circ} \mathrm{C}$ with slight changes to mole fraction to reach a combined mole fraction for air of 1.0 as was used by Harvey et al. [74].

Table 2-6 - $\quad$ Air component gases and properties - Watanabe and lizuka's molar volumes

| Air Component Gases and Properties with Watanabe et al. |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
| Molar Volumes |  |  |  |  |
| Component <br> Gas | Molar <br> mass <br> grams | Mole <br> fraction | $0^{\circ} \mathrm{C}$ <br> Molar <br> vol cm | $0^{\circ} \mathrm{C}$ density <br> gm/cc |
| Oxygen | 31.9988 | 0.20939 | 31.265 | 1.023 |
| Nitrogen | 28.0134 | 0.78101 | 35.359 | 0.792 |
| Argon | 39.948 | 0.00917 | 30.092 | 1.327 |
| Carbon di | 44.010 | 0.00040 | 35.520 | 1.239 |
| Oxide | 28.96 | 1.0000 | 34.453 | 0.840 |
| Air |  |  |  |  |

The combined equation for the partial molar volume of air then becomes:

$$
\begin{equation*}
\text { Air }: V=34.453-0.00563 T \tag{2.10.12}
\end{equation*}
$$

The effective density of dissolved air component is then:

$$
\begin{align*}
& \text { Dissolved air density } \\
& \qquad=840.66+0.137 \mathrm{Tkg} / \mathrm{m}^{3} \tag{2.10.13}
\end{align*}
$$

This density is considerably lower than water and indicates that any dissolved air will reduce the density of the solution and is likely to increase the acoustic velocity. Furthermore it indicates that if air dissolves in water at an upper surface of contact, such water will be lighter than surrounding water and should remain at that location unless solution involves temperature change. Only thermal convection currents can then move the water with dissolved air.

Comparing Bignell's and Watanabe's values for partial molar volumes points to issues with experimental techniques used to determine them. Watanabe's results used different methodology and noted that it was essential to correct for the extreme difficulty of obtaining water without any dissolved air or oxygen so that even after removing dissolved air Watanabe's team measured dissolved oxygen and then corrected for its effects. As a result of such corrections, Watanabe's measurements show a greater reduction in density than all previous experimenters including Bignell. Watanabe's quoted error for density was 0.16 ppm similar to those of Bignell whereas those of others are an order of magnitude higher. Bignell mentioned Watanabe's results and differences but concluded that they were both within the error range. Bignell after de-aerating his water samples kept them under vacuum until use and ensured that the equipment was thoroughly flushed to avoid contamination.

Harvey et al. [74] used a modified version of Bignell's results. The previous section on solution rate experiments highlighted the same problem pointed out by Watanabe and confirmed by Richardson et al. [80] with their residual $7 \%$ nitrogen after distillation in vacuum. While Bignell's results had higher resolution he was still possibly subject to the problem of obtaining air free water which appears to be more difficult than is reported. In terms of partial molar volumes, this author prefers to use the

Watanabe et al. data corrected for estimated initial air content as indicated by oxygen content. The difference is less than $2 \%$ at $0^{\circ} \mathrm{C}$.

### 2.10.2 Pressure dependence of Partial Molar Volumes

O'Sullivan and Smith [93] carried out partial molar volume measurements for Nitrogen in water from $50^{\circ} \mathrm{C}$ to $125^{\circ} \mathrm{C}$ and from 100 to 600 atmospheres pressure. They concluded that there was no pressure dependence at $102.5^{\circ} \mathrm{C}$ and below. They observed changes at $125^{\circ} \mathrm{C}$ due to pressure. Their value at $51.5^{\circ} \mathrm{C}$ of $34.05 \mathrm{~cm}^{3} /$ mole agrees with Bignell's equation above within $0.01 \mathrm{~cm}{ }^{3} / \mathrm{mole}$. Biggerstaff and Wood [94] reported Argon results from $323^{\circ} \mathrm{K}\left(50^{\circ} \mathrm{C}\right)$ to $716.49{ }^{\circ} \mathrm{K}$ for pressures ranging from 172.2 bar to 345.7 bar absolute. Their value at $50^{\circ} \mathrm{C}$ for Argon at 172.2 bar is on average $30.65 \mathrm{~cm}^{3} / \mathrm{mole}$. This differs from that calculated using Bignell's equation by $1.33 \mathrm{~cm}^{3} / \mathrm{mole}$. Their values at higher temperature indicate significant curvature in the apparent molar volumes with temperature which indicates that Bignell's equation needs to be corrected to apply to higher temperatures than $21^{\circ} \mathrm{C}$.

A curve estimating this could take the form of:

$$
\begin{equation*}
A r: V=32.760-0.0883 T+0.000861 T^{2} \tag{2.10.14}
\end{equation*}
$$

Since the contribution of Argon to the molar volume of air in water is around $1 \%$, there is no benefit in using such an equation.

Similarly the nitrogen values could be fitted to a curve however it appears that for the temperature range from 0 to $50^{\circ} \mathrm{C}$ the linear equation of Bignell is adequate.

These equations can be considered as providing the molar volume at $0^{\circ} \mathrm{C}$ as the left hand number and the temperature coefficient as the terms including $T$.

Enns, Solander and Bradstreet [95] reported the partial molar volumes of nitrogen, oxygen, argon and carbon di oxide (used later by Kell [96]) together with helium and made the comment that "all gases except helium give slightly curved plots indicating a decrease in partial molar volume with increase in hydrostatic pressure". Their experiments differed from those of O'Sullivan and Smith [93] in that they dissolved air in water at close to atmospheric pressure (not necessarily saturated) and then pressurised the water and measured the partial pressure change of the dissolved gas at pressure while O'Sullivan and Smith dissolved air in water to saturation at pressure and measured the solubility change with pressure.

Kritchevsky and Kasarnovsky (1945A) [97, 98] suggested a pressure dependence of partial molar volume with a linear relationship as follows:

$$
\begin{equation*}
\bar{v}=\bar{v}_{0}-\beta P \tag{2.10.15}
\end{equation*}
$$

where

| $\overline{\mathrm{v}}$ | is the partial molar volume |
| :--- | :--- |
| $\overline{\mathrm{v}}_{0}$ | is the partial molar volume at zero pressure (assumed gauge) |
| $\beta$ | is the partial molar volume compressibility which can be negative |
| $P$ | the pressure (assumed gauge). |

They made the comment that any dependence on pressure would be lost in the uncertainty of partial molar volume measurements.

### 2.10.3 Density of Water/Air Solution

Chappuis [77] quoted the measurements of Marek [99] of the reduction in water density due to the saturated solution of air over the range from 0 to $20^{\circ} \mathrm{C}$ and found variations of from 0.4 ppm to 3.4 ppm as shown in the following Figure 2-26.


Figure 2-26 - Plot of Marek's density difference measurements with and without air dissolved in water (blue dots and blue dashed line with left vertical axis). Also shown is the partial molar volume variation for air in water with temperature from Bignell (red dashed line with right vertical axis).

Chappuis made the comment that the Marek results were "rather uncertain" and questioned whether the samples were fully air saturated. His concerns led to experiments to determine the rate of quiescent solution to enable him to understand the level of air saturation with time once exposed. In his measurements he used Marek's results for water density correction based on the solution rate experiments to determine the fraction of saturation. Marek's data was the only available for his corrections. In Bignell's paper [91], he mentioned that Chappuis had spoken to Marek who indicated that the air free and dissolved air states may not have been rigorous.

Added to Marek's data in Figure 2-26 is the curve of Bignell's [91] partial molar volume for saturated air in water with Y axis reversed to reflect its effect on density. There is little correspondence confirming Chappuis's suspicions.

Kell [96] has estimated the density of water with dissolved air at atmospheric pressure but was limited by the available PMV values at that time (Enns and Solander [95]). Subsequently Harvey et al. [74] used Kell's methodology to obtain the density they needed which was based on a modified version of Bignell's [91] PMV values.

Harvey et al. [74] reported contacting Bignell to clarify the solubility data used in his measurements and concluded that they were based on old Henry's law coefficients. Harvey et al. then corrected Bignell's data for the updated Henry's law coefficients so that in the Figure 2-27 below there is a slight difference between Bignell's and Harvey's density curves.


Fig. 2. Calculated and experimental values for $\Delta \rho$, the change in density of water upon equilibration with air at 101.325 kPa total pressure.

Figure 2-27 - Harvey et al figure [74] comparing density changes on air saturation in water from different researchers together with his modification of Bignell's curve.

The above authors determined the density change resulting from air solution at atmospheric pressure. Publications for air affected densities at higher pressures have not been found. Such density is a minimum starting point for determining dissolved air affected acoustic velocity which failing measurements relies on the basic properties that determine acoustic velocity namely bulk modulus or its reciprocal compressibility and density of the water with dissolved air.

O'Sullivan and Smith [93] reported partial molar volumes of nitrogen dissolved in water with salt content and made the comment that the addition of salt to water made water more normal as a solvent in terms of changes in partial molar volume. They also reported solution of methane gas in both water and salt water and noted that the effect of methane differed from nitrogen.

An article titled "The $\mathrm{O}_{2} / \mathrm{N}_{2}$ Ratio Gas Solubility Mystery" by Battino and Seybold in 2011 [100] attempted to resolve the strange difference in solubility between oxygen and nitrogen. Pure oxygen has double the solubility in water as pure nitrogen and similarly in other solvents even non-polar solvents (non-water). The authors examined many different factors and came to the conclusion that the $\mathrm{N}_{2}$ molecule is slightly larger (21\%) than the $\mathrm{O}_{2}$ molecule which in turn affects the extra Gibbs energy to create a hole in the water solvent. This larger size is reflected in the Partial Molar Volume (not addressed in their article) which can be approximately determined by Scaled Particle Theory (SPT). Could this point to possible changes with the partial molar volume of water itself as a consequence of solution of gases?

Greenspan and Tschiegg [101] accurately determined the velocity of air free water at temperatures from 70 to $78^{\circ} \mathrm{C}$ and found the peak velocity occurred at $73.95^{\circ} \mathrm{C}$. Such a peak surprisingly reflects the peculiarities of water which include the maximum compressibility (minimum bulk modulus) at around $46.5^{\circ} \mathrm{C}$ and maximum density at close to $4^{\circ} \mathrm{C}$. Water is an unusual liquid and the effects of dissolved air may further affect its properties. One theory published by Davis and Litovitz in 1965 [102] and unknowingly resurrected by Vedamuthu et Al. in 1994 [103] was based on a two component structure of water with an ice-like lower density structure and a more dense structure with fractions of each varying with temperature. What is intriguing in relation to partial molar volumes of dissolved air component gases is that the two component phases have molar volumes of around 20.7 cc/mole and $13.67 \mathrm{cc} / \mathrm{mole}$ for the less and higher density structures respectively and could affect the temperature dependence of the partial molar volumes.

Kell [96] had estimated the density decrease with air content at atmospheric pressure and reported a change of around 3 ppm at $0^{\circ} \mathrm{C}$. Bignell [90] made measurements which gave similar values. Watanabe [92] measured densities from zero to $40^{\circ} \mathrm{C}$ with values decreasing from around 5 to 2 ppm respectively.

### 2.10.4 Dissolved air and Bulk Modulus or Compressibility

Bulk modulus is a function of the differential of density with respect to pressure and consequently is more difficult to measure than density which as demonstrated above is itself difficult with regard to the effects of dissolved air. Lack of any consistent information on pressure dependence of partial molar volume in Section 2.10.2 leaves the issue of bulk modulus change with air content open.

### 2.10.5 Effect of dissolved air on Acoustic Velocity

Greenspan and Tschiegg [104] performed experiments to determine the effect of dissolved air at atmospheric pressure on the acoustic velocity and found a change of around 1 ppm at $31.8^{\circ} \mathrm{C}$ and around 3 ppm around zero C. They started with water with less than $5 \%$ of possible air content which by the time they did the "air free" measurements had an estimated $10 \%$ air content. They then took measurements with $100 \%$ dissolved air content which is equivalent to a volume of $2 \%$ at atmospheric pressure. They provided statistical data for the measurements at $31.8^{\circ} \mathrm{C}$ but not at zero due to erratic measurements due to difficulties maintaining the temperature. They did not indicate the direction of change however they measured the frequency change in the signals used to measure the velocity and
the frequency increased by the order of 0.014 Hz with average frequencies of 14955.9 Hz which they stated corresponded to a velocity change of 1 ppm .

The only data on acoustic velocity change is that of Greenspan and Tschiegg quoted above.

Acoustic velocity in water equation as in many acoustics textbooks [5] is given by:

$$
\begin{equation*}
a=\sqrt{\frac{K}{\rho}} \tag{2.10.16}
\end{equation*}
$$

where:

| K | adiabatic bulk modulus, |
| :--- | :--- |
| $\rho$ | density |

if air-free water velocity is ao then using the same subscript the equation becomes:

$$
\begin{equation*}
a_{0}=\sqrt{\frac{K_{0}}{\rho_{0}}} \tag{2.10.17}
\end{equation*}
$$

The following equations and examples have been developed by this author with other authors mentioned when relevant. When air dissolves, the bulk modulus and density will change so that:

$$
\begin{gather*}
a=\sqrt{\frac{K}{\rho}}=\sqrt{\frac{K_{0}(1+\Delta K)}{\rho_{0}(1+\Delta \rho)}}=a_{0} \sqrt{\frac{(1+\Delta K)}{(1+\Delta \rho)}}  \tag{2.10.18}\\
\approx a_{0}\left(1+\frac{\Delta K}{2}\right)\left(1-\frac{\Delta \rho}{2}\right)
\end{gather*}
$$

Further simplifying and ignoring second order terms results in:

$$
\begin{equation*}
a \approx a_{0}\left(1+\frac{\Delta K}{2}-\frac{\Delta \rho}{2}\right) \tag{2.10.19}
\end{equation*}
$$

These simplifications and approximations are based on the $\Delta K$ and $\Delta \rho$ terms being of the order of $1.0 \times 10^{-6}$.

Taking Greenspan and Tschiegg's estimate at $31.8^{\circ} \mathrm{C}$ of an acoustic velocity change (assumed increase) of 1 ppm then:

$$
\begin{equation*}
\frac{\Delta K}{2}-\frac{\Delta \rho}{2} \approx 1.0 \times 10^{-6} \tag{2.10.20}
\end{equation*}
$$

But Watanabe's value for density change for this temperature is around $3 \times 10^{-6}$ reduction thus:

$$
\begin{align*}
\frac{\Delta K}{2} \approx \frac{\Delta \rho}{2}+1.0 & \times 10^{-6} \\
& \approx-1.5 \times 10^{-6}+1.0 \times 10^{-6}  \tag{2.10.21}\\
& =-0.5 \times 10^{-6}
\end{align*}
$$

From which there should be a reduction in bulk modulus of around $0.5 \times 10^{-6}$.

Around zero ${ }^{\circ} \mathrm{C}$, Greenspan and Tschiegg reported around 3 ppm change in velocity which using the above methodology and Watanabe's value of 5 ppm change, results in a bulk modulus increase of around $0.5 \times 10^{-6}$ :

$$
\begin{align*}
\frac{\Delta K}{2} \approx \frac{\Delta \rho}{2}+3.0 & \times 10^{-6} \\
& \approx-2.5 \times 10^{-6}+3.0 \times 10^{-6}  \tag{2.10.22}\\
& =+0.5 \times 10^{-6}
\end{align*}
$$

These simple calculations show that the bulk modulus change should be in the order of $+/-0.5$ $\times 10^{-6}$ for dissolved air at atmospheric pressure, with the change reversing between zero and $32^{\circ} \mathrm{C}$. This change is smaller than for density but is of the same order and not zero. It still could be an issue of error in that the estimates of density and velocity change have errors of approximately $+/-0.5 \times 10^{-6}$ which are of the same order as the bulk modulus estimates.

Measurements of water properties with large quantities of dissolved air at pressure would resolve the above issues such as velocity or alternatively both density and bulk modulus.

### 2.10.6 Air exposed water column phase velocities

Enns, Scholander and Bradstreet [95] saturated water samples at atmospheric pressure and then subjected these samples to pressures up to approximately 100 atmospheres simulating the effects of a water column 1,000 metres deep with the intention of extrapolating their findings to 10,000 metre water depth. According to Henry's law the quantity of dissolved gas is directly proportional to the gas partial pressure. They found that the gas partial pressure increased by approximately $14 \% / 100$ atm for the gases argon, nitrogen and oxygen. They also made estimates of partial molar volumes of these same gases which were those later used by Kell [96] in his density estimates. The purpose of Enns et Al. [95] experiments was to determine experimentally whether there would be increases in dissolved gases at depth since swim bladders of deep ocean fish had contained nitrogen at 10 atm. partial pressure. Their estimate for the increase in partial pressure at 10,000 metre water depth was a factor of 4 .

Their work was supported by the theoretical thermodynamic study of Klotz [105].
Using the above equations for air dissolved in water, a factor of 4 increase would cause a velocity increase at $0^{\circ} \mathrm{C}$ of approximately 14 ppm while at $31.8^{\circ} \mathrm{C}$ an increase of approximately 7 ppm . Such velocity changes are very small compared with fully air saturated water at $10,000 \mathrm{~m}$ depth.

### 2.10.7 Conclusion regarding Partial Molar Volume of Air molecules in Water

The small change in acoustic velocity due to air solubility at atmospheric pressure makes such determination difficult however at much higher pressures such changes are more easily measured. The velocimeter developed by Greenspan [104] and subsequently commercialised and extensively used for marine based acoustic purposes could be used to confirm the above equations. Furthermore, partial molar volumes obtained with great difficulty at atmospheric pressure are more readily obtained at high pressure provided there is accurate knowledge of the quantity of dissolved gases.

Any theoretical estimation of velocity changes in water with dissolved gases is fraught with the problems of unreliable experimental data values of partial molar volumes used to determine density changes and the unavailability of bulk modulus information. An experimental determination would avoid both issues and is likely to permit determination in reverse of partial molar volumes and bulk modulus of dissolved gases from acoustic velocities. Approaches to companies with velocimeters were unsuccessful and the University was unwilling to invest in such an instrument.

### 2.11 STEEL PROPERTIES RELEVANT TO HYDROTESTS

Only unusual steel properties that have an impact on final test pressure, acoustic velocity or temperatures are addressed in this section.

### 2.11.1 Strain Rate and Pressurisation

AS2885.5 [10] and previous editions stated that the effect of strain rate on pipe yield point changes approximately 8 MPa per decade of time change. Factory mill test strain rate where yield stress of say 250 MPa is reached in 10 seconds corresponds to a strain rate of 0.002 in 10 seconds or $0.0002 /$ second strain rate. In field conditions with the same pipe pressurised in 1000 seconds (two decades lower rate) the yield stress will reduce to approximately $250-2 \times 8=234 \mathrm{MPa}$ with the strain rate of $0.000002 /$ second. This effect of so called strain rate is known in the pipe manufacturing industry and mechanical testing as it affects the yield point but not so outside. It will be used in this document in regard to pressure drops following pressurisation as a possible explanation of the acoustic anomalous results highlighted in this document.

### 2.11.2 Steel Plastic Deformation

During pressurisation to strength test pressure, deviation from a straight pressure-volume line at high pressures indicates plastic deformation or yield of the pipe. This is more likely in pipe which has not been cold expanded such as ERW (Electric Resistance Welded) pipe and SW (Spiral Welded) pipe. Such deviation implies that relaxation or creep will occur once the final pressure has been reached. For high pressure tests close to or above uni-axial yield such plastic deformation is expected and usually some criteria are applied to limit the plastic deformation during pressurisation but rarely after. AS2885.5:2020 [10] and prior editions require that the strength test be continued until the pressure decline at its end does not exceed 1\% per hour which essentially requires that plastic deformation rate has been reduced to acceptable levels.

### 2.11.3 Young's Modulus Variation with Temperature

Timoshenko [106] (P 519 Figure 346) provided a small scale graph of Young's modulus variation with temperature which was digitised and expanded, as shown in Figure 2-28 below.


Figure 2-28 - Young's Modulus for Steel - Variation with Temperature - Timoshenko [106].
The trend line estimated for the digitised data is as follows:

$$
\begin{gather*}
E=-0.25883 T^{3}-7.6655 T^{2}-25873 T  \tag{2.11.1}\\
+206.0 \times 10^{6}(\mathrm{kPa})
\end{gather*}
$$

From which the differential with respect to temperature at $25^{\circ} \mathrm{C}$ can be obtained as:

$$
\begin{equation*}
\frac{\partial E}{\partial T}=-26742 k P a /{ }^{\circ} K \tag{2.11.2}
\end{equation*}
$$

### 2.11.4 Steel Thermoelastic Effect

When a water filled pipe is pressurised, the water inside is compressed and heated while the external steel is subject to tensile stress which results in cooling. The water temperature change is due to adiabatic (no heat transfer) compression effects while the steel temperature change is due to increase in tensile stress which shows up as cooling since it is the reverse of compression and is known as the thermoelastic effect.

For the thermoelastic effect a recent paper by Crump et Al., [107] pressurised an 85 mm diameter 10 mm wall thickness pipe of length 350 mm using hydraulic oil with only hoop stress applied. They cyclically pressurised the cylinder at a frequency of 10 Hz and monitored the external pipe temperature with an infrared detector capable of measuring temperature changes of the order of $0.005^{\circ} \mathrm{C}$ or 5 mK . They used this pipe as a means of calibrating the instrument using the known relationship given below. They did not provide confirmation or verification data. The equation for temperature change from stress change is as follows:

$$
\begin{equation*}
\Delta T=-\frac{\alpha}{\rho C_{P}} \Delta\left(\sigma_{c}-\sigma_{a}\right)=-K \Delta\left(\sigma_{c}-\sigma_{a}\right) \tag{2.11.3}
\end{equation*}
$$

## CHAPTER 2 - LITERATURE REVIEW

Where

| $\alpha$ | steel thermal expansion coefficient |
| :--- | :--- |
| $\rho$ | steel density |
| $C_{p}$ | steel specific heat at constant pressure |
| $\sigma_{c}$ | circumferential stress |
| $\sigma_{a}$ | axial stress |
| $\Delta$ | change in relevant parameters |
| $K$ | thermoelastic constant. |

In the case of steel the thermoelastic constant is close to $0.001^{\circ} \mathrm{C} / \mathrm{MPa}$ of stress and pressure converted to stress prior to use.

Crump et AI., [107] made the comment that 1 Hz was "lower than is usually considered necessary to obtain adiabatic conditions required to fill the assumptions of the thermoelastic equation". However this author has observed the effect in steel with sampling rates of many minutes to parts of hours.

The thermoelastic constant, K , is usually given as follows:

$$
\begin{equation*}
\Delta T=-\frac{\alpha T}{\rho C_{p}} \Delta \sigma=-K T \Delta \sigma \tag{2.11.4}
\end{equation*}
$$

where:

| $\Delta T$ | temperature change |
| :--- | :--- |
| $\Delta \sigma$ | stress change |
| $\alpha$ | thermal expansion coefficient |
| $C_{p}$ | specific heat and constant pressure, |
| $T$ | absolute temperature in Kelvin. |

A theoretical paper by Wong et Al. [108] expressed the thermoelastic parameter, K , in the following form:

$$
\begin{equation*}
K=\left(\alpha-\frac{1}{E^{2}} \frac{\partial E}{\partial T} \sigma_{m}\right) \frac{1}{\rho C_{p}} \tag{2.11.5}
\end{equation*}
$$

where:

$$
\begin{array}{ll}
\sigma_{m} & \text { mean applied stress. } \\
E & \text { Young's Modulus. }
\end{array}
$$

They specifically used the term "thermoelastic parameter" rather than "thermoelastic constant" which is normally expressed as (refer to Equation (2.11.4):

$$
\begin{equation*}
K_{0}=\frac{\alpha}{\rho C_{p}} \tag{2.11.6}
\end{equation*}
$$

so that

$$
\begin{equation*}
K=K_{0}-\frac{1}{E^{2}} \frac{\partial E}{\partial T} \frac{\sigma_{m}}{\rho C_{p}} \tag{2.11.7}
\end{equation*}
$$

with the second term correcting for stress level dependence as had been identified in experiments by others. Their derivation was intended to explain and resolve the stress dependence issue which applied correctly to a Titanium Aluminium Vanadium and an Aluminium alloy. Not addressed was pipe steel for which the stress is much lower than the Young's modulus and the differential of Young's modulus with respect to temperature is small, while the thermal expansion is around $1.17 \times 10^{-5}$ per ${ }^{\circ} \mathrm{C}$. It is difficult to find the temperature dependence of Young's Modulus at ambient temperatures which was covered in the previous section together with its temperature differential dE/dT (Equation (2.11.2)).

Using the above value for $\mathrm{dE} / \mathrm{dT}$ and the following values for steel at $25^{\circ} \mathrm{C}$ :

```
\rho Density = 7800 kg/m}\mp@subsup{}{}{3
CV Specific Heat (isothermal) = 465 J/(kg.K)
as Thermal expansion coefficient = 1.17 \times10-5/ }\mp@subsup{}{}{\circ}\textrm{C
ks Thermal conductivity = 54 W/(m.K)
E Young's modulus = 205.3 x10+3 MPa
\mu Poisson's ratio = 0.27
```

and assuming a mean stress of 182 MPa at average pressure of 15 MPa the thermoelastic parameter bracket term (Equation (2.11.5)) increases from $1.17 \times 10^{-5}$ to $1.18 \times 10^{-5}$ which is a small increase and less than the uncertainty in other factors. The overall thermoelastic parameter then becomes $3.48 \times 10^{-12 /(K . P a)}$ and the second term in the barcket term of Equation (2.11.5) can be ignored for steel.

The expected temperature change for a stress increase of 182 MPa at a Kelvin temperature, T , of 298 K is then $0.19^{\circ} \mathrm{K}$ (or ${ }^{\circ} \mathrm{C}$ ). At typical room temperatures around 300 K the combined parameter and temperature results in temperature change of $0.001{ }^{\circ} \mathrm{K}$ (or ${ }^{\circ} \mathrm{C}$ ) per MPa of stress change using Equation (2.11.4).

### 2.11.5 Water Adiabatic Temperature Change with Pressure

Similar to the thermoelastic effect is the adiabatic change in water temperature when subject to changes in pressure.

The temperature change results from the adiabatic or isentropic (constant entropy) compression or decompression of the water.

Isentropic compressibility is the reciprocal of the isentropic bulk modulus and given by (Alexandrov [109]), (Soll [110]), (Sun [111]) :

$$
\begin{equation*}
\frac{1}{B_{A}}=\left(\frac{d T}{d P}\right)_{S}=-\frac{T}{C_{P}}\left(\frac{d \rho}{d T}\right)=\frac{T \alpha}{\rho C_{P}} \tag{2.11.8}
\end{equation*}
$$

which is very similar to the thermoelastic equation for metals in Equation (2.10.4).
This has used the definition of the thermal expansion coefficient, $\alpha$, in terms of density, $\rho$ :

$$
\begin{equation*}
\alpha=-\frac{1}{\rho}\left(\frac{d \rho}{d T}\right) \tag{2.11.9}
\end{equation*}
$$

To obtain the temperature change it is necessary to integrate this equation over a range of pressures and for a particular absolute temperature, T , as:

$$
\begin{equation*}
\Delta T=\int_{P_{1}}^{P_{2}} \frac{T \alpha}{\rho C_{P}} d P \tag{2.11.10}
\end{equation*}
$$

IAPWS [30, 31, 33] provided equations for the isentropic compressibility of both pure water and sea water over a large range of pressures and temperatures. These values were integrated from atmospheric to a range of pressures for many different temperatures. These results for pure and sea water are detailed in the relevant tables in Appendix B. Pure water has negative values for a large range of pressures at $0^{\circ} \mathrm{C}$ while sea water has none and demonstrates the effect of foreign dissolved materials to change the abnormal nature of pure water. The difference between the two sets of values is misleading in that for example at $25^{\circ} \mathrm{C}$ and $20,000 \mathrm{kPa}$ pure water value is $0.384^{\circ} \mathrm{C}$ while seawater is $0.446^{\circ} \mathrm{C}$ while at $50^{\circ} \mathrm{C}$ the difference is only $0.003^{\circ} \mathrm{C}$. Seawater values are always higher. An attempt was made to reduce the pure water data into a cubic polynomial equation in pressure and temperature which was reasonably successful provided the temperature and pressures stayed away from the abnormal pure water conditions below $10^{\circ} \mathrm{C}$ or for pressures greater than $30,000 \mathrm{kPa}$.

For the steel thermoelastic effect the properties do not change with pressure and temperature to the same extent as water and so the value inside the integral is essentially a constant. For low pressures up to $10,000 \mathrm{kPa}$ the thermoelastic equation can be used with a resolution of 10 mK but deviates for higher pressure changes due to the changing water thermal properties.

Field experiments were carried out by this author which confirmed the adiabatic effect for water and thermoelastic effect for the steel container which were consistent with theory. Following such field verification a simplified form of the tables in Appendix B for water was supplied by this author and included in AS2885.5:2002 [37] and subsequent editions.

### 2.11.6 High Strength Steel Room Temperature Creep

Oehlert and Atrens [112] creep tested three very high strength steels for room temperature creep and found that creep could occur above around $50 \%$ of yield stress, which for these steels ranged from 1250 to 2000 MPa depending on heat treatment. Such yield strengths are of the order of 2 to 3 times those of pipeline steels. The authors were able to demonstrate creep under a range of conditions and for stresses below the yield stress. Creep conformed to a common equation namely the alpha equation of Wyatt [113] or an improvement to eliminate issues with infinite strains at zero time as shown below:

$$
\begin{equation*}
\epsilon=\alpha \log (\beta \tau+1)+\epsilon_{0} \tag{2.11.11}
\end{equation*}
$$

where
$\varepsilon$
creep strain
$\alpha \quad \log$ function coefficient
$\beta$ time factor constant
$\epsilon_{0} \quad$ initial tensile strain due to loading
Their creep results were monitored for 20 to 30 minutes and they referred to the creep as "Transient". While they did not extend these times they found that on significant reduction in stress at
or below $75 \%$ of the creep stress followed by the original creep stress the samples essentially continued on from their previous creep strain.

The elastic strain rates varied from around $3.0 \times 10^{-6}$ through $3.0 \times 10^{-5}$ to $3.0 \times 10^{-4}$ based on stress rates of $0.6 \mathrm{MPa} / \mathrm{s}, 6.0 \mathrm{MPa} / \mathrm{s}$ and $60 \mathrm{MPa} / \mathrm{s}$ respectively. Their strain resolution was smaller than 2 $\times 10^{-6}$ over a period of 600 seconds. If this was converted to a typical pipeline pressure test with test pressure for yield of 20 MPa and yield strain of 0.002 , their effective equivalent strain resolution expressed as kPa would be 20 kPa . In the past hydrotest strength test pressures were rarely measured with resolution better than 10 kPa which is similar to that of Oehlert and Atrens [112]. So that during the strength test part of pressure tests room temperature creep should have been able to be measured. It is the best explanation of the repeated pressure decays at progressively longer time factors. The above equation then should be able to accurately model the strain changes and from the strain the pressure changes.

Oehlert and Atrens version of the strain rate using the above equation is:

$$
\begin{equation*}
\frac{d \varepsilon}{d t}=\frac{\alpha \beta}{(\beta \tau+1)} \log (e) \tag{2.11.12}
\end{equation*}
$$

This equation implies that the log function is not the natural logarithm function but they don't specify the base unless they mean to base 10 . The value of alpha will depend on which log base is used.

Using natural logarithm ( In ) function for strain results in:

$$
\begin{equation*}
\frac{d \varepsilon}{d t}=\frac{\alpha \beta}{(\beta \tau+1)} \tag{2.11.13}
\end{equation*}
$$

### 2.11.7 Steel Creep or Relaxation Effect on Pressure Decay

Gajdos et Al., [27] reported a pressure drop they attributed to Room Temperature Creep (RTC) following pressurising of a 530 mm O.D. pipe of 7.8 mm W.T. and 4 m . length terminated with torispherical end caps with a test pressure of 8.985 MPa which was approximately $84 \%$ of the pipe yield stress (Y.S. 365 MPa, line pipe steel L360NB) and based on average of two sample measurements. They also reported on the RTC characteristics of pipe metal samples taken from the same pipe for comparison purposes with stresses ranging from $70 \%$ to $100 \%$ of yield stress.

In the following Figure 2-29 the experimental tank pressure drop from around 15 minutes until around 23 hours reduced from 8.75 MPa to around 8.52 MPa of 0.23 MPa while their trend line curve started at 8.78 MPa and reached 8.52 MPa with a drop of 0.25 MPa .


Figure 2-29 - Gajdos et al plot of pressure decay plotted against time together with trend line approximation by them and with equation on the chart. Note: the trend line equation in the figure is as calculated by Microsoft Excel with the time in days and not as displayed in hours.

Figure 2-29 was a scanned copy of Gajdos et al. Figure 3 which was manually digitised by this author and the trendline equation of the digitised points was similar to that obtained by Gajdos et al (pink equation) in terms of exponent but varied slightly in constant.

The following Figure 2-30 has been produced by removing the ambient effect on the digitised pressure trace in the above Figure 2-29 using an arbitrary factor of $0.02 \mathrm{MPa} /{ }^{\circ} \mathrm{C}$ of measured ambient change. This corrected pressure is the red trace. Their measured ambient is shown as the light blue trace with right hand axis.


Figure 2-30 - Modified data from Gajdos et al. With ambient corrected pressure, trend lines for pressure and ambient temperature.

Also added to Figure 2-30 are curves produced by this author based on Gajdos et al. creep specimens C6, C7 and C8 together with a natural logarithm function fit based on Wyatt [113]. The difference between the corrected (red) and Wyatt (brown) has been compared with and matches their measured pipe wall temperature which only changed by the order of $+/-0.1^{\circ} \mathrm{C}$ but was sufficient to affect the pressure with an estimated pressure temperature factor of $1.5 \mathrm{MPa} /{ }^{\circ} \mathrm{C}$.

Note that the time has been shifted by almost 2 hours to match the ambient with the time of pressurisation termination. They did not plot the initial pressure of 8.985 MPa on the previous Figure 2-29 as they had trouble with the trend line fit.

The paper made no mention of the details of instruments used for pressure and temperature while reference was made to other papers by the same authors which could have included such details. The only details of instrumentation were that relating to the machine, extensometers and strain gauges used for the pipe steel creep experiments.

While questions are raised below regarding their calculated decay curve, what is not in dispute are their measurements of creep in the isolated pipe coupons and their premise that pressure decay can be attributed to such creep. The coupon creep tests were performed with constant stress as is implied by the term "creep" while the pressure decay of the water filled pipe system is more an issue of "relaxation" since the pipe water volume was raised to reach test pressure then unchanged implying constant strain since the pressure and hence stress subsequently decayed. The above authors continued to refer to the phenomenon as RTC or Room Temperature Creep whereas it was relaxation at room temperature. In the case of repeated repressurisations to maintain a pressure range the
decays can be called creep since the strain is changed and the stress kept within limits. They usefully provided guidance as to the effect of proximity to yield stress on the pressure decay curves based on the coupon creep tests.

Their paper had referred to Kassner and Smith's [114] revue paper titled "Low Temperature Creep Plasticity" which has provided a smorgasbord of alternative equations to use in modelling creep. Fortunately Gajdos et Al., [27] had chosen the simplest in the following form:

$$
\begin{equation*}
\epsilon=f \tau^{g} \tag{2.11.14}
\end{equation*}
$$

where
$\varepsilon \quad$ creep strain
$f \quad$ function of creep stress
$\mathrm{g} \quad$ function of creep stress
$\tau \quad$ time
$\sigma \quad$ Stress (MPa)
Their results are reproduced in the following Table 2-7 which combines their tables 1 and 2 and provides values for the functions $f$ and $g$ which change with stress and percentage of yield in a nonlinear manner.

Table 2-7 - Creep Specimen Properties and Creep Equation Factors - Gajdos et al.

| Gajdos et Al., Specimen properties and creep equation factors. |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Specimen | Width | Thickness | Load <br> (kN) | Stress <br> (MPa) | $\%$ <br> Yield | f | g |
| C4 | 20.03 | 5.88 | 43.0 | 365 | 100 | 0.0039 | 0.0480 |
| C9 | 19.95 | 6.20 | 42.9 | 347 | 95 | 0.0025 | 0.0535 |
| C5 | 19.98 | 5.75 | 37.8 | 328 | 90 | 0.00224 | 0.0609 |
| C8 | 19.85 | 6.05 | 37.3 | 310 | 85 | 0.0017 | 0.0261 |
| C6 | 20.10 | 5.74 | 33.7 | 292 | 80 | 0.0013 | 0.0141 |
| C7 | 20.08 | 5.77 | 29.6 | 255 | 70 | 0.0012 | 0.0050 |

Note: f value for specimen C5 (highlighted in yellow) has been corrected from 0.0018 to 0.00224 to match their figure 5 reproduced below as Figure 2-31.

They considered functions $f$ and $g$ to be in the form of:

$$
\begin{align*}
& f(\sigma)=a_{1} \exp \left(a_{2} \sigma\right)  \tag{2.11.15}\\
& g(\sigma)=b_{1} \exp \left(b_{2} \sigma\right) \tag{2.11.16}
\end{align*}
$$

With the constants they determined from the above data points are as follows in Table 2-8:

## Table 2-8 - Creep Function Sub Coefficients for Gajdos et Al. Equations

| Gajdos et Al., creep function sub <br> coefficients |  |
| :---: | :---: |
| Coefficient | Value |
| $\mathrm{a}_{1}$ | $7.24275 \times 10^{-5}$ |
| $\mathrm{a}_{2}$ | $1.03221 \times 10^{-2}$ |
| $\mathrm{~b}_{1}$ | $1.93958 \times 10^{-5}$ |
| $\mathrm{~b}_{2}$ | $2.2726 \times 10^{-2}$ |

Specimen cross sections in the previous table are typical of weld test coupon dimensions and had been flattened prior to tensile creep testing which may have changed the material properties since the specimens were obtained from a pipe of outside diameter 530 mm and wall thickness 7.8 mm . There was no mention of the strain rate to reach the creep stress.

The following Figure 2-31 (their figure 5) for specimen C5 has been digitised and resulting from this process the error in the specimen properties table above for the $f$ value was identified. While Gajdos et Al., have used a time exponent equation mentioned above, Wyatt [113] has suggested two equations which he called the beta, $\beta$, and alpha, $\alpha$, equations with the beta in the same form as that of Gajdos et AI., while the alpha is a natural logarithm function in the following form:

$$
\begin{equation*}
\epsilon=\alpha \ln (\tau)+c \tag{2.11.17}
\end{equation*}
$$

where

| $\varepsilon$ | creep strain |
| :--- | :--- |
| $\alpha$ | log function coefficient |
| $c$ | constant |

Both trend lines are used in the following Figure 2-31 and appear equivalent in modelling the measured curve (upper blue with fine yellow dots for digitised values on left vertical axis). Their beta type trend line is shown as the continuous original red line while the alpha natural logarithm variant is shown as the fine red line with red dots.


Figure 2-31 - Gajdos et al Creep figure and estimated trend line to match together with the difference between the two which indicates temperature effects.

Figure 2-31 covers a 24 hour time period and the blue trace plotted on the inverted secondary (right) vertical axis is the difference between the measured and the power or beta modelling shows a similarity to typical daily ambient influences. The secondary vertical axis has been inverted to better reflect this ambient characteristic of the differences. If the initial and critical part of this creep experiment was started in the morning say around 8:00 to 9:00 am then the peak 8 hours later would have occurred around 14:00 to 15:00 pm which is consistent with solar heat input to a building. They reported the specimen temperature changes were less than $3^{\circ} \mathrm{C}$ with temperature compensating strain gauges used. However such compensation is never perfect and slight ambient effects are expected but were not noted. The likelihood of ambient influences on the creep results supports the equation modelling as accurate since it can be used to infer ambient influences on the creep measuring instrumentation and equipment.

Gajdos et AI. [27] developed a differential equation to model the effect of the creep on the pressure as follows:

$$
\begin{equation*}
-\frac{d p}{d t}=\frac{2}{K_{I}} f(p) g(p) \tau^{g(p)-1} \tag{2.11.18}
\end{equation*}
$$

where the previous $f$ and $g$ functions have been expressed as functions of pressure instead of stress.

$$
K_{I} \quad \text { is the isothermal water compressibility. }
$$

Their equation development was simplified by ignoring axial creep strains which they considered negligible.

They had to solve this equation numerically and the resulting plot was similar in shape to the pipe experiment result but had a pressure offset. They then restricted the results until after two hours had passed and then the measured and estimated better fitted.

Gajdos et Al., developed an equation relating the pressure and strain time differentials $\mathrm{dp} / \mathrm{dt}$ and $\mathrm{d} \varepsilon / \mathrm{dt}$ during creep. Combining that with Oehlert and Atrens' version of $\mathrm{d} \varepsilon / \mathrm{dt}$ (see previous section) results in the following:

$$
\begin{equation*}
\frac{d p}{d t}=-\frac{2}{K_{I}} \frac{d \varepsilon}{d t}=-\frac{2}{K_{I}} \frac{\alpha \beta}{(\beta \tau+1)} \tag{2.11.19}
\end{equation*}
$$

Since the format of $d p / d t$ and $d \varepsilon / d t$ are the same with respect to the time variable, the integral of dp/dt simply becomes:

$$
\begin{equation*}
p=p_{0}-\frac{2}{K_{I}} \alpha \ln (\beta \tau+1) \tag{2.11.20}
\end{equation*}
$$

which should be the pressure drop resulting from strain creep. This eliminates the need for numerical integration that Gajdos et Al., used. With the modified log function and using values as follows, the function accurately described Gajdos et Al., figure 5 (Figure 2-31) for specimen C5 (90\% of yield) creep strain (shown previously):

$$
\begin{equation*}
\epsilon=\alpha \log (\beta \tau+1)+\epsilon_{0} \tag{2.11.21}
\end{equation*}
$$

where the values are:

| $\alpha$ | log function coefficient $=0.00012307$ |
| :--- | :--- |
| $\beta$ | time factor constant $=559.41$ |
| $\epsilon_{0}$ | initial tensile strain due to loading $=0.001457$ |

Using the same alpha and beta coefficients in order to calculate the pressure change over time the pressure decay results match Gajdos et Al., curve as shown in Figure 2-30.

The pressure equation:

$$
\begin{equation*}
p=p_{0}-\frac{2}{K_{I}} \alpha \ln (\beta \tau+1) \tag{2.11.22}
\end{equation*}
$$

used the following values but with a "fudge factor" of 0.113 needed:

| $\alpha$ | log function coefficient $=0.00012307 \times 0.113=0.000013907$. |
| :--- | :--- |
| $\beta$ | time factor constant $=559.41$ |
| $p_{0}$ | initial pressure $=8.895 \mathrm{MPa}$ |
| $K_{I}$ | water isothermal compressibility $=4.566 \times 10^{-4} / \mathrm{MPa}$. |

Note: The water compressibility value quoted by Gajdos et Al., of $45.66 / \mathrm{MPa}$ in their table 3 is missing a factor of $1.0 \times 10^{-5}$.

Why the factor of 0.113 is needed has to be addressed. The previous table of $f$ and $g$ values had for specimen C5 a yield stress of $90 \%$. The quoted pipe test pressure was $84 \%$. Figure 2-30 above
for pressure also included modified results for specimens C6, C7 and C8 with the required "fudge factors" detailed in the following Table 2-9.

Table 2-9- Creep Specimen \% of Yield and "Fudge Factor" needed to match Pressure Creep Curve

| Gajdos et al. Specimens and \% of yield together with <br> needed "fudge factors" to match the pressure creep curve <br> above. |  |  |
| :---: | :---: | :---: |
| Specimen | \% of yield | "fudge <br> needed |
| C5 | 90 | 0.113 |
| C8 | 85 | 0.314 |
| C6 | 80 | 0.73 |
| C7 | 70 | 2.2 |
| Pipe | 84 | 1.0 |

The equivalent tensile specimen percentage of yield for the pipe is somewhere between specimens C6 and C7 and most likely around $78 \%$. This would then remove the need for a "fudge factor". Additional unknowns are the strain rates for the pipe and specimen tests which most likely differ. Also the flattening of the creep tensile specimens may have had an influence.

Gajdos et Al. [27] have assumed that the pipe stress is uniaxial whereas the true hoop stress in an unrestrained short length of pipe is lower than calculated using uniaxial stress. The fact that the "fudge factor" can be removed by selecting a suitable specimen stress value points to the validity of the pressure equation and that care needs to be taken when converting from a tensile specimen creep test to a pipe creep pressure test. Gajdos et Al., can be credited with performing the crucial experiment linking tensile creep specimen measurements to pipe pressure drop and had the foresight to test the pipe specimen creep samples over a range of different stresses.

### 2.11.8 Effect of repressurisation on pressure decays

Wyatt's [113] experimental work 70 years ago was with pure copper, aluminium and cadmium wires at temperatures from -196 to $+170^{\circ} \mathrm{C}$ over ranges of stresses and strain rates. What was unique with his work were the additional creep experiments in which he added or removed small amounts of stress during the creep process and found that the resultant creep curve changes appeared the same as either earlier or later parts of the reference creep curve depending on whether the stress was added or removed respectively. He found that this did not apply to materials which followed the beta equation relationship.

This appears to be irrelevant to the present study using steel pipe. But during a strength test at high stresses close to yield, multiple repressurisations are required to maintain the pressure range and the shape of the pressure decays following each repressurisation are similar in shape to the invert of
the creep curves. This repressurisation process is almost identical to Wyatt's creep experiments with progressively added stress increments. The initial stress in the pipe is high and the stress relaxation and subsequent repressurisations are only of the order of $1 \%$ of the initial which is consistent with the small changes made by Wyatt. While the strength test pressure decay situation is not exactly the same as Wyatt's incremental creep experiments, the similarity is sufficient to enable his equations and graphical devices to be used in the strength test situation. Possibly the same can also be used at the start of and during the leak test as the pressure and stress has been lowered as with Wyatt's similar stress reduction experiments.

Wyatt's article title is "Transient Creep in Pure Metals" and he points out that the above behaviour is typical of initial transient creep. Wyatt's experiments with copper were mainly over a period of four minutes but he extended some for four days which proved to be consistent with the shorter time period results. Such longer time periods are typical of pipeline pressure tests. While he hasn't addressed steel, the Gajdos et Al. [27] results appear to confirm steel during creep testing and pressure tests as functioning in the transient creep range and with both types of equations able to be used in the time frames of both the strength and leak test.

Wyatt's experimental results were based on room temperature copper with applied constant stress increased up and reduced down by increments of up to $3 \%$ while still complying with the basic creep curve. What is not known is whether the same applies to increments of around $10 \%$ typical of the reduction from strength test to leak test. Wyatt's experiments were at nominally 60, 100, 140 and 180 MPa with different creep slopes noted for these. 180 and 100 MPa values correspond to changes of +/- $29 \%$ relative to 140 MPa .

Oehlert and Atrens demonstrated that when high strength steel specimen stresses were reduced by $25 \%$ and then returned to the previous stress level the rate of creep was around $1 / 5$ of the original creep rate which implies that a significant reduction in stress, even for periods as short as 10 minutes, changes the creep rate. They further noted that within their level of resolution at a $25 \%$ drop in stress level the "....creep process stopped and no further room temperature creep could be measured...". For interrupted creep experiments they measured the subsequent creep as if it was independent of the initial creep. If they instead had followed the method of Wyatt and then superimposed the new creep curve on the original curve their interpretation may have been different.

The creep/relaxation measured during the strength test could then possibly be used to predict any relaxation during the leak test and enable determination of such non temperature effects.

### 2.12 SOIL PROPERTIES RELEVANT TO HEAT TRANSFER

Godbole $[115,116]$ relied on textbook quoted values of soil thermal conductivity, density and specific heat in order to calculate diffusivity needed to carry out Computational Fluid Dynamic (CFD) studies of water filled pipes in soil. Such data may not be representative of actual soils especially if the textbook values were not obtained from the same soil sample.

Angstrom [117] proposed a method for determining thermal conductivity using sinusoidal temperature changes but knowing the density and specific heat. Mathur's [118] textbook on Heat and

Thermodynamics provided equations based on Angstrom's method for determining the diffusivity of the earth by using the diurnal cycle and annual cycles as the sinusoidal input.

The following uses Angstrom's method for the periodic flow of heat based on Mathur's [118] textbook. The heat flow differential equation or Fourier's equation is given by the following equation (2.12.1):

$$
\begin{equation*}
\frac{d \theta}{d t}=\alpha \frac{d^{2} \theta}{d z^{2}} \tag{2.12.1}
\end{equation*}
$$

Where;

| $\theta$ | temperature |
| :--- | :--- |
| $t$ | time in seconds |
| $\alpha$ | diffusivity in units of $\mathrm{m}^{2} / \mathrm{sec}$ |
| $z$ | direction and dimension of heat flow. |

The definition of diffusivity, $\alpha$, is:

$$
\begin{equation*}
\alpha=\frac{k}{\rho C_{p}} \tag{2.12.2}
\end{equation*}
$$

Where for the heat transmitting medium:
k thermal conductivity
$\rho \quad$ density
$C_{p} \quad$ specific heat at constant pressure.
Solutions to equation (2.12.1) take the following form:

$$
\begin{equation*}
\theta=\theta_{0} e^{-\sqrt{\frac{\omega}{2 \alpha}} z} e^{i \omega\left(t-\frac{z}{\sqrt{2 \omega \alpha}}\right)} \tag{2.12.3}
\end{equation*}
$$

This can be re-expressed as:

$$
\begin{equation*}
\theta=\theta_{0} e^{-\sqrt{\frac{\omega}{2 \alpha}} z} e^{i\left(\omega t-z \sqrt{\frac{\omega}{2 \alpha}}\right)} \tag{2.12.4}
\end{equation*}
$$

The square root term next to $z$ in the first exponential is the attenuation and similar to a wavenumber, $\mathrm{k}_{1}$, which is normally the reciprocal of the wavelength but multiplied by 2 times $\pi$. The equation can be rearranged as follows:

$$
\begin{equation*}
\theta=\theta_{0} e^{i\left(\omega t-z\left(\sqrt{\frac{\omega}{2 \alpha}}+i \sqrt{\frac{\omega}{2 \alpha}}\right)\right)}=\theta_{0} e^{i\left(\omega t-\left(k_{R}+i k_{I}\right) z\right)} \tag{2.12.5}
\end{equation*}
$$

where
$k_{R}+i k_{I} \quad$ is the complex wavenumber
$k_{R}=\sqrt{\frac{\omega}{2 \alpha}}$ is the real part of the complex wavenumber and related to the phase velocity (see below).
$k_{I}=\sqrt{\frac{\omega}{2 \alpha}}$ is the imaginary part of the complex wavenumber and is also the attenuation.

In equation (2.12.3) the first exponential term relates to the attenuation with depth $z$ while the second exponential term relates to the time, t , for the temperature change to reach a depth z . The second exponential term can be used to provide the velocity, v , of such temperature change transmission in the form of:

$$
\begin{equation*}
v=\sqrt{2 \omega \alpha} \tag{2.12.6}
\end{equation*}
$$

This can be re-expressed in terms of the period, $T$, in seconds as:

$$
\begin{equation*}
v=\sqrt{\frac{4 \pi \alpha}{T}} \tag{2.12.7}
\end{equation*}
$$

Rearranging with diffusivity as subject:

$$
\begin{equation*}
\alpha=\frac{T}{4 \pi} v^{2} \tag{2.12.8}
\end{equation*}
$$

The velocity, v, can be determined by correlating the same frequency at different depths. The period, $T$, of 24 hours ( 86,400 seconds) is best used. Velocity is then determined from the distance between two depths and the time delay between these. This velocity will be referred to as the thermal velocity in this document with the understanding that it relates to vertical heat transfer rate of a particular frequency or period of thermal fluctuation.

For attenuation-based diffusivity measurements the first real exponential expression is used with the natural logarithm taken of both sides of equation (3) while ignoring the second imaginary exponential term. For two depths $z_{1}$ and $z_{2}$ and two measured temperature amplitudes $\theta_{1}$ and $\theta_{2}$ respectively:

$$
\begin{equation*}
\ln \theta_{1}-\ln \theta_{2}=-\sqrt{\frac{\omega}{2 \alpha}}\left(z_{1}-z_{2}\right) \tag{2.12.9}
\end{equation*}
$$

from which results:

$$
\begin{equation*}
\alpha=\frac{\omega}{2}\left\{\frac{z_{2}-z_{1}}{\ln \theta_{1}-\ln \theta_{2}}\right\}^{2} \tag{2.12.10}
\end{equation*}
$$

or if using period, T, instead of angular frequency, $\omega$ :

$$
\begin{equation*}
\alpha=\frac{\pi}{T}\left\{\frac{z_{2}-z_{1}}{\ln \theta_{1}-\ln \theta_{2}}\right\}^{2} \tag{2.12.11}
\end{equation*}
$$

From these equations can be observed the difficulty in their use in that the natural logarithm of the small amplitudes are needed and then the square of their difference which are easily affected by amplitude based noise. Whereas the velocity method is based on more easily measured time delays which when determined by correlation techniques eliminates much of the noise.

The following Figure 2-32 shows the time delay variation with depth for a range of input frequencies or in this case periods of these frequencies. The slopes of the straight lines represent the respective velocities for the quoted diffusivity value. Depth to the top of a buried pipe is usually 0.9 metres in remote areas. The centre line of the pipe is then the pipe radius below the top of pipe so
that for DN1050 pipe in a remote area the time for a cycle of one week period will experience a delay of almost five days to reach the centreline.


Figure 2-32 - $\quad$ Time Delay (days) to reach Soil Depth for Different source Periods (1, 2, 3, 4, 7, 14, 21, 28, 60, 90 days) - Diffusivity $0.7 \mathrm{~mm}^{2} / \mathrm{s}$

The attenuation term reduces exponentially with depth. The following Figure 2-33 shows the amplitude for the period of different frequencies at depth confirming rapid attenuation of the diurnal (1 day period) by pipe depth and rendering signals subject to noise and resolution issues. Attenuation based diffusivity measurements are better used only as a check on the velocity method than as the prime method.


Figure 2-33 - Amplitude Reduction with Depth for Different source Periods (1, 2, 3, 4, 7, 14, 21, 28, 60, 90,180, 270, 365 days) - Diffusivity 0.7mm2/s.

Frequency based on a period of seven days will reduce in amplitude by a factor of around 0.02 at the centreline of the DN1050 pipe at 0.9 m burial. All shorter period frequencies will be more highly attenuated while the annual period will be reduced by around 0.6 . Hence only weather fluctuations with longer periods of the order of many days to weeks will penetrate to pipe depth of sufficient amplitude to affect pressure. This effect of delayed weather pattern changes affecting temperatures at pipe depth has been added to the last edition of AS2885.5:2020 [10] by this author but not in detail. Increased diffusivity will slightly reduce the attenuation and increase the time delay with figures similar to Figure 2-32 and Figure 2-33 above.

### 2.12.1 Ambient and Soil Temperature Variation with Seasons and Weather

Carson [119] is often referenced by later publications due to his comprehensive data and study of both ambient and soil temperatures over a one year continuous period. Measurements were taken at soil depths of $0.01,0.10,0.20,0.50,1.0,3.05$ and 8.84 metres while the ambient was taken 1.7 metres above ground level typical of Meteorological instrument heights but differing in that the air was drawn through a tube containing the temperature sensor. Below ground sensors were resistance thermometers while a thermopile was used above ground. Data was recorded on charts based on 10 minute averages at the hour with the average based on 5 minutes before and after the hour and resolved to the nearest $0.1^{\circ} \mathrm{C}$. The soil was a Valparaiso moraine with grass cover and 50 to 100 mm of black soil over a deep layer of yellow sandy clay including some stones of 80 to 100 mm diameter. Grass roots extended down to 100 mm and sometimes to 200 mm . There was no location indicated other than the data was collected by the Meteorology Group at the Argonne National Laboratory which is located in the USA state of Illinois at latitude $41.7^{\circ} \mathrm{N}, 87.9^{\circ} \mathrm{E}$ and at an elevation of 200 metres above
sea level. Data appeared to have been collected from January 1953 to December 1955 covering a three year period.

Various analyses were used including:

- Analysis of the harmonics in the daily diurnal cycle.
- 24 hour average to remove the diurnal effect
- Monthly averages
- Annual averages
- Three year average
- Comparison of the progression of the average annual wave at different depths
- Quarterly figures to compare seasonal changes
- Determination of thermal diffusivity on a daily, monthly and annual basis from both the phase and amplitude for different depths
- Fourier analysis provided
o Daily harmonics of the daily diurnal cycle
o Daily harmonics for quarterly comparisons
o Annual harmonics for annual thermal diffusivity calculations
o Daily harmonics for daily thermal diffusivity calculations.
It is obvious from the above summary that the analysis was comprehensive and the article was based on a chapter in Carson's PhD dissertation published in 1961. Solar radiation has not changed much over the last seventy years nor its contribution to ground and ambient temperatures. The paper provides support and validation for some of the methods used in this document and developed before awareness of the paper.

One significant point made by Carson was that weather pattern changes influence the below ground temperatures. Another was that thermal diffusivity of the soil layer of the first 100 to 200 mm was highly irregular and best avoided while deeper diffusivity showed seasonal changes due to soil moisture content and state of aeration. His calculated diffusivity values of the 0 . to 0.5 m depth for the monthly periods from May to November ranged from $1.27 \times 10^{-7} \mathrm{~m}^{2} / \mathrm{sec}$ to $5.99 \times 10^{-7} \mathrm{~m}^{2} / \mathrm{sec}$ using daily first harmonic phase comparisons while amplitude based values were erratic. He did not report daily based diffusivity measurements for deeper locations no doubt due to the limited $0.1^{\circ} \mathrm{C}$ resolution.

Analysis of the daily diurnal cycle showed that the combination of only the first three harmonics were necessary to generate the daily soil temperature at 0.01 m depth as follows (with apologies to Fahrenheit):

$$
\begin{equation*}
T=\frac{\left\{40.4+6.08 \sin \left(2 \pi t+\frac{225 \pi}{180}\right)+1.70 \sin \left(4 \pi t+\frac{57 \pi}{180}\right)+0.27 \sin (6 \pi t+230)\right\}}{1.8} \tag{2.12.12}
\end{equation*}
$$

where angles are in radians,

```
t time in days
T temperature in degrees Celsius
```

The fact that three harmonics are needed is part explanation of why diffusivity calculations close to the surface using only the fundamental harmonic ( 24 hour cycle) are prone to problems since the small amplitude of the second and third harmonics quickly dissipate with depth.

The curve resulting from this equation is shown in Figure 2-34 below and is similar to figures later in this document. It shows the results of using the first two, three and six harmonics with three and six effectively identical and two resulting in a slight ripple compared to the three.


Figure 2-34 - Carson's Below Ground Temperatures at 0.01 m June $42^{\circ} \mathrm{N}$ Latitude with Two, Three and Six Harmonics.

Current measurements carried out for this study were blessed with resolutions of the order of $0.001^{\circ} \mathrm{C}$ and digital recording permitting direct input of data into laptop based computer programs. Carson had access to computers at a very early stage in their development but would have had to manually transfer the hourly values for all depths for the three year period from the charts onto punched cards to feed into the IBM 650 computer at a stage in computer development when very few facilities, such as the Argonne National Laboratory, had such access and especially assembly language programs that could carry out Fourier analysis using valve based electronics and rotating magnetic drum memory.

Carson did not provide equations for the annual change but provided the amplitudes and phases for ambient and different depths for the three years covered which are summarised in Table 2-10.

Table 2-10 - Contribution of Harmonics to the Annual Average for a Three Year Period at depth 0.1 m at Latitude $42^{\circ}$ North

| Annual Average Contribution of Harmonics for Three Year Period for a <br> depth of 0.1 metres at Latitude 42N. (Based on Carson). |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Harmonic | 0 or <br> fundamental | 1 | 2 | 3 | 4 | 5 |
| \% of average | 82.7 | 5.1 | 3.9 | 4.2 | 3.0 | 0.95 |
| Phase delay range <br> (days) | $260-264$ | $35-95$ | $9-349$ | $64-238$ | $0-223$ | - |

Unlike the daily cycle where the first two or three harmonics could describe the average shape, at least five were needed to model the annual cycle and even then it changed from year to year. The phase delay range for each harmonic, except the fundamental, effectively discouraged any attempt and together with changes from year to year made any annual modelling, other than using only the fundamental, a wasted effort. The Meteorological approach to the problem invokes a whole farm of cycles and oscillations such as the Indian Ocean Dipole, El Nino Southern Oscillation, Inter tropical Convergence Zone, Monsoons and many others to the effect that prediction is mostly guesswork. El Nino southern oscillation (ENSO) average period was 4 years [120] and lunar cycles such as the 3.8 year one associated with the four year lemming population cycle [121] could influence attempts to obtain average annual cycles since the experimental duration of Doctoral studies precludes obtaining data to identify longer period based averages.

### 2.13 FEA STUDIES OF TEMPERATURE CHANGES FOLLOWING FILLING

As mentioned earlier, the water source temperature may be different from the soil or ground temperature at the location where the water will be used in a pressure test. Arfiadi et al., [9] carried out finite element calculations for a range of pipe diameters and soil thermal properties to assess the times taken for the water to stabilise following filling.

They considered two common field situations in which

1. Water is pumped into a section which is then left to stabilise
2. Water is pumped through a section for a period of time and then left to stabilise in the same section.
The soil properties used were taken from textbooks similar to Godbole [115, 116] and raised the same issue of whether they applied to field conditions where cross country pipelines are normally constructed.

The modelling was two dimensional (cross section of pipe in ground perpendicular to pipe axis) with modelled periods up to 7 days, pipe diameters DN330 and DN660, burial depths of 0.6 and 1.045 metres and when applicable fill times up to 50 hours. Only bulk temperature estimates were made without any detail inside the pipe nor any discrimination between pipe steel and water contents.

Below ground temperatures resulting from diurnal and annual temperature changes were also estimated together with delay times and the effect of different soil types.

The findings are valuable for estimating the stabilisation times following the different fill scenarios but do not address internal thermal gradients.

### 2.13.1 Stabilisation after Filling

The following Figure 2-35 provides an example of the results from zero fill time (filled directly from a dam or adjoining section) up to 50 hours (typical of filling a number of sections through the section of interest).


Figure 2-35 - Effect of Fill Time on Temperature decay for DN300 pipe in Dry Topsoil of Diffusivity $0.138 \mathrm{~mm}^{2} / \mathrm{s}$. [9]

The diffusivity value chosen represented the worst case soil diffusivity resulting in the longest times. The temperature is scaled relative to the difference between the fill water and initial soil temperatures (denominator) while the numerator was the difference between the temperature result and the initial soil temperature. Hence the soil temperature for the 50 hour fill time would have increased by the warmer fill water heating it and consequently reduced the actual range at the start of stabilisation. So that the 50 hour decay would be a combination of the water cooling relative to the warmed soil and the soil cooling back to its original temperature.

Of the different coloured pairs of curves the upper is the average water temperature and the lower the average pipe steel temperature with both assumed uniform

The following Figure 2-36 for the DN660 pipe compares 0.5 hour fill time for the three different soil types used and referred to as wet sandstone, dry topsoil and silty clay with $10 \%$ moisture with diffusivities of $5.9 \times 10^{-7}, 1.38 \times 10^{-7}$ and $3.6 \times 10^{-7} \mathrm{~m}^{2} / \mathrm{s}$ respectively.


Figure 2-36 - Effect on DN660 buried pipe in Soils of different Diffusivity 0.59, 0.36 and 0.14 $\mathrm{mm}^{2} / \mathrm{s}$ after 0.5 hour fill time [9].

Comparing the top (red) curves for the DN660 in Figure 2-36 (for dry topsoil) with the bottom (dark blue) for the same diffusivity but DN330 pipe in Figure 2-35 (also for dry topsoil) shows the effect of doubling the diameter. For the DN660 a scaled temperature of 0.27 (drop of 0.73 ) was reached in 168 hours compared with approximately 40 hours for the same drop in the DN330. A factor of four or approximately the square of the diameter change for the increase in time. Depth of cover was 1.045 m for these two Figures. Changing the depth of cover from 1.045 to 0.6 m for the DN330 pipe after 50 hour fill time only slightly changed the resulting curve for the dry topsoil with worst diffusivity (dry topsoil).

The shape of the curves is not exponential as is expected of transient heat transfer.

### 2.13.2 Adiabatic Effect

Besides the FEA results, the Arfiadi et al. study published adiabatic temperature changes of water in a small vertical pressure vessel with a thermistor in the water and with the wires extending outside and connected to a data logger set for recording at intervals close to 1 second. Rapid pressure changes of $\pm 10000 \mathrm{kPa}$ or -30000 kPa were applied with temperature changes directly following the pressure change. 10000 kPa change produced a $0.25^{\circ} \mathrm{C}$ change in temperature. Then with constant pressure there was an exponential like decay or rise in temperature. The experiment was carried out by this author and the figure supported the case for inclusion of the adiabatic effect in the 2002 edition of AS2885.5 [37].

### 2.13.3 FEA Study Conclusion

Figure 2-35 showed that for DN 300 pipe after 7 days (168 hours) with the worst thermally conductive soil (type 2 - dry topsoil), the scaled temperature was still only 0.1 which for a not uncommon initial temperature difference of 5 degrees is 0.5 degrees. However this is for a short filling time of 0.5 hours. For a 20 to 30 km long section the filling time would be of the order of 15 hours which would bring the final temperature to within around 0.9 degrees which would require further stabilisation time if the final temperature is to be of the same order as the water adiabatic rise from pressurisation of $0.3^{\circ} \mathrm{C}$. For larger diameter pipes the times will be much longer.

Pressure testing being part of a construction project is time constrained and even such stabilisation periods of 7 days are subject to significant management pressure for relaxation.

For the purpose of acoustic anomaly resolution, the FEA study points to a high potential of lack of stabilisation at the commencement of the Pressure Test and subsequent commencement of acoustic velocity measurements.

### 2.14 CFD STUDIES IDENTIFYING THERMAL LAYERING IN PIPE

CFD research carried out at the University of Wollongong [115, 116] on the topic of Hydrotest Uncertainty found the presence of thermal layering soon after pressurisation and which continued and diminished over time. These computer studies needed as input the obvious pipe dimensions and the soil thermal properties. The thermal properties used were taken from textbooks and again point to a lack of typical pipeline soil thermal diffusivity values.

The results of the study showed that the external pipe wall temperatures did not correlate with the average internal water temperature and in fact the changes were inverted. Investigations also showed unusual heating and cooling effects on adjacent buried pipe from exposed pipe ends at low or high points respectively. Thermal gradients were also shown to develop in buried sloping pipe and suggestions made as to optimum measuring locations.

The time constraints of the CFD study did not permit complete consolidation of the data which has now been carried out within the current research and is reported in this document within Chapter 3. This has consolidated the data to enable scaling with diameter to be resolved together with scaling of the initial heat transfer process taking place immediately following pressurisation. The uncorrelated pattern following pressurisation led to the present thesis topic as a possible cause of the anomalous field measurements of acoustic velocity.

The CFD study did not address acoustic propagation in pipes nor, as this author understands, is it capable of doing so although it can provide the pipe thermal cross sections.

### 2.14.1 Acoustic Propagation in Thermal Layered Media

Regarding acoustic propagation in layered media, most of the work in the literature was related to marine propagation. Underwater acoustics textbooks such as Urick's [122] was one example. Kinsler and Frey [5] have a section in their book on underwater acoustics in which they provide information of refraction in ocean propagation channels resulting from a combination of temperature and density changes.

The nearest to the pipe situation is that for the arctic with refraction causing upward bending and then reflection from the underside of the ice. This refraction occurs because the water directly under the ice is coldest and least dense while at the sea bed the water is warmest and most dense with the density dominating over the temperature to cause these propagation characteristics.

This is opposite to the pipe situation where refraction causes the sound to bend downwards and reflect off the sides or bottom of the pipe for temperatures above 4 degree Celsius.

The most comprehensive book on thermal layering or layering which affects acoustic propagation was L. M. Brekhovskikh's [123] book "Waves in Layered Media". All of the underwater layered propagation is in so called sound channels where there is no lateral constraint only vertical changes in water properties resulting in combinations of reflection and refraction of propagating waves. Such conditions are essentially two dimensional in a vertical plane without any lateral constraint or boundaries unless close to shore.

The pipe situation is quite different in that there is lateral containment which is cylindrical in shape and varies from narrow at the top and bottom to broad at mid height.

No references have been found as yet for refraction and reflection inside pipes due to thermal layering.

### 2.15 OTHER INFLUENCING FACTORS

### 2.15.1 Ambient and Pipe wall Effects

A recent paper by Botros et AI. [26] simulated buried and above ground water filled pipes subject to a temperature difference as would occur due to lack of stabilisation or heat transfer from the ambient via a combination of convection heat transfer by wind and solar irradiation. The simulation used ANSYS FEA transient heat transfer with the water treated as a fixed body without convection currents and with uniform radial heat transfer irrespective of the perimeter location on the pipe surface. The results showed that the bulk water and steel pipe temperatures differed as evidenced by graphs over scaled time up to 0.14 . These results were then compared with three field pressure tests.

It was not clear with the above ground exposed pipe whether and to what extent solar radiation was considered. It was included in the equations. The field pressure tests were conducted in Alberta Canada which is at Latitude $54{ }^{\circ} \mathrm{N}$ and in mid-summer where the sun's midday altitude is around 55 to 60 degrees and due to long daylight hours can cause significant temperature rises in above ground pipe during daytime.

In their DN900 above ground pressure test result figure the pressure trace showed slight initial downward curvature most likely due to the combined thermoelastic and adiabatic effects. After depressurisation to the lower leak test pressure an initial upward curvature can be detected again possibly from the same effect. Neither were noted by the researchers but point to the use of a good quality pressure transmitter with no significant ambient influence while resolving to the order of around 50 kPa or better.

For the same pipe, comparisons were made between the average bottom of pipe wall temperature change over time and the pressure change over the same period. They estimated from an equation the internal water temperature change based on the external pipe wall change and compared the
temperature change over time with the measured pressure change and the calculated $\mathrm{dP} / \mathrm{dT}$ factor. There was a difference but was of a similar order and was not commented on.

For a DN 150 above ground pipe the same comparison resulted in an actual $\mathrm{dP} / \mathrm{dT}$ of $716 \mathrm{kPa} /{ }^{\circ} \mathrm{C}$ at an average temperature around $21^{\circ} \mathrm{C}$ while the theoretical should have been $334 \mathrm{kPa} /{ }^{\circ} \mathrm{C}$ which indicates that the actual is more than double the theoretical (actual dP/dT multiple factor 2.14). They were puzzled by the result and made a statement that "the measured wall temperature was not truly representative of the entire 15 m long pipe assembly. An important finding that needs further work." They invoked the proximity of the measuring location to massive valves and manifold fittings as a possible interfering factor. What they were unaware of was that while the bottom of the pipe was the ideal location for installation of pipe wall sensors on exposed pipe, especially to minimise solar radiation, it was the worst location in terms of obtaining temperatures that follow the pressure. While the bottom of pipe temperatures underestimated temperature contributions to the measured pressure change no consideration was given to the top of pipe temperature contribution which by a simple expedient of using the palm of the hand and feeling the shade side variation from bottom to top would have revealed a significant temperature gradient which in turn reflected the vertical thermal gradient inside the pipe similar to a hot water tank with heated water accumulating at the top. Their figure 17 for the DN50 pipe is reproduced below as Figure 2-37.


Figure 2-37 - Botros et al. figure for DN50 above ground pipe 102 m long - Pressure plot and pipe wall temperature showing the change in dp/dt at different times.

Added to Botros et al. Figure 17 [26] was the grey pressure vertical offset line to enable better comparison of pressure with temperature. For the DN 50 pipe instead of a dP/dT factor multiple greater than one they estimated it as significantly less than one with two values quoted and shown in the above Figure 2-37. The pressure trace showed a general correlation with the bottom pipe wall temperature but there appeared to be a longer term decay included in the pressure. While they referenced Matta's [18] paper (noted below) there was no evidence that they took into consideration
the effects of air and possible air solution. Initially on reaching test pressure there was a short term exponential like decay of around 20 kPa in a quarter hour which could hint at air presence but could alternatively be an adiabatic effect associated with rapidly compressed trapped air in a small diameter pipe. As the DN50 pipe assembly was 102 m long it is highly unlikely that it was pigged and that multiple air pockets were trapped during the filling process and unable to be removed by conventional means. The pressure trace starts from $14,000 \mathrm{kPa}$ and terminates at the test pressure of $15,400 \mathrm{kPa}$ and misses the low pressure portion where there could have been evidence of air during the pressurisation.

What was valuable in the paper was the above ground modelling based on Biot number which then allowed for the estimation of the pressure, pipe wall and water temperatures. The modelling results were found to be irrespective of diameter and so could be applied using scaled time to a range of exposed pipe sizes. What was needed was the incorporation of the above noted dP/dT multiple factor for bottom of pipe temperature measurements and assessment of its change with pipe diameter.

For the underground temperature modelling, the use of uniform perimeter heat transfer without convection currents in the water allowed for approximate estimations of thermal effects but would result in probably slower heat transfer than would occur with the assistance of thermal convection currents in the water. They attempted to model the effect of a constant ambient temperature different from a uniform below ground soil, pipe and water temperature and found a time delay of around 5 hours for both a DN 800 and DN 50 pipe model with subsequent exponential like rise so that by the time a 10 hour test period had occurred the temperature rises in the pipe wall were $0.04^{\circ} \mathrm{C}$ and $0.033^{\circ} \mathrm{C}$ respectively with the water temperature change less than $0.001^{\circ} \mathrm{C}$ and $0.023^{\circ} \mathrm{C}$ respectively. The soil diffusivity used was $2.4 \times 10^{-6} \mathrm{~m}^{2} / \mathrm{s}$ for both cases which appeared to be much higher than likely in the field and enabled the results to fit within the 10 hour test period. What both of these results failed to address was that the ambient effects on buried pipe are the result of contributions from previous days and weeks.

The paper relied heavily on a paper by Matta [18] with title "Collective Effects of Leakage, Temperature Changes, and Entrapped Air during Hydrostatic Testing" for field related information. Matta's paper concentrated on the water properties of density and bulk modulus and their influence on the equations relating pressure changes to volume and temperature changes. He further added the changes in these properties when free air is present in the test section. His examples with air contents of $0.1 \%, 0.5 \%$ and $1 \%$ are conveniently at "test conditions" which in his case represents a test pressure of the order of $2,000 \mathrm{psi}(138 \mathrm{barg})$ which converts to values of $13.9 \%, 16.5 \%$ and $139 \%$ when measured at atmospheric pressure. All such air contents suggest that Matta may only be familiar with pipelines filled without pigs which usually displace almost all the air and result in atmospheric pressure air contents less than $0.2 \%$, two orders of magnitude below Matta's values. His choice of air content at pressure was probably for purposes of emphasising the need to take into consideration air content. He did not provide any methodology for air content assessment although a common US based method for air assessment is when at pressure to remove quantities of water and measure the pressure drop which could explain why his air contents are at test pressure. His field example plots pressure, ground and pipe temperature with ground temperature constant at around $42.5^{\circ} \mathrm{F}\left(5.8^{\circ} \mathrm{C}\right)$
very close to the minimum of the $\mathrm{dP} / \mathrm{dT}$ factor of zero and a pipe temperature increasing from around 52.5 to $57.5^{\circ} \mathrm{F}\left(6^{\circ} \mathrm{F}\right.$ or $3.3^{\circ} \mathrm{C}$ ) over the test period of 140 minutes ( 2.3 hours) with the pressure decreasing slightly by $1 / 2 \mathrm{psi}(3 \mathrm{kPa})$. He makes the comment that the pressure appeared to follow the ground temperature (almost constant) better than to follow the pipe temperature. He makes no mention of how the pipe temperature was measured nor where. To provide a ground temperature implies buried pipe which then needs exposed pipe at both ends. No such detail is given as to section length and buried proportion. He concluded that the test was accepted but the "pressure loss was not explained". In an example he provides a P/V plot for pressurisation and states that the method of volume measurement was by pump stroke counting and states that the pump may not have worked at 100\% efficiency. AS1978-1977 [12] explicitly states "pump strokes shall not be used to determine the added volume because of the difficulty of verification" and was published 40 years earlier. The present author has had experience of a piston high pressure pump producing strokes without water being pumped as the intake filter was blocked and the pump cavitating. Only a flow meter, preferably positive displacement, can be relied on. Matta's mention of the effect or air points out that he has made no consideration of the effects of dissolved air nor that of changing air volume with solution. His equation for leakage expressed as a mass change is essentially the same as the complete differential for volume used in AS2885.5 with volume change. He makes a point of stating that "test procedures must provide for some variation between the initial and final pressures..". Often US based specifications for hydrotest insist that all pressure changes must be fully accounted for (including temperature effects). Matta's statement indirectly questions that approach. The first and subsequent Australian standards on pressure testing of pipelines had insisted on a predetermined acceptance criteria originally expressed as "agreed unaccountable pressure loss" to allow for uncertainties in measurements and temperatures in particular. The current author has had to fight for such allowance, together with the use of flowmeters instead of stroke counting, when testing in South East Asia where there is strong US influence in pipeline design and construction.

It appeared that Matta and many others in the pipeline hydrotest industry were unaware of the thermoelastic and adiabatic temperature effects which occured on pressurisation, partial depressurisation and depressurisation. The adiabatic temperature effects have been published in the Australian Standard AS2885.5 since 2002 in a standalone Appendix with only tentative mention in the 2002 edition and then incorporation of the steel thermoelastic effect in later editions together with tables of water temperature changes. These appendices were written by this author and supported by field experiments. Knowledge and application of these effects in the industry outside of Australia appears minimal if not negligible. While the Botros et Al., [26] paper mentioned AS2885.5:2012 [124] there was no evidence of recognition of these effects within their paper.

Evaluation by Botros et al., of the difference between the important hydrotest properties of water, $50 \%$ water propylene glycol mix and $50 \%$ water methanol mix was made and which showed significant differences. Graphs were provided of density, isothermal bulk modulus and density change with temperature ( $\mathrm{d} \rho / \mathrm{dT}$ ) over the temperature range from $-30^{\circ} \mathrm{C}$ (only for the mixtures) to $+50^{\circ} \mathrm{C}$. This information was then used to graph the $\mathrm{dP} / \mathrm{dT}$ factor for a DN400 pipe at a test pressure of 12 MPa over the same range of temperatures which showed that both of the mixtures were much more
sensitive to temperature changes than water. It is highly likely that the adiabatic effect is enhanced for such mixtures as is the case with hydraulic oils. Their interest in such mixtures relates to the need in high latitude climates to avoid water freezing especially when testing in winter when construction sometimes takes place due to access difficulties in swamps and permafrost which can often only be made once the ground is frozen in winter.

For the present study relating to acoustic propagation in pipelines, the above information is valuable as a reference source for thermodynamic properties of such mixes. While the density variation with temperature is useful for estimating the acoustic velocity, the adiabatic bulk modulus and not the isothermal bulk modulus is needed or the ratio of specific heats together with the isothermal bulk modulus. While not mentioned in the paper, the thermodynamic properties of the mixes significantly reduce the anomalous characteristics of water and may improve the potential for the acoustic technique to be used with such liquids.

In their conclusions they make mention that ANSYS CFX (computational fluid dynamics module in ANSYS) could be used instead of ANSYS FEA (finite element analysis) which they used to improve modelling and that they were considering evaluating ANSYS CFX and comparing the two approaches.

Of the 27 references in the paper most related to fluid mix properties and standards relating to pipeline construction or pressure testing. Very few are papers or articles on pressure testing. One is the paper by Kirkwood and Cosham [16] titled "Can the pre-service hydrotest be eliminated". None were on acoustic measurements during pressure testing since these were not relevant to the focus of their study.

### 2.16 OUTCOMES FROM ANALYSIS OF REVIEWED LITERATURE

### 2.16.1 Water Properties

The IAPWS publications [30-34] and their equations have improved the available information on important properties of water for both conventional pipeline pressure testing and the acoustic technique.

The very recent paper by Botros et al. [26] has provided valuable information on the effects of antifreeze-water mixes on liquid properties needed for pressure testing of liquid filled pipelines. The paper supplements the petroleum liquids equations and properties covered in the editions of AS2885.5 from 2002 [10, 37, 124].

### 2.16.2 Steel Creep

The section on steel creep has used pipeline strength test examples to support Gajdos et Al., [27] work and findings. Using Wyatt's [113] results and methods it is now possible to understand and model the pressure decays due to creep which can then be applied to mixed circumstances when both creep and temperature effects are both present.

Another outcome using the DN300 example is that a pressure reduction of $2.5 \%$ was sufficient to reduce creep to less than 1 kPa per day. This example also provided a methodology for determining the pressure drop needed to ensure that creep does not interfere with leak tests.

Basing the strength test pressure decays on creep and using Wyatt's equation and method has solved a long standing issue of their modelling for this author and the Pipeline Hydrotest Industry. The Pipeline Hydrotest Industry has assumed that creep does not occur following pressure reduction. The above analysis has provided quantifiable methods for confirming whether that assumption is correct.

### 2.16.3 Acoustic Attenuation and Dispersion

The extensive work by Baik, Jiang and Leighton [1-4] has finally resolved the attenuation and dispersion equations for viscous liquid filled pipes beyond the ground breaking work of Kirchhoff as published by Rayleigh [39] and Weston [40, 41] followed by authors of non-viscous pipe papers and finally Elvira-Segura [44] viscous paper. Combination of Kinsler and Frey's equations [5] and Weston's [40, 41] work highlighted in Baik's unpublished work (see Chapter 6.4) resulted in simplified equations extending into ultra-low frequencies relevant to long distance acoustic propagation in pipelines.

The field data on acoustic attenuation in buried pipe by Bernasconi et al. [48] and Del Giudice [125] was rare and valuable. The field experiments of Muggleton et al. [50], while limited, hopefully will encourage more studies into the effect of soil on buried pipe acoustic attenuation and dispersion.

### 2.16.4 Weather and Seasonal Changes in Below Ground Temperature

Reported studies have confirmed that daily and annual below ground temperatures follow sinusoidal patterns with contributing harmonics.

### 2.16.5 Air Solution Rate and Partial Molar Volume

Adeney et al. [78, 79, 81, 126] and Richardson et al. [80] have provided equations for air solution in vertical cylinders and demonstrated the time scale difference between mixed and quiescent conditions.

The work by Harvey et al. [74] on determining the effect of dissolved air on the density of water has extended Kell's [96] work and provides the basis for extension to other water properties. Harvey et al. work has highlighted the lack of high resolution partial molar value data for atmospheric gases dissolved in water over the range from zero to $50^{\circ} \mathrm{C}$. The availability and improvement of vibrating tube densitometers may help in that direction.

### 2.16.6 FE and CFD Studies

Finite Element studies by Botros et al. [26] and Arfiadi et al. [9] have provided good background for the current study especially due to their being some of the few studies relating to temperatures during pressure testing.

CFD studies by Godbole $[11,115,116]$ have established the presence of thermal layering in pipes following temperature changes and specifically addressed the limitations of using external pipe wall temperature measurements and the time decays needed to reach stable conditions suitable for conduction pipeline pressure tests.

### 2.17 KNOWLEDGE GAPS AND EXTENSIONS TO REVIEWED LITERATURE

Knowledge Gaps is intended to identify areas not addressed by previous published research as the basis for further research. In addition to satisfying this intent, this section also addresses and summarises issues that have arisen in the literature review and that have led to Industry solutions or explanations not intended or discussed by the authors.

### 2.17.1 Hydrotest Temperature Measurements.

For Matta [18] to publish a paper in 2017 on issues already addressed by some National standards and Company specifications reflects the lack of awareness of these issues in some parts of the pipeline pressure testing industry.

The paper by Botros et Al., [26] was an advanced attempt to resolve some outstanding issues with temperature and pressure. As mentioned above in the comments on their paper, deficiencies were apparent in using bottom pipe wall temperature to estimate the internal water temperature and ultimately the pressure change over time. There appeared to be no evidence of awareness of the adiabatic and thermoelastic effects resulting from pressurisation. For the DN 50 pipe there appeared to be no consideration of effects of air in their analysis and its implications for the $\mathrm{dP} / \mathrm{dT}$ factor. Their use of ANSYS FEA, while a good basis, was inferior to ANSYS CFX in that hot pockets at the top and cold pockets at the bottom were not identified nor considered. Their results showed a uniform radial distribution around the pipe. The attempt at estimating the influence of ambient on buried pipe lacked duration in that a much longer time should have been applied and moreover should have commenced many hours before the start of the test since they demonstrated a five hour delay for unusually high diffusivity soil.

This author's proposed replacement of conventional pipe wall temperature measurements with acoustic velocity-based ones has not been fully field-validated and had anomalies which needed resolving.

In summary, the following need to be addressed in relation to hydrotest temperature measurements:

- Improve modelling of ambient influence on both pipe wall and water temperature for:
o buried pipe
o above ground pipe
- Carry out experiments or modelling to determine
o Realistic soil thermal diffusivity values.
o Typical ambient temperature patterns
o Link between above ground ambient and internal and pipe wall temperatures
- short term (daily)
- longer term (weekly and seasonal).
o Air solution rates for different diameter pipes and different air contents and pressures
o whether theoretical dP/dV and dP/dT values apply.
- Use ANSYS CFX to assist in the above improved modelling to address
o Pipe wall temperatures not reflecting bulk water temperatures
o Such modelling needs the following input information:
- Realistic soil thermal diffusivity values.
- Typical ambient temperature patterns
- Longer term ambient and weather information
- Establish the factors that can cause anomalous pressure changes including:
o Air content and solution
- Air solution rate
- Undissolved air effect on dP/dT factor
- Dissolved air effect on dP/dT and dP/dV (if any)
o Room temperature creep and relaxation
o Adiabatic and thermoelastic effects from pressurisation
o Creep likelihood during leak test
o Poor number and positioning of below ground temperature probes
- For the acoustic method
o Solve the anomalous initial rise in velocity [13].
o Evaluate the acoustic properties (velocity, attenuation and dispersion) in $50 \%$ waterpropylene glycol and 50\% water-methanol mixtures
o Evaluate whether the acoustic technique is useful for pressure tests with such mixtures.
o Resolve higher field attenuation compared with theoretical.
- Influence of pipe backfill and water content
- Influence of pipe external coating (if any)
o With air content
- Resolve whether the air effect on velocity is localised to the air pocket or distributed and if so over what extent.
- Resolve the discrepancy between horizontal (Kobori et al.) measurements and theoretical.
- Check whether the theoretical effect on velocity was applicable in the field.
- Dissolved air effect on acoustic velocity (Partial Molar Volume influence on density and compressibility).
o Assess the viability of the acoustic method
- Limitations of the acoustic method
- When it can be used
- Thermal stability requirements
- Additional support measurements needed
- Advantages
- Disadvantages
- Noise sources and reduction

Some of the issues identified above have already been partly addressed in this Chapter by comments on papers or use of data and concepts from the present study.

## CHAPTER 3 - ANALYSIS OF CFD STUDIES

Note: All the CFD work reported in this Chapter was carried out by Godbole and reported [11, 115,116 ] or provided to this author. The work done by this author was the use of the CFD data of Godbole to condense into scaled results and their equations and then the application of these to the field. This author also provided the field verification figures for adiabatic effects and low exposed end results.

### 3.1 CFD THERMAL LAYERING AND TIME SCALING

Godbole's [11, 115, 116] Computational Fluid Dynamic (CFD) studies of the period following a sudden change in temperature of mainly buried horizontal and inclined water filled pipes provides guidance on the cross sectional temperature changes with time as a theoretical input to acoustic velocity analysis. The studies were briefly mentioned in the previous Chapter and are dealt with in more detail in the current Chapter with the purpose of consolidating the results into more useful forms for the acoustic velocity analysis.

### 3.1.1 Introduction

The (CFD) study provided detailed thermal cross section graphs at different times together with line graphs of bulk water and top, side and bottom external pipe wall temperatures. The heat transfer coefficient variation over time was also reported. The time constraints of the study did not permit consolidation of this data which is addressed in the scaling analysis below of both the heat transfer coefficient variation with time and the time variation of the bulk water and external pipewall temperature measurements. This analysis is considered necessary to support and complement the field temperature studies reported in subsequent Chapters.

The Arfiadi et al. [9] study demonstrated the need for significant stabilisation time periods between the end of filling and the start of the Pressure Test to ensure that the pipe thermal system is close to that of the surrounding soil. This stabilisation process is expected to continue during the Pressure Test period while the adiabatic change during pressurisation and other thermal disturbances of pressurisation as mentioned in Section 1.2.3, particularly the axial movement of the pressurising water, are all additive influences.

A major finding of the CFD study was that external pipewall temperature measurement changes were opposite to bulk water temperature changes. This opposite temperature effect lead to a period of temperature measurement uncertainty which depended on the external pipewall measurement location and resulted in the need for a time period for this opposite temperature effect to dissipate before such measurements can be used to ascertain whether the pipe section is free of leaks. This anomaly between pipewall and bulk water temperature could be one explanation for the acoustic velocity anomaly highlighted earlier in this document as buried pipeline temperature measurements are normally external top of pipe. The external top of pipe measurements resulting after a rise in bulk water temperature decay more quickly than after a drop in bulk water temperature.

The CFD modelling starting conditions generally consisted of water inside the pipe either at 10 degrees Celsius above or below the ground surrounding the pipe or the pipe (if not buried). This value of 10 degrees was initially chosen to ensure that the resolution limits of the CFD programme used at the time (PHOENICS) could provide useful results due to limited resolution. Later comparisons of runs with 1 degree Celsius changes showed that the temperature changes were scalable over time so that the 10 degree results could be applied to the less than one degree adiabatic changes.

Pipe diameters from 250 to 1250 mm nominal diameter were studied. The durations varied from 24 to 48 hours to address typical leak test durations. One study of exposed high or low pipe ends connected to buried pipe downhill or uphill respectively was simulated for a few weeks (almost 500 hours).

Three soil types modelled ranged from dry topsoil through silty clay to wet sandstone with the main factor controlling heat transfer, the diffusivity, ranging from $1.38 \times 10^{-7}$, through $3.6 \times 10^{-7}$ to 5.9 $\times 10^{-7} \mathrm{~m} 2 / \mathrm{sec}$ respectively and only covering a factor of 4.3:1 range. These values were taken from textbooks and so may not represent field conditions. Further data is needed for actual pipe backfill materials in a range of soil types which is addressed in Chapter 5 and Section 5.6.

The following sections are intended to show relevant results and their possible application to acoustic measurements.

### 3.1.2 Thermal profile following Initial Adiabatic sudden change.

Input for one part of the CFD study was a sudden rise in temperature of the pipe contents either in ground or pipe which was initially all at the same temperature. This simulates the adiabatic heating of the water during pressurisation at the start of a pressure test. Simultaneous with the water heating there is adiabatic cooling of the pipe since it undergoes tension as the pressure rises but was not included in the study as pipe thermal mass was small compared with water. The pressure reduction at the end of the test was also simulated.

## Initial Convection Flow Pattern

The focus of the current study is the resultant thermal layering present during the decay in the heat transfer curves in Figure 3-10, Figure 3-11, Figure 3-12 and Figure 3-13. The pattern that occurs during the initial rise in the heat transfer curves (refer to Section 3.3) to the maximum is shown in Figure 3-1 is referred to as the "Twin Eyes". This pattern consists of two contra rotating convection currents symmetrical about a central vertical axis through the pipe. The pipe wall in contact with cold ground causes the water on the inside adjoining it to move downwards towards the bottom which is compensated by a central upward vertical flow. The reverse takes place with pipe wall in contact with warm ground. This pattern was confirmed experimentally by Godbole et al. [11] using suspended pliolite particles in water and high speed video capture also in Figure 3-1. The reason for mentioning it will become clearer later in this document.


Figure 3-1 - Convection Flow Pattern - Experimental (Left) and CFD (Right) ten seconds after start.

For the experimental verification the internal diameter was 200 mm . Any lack of symmetry of heat transfer between the two sides will affect the pattern such as would occur with solar heating or wind and rain on one side.

## CFD Pipe Cross Section Figures for Rapid Temperature Increase

The following figures show the flow and thermal fields in the pipe cross section, progressing in time for a DN 450 pipe with rapid water temperature rise of $10^{\circ} \mathrm{C}$ in soil or pipe without temperature change.


Figure 3-2 - DN 450 Flow and Thermal fields at 600 sec (10 min).
"Twin Eyes" can be observed in the lower part of Figure 3-2 as indicated by the flow vectors within the water.

## CHAPTER 3 - ANALYSIS OF CFD STUDIES



Figure 3-3 - DN 450 Flow and Thermal fields at $1200 \mathrm{sec}(20 \mathrm{~min})$


Figure 3-4 - DN 450 Flow and Thermal fields at 1800 sec (30 min)


Figure 3-5 - DN 450 Flow and Thermal fields at 2400 sec (40 min)


Figure 3-6- DN 450 Flow and Thermal fields at 3600 sec (1 hour)
The large arrows outside the pipe are convection flow velocities of the water next to the pipe and show generally a downwards pattern while the tiny internal arrows show a central vertical rise so that there are two contra-rotating convection patterns either side of the vertical centreline.

In the last Figure 3-6 there was almost a complete vertical thermal pattern or horizontal sections of almost uniform colour (temperature) other than the periphery next to the constant temperature pipe/soil. The horizontal bands progressively decreased in width from top to bottom implying a nonuniform thermal gradient so that highest temperature changes were at the top and least at the bottom. Hence for a DN 450 pipe, thermal layering across the whole pipe cross section has been developed by around 3600 seconds or 1 hour.

The pipe/soil temperature has been artificially held constant which is not expected in buried pipe where the soil immediately surrounding the pipe should have a temperature intermediate between the internal water and external ground.

## CFD Pipe Cross Section Figures for Rapid Temperature decrease

The following figures show the flow and thermal fields in the pipe cross section, progressing in time for a DN 450 pipe in soil with rapid temperature drop. These were the opposite to those with the rapid temperature rise and appeared different in that the start temperature was effectively $20^{\circ} \mathrm{C}$ below the start of the previous rapid temperature rise set. Eventually both reached the reference temperature of $20^{\circ} \mathrm{C}$.


Figure 3-7 - DN 450 Flow and Thermal fields at 600 sec (10 min)


Figure 3-8 - DN 450 Flow and Thermal fields at 1200 sec (20 min)


Figure 3-9 - DN 450 Flow and Thermal fields at 3600 sec (1 hour)
The convection flow mentioned for the temperature rise case is reversed in this case of temperature decrease as evidenced by the perimeter arrows.

The thermal layering shown in Figure 3-9 is opposite to that in Figure 3-6 only in that the horizontal bands in the former are narrower at the top and broadest at the bottom but still with higher temperatures at the top and lowest at the bottom.

These figures show that for the DN 450 pipe it took around 1 hour to fully develop nearly uniform thermal gradients in the pipe cross section. Prior patterns showed an accumulation of hot water at the top of the rise set and cold water at the bottom in the drop set followed by slow development of the full gradient. While the modelling was based on a $10^{\circ} \mathrm{C}$ change, in reality changes will be typically of the order of $0.4^{\circ} \mathrm{C}$ and the expected temperatures would simply be $1 / 25$ or 0.04 times the displayed temperatures with the same timing.

### 3.1.3 Heat Transfer estimates

The CFD study estimated the total heat transfer coefficient (HTC) changes over time for different pipe diameters relating to the heat transfer to or from the pipe to the surrounding soil. Graph of these is shown below as Figure 3-10.


Figure 3-10 - Heat transfer estimates over time for varying diameters when water filled pipe is suddenly heated in ground previously in thermal equilibrium with the pipe.

The DN500 curve reaches a peak and then around 50 minutes starts to drop. In the previous set of cross section plots (Figure 3-5 and Figure 3-6 for DN450) the thermal gradient is only fully developed near to 1 hour so that the subsequent exponential like more rapid drop in heat transfer curves represents the attenuation of the fully developed thermal gradient. The start time of this more rapid drop increases with pipe diameter. These different heat transfer rates impact on the speed of temperature change recovery and the expected duration of uncertainty between pressure and pipe wall temperatures during pressure testing.

## Diameter-based scaling of heat transfer curves

The traces in the above chart were digitised and then scaled so that they matched each other as shown in the following Figure 3-11 with scaling based on the DN1000 time in Figure 3-10.


Figure 3-11 - Heat Transfer Coefficients for different Diameters plotted against Scaled Time referenced to DN1000 and surrounded by constant temperature pipe/soil.

There is good overall agreement in the shape of the exponential decay portion of the graph. The intermediate slightly inclined plateau portion differs in amplitude with diameter but this difference is only minor compared to the effect of diameter. There is little overall difference when the diameter based time scaling between the use of an exponent of -1.45 and -1.5 with the former providing slightly better grouping. As to why the scaling is -1.5 (or $-3 / 2$ ) has not been resolved. The above comparison was between water filled pipes surrounded by constant temperature pipe/soil.

## Effect of Soil on Heat Transfer Time Scaling and Fully Developed Thermal Layering

Amongst the research data there was one graph which provided heat transfer coefficients for diameter DN 250 pipe surrounded by wet sandstone soil of thermal diffusivity $5.89 \times 10^{-7} \mathrm{~m}^{2} / \mathrm{s}$. This pipe was horizontal as were the pipes used in the above scaling assessment. The following Figure 3-12 compares this result with that from Figure 3-10 with constant pipe/soil but time scaled or increased by a factor of 3.3 to match the one with soil.


Figure 3-12 - Heat Transfer Coefficient for DN250 pipe in wet Sandstone Soil compared with pipe/ soil at constant temperature with Time increased by a factor of 3.3.

The empirical approximation for the exponential decay in Figure 3-12 for the DN 250 Wet Sandstone soil is given by:
$h=160 e^{-0.51 t^{1.3}}(3.3 .1)$
where h is the heat transfer coefficient and t is the time in hours after 0.67 hours. The approximation was produced by this author using the Microsoft Excel Solver function optimising only the exponent coefficient and time exponent. This equation approximates both the wet sandstone and the time scaled curves. Using this scaling factor of 3.3 and the heat transfer characteristics from Figure 3-10 resulted in the following heat transfer characteristics with unscaled time for wet sandstone for the different diameters in Figure 3-13.


Figure 3-13 - Heat Transfer Coefficient Estimates for Different Diameters in Wet Sandstone
Heat transfer coefficients may appear irrelevant for thermal gradients, however they will control and determine the bulk water temperature change over time so that the time scaling should match that of the bulk water temperature. The external soil is the heat source or sink for the heat transfer process and the need for a time scale factor of 3.3 between constant external temperature and embedding in soil is the addition of thermal resistance in the soil which changes with the soil properties and pipe diameter and delays the water temperature change.

For pipeline hydrotests, the combined pressurising and strength test phases take between 3 to 6 hours. For pipes of DN250 and smaller, the exponential decay has either completed or is well under way during this period resulting in much attenuation of fully developed thermal layering. For the DN 500 pipe the exponential decay is only partially underway at the start of the test with fully developed thermal layering attenuating during the leak test. For DN1000 the start of the 24 hour leak test period occurs during both the initial part of thermal layering development so that thermal layering continues to develop until almost one third of the time into the test. The subsequent exponential decay portion with fully developed thermal layering will then apply for the balance of the test period. For the DN1250 the start of the leak test again occurs during the development of thermal layering which is only complete towards the end of the test period.

As will be shown below, these times are based on wet sandstone which results in the shortest time and will be longer for soils of lower diffusivity and for any orientation other than horizontal. Any further scaling for lower thermal conductivity soil may be subject to variation and should be checked by subsequent CFD work.

### 3.1.4 Pipe Surface Temperature Measurements

CFD simulations of the temperatures resulting from a 10 degree $C$ rise in water temperature relative to the soil temperature were carried out for DN 250,500 and 1000 mm pipe in three soil types
or diffusivities. These showed a disparity between the surface temperatures of the steel pipe and the bulk water average temperature. This disparity is likely to be the main factor in Uncertainty between the measured pressure and the measured temperatures during a hydrostatic pressure test of buried pipe which are usually measured by temperature probes in contact with the top of the steel pipe.

This section evaluates this disparity and relates it back to thermal transfer characteristic scaling.

## Variation with position and pipe diameter

A comprehensive set of data was produced for the DN250 pipe in wet sandstone with calculations carried out at short time intervals for the first hour and extended at coarser intervals out to 48 hours as shown in the following figure. Three positions on the pipe circumference of top, side and bottom were tracked and are plotted in the following figures.


Figure 3-14 - DN250 Temperature Trends in Wet Sandstone
Figure 3-14 covers the complete data set of 48 hours. This is truncated in the following Figure 3-15 to two hours to better show the variation at the start.

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Figure 3-15 - DN250 first two hours - Wet Sandstone
The bulk mean temperature (top trace with green markers) is the average of the water contents of the pipe and shows a gradual almost exponential decay over time.

The top pipe wall temperature (upper trace with dark red markers) shows a sudden rise, reaches a peak at around 30 minutes and then slowly drops with the curve crossing the bulk water temperature just short of an hour. Eventually it parallels the drop in the bulk water temperature.

The side temperature (light red) has a similar characteristic to the top but does not cross the bulk water temperature and shows a less pronounced peak. It also appears to almost merge with the bulk water temperature during the later stages of the decay.

The bottom temperature (blue) is unlike the other pipe surface temperatures and remains well below the bulk water temperature and slowly trends towards it.

Figure 3-14 needs to be compared with Figure 3-12 to assess the heat transfer factors affecting the temperatures. The peak in Figure 3-12 occurred around 40 minutes ( 2400 seconds) after the start which corresponds approximately in Figure 3-14 to top of pipe steel temperature between the peak and the crossover with the bulk mean temperature. The development of thermal layering should have occurred before the crossover as shown in Figure 3-2 to Figure 3-6 which were for DN450 pipe and their times need to be reduced by half to correspond to DN250 in the above figure.

Figure 3-16 below covers the first 10 hours. The long exponential decay in the heat transfer coefficient of Figure 3-12 should correspond to the time from 40 minutes to approximately 5 hours after the start. This is close to the time when the top and side pipe temperatures start to track the bulk mean temperature and the side temperature almost equals the bulk mean temperature.

The results for the other diameters and soils were found to be scaled versions of these figures.
The bulk mean temperature change should correspond to the pressure in the pipe. The fact that the temperatures of the pipe are rising while the pressure would be falling in the first 20 minutes will
result in most of the uncertainty in the pressure test since the two are totally uncorrelated. The correlation slowly improves until around 5 hours when the top and side track the bulk mean.

The bottom pipe temperature is totally uncorrelated with the bulk mean. Measuring the bottom temperature has value only when the bulk water temperature is lower than the pipe or soil which is when the characteristics of the top and bottom pipe temperatures are the reverse of the above figures.


Figure 3-16 - DN250 First 10 hours - Wet Sandstone.
The following Figure 3-17 condenses the DN250, DN500 and DN1000 data for wet sandstone into one graph using scaling based on the DN 250 timing.


Figure 3-17 - Different Diameters scaled to DN250 for Wet Sandstone Soil.

The fit for the bulk mean is similar to Figure 3-14 but there are differences in the side, top and bottom temperatures. Overall there is similarity. The following Figure 3-20 has the scaled time period reduced to better show the variation with top, side or bottom position.


Figure 3-18 - $\quad$ Shortened time scale for previous figure with different diameters scaled to DN 250 for Wet Sandstone Soil.

There was insufficient data for the DN500 and DN1000 pipes to permit detailed comparisons. The only conclusion is that for the critical period of the first hour of scaled time the DN250 data provides the most detailed data which can be used to evaluate trends and characteristics for the larger diameter pipes.

## Variation with combined soil type and diameter

The previous Figure 3-20 merged and plotted data for diameters from DN250 to DN1000. The basis for the scaling was DN250 pipe in wet sandstone. The temperature plotted was the bulk temperature of the water inside the pipe which correlated best with pressure in a hydrotest. Hence this scaling represents the best to model the pressure changes with time with varying diameter and soil type. The reason that DN 250 was selected as the reference was due to the fact that detailed data was obtained for a 48 hour period for this diameter of pipe. This data can then be used to cover many days for larger diameter pipes and 24 hours for smaller diameter pipes.

The following Figure 3-21 combines the scaling used for Figure 3-17 with scaling for soil type diffusivity.

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Figure 3-19 - Bulk Water Temperature for different Diameters and Soil Diffusivity with Time scale based on DN 250 pipe in wet sandstone.

The coefficients needed to achieve the above scaling are listed in Table 3-1 following and were obtained by optimising the coefficients to obtain the best fit using Excel.

Table 3-1 - CFD Scaling Parameters to condense curves for different diameters and soil diffusivity

| Scaling Parameters used in Figure 3-21 for Diameter and Soil exponents and Time Factor |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Diam | Soil Type | Diffusivity <br> x10 <br> m2/s | Diam exponent | Soil <br> exponent | Time factor | Reciprocal time <br> factor |
| 250 | Wet SS | 5.89 | N/A | 1 | 1 | 1 |
| 250 | Dry Topsoil | 1.38 | N/A | 0.79 | 0.318 | 3.147 |
| 250 | Silty Clay | 3.60 | N/A | 0.97 | 0.62 | 1.612 |
| 500 | Wet SS | 5.89 | -1.62 | 1 | 0.325 | 3.074 |
| 500 | Dry Topsoil | 1.38 | -1.62 | 0.8 | 0.102 | 9.814 |
| 500 | Silty Clay | 3.60 | -1.62 | 1.1 | 0.189 | 5.283 |
| 1000 | Wet SS | 5.89 | -1.75 | 1 | 0.088 | 11.314 |
| 1000 | Dry Topsoil | 1.38 | -1.75 | 0.73 | 0.031 | 32.635 |
| 1000 | Silty Clay | 3.60 | -1.75 | 1.03 | 0.053 | 18.786 |

While Figure 3-17 used a diameter exponent of -1.45, Figure 3-21 used different values for DN500 and DN1000. Noting that the basis for the diameter exponent of -1.45 was the theoretical situation of a pipe with fixed outer temperature and without soil, the exponents in the table may represent more realistic values for pipe in soil. The values for the larger diameter pipes end up in the upper left corner of Figure 3-21.

For the soil exponents the greatest divergence appears to be for the dry topsoil which causes the scaled time to shrink further into the top left corner of the figure relative to the other soil types. Scaling appears to change depending on the final position on the exponential like curve.

The range of data produced by the Uncertainty study [11, 115, 116] has only addressed times up to 24 and 48 hours for these pipe diameters and soil types. To properly evaluate scaling, the range of times should reflect the time factors in the last column of the table; that is extending time for many days for the larger diameters.

### 3.1.5 Scaling Equations

A simple time scaling equation relative to Figure 3-21 for horizontal pipe is:

$$
\begin{equation*}
\text { Time_scaling_factor }=\left(\frac{5.89 \times 10^{-7}}{\alpha}\right)^{0.78}\left(\frac{D}{265}\right)^{1.83} \tag{3.1.1}
\end{equation*}
$$

Where:
a
diffusivity in $\mathrm{m}^{2} / \mathrm{sec}$ with $5.89 \times 10^{-7}$ (diffusivity of wet sandstone) used as reference. D pipe internal diameter in mm with 265 mm as the internal diameter of the DN250 pipe used in the CFD simulation and used as reference.

The time (in hours) in Figure 3-21 is to be multiplied by this time scaling factor to obtain the relevant time. e.g. for internal diameter 986 mm and dry topsoil of diffusivity $1.38 \times 10^{-7}$ the time scaling factor would be 34.3 differing slightly from the 32.6 in Table 3.1. Then for this pipe and soil the first 1.4 hours of Figure 3-21 would correspond to a time of 48 hours ( $1.4 \times 34.3$ ).

The shape of the curve in Figure 3-21 appears like an exponential decay but cannot be described by such and needs a time exponent of 0.5 . An approximation to the curve in Figure $3-21$ is given by:

$$
\begin{equation*}
T=T_{G}-T_{C}\left\{1-\exp \left[-0.432\left(t\left(\frac{\alpha}{5.89 E-07}\right)^{0.78}\left(\frac{265}{D}\right)^{1.83}\right)^{0.5}\right]\right\} \tag{3.1.2}
\end{equation*}
$$

Where:

| $T_{G}$ | reference temperature or ground temperature. |
| :--- | :--- |
| $T_{C}$ | temperature change |
| $t$ | time from the start in hours |
| $\alpha$ | diffusivity in units of $\mathrm{m}^{2} / \mathrm{sec}$ |
| $D$ | internal diameter of the pipe in mm. |

This can be simplified by collecting the constants together but then removes the scaling factors for the diffusivity and diameter which also act as reminders of the units. For example it should be obvious that the diameter should be in mm by the presence of 265 . The time is scaled by dividing by the previous time scaling factor. The resulting curve is not a true exponential in that the time is raised to the power or 0.5 , i.e. square root of time which is the reason that the curve takes longer to reach TG - TC or the final temperature.

This curve can be used to approximate the pressure decay over the hydrotest period (with ambient effects removed) by substituting Pressure values for Temperature using the pressure/temperature factor. Temperature change following filling should follow the same curve. If diffusivity is not known it
can be approximated by fitting the curve to known data. This equation does not take into account sloping sections which can be approximated by use of a different diffusivity from that of the actual soil. This equation was not developed by the CFD study but by this author based on Figure 3-21 (also by this author) and is only empirical.

Using the above scaling equation (3.1.2) the following are the time constants for pipe diameters and soils relevant to this study. For this purpose the equation will be rearranged as follows with the time expressed in days as used in Excel and for comparison with other time exponents expressed per day:

$$
\begin{align*}
& \text { alpha } \\
& =-0.432\left(24\left(\frac{\alpha}{5.89 E-07}\right)^{0.78}\left(\frac{265}{D}\right)^{1.83}\right)^{0.5} \tag{3.1.3}
\end{align*}
$$

The equation for temperature changes of buried pipe in the appropriate soil then becomes:

$$
\begin{equation*}
T=T_{G}-T_{C}\left(1-\exp \left(\operatorname{alph} a \times t^{0.5}\right)\right) \tag{3.1.4}
\end{equation*}
$$

where
alpha time factor in the table below in units of per day.
$t \quad$ time in days
Tc temperature change imposed
$T_{G} \quad$ soil or ground temperature
For diameters of pipes in the following study, the following table provides the relevant time factors for different alpha values used in the above equation 3.1.4.

Table 3-2- Alpha Time Factors for different Diameters and Diffusivities used in this Document

| Table of Time Factors for different Pipe Diameters and Soils used in this document |  |  |  |  |  |  |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: |
| Pipe <br> outside <br> diameter <br> $(\mathrm{mm})$ | Pipe wall <br> thickness <br> $(\mathrm{mm})$ | Pipe <br> internal <br> diameter <br> $(\mathrm{mm})$ | Soil Type | Diffusi <br> vity <br> x10+7 <br> $(\mathrm{m} 2 / \mathrm{s})$ | Time factor <br> (alpha) for <br> time with <br> exponent 0.5 | Time factor <br> (alpha) for <br> time with <br> exponent 1 |
| 219.1 | 5.6 | 207.9 | Wet S/S | 5.89 | 2.64 | 1.32 |
| 219.1 | 5.6 | 207.9 | Silty Clay | 3.60 | 2.18 | 1.09 |
| 219.1 | 5.6 | 207.9 | Dry Topsoil | 1.80 | 1.66 | 0.83 |
| 323.9 | 5.6 | 312.7 | Wet S/S | 5.89 | 1.82 | 0.91 |
| 323.9 | 5.6 | 312.7 | Silty Clay | 3.60 | 1.50 | 0.75 |
| 323.9 | 5.6 | 312.7 | Dry Topsoil | 1.80 | 1.15 | 0.63 |
| 435 | 6.35 | 422.3 | Sandy Clay dry | 7.00 | 1.48 | 0.74 |
| 435 | 6.35 | 422.3 | Sandy Clay damp | 8.20 | 1.57 | 0.79 |
| 435 | 6.35 | 422.3 | Sandy Clay wet | 1.00 | 1.70 | 0.85 |
| 914.4 | 11.7 | 891 | Wet S/S | 5.89 | 0.70 | 0.35 |
| 914.4 | 11.7 | 891 | Silty Clay | 3.60 | 0.58 | 0.29 |
| 914.4 | 11.7 | 891 | Dry Topsoil | 1.80 | 0.44 | 0.22 |

Where other soil types (diffusivities) and or diameters apply equation 3.1.2 should be used.

### 3.1.6 Water and Pipe WALL Temperature Differences

The following Figure 3-22 shows the difference between the bulk mean water temperature and each of the top, side and bottom locations on pipe surface. These are based on an initial temperature difference of 10 C . This difference is referred to as an error since the bulk water temperature will correspond closely to the pressure and any discrepancy between this bulk water temperature and pipe surface temperature will represent an error in assessment of the pressure temperature trends.


Figure 3-20 - DN250 Temperature Errors for Top, Side and Bottom Pipe Wall Locations

The following Figure 3-21 enlarges the initial 4 hours of Figure $3-20$ to enable better assessment of changes.


Figure 3-21 - Enlarged Time Scale, first 4 hours, DN250 Temperature Errors for Top, Side and Bottom Pipe Wall Locations.

For a typical Class 600 pipeline, the test pressure is of the order of $15,000 \mathrm{kPa}$ and the adiabatic water temperature rise is of the order of 0.3 C for this pressure change if the average temperature is around $25^{\circ} \mathrm{C}$. A pressure temperature factor of $300 \mathrm{kPa} / \mathrm{C}$ would be typical of this temperature. Hence the errors in Figure 3-20 and Figure 3-21 at four hours using the top of pipe measurement of around 0.2 from a $10^{\circ} \mathrm{C}$ change would correspond to an error for the $0.3^{\circ} \mathrm{C}$ adiabatic change of $0.006^{\circ} \mathrm{C}$ equivalent to a pressure error of 2 kPa . Such change is negligible and close to the pressure instrument resolution but only for DN250 pipe in the highest diffusivity soil.

In the case of larger diameter pipes and different soils, the time scaling will change with the errors occurring over longer periods of time. Because of the scarcity of CFD data, extending the scaling to pipe wall measurements has not been attempted. The above analysis should provide the basis for such additional CFD work to enable scaling.

### 3.1.7 Field confirmation of CFD results

The following results were obtained by this author and reported by Godbole [115] when pressurising and depressurising a DN150 pipe, one metre long, encased in polystyrene and fitted with external surface temperature sensors on the top, side and bottom of the horizontally oriented pipe. This was carried out for other purposes but coincidentally showed results consistent with the CFD computer modelling. The methodology used was the same as used to measure air solution rates detailed in Chapter 4.1.

The pipe was pressurised very quickly to 154 barg ( $15,400 \mathrm{kPa}$ ) and after 2 hours depressurised quickly. Hence the pressurisation and depressurisation are considered adiabatic and show all the implications of such rapid change. The effect on temperature sensors fixed to the outside of the pipe on the top, side and bottom are as follows in Figure 3-22. What is of note is that the pressure decays after the initial peak at around 15:10 and within around 20 minutes is starting to track the temperatures.


Figure 3-22- DN 150 pipe adiabatic changes on pressurisation and depressurisation confirming the CFD results in principle without surrounding soil.

While the pressure (blue trace - right axis) initially decays, the temperatures show a reverse kink over a period of a minute or two followed by a rise in temperature in all three locations. The initial reverse kink is due to the adiabatic cooling of the steel (thermoelastic effect) as it stretches when the pressure is applied. This is then followed by the rise in temperature as the steel starts to be warmed by the adiabatically heated water inside the pipe. The opposite occurs when the pressure is dropped. Note the difference between the top of pipe (orange-brown) and bottom of pipe (uppermost) temperatures. When the water is hotter than the pipe, the top of pipe sensor has the same but reversed shape as the bottom of pipe sensor when the water is colder than the pipe. Only the side of the pipe has a consistent shape for both hotter and colder water.

The next Figure 3-23 shows the curves superimposed to better compare them with the temperature changes (converted to pressure).


Figure 3-23- DN 150 pipe adiabatic changes on pressurisation and depressurisation confirming the CFD results in principle without surrounding soil - Direct comparison for pressure and temperatures.

In Figure 3-23 the dark blue pressure curve shows a drop over 15 minutes while all three temperatures rise with the top and side responding in a similar time frame while the bottom takes 3 to 4 times longer to fully respond. Note that the top of pipe temperature tends to overshoot slightly and then after around 30 minutes starts to track the side of pipe.

The above two figures show that there is a discrepancy between the pressure and the external pipe wall temperature measurements. The internal water temperature was never measured but would be expected to change in a similar manner to the pressure. The lack of correlation between the external pipe wall temperatures and the pressure represent one significant aspect of the Uncertainty associated with pressure testing.

The characteristics seen in the above two figures provided field verification of the CFD computer studies. The above figures related to a cylinder encased in insulation which differs from the two CFD models so far which had either constant temperature pipe or were in soil.

The difference in time scale for the bottom and top in Figure 3-23 is similar to that for Figure $3-15$ so the factor of almost 16 increase in time scale is also applicable.

### 3.1.8 Inclined Pipe

The above analysis and scaling was based on horizontal pipe and would represent the shortest time frame for heat transfer with the convection development confined to the pipe cross section and uniform along the whole of the pipe. Thermal gradients for a short 5 metre length of DN 450 pipe buried under one metre are shown in the next few figures.

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Figure 3-24 - Inclined pipe Thermal gradient and Convection Flow Velocities in Central Cross Section.

The left colour chart applies to the cross section temperatures while the right applies to the colour of the convection flow velocities. For the acoustic technique intended acoustic velocity resolution is of the order of $0.01 \mathrm{~m} / \mathrm{s}$ to approximate the equivalent of 0.01 degree Celsius. The highest convection flow velocity is $0.012 \mathrm{~m} / \mathrm{s}$ with highest velocities at the bottom of the cross section and centrally located. Such velocities were unlikely to affect acoustic velocities.


Figure 3-25- Inclined DN 450 Pipe near vertical Thermal gradient along length in 5 metre section of DN 250 pipe after 1 hour with Ground temperature initially at 10 degrees and pipe contents at 20 degrees.

In Figure 3-25 the temperature range along the pipe length varied from 20 at the top to 16 degrees Celsius at the bottom as expected for the early stages.


Figure 3-26 - Inclined DN 450 Pipe showing thermal gradient through (almost) central vertical plane after 10 hours.

For Figure 3-26 at 10 hours there was only a 0.7 degree Celsius variation between the top and bottom. With the colour chart in uniform increments, there appeared to be a greater gradient at the top than at the bottom. Hence for the same DN 450 pipe diameter, changing from horizontal as in Figure 3-6 to inclined as in Figure 3-26 has extended the time needed to fully establish thermal layering from around 1 hour to 10 hours for a 5 metre length of pipe. In addition, the side elevation view in Figure 3-26 shows horizontal irregularities in the coloured bands hinting at uneven thermal layering in the central vertical slice through the pipe axis.


Figure 3-27 - Inclined Pipe showing axial velocities of convection currents after 10 hours.
For Figure 3-27 showing axial velocities there was almost a central figure eight enclosing arrows pointing downwards while the balance pointed upwards. Highest flow appeared to be at the bottom of the figure eight. Such convection related flow was unexpected as the conventional assumption was that the bottom segment should flow down and the top segment up.

Godbole provided figures for the thermal gradients at the high end, middle and low end as shown in Figure 3-28, Figure 3-29 and Figure 3-30 10 hours after a 10 degree difference between soil at $10^{\circ} \mathrm{C}$ and pipe contents at $20^{\circ} \mathrm{C}$ for the 5 metre long DN 450 inclined pipe.


Figure 3-28 - High End at 10 hours


Figure 3-29 - Mid Point at 10 hours


Figure 3-30 - Low End at 10 hours
While such large temperature changes of 10 degrees do not normally happen during pressure tests, the fact that different small thermal gradients remained in an inclined short section suggest that for much longer sections larger gradients would be expected over an extended time.

CFD modelling was carried out on a 204 metre long 355.6 mm O.D. pipe inclined at $12^{\circ}$ to the horizontal (around $1 / 5$ gradient) buried 1 metre in wet sandstone with result locations at the centre of the length and at 10 metres from the ends. Results were shown in Figure 3-31 which incorporated scaling for diameter and location along the inclined pipe length. Pipe diameter was time scaled by a diameter scaling exponent factor of -1.45 to provide the best agreement between the mean bulk water temperatures for the reference diameter of DN250. DN250 pipe was unscaled to enable comparison with horizontal results. The location time scaling factors for the DN 350 were 0.75 and 2.0 for the high and low locations respectively. While these scaling factors brought the data closer to the bulk mean temperatures, they did not correspond.


Figure 3-31 - $\quad$ Sloping Pipe of DN250 and time scaled DN350 with time scaling of Locations on DN350.

In Figure 3-31 the top of pipe and bulk water temperatures were similar for the respective low and high locations. This implied that there was a temperature gradient up the slope similar to that in horizontal pipe for the pipe cross section.

The fact that the low locations needed a time scaling of 2 could start to explain some discrepancies in field hydrotest assessments. If temperature probe locations were at low points then the temperatures they measured wouldl not correspond in time to the pressure changes (which tend to follow the mean bulk temperature). Alternatively if the temperature probe locations were at high points then there was a closer approximation to the bulk temperature but still a discrepancy with time with the smaller scaling factor of 0.75 .

The CFD study indicated that the best location for temperature probes was half way up slopes.

### 3.1.9 Inclined Pipe Ends

Unexpected CFD findings resulted from high and low point exposed pipe sections in otherwise buried pipe. This situation is typical of test headers installed on a sloping section of pipe.

## CFD Simulation for high Exposed End.

CFD simulations were carried out for a section of DN1000 pipe 340 metre long inclined section as shown in the following Figure 3-32 with 20 metres exposed at the upper end.


Figure 3-32 - Inclined exposed end with header at upper end.
The input was a sine wave simulating the diurnal ambient temperature change affecting the exposed pipe. The following Figure $3-33$ shows an ambient change of $+/-10^{\circ} \mathrm{C}$ and the resulting average bulk water and pipe wall temperature changes.


Figure 3-33 - Input ambient and resulting bulk water and average pipe wall temperatures.
What was not obvious on first view of Figure 3-33 was that the resulting temperatures were slowly decreasing. The bulk water temperature is lagging behind the average pipe wall temperature as expected. The amplitude of the bulk water temperature change is approximately $+/-1^{\circ} \mathrm{C}$ which is significantly less than the ambient change and is dependent on the ratio of exposed pipe to total affected pipe which in this case is $20 \mathrm{~m} / 340 \mathrm{~m}=0.06$ or $+/-0.6^{\circ} \mathrm{C}$.

The above change is as expected whereas the unusual aspect of the results starts to appear in the following Figure 3-34. The pattern no longer is similar to the input sinusoid but takes on a very different shape. The reason for this is due to convection currents and the fact that in this case the test header is at the upper end. During the hottest part of the day the radiation from the sun and ambient air heats up the pipe and in turn the water in the exposed pipe which will rise and accumulate in the upper end in the test header. The only longitudinal convection movement taking place is in the exposed section. This accumulation will continue as long as the ambient temperature is above the buried pipe temperature. Only once the ambient temperature drops below the buried pipe temperature will water in the exposed pipe start to move by convection along the bottom of the pipe towards the lower buried end. Hot water will remain at the exposed top and will continue to cool but will not move. Only colder water accumulating at the bottom of the exposed section will move if cooler than the adjoining buried pipe contents. Water displaced by the downward movement along the bottom will move upwards along the top of the pipe.

The effect can be summarised as only permitting changes which are below the buried pipe temperature to be transferred from the exposed pipe to the buried section. Temperatures in the exposed pipe higher than the buried pipe temperatures will be trapped in the exposed pipe. Hence only the bottom part of the ambient sinusoid in Figure 3-33 will appear in the buried pipe with all of the top part of the sinusoid trapped in the exposed pipe.

The fact that only exposed pipe temperatures lower than the buried section will propagate down the pipe also means that the buried pipe section will be cooled over time. These two effects are seen
in Figure 3-34 with the negative part of the sinusoid present followed by an almost flat portion where the positive part of the sinusoid would have been. The cooling effect is obvious. The figure also plots the differences between the top, side and bottom of the buried pipe at this location.


Figure 3-34- Location 40 metres from the exposed pipe or 60 metres from the end cap. The near vertical dashed light blue traces are of the exposed surface input.

While Figure 3-34 was only for the first 96 hours or 4 days, the following Figure 3-35 covered around 20 days for a location 100 metres from the high exposed end. The temperature pattern is not as clear as for Figure 3-34, but the downward temperature trend is seen to continue but progressively slow down as the buried pipe temperature gets closer to the lowest ambient temperature.

## CHAPTER 3 - ANALYSIS OF CFD STUDIES



Figure 3-35 - Location 100 metres from end cap of inclined pipe with exposed pipe at the high end.

For locations further from the end cap the daily fluctuations reduce and mainly a slow downward temperature change is observed.

The above traces have been digitised to extract the exponential like decay starting from 120 hours. The daily time exponent values range from 0.08 to 0.10 per day as shown in the following Figure 3-36.


Figure 3-36 - Exponential decay of Top, Side and Bottom buried Pipe wall Temperatures 80 m and downhill from DN1000 Exposed Pipe at upper end.

The exponential fit is not perfect and it appears that the projected trend lines out to 900 hours are not correct and should probably still continue to diverge. An attempt was made to see whether a time exponent would improve the longer term fit without success.

The only driving input in the above case of an exposed high end is the lower half of the ambient cycle which cools the exposed pipe and generates the downward moving cooler convection current. This occurs for less than half of the daily cycle so that the heat removal is smaller than for continuous heat exchanges.

## CFD Simulation for Low exposed end

Due to the long-time taken to do the 23 day simulation, the opposite situation was not simulated but would be expected to be the reverse of the above case with the temperatures rising in the buried pipe section and only the highest temperature part of the ambient input sinusoid being transmitted to the higher buried pipe.

The patterns observed are similar to that observed in electrical circuits when a sine wave is passed through a rectifier. Only one half of the sine wave is transmitted. This author refers to this effect on pipelines as the "rectifier effect".

## Field Verification

On a DN1050 project, the above effect was observed by this author with a temperature sensor installed on top of buried pipe 350 metres from the lower exposed end. Hence only the upper part of the exposed pipe ambient sinusoid should be transmitted upwards into the buried pipe. This is shown in Figure 3-37 below together with a gradual rise until the depressurisation at the end of the test when the ambient measurements ceased.


Figure 3-37- Buried pipe temperatures on an upward inclined pipe with exposed pipe at the lower end - comparison of Ambient (blue) and buried top of pipe (yellow).

The start of the ambient measurements (blue) coincided with the final pressurisation to strength test which distorted the buried pipe trace (yellow). The similarity (reversed) to Figure 3-34 demonstrates the capability of the CFD simulations. The location of the below ground temperature sensor was not far from a high point which partly explains the gradual reduction in the overall rise. Also the ambient range is mostly below the below ground temperature which would also affect the rise.

Below ground pipe wall temperature probe was manufactured by this author using PT1000 sensors and digitised by the ADuCM360 microcontroller with 24 bit A/D converter with data transferred by cable and stored in a Data Electronics DT80 datalogger as shown in Figures 1-7 and 1-8 respectively. The ambient was measured with an LM35 based sensor and recorded in the Test Container with recording set up shown in Figure 1-6 while the exposed pipe generating the below ground changes was that shown on the far left of Figure 1-3.

### 3.1.10 PHOENICS - ANSYS CFX Comparison on horizontal and inclined pipe

Initially the CFD work by Godbole [11, 115, 116] was carried out using Phoenics and later changed over to ANSYS CFX. A comparison study was carried out by modelling a 5 m long DN 439 pipe both horizontal and at an incline of $15^{\circ}$ to the horizontal (close to $1 / 4$ gradient). The initial water temperature was $20^{\circ} \mathrm{C}$ and the pipe temperature remained at $10^{\circ} \mathrm{C}$ for the duration (approximating a soil with high diffusivity at that temperature).

The following figures have been copied from Godbole [11, 115, 116] and suffer from the limited resolution in that publication. They view the central section at 5 hours (typical of the start of the leak test) and 10 hours (the last figures recorded). The first two figures were for horizontal pipe and the second two for the inclined pipe.


Figure 3-38 - Phoenics - ANSYS CFX Comparison for DN440 at 5 hours - Horizontal
At five hours both show evidence of thermal convection currents flowing down the inside of the pipe surface. On the left one there appeared to be better resolution of the upper half. The patterns of the lower half were quite different.


Figure 3-39 - Phoenics - ANSYS CFX Comparison for DN440 at 10 hours - Horizontal
The 10 hour patterns have become markedly different with the left showing almost uniform thermal gradients across the width at each level and the right emphasising the two sides of the pipe.

For these two comparison figures there is a distinct difference between the Phoenics (left) and ANSYS CFX (right). The two colour scales differ visually in that around 40\% of the Phoenics scale has red to yellow while for ANSYS it is only around 30\%. This has the effect of changing the colour appearance of the two sides with red to orange dominating the left and greens more prominent on the right.


Figure 3-40 - Phoenics - ANSYS CFX Comparison for DN440 at 5 hours - Inclined $15^{\circ}$
For the above inclined Figure 3-40 at 5 hours there is no comparison. The longitudinal convection currents have been mixed with the circumferential.


Figure 3-41 - Phoenics - ANSYS CFX Comparison for DN440 at 10 hours - Inclined $15^{\circ}$.

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Only for the 10 hour version do the figures for the respective software packages bear any vague similarity. According to Godbole, the meshes used for the two different CFD packages were similar. This significant difference between results using different packages was only identified at a late stage in the current study and needs to be investigated in subsequent research. The left side of Figure 3-41 appears to be the same as Figure 3-27 with the same figure eight central section.

The use of discrete colours to represent a range of temperatures has distorted the appearances of the above four figures. Much later plots using ANSYS CFX had a continuous colour scale as in the following Figure 3-42.


Figure 3-42 - ANSYS CFX plot of early stage in response to rapid temperature rise.
The figure showed the central portion of the pipe at the original undisturbed temperature and the water in contact with the pipe at a uniform colour of the constant temperature pipe. The temperature scale only covered 2.8 degrees and had a distinct outer annular region while only narrow in appearance occupied almost $30 \%$ of the cross section area. The following Figure $3-43$ showed a later stage.


Figure 3-43 - ANSYS CFX plot of pipe exposed to sudden temperature rise after 20 minutes but appears vaguely similar to that in the PHOENICS Figure 3-38 at 5 hours.

The plotted temperature range was only 0.45 degrees demonstrating the high resolution of the ANSYS CFX software.

### 3.1.11 CFD Conclusions

The data generated by the CFD study appeared to be useful for the current study on acoustic propagation with a thermal profile, however the data did not include numerical values of central vertical temperature changes. Experimental work intended to use internal temperature probes inside pipes to provide such data. With the PHOENICS thermal gradients extending laterally and with little evidence of lateral temperature changes, central vertical probes were envisaged as being sufficient to predict effects of the gradients on acoustic velocity.

Hydrotest Uncertainty - CFD results confirmed by field results demonstrated that external pipewall temperature measurements have characteristics opposite to the average internal water temperature reflected in the pressure. The scaling equations developed showed the bulk water temperature changes with time for different pipe diameters and soil types that can be used to predict expected pressure changes during the leak test. These changes were opposite to the external pipewall measurements. Scaling equations were needed for the external pipewall measurement errors over time. This was not adequately addressed during the CFD study and needed further research.

The CFD extermal pipewall predictions were dependent on the location of the sensor and whether the internal water temperature was rising or falling. These predictions provided the error or uncertainty in the external pipewall measurements over time and provided guidance for comparison with the uncertainty of acoustic temperature measurements.

The CFD progressive figures showed the development of thermal layering over time and although only plotted for a time period of 48 hours for DN 250 pipe provided guidance for its continuation for longer periods such as during thermal stabilisation between filling and pressure testing. Whether that assumption of continuation was correct needs further research.

## CHAPTER 4 AIR SOLUTION RATE AND BUBBLE SHAPE IN HORIZONTAL CYLINDERS

Acoustic velocity results for a number of buried DN300 test sections showed an exponential like rise which appeared to correspond to Chappuis' [77] solution rate curve. As mentioned in a previous chapter, Richardson et al. [80] and Chappuis [77] only carried out solution rate experiments on vertical axis cylinders but not horizontal. Houghton et al. [85] and Krieger et al. [87] only addressed the final stages of spherical bubble solution and diffusion. All of the literature reported solution rate experiments were performed at atmospheric pressure which does not apply to pipelines.

This chapter provides the solution rate experiment results, bubble experiments and then computer modelling of the bubble shape and its variation with surface tension, pipe radius and contact angle.

NOTE: With the exception of those noted as from De Gennes et al. [127], all equations in this chapter were developed by the author. All experimental work and analysis was also carried out by the author.

### 4.1 AIR SOLUTION RATE EXPERIMENTS

A number of different setups were used depending on the location, pipe or tank size and material, available instruments with data loggers and whether insulation was used.

### 4.1.1 Purpose of air solution rate experiments

The literature survey identified a general lack of research on the rate of air solution and none was found applicable to horizontal pipes or tubes with the exception of gas diffusion experiments with small isolated spherical bubbles. This work appeared to be only at atmospheric pressure. To properly address the acoustic anomaly it was considered necessary to be able to predict the solution rate of air inside pipes of different diameters, air content and pressures which due to the lack of such research required detailed study and experimentation to address that problem. Since larger diameter pipes were not available for experimental purposes it was considered beneficial to carry out simulations for such diameters in terms of air bubble shape and variation with diameter. This in turn lead to attempts to model in Microsoft Excel the bubble shape and variation with diameter and air volume. While the overall purpose was to obtain data for air solution rates for horizontal pipes it was found essential to extend the study into bubble shapes and their modelling to achieve a more comprehensive coverage of pipe diameters, air contents and different pressures.

### 4.1.2 General Setup and Instruments.

The following photo Figure $4-1$ shows a DN 180 tank with an air solution rate experiment in progress. It was located in the basement of this author's house and was not insulated. It was previously a high pressure nitrogen gas cylinder and was pressure tested prior to experimental use as were other tanks or pipes. Tanks or vessels for air solution experiments were similarly configured with a pressure manifold used for multiple purposes as detailed below.


Figure 4-1 - DN 180 Tank - Air Solution Rate Experiment - Pressure manifold on left hand side, Thermistor Temperature Sensors centre of Tank - Pressure Transducer far left in line with Tank axis.

The $1 / 4$ " and $1 / 2^{\prime \prime}$ NPT manifold on the left side has valves and fittings for multiple purposes such as:

- water filling
- air injection
- connection to manual high pressure pump for pressurisation
- depressurisation
- connection of pressure transducer (shown far left side in line with tank axis).
- water draining
- measurement of pressure/volume characteristics during pressurisation or depressurisation.
- attachment of pressure gauge for visual pressure indication.

If insulation encased the tank then a high pressure small diameter tube connected the manifold to the tank so that the manifold was outside the insulation for access.

The different coloured wires shown were connected to the pressure transducer (far left side) and to the thermistor temperature sensors located at the top, side and bottom of the centre of the tank under the masking tape. These wires were then connected to the Data Electronics DT85M dataTaker shown in the following photo Figure 4-2 which recorded the data at specified time intervals and then at preselected times during the day emailed the cumulated data using the internal GSM based modem. The dataTaker also supplied power to the 250 bar (25,000 kPa) 4-20 mA based pressure transducer and the power needed to measure the resistance of the thermistors.


Figure 4-2 - Data Logger - dataTaker DT85M - Connections to Pressure Transducer and Thermistor Temperature Sensors. GSM modem aerial in foreground.

Prior to use, the pressure transducer was connected to a Budenberg 380D Dead Weight Tester, DWT, and calibrated while the transducer was connected to the dataTaker. The resultant calibration curve was then programmed into the DT85M and confirmed against the DWT.

The experiment shown in Figure 4-1 continued for 20 months with $194 \%$ air at atmospheric pressure but compressed initially to 233 bar or $23,300 \mathrm{kPa}$. The purpose for using such high air volume was to determine whether the water compressibility and thermal expansion coefficients were affected by dissolved air since the literature avoids the issue. After twenty months almost all the air had dissolved but the pressure continued to very slowly drop indicating that very small residual air volume in the form of a small bubble took a long time to dissolve.

The dataTaker shown in the above photo differed from the DT600 units used for the bulk of the DN 100, DN 150 and DN 300 solution rate experiments. Pressure transducers were changed according to the pressure range required.

The abovementioned experiment of Figure 4-1 was exceptional in the long time duration. The experiments mentioned below were to measure the initial solution rate and were terminated much earlier. The overall setup was similar to the above.

A number of different methods were used to achieve the required combinations of initial air content and pressure:

- partially empty a full tank leaving a known air volume at atmospheric pressure and then pressurise with water with the removed volume measured either by volume of weight.
- pressurise a full tank using compressed air from a diving air tank. The known pressure/volume characteristic and final pressure were used to calculate the injected air volume.
- same as previous but commencing from a known pressure without air.
- combination of some of the above methods.

In some cases it was necessary to repressurise the tank during the solution process if the pressure reduction on solution was greater than expected. This was done with water only.

### 4.1.3 Basic Equations for Air in Water Filled Pipes

AS2885.5:2020 [Australia, 2020 \#357] has an extensive Appendix G (written by this author) titled "Evaluation and measurement of residual air" providing equations for $\mathrm{dV} / \mathrm{dP}$ and its derivation. Missing from those equations was the contribution of the partial molar volume which was addressed in Equation (4.1.5) below together with the relationships between Initial Pressure and Final Pressure used below. Equation for dp/dT is given in Equation (5.3.1).

### 4.1.4 Method of Analysis of Results

Solution rate experiment results for a DN150 horizontal pipe are shown in the following Figure 4-3 which highlights the overall analysis methodology and a few issues associated with obtaining results.


Figure 4-3 - $\quad$ Pressure and Temperature plotted against Time for Air solution in a horizontal DN150 Water filled Pipe.

The black exponential decaying pressure curve has fluctuations which appear to correspond to the pipe wall temperatures shown as dashed lines. The orange decaying curve is the temperature corrected version of the pressure and has been approximated by the light blue curve with a time exponent, or alpha value, of $0.275 /$ day. The air fraction ratio at pressure determines the amplitude of the exponential decay curve which should be the same as the pressure drop on removal of the air. In this example the air fraction ratio at pressure was 0.0099 for an air content of $21 \%$ at atmospheric pressure. Atmospheric pressure air contents represent the air volume divided by the tank or pipe volume with the air volume converted to atmospheric pressure using the ideal gas law or Boyle's law when ignoring temperature effects. For many of the experiments the air content was converted to a fraction at the final pressure at completion of air solution. Generally it was this air fraction at final pressure that was plotted against alpha.

The orange temperature corrected pressure curve followed the light blue exponential curve only until late on the $7^{\text {th }}$ August when the yellow curve flattens as would occur when there was no further
air to dissolve. This in turn implies that the rate of air solution had remained almost constant until the air dissolved. With the residual fluctuations in the orange temperature corrected pressure curve it is difficult to conclude whether all air solution ceased at the sudden change in slope or whether there was a sudden change in solution rate.

Factors and information needed to produce the above typical figure are the following:

- Tank or pipe volume
- Air volume
- Pressure/volume factor without air
- Pressure/temperature factor without air.

This information was required to determine the air content both at atmospheric pressure and at pressure, pressure reduction following air solution and temperature correction to pressure. Because the tank or pipe was relatively short and had welded fittings and caps, theoretical pipe calculations could only be guidelines or approximations. It was necessary to carry out air free pressure/volume measurements either during pressurisation or depressurisation and sometimes both as a check. The most difficult of these factors to determine was the pressure temperature factor which was also dependent on the pressure/volume factor and volume and varied with temperature. The pressure/temperature factor could only be determined by instrumenting a pipe or tank with temperature sensors and measuring it over time since any rapid temperature changes distorted the results. This was often done during the air solution experiments but was unreliable until the air had dissolved as the undissolved air affected the pressure/volume factor and also the pressure/temperature factor. For a number of tanks or pipes such factors were measured and reported in Chapter 5.

To obtain a single alpha value (air solution decay exponential time exponent factor) was time consuming beyond the actual time of the experiment in order to obtain the required information and factors and then the time to analyse the large volume of accumulated data. Before each experiment it was necessary to estimate the air content needed and the initial pressure to ensure that the air would completely dissolve and leave sufficient pressure during a reasonable time period.

Figure 4-3 showed a time period of 19 days of displayed data to achieve one alpha value for one air fraction value at pressure. This time did not include the peripheral activities outlined above nor the time for the sourcing of materials, supervision of fabrication, arranging NDT and then setup with manifold and instrumentation and finally filling, pressurising and air injection. Generally only one solution rate experiment was conducted at a time.

### 4.1.5 DN 100 Experiment with Repressurisation

The following Figure 4-4 for a horizontal DN100 pipe included the black raw pressure curve which showed fluctuations which approximated the measured pipe wall temperatures. Near and almost parallel to the raw pressure curve is the blue temperature corrected pressure curve which has less fluctuation. Besides the pipe wall temperatures was the red "TDR" temperature obtained by attaching a thermistor to the body of the pressure transducer for comparison. It showed greater extent of fluctuations than the pipe wall as expected of a smaller mass.


Figure 4-4 - $\quad$ Pressure and Temperature plotted against Time for Air dissolving in DN100 Water filled Pipe - Horizontal - Repressurised.

The brown continuation of the blue curve showed that had repressurisation not taken place air solution would have continued well past 19 days and probably well beyond one month. Following repressurisation it took only another five to six days for the blue curve to flatten out. This demonstrated that higher pressure accelerated solution rate. Due to the repressurisation there were two decay rates or alpha values for the two different exponential decays. Also the magnitudes of the pressure drop of each decay differed. Since the decay rate changed, the solution rate changed as shown in the following Figure 4-5 in a different format with solution rate on the vertical axis and pressure on the horizontal.


Figure 4-5 - Solution Rate Plot against Pressure for DN100 Pipe before and after repressurisation.

A purely exponential pressure decay resulted in a linear solution rate change with pressure when the solution rate was plotted on a log scale as in the above Figure 4-5. The set of mauve points represents the first exponential decay in Figure 4-4 while the orange, the second after repressurisation. While both curves started at a pressure around 170 barg the start solution rate and slopes differed as the exponential curves differed. What was interesting was the change of the orange points from linear to a more rapidly inclined from around 147 to 144 bar and then almost a vertical drop thereafter. In Figure 4-4 this change occurred when the exponential decay appeared to became flat around the $8^{\text {th }}$ of November. These two subsequent much reduced solution rates could indicate a different solution mechanism or some other controlling factor.

The mauve markers in the above Figure 4-5 appeared to deviate from the trend line around 95 bar with those at higher pressure generally above the trend line. A hand drawn copy of the orange markers' shape appeared to fit this change with similar slope as if the mauve slope was starting to change to the orange slope.

The following Figure $4-6$ showed the percent solution for the two curves but with time as the $X$ axis instead of pressure.


Figure 4-6 - Air Solution Percent plot against Date for DN 100 Water filled horizontal pipe including effect of repressurisation.

This Figure 4-6 showed that at the time of repressurisation $80 \%$ of the air had dissolved and from the previous Figure 4-5 the pressure was around 93 barg. With a DN100 pipe of 4.5 litre volume the residual of the 6.3 litre air volume would be approximately 1.26 litres compressed into 13.5 ml at pressure. In a DN100 pipe the typical width of a bubble trapped at the top of the pipe should be around 23 mm and average height of approximately 4 mm which implies that the length of such bubble would be approximately 150 mm long which is well short of the pipe length of around 600 mm .

This air volume when repressurised and compressed to 170 bar would be around 7.3 ml and the bubble length reduced to around 80 mm with the same width but soon to start reducing in both width and length as it dissolved until the solution rate dropped rapidly at around 147 bar where the residual volume at this pressure was around 1.4 ml which should be an almost round bubble approximately 20 mm in diameter and then rapidly reducing in diameter. The slope change in the orange data points in Figure 4-5 appeared to be the transition from a uniform width bubble to an oval then circular bubble with the almost vertical part of the curve as the circular bubble contracted in diameter and surface tension forces increased its resistance to solution.

The decision to repressurise at 95 bar was unrelated to $80 \%$ air solution and purely coincidental. However during solution experiments, including the one shown in Figure 4-3, solution appeared to stop at or near 80\% for unknown reasons. Initially this was thought to be somehow related to dissolved oxygen content converting to rust since the magnetite form of rust was found in some experiments and the water of blackish colour. Based on the discussion in the previous paragraph it could represent a change in the solution rate mechanism relating to the air bubble shape when the surface area reached an estimated 80 mm long and 23 mm wide with a length/width ratio of 3.5.

### 4.1.6 Vertical Orientation of DN 100 and DN 25 cylinders

The DN 100 cylinder used in Figure 4-6 in its polystyrene cocoon was subsequently oriented in the vertical direction for the following measurements also with high air content. There was a break in data for a period of 1.5 days. The temperature corrected pressure (red heavy line) shows initially a more rapid drop followed by an almost linear but steady drop.


Figure 4-7- Pressure and Temperature plotted against Time for Vertical DN100 Water filled Pipe with large air content.

The location of the different temperature sensors is more easily understood by referring to the following Figure 4-8.


Figure 4-8 - DN 100 Vertical Pipe Temperature Sensor Locations.
Five pipe wall temperature sensors were installed at the top, bottom and three locations up the side of the pipe designated "lower", "centre" and "upper". Prior to welding the cap to the cylinder, the variation in internal cap surface area was measured by upturning and supporting the cap. Then known volumes of water were injected into the cap and the water diameter measured. This was done so that air bubble surface area could be calculated from known trapped air volume when the tank was vertical. The following figure showed the solution rate calculated from this pressure decay curve.


Figure 4-9 - Solution rate and Air Bubble Area plotted against Pressure for Vertical DN100 pipe Water filled. Blue markers - Bubble Area, Red markers - Solution Rate.

The blue markers with their down left diagonal trend in Figure 4-9 represent the bubble area with axis on the right covering only a very small range from 48.7 to $48.5 \mathrm{~cm}^{2}$ which is essentially constant even though the pressure had dropped over 10 bar. The red markers represent the highly scattered
estimates of solution rate. Although there is an initial slope (shown on the far right with trend line) the data is essentially of constant solution rate (left vertical axis).

Such small area change of less than $5 \%$ for 10 bar pressure change indicates the significant difference between a vertical and horizontal pipe. For areas of this size, the bubble diameter is just below 80 mm which is close to the maximum internal diameter of the DN100 weld cap and was hardly changing with air solution. In a horizontal pipe a similar air volume would be represented by a bubble around 23 mm wide and extending the full pipe length of 400 mm with the bubble length contracting as air was absorbed. The surface area in a horizontal pipe for the same air volume would be double that of the vertical so that initial solution rate should be higher in the horizontal as evidenced by the difference between the above figure initial rate around $40 \mathrm{ml} /$ hour compared with the horizontal one in Figure 4-5 where solution rates were initially around $100 \mathrm{ml} / \mathrm{hour}$.

Solution rate data scatter was a consequence of the difficulty of fully correcting the pressure for average water temperatures as can be seen by the slight ripple in the temperature corrected pressure trace in Figure 4-7. Differences in the five pipe wall temperature measurements can be seen in Figure 4-10 below from the start of the experiment.


Figure 4-10 - Pressure plotted against Pipe wall Temperature for Vertical Water filled DN100 Pipe during Air Solution.

While overall characteristics were similar, there were shape differences in the peaks on the right hand side for temperatures between 23 and 23.7 C and close to 176 barg. As temperatures changed up and down, convection currents reversed direction and produced differences between sensors. At the change in direction of convection currents, correlation with pressure was more difficult to predict.

Reviewing one experiment where tubes of identical dimensions were in the horizontal and vertical orientation simultaneously and with an air content of around $400 \%$. Such high air content was achieved by filling the 347 ml steel tubes of 27.5 mm ID and approximate length of 585 mm and then removing 7 ml of water and then pressurising up to around 160 barg for the vertical and 148 barg for the horizontal tubes with air volumes of $445 \%$ and $406 \%$ respectively. The results are shown in the following Figure 4-11.


Figure 4-11 - Comparison between horizontal and vertical air solution caused pressure drops in DN 25 steel pipe.

With almost the same starting air volumes and pressures the pressure decays are distinctly different with air solution in the vertical tube much slower than in the horizontal as would be expected from the different bubble areas. At pressure the air volumes were compressed to around 10 ml which in the vertical tube would fill the top of the tube of cross sectional area $594 \mathrm{~mm}^{2}$ to a depth of around 16 mm and which would not change in surface area until almost all dissolved. In contrast the horizontal tube would have a bubble width of around 14.7 mm and depth around 4 mm with the bubble extending for around 173 mm or $30 \%$ of the tube length with a surface area $2543 \mathrm{~mm}^{2}$ or 4.3 times that of the vertical area. The increased area accounted for the higher solution rate in the horizontal tube indicated by the faster pressure drop.

Adeney [78, 79] had postulated that the decay constant for air solution was directly dependent on the air/water interface area and inversely dependent on the water volume. The above figure confirms the area factor for identical water volumes. Other experiments were needed to check the water volume for the same interface area.

### 4.1.7 Experimental Results

The following Figure 4-12 showed the variation of alpha (exponential exponent time factor) with experimental data with values of alpha in units of /day for a range of internal diameters mostly from 25.4 to 38.5 mm with general trending of the alpha value with the air fraction with both scales logarithmic. Generally the air fraction was expressed as the air volume ratio at atmospheric pressure then reduced to the air ratio at the final pressure when all air was dissolved. This involved multiplying the air volume ratio by atmospheric pressure divided by the final pressure with both pressures in absolute units of pressure. If pressure was in units of bara (bar absolute) then the air ratio at pressure was approximately the air volume ratio divided by the final pressure in bara.

A number of experimental results were not included in Figure 4-12 below because of such issues as poor resolution, high temperature based fluctuations, non-exponential like pressure decay and
incomplete data. Part of the problem was that the solution rate parameters and methodology was a work in progress with experiments needed from which to learn how to conduct such experiments. Only after the consolidation of results and determining of the controlling factors could a useful series of experiments be devised and conducted.


Figure 4-12 - $\quad$ Plot of Alpha (exponential exponent time factor) against Volume Fraction at Final Pressure with Pressure in bar.

Figure 4-12 relied on the initial pressure decay during air solution with the alpha value as the time factor in the exponential expression. The $X$ axis was the air fraction at final pressure on complete solution obtained using the following equation:

$$
\begin{equation*}
\text { Volume fraction }=\frac{V_{\text {air }}}{V} \frac{P_{0}}{\left(P_{f}+P_{0}\right)} \tag{4.1.1}
\end{equation*}
$$

The equation for alpha including pressure (gauge) was given in the following equation with respect to time, t :

$$
\begin{equation*}
P=P_{i}-\frac{V_{a i r} P_{0}}{\left(P_{i}+P_{0}\right)} \frac{d P}{d V}\left(1-e^{-\alpha t}\right) \tag{4.1.2}
\end{equation*}
$$

or

$$
\begin{equation*}
P=P_{i}-\left(P_{i}-P_{f}\right)\left(1-e^{-\alpha t}\right) \tag{4.1.3}
\end{equation*}
$$

The pressure drop due to air solution was the direct conversion of the air volume at the initial pressure $P_{i}$ into an equivalent volume which was then back converted to pressure using the air free $\mathrm{dP} / \mathrm{dV}$ factor as in the following equation.

$$
\begin{equation*}
\frac{V_{\text {air }} P_{0}}{\left(P_{i}+P_{0}\right)} \frac{d P}{d V}=P_{i}-P_{f} \tag{4.1.4}
\end{equation*}
$$

Where

| $V_{\text {air }}$ | air volume at reference atmospheric pressure $P_{0}$ (in absolute units). |
| :--- | :--- |
| V | pipe or tank volume. |
| $\mathrm{P}_{\mathrm{i}}$ | initial pressure (in gauge units). |
| $\mathrm{P}_{\mathrm{f}}$ | final pressure after complete air solution (in gauge units). |
| $\mathrm{dP} / \mathrm{dV}$ | normal air free pressure volume factor which in cases of large dissolved air volumes <br> will change slightly as air dissolved to account for and include the molar volume of |
|  | dissolved air. |

A more accurate version of the above equation for $P$ needed to include the volume of dissolved air using the partial molar volume factor $f_{s}$ as in the following version of the equation:

$$
\begin{equation*}
P=P_{i}-V_{a i r}\left(\frac{P_{0}}{\left(P_{i}+P_{0}\right)}-f_{s}\right) \frac{d P}{d V}\left(1-e^{-\alpha t}\right) \tag{4.1.5}
\end{equation*}
$$

This reduced the pressure drop due to the product of $\mathrm{V}_{\text {air }}$ and $\mathrm{f}_{\mathrm{s}}$ times the pressure volume factor and was only relevant for large relative air volumes causing significant pressure drops.

### 4.1.8 Diameter Scaling

Figure 4-12 mostly covered pipe diameters from 25.4 to 38.5 mm . Experiments carried out on larger diameters did not fit the relatively tight pattern of Figure 4-12. The combined results were displayed in the following Figure 4-13 up to DN 300 plus an estimate for DN 900.


Figure 4-13 - $\quad$ Air solution rate variation of Alpha for different pipe diameters with their trend lines. DN900 data is a provisional estimate and not based on solution rate experiments.

Table 4-1 was based on the diameters in the above Figure 4-13 where air fractions at pressure were around 0.00026 or 0.0003 . The table included estimates of average cross sectional areas and bubble types. The bubble width scaling developed below was used to determine the maximum air bubble width and then the estimated bubble length and type.

Table 4-1 - Diameter variation of Bubble cross sectional Area, average Height, Length and Type for 0.0003 Air Fraction at Final Pressure.

| Table - Diameter variation of Bubble cross sectional Areas, Length and Type for 0.0003 Air |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| Fraction at Final Pressure. |  |  |  |  |  |
| Diameter <br> $(\mathrm{mm})$ | Pipe cross <br> sectional <br> area (mm ${ }^{2}$ ) | At pressure <br> air cross <br> sectional <br> area (mm $\left.{ }^{2}\right)$ | Maximum <br> air bubble <br> width <br> $(\mathrm{mm})$ | Bubble <br> length (mm) <br> per lineal <br> metre | Bubble type |
| 25 | 491 | 0.127 | 12 | 2.8 | Circular bubble |
| 38 | 1134 | 0.295 | 15 | 5.2 | Circular bubble |
| 146 | 16741 | 4.35 | 26 | 44 | Oval shaped |
| 308 | 74506 | 19.4 | 33 | 154 | Full width partial |

The 308 mm diameter pipe had a full width bubble for approximately one sixth of the length per metre. For the 146 mm diameter pipe the bubble was almost full width but of oval shape while the smallest two diameters were small circular shaped bubbles. Hence having the same air fraction did not represent similar conditions and consequently the significant variation in alpha with diameter.

Plotting the alpha exponent on the vertical axis and the bubble length on the horizontal axis showed in Figure 4-14 that alpha values were almost directly related to bubble length within a 3 order of magnitude range in bubble length.


Figure 4-14 - Variation of Alpha with average bubble Length for diameters from 27.5 to 886 mm.

In the above Figure 4-14 the bubble width has been based on the previously found cube root scaling with diameter (refer to subsequent section) for water drops on paraffin which was similar to air bubbles at the top of a pipe. The air fraction allowed a bubble volume to be estimated. Using a typical bubble height of 4 mm and bubble width variation with diameter determined bubble lengths which were calculated for a nominal pipe length of one metre. Bubble lengths for alpha values of 0.3 mostly exceeded this pipe length which would result in the bubbles becoming wider once they reached the pipe length.

Bubble widths for elongated bubbles varied from 45 mm for the DN900 pipe to 14 mm for the DN 27.5 pipe, a width range of $3: 1$ for a diameter range of $32: 1$. Once bubble lengths reduced to twice these widths the bubbles contracted in both directions into initially oval shapes and eventually circular shapes which would apply for alpha values exceeding 3 for the smaller bubble lengths. Hence bubbles can be grouped into 3 regions:
a) Full length bubbles - increasing in width with increasing air fraction.
b) Partial length bubbles - changing in length with air fraction but with constant width bubbles.
c) Oval then circular bubbles changing in diameter as the air dissolved and the air fraction decreased.

The following Figure 4-15 used these three regions with the vertical axis based on the inverse bubble area (and not alpha) while the horizontal axis was the usual air fraction at pressure.


Figure 4-15 - Plot of inverse bubble area against air/pipe volume ratio at pressure showing similarity to Alpha/air fraction plots with diameter.

The three phases a), b), c) were highlighted by the red text and the slowly rising dashed diagonal lines. During all the solution experiments, no consideration was given to the impact of bubble length. The above figure assumed one metre length however the 308 mm tube was a propane gas bottle on its side which was well less than a metre while most of the small diameter tubes were of the order of 600 mm long, the DN100 around 800 mm , the DN150 around 1000 mm long and the DN300 around 400 mm long. Hence the "full length" line is artificial in that it is based on an assumed 1000 mm length
and should be addressed on a pipe diameter-length combination. Further refinement of the bubble surface areas and correction for experimental pipe lengths may modify this graph.

Almost all the data in Figure 4-13 lay between air fractions of 0.0001 and 0.02 which in Figure 4-15 represented the green and blue kinked lines of 27.5 and 38.8 mm diameter. There was no kink in the trend line of Figure $4-13$. The kink in Figure $4-15$ represented the change from circular to constant width bubbles. As will be demonstrated later in this Chapter with the bubble shape modelling, there was more of a gradual transition from circular to oval then increase in oval size until the constant bubble width was reached and then the bubble extended in length. Hence no abrupt kink was likely.

Figure 4-15 needed refinement requiring further detailed work and was missing larger diameter data on air solution. The Pipeline Industry and this document needs usable guidelines to estimate the solution rates for air at test pressure which will be estimated in the following subsection.

### 4.1.9 Practical Diameter Scaling for Air Solution Rates.

The following Figure 4-16 plotted the variation of alpha with diameter for an estimated air fraction value of 0.00026 or 0.0003 .


Figure 4-16 - Variation of Alpha with Pipe Diameter up to DN 300.
Trend line exponent in Figure 4-16 was 0.87 . Bubble width experiments established that the bubble area was almost linearly related to the bubble volume with a power law trend line exponent of 0.87 . Hence 0.9 was adopted as the diameter exponent consistent with the above figure and the bubble experiment results. In the following Figure 4-17 the diameter has been factored into the value of alpha with the air fraction at final pressure. The reference diameter was 38.8 mm and the pipe diameter ratio raised to the power -0.9.


Figure 4-17 - Alpha variation with Air Fraction at Final Pressure with Diameter scaled to reference diameter of 38.8 mm .

This figure was not as useful as one based on Air Fraction at Initial Pressure which the following Figure 4-18 showed. The resultant trend line differed and the $\mathrm{R}^{\wedge 2}$ value was not quite as high.


Figure 4-18 - Alpha Variation with Air Fraction at Initial Pressure with Diameter scaled to reference Diameter of 38.8 mm .

The trend line in Figure 4-18 had the following empirical form once the diameter relationship was added:

$$
\begin{equation*}
\alpha=0.018\left(\frac{\text { Reference Diameter }}{\text { Diameter }}\right)^{0.9} \frac{1}{\left(\text { Air }_{\text {fraction }}\right)^{0.72}} \tag{4.1.6}
\end{equation*}
$$

Airfraction was given by the following equation:

$$
\begin{align*}
\text { Air }_{\text {fraction }}= & \frac{\text { Air_volume } \times P_{0}}{\left(P_{i}+P_{0}\right) \times \text { Pipe_volume }} \\
& =\frac{V_{\text {air }} P_{0}}{V\left(P_{i}+P_{0}\right)} \tag{4.1.7}
\end{align*}
$$

Where Bubble_volume was at pressure Pi (gauge).
Combining Equations (4.1.7) and (4.1.8) and substituting 38.8 mm for the Reference Diameter resulted in the basic empirical equation at the initial pressure $\mathrm{P}_{\mathrm{i}}$ :

$$
\begin{equation*}
\alpha=\frac{0.49}{(\operatorname{Diameter}(\mathrm{~mm}))^{0.9}}\left(\frac{V\left(P_{i}+P_{0}\right)}{V_{\text {air }} P_{0}}\right)^{0.72} \tag{4.1.8}
\end{equation*}
$$

This equation or value for alpha can be substituted into the time equations for pressure (4.1.2), (4.1.3) or (4.1.5) to give the pressure variation over time.

While the solution rate experiments were generally conducted and compared using the final pressure, the initial pressure was considered as a more practical value to use. The above equations allowdc for both to be used as preferred.

### 4.2 BUBBLE SHAPE EXPERIMENTS

The previous section has presented the results from air solution rate experiments and has hinted that the bubble surface area somehow controlled the rate as evidenced by the difference between vertical and horizontal pipes. Mention was made of expected bubble widths for particular pipe diameters. In this section, a brief look at surface tension will be followed by experiments initially into bubble shapes and then the variation of width with pipe diameter for horizontal pipes only. This background will then form the basis for the final section modelling the bubble shapes.

### 4.2.1 Basic Surface Tension Equation - Young-Laplace

The governing equation which determines bubble shape is the Young Laplace equation (De Gennes et al.,[127]) written as:

$$
\begin{equation*}
\left(\frac{1}{R_{1}}+\frac{1}{R_{2}}\right)=-\frac{\rho g h}{\gamma} \tag{4.2.1}
\end{equation*}
$$

or

$$
\begin{equation*}
\gamma\left(\frac{1}{R_{1}}+\frac{1}{R_{2}}\right)=-\rho g h \tag{4.2.2}
\end{equation*}
$$

where:
$R_{1} \& R_{2} \quad$ orthogonal radii of curvature of the bubble surface
$\rho \quad$ water density
g gravitationual constant
$\mathrm{h} \quad$ vertical height of the point on the bubble where the radii apply and has zero value when both radii are infinite (the surface is flat).

Y Surface Tension which for water/air interfaces is $0.073 \mathrm{~N} / \mathrm{m}$ at $20^{\circ} \mathrm{C}$ and varies only slightly with temperature.

The expression $\rho g h$ represents pressure changing with height so that the curvature of the bubble surface is determined by the height above a datum.

The right hand side of the first equation but without the height, $h$, appears often in surface tension equations and is given as the square of the constant, K, by:

$$
\begin{equation*}
K^{2}=\frac{\rho g}{\gamma} \tag{4.2.3}
\end{equation*}
$$

The inverse of K has dimensions of length and is referred to (De Gennes et al.,[127]) as the capillary length, $\mathrm{K}^{-1}$, which for water/air interfaces at ambient temperatures has a value of 2.7 mm . It is often accompanied by factors of $\sqrt{2}$ or 2 resulting in values of 3.9 and 5.5 mm respectively.

### 4.2.2 $\quad$ Air-Water surface tension contact angle experiments

Bubble contact angle is related to surface tension and is an important factor for determining bubble shape. Such contact relates to the surface material, water and air. Failing reliable data on contact angles it was found valuable to carry out experiments to determine such contact angles for the surface materials used in bubble experiments. The following table summarised such simple experiments with water bubbles on the respective flat surfaces. In the case of paraffin the contact angle should be around 105 deg.

Table 4-2 - $\quad$ Surface Tension Contact Angles - Estimated from Bubble Experiments

| Estimated Surface Tension Contact Angles from Bubble Experiments |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| Material | Average <br> diameter <br> $(\mathrm{mm})$ | Area <br> $\left(\mathrm{mm}^{2}\right)$ | Volume <br> $(\mathrm{ml})$ | Average <br> height <br> $(\mathrm{mm})$ | Contact <br> angle <br> $(\mathrm{deg})$ |
| Acrylic sheet | 65 | 3318 | 10 | 3.0 | 65.5 |
| Polycarbonate just removed <br> from protective sheets | 61.25 | 2946 | 10 | 3.4 | 75.1 |
| Rusty steel plate with mill |  |  |  |  |  |
| scale | 49 | 1886 | 5 | 2.65 | 56.9 |
| Worse rusty steel plate with |  |  |  |  |  |
| mill scale |  |  |  |  |  |

The equation used to calculate the contact angle from the height (De Gennes et al., [127]) was:

$$
\begin{equation*}
H=\sqrt{\frac{2 \gamma}{\rho g}(1-\cos (\alpha))} \tag{4.2.4}
\end{equation*}
$$

From this equation the angle, $\alpha$, (not to be confused with the solution rate decay factor) can be found from:

$$
\begin{equation*}
\alpha=\operatorname{acos}\left(1-\frac{\rho g}{2 \gamma} H^{2}\right) \tag{4.2.5}
\end{equation*}
$$

Average of the plastics was 70 degrees and rusty steel close to 60 degrees. These calculations are approximate as they imply that the height is uniform over a circle of the average diameter given however the outer edges are rounded and height is likely to be slightly larger than the simple estimate. While the bubbles are assumed to be circular, most were elliptical with irregularities due to slight surface irregularities or presence of contaminants. Surfaces were washed in detergent and then rinsed with the exception of the polycarbonate which simply had the protective film removed.

The contact angle is the same regardless of whether the bubble is on the underside of the top of the pipe or at the bottom of a horizontal partial cylinder. The observed difference relates to what is inside the bubble or drop. In the case of an air bubble under an upper curved surface, air is inside the bubble and the contact angle is made by the surrounding water in contact with both the surface and the air. From the above table for acrylic the contact angle should be around 66 degrees which would result in an end view of the air bubble showing the edges wrapped over because the contact angle refers to the edge of the water and not the air as in the following sketch for the pipe cross section.


Figure 4-19 - Geometry of Air Bubble on top of Water in a Horizontal Pipe - Cross Section.
For a longitudinal section through the pipe axis the following Figure 4-20 results.


Figure 4-20 - Geometry of Air Bubble on top of Water in a Horizontal Pipe - Longitudinal Section

These figures also show the orientation of the $\mathrm{X}, \mathrm{Y}$, and Z axes to be used in this document for air bubbles.

For a water drop or bubble on top of a horizontal cylindrical trough the contact angle was still around 70 degrees but since that angle is for the water and surface the bubble shape will be very different and will appear to want to spread out on the surface with the height of the bubble much reduced. It was for this reason that paraffin was used on the plastic surface with its contact angle of 105 degrees which made the water bubble look similar to the air bubble in Figure 4-19 with the contact angle of 75 degrees but in the opposite orientation and with water as the drop or bubble.

The above equation for bubble height and contact angle resulted in two times the capillary length or 5.5 mm when alpha was zero and square root of two times the capillary length when alpha was 90 degrees or 3.9 mm as indicated above but only for a flat surface.

### 4.2.3 Bubble Shape Photos

The following photo shows the end view shape of the air bubble extending the whole length of a water filled acrylic pipe.


Figure 4-21 - End view photo with 5mm grid showing air bubble shape in acrylic cylinder filled with water.

This photo differed from the above cross section Figure 4-19 in that the figure was for a very small contact angle while the photo showed a larger contact angle but less than 90 degrees. The view was partly obscured by the curvature at the left hand end of the bubble as can be seen in the following top view in Figure 4-22 which is the same end as in Figure 4-21 above.


Figure 4-22 - Photo from above of acrylic tube with flat ends showing constant width air bubble and curvature at the left hand end. Previous figure is taken of the left hand end.

The bubble width can be seen to be constant along the length with the sole exception of the ends. Any non-constant width was an indication of slight pipe axis inclination.

### 4.2.4 Measured Bubble Shapes

Bubbles photographed inside a clear plastic pipe were previously measured to give an indication of the variation of width with length. An attempt was made to determine whether the shape of the bubble as viewed from above could approximate an ellipse and whether the longer bubbles were a combination of half ellipses at each end and a parallel section between. Photos taken of the bubbles were used and the bubble outline drawn as best as could be estimated. These were then manually digitised and displayed in red on Excel charts. Calculated ovals were then inserted on the chart and adjusted to fit the bubble outline as best as possible but formed of two half ellipses with the upper orange and lower grey. The dimensions shown were for the photo in mm and not the measured dimensions. Dimensions were not relevant for the plan view shape comparison.

For the shortest bubble measured, there was a slight difference as shown in the following Figure 4-23 with the ellipse width less than the bubble based on the same length and only a reasonable fit.


Figure 4-23 - Measured bubble 28 mm long and 18 mm wide compared with ellipse approximation - reasonable fit.

With a slightly longer bubble of 5.5 cm as in the following Figure $4-24$ it continued to track an elliptical shape.


Figure 4-24- Measured bubble 55 mm long and 22 mm wide compared with ellipse approximation - good fit.

The following Figure $4-25$ showed the discrepancy for 8.8 cm length which had a poor fit.


Figure 4-25 - Measured bubble 88 mm long and 21 mm wide compared with ellipse approximation - poor fit.

Using an ellipse based on a bubble of length 4.4 cm and width 2.1 cm and inserting a rectangular section in the centre resulted in the following Figure 4-26 which approximated the shape in 3 out of 4 corners and confirmed that an elliptical shape with length of approximately twice the width was a good approximation to the bubble shape.


Figure 4-26 - Measured bubble 135 mm long and 21 mm wide compared with two half ellipses and rectangle between - good fit.

### 4.2.5 Measured Bubble Shape Conclusion

Viewed from above, the bubble shape appeared to be elliptical for length to width ratios up to 2.5 after which it was necessary to insert a rectangular section between two half ellipses. For the smallest
ratio of 1.5 the fit was reasonable but not good. Once the width reached 2.1 to 2.2 cm it remained the same for all subsequent lengths observed.

There appeared to be some mechanism controlling the width of the bubble. The above photo analysis was based on only one pipe diameter so the effect of diameter change on bubble width needed to be determined.

### 4.2.6 Bubble Shape variation with Pipe Diameter

Experiments on tubes or curved Perspex and polycarbonate sheets supported by curved end plates approximated a range of pipe diameters from 5 mm to 1 metre. These surfaces were immersed in water and increasing volumes of air injected under to approximate air bubbles inside water filled horizontal pipes. Experiments also took place with water drops on top of horizontal cylindrical part cylinders. Some of the water on cylinder experiments had paraffin wax coating on the surface to better approximate the air pockets on top of pipes as mentioned above. The constant widths were plotted in the following Figure 4-27.


Figure 4-27 - Air Bubble Width variation with Pipe Diameter - Bubbles on top of water under curved clear Plastic or in small cylinders.

The upper blue curve was for the uncoated air pocket experiments while the lower red curve was for the paraffin lined water drop experiments. The power trend line exponents were similar with 0.34 for the upper and 0.32 for the lower and the initial constants similar with the upper 4.75 and the lower 4.69.

What was observed in these experiments was that an initially circular bubble (as viewed from the top) grew in diameter and then started to extend axially with constant width until the bubble reached the end supports when it started to enlarge in width. This constant width in the above figure satisfies a power law relationship with diameter of exponent 0.32 to 0.34 or approximately $1 / 3$. The relationship was consistent over two orders of magnitude of pipe diameter.

The equation relating this width ( $2 x_{0}$ ) to the pipe internal diameter ( $2 R$ ) was as follows based on the above graph and using $1 / 3$ instead of the measured exponents:

$$
\begin{equation*}
2 x_{0} \cong 4.75(2 R)^{\frac{1}{3}} \tag{4.2.6}
\end{equation*}
$$

or

$$
\begin{equation*}
x_{0} \cong 3 R^{\frac{1}{3}} \tag{4.2.7}
\end{equation*}
$$

or

$$
\begin{equation*}
R \cong\left(\frac{x_{0}}{3}\right)^{3} \tag{4.2.8}
\end{equation*}
$$

The above figure and equations only summarised the constant bubble width but did not provide other bubble information. The following Figure 4-28 was an example for DN102 paraffin lined trough with water drop of changing volume showing changes in both length and width.


Figure 4-28 - Water drops on DN100 paraffin lined cylindrical troughs - variation of width and length with volume both with linear scales.

The bubble width experiments established that the bubble area was almost linearly related to the bubble volume as in the following Figure 4-29 for water puddles/drops on paraffin lined plastic from DN100 to DN1000. Using a power law trend line resulted in an exponent of 0.85 . For bubbles more that 2 ml in volume a straight line could approximate the bubble surface area/volume data. Although the areas in the above figures were simply the bubble length multiplied by the width and ignored the curvature at the ends, the linear portion of the results provided an estimate of the average bubble height of 3.8 mm which gave a contact angle of close to 90 degrees consistent with that for paraffin.


Figure 4-29 - $\quad$ Summary of rectangular water drop surface area against drop volume for pipe diameters from DN102 to DN1000 for water drops on paraffin lined plastic troughs.

For the DN102 pipe troughs the following Figure 4-30 showed the difference between uncoated plastic and paraffin wax coated surfaces. The areas for the paraffin coated were around $2 / 3$ of the unlined which implied that the bubble height was higher and the contact angle significantly different as expected. Hence bubble widths for unlined would be wider than for paraffin lined. The water on paraffin lining data was used to approximate the contact of air pockets on top of a water filled pipe.


Figure 4-30 - Water Drop surface area plotted against drop volume - comparison of unlined plastic and paraffin lined.

### 4.3 BUBBLE SHAPE MODELLING

The bubble width and area experiments in the previous section provided guidance as to the controlling parameters including surface tension based contact angle and scaling exponents. The solution rate experiments provided an indication of diameter scaling to the exponent -0.9 which was purely empirical without basis and did not bear any relation to the bubble width scaling of 0.33 . The only experimental result close to an exponent of 0.9 was 0.85 for Figure $4-29$ for the rectangular bubble area relative to the bubble or drop volume but only for the initial curved portion before it became linear.

The following outlines modelling in Microsoft Excel of the bubble cross section and then the modelling of the bubble shape as seen in plan view if the pipe was transparent. The ultimate purpose was to find scaling or confirmation of the experimental scaling mentioned above. Other than Equation (4.3.1) provided by DeGennes et al. [127], all the Excel Modelling and necessary equations were developed and carried out by this author.

### 4.3.1 Single Radius of Curvature in Vertical Plane

DeGennes et al. [127] provided an equation solution (4.3.1) below to the problem of the shape of a large bubble or drop in contact with a flat surface satisfying the Young Laplace equation but with one radius infinite. This equation was the only complete solution while the others required numerical solutions.

$$
\begin{equation*}
y-y_{0}=K^{-1} \cosh ^{-1}\left(\frac{2}{K z}\right)-2 K^{-1}\left(1-\frac{K^{2} z^{2}}{4}\right)^{\frac{1}{2}} \tag{4.3.1}
\end{equation*}
$$

Where:
$z \quad$ is the vertical direction
$y \quad$ is the lateral horizontal direction.
$x \quad$ is the longitudinal horizontal direction
The same solution can describe the edge of a large round bubble/drop or the edge of a very long drop as shown in the following Figure 4-31.

### 4.3.2 Two close inclined plates

Bouasse [128] provided a method for numerical solution for the case of two close inclined plates based on Laplace. After many attempts the following figure for a bubble width of 10 mm was generated:


Figure 4-31 - Comparison of single edge bubble with Bouasse's solution for bubble between two parallel but symmetrically inclined plates with pipe internal surface shown in orange.

The red curve was based on Bouasse's method of Laplace example. The grey curve was based on the single wall complete solution given by DeGennes in Equation (4.3.1) which differed slightly in shape from the Bouasse two wall method result. In the above Figure 4-31 the total bubble width was approximately 10 mm (dimensions shown are in metres). The method correctly produced the central bottom curvature for lateral position $\mathrm{y}=0$ and a corresponding vertical z value in this case of approximately 0.45 mm . The orange curve represented the pipe cross section internal surface and was positioned to show a small contact angle. The pipe surface could be moved up or down to suit different contact angles. The curvature of the upper part of the double wall curve was high (small radius) and the effect of changing the contact angle made only a small change in vertical pipe position provided the contact angle was less than 90 degrees.

For the double wall model the Figure 4-31 showed one varying radius of curvature controlling the shape with the second radius of curvature infinite and with no effect on the shape. The sides of the bubble as seen in the figure contact the curved pipe surface below and offset from the top centre of the pipe and depend on the contact angle.

This relatively simple model assumed the bubble extended to infinity in both directions of the pipe axis. A model was needed to terminate the length of the bubble which was where Bouasse's circular bubble model came in. It used two radii of curvature which was essential in resolving the overall bubble shape.

### 4.3.3 Circular bubble

Bouasse [128] provided a method for calculating a circular bubble but based on a different version of the method of Laplace. Such a bubble shape was like a distorted oblate spheroid or squashed sphere which has two radii of curvature both of which are relatively small. The two combined radii for a diameter to match the double wall result above caused the bottom of the bubble to be higher than in the above case and allowed the top of the bubble to contact the centre top of the pipe. This result suggested that the overall bubble shape was controlled by single radius of curvature of the double wall model in the centre of the bubble length (touching both sides) but by double radius of curvature similar to the circular model at the extreme ends of the bubble where it was necessary to contact the top of the pipe at the centre. This contact would be at the same contact angle as the double wall contact.

### 4.3.4 Combined model

Using Excel, an attempt was made to trace the outline on the pipe surface of the bubble while maintaining a constant contact angle. A macro was used to expedite the Goal Seeker operation to determine the vertical bubble angle needed to achieve the constant contact angle with the model including 100 progressive angular steps (later 200 and then 500 ) for one quarter of the bubble shape (since the other quarters were identical in shape). After resolving a few issues and experiencing a few unsuccessful attempts the following resulted for DN100 pipe with 50,70 and 90 degree contact angles with 70 and 90 almost identical.


Figure 4-32 - plan view of ellipse shapes and contact points for different contact angles.
A starting point was needed and chosen as the bubble end with double curvature. The horizontal curvature of the end of an ellipse was used to determine the curvature of the smaller vertical radius of curvature and then the iterative calculation progressed.

Figure 4-32 included an ellipse (dashed) based on 10 mm half width and appeared to approximately match the three modelled curves which confirmed the model's validity as a close approximation to the experimentally observed elliptical bubble shape.

Figure 4-33 following was the attempt at bubble width-pipe diameter scaling which was very similar to the experimental result with little difference between the curves for the different contact angles of $50,70,90$ and 110 degrees.


Figure 4-33 - Variation of bubble width with pipe diameter for different contact angles of 50, 70, 90 and 110 degrees.

Experimental result was:

$$
\begin{equation*}
\text { Width }=4.765 D^{0.34} \tag{4.3.2}
\end{equation*}
$$

Exponents are essentially the same while the initial constant varied slightly. The 90 degree curve was within a factor of 1.06 or $6 \%$ of the experimental while the 50 degree was within 1.16 or $16 \%$. While the above figure only traced the pipe/bubble contact, experimental data was based on the maximum observed width. For contact angles less than 90 degrees the maximum bubble width was larger than the contact width. Hence it appeared that the maximum bubble width was almost independent of the contact angle and close to that for 90 degrees.

For the bubble width experiments under curved plastic sheet there was a parallax observation error when looking down through water then curved plastic sheet of 3 to 6 mm thickness and then trying to determine the air bubble width surrounded by water while using a ruler on the water surface. A 6 to 10\% width error was easily possible.

With the Excel model, input variables were adjusted until the maximum bubble size resulted. As this process took place the almost circular bubble increased in diameter and then started to extend in length and ovalise as shown in the following Figure 4-34. This shape change was similar to observed bubbles when enlarged or in reverse when dissolved. Note the large length change with small input change from 5.7 to 5.77 to 5.77395 values for $R_{2}$. A value of 5.774 would push the right hand edge of the largest bubble past the right hand side of the figure.


Figure 4-34 - Plan view of bubble shape showing width contraction as bubble length reduces based on the model using constant contact angle of 50 degrees around the bubble perimeter for a pipe of 39 mm internal diameter.

Vertical and horizontal scales were the same in Figure 4-34 with a square grid so that circles should appear round as is the case for the smallest input values of $R_{2}$ after which the shapes became approximately ellipsoidal. Note that for the two longest bubbles, the left hand ends are almost identical in shape so that the long bubbles are in effect shorter bubbles with a rectangular insert in the middle as observed in the bubble photo comparisons. As in a previous Figure 4-33, the end shapes slightly differed from ellipsoidal and tended slightly towards circular.

The following equation proposed by this author was a much better approximation to the bubble shape than its more familiar ellipsoidal version with exponent 2 instead of the 2.5 :

$$
\begin{equation*}
\left(\frac{x}{a}\right)^{2.5}+\left(\frac{y}{b}\right)^{2.5}=1 \tag{4.3.3}
\end{equation*}
$$

This was readily seen in the following Figure 4-35 where the modified ellipse using this equation was compared with a conventional ellipse and the second largest bubble shape in the above Figure $4-34$. The bubble shape and the modified ellipse are almost identical whereas the conventional ellipse only matched at the two ends, top and bottom.


Figure 4-35 - Comparison of new bubble perimeter shape model with normal ellipse and modified ellipse.

It was thought that such an equation may be able to be used to estimate initial model seed curvatures as was previously obtained with the ellipse equation.

The curvature, C , for this modified ellipse equation was:

$$
\begin{equation*}
C=\frac{\left|1.5\left(\frac{b^{2}}{a}\right)^{2.5} x^{0.5} y^{0.5}\right|}{\left[y^{3}+\left(\frac{b}{a}\right)^{5} x^{3}\right]^{1.5}} \tag{4.3.4}
\end{equation*}
$$

This equation has zeros in the numerator. At the end of the bubble, y is zero which resulted in zero curvature. At the centre of the bubble $x$ is zero again resulting in zero curvature. This equation was checked in Excel and found to be correct.

For a normal ellipse the curvature equation is given by:

$$
\begin{equation*}
C=\frac{\left|\left(\frac{b^{2}}{a}\right)^{2}\right|}{\left[y^{2}+\left(\frac{b}{a}\right)^{4} x^{2}\right]^{1.5}} \tag{4.3.5}
\end{equation*}
$$

which does not have the numerator problem for $x$ or $y$ equal to zero at the extremities.
The only way around the problem was to seed the calculation with the normal ellipse curvature at the end or side and work from there. The model only tracked the contact of the bubble with the pipe surface and did not plot the 3D shape although it could be extended to do this but only in Matlab. Most
important is the confirmation of the bubble pipe contact shape which has been shown to match the photos and experimental bubble width/pipe diameter scaling. This model can then be used to estimate accurate bubble surface areas and volumes. What hasn't been resolved is the diameter scaling for air solution rates.

### 4.4 DISSOLVED AIR EFFECT ON MIXED PROPERTIES

In section 2.7.3, Greenspan and Tschiegg's [104] measurements of velocity changes resulting from air solution were discussed and Equation (2.7.19) for the effect on velocity from changes in liquid density and bulk modulus is repeated here provided the changes were of the order of $1 \times 10^{-6}$.

$$
\begin{equation*}
a \approx a_{0}\left(1+\frac{\Delta K}{2}-\frac{\Delta \rho}{2}\right) \tag{4.4.1}
\end{equation*}
$$

### 4.4.1 Purpose of DN 180 Tank Experiment

At the beginning of this chapter, Figure 4-1 was a photo of the DN 180 tank air solution experiment for the purpose of trying to determine whether the pipeline based equations for $\mathrm{dP} / \mathrm{dV}$ and/or $\mathrm{dP} / \mathrm{dT}$ could be used to assess changes in bulk modulus and thermal expansion coefficients for large volume of dissolved air. The DN180 tank experiment was not intended to measure solution rate and used agitation by rocking to accelerate initial solution to speed up the process.

### 4.4.2 Method

The tank shown in Figure 4-1 was located in this author's basement to minimise temperature changes. It was not insulated. Tank volume was measured at 14.3 litres and air from a high pressure diving cylinder was used to pressurise it with a resultant air volume of 32 litres estimated as injected (at atmospheric pressure). Thermistors were attached to the external central top and bottom of the horizontal tank and were monitored by the DT85M Data Electronics DataTaker data logger along with the 4-20 mA 250 bar pressure transducer. Before use the pressure transducer was calibrated with a Budenberg 380D dead weight tester over a higher range and the coefficients incorporated into the DT85M software. Following initial solution with the pressure dropping from around 23500 kPa to 15000 kPa , the tank was repressurised after almost three months by water to 25000 kPa to improve the solution rate. The changes in the pressure/temperature curve had been followed over the subsequent 20 months and the final two curves were shown in the following Figure 4-36 together with the air free theoretical curve.

Just prior to tank depressurisation, $\mathrm{dp} / \mathrm{dV}$ values of the tank with fully dissolved air were obtained by pressurising to around $27,000 \mathrm{kP}$ and measuring the volume released to lower the pressure to around $20,000 \mathrm{kPa}$ using scales capable of measuring to 0.01 gm and the pressure transducer readings with resolution of 1 kPa .

### 4.4.3 Results

The dp/dV measurements from around 27,000 to $20,000 \mathrm{kPa}$ with fully dissolved air resulted in an average of 11 values of $121.7 \mathrm{kPa} / \mathrm{gm}$ with standard deviation of 1.6 reflecting the scatter in the
values over a limited pressure range. After depressurisation and dissolved gas released the dp/dV values were again measured over a range from around $27,000 \mathrm{kPa}$ to a few hundred resulting in an average of $120.16 \mathrm{kPa} / \mathrm{gm}$ with standard deviation for 4 measurements of 0.23 . Working at a confidence level of 1 standard deviation the two results overlapped marginally with low confidence. The used water was removed and had black oxide deposits indicative of dissolved oxygen converstion into black magnetite. Tank was refilled and the dp/dV exercise repeated with a value of $119.94 \mathrm{kPa} / \mathrm{g}$ and standard deviation of 0.07 for 3 readings. Again within 1 standard deviation the results overlapped marginally. The conclusion has to be that while it appears the water with dissolved air at pressure has a slightly higher dp/dV value than without such cannot be statistically justified so that the bulk modulus and compressibility of water with and without dissolved air are the same. This is an important conclusion for the evaluation of the $\mathrm{dP} / \mathrm{dT}$ curves in Figure 4-36 in that it eliminates any contribution from bulk modulus or compressibility. The water temperature for the $\mathrm{dp} / \mathrm{dV}$ measurements was around $15.5^{\circ} \mathrm{C}$. Following the above exercise the pressure transducer was verified and found to differ from the dead weight tester over the range of $28,000 \mathrm{kPa}$ by no more than $-18 /+11 \mathrm{kPa}$ with hysteresis resulting in the lower readings on rise and higher readings on fall in pressure. Hence the pressure transducer measurements during the almost two year period of use were reliable. Tank volume was remeasured and confirmed as 14.3 litres.


Figure 4-36- DN 180 Tank with 220\% air dissolved - Comparison of dP/dT values - Measured and Air Free Calculated.

In Figure 4-36 the blue line was obtained in August 2023 of the tank temperature drop from summer to winter in August, the red line obtained in January 2023 of the period from winter to summer and the black dashed line the theoretical based on air free conditions. The blue August 23 line had been shifted up to match the lowest temperature of the red January 23 line whereas the two original
curves met at the upper end prior to the shift. The higher slope of the earlier red curve hinted at higher bulk modulus values and increased dp/dV values which have been rendered incorrect as evidenced by the dp/dV measurements in the previous paragraph. Since the curves were based on the bottom external pipe wall temperature measurement as the proxy for the internal average temperature to avoid the top of pipe fluctuations, the rising red curve and falling blue curve may be a consequence of the difference between the internal average and the bottom of pipe temperatures. in a later Chapter a similar pressure/temperature figure will be shown to indicate the presence of air and was used to estimate the air content. Free air causes the dP/dT curve slope to be reduced below the theoretical. The blue August 23 measured curve was slightly above the black dashed theoretical. The two curves can be made to match by increasing the thermal expansion coefficient by a factor of 1.0185 however the theoretical was calculated using the equations from AS2885.5:2020 after correcting for the numerical errors present since 2002 and identified by this study. These equations are approximations for field use so that such slight difference noted in Figure 4-36 is negligible and shows that with high fully dissolved air content the thermal expansion coefficient has not changed significantly.

### 4.4.4 Conclusions

Equation (4.4.1) related acoustic velocity changes to bulk modulus and density changes. The above measurements of dp/dV confirmed that bulk modulus had not changed measurably with dissolved air. Regarding density changes, dissolved air reduces the combined density which would then increase the velocity since the density contribution in the above equation is negative. Hence the effect of dissolved air was to increase the acoustic velocity by only reducing the density.

As noted in Chapter 2.10.5 with Greenspan and Tschiegg's velocity measurements, they could imply the bulk modulus changing in sign between 0 and $32^{\circ} \mathrm{C}$, however the above $\mathrm{dp} / \mathrm{dV}$ measurements and their implications for bulk modulus negate that possibility especially since the pressure and dissolved air was two orders of magnitude higher than was likely for Greenspan and Tschiegg's measurements. This supports the conclusion that the estimated bulk modulus changes in Chapter 2.10 .5 were in fact due to measurement tolerances and not factual.

It appears from the DN 180 tank experiment that only density reduction with fully dissolved air increases acoustic velocity which further suggests that direct acoustic measurements using Greenspan and Tschiegg [104] methodology or velocimeter is the best approach and can then in turn provide information on partial molar volume of dissolved air at high pressure.

### 4.5 KNOWLEDGE GAPS ADDRESSED

The above studies have provided empirical modelling of quiescent solution rates in horizontal cylinders over a range of diameters and air contents and has thus satisfied an outstanding gap in such knowledge.

These studies lead to diameter based bubble shape experiments and ultimately Excel based modelling which has shown excellent agreement and could provide the basis for an improved modelling of the above current empirical modelling of solution rate and in particular confirm or adjust the empirically based estimated diameter scaling beyond the limited DN 300 experimental support.

### 4.6 CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

Solution rate experiments covered diameters up to DN 300 and provided graphs and empirical equations for estimating the pressure reduction rate as air dissolved at pressure. The same equations can also be used to determine air fraction limits to avoid air solution related pressure drops from interfering with pressure tests. The information is valuable for estimating whether air solution could be interfering with other measurements such as the acoustic velocity anomalies in this document.

The alpha values have generally been based on the initial solution rates which have been the only consistent basis. The study has identified possible regions where different bubble areas applied and could control solution rates. This could be addressed in further studies possibly using some of the existing data. These regions may enable comparisons of results and equations with those of Adeney et al. and Richardson et al. [78, 79, 81] but will then need to address the pipe orientation change from horizontal to vertical.

In the solution experiments there was sometimes a $20 \%$ anomaly in the solution experiments and the presence of magnetite rust with no oxygen in the air released on depressurisation raised the possibility of oxygen being removed through rust as a cause of the $20 \%$ anomaly. While the oxygen had been removed from solution the $20 \%$ anomaly was more likely to have been due to a change in solution rate at $80 \%$ of air solution based on changes in bubble area such as transition from long uniform width to contracting oval shaped bubbles. Figure 4-4, Figure 4-5 and Figure 4-6 seemed to indicate such change but needed confirmation.

Such oxygen based corrosion supports the Industry practice of using chemical oxygen scavengers to remove dissolved oxygen in the fill water but may not be sufficient if there was a large concentration of air and hence oxygen at high points. This suggests the need for ensuring minimal air content during filling of non-internally coated pipe. The acoustic technique could identify such locations for subsequent checking during the life of the pipeline.

For future solution rate experiments, use of a stainless steel pipe or only nitrogen gas in an experiment would reduce the corrosion effect and finally resolve the $20 \%$ anomaly noted above.

The DN 100 horizontal experiment in Figure 4-4 and the DN 150 in Figure 4-3 showed a rapid change in solution rate which was likely due to the change in solution rate based on bubble shape. Once bubbles became very small they approached diffusion measurements. In the intermediate region when the bubble was a fraction of the pipe length, the location of the bubble along the length and the number and distribution of bubbles could have affected solution rates.

The DN 180 tank solution experiment has indicated a significant change in solution rate once most of the air had been dissolved and the air bubble size had reduced to a small oval or circular bubble. No solution rate analysis has been done on this region and needed addressing in regard to future work.

The same DN 180 experiment has indicated no change in bulk modulus and thermal expansion of the water with dissolved air. It pointed to significant acoustic velocity increases resulting from air solution opposite to the normal velocity reduction with free air.

The Excel bubble perimeter model has proved valuable in matching the observed bubble outer shape and the bubble width variation with pipe diameter. It needed conversion into a Matlab program
and then modelling of the complete three dimensional bubble shape. Once this has been done then accurate estimates of bubble volume and surface area would follow enabling better modelling of the solution rate process and possibly replacing the empirical equations and graphs of experimental results with the approximate pipe diameter scaling.

No detailed consideration was given to length of pipe samples during the solution rate experiments. Results need to be based on a standard length or scaled length such as a number of diameters.

While pipe wall temperatures were essential to remove temperature effects from pressures to obtain the solution rates, they have not been incorporated into the solution rate summaries. As air solution is temperature dependent, this would be an important next step but would be much easier to do once a computer model of solution rate had been established. Also such experiments would require a temperture controlled room for an extended period of time to perform such experiments.

Whereas the values estimated above for DN 900 have not been confirmed. Experiments for diameters of DN 600 and DN 900 would resolve the diameter scaling lack of experimental support.

## CHAPTER 5 TEMPERATURES - INTERNAL, EXTERNAL, AMBIENT AND GROUND

Experiments were carried out to examine the relationships between pipe wall and internal temperatures and pressures over a range of pipe diameters.

### 5.1 PURPOSE

The purpose behind these experiments was field verification of the CFD predictions and identification of thermal layering for later assessment of its effect on acoustic velocity and resolution of the acoustic anomaly. These experiments are separated into above and below ground sections. Included with the buried experiments is the tank experiment. Added to the below ground section are details of the diffusivity probe measurements. The last section addresses modelling of ambient temperatures.

### 5.2 METHODOLOGY AND INSTRUMENTATION

Pipes or pressure vessels (tanks) of DN 50, DN 200, DN 400, DN 600 and DN 900 were used with internal probes in all and external pipe wall sensors in most. The internal probe in the DN 50 differed in orientation being axial whereas for the other pipe diameters the orientation was radial with all pipes horizontal.

Multisensor internal temperature probes were designed and manufactured by this author with either direct microcontroller connection or cable connection to originally a DT600 Data Electronics DataTaker then eventually to a microcontroller. The sensors were thermistors because of their small size of approximately 2 mm diameter and fine leads enabling them to be installed in tapered fibreglass rods at equal sensor separation. The main problem was the sealing of the wires passing through a $1^{\prime \prime}$ or $3 / 4$ " NPT steel or brass hexagonal plug or nipple while at the same time retaining water pressure of the order of $20,000 \mathrm{kPa}$ without electrical shorting while maintaining insulation. Different methods were trialled and used.

Initially a long probe with 8 sensors was manufactured for DN 900 pipe with external cable attachment to a DT600 DataTaker data logger which had the capability of connection to such number of sensors and also recording pressure from a pressure transducer and its own internal temperature as a proxy for the ambient. Readout of data from such loggers was via insertion of a USB memory stick subsequently read by computer. Programming was via USB memory stick or by cable connection either USB or Ethernet.

The same probe was used for a DN600 pipe by installing a 1 " pipe extension and fitting on a valve on top of the header. This probe was also recorded by the same data logger.

For the DN200 and DN400 pipe experiments dedicated probes were manufactured and connected to prototype and later manufactured circuit boards including an Analog Devices ADuCM360 24 bit sigma delta analog to digital converter with multi-channel input. Programming of the microcontroller was in C language by this author. Readout was via a special RS232 cable from the microcontroller unit to the USB port of a laptop computer.


Figure 5-1 - DN 200 internal Temperature Probe with Microcontroller Unit active.
Experience with the thermistor sensors found that their accuracy was generally within specification of the order of $+/-0.1^{\circ} \mathrm{C}$ while resolution was better than $0.01^{\circ} \mathrm{C}$.

### 5.2.1 Pressure related Difficulties

For the internal probes, the major difficulty was the high pressure seal of the thermistor cables when passing through the threaded fitting. The brass plug, acetyl insert and pins were machined by the author as shown in Figure 5-2.


Figure 5-2 - Brass 3/4"BSP fitting (left) machined for the Acetyl multi pin assembly (right).
Each of the 9 pins in the assembly on the right hand side of Figure 5-2 consisted of a machine brass member (lower part) of 2.4 mm diameter with shoulder to accept a 2.4 mm O.D. O-Ring with 1 mm I.D. A 1.04 mm diameter copper wire (upper part) was silver soldered into the brass member. Each of the 9 stepped holes in the Acetyl member had to be machined concentrically for a sliding fit of the wire and housing for the O-Ring. The nine wires from the thermistors had first to be soldered to the brass members, fitted with O-Rings and pushed through the bottom of the Acetyl member. When all were inserted the thermistors, cables and internal soldered connections were then epoxy encapsulated. The Acetyl member with outer O-Rings was then inserted into the brass member and the completed assembly installed in a specially made tube for pressure testing at 100 bar (10,000 kPa ). Leakage resulted in partial disassembly and reassembly and sometimes surgery. Once pressure tested the 1.04 mm copper leads were then attached to either a cable or to the microcontroller circuit board in the enclosure as shown in Figure 5-1. The position of the brass fitting and length of the probe had to ensure it did not foul on the inside of the tank.

### 5.2.2 Electronic related Difficulties

Initially Analog Devices Evaluation Boards were used as shown in the following Figure 5-3. The Analog Devices Evaluluation Board was mounted via push in headers onto an interface board with connectors to probe cables, RS232 interface socket, push button switch for data download and battery connection. Such boards were also used for Diffusivity probes and prototypes of the internal multi sensor probes. Experience with these boards was used to finalise the design by the Electrical Engineer of the circuit board with LCD display shown in Figure 5-1 above. All the work with the Evaluation Boards including software was carried out by this author together with the specification requirements and design parameters provided to the Electrical Engineer whose work consisted in the circuit design, supervision of board manufacture and component assembly together with design of the keypad with electrical connections to interface to the circuit board. All software was developed by this author.


Figure 5-3 - Layup of ADuCM 360 Microcontroller Evaluation board (centre) on Interface board inside Enclosure as initially used until manufactured boards became available.

The thermistor sensors function as resistances. The microcontroller needed a reference resistor which was housed in the enclosure to avoid the need for additional cables to the probe. It also needed an offset resistance to analog earth. These additional resistances created problems in that the microcontroller documentation was terse and some specification limitations were either unclear or missing. This resulted in strange results, trouble shooting, modification of current source values and sometimes changing of reference and offset resistance values.

One time the current source supply value suddenly dropped and remained lower than specified. Fortunately programming of additional inputs to check on microcontroller performance highlighted the problem. The microcontroller had to be changed. Other issues are covered in the section on the Diffusivity probes.

### 5.2.3 Programming Difficulties

All microcontroller programming had to be developed and tested. The language was $C$ but with many specific commands for the analog and digital interfaces. The Analog Devices ADuCM360 microcontroller has 24 bit A/D conversion capability which was reduced by gain settings and noise. It
is not a common unit and differs from those used in the Arduino and other common units. Consequently the only programs that could be adapted were those terse and limited sample ones supplied by the Manufacturer.

Figure 5-1 above proudly displays the LCD screen and backlight working. The LCD module selected by the Electrical Engineer was commonly used and had an $I^{2} \mathrm{C}$ interface. No programs existed for interface of this module to the ADuCM360 using such interface. A program for the Arduino eventually was found and had to be re-engineered and after many failures finally worked. As highlighted elsewhere in this document, a circuit board component caused the LCD backlight to turn on when power was supplied and only through programming was it turned off. It had adverse effects when battery power was low as software could no longer turn it off and it quickly drained the battery leading to premature battery failure.

### 5.2.4 Methodology for external pipe wall sensors

Thermistors were soldered to cables of sufficient length to reach either DT600 DataTaker data loggers or a DT85 similar data logger but with greater number of connections and internal GSM modem which permitted emailing of recorded data. The sensors were directly placed on the pipe surface and held in place by tape. Thermal insulation was not used. Typical locations were top, side and bottom of the pipe usually in the centre of its length and if subject to solar radiation an additional sensor might be located on the opposite side so that shade and sunny side readings could be taken.

### 5.2.5 Difficulties

Difficulties can be summarised in relation to:

- Manufacturing the multisensor probes.
o Manufacturing the multiwire high pressure seals through the hex threaded high pressure fitting together with pressure testing and remedial work if needed.
o Designing and then assembling the prototype boards and connections
o Assisting the Electrical Engineer with the circuit board and keypad design.
0 Assembling the circuit boards and keypads with the enclosure which entailed making cut-outs for the keypads and holes for attachment to the multisensor probe.
- Programming the microcontrollers and resolving programming errors.
- Checking the final assembly including pressure testing

The Electrical Engineer's work included designing and supervising manufacture of the circuit boards and component assembly and similarly for the keypad installed in the enclosure shown in Figure 5-1. All other works were carried out by this author.

### 5.3 GENERAL METHODOLOGY FOR THE ABOVE GROUND TEMPERATURE EXPERIMENTS.

Tanks or pipes were prepared with appropriate fittings, filled with water and pressure tested with a hydraulic hand pump used for the pressurisation and calculations and estimates made of the $\mathrm{dP} / \mathrm{dV}$ factor. Subsequent pressure and external pipe wall temperatures were used to estimate the $\mathrm{dP} / \mathrm{dT}$

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factors. Such factors are not easy to calculate for tanks due to the small size, multiple fittings and end caps and the relevant equations are usually for long lengths of pipe.

### 5.3.1 DN 900 Experiments on 375 m long Pipe Section

Measurements were carried out on DN900 pipe 375 metres long above ground section. Other than acoustic measurements, the only temperature measurements were the following external pipe wall measurements late in the afternoon when there was still daylight (possibly around 18:00 hrs to 19:00 hrs). Three sets of readings are shown in Figure 5-4 taken on two consecutive days which show the consistency between consecutive days. The location of the heights was determined by placing a measuring tape around the circumference with zero at the top centre and calculating the heights from the circumference values for the temperature readings taken.


Figure 5-4 - External Pipe wall Temperature measurements of DN900 pipe exposed to ambient - late in afternoon.

Since no other temperatures were taken on this pipe section, two short DN900 test headers were welded together and used to obtain internal temperature measurements as detailed in the following section.

### 5.3.2 DN900 Short Exposed Pipe Experiment

A multi-sensor temperature probe consisting of thermistors was inserted into the pipe with sensor locations as shown in the following Figure 5-5. Three of the sensors malfunctioned and were excluded (1, 3 and 5). The slight inclination was a consequence of the position on top of the pipe of two connections installed opposite each other to minimise the length of the short test headers.


Figure 5-5 - Figure showing the internal probe sensor locations inside the DN900 tank with dimensions and details.

The original purpose for this experiment was the measurement of the adiabatic temperature effect on internal temperatures of a pipe. Previously only a small pressure vessel was used to perform the first verification of the effect (mentioned in Chapter 3).


Figure 5-6 - Internal Water Temperatures DN 900 exposed pipe - Adiabatic Pressure and Temperature changes removed.

In the above Figure 5-6 the adiabatic changes have been removed by offsetting the pressure and temperatures in an attempt to achieve reasonably continuous curves. However the pressure trace

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shows unusual variations due to the adiabatic effects. While a pressure change of around $12,000 \mathrm{kPa}$ resulted in adiabatic temperature changes of around $0.3^{\circ} \mathrm{C}$, this temperature change of the water and subsequent recovery in turn was reflected back into the pressure change as the unusual variations.

The original data was logged at three second intervals which quickly used up memory and resulted in the logger no longer recording in the early part of the first morning and hence the straight line section of the chart from around 1:00 to 7:00 am. The data interval was changed to one minute for the subsequent portion of Figure 5-6.

Pressure peaks around 16:00 hrs to 17:00 hrs, earlier than the temperature peaks around 18:00 pm to 19:00 pm. This suggests that the central internal temperature measurements do not fully cover the temperatures contributing to the pressure changes.

The data used for Figure 5-6 was rearranged to produce Figure 5-7, showing the variation of temperature with height within the pipe for each hour of one day.


Figure 5-7 - Internal Temperature Profiles of DN900 Exposed Pipe at Hourly intervals.
With such a large set of lines, the figure can be confusing. There are two superimposed patterns in the figure; one from 18:00 hrs to 8:00 hrs which will be referred to as the "night pattern", and from 9:00 hrs to 19:00 hrs as the "day pattern". These are shown separately in the following two figures (Figure 5-8 and Figure 5-9) extracted from the above.


Figure 5-8 - Internal Temperature Profiles of DN900 Exposed Pipe - 18:00 to 8:00 - Night Pattern. Surface Pipe wall Temperatures added (with offset).

This "night pattern" chart shows the progressive retraction of both the upper section above 500 mm and the lower section below 200 mm . Between 6:00 hrs and 7:00 hrs there appears to be rapid cooling which slows down on reaching the lowest point at 8:00 hrs. This could be due to early morning dew forming on the pipe. When solar radiation hits, it results in rapid evaporative cooling. Added to this and the following charts is an offset version of the previous external pipe wall measurements (offset $+3.8^{\circ} \mathrm{C}$ ) indicating that the pipe wall was around $4^{\circ} \mathrm{C}$ cooler than the central vertical water temperatures.


Figure 5-9 - Internal Temperature Profiles of DN900 Exposed Pipe - 9:00 to 19:00 - Day Pattern. Surface Pipe wall Temperatures added (with offset).

The following "day pattern" chart in Figure 5-9 is entirely different and is a result of direct solar radiation on the exposed pipe, especially the upper half.

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From the lowest temperatures around 8:00 a.m. there is an accelerated rise above 400 mm and a progressive rise below. While no upper sensor was present, the external pipe wall measurements, shown as the blue dots, indicate a progressive rise in temperature almost up to $45^{\circ} \mathrm{C}$ and possibly higher. The similarity of the external and central internal temperatures around 18:00 hrs to 19:00 hrs and the fact that it appears to be the time of the turning point from "day pattern" to "night pattern" points to thermal layers extending horizontally right across the pipe cross section including the pipe wall. As noted above, the pressure peak occurred an hour or more earlier. If the $+3.8^{\circ} \mathrm{C}$ temperature offset (increase) to the external pipe wall temperatures was not justified, it would represent a difference between internal and pipe wall temperatures a few hours earlier and possibly help explain the timing of the pressure peak.

Since the internal probe did not account for the top 180 mm of the pipe cross section, the following Figure 5-10 was produced to determine the temperatures in that $14 \%$ to allow the internal central probe temperatures to fully account for the pressure.


Figure 5-10 - DN 900 Pipe above ground - Estimation of top layer Temperature.
The peak of $60^{\circ} \mathrm{C}$, while possible, appears too high. The estimated temperatures around 18:00 hrs to $19: 00$ hrs were $52^{\circ} \mathrm{C}$ to $47^{\circ} \mathrm{C}$ which are higher than the pipe wall temperatures of around $40^{\circ} \mathrm{C}$ or (with the $3.8^{\circ} \mathrm{C}$ offset) around $44^{\circ} \mathrm{C}$. Adjusting the $60^{\circ} \mathrm{C}$ peak down to around $50^{\circ} \mathrm{C}$ would be more realistic, but then requires some additional input source of temperature to match the pressure.


Figure 5-11 - Pressure and Temperature of Exposed DN900 Pipe with Needed Temperature.
Figure 5-10 and Figure 5-11 included pressure correction for a leak of one drop every two seconds. There is a slight increase in temperatures over the period as evidenced by the slight rise in the minimum values. The average was based on a weighted average of the areas attributed to each measured temperature and did not allow for much higher likely temperatures above the top most sensor as indicated by the external pipe wall measurements. Added to Figure 5-11 is the "Needed Temperature" to balance the average central temperature to produce the measured pressure change. This "Needed Temperature" could be the peripheral layer of water in contact with the pipe in direct sunlight. This "Needed Temperature" was based on $50 \%$ contribution to the pressure equivalent. If a lower percentage contribution applied then the temperature range should be increased proportionally.

Based on the above two figures it appears that a contribution from the upper $14 \%$ of the pipe is required together with some peripheral contribution to correctly match the pressure.

The average water temperatures along the central vertical in the following Figure 5-12 varied from $30.8^{\circ} \mathrm{C}$ to $36.5^{\circ} \mathrm{C}$ (blue trace). The trend lines of the rising and falling pressures show slopes 510 $\mathrm{kPa} /{ }^{\circ} \mathrm{C}$ and $680 \mathrm{kPa} /{ }^{\circ} \mathrm{C}$ well above the theoretical $439 \mathrm{kPa} /{ }^{\circ} \mathrm{C}$ for $33^{\circ} \mathrm{C}$ average. If much higher central temperatures existed above the uppermost sensor, then the average would be increased together with the theoretical $\mathrm{dP} / \mathrm{dT}$ factor. There is disagreement between pressure temperature factors based on water temperatures and the theoretical, most likely due to insufficient data.


Figure 5-12 - $\quad$ Pressure plotted against Average Central Internal and Needed Temperature for DN900 Exposed Pipe.

Also plotted in Figure 5-12 is the "Needed Temperatures" from Figure 5-11. The average trend line slope for the average central vertical temperatures is $519 \mathrm{kPa} /{ }^{\circ} \mathrm{C}$ while for the "Needed" temperatures $349 \mathrm{kPa} /{ }^{\circ} \mathrm{C}$. What is not known is the relative contribution of the central vertical and the "needed". 50\% has been assumed. The theoretical should be the linear addition of the $519 \mathrm{kPa} /{ }^{\circ} \mathrm{C}$ and $349 \mathrm{kPa} /{ }^{\circ} \mathrm{C}$ using different factors. If the theoretical value for an average temperature of $34^{\circ} \mathrm{C}$ and $15,000 \mathrm{kPa}$ is $356 \mathrm{kPa} /{ }^{\circ} \mathrm{C}$ the factors would be $96 \%$ "needed" and $4 \%$ central vertical. If the theoretical value for average temperature of $36^{\circ} \mathrm{C}$ and 15000 kPa was $414 \mathrm{kPa} /{ }^{\circ} \mathrm{C}$ then the factors would be $62 \%$ "needed" and $38 \%$ central vertical. The first set appears rediculous while the second set more realistic. Either way the "needed" portion appears significant and likely more than the central vertical.

Factors which could cause to the "Needed" temperature contributions could be:
a) Higher temperatures in the lateral parts of the pipe not represented by the sensors in the central vertical plane of the pipe.
b) Convection currents moving water inside the pipe that are not being measured by the central water sensors.
c) Much higher temperatures at the top of the pipe which was not measured.
d) Calculated pressure temperature factors were based on the average temperature in the above figure as were the Excel trend lines. The factors are not linear and should be calculated accordingly.

The above result is significant in that reliance was initially placed on the central vertical internal temperatures and pipe wall temperatures. The $4^{\circ} \mathrm{C}$ offset needed in Figure 5-8 and Figure 5-9 puts the reliance further in doubt. Failure of the top sensor in the internal probe did not help. The following experiments have concentrated on central vertical temperatures and pipe wall temperatures intended
to be the basis for this study. The above result implies that this study is missing data of the order of of $62 \%$ or more of that needed to correctly relate temperature to pressure changes. The CFD data provided by past research and detailed in Chapter 3 mainly addressed the thermal response of the water filled pipe to a single sudden temperature change in the water and showed almost uniform thermal gradients across the pipe section but only after an initial diameter and soil dependent stabilisation period. The DN 900 above ground pipe is not the same. It represents a multitude of different temperature inputs over the 24 hour period with the CFD stabilisation period applied repeatedly for most of the day. Only for buried pipe would the CFD results apply provided there was only one initial temperature change. If there was continual change throughout the day then the CFD results may not be fully applicable. Maybe the above estimated factors for central vertical and "needed" are required to vary depending on the nature of the imposed temperature changes.

### 5.3.3 DN 600 Experiments

The following figure was prepared from data for a DN 600 pipe exposed to ambient. It shows variations in the temperature profile for different times of day. The internal temperature probe was the same as used for the DN900 pipe with a 1-inch (DN25) NPT extension pipe on the valve to accommodate the additional length.


Figure 5-13 - DN 600 - Hourly internal water temperature changes measured in the vertical central plane from 8:00 hrs to 20:38 hrs.

The daytime pattern is similar to the DN900 pattern in Figure 5-9, while the peak temperatures were reached around 17:00 hrs to 18:00 hrs, earlier than the DN900 as expected for the smaller crosssectional area. The start of the night-time pattern from around 18:00 hrs was similar again to the DN900 in Figure 5-8.

The uppermost sensor was within 50 mm of the top of the pipe and maximum temperature was just below $43^{\circ} \mathrm{C}$ with the trend of the slope heading for $45^{\circ} \mathrm{C}$ at the top of the pipe.

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The intended purpose of the DN600 experiments was mainly to assess the adiabatic changes on the water inside the pipe by using the vertical central probe. Consequently, no external pipe wall measurements were taken.

The following Figure 5-14 shows the adiabatic temperature changes detected by two internal sensors together with the pressure converted to temperature for comparison.


Figure 5-14 - Adiabatic Temperature changes inside DN600 Exposed Pipe subject to Pressure changes of 8000, 2000 and 10000 kPa .

The above Figure 5-14 shows the temperature changes at two internal locations 45 mm and 445 mm above the bottom of the pipe from pressure changes (converted to equivalent temperature) of the order of $\pm 10,000 \mathrm{kPa}$. The expected adiabatic changes for such pressure changes at an average temperature of $29^{\circ} \mathrm{C}$ should be around $0.22^{\circ} \mathrm{C}$, similar to the changes in the figure for the location nearest the pipe bottom. Proximity to the pipe surface may be affecting the results since the pipe should cool. The trends suggest that exposed pipe is not ideal for demonstrating adiabatic temperature changes even with internal temperature probes.

Insufficient data was available to replicate the "Needed" Figure 5-11 for this diameter pipe.

### 5.3.4 Shaded DN 435 Experiments

The DN 435 pressure vessel was originally designed and tested for working pressures up to around 30 bar. The vessel has subsequently been progressively pressure-tested to bring the pressure up to 76 bar ( $7,600 \mathrm{kPa}$ ) to provide a much larger working range for experiments.

Pressure measurements were logged with a DataTaker DT85M data logger using a 4-20 mA 160 barg range WIKA pressure transducer. The pressure transducer has been calibrated against a Budenberg 380D dead weight tester and the coefficients used for the logging. External pipe wall
temperature measurements were made using negative temperature coefficient thermistors also connected to the data logger. These were carried out in preparation for later experiments with internal and external temperature measurements.

### 5.3.5 Thermoelastic Effect - DN435 Tank

While the tank was in the author's garage during one depressurisation the thermoelastic effect was evident from the average of the top, side and bottom pipe wall thermistor sensor measurements as shown in the following Figure 5-15.


Figure 5-15 - Thermoelastic Effect in External Pipe wall Temperatures on rapid Depressurisation of DN435 Tank.

The estimated thermoelastic factor from the figure was $0.90 \mathrm{mK} / \mathrm{MPa}$ of stress change. It was seen in Chapter 2 that the overall thermoelastic parameter for steel was $3.48 \times 10^{-12} /(\mathrm{K} . \mathrm{Pa})$. This when multiplied by the absolute temperature $291^{\circ} \mathrm{K}$ and stress 255 MPa results in a temperature change of $0.258^{\circ} \mathrm{C}$ of which the estimated $0.23^{\circ} \mathrm{C}$ is $89 \%$. The above estimate of $0.23^{\circ} \mathrm{C}$ has assumed a polynomial trend line for the subsequent temperature decay (dashed line) which appears a good match and was better than an exponential. The rollover and decay are a consequence of the heat in the pipe dissipating into the adiabatically cooled tank water. The rate of rise is due to the thermal response of the thermistor. The pipe steel was previously under tension and its temperature has risen because the tension was released or was effectively compressed (heated).

### 5.3.6 Solar Exposed DN435 Experiment Setup

When filled with water this tank was too heavy to manipulate by hand and so was located on top of a garage where access via wheeled trolley was possible. Cables could be directed through ventilation openings to the enclosed garage below where the DT85M data logger was located and where mains power was available to power it. Tank orientation was east-west.

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This tank was fitted with a vertical 8-sensor temperature probe and a horizontal probe (both specifically made for the diameter). Both were at right angles to the tank long axis in order to measure the vertical temperature profile and any indications of lack of uniformity of the profile across the central diameter. Sensor separation on these probes was about $52-53 \mathrm{~mm}$. Both were monitored by microcontrollers mounted on the probe similar to Figure 5-1. Five external pipe wall temperature sensors were connected to the data logger: underneath, on the shaded side, on top, on the side facing the sun, on the centre of the western end cap. The location is exposed to the sun over most of the morning and mid-afternoon after which there was shading from the house on the western side.

The photo below shows the tank in position, with two DN435 8 sensor probes installed together with the surface temperature sensors including the one on the end cap.


Figure 5-16 - Side view of DN435 tank experimental setup with pressure transducer and manifold on left top, top internal multi sensor probe on its right, central horizontal internal multi sensor probe in front and the external pipe wall sensors mounted under the aluminium tape measuring top, side and bottom temperatures. Solar radiation hits the tank on the side shown.

The tank was originally an air pressure receiver with hand inspection hole (located in the oval protrusion above the side multi sensor probe) which had been welded up but could trap air. The following photo in Figure 5-17 shows the end view.


Figure 5-17 - DN435 tank experimental setup showing manifold with pressure transducer behind top internal sensor and left side internal sensor assembly, together with external pipe wall sensors. Cables ran to the DT85M in the garage underneath where power was available.

### 5.3.7 DN435 Tank Results - Central Cross Section

The most interesting results relate to the horizontal probe at the centre of the pipe cross section over an hour period just after winter sunrise in Figure 5-18.


Figure 5-18 - DN 425 tank - horizontal multisensor temperature probe differences over short time period in morning.

It appeared that the sensor next to the sunny exposed side (T8) showed upward moving natural convection currents due to solar heating on that side. This then resulted in a compensating downward moving convection current on the opposite side of the pipe concentrated near sensor (T3), which was
two sensors away from the pipe wall on the shaded side. The sunny side sensor (T8) values rose with time, even as the shade side sensor (T3) values dropped. The reading on T1, the sensor on the shade side nearest to the pipe wall also drops as the reading on T8 rises. The readings on T2 and T5-T7 hardly change.

These results are only for the time when the sun shone on the pipe for the first hour in the morning. They highlight possible rotational convection currents generated by the heating effect of the sun. They differ significantly from the CFD "double eye" circulating pattern of two opposite contra-rotating currents generated by soil-to-pipe heat transfer around the pipe circumference but enhanced at the two sides of the pipe. In the above case with the solar radiant energy providing the heat input only on one side, a single rotating current appears to be set up with the source at the pipe wall heated by the sun. The compensating downward current forms not at the opposite pipe wall but around $40 \%$ of the radial distance from the centre. This pattern has been identified mainly because the horizontal central probe sensor temperatures were very similar to each other in contrast with the central vertical probe where significant differences occurred. The temperature difference scale shows around $0.22^{\circ} \mathrm{C}$ maximum rise on the sun side and $0.14^{\circ} \mathrm{C}$ drop at T 3 .

The reading at 9:05 hrs in the left half of Figure 5-18 has a completely different pattern indicating that a change has occurred with the dip at T3 shifting outward to T2. The following Figure 5-19 takes a different approach and plots the differences of the horizontal internal probe from the average over time. The average of these readings is also shown as the upper dark blue trace with vertical axis on the right hand side.


Figure 5-19 - Central Horizontal Average and Differences from Average plotted over two weeks.

Figure 5-19 shows that the pattern in the orange trace (sunny side sensor T8) has the highest fluctuations while the central average rises and peaks and then inverts to a nearly steady value until the next day. The first day was sunny, followed by progressively rainy days which reduced the central
average changes and also the extent of fluctuation of sensor T8. The pattern on the first day is not repeated until around four days later. During the rain periods the pattern changes, with the second day the best example with the red T2 readings flipped and enlarged followed by T1. According to the Bureau Of Meteorology Sydney Airport weather data (around 7 km away), heavy rain fell on $5^{\text {th }}$ and $6^{\text {th }}$ June with minor rainfall on $8^{\text {th }}$ to $11^{\text {th }}$. This figure shows that the changes in the horizontal central temperatures are less than $\pm 0.3^{\circ} \mathrm{C}$ from the average while the average itself fluctuates maximum $\pm 4^{\circ} \mathrm{C}$ for this diameter pipe in winter conditions. The oscillation and swinging of internal temperatures next to the pipe wall is dependent on weather conditions including solar radiation, rain and wind and direction.

The following Figure 5-20 compares the pressure with both the average of the vertical probe temperatures and the horizontal probe temperatures.


Figure 5-20 - Pressure plotted against Temperature - External Pipe wall and Internal Vertical Central and Horizontal Central.

In this figure the horizontal average (red) has less scatter than the vertical (light blue) as would be expected. Adding the external pipe wall temperatures increases the scatter especially for the top (yellow), less so for the side (green), with the scatter in the bottom (dark blue) further reduced. Also plotted are the expected changes in accordance with AS2885.5:2020 (theoretical) of which there are two copies for the respective horizontal axes. The side (green) pipe wall sensor readings appear to follow the theoretical while the bottom (dark blue) appears to be closer in slope to the internal probes and deviates away from the theoretical. The two horizontal temperature axes are offset by 4 degrees to enable better comparison of the internal and external temperatures.

Trying to find reasons for the difference between the theoretical expectations, the internal measurements and the bottom pipe wall led to discovery of an error in AS2885.5:2002 which had continued through to AS2885.5:2020 [10, 37, 124]. It was in the equation for the B factor for restrained
pipe which was in fact the water thermal expansion equation, $\beta$, based on IAPWS-95 [30, 33, 34]. The contribution of this error was small. The only remaining factor to explain the discrepancy was the presence of air. Using the following dP/dT equation with 120 ml air (at atmospheric pressure) the horizontal internal was matched. Before the AS2885.5 correction the estimated air was 200 ml . Such air-included dP/dT will affect all the internal and external temperature results. The equation used was as follows:
$\frac{d P}{d T}=\frac{\left(P_{2}-P_{1}\right)}{\left(T_{2}-T_{1}\right)}=\frac{\left[V_{W} \beta-V_{P} G \alpha+V_{1 D A i r} \frac{d f_{s}}{d T}+\frac{V_{1 A i r} P_{0}}{T_{0}\left(P_{2}+P_{0}\right)}\right]}{\left[V_{P} \frac{D C}{E t}+V_{W} K-V_{1 \text { DAir }} \frac{d f_{s}}{d P}+\frac{V_{1 \text { Air }} P_{0}\left(T_{1}+T_{0}\right)}{T_{0}\left(P_{2}+P_{0}\right)\left(P_{1}+P_{0}\right)}\right]}$

Where

| $\mathrm{P}_{1}, \mathrm{P}_{2}$ | initial and final pressures |
| :--- | :--- |
| $\mathrm{P}_{0}$ | atmospheric pressure |
| P | pressure |
| $\mathrm{T}_{1}, \mathrm{~T}_{2}$ | temperatures |
| T | temperature |
| $\mathrm{T}_{0}$ | reference temperature for air volume |
| $\mathrm{V}_{\mathrm{w}}$ | Water volume |
| $\mathrm{V}_{P}$ | pipe internal volume |
| $\mathrm{V}_{1 \text { Air }}$ | Air volume at atmospheric pressure P0 |
| D | pipe average diameter |
| C | pipe restraint factor |
| E | Young's modulus |
| $t$ | pipe wall thickness |
| K | water compressibility |
| $V_{1 D A i r}$ | volume of dissolved air |
| $d_{s} / d T$ | differential of dissolved air volume with respect to temperature. |
| $d f_{s} / d P$ | differential of dissolved air volume with respect to pressure. |

The dissolved air volume $\mathrm{V}_{1 \text { DAir }}$ was considered zero (along with the differentials of $\mathrm{f}_{\mathrm{s}}$ ) and $\mathrm{V}_{\mathrm{w}}$ and $V_{p}$ considered equal (water and pipe volumes respectively) since 120 ml air volume at pressure of 5000 kPa is only around 2.5 ml . This is negligible except for its effect on the above equation. The P/T curve with air using this equation can be seen superimposed on the red horizontal average trace. The P/V factor used in these estimates was $11.7 \mathrm{kPa} / \mathrm{ml}$.

With around 120 ml of undissolved air in 110 litres of water the air volume ratio at pressure of 5000 kPa would be around 0.00002 . This would have a solution rate alpha exponent using Figure 4-13 but extrapolating beyond the chart range of around 3.5/day so that almost all air should dissolve in 24
hours unless the air pocket was concentrated at one location. In the latter case, it would take longer for the air to dissolve. This particular experiment had continued for two weeks, thus providing sufficient time for air solution.

From Figure 5-20 it can be observed that the internal vertical average temperature ranged from $11.5^{\circ} \mathrm{C}$ to $20.7^{\circ} \mathrm{C}$ while the internal horizontal average ranged from $11.0^{\circ} \mathrm{C}$ to $21.0^{\circ} \mathrm{C}$. Whereas the bottom pipe wall ranged from $9.7^{\circ} \mathrm{C}$ to $19.0^{\circ} \mathrm{C}$, side pipe wall from $10.6^{\circ} \mathrm{C}$ to $20.2^{\circ} \mathrm{C}$ and top pipe wall from $10.4^{\circ} \mathrm{C}$ to $25.8^{\circ} \mathrm{C}$. The looping of the central vertical internal trace was around one degree while that of the bottom pipe wall was around $2.5^{\circ} \mathrm{C}$, the side pipe wall less than 2 degrees and the top sidewall almost nine degrees.

For exposed pipe and using only external pipe wall measurements, the bottom most closely matched the internal while the shaded side had less scatter but deviated from the internal.

The intention behind the above figure was a comparison between the internal and external temperature changes with pressure and the theoretical. In the previous section on the exposed DN900 pipe only the internal results were available and a "Needed" temperature was required to combine with the internal to match the pressure in Figure 5-12. The "Needed" temperatures on the plot had a P/T slope lower than the central vertical. In the DN435 tank, the internal and bottom external appear to match each other and the theoretical with air. The external side and top have lower P/T curves not unlike the "Needed" portion in Figure 5-12. This indicates that the "Needed" portion relates to the pipe wall side and top and probably the adjoining internal portions. The fact that the internal vertical probe sampled the top (unlike the missing top sensor for the DN900) reduces the likelihood that the top segment was missing in the "Needed" grouping of contributions.

### 5.3.8 DN 200 Experiments

A special eight sensor internal probe was made for the DN200 tank experiments (shown in Figure $5-1$ ) and inserted vertically into the tank. The sensor separation was 25 mm . The following Figure $5-21$ plots the pressure against the temperature. The external temperature shown was the Side and showed higher levels of noise than the bottom and top.


Figure 5-21 - DN200 Exposed tank Pressure and Temperatures - Internal sensors, Internal average and external pipe wall Side.

To minimise confusion, two horizontal scales have been used with the side pipe wall and average internal plotted against the top scale. Two copies of the theoretical P/T curve based on corrected AS2885.5 are shown as black dashed lines to cover both scales.

The pipe wall side is close to the theoretical but not as good as the internal bottom. The external pipe wall bottom was not plotted because of the noise. The central internal average appears away from the theoretical as do the more central internal sensor temperatures. The internal top has the highest deviation.

The temperature excursion of the average internal for the DN200 was from 8.5 to $33^{\circ} \mathrm{C}$ for $24.5^{\circ} \mathrm{C}$ change compared with the DN435 of $9.2^{\circ} \mathrm{C}$ and showing the effect of pipe diameter on internal temperature excursions. This excursion was over many days and represented the maximum range but still gave a good indication of range. For the DN900 above ground pipe the average internal change over 24 hours was less than $6^{\circ} \mathrm{C}$.

### 5.3.9 DN 50 Experiments

The DN200 internal probe was installed at one end of the 1.8 metre long DN 50 pipe having 54 mm O.D. and 1.25 mm W.T. Its orientation was in line with the pipe centreline and so could not measure any vertical thermal gradient. The diameter/thickness (D/t) ratio was 43 which was similar to that for 219 mm diameter pipe of 5 mm wall thickness. While not typical of DN50, this matches the D/t ratios for larger pipes. The material was only mild steel and was subject to almost continuous yielding and creep. Figure 5-22 shows the Pressure/Temperature plot.


Figure 5-22 - $\quad$ Pressure Temperature plot for the DN 50 pipe during winter showing the rapid change in characteristics close to the highest density of water at $4^{\circ} \mathrm{C}$.

The shape of the curve in Figure 5-22 reflects the known variation with temperature of the $\mathrm{dP} / \mathrm{dT}$ factor and confirms the water thermal expansion coefficient has a minimum at $4^{\circ} \mathrm{C}$. Progressive lowering of the curves over time reflects ongoing steel creep evidenced by creep-like decay on reaching high pressures. The temperature range of the internal probe was from $5^{\circ} \mathrm{C}$ to $32^{\circ} \mathrm{C}$ or $27^{\circ} \mathrm{C}$, slightly higher than the DN200 range of $24.5^{\circ} \mathrm{C}$. With such a small water volume surrounded by steel the whole pipe will act thermally as a unit without much variations. The difference between $27^{\circ} \mathrm{C}$ and $24.5^{\circ} \mathrm{C}$ is mainly a matter of the ambient/solar radiation induced temperature change in a dark rusted metal coloured object.

### 5.3.10 Conclusions

- The overall trend of the pressure/temperature plots follows the $\mathrm{dP} / \mathrm{dT}$ variation with temperature for the relevant pipe parameters unless air is present.
- In the case of the DN 50, creep resulted in the P/T curve moving downwards.
- The separation of the rising and falling portions of the loop pattern increases with pipe diameter.
- The amplitude change from peak to minimum follows ambient changes for smallest diameter and reduces with increase in diameter.
- Rainfall disturbs the trends.
- Overcast cloud conditions improve the correspondence between amplitude of pressure temperature plot and ambient range.
- Pressure testing at lower temperatures, especially close to but above $4^{\circ} \mathrm{C}$, decreases sensitivity to temperature changes and improves leak detection.


### 5.4 AMBIENT MEASUREMENTS AND MODELLING

The DN900 above-ground short pipe experiments were intended to provide the missing internal temperature data from the acoustic velocity experiments on the 375 metre long pipe string. While internal measurements were made of the short length, no ambient temperatures (ambients) were recorded and not even the internal temperature of the data logger. Consequently, ambient temperature data was recorded during the pressure testing and other activities where data loggers were used to see whether any patterns could be established and possibly used.

During one DN 900 pressure test the data logger temperature was recorded at four locations over a 16-km range and covered just over four days. They resulted in the following Figure 5-23.


Figure 5-23 - Data Logger Internal Temperature at five locations in a 16 km range - Tropical Location.

The traces in this figure are a proxy for the ambient as they are the internal temperature of the data loggers. What they show is short range variation in solar thermal input most likely due to variable cloud cover which is highly localised as evidenced by the daily changes. They also indicate more widespread daily changes.

### 5.5 AMBIENT APPROXIMATION

Based on a number of field ambient measurements during pressure testing in locations similar to the above, resulted in the following Figure 5-24 which consists of the dashed black line average of the hourly data and the red approximation consisting of a half sinusoid and linear sections.


Figure 5-24 - Average of a number of field pipeline ambient temperatures with a simple approximation using a combination of part sinusoid and linear slope. The average for one day has been repeated to cover a 48 hour period for potential use as an input to CFD modelling.

The red line in the above Figure 5-24 is a combination of a half sine from 8:00 hrs to 19:00 hrs with the intermediate times approximated by a negatively sloping straight line which then becomes flat a couple of hours before the start of the sine half curve. The fit is good and allows for simple ambient modelling and flexibility in terms of local time, ambient range between maximum and minimum and the component durations. It is likely that a pattern prevails in a particular latitude reflecting the solar input and daylight time.

Carson's [119] data plotted in Chapter 2 had a maximum change of $7.5^{\circ} \mathrm{C}$ while the smallest change in the above figure is around $12^{\circ} \mathrm{C}$ and the maximum $27^{\circ} \mathrm{C}$ although a black lunch box-size waterproof enclosure of the DataTaker data logger is likely to exaggerate temperatures when exposed to direct sunlight. The shape of the overnight portion of the above figure is almost flat but with a slight decline, while Carson's data shows a decline almost from the peak. The above figure was for the tropics while Carson's was for temperate regions with reduced solar radiation, ground and ambient temperatures.

Figure 5-23 highlighted that such a pattern as in Figure 5-24 was not typical and would rise and fall with cloud cover and weather changes.

### 5.5.1 Pressure - Ambient Temperature Relationship

All pressure data for the above ground 375 metre DN900 pipe was rearranged so that progressive days could be compared. The aim was to approximate the ambient temperatures and subsequently to assess the effect of air absorption on the pressure and acoustic velocity. Knowing the general shape of the pressure variation, the following Figure 5-25 was the outcome of an attempt to integrate the ambient model similar to Figure 5-24 to obtain the shape of the pressure variation with time.


Figure 5-25 - Integration of Ambient model to obtain Pressure trace and use of Ambient model's Sine function to obtain equivalent integration using a Cos function.

The blue trace is the integration of the ambient model (brown) and has a similar shape to the pressure traces. An alternative means of integration was to use the cosine integral of the sine part of the ambient model to generate a simpler version of pressure (red). The ambient model is missing the downward sloping portion from 19:00 hrs since it produced a kink in the pressure trace which was not observed in reality.

Differentiation of the pressure trace to reconstruct the ambient was carried out and is presented in the following Figure 5-26.


Figure 5-26 - Differentiation of the approximate pressure trace which approximates the ambient half sinusoid.

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The resulting green curves are crude approximations of the previous half sinusoid but are more realistic versions of ambient or solar input. The following Figure 5-27 integrates the Data Taker Logger internal temperature for comparison with 0.1 m below-ground temperature and pressure.


Figure 5-27 - Below Ground temperature at 0.1 m depth. Logger internal temperature and integration of Logger temperature to compare with below ground and pressure in DN900 pipe.

The peaks in the integrated ambient proxy (red) trace are delayed relative to the ground (green) which tends to indicate that the ambient proxy is itself delayed. This is likely to be caused by the plastic instrument case in that the logger temperature (blue trace) should be delayed by solar and ambient heat transfer first into the black plastic logger case and then into the metal casing and finally into the circuit boards where the temperature sensor is located.

The shape of the integrated (red) ambient proxy is similar to the pressure in Figure 5-26 and the below ground. The below ground at 0.1 metre is similar to Carson's [119] shape in Figure 2-34 for a depth of 0.01 metre while the former was in the tropics and Carson's at high latitudes in summer with both at similar times of year.

Of note in the above Figure 5-27 is that for almost all days the minimum logger "ambient" (right axis) remains at around 24.0 C and the minimum below ground at 28.0 C while for both the peaks change. The logger was sitting flat on the ground which should provide some means of heat transfer between the two. This observation suggests that the weather controls the general variation above a minimum.

### 5.6 DN 900 TANK EXPERIMENT - BURIAL APPROXIMATION

The DN900 short pipe section was installed inside a large water tank and instrumented with the near vertical multi sensor probe and only one external probe in contact with the outside of the pipe at the lower quadrant as shown in the following Figure 5-28.


Figure 5-28 - Cross section view of DN900 short pipe in water tank with internal probe and one external probe.

The purpose of the experiment was to minimise ambient effects and simulate burial conditions while abruptly lowering and increasing the pressure to better observe the adiabatic heating and cooling.

The following Figure 5-29 displays the average of the internal sensors (pink) and a version with the pressure changes removed, only as offsets, to provide a continuous curve (orange). The after effects of the adiabatic changes are still present as evidenced by comparing the sections with pressure changes with the central undisturbed region. No attempt was made to extract the adiabatic after effects. The adiabatic change was of the order of $0.3^{\circ} \mathrm{C}$ up and down from pressure changes of the order of $12,000 \mathrm{kPa}$. Theoretical for an average temperature of $30^{\circ} \mathrm{C}$ for this pressure change was $0.27^{\circ} \mathrm{C}$.


Figure 5-29 - DN900 submerged Pipe - Internal average temperature change resulting from Pressure changes of +/- 12000 kPa.

Of more relevance to the present study was whether the average internal temperature related correctly to the pressure changes. For this reason the following Figure 5-30 showed the average internal temperature measured by the central vertical probe compared with the pressure change. As in the above ground DN900 experiments a "Needed" temperature was calculated to assess what the near-vertical central probe was missing.


Figure 5-30 - $\quad$ Submerged DN900 Pipe - Comparison of Pressure (as temperature), Average Internal Central near Vertical Temperature and "Needed" Temperature.

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What was strange in the previous and the above figure was that the internal central average (red trace) has a peak around 21:00 hrs which is emphasised in the above figure when compared with the flattened pressure peak extending from around 13:00 hrs to 16:50 hrs (black trace). The pressure should correspond to the true average temperature of the whole of the pipe and contents which the central internal average was not showing. The blue trace was the estimated additional contribution "needed" to be added to the near vertical central average to achieve the measured pressure. Its peak is around 13:00 hrs to 14:00 hrs more typical of peaks in both temperature and pressure. What internal area this applies to is a mystery but is likely to be lateral quarter moon shaped areas not near the central vertical section. These areas would be those where the tank water was heating and cooling the outer sides of the pipe which would drive convection currents similar to the "double eye" pattern in the CFD study.

The following Figure 5-31 plots the average central temperature and the additional or "needed" temperatures against the pressure approximation as temperature (solely for convenience).


Figure 5-31 - Pressure Temperature plots for Central near Vertical Average and "Needed" Temperatures.

The orientations of the two supposed temperature contributions are quite different with the dark red central average inclined slightly to the upper left while the "needed" slopes up to the right. Since there was an underlying overall drop in both temperature and pressure over time this has affected the above traces by causing the dark red to drift to the left while the blue is drifting to the lower right. Pressure temperature plots should have a positive slope which only the blue "needed" trace has, indicating that the dark red central near vertical average is missing contributions from inside the pipe that it is not measuring. The P/T slope test suggests that the "needed" part should have a dominant contribution.

This analysis is simply a recognition and emphasis that a central near vertical multi sensor probe only senses the thermal gradients and average of only this central region and not the whole of the pipe
contents. This may be a peculiarity of the tank set up where the external water is mobile and subject to its own convection currents as distinct from the underground situation where the soil cannot move and has lower heat transfer capabilities. However it has been observed in above-ground examples and so does not appear to be a function of burial or burial simulation.

### 5.7 DIFFUSIVITY MEASUREMENTS

Thermal diffusivity determines heat transfer and is a combined value composed of density, thermal conductivity and specific heat..

### 5.7.1 Purpose of Diffusivity Measurements

The CFD studies by the University of Wollongong [11, 115, 116] identified a lack of available soil diffusivitivy values likely to represent typical pipeline locations. As a consequence, this student has fabricated, tested and then used special multi-sensor probes to measure the soil temperatures at depths up to 1.5 metres on a rural property north of Dubbo typical of the locations where pipelines are routed in rural Australia. Such temperatures can be used to determine diffusivity directly without the necessity of measuring the component contributions of density, thermal conductivity and specific heat.

Unintended consequences and results arose from this study as it was conducted over a period of four years and was affected by climate changes from drought to wet. Also as a means of identifying the relative importance of the component properties of density, thermal conductivity and specific heats a sample of the soil adjoining the buried DN 450 tank was analysed.

### 5.7.2 Methodology for Diffusivity Determination

Diffusivity measurements require a known frequency, the most convenient being the diurnal ambient change with a 24 -hour period and frequency of 1 cycle/day. The ambient is not a pure sinusoid as noted in Chapter 2 and has harmonics. However these harmonics are of shorter period and are more rapidly attenuated. They are no longer significant tens of centimetres below the surface. Commencing measurements from the first sensor below the surface usually suffices.

### 5.7.3 Instrumentation

Initially one Model Type 2 probe was made as a prototype. It had a tapered fibreglass member cut into five segments, with five sensors embedded in aluminium modules located at the bottom and as joiners for the fibreglass segments. The housing at the top was the same as in the photos shown below in Figure 5-32 and Figure 5-33 but without the LCD display window and keypad. This was joined to the fibreglass unit by a CNC machined interface unit to match the unusual shape of the enclosure base. It also permitted the cylindrical section to be machined to suit the variable internal diameter of the fibreglass tubes or when threaded permitted the installation of adaptors for pressure measurement. The Model Type 2 configuration was improved and three Model Type 3 units with six sensors were assembled. The microcontroller unit installed in the top enclosure was an Analog Devices Evaluation Board which required a hand made board for mounting and for connecting the wires from the probes as shown in Figure 5-3. Initially after experimentation and programming, two of the Model Type 3 were
installed at the end of December 2015 in a rural property North of Dubbo referred to as Dubbo North in this document.

The other Model Type 3 probe was later sent to Victoria for McConnell Dowell to trial but failed to be useful during pressure tests conducted in early 2016 and the probe was returned to Sydney. The previous Model Type 2 was installed in this author's rear yard in Sydney with data recording commencing from April 2016.

Eventually dedicated circuit boards were manufactured, components installed, the keypad panel with LCD clear window was designed and manufactured. Three enclosures were drilled and milled to enable installation of the keypad panel and mounting the circuit board with two used to change out the evaluation boards at Dubbo North in January 2018 and similarly in Sydney. Then battery life problems were discovered to have been caused by the LCD display backlight. Eventually when the DN435 tank was buried at Dubbo North the remaining Model Type 3 was installed in the corner of the excavation in November 2018.

Two photos are shown below of the final diffusivity probes. The first photo in Figure 5-32 is of the Sydney probe with five sensors installed in clayey sandy soil which included some loose sandstone. Photo in Figure 5-33 shows a later Model 4 type probe with 6 sensors.


Figure 5-32 - Diffusivity Probe installed in Sydney with later manufactured circuit board which replaced temporary prototype unit.

An augur was made and used in Sydney and Dubbo North to excavate a 40 mm diameter hole into which the tapered probe was placed and then soil installed and tamped around its perimeter. When dedicated circuit boards and keypads were manufactured the prototype unit on top was replaced without removing the probe by unscrewing the previous enclosure, installing the new one and then rewiring.

The Model Type 4 shown in Figure 5-33 had PT1000 sensors as the lowest two instead of the thermistor sensors used in the upper sensors and all the other probes. Thermistor sensors for Model 3 were numbered from the bottom as T1, T2, T3, T4, T5 and T6 for the Dubbo North sensors with T6 missing from the Model 2 installed in Sydney.


Figure 5-33 - Diffusivity Probe showing below ground sensors and fibreglass separators.
The six-sensor Model 3 probes installed at Dubbo North had sensor separation shown in the following sketch, Figure 5-34, with the nominal distance from the underside of the circuit board enclosure to the respective sensors and from the bottom tip upwards. The bottom two sensors are closer apart at 155 mm , the next at 215 mm while the upper four have around 300 mm spacing. These dimensions were important when calculating diffusivity. In addition it was necessary to record the distance from the underside of the circuit board enclosure to ground level to determine depth of burial of each sensor.


Figure 5-34 - $\quad$ Schematics of Diffusivity Probes with six sensors in tapered fibreglass tube, Measurements from bottom and top.

For the six sensor probes the top sensor was usually located above ground to act as an ambient reference and as a visual indicator of the buried depth of each sensor. Data had to be recovered every 4 months for the two original units at Dubbo North and every 3 months for the Sydney probe and the one nearest the buried tank at Dubbo North due to the sampling times of 45 and 30 minutes respectively.

The collected data was entered into Excel spreadsheets and weather data was obtained from the Bureau of Meteorology (BOM) websites for Sydney and Dubbo airports. In addition the farm monitored rainfall at Dubbo North was recorded which often differed from Dubbo airport data. All diffusivity probes recorded the microcontroller internal temperature as a proxy for the ambient. Daily BOM data for maximum and minimum ambient, rainfall, wind and direction was obtained and could be checked against the 45-minute or 30-minute data recorded by the probes.

### 5.7.4 Raw Data Collection- Sydney

First data was recovered in Sydney in April 2016. Data from Sydney was not of direct use for most of the study other than providing a multi-year set of data for a totally different geographical location and coastal climate. Its main use was as the basis for the redesign of the Model 3 probes to be used at Dubbo North. All the software improvements needed for the Model 2 were then incorporated into the Model 3 which when in service was further updated as issues with battery life became apparent. Trials of software changes were easier to carry out in Sydney rather than at Dubbo North with driving time of 6 hours each way and travel distance of close to 450 km each way.

### 5.7.5 Raw Data Collection - Dubbo North

Initial installation of the two six sensor diffusivity probes at Dubbo North took place in late December 2015. Field problems discovered at Dubbo North were generally fixed on site and if needed further work exported to Sydney where the third Model Type 3 and Model Type 2 could be used for checking without removing the below-ground portion of the probe.

When the buried DN435 tank was installed in early November 2018, another diffusivity probe (PIT probe) was installed in the north east corner of the excavation in contact with $75 \%$ of undisturbed soil. One of the original probes was around 5 metres away to the south west and just the other side of the fence surrounding the solar panels (SP) but in sandy soil as compared with the sandy clay soil at the excavation. The location in the sandy soil immediately borders a small grove of Cyprus pines which prefer such sandy soil and avoid the sandy clays and rock which Ironbark trees normally prefer.

The other probe at Dubbo North was located to the south east around 50 metres away on the diagonally opposite side of the Homestead on the property (SE probe).

The following discussion will focus on the newly installed probe next to the buried tank since it allows for direct comparison with the tank temperature measurements. The other two probes provided a longer duration record in a similar location and permitted checks on whether the tank probe has been thermally contaminated by its proximity to the tank.

The one in the excavation (referred to as the PIT probe) showed the backfill installation on the afternoon of the $4^{\text {th }}$ of November and appears to have recorded a higher range of temperature changes compared with the probe 5 metres away (referred to as the SP probe) reflecting the more exposed location without any shading throughout the day. There is a sudden change in the SP probe values around the $6^{\text {th }}$, possibly resulting from rain as it is a more sandy location than the one in the excavation where clay minimises rain penetration at depth.

The following chart is for the diffusivity probe next to the buried tank (PIT) and comparison with the other diffusivity probe 5 metres away in more sandy soil (SP).


Figure 5-35 - Dubbo North -Comparison of diffusivity probes near buried tank - Pit in excavation and SP 5 m away.

There is only a general correspondence between the two probes only 5 metres apart. The top probe (T6) readings are not included. Most of the similarities are with sensors from the same probe such as the deepest SP sensors (dashed). The dashed "solar panel" SP sensor measurements are higher in mid-winter than the PIT probe next to the tank which could be a consequence of the different sandy soil. In summer the topmost PIT sensors read higher. The period was in drought and hence less affected by rainfall. While the soil type could be the reason for differences, the proximity to the buried tank and installation in $25 \%$ undisturbed soil could contribute.

The figure does highlight the significance of soil and/or burial conditions on below ground measurements and ultimately on diffusivity values.

### 5.7.6 Effect of Rainfall

In the above figure the deeper probe temperature changes were later than the shallower. However, when significant rain fell either in Sydney or Dubbo North there was a rapid temperature change at all depths. This indicated that rain water had penetrated the ground and with it changed the temperature. End of March 2019 was a significant example with 43 mm of rain falling in the last 10 days of the month. Such events need to be avoided when determining diffusivity values.

### 5.7.7 Data Manipulation for Diffusivity Measurement

The raw data consisted of the recorded sensor temperatures at the programmed time together with the microcontroller internal temperature for both interest and as an ambient proxy (if needed). The microcontrollers were not programmed for data manipulation beyond the logging function although they could be. Recorded data was downloaded via RS232 based serial cable to a laptop computer as
a CSV file for later analysis with Microsoft Excel. Through trial and error, it was found that the following steps (in Excel) could optimise the data reduction for diffusivity determination:

1. Obtain continuous 24 -hour or 48 -hour running averages for approximately 10 days for all sensors and microcontroller ( $\mu \mathrm{C}$ ) temperature.
2. Obtain differences between the running averages and the raw data for all sensors and $u C$.
3. Correlation of the top and bottom buried 10-day running average differences.
4. Cube the correlation to preserve the sign but exaggerate the peaks.
5. Determine the correlation delay.
6. Use the delay time and sensor separation distance to calculate the diffusivity.
7. Repeat as needed.

The recommendation to obtain differences between running averages and the raw data may appear strange. It is intended to remove any longer period weather related fluctuations and leave mostly the 24 -hour cycle even though a 24 -hour filter is effectively being used in the 24 -hour or 48 hour running averages. This is shown in the following Figure 5-36.


Figure 5-36 - Example of Data with 24 hour running Average removed.
The 0.11 m buried results (dark blue, upper group, right scale) have a shape similar to Carson's [119] at 0.01 m . While the lower three deepest traces start to deviate on the far right, a quick look at the temperature scale should allow a little leeway. Once such deviant data is introduced to the Correlation coefficient it is straightened out as shown in the following Figure 5-37 where the uC internal temperature was used as the reference for the correlation process for the six below-ground sensors.


Figure 5-37 - Correlation of $\mu \mathrm{C}$ with Below Ground Sensors - 20-day Correlation - 2-Day View Window

Surprisingly, the correlation of the microcontroller ( $\mu \mathrm{C}$ ) with the bottom S 1 sensor at 1.4 m depth produces a part-sinusoid, but with strange shape (light blue) not unlike the previous attempts at pressure modelling from ambient temperature. This is a consequence of the small amplitude of the S1 readings enabling the $\mu \mathrm{C}$ readings to dominate it with the other harmonics in the diurnal cycle. This suggests that using two correlation inputs with the same harmonics should be avoided. Using the $\mu \mathrm{C}$ with the other five deeper sensor data produced no such effects. An observant reader may notice an intruder in terms of the black dashed trace marked "Sinusoid S1". It was a failed attempt to resurrect the $\mu \mathrm{C}$ - S 1 correlation result by trying to replace it with a sinusoid. Comparing the sinusoid with the green nearby trace for S 6 sensor at 0.11 m further provides evidence of the harmonic distortion from the microcontroller. The peak of the sinusoid does not match, while the minima are close. The overall shape of the green UC - S 6 trace has the rising portion almost leaning backwards not unlike the pressure traces in relation to ambient temperature.

The use of a sinusoid failed in above case of $\mu \mathrm{C}$ - S 1 but proved successful in other cases where the matching sinusoid provided the phase shift used to determine the times between the different correlations for the diffusivity calculations. An example is shown in the following Figure 5-38.


Figure 5-38 - Using cross correlation values and comparing to a sinusoid with varying time delay produced the above points for the depths indicated (left axis) but with the second deepest value removed to give a linear trend line corresponding to the thermal velocity in the soil which can then be converted to a diffusivity value.

Corresponding diffusivity to the thermal velocity of $0.9264 \mathrm{~m} /$ day in Figure $5-38$ is $7.90 \times 10^{-7} \mathrm{~m}^{2} / \mathrm{s}$.
It was necessary to add and remove multiple values of $2 \pi$ to the sinusoids in order to create a linear sequence of time against sensor depth where $2 \pi$ corresponds to a period of one day. The sensor 150 mm from the bottom had been excluded in the above figure since it had an offset which did not fit the other 5 points. It appears that a sensor spacing of around 300 mm leads to a delay of around 8 hours so that sensor spacing from 200 to 300 mm gives reasonable time delays less than 12 hours which avoids difficulties due to the one day wrapping effect. The second lowest sensor was likely near to the end of the tank which may have been influencing it.

### 5.7.8 Variation over long time periods

Using the above methodology, the following Table 5-1 was produced with the approximate date, measured diffusivity, ground conditions and previous month's rain listed.

Table 5-1 - Diffusivity Values Dubbo North next to DN435 Buried Tank during time of Experiment

| Diffusivity using probe at corner of DN450 tank excavation |  |  |  |
| :---: | :---: | :---: | :---: |
| Time of Year | Diffusivity <br> $\left(\mathrm{m}^{2} / \mathrm{s}\right)$ | Ground Condition | Approx. rain previous <br> month (mm) |
| Mid November 2018 | $7.90 \times 10^{-7}$ | Month after backfill which <br> was moist with damp <br> layer around top of pipe <br> depth. | 80 |
| February 2019 | $8.16 \times 10^{-7}$ | Drying | 40 |
| Late April 2019 | $7.31 \times 10^{-7}$ | Upper layer drier | 23 |
| Late August 2019 | $7.34 \times 10^{-7}$ | Surface cracks in clay | 7 |
| Late December 2019 | $6.99 \times 10^{-7}$ | Dry, end of drought | 30 |
| Late February 2020 | $10.1 \times 10^{-7}$ | Wet | 90 |
| Early May 2020 | $9.92 \times 10^{-7}$ to | $11.7 \times 10^{-7}$ |  |
| End July 2020 | $9.73 \times 10^{-7}$ to | Wet (saturated) | 80 |

The maximum change in the above table is from $6.99 \times 10^{-7} \mathrm{~m}^{2} / \mathrm{s}$ to $11.9 \times 10^{-7} \mathrm{~m}^{2} / \mathrm{s}$ or a $70 \%$ increase over a period of two months, which included a significant change in rainfall and weather patterns. Hence the frequency of diffusivity determinations need not be less than 1 month, unless significant changes occur such as breaking of the drought in January/February 2020. This Table 5-1 highlights the significant effect of rainfall and subsequently soil moisture on diffusivity. The following section investigated that connection further.

### 5.7.9 Dubbo North Soil Thermal Property Measurements

A soil sample was taken of the sandy clay backfill around the buried tank and analysed in Sydney using simple methods. The soil moisture content was not known but assumed to be around $9 \%$ for diffusivity of $7 \times 10^{-7} \mathrm{~m}^{2} / \mathrm{s}$ recorded in Table 5-1. It was necessary to estimate the density, specific heat and thernal conductivity. Density was measured by drying the soil in an oven and then slowly adding water while measuring the volume and weight which produced the first two columns in Table 5-2 below.

For a sample with water content of $43 \%$ an experiment was carried out with a block of aluminium to assess the specific heat by measuring the temperature change resulting from adding the aluminium block to the soil sample. The soil specific heat was estimated as $1.34 \mathrm{~kJ} / \mathrm{kg}$ based on the sum of the water fraction multiplied by its specific heat of $4.18 \mathrm{~kJ} / \mathrm{kg} . \mathrm{K}$ and the soil fraction multiplied by a specific heat of $0.42 \mathrm{~kJ} / \mathrm{kg} . \mathrm{K}$ and density of $2.49 \mathrm{gm} / \mathrm{ml}$. Using the estimated water specific heat and the water content, the third column of Table 5-2 was estimated. With the assumed water content for a diffusivity
value of $7.0 \times 10^{-7} \mathrm{~m}^{2} / \mathrm{s}$ assumed to be around $9.5 \%$ the variation of diffusivity with water content was estimated as the fifth column of Table 5-2 with these values then used to estimate the thermal conductivity shown in column 6. These table values are based on measured densities, a single measured specific heat and a single measured diffusivity with estimated water content and hence are not reliable, However they do provide the basis for assessing the relative contributions of water content, density, thermal conductivity and specific heat to diffusivity with the values in Table 5-2 plotted in Figure 5-39.

Table 5-2 - Dubbo North Thermal properties from experiments

| Dubbo North Soil Thermal Properties from experiments |  |  |  |  |  |  |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| Water <br> content <br> by vol (\%) | Density <br> $\mathrm{kg} / \mathrm{I}$ or <br> $\mathrm{gm} / \mathrm{ml}$ | Specific <br> Heat, <br> Cp <br> $\mathrm{kJ} / \mathrm{kg} . \mathrm{K}$ | Dens <br> x Cp <br> $\mathrm{kJ} / \mathrm{IK}$ | Diffusivity <br> $\mathrm{m}^{2} / \mathrm{s}$ | Conduct <br> W/m.K | Diff $\times 10^{6}$ <br> $\mathrm{~m}^{2} / \mathrm{s}$ |
| $0.0 \%$ | 1.41 | 0.42 | 0.60 | $5.92 \times 10^{-7}$ | 0.35 | 0.59 |
| $5.0 \%$ | 1.46 | 0.55 | 0.80 | $6.49 \times 10^{-7}$ | 0.52 | 0.65 |
| $8.0 \%$ | 1.48 | 0.63 | 0.93 | $6.83 \times 10^{-7}$ | 0.63 | 0.68 |
| $9.5 \%$ | 1.50 | 0.66 | 0.99 | $7.00 \times 10^{-7}$ | 0.69 | 0.70 |
| $15.0 \%$ | 1.54 | 0.79 | 1.22 | $7.62 \times 10^{-7}$ | 0.93 | 0.76 |
| $20.0 \%$ | 1.58 | 0.90 | 1.42 | $8.19 \times 10^{-7}$ | 1.16 | 0.82 |
| $23.7 \%$ | 1.62 | 0.97 | 1.57 | $8.61 \times 10^{-7}$ | 1.35 | 0.86 |
| $25.0 \%$ | 1.63 | 1.00 | 1.63 | $8.76 \times 10^{-7}$ | 1.42 | 0.88 |
| $28.0 \%$ | 1.65 | 1.06 | 1.75 | $9.10 \times 10^{-7}$ | 1.59 | 0.91 |
| $30.0 \%$ | 1.67 | 1.10 | 1.83 | $9.33 \times 10^{-7}$ | 1.71 | 0.93 |
| $35.0 \%$ | 1.71 | 1.19 | 2.04 | $9.89 \times 10^{-7}$ | 2.02 | 0.99 |
| $40.0 \%$ | 1.75 | 1.28 | 2.24 | $1.05 \times 10^{-6}$ | 2.35 | 1.05 |
| $43.0 \%$ | 1.78 | 1.34 | 2.39 | $1.08 \times 10^{-6}$ | 2.58 | 1.08 |



Figure 5-39 - Plot of diffusivity factors (conductivity, specific heat and density) and diffusivity for sandy soil from Dubbo North showing the variation of respective factors with water content as $\%$. Units detailed in Table 5-2 for vertical axis with legend indicating the respective factors.

The density was based on linear additions of the two components and has a linear graph (red). The product of specific heat and density has very slight curvature (darker blue with diamond markers) while the diffusivity has been assumed to be linear for estimation purposes (grey). The thermal conductivity is the product of the diffusivity and the density-specific heat product which in the above graph has amplified curvature (lighter blue with square markers).

The following literature values were taken from Bejan's "Heat Transfer" [75] with the highlighted entries based on the above estimates for comparison purposes. The Dubbo $9.5 \%$ wet sandy clay soil in the following table is based on a guess or estimate as to the density and water content of the lowest diffusivity value measured. The resulting Table 5-3 has been sorted based on increasing conductivity.

Table 5-3 - Comparison of field measurements with Bejan's Data [75]

| Comparison of field measurements with Bejan's Data |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
| Material | S.G. | Specific <br> Heat, Cp | Diffusivity $\mathrm{x} 10^{7} \mathrm{~m}^{2} / \mathrm{s}$ | Conductivity k |
| Portland cement dry | 3.1 | 0.75 | 1.30 | 0.3 |
| Dry Sand |  |  |  | 0.58 |
| WATER | 1 | 4.18 | 1.42 | 0.59 |
| Coarse grained earth | 2.04 | 1.84 | 1.60 | 0.59 |
| Dubbo 9.5\% moisture, dry sandy clay soil | 1.44 | 0.78 | 7.00 | 0.79 |
| Sandy clay | 1.78 |  |  | 0.9 |
| Dry soil | 1.5 | 1.84 | 4.00 | 1.0 |
| 8\% moist sandy earth | 1.5 |  |  | 1.05 |
| Moist Sand | 1.64 |  |  | 1.13 |
| Quartz | 2.3 | 0.78 | 8.00 | 1.4 |
| 28\% moist clayey earth | 1.5 |  |  | 1.51 |
| Slate perpendicular to laminations | 2.7 | 0.75 | 9.00 | 1.83 |
| Wet soil | 1.93 |  |  | 2 |
| ICE | 0.917 | 2.04 | 13.6 | 2.55 |
| Dubbo 43\% moisture, wet sandy clay soil | 1.76 | 1.34 | 10.8 | 2.58 |
| Granite | 2.75 | 0.89 | 12.0 | 2.9 |

In this table, ice and water have been included for comparison purposes and to highlight the unusual situation that porous materials such as dry soils and materials have similar conductivity to water while ice has similar conductivity to wet soils and granite which are not porous.

### 5.7.10 Difficulties

The 3.6 V size C Lithium Thionyl Chloride (LiThCI) batteries used had limited life initially which required regular checking of voltage and progressive changes to the software used to record the data. These batteries are classified as dangerous goods due to their lithium content and size and can only be transported by road or hand carried on aircraft with limits on numbers. Eventually after discovering poorly documented microcontroller hibernation commands by trial and error, battery life of around 15 months was achieved.

Problems related to the Liquid Crystal Display on the new circuit boards were that the default was the backlight on. This was rectified in software while battery power enabled the microcontroller to control but once batter power reduced the default turned on the backlight which quickly drained the battery. It was found that the circuit elements controlling the power supply to the backlight needed to be changed to ensure the default was for the backlight off. This was only carried out after all the field work.

The microcontroller did not include a real time clock so that when supply battery voltage was interrupted the date and time were lost. Software recovered the last recorded time which did not
address long periods without power. The only way to correct the date and time was reprogramming which was awkward in the field.

When attempts were made to finally remove the three probes at Dubbo North, only the most recent probe nearest the buried tank could be removed. The others had to be cut off below ground level to recover the microcontroller unit and first buried sensor. The problem was extensive corrosion of the aluminium housing for the sensors which had a dual function as the coupling for the fibreglass interconnecting units. In addition, a combination of rain action on the backfill with subsequent compaction over the years of installation made the tapered units impossible to remove even though there was a high strength small diameter marine rope connected from the bottom sensor to the top.

The microcontroller ABS housing discoloured over the years of sun exposure without affecting performance. The manufacturer recommended changing to a polycarbonate material at purchaser's additional cost. Pipeline use would normally be of the order of days to weeks and maximum a month so such discolouration would not be an issue. Similarly with the corrosion, however for long term use stainless steel could be substituted but with reduced thermal conductivity to the sensors.

### 5.7.11 Diffusivity Probe Conclusions

Above results indicated a relationship between diffusivity and soil water content to such an extent that diffusivity could be used to measure soil water content. Use of multi sensor diffusivity probes would enable the determination of diffusivity changes with depth and variation of water content with depth.

Overall the following conclusions can be made regarding the performance of the diffusivity probes:

- The probes proved to be reliable and able to operate in all weather conditions from drought to unusual rainfall with the exception of battery issues.
- They were able to identify rain events by a sudden change of temperature at multiple sensors.
- Some of the earliest probes had bottom two sensor separation around 150 mm which proved too close.
- Aluminium for buried sensor housing is not suitable for multiyear use and stainless steel or other corrosion resistant metal should be used.
- While readings were taken at 45-minute intervals, no attempt has been made to evaluate longer sampling periods.
- 300 mm sensor separation proved to be adequate for diffusivity measurements.
- It may be possible to incorporate diffusivity determining software in the microcontrollers but is better assessed by analysis of recorded data in Microsoft Excel.
The intended purpose of the diffusivity probes of obtaining field diffusivity measurements has been achieved with valuable peripheral findings such as dependance on moisture content and soil dependancies for locations even a few metres apart.


### 5.8 WEATHER AND MEASURED TEMPERATURES.

The previous section on diffusivity has relied on multiple data samples per day for the sole purpose of obtaining accurate data on the 24 -hour diurnal cycle. One feature of the method of analysing data
to determine diffusivity was removing any other data not related to the 24 -hour cycle. It is this discarded data that is of interest in this subsection together with whether such data can be obtained at less frequent intervals than for diffusivity measurements.

The local data collecting station of the Government Bureau of Meteorology (BOM) nearest to the buried DN 435 tank site was at Dubbo airport which records daily ambient temperature readings at 9:00 hrs and 15:00 hrs as nominal minimum and maximum. These daily records extend well beyond temperatures to include rainfall, humidity, wind direction and strength and while recorded daily are archived and available on line for immediate retrieval over a broad range of years. The so called maximum and minimum are of little value however they can be used to generate a simple average twice a day at the intermediate times of midnight (halfway between 15:00 hrs on the previous day and 9:00 hrs on the consecutive day) and midday (halfway between 9:00 hrs and 15:00 hrs on the same day.

The following Figure 5-40 covering more than a two year period has been constructed using these twice daily averages as the orange traces while a 24-hour running average of one of the microcontroller internal temperature records is the blue trace with $50 \%$ transparency so that where the two sets match the colour changes to green.


Figure 5-40 - Dubbo Airport Temperature Data compared with Microcontroller Data.
The microcontroller and its internal temperature sensor is encased in a light coloured plastic housing which increases the internal temperature and hence the scale used is a nominal $5^{\circ} \mathrm{C}$ higher. The two traces overlap for most of the 2.5-year period. Where they do not then either blue or orange is displayed. The microcontroller readings were taken at 30 -minute intervals and so 48 readings were progressively averaged in one day to eliminate the diurnal fluctuations.

While 48 readings have been used for the microcontroller average only two have been used for the BOM average and these have been a nominal maximum and minimum and not an average
determined by the BOM. It highlights the usefulness of the BOM limited data which will be extended later. No attempt has been made to refine the nominal $5^{\circ} \mathrm{C}$ offset but could easily be done if used for a pressure test where the pressure is more sensitive to changes in temperature rather than any reference temperature (within limits).

There is a period from late November 2020 to early January 2021 in which the blue appears below the green. From the $17^{\text {th }}$ to $19^{\text {th }}$ December the microcontroller location received 289 mm of rain while Dubbo Airport received only 43 mm . At other times there were similar rainfalls. Observed cloud and rainfall patterns from the BOM radar often showed differences between the two locations even though approximately 60 km apart.

What is surprising with this comparison is the ability of the BOM simple data to match the longer term patterns over many days to a week or more including of course the annual cycle and fluctuations within the seasons.

### 5.9 DN 300 PIPELINE, B.O.M. DATA

To assist in trying to resolve the acoustic velocity anomalies identified during the pressure testing of the Roma Gladstone Gas Pipeline, Bureau of Meteorology (BOM) data was accessed online and the daily maxima and minima were obtained for nearby weather stations. A period of at least one year is best to enable extraction and removal of the annual cycle which then allows the adjusted changes to be analysed by computer. The following Figure 5-41 uses a fifth order polynomial trend line (smooth dotted line) to approximate the annual cycle which is then deducted from the daily averages to obtain the red lower trace which is then usable for input into Fast Fourier Transforms (FFT) for estimating the temperatures at pipe depth.


Figure 5-41 - BOM based average Seasonal changes and extracted Weather based changes using Sinusoid and Polynomial approximations to the Seasonal underlying pattern.

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The alternative was to use at least two sinusoids optimised for the same purpose. Microsoft Excel's "Trend line" feature did not cooperate. Instead, the "Solver" feature has to be played with to achieve the same result. It provided the above grey (continuous line) approximation to the mean but only with the fundamental period of 365 days and ignored the harmonic of 183 days by setting the amplitude to zero. Manual attempts to include the other harmonic did not improve the fit and supported "Solver's" solution based on the fundamental. The two differences between the trend lines and results are compared at the bottom of the figure. There is general agreement between the two versions with deviation mainly at the two ends although the reduced scale may hide differences evident between the continuous grey sine curve and the dotted polynomial trend line. The polynomial poorly approximates the ends and would improve with a longer set of data. To avoid strange trend line equations and facilitate programming the time started from zero on $1^{\text {st }}$ January.

The sine equation was:

$$
\begin{equation*}
\text { Temperature }=20.055+7.879 \sin \left(\frac{2 \pi}{365} t+1.3011\right) \tag{5.9.1}
\end{equation*}
$$

where time, $t$, was in days. This equation is much simpler than the quintic polynomial. It may also assist programming when assessing the effect of delays with depth using FFTs and diffusivities. The main programming issue was whether data based on two values per day was sufficient to generate useful below ground values.

Matlab was used to predict the below ground temperatures from the above ambient averages as shown in the following Figure 5-42.


Figure 5-42 - Matlab Prediction of Below Ground Temperatures from B.O.M daily averages Including Annual Sinusoid.

The attenuation with depth and delay was based on a diffusivity of $8.0 \times 10^{-7} \mathrm{~m}^{2} / \mathrm{s}$. The time-based waveform was converted by FFT to the frequency-based version where the attenuation and delay were applied and then converted by inverse FFT back to the time-based waveform. The values without the
superimposed delayed sinusoid are shown in the following Figure 5-43 with the rising portion from 250 days to 330 days expanded in a later figure.


Figure 5-43 - Matlab Prediction of Below Ground Temperatures from B.O.M. daily averages Annual Sinusoid removed.

What is surprising is the result of the longer term average weather changes and the subsequent below ground changes. The four depths selected were 0.75 m and 1.074 m as the top and bottom of DN300 pipe at 0.75 m depth of burial and 0.9 m and 1.224 m below the surface representing the top and bottom of DN300 pipe at 0.9 m depth of burial. The worst case range from 0.75 m to 1.224 m is around $0.8^{\circ} \mathrm{C}$ at approximately 340 days. Some of the changes have highest temperatures at the shallowest depth while the reverse also occurs. Coupled with these differences with depth is the pattern following a reversal in which there is a rapid rise or fall in all the temperatures with a change of almost $1.5^{\circ} \mathrm{C}$ over a period of the order of a week.

What appears to be the driver for these significant changes is the average ambient excursion from the annual sinusoid with the largest excursions resulting in the largest changes with depth.

### 5.10 BELOW-GROUND DN 435 EXPERIMENTS

One of the early contributors and developers of the Australian Standard for Pipeline Pressure Testing, Ken Bilston, suggested that an alternative to temperature measurements was to bury a short section of leak free pipe near to the pipeline under test and simply compare the pressure of the short section with that of the pipeline test section without any temperature measurements.

### 5.10.1 Purpose of Below Ground Tank Experiment

The proposed experiment of instrumenting and burying a DN 435 tank was not to test Ken Bilston's proposed method of eliminating temperature measurements but mainly to provide thermal layering data for the purpose of resolving the acoustic anomaly. The CFD results reported in Chapter 3 were focussed on comparing the average internal water temperature with the external pipe wall temperature
measurements at the top, side and bottom to address the uncertainty or lack of correlation between pressure and external pipe wall temperatures. Figures showing thermal layering were produced but only for the first hour of a DN 450 pipe subjected to a single sudden temperature change. Longer term thermal layering data was needed for DN 300 size pipe.

Some of the effects expected from a buried tank were:

- Difference in internal temperature profiles between consistently rising and lowering seasonal temperatures.
- Small effect of ambient changes on below ground temperatures.
- Likely effect of adiabatic effects of pressure changes on pressure and temperature profiles.
- Possible effect of rain on buried temperatures.
- Possible effect of seasonal changes.
- Variation in amplitude and shape of the central vertical internal temperature gradient.
- Good correspondence between the external pipe wall temperatures and central vertical internal temperatures.


### 5.10.2 Methodology

The DN435 tank previously used for above ground experiments was fitted with the two 400 mm long multi sensor internal temperature probes mounted vertically with one as backup for the other. Also external pipe wall sensors were installed on top, side and bottom. A small diameter high pressure plastic tube was attached to the side of the tank and connected to a $1 / 4$ " high pressure fitting manifold with multiple connections to allow for two pressure transducers, pressurising with the hydraulic hand pump, depressurising as needed and spare fittings. The Wika 4-20 mA pressure transducer used for the above ground measurements was attached to the manifold and connected to and powered by the DT85 data logger. A separate Wika TTF-1 transducer was attached to the manifold and had a dedicated microcontroller unit connected with prior calibration by a Budenberg 380D dead weight tester. One of the multi sensor internal temperature probes was connected to the DT85 while the other was connected to a separate microcontroller with an output RS232 serial connection to the DT85M serial port.

The tank was filled with water above the hand excavated hole and pressure tested to ensure all fittings were leak tight. Then lowered into the hole with split conduit encasing the electrical cables to prevent backfill damage. A diffusivity probe was installed in one corner of the excavation prior to backfill (referred to as the "PIT probe").

Once lowered in, the tank was carefully backfilled initially with local nearby sandy soil around it and then with the material removed from the excavation. The location of the tank was exposed to all day sun but was near to solar panels which provided partial weather protection for the DT85M data logger, pressure manifold and two microcontroller units.

Programming of the DT85M data logger and microcontrollers had taken place before and was then checked and modified as needed. A wireless aerial was set up on the solar panels for transmission of the GSM modem signal as the location had poor GSM mobile reception. A separate solar panel and battery were installed to provide power to the DT85M.

The DT85M was enclosed in a plastic box and covered by a plastic sheet held in place by house bricks to prevent wind disturbance. While the location was on the ridge line, the plastic box was supported on bricks to avoid local flooding. The location of the tank excavation was in a small fenced area surrounding the solar panels which prevented livestock disturbance.

### 5.10.3 Monitoring and Data Collection

The DT85M was programmed to email data twice daily with most measurements at 30 minute intervals. The microcontroller reading the backup pressure transducer was recording at the same interval and required downloading every two months while the diffusivity probe needed data recovery every 3 months with the same sampling interval. This entailed bimonthly trips from Sydney to Dubbo North to download data and to check on battery condition and if needed make repairs or modify programs.

### 5.10.4 Difficulties

The difficulties can be summarised as follows:

- The GSM aerial proved of insufficient power to provide reliable data transmission and an additional aerial had to be installed.
- The DT85M needed rebooting a number of times due to GSM provider issues. This required the author's brother in law being remotely instructed in the process and carrying it out successfully.
- One of the multi sensor probes started to malfunction due possibly to water breaching insulation and affecting output resistance. Eventually the tank was excavated to the level of the installation and repairs attempted but subsequently failed.
- The backup pressure transducer connected to a microcontroller had some field problems. It had been calibrated and programmed in Sydney prior to mobilisation but the software required modifications after installation.
- Grass grew as a result of unusually high rainfall and affected some electrical connections and cables which had to be repaired and resulted in data loss of the DT85 including pressure.
- A mouse plague following the high rainfall prevented staying at the farmhouse and required motel accommodation in Dubbo City on two occasions with the second used as the excuse to abandon the experiment and remove the tank, instruments and fittings.
- The microcontroller did not have an inbuilt real time clock and when battery failure occured it was necessary to either reprogram the time or correct for the missing time.
- A program change for the microcontroller was made to effectively record any power loss and to restart the time from the previous last time with allowance for the delay between readings.
- Care had to be taken when opening the microcontroller housing when downloading data in that the battery could come loose and result in a power loss and time restart.
- The 3.6 V batteries in the microcontroller units maintain a steady voltage and then over a short period of time reduce to a level that causes the LCD backlit display to turn on and quickly discharge the battery. The battery voltage was slightly affected by the ambient and so was
difficult to predict when failure was likely to occur. Some batteries thought to be fully charged failed early resulting in missed data and need to reprogram the time.
- One keypad failed and would not permit data download so the whole microcontroller enclosure had to be replaced and the data eventually recovered.
- It appeared that one surface mounted microcontroller circuit board component which controlled the LCD backlight power possibly had the wrong pin configuration which caused battery life issues. This was worked around by programming. Otherwise the circuit board and design worked extremely well.
- Covid-19 lockdown in Sydney prevented one scheduled trip which was needed to repressurise the tank. As a result the tank went into vacuum and caused dissolved air to release and needing time to re-dissolve when pressure was raised. No pressure data was recorded during the vacuum period as the transducers measure gauge pressure.
- Frosts occurred and caused unusual pressure readings due to frozen hydraulic tube to the transducers. This required the water inside the above ground manifold and small diameter high pressure tube to be replaced by a $50 \%$ water/antifreeze mix to prevent freezing. Also the negative temperatures were unexpected and the software had to be changed to allow for this. In the meantime some ambient temperature data was missed.
- Initial solar panel sizes had to be changed to better cope with cloud cover.
- A 9 amp-hour 12-volt gel cell battery had to be doubled to 18 amp-hour to cope with GSM modem demands. Wiring and charger had to be modified for the larger battery.
- Adverse high velocity winds made it necessary to secure the solar panels and GSM aerials from wind damage.
- Internal $1 / 2$ AA size Lithium-Ion battery for timing circuit failed and had to be replaced in the DT85 DataTaker to correct timing.


### 5.10.5 Installation

Tank was filled over the excavation on $3^{\text {rd }}$ November 2018 with bore water from a long hose exposed to the ambient. It was left overnight and pressurised on the $4^{\text {th }}$ with data recording started around midday. Pressure leak checks commenced at 13:50 and were completed with pressure at 1784 kPa at 16:30. Lowering into the excavation with backfill was completed by around 17:30 including around the diffusivity probe installed in the north east corner. It was repressurised the following day to around 1355 kPa at 16:10 when the system was isolated by valve and blind hexagonal plug after the hand pump and pressurising hose had been disconnected.

The following photo Figure 5-44 shows the DT85M with battery, solar panel charger (on top) and wiring connections. The light grey box on the right is the interface for the RS232 serial cable from the microcontroller monitoring the second internal pipe multisensor temperature probe. The location is better shown in Figure 5-45.


Figure 5-44 - Photo of the multiple connections to the DT85M DataTaker together with the large 12 V battery and the charger on top of it for the solar panels and for powering the microcontroller connected to the other 8 sensor internal probes. On the right is a box for the interface between the microcontroller and the RS232 serial port of the DT85M.


Figure 5-45 - View towards East showing DT85M enclosed in plastic case and partially protected by the Solar Panels. Solar panel for the Logger is mounted on the lower left side of the House Solar Panels.

In Figure 5-45 the solar panel is shown attached to the end of the household solar panels. The pressure manifold with pressure transducer and backup microcontroller recorded TTF-1 transducer are slightly distinguished at the lower left connected by small diameter hose to the buried tank. The large black conduit leads to the DT85M DataTaker and to the other microcontroller just distinguishable to the right of the left solar panel support leg with additional cable leading to the DT85M to enable backup storage of the second internal probe on the DT85M. What appeared to be the smaller black

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conduit was the high pressure hose still connected to the hydraulic hand pump (out of view). The other diffusivity probe was the other side of a fence behind and to the right of the photographer about 5 metres away.

The following photo Figure 5-46 shows the pressure manifold with small tube connection on the right leading to the buried tank while the larger hose was connected to the hand pump just outside the field of view on the left. The Wika 4-20 mA transducer was on top of the manifold and partly hid the microcontroller housing with Wika TTF-1 transducer mounted in the threaded fitting at the connection to the manifold. The twin cable from the Wika 4-20 mA transducer to the DT85M DataTaker was the one that was stretched and ultimately failed due to the high weed growth after the drought finally broke. The corner of the excavation where the small diameter hydraulic tube entered was the installation location of the last diffusivity probe (PIT probe).


Figure 5-46 - Photo of Pressure Manifold including Transducers, Gauge, valves and fittings connected to below ground DN435 Tank.

### 5.10.6 Tank Heat Transfer Characteristics - Initial changes on Burial.

The pressure and internal temperatures dropped rapidly in an almost exponential manner as shown in the following Figure 5-47 with the repressurisation offset removed.


Figure 5-47 - DN 425 buried tank experiment - initial pressure and temperature decay with the nearby (PIT) diffusivity probe temperature also shown for comparison.

With much data manipulation the following exponential like blue curve of the tank and the red exponential approximation are shown in the following Figure 5-48. Another trace using an exponential with time exponent is partly obscured by the blue trace.


Figure 5-48 - Comparison of the exponential like initial temperature decay (blue) and exponential.

The blue curve is closely approximated by the "Tank Decay Approx." curve calculated using the following equation:

$$
\begin{equation*}
T=10.2 \times e^{-0.876 \times t^{0.739}} \tag{5.10.1}
\end{equation*}
$$

Where:
T t final temperature in the tank, $\mathrm{t} \quad$ time in days.

The coefficients were found empirically by repeated goal seeking in Excel. The equivalent alpha exponent for the exponential (product of time exponent and amplitude) is 0.647 /day for the blue curve while the red exponential value is 0.723 /day. For a DN435 pipe with diffusivity value of $7.0 \times 10^{-7} \mathrm{~m}^{2} / \mathrm{s}$ the CFD based alpha value should be 0.147 /day which is 4.4 times smaller. For the factors to match the diffusivity value needs to be multiplied by a factor of 45 or have a value of $3.2 \times 10^{-5} \mathrm{~m}^{2} / \mathrm{s}$ which is an impossible change in diffusivity.

This attempt at measuring thermal decay in soil is highly suspect in that it is immediately following backfill of an excavation containing a tank filled with initially hot water. No stable conditions applied. It was instructive in so far as an exponential with time exponent was able to accurately describe the observed decay as against a pure exponential without time exponent.

### 5.10.7 Anomalous dP/dT variation

Pressurisation following vacuum in the tank in June 2020 showed air present which was calculated at around 65 ml and was the first evidence that air had been or was present. The following Figure 5-49 shows the pressure decay immediately following that pressurisation together with the average internal temperature for reference.


Figure 5-49 - Pressure Decay following Pressurisation from Vacuum.
The adiabatic effect of the 2180 kPa rise was evident in the internal temperature with a rise of around $0.06^{\circ} \mathrm{C}$ at the same time as the pressurisation which could account for a subsequent pressure
decay over time of around 18 kPa (assuming a dP/dT factor of $300 \mathrm{kPa} /{ }^{\circ} \mathrm{C}$ at $19^{\circ} \mathrm{C}$ ) but not the 24.5 kPa indicated by the dashed red line which is more likely due to air solution.

The pressure decay time exponent, alpha, was 4.5/day (red dashed line). With an air content of 65 ml compressed to a volume of 2.85 ml at a pressure of 2180 kPa in a water volume of 110 litres the air ratio at pressure was $0.0026 \%$ and with pipe diameter of 435 mm the expected alpha value was around 4 to 4.5 consistent with the above exponential based on air solution rate experiments. Over the period of 24 hours the pressure has dropped 24.5 kPa . The air free P/V factor was around $10 \mathrm{kPa} / \mathrm{ml}$. The 65 ml at pressure is 2.85 ml and if completely dissolved should account for more than the measured pressure drop which indicates that most but not all of the 65 ml of air has dissolved with the balance needing longer time.

It was hoped that the pressure-temperature plot following the vacuum recovery pressurisation would provide guidance on any further solution of air over time. The following Figure 5-50 plotted the pressure and the PIT diffusivity probe temperature from sensor T2 following the pressurisation. Also shown are the air free theoretical PT curve and another with air content of 0.6 ml to match the T2 sensor curve. Added is a plot of pressure against the side wall temperature (green).


Figure 5-50 - Pressure Temperature Plot for Air Free Theoretical, 0.6 ml air estimate, PIT probe T2 Temperature and Side pipe wall Temperature.

The fit of the red with crosses 0.6 ml air curve to the orange T2 $(1.25 \mathrm{~m})$ curve is very good and appears to confirm the conclusion from the previous figure that most of the 65 ml of air had dissolved. This curve is evidence of the remaining 0.6 ml . It also showed the sensitivity of the P/T curve to the presence of air which in this case was 0.6 ml in 110 litres or $0.0005 \%$ at atmospheric pressure. The green curve of pressure with the side pipe wall temperatures follows both the orange and the 0.6 ml air curve but with a temperature offset of around $0.6^{\circ} \mathrm{C}$. Equation 5.3.1 was used to obtain the $\mathrm{dP} / \mathrm{dT}$ factor and P/T curve when air was present.

### 5.10.8 Tank Thermal Layer Variation with Weather and Season - DN435 Tank

Expected thermal gradients were based on the hot water tank principle in that heating from the bottom results in thermal mixing and uniform temperature distribution while heating from the top only produces a hot layer at the top and negligible mixing. The opposite was expected from cold application with cold applied to the top resulting in thermal mixing while cold at the bottom resulted in negligible mixing. Applied to the buried pipe or tank with the ambient driving the below ground temperatures the spring summer period with warming surface temperatures should produce thermal layering with negligible mixing while the autumn winter period with falling surface temperatures should produce maximum mixing and limited thermal layering.

The following Figure $5-51$ shows the pressure variation over time (light blue with right axis), different versions of the ambient temperature changes (orange colour with large fluctuations) and the pipe wall and internal tank temperatures (large number of close together readings).


Figure 5-51 - DN 435 Buried Tank Experiment Data Overview.
There are two variants of pressure; light blue (as measured with sudden jumps) and darker blue with offsets to provide a smoother continuous trace. The time period has been truncated as the internal probe results can be observed to deviate on the far right of the figure. What is shown is more than 15 months and covers a complete seasonal cycle. The shape of the pressure curve generally corresponds to the pipe temperatures. The ambient peak is in mid to late January while the pipe temperatures have a broad peak extending from mid-January to mid-March with the ambient generally dropping lower than the pipe from February through to the start of September and driving the slow drop in pipe temperatures. During the rise in ambient there are times when it is above the pipe which shows up as delayed bumps in the general rise of the pipe values. Fluctuations in the ambient
generally show up as bumps in the pipe temperature. There is no consistency in the ambient pattern from year to year other than the underlying sinusoidal like seasonal pattern.

The following Figure 5-52 expands much of the last half of the above Figure 5-51 to enable better viewing.


Figure 5-52 - DN435 Buried Tank - Detailed view of Data.
The following observations can be made regarding the data presented in Figure 5-52:

- The upper group consists of the internal temperatures T1 to T8.
- The lower group of dotted traces consists of the external pipe wall temperatures with two Tops, one Side and two Bottoms.
- The rapidly changing are the 48 and 96 hour running ambient averages.
- The finely dotted black lowermost trace is the pressure (right axis) which generally follows the bottom pipe wall and central internal values.
- Any "hills" in the internal or pipe wall traces usually follow after four to seven days jumps in the average ambient temperatures.
- The overall long-term rising trend of the ambient is reproduced below ground in the pipe almost without amplitude change.
- Reduction in below ground temperatures only occur when the average ambient has dropped to or below the below ground temperature.
- Increases in below ground temperatures only occur when the ambient is consistently above the below ground temperature.
- The 96 hour average ambient is a better indicator of below ground patterns than the 48 hour average version. A longer average of multiple days would be a further improvement.


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Of main interest to this study are the changes in thermal gradient within the pipe and the conditions which generate them. The pipe temperatures are a delayed consequence of the ambient seasonal and weather-related fluctuations and because of the delay it should be possible to anticipate and predict the below ground pipe temperatures from the weather and seasonal changes before the pressure test which is highly dependent on such pipe temperatures.

The following Figure 5-53 shows temperatures from the internal tank probe and the external pipe wall during the spring-summer period with generally rising below ground temperatures. This figure shows the effect of weather changes on the rising pattern.


Figure 5-53- DN 435 buried tank measurements showing significant change in thermal profile when temperature direction changes from rise to fall.

Included in this figure is the pressure shown as the lowest blue dashed line with scale to the right. The figure also shows measurements from the two top external pipe wall sensors, two external bottom pipe wall sensors and the single external sidewall sensor as finely dashed lines. While the initial rise in temperatures and pressures has all probes trending together, the downward slope shows the external top of pipe sensors dropping faster than the pressure and internal sensors, while the external bottom of pipe readings change less than the pressure. During the rising period all internal sensors except the bottom (T1 and T2) remain bunched together implying that heating was from the top or at least the upper soil layers with the bottom T1 and T2 sensors indicating the lowest temperature water accumulating at the bottom of the pipe. After the peak there was better temperature distribution. If the pipe was inclined, the rising portion would be more exaggerated with warmer water rising up the incline at the top of the pipe cross section and falling down the incline at the bottom with most likely a greater temperature difference than in the above horizontal case. The strange dip on the $28^{\text {th }}$ would most likely correspond to heavy rain with the upper sensors more affected than the lower.

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The range of temperatures inside the pipe is approximately 0.8 to $1.0^{\circ} \mathrm{C}$. Daily rise was $0.18^{\circ} \mathrm{C}$ per day and the fastest drop slightly higher. Adiabatic temperature changes for typical ANSI Class 600 pressure rated pipelines are generally below $0.4^{\circ} \mathrm{C}$ and dependent on ground temperature. While smaller than the range of temperatures across the pipe in the above figure, the adiabatic rise at the start of a test will supplement and disturb the pattern inside the pipe especially in the spring summer period where the surrounding ground temperature is higher and a sudden increase in water temperature will change that ground-pipe temperature differential especially if it coincides with weather induced disturbances. Following vacuum in the tank, pressurisation only resulted in an average water temperature rise of $0.06^{\circ} \mathrm{C}$ but disturbed subsequent temperatures.

The following graph Figure 5-54 includes and extends the above figure and shows the internal and external temperatures at a lower scale. The change from rising to dropping pattern observed in the above figure is repeated at each major direction change. Major changes are approximately from one to several weeks apart and not predictable. The external pipe wall temperatures closely match the internal at the same elevation.


Figure 5-54- DN 435 Buried Tank - comparison of DT85M recorded temperature measurements over same time as previous figure but with smaller scale.

The following Figure 5-55 shows the change in August from the autumn-winter drop in temperatures to the spring-summer rise. The green dashed bottom trace deviations are possibly a result of water accumulation in the bottom of the excavation (filled with sand but surrounded by hard sandy clay soil).


Figure 5-55 - DN 435 buried tank experiment - DT85M based temperature readings.
The following Figure 5-56 is a continuation of the above Figure 5-55 and highlights the delay between ambient average (blue) and the buried pipe on the same scale. The ambient changes are approximately 5 days ahead of the pipe.


Figure 5-56 - DN 435 buried tank experiment DT85M based temperature readings.
20 mm of rain on the $3^{\text {rd }}$ to $4^{\text {th }}$ November 2019 affected the readings with the rain percolating to the pipe, possibly via cracks in the ground or through the split conduit used to protect the buried cables.

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This is mainly shown in the above figure affecting the bottom green dotted bottom of pipe external sensor and also temporarily the external top of pipe dotted blue trace around this time.

The following Figure 5-57 of the tank internal and external temperatures was one year after the previous. It followed excavation to try to rectify the faulty signals from the internal temperature probes.


Figure 5-57- DN 435 buried pipe experiment DT85M readings.
Particularly interesting are the fluctuations in the top of pipe external measurements (dotted upper two traces of the lower group). Internal pipe temperatures do not change quite as much. These top of pipe changes implied that the higher temperatures in the ground above the pipe were causing thermal layering to be generated. In August there were only slight changes but in September the situation changed once the ambient temperatures reached or exceeded the tank temperatures. The ambient leads the top of pipe which leads the pressure. It appeared to confirm that the spring-summer period of rising ambient temperature is the major time period for thermal layering to be generated inside the pipe/tank which was the initial hypothesis.

All the above figures have concentrated on the spring-summer period where maximum thermal gradients were expected and temperatures generally rising. The following Figure $5-58$ shows the start of the autumn-winter period in which the pipe wall sensors merge together in the downward tranding period from lat March through to the end of April.


Figure 5-58 - DN435 Buried Tank - Falling Autumn-Winter Temperature Pattern.
The spread of the internal readings converges in late March from $0.7^{\circ} \mathrm{C}$ to $0.4^{\circ} \mathrm{C}$ and only starts to spread slightly in early April. The following Figure 5-59 shows the time in later 2019 and early 2020 up until the internal probe measurements became erratic.


Figure 5-59 - DN435 Buried Tank Experiment - Temperature change approaching AutumnWinter

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Internal sensor T2 has been removed as its readings were erratic and faulty. For the internal probe temperatures the range for $8^{\text {th }}$ January was $1.4^{\circ} \mathrm{C}$ whereas on $12^{\text {th }}$ February was $0.3^{\circ} \mathrm{C}$, a significant reduction. So that up until the last peak on $5^{\text {th }}$ February there was a large range of internal temperatures while a week after there was a small range especially during the continuous downward slope. Only when there was disturbance by weather changes did the range increase and then took time to re-establish but not to the same extent as with the high continuous downward slope. The external pipe wall pattern showed a large range of around $1.4^{\circ} \mathrm{C}$ on $8^{\text {th }}$ February after which it contracted to $0.1^{\circ} \mathrm{C}$. If thermal layering was responsible for acoustic velocity reduction then the period up to the end of January 2020 would have the greatest effect while February would be the time of least effect. Timing would be different in the previous year due to the longer period of time at maximum temperatures compared with the short time of the 2019-2020 peak.

### 5.10.9 Seasonal Change

The offset pressure curve was used for comparison purposes with nearby diffusivity probe readings from the five deepest sensors in the following Figure 5-60.


Figure 5-60 - DN435 Buried Tank - Pressure comparison with nearby PIT Diffusivity Probe Measurements.

The pattern of ground temperature driving the pipe temperature can be easily seen with the upper sensors at higher temperatures in the spring-summer phase and at lower temperatures in the autumnwinter phase. The pattern of the pressure curve was similar to one of the lowest three sensor temperature patterns. At the start it followed the T3 (red). On the first rapid decline it followed T2 (brown). The second rise was closer to the T3 (red) and the second decline again followed T2 (brown).

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These two sensors are at depths corresponding to a height above the bottom of the tank of 90 mm (T2 brown) and 315 mm (T3 red) which was very close to the centre height of the tank.

The inversion point where the one ground temperature pattern reversed into the other was easy to observe in the above figure and occurred around $27^{\text {th }}$ March 2019, $6^{\text {th }}$ September 2019, $8^{\text {th }}$ February 2020 and $30^{\text {th }}$ August 2020. The lower inversion points were within one week of each other whereas the upper one had a period of almost seven weeks separating them. The shape of the bottoming out of the pressure appears similar while the peaks differ significantly. It is always unwise to generalise about seasonal changes with just over two seasons of data. Longer term patterns can be inferred from the other diffusivity probes on the property within 50 metres of the buried tank location.

### 5.10.10 Effect of Depth of Burial on Thermal Gradients

The buried DN 435 experiments showed that the nearby diffusivity probe temperatures at a depth equivalent to around 100 mm above the bottom of the tank correlated well with the pressure changes. The top of the tank was buried 900 mm below the ground surface. What would be the effect of changing the depth of burial and in particular the effect of reducing it to 700 mm ? This experiment was not carried out but the 900 mm depth results may provide guidance. The main period for investigation was that where the anomalous acoustic velocity results occurred which was from late August to mid-October.

## Nearest Diffusivity probe and Tank Pressure

The following graph Figure 5-61 showed limited readings from the diffusivity probe installed in the corner of the trench and the pipe pressure. It indicated that the diffusivity probe can fairly accurately indicate the pressure and its variation even though not in contact with the tank.


Figure 5-61 - Comparison of initial pressure changes with the pit diffusivity probe next to the tank for different depths of $1.4 m, 1.25 \mathrm{~m}$ and 1.02 m with the best correlation with the sensor at 1.25 m depth near to the level about 100 mm above the bottom of the tank.

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The best correlation occured for the trench sensor at a height close to a position 0.1 metres above the bottom of the pipe. The pressure leads lower sensors and follows upper sensors as shown in the following pressure temperature plot, Figure 5-62.


Figure 5-62 - DN435 Buried Tank - Pressure compared against nearby Diffusivity Probe Temperatures.

This pressure-temperature graph for data from the previous figure showed in blue the close correspondence between pressure and diffusivity probe T2 temperature while the two either side have loops on the inner side closer to T2. T2 itself has such loops which imply that a better correlation could be obtained if T2 was slightly closer to the red T3 trace with a location possibly around 1.2 m or 1.15 m below the surface and around 150 mm to 200 mm above the tank base.

### 5.11 ADIABATIC EFFECT AND STABILISATION - FIELD EXAMPLES

One test section of a DN 1050 pipeline was pressure tested 6 days after filling with temperature probes installed a few days before filling as shown in Figure 5-63 which plots ground and pipe wall temperature together with the diffrence between the two with the secondary vertical axis. The ground temperature appeared to be free of any pipe temperature effects with the exception of the filling and possibly the period following depressurisation.


Figure 5-63 - DN 1050 Ground and top of pipe Pipe Wall Temperatures following Filling and during Pressure Test.

A different version of the difference plotted in Figure $5-63$ is shown in Figure $5-64$ with a $U$ shaped overall temperature change in the pipe wall temperature wiith superimposed pressurisation in two stages on $11^{\text {th }}$ and $12^{\text {th }}$ October and single stage depressurisation on $18^{\text {th }}$ October. The temperature change during the test has been copied and displaced next to the overall trend and shows a gradual reduction in relative temperature during the six day test period due to lack of correlation between pressure and average pipewall temperature.


Figure 5-64- DN 1050 Pipe Section Pipe Wall (Top) Temperature variation following Filling and during Pressure Test.

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The measurement location for Figure 5-64 was within a kilometre of the filling pump station and was affected by the dam source water temperature and the filling history of the test section with water flow cooling the ground. In the same test section the next temperature measuring record is shown in Figure 5-65 with both ground and pipe wall temperatures shown with the rapid fall in temperature on $7^{\text {th }}$ October a consequence of the probe installation. The ground probe was installed at pipe centre height in the backfill to the side of the pipe but still showed influence from the changes inside the pipe. The top of pipe wall temperature reflected the dual stage pressurisation and decay during the test followed by the single stage depressurisation. In both Figure 5-64 and Figure 5-65 the pipe thermoelastic effect can be observed as a slight depression at the start of each pressurisation and rise at the start of depressurisation both followed by the adiabatic water temperature changes. The location for Figure 5-64 was near a river crossing low point while for Figure 5-65 was at a high point to enable radio modem data transfer to the test container location near the pump station. Ground and pipe temperatures were expected to rise in October following the winter minimum most likely in August as reflected in the final rise in Figure 5-64 and the continual rise in Figure 5-65.


Figure 5-65 - Next Temperature Measurement Location for DN 1050 Pressure Test showing Ground and Pipe Wall Temperature changes.

In Figure 5-65 the lower dashed line is the linear trend of the ground temperature with the upper one a copy for comparison with the pipe wall temperature changes. The pipe wall overall trend is towards the ground trend but is still recovering from the filling induced changes with filling completed on $5^{\text {th }}$ October as evidenced in Figure 5-63. Even 6 days after filling the pipe temperature has not stabilised and needed a few more days confirming the work of Arfiadi et al. [9]. The depth of pipe cover at the location of Figure 5-63 was of the order of 1.8 metres and the soil was fine clay referred to as "black soil" with consequent difficulty in vehicle access following rain.

### 5.12 KNOWLEDGE GAPS ADDRESSED

Lack of field determined diffusivity data identified by Godbole [11, 115, 116] has been addressed for one location typical of cross country pipelines with two soil types and extended by simple experiments showing the effect of water content supported by field diffusivity change over periods from drought to wet.

Buried and above ground horizontal tanks of different sizes instrumented with external and internal temperature sensors and monitored by pressure have been examined and the effects of ambient studied. Pressure temperature plots for above ground tanks have demonstrated a relatively smaller response with larger diameter together with a larger separation of the rising and falling patterns for the larger diameter.

For the buried DN 435 tank, a nearby diffusivity probe with sensors at a depth between the bottom and centre height of the tank provided good correlation with the tank pressure.

Weather pattern and not diurnal changes dominated the buried tank pressure changes, an unexpected result but one consistent with Carson's [119] comments on weather changes. This lead to the suggestion that simple daily averages of Bureau of Meteorology data could be used to predict expected below ground changes many days later which would be of great benefit to the Pipeline Pressure Testing Industry. Such predictions were dependent on diffusivity values for the representative soils.

The work of Godbole [11, 115, 116] on hydrotest uncertainty concentrated on the after effects of sudden initial temperature changes modelling the adiabatic effects of pressurisation. Weather induced below ground temperature changes have now been found to be of comparable and even higher amplitude than such adiabatic changes and since will change over time unlike the decaying adiabatic effect may have ongoing consequences on temperature measurements during pressure testing.

### 5.13 CONCLUSIONS

The following points summarise the findings of this Chapter.

- Nearby diffusivity probe was able to predict pressure.
- AS2885.5 recommends ground probe at centre height of pipe which differs slightly from the above finding of 150 to 200 mm above base of 435 mm O.D. pipe.
- BOM daily maximum and minimum temperature data can be used to predict below ground temperatures.
- Ambient temperature measurements averaged over 48 or 96 hours to remove diurnal changes can also be used to predict below ground temperatures.
- Soil diffusivity is needed for the below ground temperature prediction from ambient.
- The overall trend of the pressure/temperature plots followed the $\mathrm{dP} / \mathrm{dT}$ variation with temperature for the relevant pipe parameters unless air is present.
- When air was present the pressure/temperature plots were rotated with the plots able to be used to estimate air content.
- The separation of the rising and falling portions of the pressure temperature loop pattern increased with pipe diameter.
- The amplitude change from peak to minimum followed ambient changes for smallest diameter and reduced with increase in diameter.
- Rainfall quickly disturbs below ground temperature measurements through rapid ground penetration and can distort results.
- Overcast cloud conditions improve the correspondence between amplitude of pressure temperature plot and ambient range.
- Pressure testing at lower temperatures, especially close to but above $4^{\circ} \mathrm{C}$, decreased sensitivity to temperature changes and improved leak detection.
- Adiabatic effects may be minor compared to continuing stabilisation after filling especially for larger diameter pipes.
- Adiabatic effects may be minor compared with weather induced below ground temperatures.
- Traditional top of pipe temperature measurements do not correlate with pressure as well as measurements at or below the pipe centre line or adjoining backfill measurements.


## CHAPTER 6 PERIPHERAL ISSUES FOR ACOUSTIC ANOMALY RESOLUTION

This chapter initially highlights peripheral factors that could be responsible for the acoustic anomaly. The acoustic anomaly in summary is the lack of correlation between acoustic velocity measurements and pressure during the pressure test. Any factors causing pressure changes without affecting velocity need to be identified and separated. Knowledge of the variation of acoustic velocity variation with frequency and temperature is important as is attenuation which affects the signal shape and velocity resolution.

Particular issues addressed in this chapter are; creep relevant to the DN900 and DN300 pipe acoustic measurements, distinguishing between creep and adiabatic based pressure decays, details of attenuation and phase velocity variation with diameter and wall thickess needed for acoustic measurements, acoustic differentials relevant to pipe diameters addressed later.

### 6.1 PRESSURE DECAY DUE TO CREEP

When pipe is manufactured a pressure test is carried out at a pressure which generates stresses around $90 \%$ of yield stress for a very short time of the order of 10 seconds and with very rapid pressure rise and strain rate. As noted previously, high strain rates result in yield stresses higher than for lower rates, Field pressure testing with pressurisation occurring over minimum periods of 30 minutes has a strain rate more than two orders of magnitude below that of the factory "Mill" test and yield will occur at stresses at least 16 MPa lower than in the Mill. When field pressure testing at or above Mill test pressure yielding may occur and creep or relaxation may follow resulting in exponential like decaying pressure. Pressurisation also generates adiabatic heating of the water inside the pipe which confounds the creep effect since such heating will cause exponential like pressure decay as the heat dissipates into the backfill and surrounding soil.

This section addresses examples of creep resulting from pressurisation to high pressures near pipe yield stress and its implications for effects on pressure decay and thermal effects which is important for resolution of the acoustic anomaly.

### 6.1.1 DN900 Creep Examples

Using a DN900 example where strength and leak tests were carried out at the same pressure, the following figure shows two main curves, a saw tooth blue curve using the left side vertical axis of pressure and the almost smooth red and green curves using the right side vertical axis of creep based pressure drop using Oehlert and Atrens' [112] version of Wyatt's [113] equation.


Figure 6-1 - DN 900 pipe subjected to repeated strength test repressurisations and estimated resulting creep curve using Wyatt's methodology

The first 0.042 days ( 1.0 hour) were used to generate the bottom smooth curve using Oehlert and Atrens' version of Wyatt's equation with the following coefficients:
$\alpha \quad$ alpha log function coefficient $=77.2$.
$\beta \quad$ beta time factor constant $=620.2$
To understand how the superimposed (less smooth) curve was achieved requires use of Wyatt's methodology which essentially requires shifting different parts of the saw tooth trace so as to match the other. For example the last saw tooth decay over two days has been shifted down and slightly to the left with the right hand end of the shifted curve visible at 1.900 days and 539 kPa . The other parts of the saw tooth are moved similarly to match the smooth curve. The start and stop positions of the new accumulated curves are plotted in the following Figure 6-2 with a logarithmic time axis. They follow a straight line the same as the above creep curve when plotted on a semi log scale.


Figure 6-2 - $\quad$ Same data as previous figure with start and end points of relocated creep/yield curves superimposed on the resultant creep curve using Wyatt's method..

There is a slight deviation from a straight line at the shortest times as a consequence of the one included in the logarithm bracket term (to avoid issues at zero time). The slope of the trend line changes with the stress (or applied constant pressure - in this case of 12550 kPa ).

In the above example, Figure 6-1 had pressure continuing to drop during the second day at a rate of 50 kPa /day and continuing at a lower rate into the third day purely as a consequence of creep or relaxation. This was an extreme example but pointed to the need to avoid maintaining the initial pressure, and stress, for assessment of leak tightness of the pipe. However it was important background for the DN 900 above ground acoustic measurements later in this document where over a period of many days the pressure returned to high stress levels at peak ambient times of day with the likelihood of creep or relaxation recurring.

### 6.1.2 DN 300 Creep Estimates

For DN 300 test section No. 8 (detailed later in this document) the following is the strength test plot used to generate the creep curve.


Figure 6-3- DN 300 strength test pressure decays from Roma Gladstone Project Test Section No. 8.

Three readings were used to generate an initial curve then the remaining readings superimposed. The combined set of points were used to find the alpha and beta values for Wyatt's equation with the following coefficients:
$\alpha \quad$ alpha $\log$ function coefficient $=58.24$.
$\beta \quad$ beta time factor constant $=950.16$
with the result in the following Figure 6-4 shown in terms of pressure decay relative to start.


Figure 6-4 - $\quad$ Strength Test decays modified and relocated to form a creep curve using Wyatt's method for DN300 Test Section No. 8. Note the inverted vertical axis depicting decay.

There was slight scatter in the data points which is a consequence of the difficulty of measuring a moving target in that a volume of water is added to repressurise while creep is continuing and the pressure measured with a dead weight tester which takes tens of seconds. An electronic pressure measuring instrument would improve the resolution and curve approximation. The following Figure 6-5 extends the blue curve in the above figure out to four days, well beyond the four hour measurement period of the Strength Test.


Figure 6-5 - $\quad$ Same figure as previous with time extended for four days

Changing to the log time version results in Figure 6-6.


Figure 6-6 - $\quad$ Previous plot with log time scale only for the continuous creep curve.
According to Wyatt [113], for reduction in pressure the shift is to the right along the curve in Figure 6-6. Reducing the pressure for the leak test resulted in a pressure drop from 13736 to 12421 kPa of 1316 kPa or $9.6 \%$. According to Wyatt's methodology, reducing the pressure by this amount requires the last red dot on the previous figure to be moved up to the right along the blue line for 1316 kPa above its value of 289 kPa at 3:34 ( 0.149 days) which would represent a vertical axis value of 1605 kPa which is not on the chart which only extends to ten days.

To ensure that leak test pressure is not affected by creep, the following Figure 6-7 shows the pressure drop (as percentage of last strength test pressure) and the expected 24 hour leak test pressure change due to creep.


Figure 6-7- Based on previous figures for DN300 Test Section No.8, estimating the effect of a pressure drop $(\mathrm{kPa})$ from strength to leak test pressure on the subsequent creep pressure change over 24 hours at the lower pressure based on Wyatt's methodology.

To achieve the same pressure change of 1 kPa as the pressure instrument resolution, a minimum pressure drop of $2.5 \%$ is needed which corresponds to 347 kPa drop. For higher creep amplitudes the minimum pressure drop will increase.

DN 300 Test Section No. 8 had evidence of yielding in the P/V plot which has been confirmed by the above creep plots. The assessment of unlikelihood of creep at leak test pressure removes one potential explanation of the acoustic velocity anomalies to be discussed later.

### 6.2 COMBINED CREEP AND ADIABATIC TEMPERATURE CHANGES

Figure 3-1 showed the maintenance of pressure within a required range for the strength test and without any drop in pressure permitted for the leak test. The result when pressurisings were removed was an exponential like pressure decay as a consequence of creep evidenced by Figure 3-2. Such creep related pressure drop has dominated adiabatic temperature related pressure decay. In the following figure are a series of similar tests without any pressure drop for the leak test but instead of being displayed as pressure decay are converted to an equivalent temperature decay to enable comparison with the estimated adiabatic temperature decay of approximately $0.3^{\circ} \mathrm{C}$. These tests were conducted at lower pressures where creep was less likely but still possible. Any repressurisation changes to maintain the pressure have been offset to provide relatively smooth curves (similar to the lower curve in Figure 6-1).


Figure 6-8 - Pressure Decay during Pressure Test where Strength Test Pressure maintained for Leak Test - DN 900 buried pipe.

Also plotted is an exponential decay (dashed) equivalent to the average decay. The average approaches $0^{\circ} \mathrm{C}$ after a few days and approximates the trends of almost all the curves above it but fails to plot those below and especially the rising blue curve. The curves below the average may have been caused by continuing creep in addition to the adiabatic decay while the rising blue curve may be
the result of lack of thermal stabilisation following filling possibly from a colder water source. Field data consisting of only pressure and top of pipe wall temperature measurements is not sufficient to enable separation of the two effects of creep and adiabatic temperature changes.

Figure 6-8 highlights a common observation of pressure tests, that of almost always a drop in pressure over time with an exponential like characteristic not unlike that of a leak. A consequence of the bulk water temperature rise due to adiabatic effects of pressurisation but in the above case augmented by creep. It also highlights the difficulty of distinguishing creep from adiabatic related pressure drops.

### 6.3 ACOUSTIC TEMPERATURE DEPENDENCE.

Fundamental to the acoustic technique is the variation of phase velocity with temperature and pressure. These relationships are normally expressed as differentials as were detailed in Chapter 2. Figure 6-9 provides graphic examples of such differentials for DN900 pipe.

Figure 6-9 shows with the grey curve that pressure/temperature or $\mathrm{dP} / \mathrm{dT}$ increases with temperature consistent with greater sensitivity at higher temperatures. The blue trace for acoustic velocity/temperature or da/dT reduces with temperature with reduced sensitivity at higher temperatures. The acoustic technique proposes the use of only pressure and acoustic velocity with the pressure/acoustic velocity or dP/da significant. The red dP/da curve combines the above $\mathrm{dP} / \mathrm{dT}$ with the invert of da/dT with heightened sensitivity at higher temperatures similar to the $\mathrm{dP} / \mathrm{dT}$ but heightened for pressure change and reduced for acoustic velocity change.

During leak tests, normally only small temperature and consequently acoustiv velocity changes occur which permits the use of the differential values in the Figures.


Figure 6-9 - Acoustic Differentials: dP/da, da/dT and combined dP/dT for DN900 Water filled Pipe at 11000 kPa - Variation with Temperature

When large temperature changes occur, the above differentials continuously change and estimation of the velocity or pressure change requires integration of the differentials over the range. While the pressure used to generate Figure $6-9$ was $11,000 \mathrm{kPa}$, minor changes in pressure do not affect the curves.

Similar Figures to Figure 6-9 for other pipe diameters were similar and are presented later when relevant.

### 6.4 ATTENUATION AND PHASE VELOCITY - DIAMETER AND W.T. VARIATION

In Chapter 2 there was detailed analysis of the low and ultra low frequency region mainly for air and less detailed treatment for water filled pipes. Properties of air (air velocity around $1 / 4$ that of water in steel pipes and much lower viscosity than that of water) permitted Weston [41] to achieve attenuation and phase velocity measurements at the equivalent of low to ultra low frequencies than would be unobtainable with water. Measurements of pressure surges in extremely long pipelines of many hundreds of kilometres and even longer would enable approaching these limits. Weston's [40] equations were approximations to the solutions but could not address the region between the low and ultra low frequencies. Textbooks such as Kinsler et al. [5] only addressed the linear portion of low frequencies. Baik et al. comprehensive equations [1-4] addressed the low and ultra low region but the equation solution is difficult which is the reason that this author contacted and requested the assistance of Kyunmin Baik to provide low frequency solutions for typical pipe diameters and wall thicknesses of water filled pipelines. Such numerical solutions are addressed below and further show the inability of textbook equations [5] to address the higher end of frequencies for the fundamental mode. These calculations are only for water filled steel pipe without any externally surrounding material such as pipe coating, water, concrete coating, soil or backfill. Bernasconi et al. [48] results shown in Figure 2-14 and modified with logarithm scaled frequency and attenuation in Figure 2-15, by this author, point to a change in attenuation from one with square root ( 0.5 exponent) frequency dependance to higher exponent frequency dependance.

Since phase velocity measurements are the fundamental basis of the acoustic technique and frequency based attenuation significantly affects the ability to measure such velocities, it is important to be able to predict the phase velocities and attenuation. Hence the following sections address Baik's calculations, field attenuation estimates and then factors that affect the shape of the produced signal and final echoes on which the phase velocity measurements are based.

### 6.4.1 Baik Calculated Attenuation and Phase Velocity

This Section reports the unpublished solutions by Kyunmin Baik of the Baik et al. [1-4] comprehensive equations including pipe elasticity and fluid viscosity. These calculations were carried out to resolve discrepancies in the low frequency region and the higher frequency region where the transition occurs between the fundamental ETO or $(0,0)$ mode and subsequent higher order modes. Also to be resolved were the variations with pipe diameter and wall thickness. These calculations were performed at the request of this author to finally detail these parameters for the working range associated with pipeline pressure surges and the related acoustic technique.


Figure 6-10 - Baik's Calculations of Phase Velocity for different pipe diameters and for different thicknesses of DN900 (ubpublished results)

Figure 6-10 plots the phase velocity variation for different pipe diameters of DN150, DN300 and DN900 with different wall thicknesses plotted for the latter. The overall shape appears similar for all curves with a progressive shift to the left as diameter rises. As wall thickness decreases the velocity decreases. The dip at high frequencies shifts to lower frequencies with increasing pipe diameter only. The low frequency rollover is similar to Weston's low frequency region.


Figure 6-11 - Baik's Calculations of Attenuation for different pipe diameters and for different thicknesses of DN900 (unpublished results)

In Figure 6-11 can be seen the effect of pipe diameter and wall thickness on attenuation in unburied pipe. The high frequency rise occurs at the highest frequency for the smallest diameter and progressively changes with diameter. Attenuation overall is radius or diameter dependent so that the smallest diameter has the highest attenuation for the bulk of the frequencies. For the DN900 pipe, the wall thickness is responsible for the dip centred around 300 Hz with the dip minimal for 20 mm and deepest for the 9 mm . The calculations produced negative attenuations requiring the calculations to terminate either side of the bottom of the dip. The smallest thickness which did not result in negative attenuation was 17.8 mm where the $\mathrm{D} / \mathrm{t}$ ratio was 51.4 . Note that for the bulk of the frequencies the attenuation is the same for the DN900 with the only changes in the location of the dip and at the highest frequencies with only minor changes. For the DN150 pipe there is only a very slight hint of a dip whereas for the DN300 it is more prominent.

The dip in attenuation at higher frequencies occurs at frequencies an order of magnitude smaller than the dip in phase velocity (Figure 6-10). The peak in attenuation (Figure 6-11) occurs at frequencies closer to the dip in phase velocity (Figure 6-10).

Since attenuation shown in Figure $6-11$ is expressed as dB/km, small increases in value when applied over many kilometres result in high attenuation. Hence the frequency region higher than the dip is effectively eliminated since it is difficult to detect such frequencies. What potentially could be of use is the dip frequency which appears to have the same attenuation as for around 10 Hz and lower (depending on D/t ratio) for the DN900 pipe. This would require sensitive attenuation measurements centred around the dip to confirm provided the pipe was above ground to avoid backfill/coating influences.

If the DN 150 pipe in Figure 6 -11 was plotted with a linear frequency scale, the result would be similar to the Baik et al. Figure 2-13 with the drop below 1 Hz dissapearing into the zero frequency axis and appearing as if it remained constant up to zero frequency. The dip at the high frequency end occurs around $10,000 \mathrm{~Hz}$. What is particularly of concern for the pipeline acoustic technique is the frequency range from 1 to 100 Hz where fortunately the phase velocity is approximately constant. Fundamental pressure surge frequencies for typical 20 to 50 km pipeline lengths occur around 0.01 to 0.03 Hz where the phase velocity is declining.

Figure 6-12 includes Baik's modification of Kinsler et al. [5] at the very low frequencies as their equation is linear even at such frequencies below 0.0001 Hz . At around 200 Hz there is a dip which again is not covered by the linear Kinsler et al. equation. Otherwise there is good correspondence.

Figure 6-12 suggests that for attenuation the Low Frequency equations of Weston may be a good starting point and similarly for phase velocity but with water properties used instead of air. Another factor is necessary and that is the non-viscous velocity of the ETO or $(0,0)$ mode velocity. Hence the approximation approach requires firstly to determine the non-viscous phase velocity which is then used as the reference velocity in Weston's Low Frequency equation instead of the velocity in a large volume of fluid. Such calculations of the ETO non-viscous velocity are addressed in the following section.


Figure 6-12 - Baik's Matlab low frequency attenuation (blue) comparison with his modification of Kinsler et al. equation (red) for DN900 pipe of wall thickness 20 mm showing higher frequency dip and lowest frequency divergence (unpublished).

This author's approximation to Weston's low frequency equations for water, Equation (2.6.3), is plotted in the following Figure 6-13 to permit comparison with Baik's complete calculation for DN900 pipe of 20 mm W.T.


Figure 6-13 - Water filled DN 900 pipe - Phase Velocity - Log Frequency - Weston's Low Frequency Equation and reduced Equation compared with Baik's Calcuations.

Baik's calculations only extended to 0.000005 Hz which would be a fundamental surge frequency for a pipeline of length $167,000 \mathrm{~km}$, two orders of magnitude longer than the longest of any current subsea pipelines. Hence there is no need to consider frequencies below 0.0005 Hz and no need to consider the Ultra Low Frequency region other than from the academic point of addressing phase
velocity going to zero at zero frequency which the Low Frequency equations cannot manage. At this frequency of 0.0005 Hz , Baik's curve is higher by around $5 \mathrm{~m} / \mathrm{s}$ and most likely reflects the difference between the Baik et al. full equation and the approximation using the combination of Weston's Low Frequency equation and the non-viscous pipe velocity as in Equation (2.4.13).


Figure 6-14 - Superposition of Frequency Scaled Attenuation and Phase Velocity together with Empirical Model of Attenuation at High Frequencies only. Attenuation and phase velocity adjusted to match 168 mm O.D. pipe results.

Attempts were made to find a relatively simple empirical equation to address the upper frequency characteristics with one attempt shown as the "Empir Atten" in Figure 6-14 using scaled attenuations relative to the DN150 pipe results. The following figure compares fourth order polynomial approximations to the attenuation curves using a linear scale and including the negative values calculated by Baik. The attempt to derive an empirical equation combining multiple fourth order polynomials was made but would have resulted in a very complex set of equations and was abandoned as of little value.

Kyunmin Baik offered to calculate the effect of surrounding backfill and soil on attenuation and dispersion which this author declined as he had the mistaken idea that the above solutions of Kyunmin Baik were sufficient and that soil and backfill effects simply added attenuation. This author was at the time unaware of Bernasconi et al. [48] work.

Field attenuation measurements (detailed below) point to any attempt to detail the upper frequency dip as totally irrelevant since burial conditions completely dominate increasingly with frequency and such frequencies are very difficult to detect in normal length pipeline sections.


Figure 6-15 - Polynomial approximations to high frequency attenuation dip for range of pipe diameters and wall thicknesses with frequency scaled to DN 150.

### 6.4.2 Field Measurements of Attenuation

While carrying out field measurements of velocity for the acoustic testing technique and measurement of pressure surges, attempts were made to measure frequency dependent attenuation. Pressure surges eventually become sinusoidal thus enabling very low frequency estimates of attenuation. The first surges analysed simply measured the change in sinusoid amplitude with time. Subsequent analysis of more complex surge shapes required manual digitisation of the waveforms and then computer based frequency analysis and comparison of amplitude reduction with frequency. Once the electromagnetic transmitter was designed, made and tested, single frequency measurements were carried out but failed to record the outgoing source signal and were of limited value. Later attempts when testing the DN900 buried pipe section were made again using single frequencies with the use of measured outgoing source signals.

Equations of attenuation such as Equation (2.6.6) have units of Nepers/metre ( $\mathrm{Np} / \mathrm{m}$ ) while the field attenuation measurements are expressed in $\mathrm{dB} / \mathrm{m}$ or $\mathrm{dB} / \mathrm{km}$. With the attenuation, $\alpha_{g}$ as in Equation (2.6.6), the expression for attenuation variation with distance, $x$, with the measured quantity as pressure, $p$, the general equation is:

$$
\begin{equation*}
p_{2}=p_{1} e^{-\alpha_{g}\left(x_{2}-x_{1}\right)} \tag{6.4.1}
\end{equation*}
$$

where
$\mathrm{p}_{1} \quad$ pressure at position or length $\mathrm{x}_{1}$
$\mathrm{p}_{2} \quad$ pressure at position or length $\mathrm{X}_{2}$
$\alpha_{g} \quad$ attenuation in Nepers/metre
Attenuation can then be found by taking the natural logarithm of Equation (3.4.1) and rearranging to give:

$$
\begin{equation*}
\alpha_{g}=-\frac{1}{\left(x_{2}-x_{1}\right)} \ln \left(\frac{p_{2}}{p_{1}}\right) \tag{6.4.2}
\end{equation*}
$$

This result is in Nepers/metre. For attenuation in terms of $\mathrm{dB} /$ metre the logarithm to base 10 can be used with the conversion factor from Nepers to $d B$ being 8.7. Hence the following version of the above Equation (3.4.2):

$$
\begin{equation*}
8.7 \alpha_{g}=-\frac{8.7}{\left(x_{2}-x_{1}\right)} \ln \left(\frac{p_{2}}{p_{1}}\right)=-\frac{20}{\left(x_{2}-x_{1}\right)} \log _{10}\left(\frac{p_{2}}{p_{1}}\right) \tag{6.4.3}
\end{equation*}
$$

The resulting units of Equation (3.4.3) are $\mathrm{dB} /$ metre if $\mathrm{x}_{1}$ and $\mathrm{x}_{2}$ are in metres with dB or deciBels being 20 times the logarithm to base 10 of the amplitude ratio. Hence to convert from $\mathrm{dB} /$ metre to units of attenuation as expressed in Equation (2.6.6) requires dividing the $\mathrm{dB} /$ metre value by 8.7.

## Summary of Pipeline Attenuation Measurements

Figure 6-16, following, summarised attenuation measurements for a range of pipe diameters from DN150 to DN900 for both buried and above ground. To enable the different diameter results to be compared, they have been scaled to heavy wall DN1000 pipe. As the theoretical attenuation equation included the reciprocal of both radius and velocity, a heavy wall velocity of $1480 \mathrm{~m} / \mathrm{s}$ has been chosen as the reference velocity for Figure 6-16. Thinner wall pipe will thus have higher attenuation as velocity is inversely related to wall thickness resulting in almost all measurements falling above the theoretical line.


Figure 6-16 - Pipeline Attenuation Measurements - DN150 to DN900 - Compared with Theoretical Linear Equation. Attenuation has been scaled for pipe diameter based on heavy wall DN1000 pipe.

The lower frequency of 0.01 Hz in the horizontal scale corresponded to a signal travel distance of 120,000 metres which can occur in a 30 km long pipe section with attenuation measurements based on fundamental surge frequencies and using multiple surge echoes. The DN 650 measurements were based on computer frequency analysis of pressure surges but relied on manually digitised input data taken from continuous pressure recorder charts.

While a number of data points were close to the theoretical line, a number of sets were above with a higher slope than the theoretical similar to that of Bernasconi et al. [48] but of lower slope. It is suspected that water content of soil and level of compaction of backfill may be important factors in increasing attenuation through a mechanism of contact damping of the pipe surface movement. Such damping would be expected to be higher in well compacted wet soil than in dry sandy or uncompacted soils. The DN 900 buried attenuation data was from a pipe in an irrigation area with high water table in clayey black soil whereas the data that closely following the theoretical were generally in dry arid soils. Bernasconi et al.'s [48] data from northern Italy for a pipeline constructed long ago should have well compacted backfill and likely have high water content. The variation of attenuation with soil type needed investigation with the work of Bernasconi and the above data hinting at the relationship to the theoretical above ground equation.

The DN 200 above ground data set showed higher attenuation and much scatter. The DN200 was only 108 metres long which limited frequency resolution and may be subject to signal analysis issues relating to transient response of transmitter and amplifier. Thermal convection in the water and thermal layering may also have had an influence. Neither of these factors were addressed when estimating attenuation.

The measured frequencies ranged from 0.01 to 600 Hz and covered both pressure surges and transmitter generated signals. Only in the case of DN 900 was the frequency close to the upper dip in Baik's calculations as shown in Figure 6-12. The low frequencies did not approach Weston's transition from Low to Ultra Low frequencies for water and nor did it approach the frequencies where the theoretical line started to curve upwards for lower frequencies.

## DN900 Attenuation Measurements.

Attenuation measurements were carried out using single frequencies for a DN900 buried pipeline of 3948 metre length. These results are shown in Figure 6-17 and were based on ignoring what appeared to be intermediate echoes. The same results were included in Figure 6-16 as "DN 900 buried" for comparison with other pipeline data measured by this author.


Figure 6-17 - DN900 Buried Scaled Attenuation Variation with Frequency $(\mathrm{Hz})$ compared with Theoretical..

Theoretical Kinsler et al. [5] attenuation estimates for the same diameter are shown in the lower continuous blue line of Figure 6-17. Using a power based trendline the slope of the DN 900 data has an exponent of 0.93 instead of the Kinsler et al. theoretical of 0.5 . Location was in irrigated agricultural land with around 100 metres of pipe nearest the instrument location submerged in water with a high water table expected. The estimated take off point from the Kinsler et al. theoretical line of around 1 Hz was significantly below the 35 Hz in Figure 2-15 adapted from Bernasconi et al. [48]. Shape of the Bernasconi et al. based Figure 2-15 differed slightly from the above Figure 6-17.

Of further interest was the lack of pressure effect on the attenuation with halving of the pressure with the two data sets indistinguishable. Theoretical attenuation reduction on halving the pressure was around $0.3 \%$. With air, attenuation reduces significantly with increased pressure while the above results show water to completely differ. Difficulties applied to estimations of the lowest frequency of 2.5 Hz in that the source had spurious higher frequency components which did not appear in the intermediate echo and were just discernible in the main echo making attenuation measurements approximate. Superimposed noise affected the high frequency measurements and were unreliable above 25 Hz .

With phase velocity, there was a significant effect of pressure as shown in Figure 6-18 with halving of pressure. Phase velocity was dependent on non-viscous pipeline velocity which varied with pressure with the theoretical reduction $2.9 \mathrm{~m} / \mathrm{s}$ or $0.25 \%$ with reduction from 14900 to 7750 kPa .


Figure 6-18 - DN 900 Buried Pipe Phase Velocity Variation with Frequency and Pressure.
The phase velocity reduction appeared significant in Figure 6-18 compared with the effect on attenuation in Figure 6-17 but was a consequence of the difference in graphs with the phase velocity vertical axis enlarged whereas the attenuation had a log scale with the measures in dB/km, also a logarithmic measure. The blue continuous line in Figure 6-18 is the theoretical from Kinsler et al. [5]. Increased frequency based attenuation has the effect of increasing the phase velocity variation with frequency provided the attenuation exponent did not exceed one (according to Equation (2.6.7). The green and orange dots represented values using Matlab while manually manipulating the attenuation and velocity to get the best visual match. The other set of blue and red dots were estimated from the attenuation values shown in Figure 6-17 using Equation (2.6.7). Other than at frequencies below 10 Hz there was reasonable similarity between the two sets.

These findings demonstrated the necessity for determining attenuation and phase velocity characteristics of the pipe prior to carrying out acoustic pressure testing in order to optimise measurement frequency ranges and waveform shape.

## Source Signal Doubling

The attenuation measurements reported in the previous section assumed that the measured source needed doubling in amplitude. Figure 6-19 following shows one recorded waveform based on stacking 8 records to reduce the noise associated with the intermediate echo.


Figure 6-19 - Complete Waveform with Source, Intermediate and Main Echoes for a 4.5 cycle source of 2.5 Hz resulting from stacking 8 waveforms.

Figure 6-19 contained three similar waveforms which were assumed to be the measured source, intermediate echo and the main echo respectively. The waveform was accumulated from 8 generated signals which were then averaged to reduce noise.


Figure 6-20 - Unstacked Source and Echo of 4.5 cycles of 2.5 Hz .
Figure 6-20 was without stacking and has no evidence of an intermediate echo although there is much low frequency noise which could disguise an intermediate echo. Amplitudes and shapes of the source and main echo in both Figure 6-19 and Figure 6-20 are consistent although with expected minor variants due to the higher noise level in Figure 6-20. The prominent intermediate echo in Figure 6-19, if real, should have appeared in Figure 6-20 even if modified. Another anomalous feature of the intermediate echo is that while appearing between the source and main echo it lacks any of the higher frequency features of both and appears as a low frequency filtered version of the main echo. It was thought to have been the result of reflections from heavy wall pipe at that location as it appeared in
many waveforms but at different amplitudes which decreased with source frequency. The only solution that can explain these anomalies was that the intermediate echo is in fact a subsequent echo following the main first echo but translated to a different location. If the timing of stacking of the 8 waveforms did not allow for sufficient decay of the multiple main echoes (especially for a low frequency with reduced attenuation) then such echoes may be repeatedly captured within the record at the same location. With stacking and averaging of 8 waveforms the amplitude of the second main echo should be $7 / 8$ times the actual because the first recorded waveform will not have the second main echo while all subsequent 7 had. Hence the intermediate echo needed to have the amplitude increased by a factor of 1.14 or $8 / 7$ besides relocation.

Amplitude of the source appeared slightly less than the main echo and hinted that its effective amplitude needed correction. Figure 6-21 following had the source amplitude doubled and the pseudo intermediate echo relocated to a second main echo location and appears far more realistic and points to the need for care in assuming that the recorded waveform reflected reality.


Figure 6-21 - Complete Waveform with Double amplitude Source, Main Echo and Pseudo Intermediate Echo relocated for a 4.5 cycle source of 2.5 Hz .

The doubling of the source amplitude can be justified by viewing the initial stages of pressure surge generation in Figure 2-1 and Figure 2-3 where the initial drop from the peak is only half of subsequent drops. Figure 2-2 did not capture this transition and is not relevant. It is difficult to explain in physical terms the basis for doubling the source. A test was carried out on the DN900 above ground 375 m long pipe with the transmitter and transducer positions reversed resulting in no overall change in source amplitude. Other than referring to pressure surge records such as Figure 2-1 and Figure 2-3 it is difficult to justify the doubling of the source other than it works. Attenuation results in Figure $6-16$, Figure 6-17 and Figure 6-18 were based on the doubled source.

Relocation of the pseudo intermediate echo in Figure 6-21 identified another way of estimating attenuation when the source is distorted and that is only to use the main echo and the pseudo
intermediate echo. Using these from Figure 6-21 resulted in an improved attenuation result at 2.5 Hz for Figure 6-17.

Applying the same approach to another waveform of 9.5 cycles of 5 Hz resulted in improved estimated attenuation for Figure 6-17.

### 6.5 SIGNAL PROCESSING ISSUES

Some issues relating to signal processing have been addressed in relation to attenuation such as false intermediate echoes for the DN900 pipe and the lack of true source pressure measurments for the DN 300 pipe. Below are other issues which impact on accurate measurements of phase velocity and attenuation which may impact on resolution of the acoustic anomaly.

### 6.5.1 Amplifier-Transmitter-Header Resonances

Attempts to determine combined power amplifier - transmitter response and characteristics were carried out by simply generating sinusoidal signals and measuring resonanances by changing the frequency and searching for the highest resulting amplitudes. The lowest frequency resonances corresponded to wavelengths as fractions and multiples of the pipe length. High frequency resonances appeared to correspond to wavelengths similar to distances between the transmitter and closed ends of nearby branch connections. Resonances relating to the transmitter were measured as shown in Figure 6-22 using a four litre accumulator.


Figure 6-22 - Large Transmitter Low Frequency Response with two Line Pressures of 7750 and 14900 kPa .

The accumulator nitrogen precharge pressure was similar at 7400 and 8000 kPa but the transmitter response was measured at different pipeline pressures and showed a shift in resonant frequency from 9 to 14.55 Hz when the pipeline pressure was doubled. A second sharper resonance was noted at higher frequencies of 21.5 and 27.5 Hz respectively which could be the response of the internal metal springs supporting and restraining the piston while the lower frequency resonances were
most likely those of the accumulator functioning as a gas spring not unlike a Helmholtz resonator. The amplitudes in Figure 6-22 were the highest of those measured. Prior to purchasing the four litre accumulator, the one litre accumulator normally used with the small transmitter was connected to the large double acting transmitter with precharge pressures of 1600, 2800 and 3400 kPa with operating pressures of 4000 kPa in all cases. The resonant frequency respectively reduced from 19, then 14 and finally around 13 Hz . A minor secondary resonance was detected at 38.5 Hz with amplitude less than a quarter of the main and appeared to be independent of the accumulator precharge and thought to be due to the piston retaining springs. It may also have been determined by the constant operating pressure.

Kinsler et al. [5] provided equations relating to the Helmholtz resonator consisting of a cavity of volume $V$ attached to a major space via a tube of length $L$ and cross sectional area $S$ with the relevant equation providing the resonant frequency. The transmitter-accumulator case differs from the Kinsler et al. case in that water is present between the pipe to tube branch and the base of the accumulator bladder with the bladder filled with nitrogen while the Helmholtz equations only relate to the same fluid filling both the tube and cavity. This author has derived the following Equation based on similar premises to Kinsler et al. but allowing for accumulator precharge, operating pressures and the presence of water.

$$
\begin{equation*}
f=\frac{1}{2 \pi} \sqrt{\frac{\pi d^{2} p^{2}}{4 p_{0} V_{0} L \rho_{0}}} \tag{6.5.1}
\end{equation*}
$$

where dimensions are assumed to be smaller than the wavelength corresponding to the frequency and:
$f \quad$ Resonant frequency without damping.
d Diameter of tube connecting accumulator to pipe (assumed constant and including transmitter).
p Line pressure (Pa).
$p_{0} \quad$ Accumulator charge pressure ( Pa ).
$V_{0} \quad$ Volume of accumulator when charged (cubic metres).
$L \quad$ Length of tube (m).
$\rho_{0} \quad$ Density of water $\left(\mathrm{kg} / \mathrm{m}^{3}\right)$.
Pressure ratios in this equation agree with the abovementioned resonant frequency changes from 19 to 13 Hz with accumulator precharge increasing from 1600 to 3400 kPa with constant line pressure of 4000 kPa .

The resonant frequency of the small transmitter with the one litre accumulator was measured at 17.9 Hz with no record of the relevant precharge nor operating pressures.

Position of transducer relative to transmitter was addressed in the DN 900 above ground pipe acoustic measurements. The test header has 7 valves with the first three DN 50 ball valves and the following two DN 25 ball valves followed by the DN 150 plug valve with blind flange on top and then another DN 25 valve. Valves were numbered from 1 to 7 with the DN 150 valve number 6 . All the
high pressure acoustic measurments were taken with the transmitter on valve 4 and the transducer on valve 5, the reverse of that shown in Figure 1-8. After the pressure was reduced the position of the transmitter and transducer were swapped to observe the change as shown in Figure 6-23.


Figure 6-23 - DN 900 above ground pipe - effect of swapping Transmitter and Transducer
Two waveforms are shown for comparison with the blue corresponding to the configuration of Figure 1-8 while the grey three hours earlier with similar pressure but had the transmitter on valve 4 and transducer on valve 5 as had been the case for all high pressure measurements. For other cases of the transmitter on valve 5 and the transducer on either of valve 4 or valve 7 there was no change in the two waveforms. The only contributor to any change in initial waveform shape was the location of the transmitter whether on valve 4 or 5 as shown in Figure 6-23. First peak time location difference is around 0.01 second which corresponds to a signal travel length of approximately 11.7 metres or pipe length of 5.85 metres which is close to the distance from the transmitter on valve 5 to the end cap. Trough to peak amplitude of the blue is approximately double the red. In Figure 6-23 the computer generated source is also shown which appears closer to the shape of the red waveform than the blue. Subsequent lower frequency peak (around 0.08 seconds) is earlier in the red than the blue with both likely to be the transient response. Ringing in the signals is the 76 to 78 Hz resonance which afflicts both signals similarly. Why a position change of 0.5 metres can result in such a significant difference is a mystery and requires further investigation. Such a difference with only a small location change partly explains the lack of similarity between the computer generated signal and the measured, implying that position of the transmitter on the test header has a significant influence on produced signal shape.

Source shown in Figure 6-23 has been changed from the computer generated signal by high frequency filtering using a single stage simple RC (resistor - capacitor) type filter to approximate the $8 \mathrm{~Hz}-3 \mathrm{~dB}$ response of the Australian Monitors AM1600 power amplifier used for the measurements when in AC and not in DC mode. Start of both measured signals are delayed by around 0.003 seconds from that of the computer generated signal and only bear an approximate shape similarity.

Figure 6-24 appears similar to Figure 6-23 except for 60 Hz instead of 40 Hz but with the opposite result from moving the transmitter. When on valve 4 the amplitude is greater but the signal spread out compared with the position on valve 5 . The measurements were taken 44 minutes apart so that extraneous effects such as pressure or temperature would have minimal effects with the pressure change from 6497 to 6604 kPa .


Figure 6-24 - DN 900 Above Ground Pipe - effect of swapping Transmitter and Trandsucer for 60 Hz

Why the reversal in shape for 60 Hz compared with 40 Hz ? Could the generated frequency determine the waveform shape in combination with the position? An attempt to resolve this issue compared a range of signals with frequencies of $10,15,20,25,30,40,50,60$ and 80 Hz which bridged across the range of the above two Figures. There was no significant difference between the signals before and after the relocation of the transmitter. The only confounding issue was that the pressures before the change were almost double those after the change together with the accumulator pressures whereas the above two Figures were for almost the same line pressure and accumulator pressure.

With no difference also between the transducer location relative to the transmitter, there is no support to speculation as to how and why the source signal needs doubling as mentioned in a previous section.

### 6.5.2 Source Signal Transients

Start and end transients resulting from the power amplifier, transmitter and pipe response will be discussed below. Prentis and Leckie [129] provide an equation for the transient mechanical response to an impulse at time zero in terms of displacement, $x$, as:

$$
\begin{equation*}
x=A e^{-c \omega_{n} t} \sin (\beta t+\varphi) \tag{6.5.2}
\end{equation*}
$$

$$
\begin{equation*}
\beta=\omega_{n} \sqrt{1-c^{2}} \tag{6.5.3}
\end{equation*}
$$

where
x
A
c
$\omega_{n}$
$\beta \quad$ damped natural angular frequency which equals $\omega_{n}$ if $\mathrm{c}=0$ but $0.92 \omega_{n}$ if $\mathrm{c}=0.4$ (See equation 3.4.2 above).
time (seconds)
phase which is zero if displacement is zero at time zero or $\pi / 2$ if unity at time zero.

This equation takes the form of a sinusoid quickly reducing in amplitude. Transients result from sudden commencement or cessation of signals and their influence on the signal is mainly at the start since it can interfere with and change the source while the end transient does not interfere with the prior signal.

### 6.5.3 Signal Generation and Characteristics

The following two source signals in Figure 6-25 and Figure 6-26 were generated by the large transmitter on the DN 900 above ground 375 m long pipe.


Figure 6-25 - DN 900 Pipe - Output Signals - Computer and System and Differentiation of Computer Output. Signal 3 x half sinusoids of 40 Hz .

The computer-generated signal (blue) consisted of 3 half sinusoids of 40 Hz frequency. This signal was sent to the power amplifier and then to the transmitter with the red signal then recorded by the pressure transducer and preamplifier. This output pressure waveform has 850 Hz noise superimposed and with a very slight start delay of around 0.0025 seconds after the computer waveform start with half of that time needed for the signal to travel 1.6 metres from the transmitter to the pressure transducer.

The system generated waveform appeared reversed (easily achieved with lead reversal) and then slowly climbs as a result of generating a transient. The transient includes a frequency close to the source frequency which may reflect a pipe resonance. An offset of around 0.06 seconds has been added to all traces in the figure to make visualisation easier rather than abruptly starting at the left axis.

According to acoustics and water hammer theory, to generate a pressure pulse a form of the Joukowsky equation [17] or the input impedance of a pipe [5] is needed given by:

$$
\begin{equation*}
p=\rho c v \tag{6.5.4}
\end{equation*}
$$

Where
p pressure
$\rho \quad$ liquid density
C speed or velocity of sound in the liquid filled pipe
v flow velocity of the liquid or fluid in the pipe.
There is movement of water generated by the transmitter's piston in a branch connection attached to the pipe (Figure 1-8). The flow velocity of liquid in the branch gets converted to a much slower flow velocity in the pipe. What is important is that only flow velocity generates pressure in accordance with Equation (6.5.4). The signal from the computer, ultimately to the piston coil, produces a displacement in proportion to the output signal current. Hence the final pressure signal will be proportional to the velocity of the coil displacement which in basic mathematical terms is the differential of the displacement. Added to Figure 6-25 as the orange trace is the differential of the computer signal which then appears to be shifted by 90 degrees ( $\pi / 2$ radians) corresponding to the effect of differentiation. The shape of the resulting signal is not fully aligned with the transmitter generated pressure but is close and just needs a small phase adjustment to the right. What has so far not been considered is the effect of piston coil inductance. The piston has a 2 or 4 ohm coil moving in a magnetic field with an iron core inside it which will result in inductance which should cause a phase shift in the current relative to the voltage output from the power amplifier. As mentioned above, current determines the movement of the coil so that an induction produced phase shift will affect the initial signal shape.

A higher frequency signal based on 80 Hz half sine waves is shown in Figure 6-26, similar to the above, with blue computer generated signal, red transmitter generated signal with again 850 Hz noise and the orange differentiation of the computer signal (right axis).


Figure 6-26- DN 900 Pipe - Output Signals - Computer and System and Differentiation of Computer Output. Signal 11 half sinusoids of 80 Hz .

Time scale is the same as the previous and the differentiated signal similar to the transmitter signal without the transient and noise. The time delay of the transmitter output signal is the same as the previous and not dependent on the input frequency and confirms its source with the signal generation hardware. A consistent initial delay is beneficial in ensuring the same effect on all signals. Again there is the same overall rising of the signal over almost 0.1 seconds but unlike the previous then drops back at the end of the signal as if there was a second transient generated by the signal end.

An investigation of pressure signal generation as the differential of the voltage output signal with phase shift due to piston coil inductance was never carried out. Only the DN900 pipe tests included both the computer and transmitter generated signals which enabled the above comparisons but doesn't fully resolve the initial discrepancy.

The transients identified in the above two figures interfered with the echo detection on the 375 metre long pipe section. Echoes were expected from the change in wall thickness in the further half of the pipe and from air pockets in both halves. The signal duration in the last figure was 0.07 seconds equivalent to a pipe length of 77 metres or echo distance of around 38 metres. The presence and continuation of the transient then made detection of near echoes more difficult.

### 6.5.4 Buried DN 900 Source Transients

Figure 6-18 highlighted phase velocity measurements at two different pressures. Source waveforms had start and end transients which in the case of the highest frequencies affected the measurements. One example of the source start and end transients is shown in Figure 6-27 for the higher pressure of 14920 kPa with transient decay frequency around 14 Hz , close to the resonant frequency of 14.55 Hz in Figure 6-22 for the higher pressure.


Figure 6-27 - DN900 Initial and End Source Transients at Higher Pressure for a Source Signal of 24.5 cycles of 32.5 Hz .

Shape of the end transient in Figure 6-27 has been affected by gain change and overloading so that the initial signal appears discontinuous with flattened peaks. A similar figure for a lower pressure of 7760 kPa with transient frequency around 8.3 Hz is shown in Figure 6-28 below for a signal of 22.5 Hz and with clearly displayed end transient. Transient frequency 8.3 Hz is close to the lower resonant frequency of 9 Hz in Figure 6-22 and was for a pressure of 7760 kPa . The initial transient has been recovered by subtracting the computer generated constant frequency of 22.5 Hz from the measured source signal. It has then been compared with a shifted copy of the end transient with good agreement.

Such transient frequencies appear to be dependent on the pressure accumulator precharge pressure which was 7300 kPa for the 7760 in Figure 6-28 but not recorded for the higher pressure of Figure 6-27. Both start and end transients represent the system response to a sudden imposition of the 32.5 Hz or 22.5 Hz signal onto a system at equilibrium. The sudden onset of a signal produces the start transient response while the end transient response is a consequence of the sudden cessation of the 32.5 Hz or 22.5 Hz signal. What is not obvious is that all of the intervening signal is subject to a transient response which can only be observed by the signal processing operation of convolution of the transient response with the input waveform which was programmed in Matlab.


Figure 6-28 - DN900 Initial and End Source Transients at Lower Pressure
In Figure 6-27 and Figure 6-28 only the source waveforms have been shown. A consequence of the transients is that such lower transient frequencies are less attenuated than the main source signal and hence dominate the main echo and make resolution of the higher frequency signal difficult as shown in Figure 6-29 below where the amplitude scaling has been adjusted based on end transient amplitudes and with the main echo waveform very different from the source. The echo has been time shifted so that the time does not reflect the true time for the echo.


Figure 6-29 - DN900 Source and Main Echo - Comparing Transients

## CHAPTER 6 - PERIPHERAL ISSUES FOR ACOUSTIC ANOMALY RESOLUTION

One consequence of the transients was the disturbance of the source signal as shown in the following Figure 6-30 for a 5 Hz source when the transient frequency was around 14 to 15 Hz . This affected the determination of attenuation at such low frequencies especially at 2.5 Hz as shown by the affected source shape in Figure 6-19, Figure 6-20 and Figure 6-21.


Figure 6-30 - DN900 Buried 3948 m Section, Source and Shifted End Transient for 9.5 cycles of 5 Hz .

The shifted end transient in Figure 6-30 approximately matches the superimposed interfering higher frequency signal as can be seen in Figure 6-31. The difference signal (red) between the computer generated source and measured source in Figure 6-31 more closely matches the transient (black) and points to the origin of the approximately 15 Hz signal as the continuous application of the transient to the source signal as mentioned above and which can be generated by convolution of the computer source and transient.


Figure 6-31 - DN900 Buried Pipe, 3948 m long, Source End Transient and Difference between 5 Hz Sinusoid and Measured Source.

A significant difference between Figure 6-30 and Figure 6-29 was that the source frequency was respectively lower and higher than the transient frequency. The source in Figure 6-30 has a maximum amplitude of $+/-100$ units while the difference shown in Figure 6-31 has a significant amplitude of $+/-$ 30 units so that the consequential effect of the transient response is to significantly modify the computer generated source. For significantly different source and transient frequencies this can result in errors in estimating the source amplitude since the two frequencies attenuate differently. While the source amplitude in Figure 6-30 has an amplitude of around $+/-100$ units, the sinusoid needed to produce the difference signal had an amplitude of $+/-80$ units which means that the source signal amplitude should be around $+/-80$ units with the difference signal of $+/-30$ units superimposed. This implies that the attenuation for 5 Hz in Figure 6-17 and for 2.5 Hz in Figure 6-19 will not be correct if based on the measured source waveforms.

Figure 6-30 only showed the source waveform. Figure 6-32 added the main echo and the intervening signals which showed traces of small amplitude echoes but no intermediate echo as appeared in Figure 6-19. Superimposed on this Figure 6-32 was a very low frequency sinusoid of 0.58 Hz to approximate the sinusoidal baseline of the waveform together with an averaged version of the measured signal to eliminate the 5 Hz signal.

The input is 5.5 cycles of 60 Hz which should last until 0.092 seconds. Superimposed on the 5.5 cycles is a lower frequency shape of around 10 Hz which is seen more clearly in the first echo occurring after 0.69 seconds. This is likely to be the result of the input pulse generating a transient response from the pipe system. This transient response needs to be identified and means developed to avoid its generation and for the existing data its removal.


Figure 6-32 - DN900 Buried 3948 m Pipe - Source and Echo - 9.5 cycles of 5 Hz .
Duration of the source waveform is 9.5 cycles each of 0.2 seconds which totals 1.9 seconds and corresponds to a fundamental frequency of 0.53 Hz similar to the 0.58 Hz . Peaks of the 0.58 Hz signal occur at the start and end of the source waveform and coincidentally at the start and end of the main echo with exactly 3 cycles occurring between the source and main echo. The measurement took place 13 minutes after a previous measurement with such duration sufficient to attenuate any existing low frequency noise in the pipeline section. However another example of 9.5 cycles of 5 Hz did not have the superimposed 0.58 Hz sinusoid which may imply an isolated spurious signal.

All of the waveforms generated for DN 900 Test Section No. 7 consisted of odd number of half cycles so that the start and end of the computer generated waveform were like mirror images of each
other. Observed transients appeared to have the same shape whether at the start or end of the waveform. Does the odd or even number of half sinusoids affect the transients? All the above transients were generated by the large transmitter with a four litre nitrogen filled pressure accumulator used on a DN900 buried pipe.

### 6.5.5 Above Ground DN 900 Source Transients

For the 375 metre long above ground DN900 pipe it was difficult to determine the nature of the transients since it was necessary to use short duration source waveforms and of higher frequency to obtain recognisable echo signals. A further issue was the presence of two significant air pockets and an increase in wall thickness 299.4 metres from the source end. A range of frequencies were used with the most common 40 and 60 Hz of 1.5 cycles duration and occasionally 5.5 cycles. The following figure provides a typical record using 1.5 cycles of 40 Hz .


Figure 6-33 - DN 900 above ground 375 m pipe - Source 1.5 cycles of 40 Hz .
The red trace is the computer generated signal while the central peak at 0.73 seconds is the main echo of the noisy signal from 0.06 to 0.1 seconds. The peak at 1.38 seconds is the echo of the peak at 0.73 seconds. The main echo of the source signal is the negative minimum consisting of two minima between 0.66 and 0.68 seconds.

The following Figure 6-34 shows a different result for 5.5 cycles of 40 Hz with two central peaks with the first around 0.73 seconds as for the previous Figure $6-33$ and the second around 0.84 seconds. The second peak results from the end of the source signal with the separation of the central peaks approximating the source length. The second main echo also had twin peaks.


Figure 6-34- DN 900 above ground 375 m pipe - Source 5.5 cycles of 40 Hz .
Each of the waveforms in Figure 6-33 and Figure 6-34 were generated by stacking or averaging 10 waveforms for the same source to reduce noise. The following Figure $6-35$ was produced by averaging 11 different waveforms for sources from 15 to 150 Hz and with different numbers of cycles.


Figure 6-35 - Estimate of Start Transient by stacking 11 different waveforms with Estimated Transient of 7 Hz .

Instead of aligning the source signal start times in the above Figure 6-35 the following Figure 6-36 used the same waveforms and delaying them so that the source signal end times were aligned at 0.285 seconds which was the end of the longest source signal.


Figure 6-36 - Estimate of End Source Transient by stacking 11 different waveforms with Estimated Transient of 7 Hz .

While the 7 Hz transient appears to approximate the start and end source transients the match is poor. These estimates of start and end transients were for a pressure of 3100 kPa . A similar exercise was carried out for 13200 kPa with resultant frequencies of 9.8 and 10.5 Hz for an accumulator precharge of 11500 kPa . These figures show that the generated signals are dominated by transients for almost half of the duration up to the first main echo.


Figure 6-37 - Comparison of Waveforms for 40 Hz and 850 Hz signals without Stacking.
Only two usable waveforms were recorded where stacking of multiple waveforms had not taken place amongst over 200 records. These two are plotted in Figure 6-37 and have an overall shape quite different from Figure 6-33 to Figure 6-36 which suggests that with the exception of these two
waveforms in Figure 6-37 all the others have been affected by echoes superimposed on the waveforms similar to Figure 6-19 for the buried DN900 pipeline.

There are no transient echoes in Figure 6-37 for the 850 Hz signal, most likely because the frequency is two orders of magnitude greater than the accumulator resonant frequency and unable to excite it. An averaging filter has been used for the 850 signal to remove its continuing interference in the signal. What is of most interest in Figure 6-37 is the basic shape of both which are very similar, excluding the low frequency transients of the 40 Hz responsible for most of the main and second echoes.

Comparing the 40 Hz signal in Figure 6-37 with a stacked one similar to Figure 6-33 and plotting both with the difference is shown in the following Figure 6-38 but with the difference time shifted 1.8 seconds so that the first peak of the difference appears as the third echo. The difference is also shown under the two signals but using the secondary vertical axis to allow it to be clearly seen.


Figure 6-38 - Comparison of 40 Hz Waveforms with 1 and 10 repeats and time shifted difference.

This exercise suggests that most of the recorded waveforms were a consequence of superposition of later echoes on the waveform due to inadequate delays between each repeated waveform. While Figure 6-38 indicated either of 1 or 10 repetitions, in fact the 10 represents only one set of repeats while the other resulted in a total of 100 so that the superposition is strongly reinforced. It further calls into question the above estimated transient frequencies since the first peak of the dark red difference trace at 2.03 seconds is a result of the peak in the stacked waveform at 0.23 seconds which coincides with the transient. Estimates of the transient attenuation appeared low and were most likely a consequence of the interference of this peak. Shape of the first difference peak appears to be an attenuated version of the second echo which in turn is an attenuated version of the first peak and in turn an attenuated version of the transient following the source in the first 0.1 seconds. Most records used only 40 and 60 Hz source signals and with only one usable single repeat waveform it is difficult to reconstruct the recorded waveforms and more difficult to extract the intended useful information
such as the air pocket echoes and their change over the recording period. Both the signal with stacked repeats and the one without show little evidence of higher frequencies around the time of the second echo at 1.4 seconds which would mean that the subsequent echo around 2.0 seconds will have little of the 40 or 60 Hz signals remaining so that when such echoes are time shifted forward they will not include higher frequencies as evidenced in the following simple construction in Figure 6-39.


Figure 6-39 - DN 900 Above Ground Pipe 40 Hz Stacked Waveform and Time Shifted Second Echo halved in amplitude. Single non-repeat waveform below for comparison.

In Figure 6-39 the second echo commencing around 1.26 seconds has been time shifted and effectively halved in amplitude as the red trace superimposed on the initial 0.5 seconds of the waveform. Other than the first 0.15 seconds, there is similarity between the two signals from 0.16 to 0.5 seconds as confirmation of superposition suggested above. It also verifies the need to double the initial source of the waveform (or halve the echo). It may provide a means of removing the superposition of later echoes. While the second echo has been used, the missing third echo should be used as identified in Figure 6-38. In addition the second echo has been subtracted from the source to produce the "difference" signal shown in orange (also translated vertically for better viewing) leaving the initial transient generally untouched but has removed the major fluctuations between 0.2 and 0.5 seconds. The exercise also demonstrates that the first period between source and first echo contains most of the high frequency signal features which are missing in later echoes.

Hence higher frequencies between the source signal and first echo will represent true signals with little to no contribution from the repeat stacking process. What may not be realised is that the stacking process progressively adds later and later echoes at different time points. The first signal does not include any echoes beyond the first two. The second signal will have included within it the first signal plus the delayed attenuated copy. The third signal will be similar to the second signal with a delayed attenuated copy added. This process will continue with more and more later echoes superimposed in the stacked signal which explains the significant difference between the two blue signals in Figure 6-37 and all the other signals obtained by the stacking process. This process suggests the possibility of

Matlab modelling of the stacking process and retrieving the original signal. The starting point is confirmation of the time delay between each progressive stacked waveform estimated for Figure 6-38 as 1.8 seconds. A second point is the expected attenuation which can be based on the DN900 buried pipeline results or the theoretical.

Towards the end of the series of above ground DN 900 acoustic measurements, the pressure was progressively lowered over two days to permit acoustic velocity measurements and assess the residual air effect. The following waveform in Figure 6-40 was obtained with the pressure close to 6000 kPa when the waveform shape appeared to be a decaying transient estimated to have a frequency of 7.1 Hz and a low damping factor of 2.8.


Figure 6-40 - Waveform, Estimated Transient and Difference for 1.5 cycles of 40 Hz in DN 900

## Above Ground Pipe.

This estimated transient was used to generate a difference curve shown in orange. Based on the above analysis of superimposed later signals in the stacking process, the estimated transient characteristics may be spurious but provided an opportunity to remove distorting signals while the 40 Hz higher frequency signals were likely to have attenuated sufficiently not to interfere in the first 0.7 seconds. Around 0.42 seconds in the main and difference signal was a small amplitude echo which could be from either the wall thickness change or an air pocket with the source comparison shown in Figure 6-41.


Figure 6-41 - $\quad$ Transient Difference signal compared with Source Signal with time shift of 0.41 seconds.

The echo waveform shape in Figure 6-41 generally matched the source although other similar shapes of smaller amplitude occurred throughout the signal in Figure 6-40. Echo axis is inverted which for an echo could indicate an air pocket.

With a time difference of 0.422 seconds between the source and echo in Figure 6-41, the location should be around 247 metres from the source end and very close to the surveyed pipe elevation peak at 250 metres, the location of the second air pocket as shown in Figure 6-43. If the estimate of 247 metres is correct then the air pocket could be around 4 metres long as a shallow pocket along the top of the overbent pipe. There does not appear to be obvious evidence of reflection from the far end of such air pocket other than the signal peak at 0.074 seconds in Figure 6-41. The time difference between this peak at 0.074 seconds and dip at 0.021 seconds is 0.053 seconds for an approximate signal travel length of 2 times the estimated 4 metre air pocket length resulting in a velocity of $150 \mathrm{~m} / \mathrm{s}$ for the air pocket. If this was the case the air fraction corresponding to such velocity according to Figure 2-17, copied from Ruggles [56], would be around $0.7 \%$ representing an air volume at pressure of approximately 4 litres with pressure of 5950 kPa . Such pocket would have a central bubble height of around 23 mm and width of 290 mm .

While the above analysis relating to the possible air pocket, another set of data using the difference from Figure 6-39 and comparing with the difference from Figure 6-40 and Figure 6-41. They both concur with the echo with peak around 0.44 seconds and minimum at 0.42 seconds with the amplitude much lower for the later date and lower pressure. The difference from Figure 6-39, the much earlier date of $22 / 01$ has a high amplitude signal commencing around 0.34 seconds (blue curve) where the first air pocket is located. The amplitude is high as expected while that of the much later 29/01 (red curve) is absent as noted above probably with all air dissolved. Can these two air pocket echoes be tracked in time in order to assess solution rates? The red curve was produced from the spurious difference between a highly suspect transient and the measured signal while the blue curve
was produced from the difference between the measured signal and a time shifted signal near the second echo. This strange combination provides support for the validity of the two approaches even while considering them potentially spurious. The next echo commencing around 0.53 seconds is highly likely from the change in wall thickness with a characteristic opposite to the air pocket reflections (non inverted) which is located 308.76 metres from the source end and only present in the red curve as the blue stops just prior. Detecting the wall thickness change is important as it provides a precise location against which to calibrate acoustic velocities, possibly assess the length of the air pockets and then assess the acoustic velocity effect of the air pockets which is normally difficult.


Figure 6-42 - DN 900 Above Ground Pipe, Difference measurements on 22/1 and 29/1 showing different echoes most likely from air pockets.

In Figure 6-42 the light blue waveform and green have been produced from the high pressure waveform with the blue by obtaining the difference between the time shifted waveform and the waveform. The green has been produced by a simple high pass filter of the the same waveform based on a -3 dB reduction at 32 Hz which then allow for the whole time period to be analysed as against a limited period for the light blue waveform. The filtered green also has less fluctuation than the blue.

The date when the above lower pressure waveforms were recorded was 12 days after initial pressurisation allowing time for significant air solution and consequent air pocket size reduction. If the location was the second air pocket as shown in Figure 6-43 then the first located around 200 metres must have fully dissolved which is likely as the location is relatively flat with the air distributed over a greater surface area of air/water contact compared with the second location where such conditions are absent. When the pressure was reduced, the discharged water at the opposite end to the source was milky indicating that it included dissolved air although the air pockets were minimum 120 metres away. Somehow water with dissolved air had been moved over 120 metres to the end low point most likely through longitudinal thermal convection currents. Such longitudinal convection currents, as shown by the CFD research for larger inclines, are generated when the pipe is daily heated and cooled by ambient temperature changes and also solar and night time radiation heat transfer. Such
movement of air saturated water is consistent with observations of Adeney [78, 79] who expressed surprise at what he called "streaming" of air saturated "quiescent" water.


Figure 6-43 - $\quad$ DN 900 Above Ground Pipe - Location of Air Pockets
For the DN900 above ground pipe, signal amplitude varied with the different source frequencies confirming the resonant character of the transmitter response as shown in Figure 6-44. Two features of note are the high amplitude at 10 Hz , the lowest frequency used, and a gradual rise through 150 Hz to a data point at 850 Hz . The 10 Hz is above the 7 Hz low pressure transient frequency while the high pressure resonant frequency was around 10 Hz .


Figure 6-44 - Transmitter Output Variation with Source Frequency and Log Scaled Relative Amplitude.

Another effect was that of an 850 to 900 Hz superimposed signal which can be seen from 0.3 to 0.7 seconds in Figure 6-36 dominating the 150 Hz based source waveform. Figure 6-41 also evidenced the same high frequencies in the source waveform and which appeared soon after initiation of the source. For a transient resonant frequency around 7 Hz the input length for Equation (6.5.1) is around 0.7 metres. This same length can be responsible for resonances of 850 to 900 Hz unrelated to Helmholtz type resonance but simply from a length of small diameter pipe whose length corresponds to a factor of the relevant wavelength or harmonic of the input frequency. Another possible resonance was 76 to 78 Hz consistent with the higher amplitude at 80 Hz in Figure 6-44. Some signals were deliberately generated at 78 Hz frequency as also the range 850 to 900 Hz to investigate the system response. 78 Hz corresponds to a wavelength of around 15 to 16 metres dependent on the velocity which could relate to the test header and in particular to twice the distance of 7.8 metres between the end cap and the blind flange on top of the DN150 valve.

These transients made it difficult to estimate attenuation and phase velocity for the above ground DN 900 pipe. Only the phase velocities for the transients were easily obtained.

### 6.5.6 DN300 Transients and Attenuation Analysis Issues

In Test Section No. 2 of the DN 300 Pipeline project there were no intermediate echoes that could interfere with attenuation measurements but the expectation was premature once transients were detected.

Constant frequency echoes were generated with 2 cycles and 6 cycles. The start of both has been shifted to enable direct comparison as shown in the following Figure 6-45.


Figure 6-45 - 14 Hz Echoes from 2 cycle and 6 cycle Sources superimposed to enable direct comparison of Start Transients.

For the end transient, the following Figure 6-46 has been prepared.


Figure 6-46-14 Hz Echoes from 2 and 6 cycle Sources superimposed to enable direct comparison of End Transients.

The end transient as seen in Figure 6-46 appears to be a rapidly decaying sinusoid with frequency close to the 14 Hz source frequency and in the form of a decaying sinusoid as in Equation (6.5.2). The start transient is not easy to comprehend. The 6 cycle echo sinusoid has initial changes in amplitude and slight vertical displacement differing for each cycle. 20 and 10 Hz echoes had similar start and end transients apparently independent of the source frequency. Figure 6-45 and Figure 6-46 were of echoes generated from constant amplitude and frequency sinusoidal source waveforms. Figure 6-47 is an example for 6 cycles of the higher frequency 18 Hz .


Figure 6-47 - Computer source and echo for 6 cycles of 18 Hz .
Figure 6-47 source and echo are positioned similarly to Figure 6-46 in an attempt to align the last cycle. Earlier echo peaks do not coincide with the source peaks with the first peak completely inverted. An attempt to replicate the shape of the echo in Figure 6-47 was carried out in Matlab using a 14 Hz frequency transient convolved with a constant amplitude computer generated 18 Hz signal as shown in the following Figure 6-48.


Figure 6-48 - $\quad$ Matlab produced Convolution of 14 Hz transient with 18 Hz constant amplitude Source with Transient and Source shown in the background.

End transient is as expected, although occurring later than the termination of the source, and the vertical position of peaks and troughs of the convolved signal (blue) show evidence of the start transient for the first three cycles. Figure 6-49 below shows the Matlab estimated echo using the convolved source signal from Figure 6-48 and appears to be a good approximation (although inverted) to the measured echo in Figure 6-47 but is missing the precursor signal: the gradual rise prior to the large drop.


Figure 6-49 - Matlab generated attenuated Echo from computer Source convolved with Transient.

The following figure superimposes waveforms at times of 15:15 hrs, 15:30 hrs, 15:40 hrs and 14:40 hrs for echoes of respectively 2 cycles of $50 \mathrm{~Hz}, 1$ cycle of $50 \mathrm{~Hz}, 1$ cycle of 70 Hz and 3 cycles from 30 to 50 Hz .


Figure 6-50 - DN 300 Section No. 10 - Superposition of echoes from different Source Waveforms showing the similar initial response by all but of different amplitude.

The DN 900 based Figure 6-44 showed variable amplitude response relative to the nearest resonant frequencies not unlike the variation in Figure 6-50. There is similarity in shape of the first negative pulse only, after which the difference in input waveform affects the result. As seen in Figure 6-51 the echo bears no correspondence to the input signal of 1 cycle of 70 Hz and is a feature of the amplifier/transmitter/accumulator system response into which the signal is submitted. For a short pipeline section length in the above case of 2045 metres, the effect of attenuation and delay from phase velocity make very minor difference so that the echo waveforms in the figure are very close in shape to the system response to the input signal. For much longer section lengths this does not apply.


Figure 6-51 - DN300 Pipe - Test Section No. 10 - Attempted identification of Transients. Source signal one cycle of 70 Hz .

Above estimates of the transients in the DN300 pipeline waveforms of 14 Hz are lower than the 17.9 Hz resonant frequency mentioned previously in relation to the small transmitter. Using Equation (6.5.1) for the 1 litre accumulator and an estimated water column length of 0.35 metres with internal diameter of 15 mm at line pressure of 12500 kPa and accumulator precharge pressure of 10000 kPa results in a resonant frequency of 14.15 Hz consistent with the estimated value of 14 Hz . The 17.9 Hz value was most likely for a higher operating pressure typical of the project where the measurement was made.

### 6.5.7 Amplifier Effect

Mentioned previously was the -3 dB low frequency cutoff of the Australian Monitors AM1600 power amplifier. The blue signal in Figure 6-52 was recorded and initially thought to be the pressure signal but later identified as the signal after passing through the power amplifier. The computer generated signal is shown in red and the amplifier has shifted the waveform and has superimposed an exponential characteristic to the upper peaks and at the termination of the signal. For frequency variable signals such as shown in Figure 6-53 the power amplifier has the effect of displacing the computer generated signal earlier but dependent on frequency. To the effect of the amplifier then must be added the resonant response of the transmitter. So that the measured waveforms in Figure 6-52 and Figure 6-53 are not the pressure signals and for all of the DN300 measurements no recordings were made of the outgoing pressure signal. Hence it was not possible to estimate attenuation and phase velocity variation with frequency. Only relative estimates could be made by using Matlab modelling of the outgoing pressure signal but such modelling is iterative and does not result in reliable estimates.


Figure 6-52 - Recorded Source Waveform of constant amplitude and 3 cycles of 8 Hz together with the computer generated waveform (red).

Exponentials were applied at the start and end of the recorded signal with both exponentials having the same time decay factor. The end of the recorded signal extends above the zero axis value
but much further. The following Figure 6-53 of a swept frequency shows the same effect as Figure 6-52 but not as obvious due to the longer signal duration.


Figure 6-53 - Measured Source Waveform of 10 cycles from 20 to 30 Hz with constant amplitude together with Computer generated Source.

The following Figure 6-54 shows the computer generated source (red) and the measured echo (blue). An unexpected aspect of the echo is the very low amplitude of the lowest frequencies at the right side in comparison with the left side. Frequency differences in phase velocity may enhance the amplitude of lower frequencies after the start transient and reduce them befor the end transient.


Figure 6-54 - $\quad$ Source signal of swept frequencies from 10 to 20 Hz then back to 10 Hz with total 20 cycles. Computer Source Waveform and Measured Echo.

At the end of the echo when only the lowest frequencies remain is there clear evidence of an estimated 12 Hz transient. This figure demonstrates that without a measured source signal estimation of attenuation and phase velocity is difficult and most likely unproductive.

A Matlab program was developed to estimate the echo waveform using theoretical attenuation and phase velocity. This program used Fast Fourier Transforms (FFT) to perform the process and such transforms are reversible. An attempt was made to predict the source waveform from the measured echo but was frustrated by high noise levels generated by the inverse process since the reverse process requires progressive amplification of higher frequencies including noise in the echo.

## Modelling of Amplifier Response

The algorithms used to estimate the power amplifier response and for the reverse process were developed by this author and are respectively as follows:

$$
\begin{gather*}
y_{i+1}=y_{i} \times \exp (-\alpha \times d t)+\left(x_{i+1}-x_{i}\right)  \tag{6.5.5}\\
x_{i+1}=x_{i}-y_{i} \times \exp (-\propto \times d t)+y_{i+1} \tag{6.5.6}
\end{gather*}
$$

where, based on input $X$ values and output $Y$ values for the instrumentation response;

| $y_{i+1}$ | new or current $Y$ value |
| :--- | :--- |
| $y_{i}$ | previous $Y$ value |
| $x_{i}$ | previous $X$ value |
| $x_{i+1}$ | current $X$ value |
| $d t$ | sampling time increment of digital data |
| $\alpha$ | decay exponent equivalent to the RC time constant of the instrumentation and with <br> units (such as seconds) consistent with the sampling time increment. $\alpha$ equals $2 \pi$ <br> times -3dB cut off frequency. <br> is the progressive index number of the sample input or output. |
|  |  |

The first input and output must be provided so that the equations only apply for the second and subsequent values. For the recovery operation, the inputs are the $Y$ values and $X$ the output values which enables complete recovery using values generated by the first Equation (3.4.6). The process causes a shift of one sampling interval, dt , which in most cases is negligible.

While used to model the effect of the power amplifier on the computer generated signal, this same algorithm can be used to perform a high pass filter operation by selecting the lower -3 dB frequency. This has been used as a simple filter to remove interfering frequencies as it is very easy to impliment in spreadsheets such as Microsoft Excel as it only relies on the current and previous values.

### 6.5.8 DN300 Crossing Waveforms.

The Table from Hough [13] is repeated for convenience as Table 6-1 below with an additional column for the distance from source to crossing start.

Table 6-1 DN300 Crossings with Known Length and Cepstrum estimated Length [13].

| DN 300 Crossings with Known Length and Cepstrum estimated Length |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
| No. Test Section | Crossing |  |  |  |
| Type | Known <br> Length (m) | Estimated <br> Length (m) | Distance to <br> Crossing Start <br> $(\mathrm{m})$ |  |
| 1 | Highway | 98 | $95+/-8$ | 26,196 |
| 3 | Creek | 126 | $136+/-7$ |  |
| 8 | Creek | 72 | $72+/-7$ |  |

Normal wall thickness pipe on the project was 5.4 mm thick while the pipe in the above crossings was 8.4 mm . For any wall thickness change the acoustic signal approaching the change is partially reflected which can be attributed to a change in the internal cross sectional area and the consequent change in acoustic velocity with it increasing with wall thickness.

The problem to resolve was the different nature of the acoustic signal reflection from the increase in wall thickness at the start of the crossing relative to the reduction at the end. Reflection from an increase in wall thickness is known to have the same but attenuated shape as the approaching waveform. What is not clear is whether there is an inverted signal from the reduction in wall thickness at the end of the crossing.

In Test Section No. 1 mentioned in the above Table 3-1, the following echo was obtained from the Highway crossing as shown in Figure 6-55.


Figure 6-55 - DN300 Pipeline Crossing Echo at distance of 26196 m from Source Location. Source signal was a swept sine from 1 Hz to 3 Hz over 20 cycles, all of constant amplitude.

Avoiding the complexity of Cepstrum analysis, a simple exercise was carried out by adding a copy of the source signal to a time delayed copy of itself with the time delay based on twice the crossing length of 98 metres and phase velocity of 1210 metres/second as shown in the following Figure 6-56.


Figure 6-56 - Estimate of Crossing Echo using unattenuated source and delayed copy of same.

There is obvious interference between the two component waveforms. The source signal is shown in red while the resultant of the two waveforms is shown in black. Overall shape does not match that of Figure 6-55 and while the measured waveform has a central bulge the estimated echo has an hour glass like shape.


Figure 6-57 - DN300 Crossing Echo estimate with source and inverted delayed copy of source combined.

Alternatively, the delayed copy of the source was inverted before adding resulting in the following Figure 6-57. Overall appearance is quite similar to the measured echo in Figure 6-55 and confirms the need for the echo from the reduction in wall thickness to be inverted before adding it to the source waveform; not unlike that from the start of an air pocket. Attenuation has not been applied to this estimated echo but would result in a progressive reduction in amplitude with higher frequency with the highest amplitude shifting from near centre in Figure 6-57 towards the left in Figure 6-55.

Changing the frequency sweep to 2 Hz to 5 Hz changes the interference pattern, as expected, and is shown in the following Figure 6-58. This Figure appears similar to that of Figure 6-56 but the recorded crossing echo in Figure 6-59 closely resembles Figure 6-58.


Figure 6-58 - DN 300 Crossing Echo estimate with source and inverted delayed copy of source combined. Frequency sweep from 2 Hz to 5 Hz over 20 cycles. Delay has been changed from 0.162 to 0.18 to match the recorded crossing echo.


Figure 6-59 - Recorded Crossing Echo in DN300 pipe with input signal of swept frequency from 2 Hz to 5 Hz over 20 cycles. Source was of constant amplitude.

While the estimated crossing echoes in Figure 6-57 and Figure 6-58 were based on different swept frequency ranges the expected attenuation difference for the frequency range will be small as it is based on the square root of the frequency. The worst change is from 1 to 3 Hz resulting in a reduction in amplitude of 0.58 for the higher frequency. The location of the minima in Figure 6-58 and Figure 6-59 was used to fine tune the time delay from 0.162 to 0.18 . Assuming an acoustic velocity around $1210 \mathrm{~m} / \mathrm{s}$ suggests that the crossing length is longer than 98 m at around 109 m . Heavier wall pipe should have a higher acoustic velocity than $1210 \mathrm{~m} / \mathrm{s}$ with a value of $1285 \mathrm{~m} / \mathrm{s}$ expected based on the wall thickness ratio. Such higher velocity suggests a crossing length of 116 m which is $18 \%$ longer than the "Known Length" in Table 3-1. What is not known is the effect of the slight attenuation on the shape of the source waveform reaching the crossing and the resultant echo shape relative to the theoretical one in Figure 6-58. This exercise highlights the possible use of wall thickness echoes to estimate their length besides the obvious of identifying their location and possibly their relative wall thickness change.

Another crossing with the same wall thickness change was located in the same Test Section but was not recorded as the source computer signal was recorded for the first 40 seconds and then switched to the return measured signal with a gain of 10 . The timing of the other crossing echo was approximately 17 seconds, well within the missing first 40 seconds. With two heavy wall crossings in the section the main echo would be reduced by the energy reflected back from these. In Test Section No. 1, no source signals were measured which together with the presence of two highly reflective crossings makes any attempt at estimating attenuation difficult.

Another ramped frequency example had a main echo with only minor overloading. It was combined with an inverted and delayed copy to approximate an attenuated version of the crossing waveform in the following Figure 6-60.


Figure 6-60 - Main echo (light blue) and combined copy with inverted delayed copy to approximate the crossing waveform.

The measured crossing waveform is shown in the following Figure 6-61.


Figure 6-61 - Main Echo from swept source from 5 Hz to 10 Hz over 10 cycles with constant amplitude.

The above exercise has demonstrated that echo waveforms from lengths of heavier wall pipe at crossings can be simply estimated by adding an echo from the start of the crossing to the inverted version from the end of the crossing without any change in amplitude. This confirms that any factor
which increases velocity such as extra wall thickness and reduced internal diameter produces an echo similar to closed end echoes and factors reducing velocity produce an inverted echo.

In the case of air pockets, the section of water filled pipe with air above it will function as a low velocity section with an inverted echo from the start and a normal echo from the end. Phase velocity reduction in an air pocket is expected to be much greater than any phase velocity increase from wall thickness change which will produce higher amplitude echoes from air pockets than wall thickness changes.

### 6.5.9 DN 900 Air Pocket Effects

Mention was made in a previous section relating to the above ground DN900 pipe of a possible detection of the second air pocket with location identified in Figure 6-43. Further analysis was carried out as shown in the following Figure 6-62.


Figure 6-62 - DN 900 Above Ground Pipe - Estimation of Air Pocket Reflection
The measured waveform has been filtered and a copy of the waveform time shifted with the start at 0.4263 seconds in order to match the same shape as the measured waveform from 0.45 to 0.49 seconds with this time shift corresponding to a velocity of $1162.7 \mathrm{~m} / \mathrm{s}$ if the location was 248 metres which was within 2 metres of the second air pocket peak at 250 m in Figure 6-43. A similar exercise to Figure 6-62 was carried out for the main echo with the velocity determined as $1160.4 \mathrm{~m} / \mathrm{s}$ (which was higher than the $1090 \mathrm{~m} / \mathrm{s}$ reported in Figure 7-19). Using Matlab calculated velocities for the component pipe sections resulted in an estimated air pocket average velocity of $427 \mathrm{~m} / \mathrm{s}$ in the air pocket location. Such velocity using Ruggles' Figure 2-17 or Silberman's Figure 2-18 resulted in an estimated air content of $0.053 \%$ at the pressure of 3104 kPa , estimated air volume of 32 litres at atmospheric pressure and an estimated air volume of around 1 litre at 3104 kPa which would be further compressed to 0.24 litres at $13,000 \mathrm{kPa}$. As per the heading in Figure 6-62 this measurement was for $29^{\text {th }}$ January around noon with the pipeline first at pressure around $14,500 \mathrm{kPa}$ on the afternoon of the $17^{\text {th }}$ January. Hence there have been 12 days during which air solution has taken place of which 10
days had been at an average pressure around 13000 kPa . On the $17^{\text {th }}$ January the measured air volume was around 8600 litres at atmospheric pressure or around 60 litres at 14,500 kPa. Filling took place some days before without any pigs to displace air and with filling from the low point end and air discharge from the upper end which could trap a maximum air quantity of 20,000 litres as shown in Figure 6-63. Filling was carried out with a centrifugal pump capable of generating around 600 kPa and the pipe was left with a similar pressure until the time of pressurisation when a pressure volume measurement was carried out which determined the 8600 litres (nominally 9000 litres) of air remaining (at atmospheric pressure). As shown in Figure 6-63 this air volume was compressed at test pressure into two air pockets of approximate volume 40 and 20 litres each with any air at the high point end vented. The above acoustic measurement did not detect the first air pocket, implying that it had dissolved, and the second air pocket had an estimated small quantity of air remaining of 1 litre at 3100 kPa or 32 litres at atmospheric pressure.


Figure 6-63 - DN 900 Above Ground Pipe - Surveyed Top of Pipe and Estimated Air Locations
The total pipe water volume was around 230 cubic metres which according to Figure 2-24 can dissolve around 4.6 cubic metres of air. So the estimated 9 cubic metres ( 9000 litres) can dissolve provided the pressure exceeds 100 kPa gauge, given sufficient time. According to the air solution rate Figure 4-18 the alpha value for this air fraction of 0.0003 at pressure was $6 /$ day which adjusting for an internal diameter of 885 mm resulted in an alpha value of 0.36/day at a pressure of around 13000 kPa . Over 10 days using such alpha value should reduce 60 litres at 14500 kPa ( 67 litres at 13000 kPa ) to 1.9 litres at 13000 kPa above the estimated 0.24 litres at 13500 kPa from Figure 6-62. However this volume according to Figure 6-63 was distributed with $67 \%$ in the first air pocket ( 40 litres) and $33 \%$ in the second air pocket ( 20 litres) so that of the estimated reduced air pocket of 1.9 litres only around 0.63 litres should have remained in the second pocket of which the 0.24 litres was $40 \%$.

In Figure 6-62 the time shifted axis was inverted for the air echo to match the source waveform. If a first air pocket was present it was not possible to reconcile the measured air echo time delay and the main echo time delay which was significant indirect confirmation of complete solution of the first air pocket. An attempt was made to approximate an inverted air reflection from the start of the air pocket and a non inverted echo from the end without success. It appeared that for an air pocket of short length, modelling was best based on an inverted echo from the centre of the air pocket.

### 6.5.10 DN 300 Air Pocket Analysis

Test Section No. 6 in the DN 300 project had the most significant air content and the section most likey to confirm whether the air content was responsible for the acoustic anomaly by velocity increasing as air dissolved. The following Figure 6-64 shows the section profile. The pressure instrument and equipment were located at the far left and red dots denoted temperature probe locations.


Figure 6-64- Test Section No. 6-Ground Profile with location of air pocket (black dot) and Temperature Probes (red dots).

The air pocket location was located acoustically around 627 metres from the far end of Test Section No. 6 and is highlighted in Figure $6-64$ by a black dot at the high point near the remote end. There was no evidence of air at the other high point at KP 172.937 (as noted on the figure).

The following Figure 6-65 shows the echoes from the location of the air pocket, the end of the section and then another echo of the end of section reflecting back from the air pocket. Such echoes continue repeatedly, but attenuated, with the next appearing at the end of the trace. The blue trace is prior to noise removal and the red after.


Figure 6-65 - Test Section No. 6 - Acoustic Waveforms for Air Pocket and identifying air pocket acoustic velocity.

This combination of strong air echo close to the end provided an opportunity to assess the effect on acoustic propagation in air pockets which have had little firm resolution in the literature.

The first echo shown commencing at 45.35 seconds was thought to be from an air pocket. However the initial shape has a negative excursion similar to the second larger echo from the end. For the shape to be similar means it cannot be from an air pocket but more likely from the start of a heavy wall factory bend which encases the air pocket. The third echo commencing after 47.5 seconds is inverted with the initial excursion upwards and opposite to the first two echoes. Such inversion is the characteristic of reflection from an air pocket. The shape of the fourth echo commencing around 48.6 seconds is indeterminate due to noise and low amplitude.

As shown in the figure there is a time gap between the first echo and the main echo of 1.081 seconds. The first echo has bounced off the start of the heavy wall pipe containing the air pocket but has not passed through. The larger main echo has passed through the air pocket twice with the first time in reaching the end and then when passing back through. The next echo is of the main echo reaching the air pocket and bouncing back without passing through then bouncing off the end and returning through the air pocket. It has passed through the air pocket only twice, the same as the large main echo, and so the time gap is shorter at 1.028 seconds. This time of 1.028 seconds is for the signal to bounce between the end and the air pocket twice without passing through it. The difference between 1.081 and 1.028 seconds is 0.053 seconds and is the time taken to pass twice through the combined length of air pocket and the distance from the air pocket to the start of the heavy wall factory bend.

Such bends are normally with bend radius of 5D which in this case would be $5 \times 323.9 \mathrm{~mm}$ or 1.62 metre radius with bend length for 22.5 degree bend of 0.636 metres with the remaining pipe providing the straight tangents to the curved section which usually are only a few diameters in length. Assuming a factory bend of length 3 metres with the air pocket at the centre and of estimated length 1.0 metre for 8.4 litres of air (at pressure) in the top of a 22.5 degree heavy wall factory bend the distance from the start of the heavy wall to the start of the air pocket would be around 1 metre. The air free velocity was around $1220 \mathrm{~m} / \mathrm{s}$ so that passage twice through one metre without air would take less than 0.002 seconds which is small with respect to the difference of 0.053 seconds. The length of twice 1 metre with air divided by the difference of 0.051 ( $0.053-0.002$ ) seconds gives a velocity of $39 \mathrm{~m} / \mathrm{s}$. Such air pocket has a cross section area at the highest location of $18 \%$ while the average over the 1 metre is $11 \%$. Using Ruggles' [56] figure, (Figure 2-17 for atmospheric pressure) air fractions of $18 \%$ and $11 \%$ result in estimated velocities of 45 and $35 \mathrm{~m} / \mathrm{s}$ respectively with the current estimate in the centre of this range. Ruggles' figure was for atmospheric pressure and the air fraction used above was that with the air compressed to the test pressure which should have similar results if the density difference between water and air controls reflection. At a pressure around 128 times atmospheric pressure the air density is still an order of magnitude less than water and sufficiently different to produce reflection.

If an air pocket was undetected but present, then the acoustic travel time for the main echo would have given a velocity around $1220 \mathrm{~m} / \mathrm{s}$. If the section was air free the velocity would be around 1.5 $\mathrm{m} / \mathrm{s}$ higher at $1221.5 \mathrm{~m} / \mathrm{s}$. This is due to the very low velocity through the short distance of the air pocket. For small air contents ( $0.07 \%$ of the total volume of this test section) the water hammer calculation uses Ruggles' approach to determine the air affected velocity based on this air fraction and generally only approximates the effect of air. The above has demonstrated a better approach. For large quantities of air, water hammer calculations usually split the pipeline into sections with the air containing section separate. The above has confirmed this approach.

Ruggles' figure (Figure 2-17 in this document) was based on evenly distributed air bubbles. The above is definitely not the same but a short consolidated continuous air pocket and appears to have the same effect as the equivalent air volume in distributed bubbles.

Measurements of the air pocket delay over a 20 hour period during the leak test has shown no significant change with only a very slight decreasing trend in resultant air pocket velocity of $5 \mathrm{~m} / \mathrm{s}$ over the time period which means either an increase in air pocket length from the estimated 1.0 metre or a slight increase in the delay time. The first alternative doesn't make sense. For an average time delay of 0.059 seconds with standard deviation of $+/-0.0058$ the indicated trend gets lost in uncertainty especially since the sampling interval of 0.002 seconds has an error of $+/-0.001$ seconds and has been used multiple times in the calculations. The conclusion is that there is no evidence of air solution taking place in the air pocket.

### 6.5.11 DN 150 Air Pocket Reflections

A 30 km long DN 150 pipeline had evidence of air pockets located at high points close to the Test Cabin end and shown in the following Figure 6-66 of the main echo and ensuing air pocket related echoes.


Figure 6-66 - DN 15030 km pipelilne showing Main Echo and Air Pocket Echoes.
The start of the waveform included the same echoes but were rendered more difficult to discern due to higher frequency content than the Main Echo and subsequent air pocket echoes. The Main Echo commenced around 46.8 seconds. A smaller amplitude version of it, but inverted, commenced around 48.2 seconds and another just before 50.5 seconds. These two minor echoes were inverted copies of the main echo indicative of air pockets. There was an intermediate echo commencing around 49.2 seconds which may be a composite echo of two air echoes close together. A similar echo occurred around 51.7 seconds. Implications air pockets will be discussed further in Chapter 7.

### 6.5.12 DN 300 Noise

Another issue identified was that of noise as shown in the following Figure 6-67. The second half of the time trace had been amplified by a factor of 10 with the echo occurring around 33 seconds. Low frequency noise of around 1 to 2 Hz can be observed from around 20 seconds until the echo. Similar figures for other measurements have similar noise which occurs at different time positions which confirms it as noise and not a reproducible echo. Such noise can interfere with echo detection and is most likely due to ground vibration from vehicle movement over or adjacent to the buried pipeline.


Figure 6-67- TS20938 complete waveform with latter half amplified by factor of 10 and showing evidence of low frequency noise.

## CHAPTER 6 - PERIPHERAL ISSUES FOR ACOUSTIC ANOMALY RESOLUTION

Noise present after 20 seconds should appear at one tenth amplitude in the first 20 seconds if the recorded source and subsequent 20 second period was measured by a transducer connected to the pipeline. The type of noise present is typical of electrical noise likely to be present in the A/D converter. The source signal is a pure sine wave of constant amplitude and frequency of 18 Hz for 6 cycles.

Most of the Figures from Figure 6-55 to Figure 6-53 have had higher frequency noise similar to mains electrical hum which was removed by means of averaging samples using the number of samples which correspond to the period of the noise. Input values for the average were evenly split either side of the result where possible. A comparison of and echo signal before and after noise removal is shown in Figure 6-68.


Figure 6-68 - Echo of 8 cycles of 18 Hz with and without high frequency noise.
In Figure 6-67, such higher frequency noise can just be seen but becomes more obvious when short intervals of time are viewed such as that for the main echo in Figure 6-68. The level of noise in this figure is relatively small.

Another feature of Figure 3-48 is the initial and end transients and interference with the amplitude of the 6 cycles of 18 Hz which appear to progressively decrease. What cannot be easily discerned is the fluctuation in amplitude most likely as a consequence of the continuing transient response.

### 6.5.13 Possible identification and removal of ground noise

The end of the previous section identified ground vibration induced noise which could interfere with the measured echo. Unfortunately for the measurements already carried out there was a memory limitation of 32,767 samples which restricted the recording to only one main echo to ensure best resolution. With higher resolution and greater memory capacity, multiple main echoes should be observed which would enable better estimation of attenuation but also enable identification of repetitive ground vibration induced noise since such noise has much lower frequency with consequent lower attenuation but also lower phase velocity. These features then may enable removal of such noise from the initial main echo better enabling the determination of the attenuation and phase velocity and consequent determination of the average pipeline internal temperature.

### 6.6 SIGNAL ANALYSIS

### 6.6.1 Correlation for Acoustic Velocity Determination

A relatively easy way to assess the delay time between source and echo is the use of correlation where one waveform is reversed and moved past the other progressively one sample at a time and the product of the two waveforms obtained. The correlation function then provides a positive or negative peak if parts of the two waveforms are identical. Matlab has a built in correlation function. Most of the results reported in this document used programs written in Pascal to achieve the same result with FFTs used to speed up the correlation calculation process.

The Analog Devices RTI815 circuit board had the ability to swap between two signal sources which was done only for the source signal while the echo was always recorded (as was the case with the previous Figure 6-67 and Figure 6-68). Two sources were available; that from the D/A converter sending the signal to the power amplifier and the pressure transducer signal from the test header. If the signal from the pressure transducer was used then the real outgoing signal was recorded and could reliably be used to correlate with the echo. Ideally the outgoing signal was attenuated and phase shifted to match the delay and attenuation of the echo. When the D/A output signal was used, the signal was prior to any influence of the power amplifier, transmitter and the pipe system. For short sections such as Test Section No. 10 ( 2045 m long) DN300 pipe the D/A signal was generally used which made the source signal simpler but did not record the system response. As a consequence there was considerable difference between the source signal and the echo as shown in the following Figure 6-69 for a single period of a sine (almost square) wave and its echo.


Figure 6-69- DN 300 Test Section No. 10 - Output and Echo Waveforms
There were a number of notable issues:

- Shape of the echo bears no relation to the source.
- The scale for the echo amplitude has been reversed - a common issue where terminals are easily swapped.
- The above signals have had DC offsets removed and the X10 gain normally applied to the echo removed so that they have the same scale.
- The signal length is determined by the memory accessible by the RTI815 circuit board of 32767 samples (2^15) which then limits time intervals in the above case to $1.16 \times 10^{-4}$ seconds with resolution of half that value and an acoustic velocity resolution of $+/-0.02 \mathrm{~m} / \mathrm{s}$ which can be improved slightly when correlation is used by peak detection of a curve through the points at the peak. Resolution could be improved with a larger memory size than 32767.
- There is minor noise prior to the echo and then a sinusoidal pattern after with the same minor noise superimposed.
- Just before the rise in the echo there is a dip of around 0.03 seconds from 3.33 to 3.365 seconds (top horizontal scale) which is most likely the response of the amplifier and transmitter to the input signal.
- The only reliable time point on the echo signal to use for velocity estimation is the sudden change to a rising signal.
- Echoes are attenuated and phase shifted with the higher frequencies having higher acoustic velocities so that the first arrivals are the high frequencies which correspond to the sudden shape change at the start of the echo.
- The source starts very close to zero time while the initial rise in the echo commences around 3.365 seconds giving for a section length of 2045 metres an acoustic velocity of around $1215.45 \mathrm{~m} / \mathrm{s}$.
- Using the Matlab correlation function resulted in a peak at 3.4097 seconds for an acoustic velocity of $1199.51 \mathrm{~m} / \mathrm{s}$. Significantly different from the correct acoustic velocity.
- Correlation use where the echo does not resemble the source results in erroneous results as evidenced by the above two results and the scatter for the Test Section No. 10 results.
- The shape of the echo appears like the transient response of an oscillating system which could include the nitrogen filled pressure accumulator above the transmitter acting as a spring/damper system together possibly with pipe vertical deflection and bending. The pressure pulse is injected vertically with the transmitter on top of the pipe and the pipe commonly supported away from the transmitter (for other reasons) which permits pipe vertical flexure.
- The initial part of the echo signal appears reasonably damped while the continuing constant amplitude sinusoid is highly undamped. The first is most likely the transmitter/accumulator transient response while the second is possibly the pipe flex resonance. The frequencies of both appear similar with the main echo period around 0.055 seconds and the other just below 0.05 seconds.

While the above list appears to invalidate the use of the correlation function it still has a use in that while there is poor correlation between the above source and echo there will be high correlation between echoes generated using the same source signal waveform. Most of the acoustic velocity
measurements were determined as time delay differences between a reference echo and similar echoes from the same shaped source. In the recorded signal the position of the source signal was always the same and at the record start as the triggering of the start of the A/D conversion and the output of the D/A signal occurred simultaneously.

The following figure shows two echo waveforms from the same source (30-50-3) at different times of 1:25 am (blue reference) and 14:45 pm (red) on the same day. Using Matlab's correlation function the time difference between the two was -0.00012 seconds whereas by viewing the two figures the red signal of $14: 45$ appears slightly ahead by around -0.0010 seconds which is an order of magnitude difference in delay and reduces the acoustic velocity by $0.35 \mathrm{~m} / \mathrm{s}$ instead of $0.03 \mathrm{~m} / \mathrm{s}$. While the initial part of the signal appears to match, a later part differs. This is compounded by the slight differences in the two echoes.

Relying on the correlation function even when the waveforms appear very similar but with a delay can result in discrepancies. Other techniques and probably different source signals are needed to improve echo time resolution and differences. Waveform stacking was not carried out for the DN 300 measurements and was essential for the DN 900 ones. Stacking would have improved the similarity between echoes from the same shaped source.


Figure 6-70 - DN 300 Test Section No 10 - Echoes 13 hours apart of the same Source Signal - Variation in Echo Waveform shape.

What is noticeable is that the initial drop of the first pulse is earlier for the red signal than the blue (reference) further confirming that the correlation calculation is deficient.

Differences in the shape of the echo waveforms for the same output signal may provide information on the internal conditions of the pipe over its length. What had been noted during measurements (possibly section 9) was that during the middle of the day the amplitude of echoes was reduced. So some factor, most likely thermal, was affecting the waveforms. Such changes have not been investigated and could for example identify presence of thermal convection currents in the pipe axial direction.

### 6.6.2 Conclusions regarding Signal Analysis

DN 900 buried pipe analysis was able to provide estimates of attenuation and phase velocity over the frequency range 2.5 to 35 Hz with the estimates at both extremes subject to errors. The results highlighted the influence of backfill in causing deviation from the theoretical for this frequency range. In the DN 300 case, what were thought to be measured sources turned out to be computer generated with or without an instrumention response but proved unsuitable to determine attenuation and phase velocity. A number of issues affecting the use of correlation to determine acoustic velocity have been identified which then questioned many of the acoustic velocity measurements. Dominating almost all measured waveforms were the transients most likely generated by the nitrogen filled accumulators above the transmitters. Their low frequency nature dominated the echoes and in turn adversely affected the use of correlation as an analysis tool. Echoes from wall thickness changes were able to be simply modelled provided the different wall thickness section was of sufficient length. Air pocket effects on phase velocity appeared to be limited to the extent of pipe in which the air pocket was constrained. This result confirms the Civil Engineering water hammer approach to the effect or air but seriously calls into question other approaches which assume the air is distributed over the whole pipe section. Resolution of the air pocket effect has important consequences for resolution of the air solution effect on acoustic velocity changes over the leak test period (acoustic anomaly) as was originally suspected (Hough [13]). The DN900 above ground pipe section provided an unexpected opportunity to merge the effects of air pockets and the modelling resulting from solution rate experiments on acoustic velocity.

The most important determination was the need to minimise or eliminate the source generated transients which most likely requires a significantly revised method of signal generation incorporating feedback. This may require some means of measuring the piston displacement, having the pressure transducer close to the transmitter output and controlling the computer generated signal to match the intended signal. In turn this would require experimental investigations of transmitter response and feedback methods to determine the required algorithms for transient correction.

Noise was reduced in the case of the DN 900 measurements by stacking up to 256 measurements but introduced spurious echoes though insufficient time delays between the measurements. This raised the need to first determine the likelihood of such effects and then to ensure adequate time delays before using such stacking techniques. Some noise was generated by identifiable sources such as the resonant length between the accumulator diaphragm and the pipe branch connection (DN 900850 to 900 Hz ), possibly the test header resonance (DN 90078 Hz ) and the ubiquitous mains frequency and its harmonics. Specific notch filters could be applied to remove such sources. Ground
vibration noise is not easily removed by the above approaches and may require patient waiting until dissipated or recording and subsequent removal.

Measurements have also highlighted the need for longer recording than the 32767 samples used in the analysis and for 16 bit or higher resolution than the 12 bit used. They also highlight the need for better measurement of the source pressure signal and the echo for which it may be necessary to use different transducers to cover the greatly different amplitudes.

Initial acoustic measurements on a test section need to assess the section specific attenuation and phase velocities on which the subsequent source signals are optimised to ensure maximum acoustic velocity resolution for temperature determination. In the process, air pockets and other intermediate echoes can be detected and their effects on velocity resolution resolved.

Further experimental measurements of attenuation and phase velocity of buried water filled pipe are needed to resolve the effect of backfill. Some theoretical modelling has been carried out [50] but inadequate field measurements.

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This author is unaware of acoustic measurements carried out by others in pipelines during pressure testing. In Chapter 6 attenuation measurements were reported for a range of pipeline diameters and for lengths up to the order of 30 km . Chapter 6 also reported phase velocity measurements for a DN900 buried pipeline almost 4 km long. This chapter reports on field measurements of acoustic velocity taken with the aim of using such measurements to assess the leak tightness of pipelines during the field pressure test or hydrotest. It specifically addresses what was reported at the APIA conference in Cairns, Australia [13] as anomalous acoustic measurements thought at the time to be a consequence of air solution. All of these measurements were carried out by this author.

### 7.1 FIELD RESULTS

The only published results of measurements by this author were those of the Oil and Gas Journal paper [21] and the APIA conference in Cairns [13]. The former confirmed the technique's use for above-ground air-free pipe, while the latter raised issues relating to possible air solution interference in buried pipeline test sections. The latter demonstrated the feasibility of the technique in the field during pressure testing with DN300 pipe and test section lengths up to 39 km long. As noted above, measurements enabled the detection of wall thickness changes 26 km away from the instrument location. This section provides other data not detailed in the above papers and other unpublished field results which this author considers relevant background to the present study.

### 7.1.1 Above Ground DN 200

Published results in the Oil and Gas Journal [21] were of acoustic measurements carried out on a DN200 pipe 108 metres long mounted on supports above ground. The results presented here extend those reported to address other issues relevant to the current document. The centre of the pipe length was instrumented around the perimeter with temperature sensors. The following Figure 7-1 compared the pressure and temperature when exposed to the sun with the pipe axis in an east-west direction with slight incline to ensure no air was trapped. Added to this figure are bottom of pipe (BOP) temperatures 17 m back from the highest end point of the pipe which pointed to a thermal gradient along the length of the pipe. This was further supported in that the centre length top of pipe (TOP) temperatures (blue) were the same as the bottom of pipe near the high point. There was a time lag between the central TOP temperature around 14:15 and the BOP peak around 15:30 hrs implying a convection flow of 40 metres in 1:15 hours or around $30 \mathrm{~m} / \mathrm{hr}$. Slope was of the order of 1 metre in the 108 -metre length. This points to an upper layer of warm water which was slowly moving towards and collecting at the high point which must be counterbalanced by a reverse flow along the bottom of the pipe which could explain the similarity between the bottom of pipe and centre of pipe measurements. The best correspondence between temperature and pressure was that of the "back" which was at the centre height of the pipe on the shade side. It was also similar in overall trend to the bottom but without the lower and upper deviations.

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Figure 7-1 - DN 200 above ground 108m long pipe - pressure and pipe wall temperature measurements (carried out at the same time as acoustic velocity measurements).

The vertical scales have a $\mathrm{P} / \mathrm{T}$ ratio of $280 \mathrm{kPa} /{ }^{\circ} \mathrm{C}$ at an average temperature of around $20^{\circ} \mathrm{C}$ which agreed with the theoretical in the following Figure $7-2$ of $283 \mathrm{kPa} /{ }^{\circ} \mathrm{C}$. The so called "bottom 17 m from high point" temperatures were close to that of the top of pipe and being within 17 metres of the high point indicated that at the high point most likely all the pipe cross section was hot.


Figure 7-2 - DN200 Acoustic Differentials $d P / d a$ and da/dT and their combination $d P / d T$
The pressure and velocity are plotted in the following Figure 7-3.

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Figure 7-3 - DN 200 above ground 108m long pipe - Pressure and Acoustic Velocity changes during the middle of the day - No air present.

There was very good correspondence between acoustic velocity and pressure except at the low end. When the pressure was released (indicated by the drop off) the acoustic velocity showed a small dip due to the influence of pressure. Comparing the vertical scales resulted in a dP/da ratio of 175 $\mathrm{kPa} /{ }^{\circ} \mathrm{C}$ which agreed with Figure 2-14. The theoretical acoustic velocity for a temperature of $20^{\circ} \mathrm{C}$ and 9500 kPa was $1267 \mathrm{~m} / \mathrm{s}$ which was consistent with the measured velocity at $13: 30$ of $1271 \mathrm{~m} / \mathrm{s}$. This theoretical calculation was based on an average wall thickness of 5.89 mm for 14 pipes of varying lengths and wall thickness from 4.9 to 6.4 mm . A slight increase in average wall thickness of 0.1 mm wouldl increase the velocity by $3 \mathrm{~m} / \mathrm{s}$ hinting that the wall thickness measurements may be slightly low.

These measurements were made in early August. However, direct exposure to the sun was responsible for the temperature rise and should generate some convection mixing other than the high point accumulation of hot water. With larger temperature changes in exposed pipe compared with buried, acoustic velocity changes are greater. This allows for better resolution which improved the correlation.

This DN200 exposed example demonstrated that without air the acoustic velocity measurements corresponded with both pressure and average temperature changes in ambient exposed pipes.

### 7.1.2 DN 150 Below Ground Pipe

A DN150 buried pipeline with an elevation range of 410 metres was hydrotested in mid-December with the pressure and temperature measurements shown in the following Figure 7-4.

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Figure 7-4 - DN 150 buried pipeline pressure and pipe wall and water temperature - using thermowells on the side of the pipe at multiple locations.

The two vertical axes have a matching scale so that 220 kPa pressure change is equivalent to 1.0 degree $C$ temperature change. With such scaling, the pressure drop was less than that from temperature. What was unusual in the temperature data was that the "water" temperature had been obtained by inserting temperature sensors via horizontal thermowells into the pipe at four locations and used to measure the internal water temperature. The pipe wall temperature change from around 18:00 to the end was closer to the pressure change than the water temperature. Since the measurements were made in mid-December west of Sydney during mid-summer, temperature drops appear unusual unless there had been a weather pattern change. No information was available on ambient temperatures.

Of significance was that the quantity of air detected was $0.36 \%$ which when compressed at a test pressure of $12,000 \mathrm{kPa}$ would be 18.3 litres based on fill volume of 608 cubic metres. Acoustic echoes identified two possible locations for air pockets at high points. Such air volume at pressure represented a pipe length of 0.93 metres full of air. However such air will be in over bends and form air pockets at the top of the pipe with water underneath sufficient to allow the acoustic signal to pass through. Such air pocket echoes were easy to identify acoustically by their typical inverted waveform.

Unusual about the acoustic measurements was the overall rise in velocity with time as shown in the following Figure 7-5 again with similar scales for pressure change and velocity change. This rise in velocity was completely opposite to both the pressure and temperatures in the above Figure 7-4. Note that the pressure scale has been changed from a range of 220 kPa in Figure $7-4$ to 2800 kPa in Figure 7-5, an order of magnitude increase to enable inclusion of all the acoustic data points.

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Figure 7-5 - DN 150 pipeline - pressure and acoustic velocity comparison over time.
The scatter in the acoustic data was due to noise effects on signal processing. The significant rise in velocity was thought at the time to be a consequence of air solution.

With an air content of 18.3 litres at pressure, the result of this air dissolving would be a pressure reduction of $49 \mathrm{kPa}(0.37 \mathrm{It} / \mathrm{kPa})$ whereas the pressure reduction seen more easily on the previous Figure 7-4 was 25 kPa which indicated that temperature reduction could account for 18 kPa pressure drop leaving 7 kPa unaccounted and possibly due to air solution.

Air pockets identified in Section 6.5, had sufficient water below the centre of each pocket to transmit the source signal to the test section end and return back to the source end. As evidenced by the air pocket locations, such air was distributed over the high point area which had an elevation range of 6 metres over 1.7 km and relatively flat. With such small diameter of DN 150, multiple localised high points of a fraction of the pipe diameter in elevation difference were easily produced during pipe laying. With multiple air pockets, estimation of solution rate was difficult due to the need to estimate an initial air fraction at pressure. If based on the 18 litres over 1.7 km the air fraction was 0.00054 at test pressure resulting in a diameter scaled alpha using Figure 4-18 of 1.1/day which would reduce the pressure by 33 kPa in 24 hours (1 day). Limiting the air fraction to say 6 pockets each of 10 metres would result in an air fraction at pressure of 0.015 and a diameter scaled alpha of $0.11 /$ day with a pressure reduction of only 5 kPa in 24 hours. The latter value of 5 kPa was closer to the unaccounted 7 kPa mentioned above and could provide guidance. This estimated combined length divided by the internal diameter produces a ratio of 385 . Such minor air solution related pressure drop cannot account for the significant acoustic velocity rise nor can the isolated air pocket locations with relatively short lengths.

The following questions arise:

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- Could air solution explain an acoustic velocity rise of around $4.5 \mathrm{~m} / \mathrm{s}$ ?
- Is thermal layering likely to affect the acoustic velocity in mid-summer to the extent noted?
- Could 18.3 litres of air at pressure dissolve over the 24 hour test period?
- Was the initial temperature drop of around $0.5^{\circ} \mathrm{C}$ over the first few hours consistent with adiabatic effects or other known temperature effects?
- With only four temperature measurement locations in 30 km , were the averages of measured temperatures representative of the whole section?

All of the above questions highlight the field difficulties in assessing whether there was adequate correlation between pressure and temperature or with velocity as a means of assessing leak status.

### 7.1.3 DN 400 - Buried Pipeline

A DN 400 pipeline around 14 km long but with only 12 metre elevation difference was tested in early winter. The following Figure 7-6 shows the acoustic differential variation with temperature at the average leak test pressure of 11870 kPa.


Figure 7-6 - $\quad D N 400$ Pipe - Acoustic Differentials of $d P / d a, d a / d T$ and combined dP/dT
For the average leak test pipe wall temperature of $17.65^{\circ} \mathrm{C}$ the important differentials are listed in the table below:

Table 7-1 - DN 400 Pipe - Acoustic Differentials

| DN 400 Pipe - Acoustic Differentials |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| Pressure (kPa) | Temperature <br> $\left({ }^{\circ} \mathrm{C}\right)$ | $\mathrm{da} / \mathrm{dT}\left(\mathrm{m} / \mathrm{s} /{ }^{\circ} \mathrm{C}\right)$ | $\mathrm{dP} / \mathrm{da} \mathrm{(kPa} /$ <br> $\mathrm{m} / \mathrm{s})$ | $\mathrm{dP/dT}\left(\mathrm{kPa} /{ }^{\circ} \mathrm{C}\right)$ |  |
| 11870 | 17.65 | 1.62 | 145 | 235 |  |

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Using these factors allows the following assessment was made.
Table 7-2 - DN 400 Test Section - Assessment

| DN 400 Test Section - Assessment |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Parameter | Initial | Final | Change | Vel. <br> equiv. <br> $(\mathrm{m} / \mathrm{s})$ | Temp <br> equiv. <br> $\left({ }^{\circ} \mathrm{C}\right)$ | Pressure <br> equiv. <br> $(\mathrm{kPa})$ |
| Pressure (kPa) | 11823 | 11914 | 91 | 0.63 | 0.39 | 91 |
| Average pipe <br> wall temp. $\left({ }^{\circ} \mathrm{C}\right)$ | 17.52 | 17.97 | 0.25 | 0.41 | 0.25 | 59 |
| Acoustic <br> Velocity (m/s) | 1174.28 | 1175.28 | 1.0 | 1.0 | 0.62 | 145 |

Using the pressure as the reference, the acoustic velocity change was $59 \%$ higher while the pipe wall change was $35 \%$ lower and in opposite directions. If the leak test acceptance criterion was based on the equivalent of $+/-\left(0.1^{\circ} \mathrm{C}+10 \mathrm{kPa}\right)$ or $+/-34 \mathrm{kPa}$ the pipe wall temperature would allow the test section to just pass ( $32<34 \mathrm{kPa}$ ) whereas based on the velocity it would fail ( $54>34 \mathrm{kPa}$ ).

The following Figure 7-7 and Figure 7-8 showed the acoustic velocity, pipe wall temperature and pressure variation over the leak test period


Figure 7-7- DN 400 buried pipeline around 14 km long with 12 metre elevation difference Pressure and pipe wall temperatures over period of pressure test - late June.

These two figures were constructed with the vertical axis scales consistent with dp/dT and dp/da respectively which allowed visual confirmation of the contents of the above table of changes.

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Figure 7-8 - DN 400 buried pipeline around 14 km long with 12 metre elevation difference Pressure and acoustic velocity showing general agreement and similar trend - Late June.

The pressure trace showed hints of ambient effects superimposed on a continuous rise with a minimum dip at around 11:00 then rise and fall while the initial part of the trace from midnight to 11:00 am showed a steady fall but one that on extension matches the end of the trace implying that the initial fall ws a composite of an ambient based fall and a rise due to some other factor. No ambient temperature measurements were recorded in the field notes to allow for better understanding of the pressure fluctuations.

The test section was filled with water 34 hours before the start of the leak test with a temperature of $13.5^{\circ} \mathrm{C}$ recorded at that time and which had risen to $16.06^{\circ} \mathrm{C}$ at the leak test start and continued to rise during the leak test. Water was from a nearby river which would reflect average ambient temperature while the ground temperature represented average ambient temperature weeks prior and for mid-June in southern Queensland, warmer. Warmer ground would heat the pipe contents from the bottom like a kettle on a stove generating mixing convection currents which in turn ensured consistent velocities. No air was measured in the section. Acoustic measurements had to stop when a tracked sideboom was operating nearby and the ground vibration could be felt while sitting in the test cabin. The soil at the test cabin location appeared to be sandy and the high ground vibration implied a high water table in the sandy soil. The location could have been an old river flood plain.

With cold water inside warmer ground and resultant good thermal mixing the acoustic velocity rise almost consistent with pressure is expected but implies that some other factor is involved. The convergence of the pressure and velocity traces over the period of the test indicated that with more time the leak test acceptance uncertainty value could be reached using only pressure and acoustic

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velocity. The red dashed line in Figure 7-8 was based on the three pipe wall temperatures recorded from the end of filling which showed an exponential exponent of $-0.033 /$ hour or $0.79 /$ day with time exponent of 1.0. Comparing the measured pressure with this dashed line did not provide a sensible ambient pattern and it had not rained for two weeks.

For this test section the following questions arose:

- Was the acoustic velocity rise wholly attributable to temperature effects?
- Could very small quantities of air cause the slight difference in slope between pressure and acoustic velocity?
- Has the assumed ground heating of the pipe contents affected the acoustic velocities?
- Can complete mixing with no internal thermal gradients be confirmed?
- With rising temperatures, did the temperature measurement location on top of the pipe correctly record the change?
- What was causing the convergence of the pressure and acoustic velocity and how long would it take to converge?
- Would test results have been different if more than three pipe wall probes were used?

As for the DN 150 test, the above questions cannot be answered at this stage.

### 7.1.4 DN 300 - Buried Test Sections.

For DN 300 pipe at $12,000 \mathrm{kPa}$ the following Figure $7-9$ provided the velocities and da/dT factor variation with temperatures from $10^{\circ} \mathrm{C}$ to $40^{\circ} \mathrm{C}$. This was based on the minimal wall thickness but adjusted from 5.6 mm to 5.95 mm to account for distribution of heavy wall pipe at road and water crossing locations.


Figure 7-9 - DN 300 Pipe - Velocity and da/dT variation with Temperature (10 to 40 C).

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The da/dT factor for DN300 pipe was repeated in the following Figure 7-10 together with dP/da and the product of $\mathrm{dP} / \mathrm{da}$ and da/dT namely $\mathrm{dP} / \mathrm{dT}$ for comparison and checking purposes.


Figure 7-10 - $\quad D N 300$ - Acoustic Differentials da/dT, dP/da and combined dP/dT.
The factors changed little with pressure and mostly with temperature as displayed. Values from these figures will be used in the subsequent discussion and calculations.

Extensive acoustic velocity measurements were carried out during the pressure testing of a DN 300 gas pipeline and reported at the APIA Cairns Conference as anomalous [13]. Initial acoustic velocities rose in an exponential like manner as indicated in the following Figure 7-11. The rate of rise appeared to be similar to the air solution rate measured by Chappuis [77] which led to the speculation that air solution was the cause of the rise and was mentioned as the possible cause at the Conference.

Mention was made in the same paper [13] of detection of wall thickness changes at road or river crossings together with estimates of their length using signal processing techniques (detailed in Chapter 6). Such measurements can be used to assess acoustic velocities and temperatures of subsections of the test section delineated by such wall thickness changes.

Observed acoustic velocities were generally similar to theoretically predicted ones, but attenuation measurements were found to be incorrect due to lack of source measurements (refer to Chapter 6).

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Figure 7-11 - DN 300 Test section acoustic velocity rising during the leak test - Absolute acoustic velocity values.

The following Table 7-3 compared measured and calculated velocities of the sections mentione in Figure 7-11 and additional sections for comparison purposes.

Table 7-3 - DN 300 - Test Section Measured and Calculated Acoustic Velocities.

| DN 300 - Test Section Measured and Calculated Acoustic Velocities |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| TS No. | KP <br> Length <br> $(\mathrm{m})$ | Average <br> Wall <br> thickness <br> $(\mathrm{mm})$ | Average <br> Pipe wall <br> temperature <br> $\left({ }^{\circ} \mathrm{C}\right)$ | Average <br> Pressure <br> $(\mathrm{kPa})$ | Measured <br> Velocity <br> $(\mathrm{m} / \mathrm{s})$ | Calculated <br> Velocity <br> $(\mathrm{m} / \mathrm{s})$ |
| 4 | 30743 | 5.610 | 15.715 | 12191 | 1218.9 | 1184.8 |
| 5 | 29657 | 5.608 | 14.575 | 12885 | 1199.5 | 1182.1 |
| 6 | 28252 | 5.636 | 17.31 | 12292 | 1219.8 | 1188.6 |
| 7 | 25598 | 5.626 | 18.3 | 12541.5 | 1202.1 | 1190.1 |
| 8 | 35347 | 5.609 | 18.03 | 12417.5 | 1202.2 | 1188.9 |
| 9 | 11618 | 5.600 | 19.96 | 12879.5 | 1227.7 | 1192.1 |
| 10 | 2045 | 5.600 | 22.655 | 12566.5 | $1215.8($ Ave) | 1196.0 |
| 12 | 9171 | 5.633 | 21.8 | 12811.5 | 1227.7 | 1196.2 |

The following Figure 7-12 compared the maximum measured velocity (red markers) with the theoretical (blue markers) which considered the average pipe wall thickness based on a combination of 5.6, 6.6 and 8.4 mm according to length. The varying theoretical acoustic velocities were affected by the average wall thickness and the average temperature.

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Figure 7-12 - Difference between measured and theoretical acoustic velocities.
As this pipeline route crossed parts of the Great Dividing Range and other similar areas with rock present, pipe with a concrete wrap containing wire reinforcing was used in sections where the trench had been rock blasted. The proprietary product name was Rock Jacket. Based on the following Figure 7-13 including the percentage of Rock Jacket, sections 4, 9 and 12 were some 30 to $35 \mathrm{~m} / \mathrm{s}$ higher than the theoretical (without Rock Jacket). Sections 5, 6, 7 and 8 appeared to follow a pattern parallel to the dashed blue line with 10 around $8 \mathrm{~m} / \mathrm{s}$ lower. The concrete reinforcing mesh is the main factor increasing the velocity as shown by the general increase in velocity difference with percentage of Rock Jacket.


Figure 7-13 - Variation in Difference between Measured and Theoretical Velocity and Percentage of Rock Jacket Concrete Coating.

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The strength test pressure was at the equivalent of $100 \%$ of pipe yield stress at the test section low point. Pipe Manufacturers normally in the factory do a pressure test on each pipe to $90 \%$ of yield stress called a Mill Test. When they are made aware that the pipe will be tested in the field to $100 \%$ of yield stress take the precaution of increasing the wall thickness or the steel strength. In addition there is a thickness tolerance for the plate used and to ensure the pipe can withstand the Mill Test Manufacturers select for slightly higher wall thickness to account for the thickness tolerance. This partly explained why the measured velocities were higher than theoretical based on nominal wall thickness. Another possible source of higher velocity is the reported section length. During construction reroutes were common due to difficult terrain and may not have been included in the reported section length. A higher actual length than the reported length would increase the echo time and result in a lower velocity with the opposite for a reduced actual length if the reroute decreased pipe length.

This simple comparison of measured with theoretical velocities has been able to identify:

- Presence of external Rock Jacket coating and approximate extent.
- Slightly increased wall thickness relative to nominal.
- Probable shorter pipe lengths than indicated by the horizontal based KP differences.
- Consistency in acoustic measurements to be able to highlight the above factors.
- Lack of other factors interfering with the acoustic results.
- No evidence of the air in Test Section 6 affecting velocity measurement results.

This exercise has also confirmed that the average pipe wall thickness based on length fractions was a reliable means of determining the velocity as was the average measured pipe wall temperature.

The velocity anomalies in Figure 7-11 were of the order of up to $2 \mathrm{~m} / \mathrm{s}$ during the leak test period, always with rising velocity and reducing over time. If the leak test was delayed after reaching pressure by one day for the DN300 pipe then there should be better correspondence between velocity and pressure

### 7.2 DN 900 ABOVE GROUND PIPE

An above ground DN 900 pipe of length 375 m inclusive of the mainline test headers at each end was pressure tested as required for certification purposes and then kept on test for around 10 days. Air was known to be trapped inside the pipe and the pipe profile surveyed to determine the likely locations of air pockets as shown in Figure 6-63. The following are details relevant to the subsequent analysis.

- Pipe consisted of two wall thickness with the smaller nearest the transmitter and pressure transducer location. A small echo was expected from the wall thickness change.
- Estimated initial air volume: 20,000 litres at atmospheric pressure based on Surveyor measured detailed pipe elevation and which also allowed estimation of the locations of the air content (see Figure 6-63).
- Pipe was left under pressure around 600 kPa during the waiting period before pressurisation.
- Delay time between water filling and pressurisation unknown but estimated as 2 to 3 days.
- Start pressure for pressurisation was 456 kPa .


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- Air volume estimated during pressurisation was around 8,600 litres.
- Pressure initially decayed during strength test and then rose as shown in Figure 7-14 below.
- Pressure was not reduced following the strength test so that any creep would continue. There was no indication of yielding during pressurisation. A typical creep curve for another test section of pipe with similar characteristics indicated likely creep should it occur.
- Pressure and acoustic measurements then followed over the next 10 days.
- During depressurisation over two days, acoustic measurements were taken at progressively lower pressures. Air was evident in the discharged water.
- Residual air volume prior to depressurisation was estimated from the velocity changes during depressurisation.
- No pipe wall measurements were taken during the process. Ambient measurements were only taken during the 4 hour strength test period.

Acoustic measurements were carried out initially to look for natural resonances in the system suspecting that the transmitting test header had such resonances. Measurement of the performance of the large transmitter was also carried out as reported in Chapter 6.

Acoustic measurements consisted of transmitting swept or constant frequency signals and detecting the initial and subsequent echo only. This was due to the memory limitation of 32,767 readings and the need to maximise velocity resolution. Due to signal noise of unknown origin multiple signals were progressively stacked on top of each other following each reading. Signal resolution was 12 bit while data memory storage was 16 bit thus allowing maximum 16 samples to be stacked without overload. A maximum of $16 \times 16$ or 256 stacked records was achieved by first stacking up to 16 and then dividing by the number prior to repeating the process and stacking the results. A range of frequencies were used from around 5 Hz to 900 Hz .

Since no pipe or ambient temperatures were taken, a subsequent above ground test of two short DN900 test headers was carried out with internal temperature measurements and pressure, as reported in Chapter 5 of this document. This was done to provide supporting information for the acoustic experiments. The only temperature measurements were late afternoon of the external pipe surface of the above 375 m pipe at one location only which appeared consistent with the internal temperatures of the short DN900 test headers, again reported in Chapter 5.

The following Figure 7-14 showed the strange pressure behaviour (black) when the pipe reached test pressure with an initial slight dip followed by an almost constant rise.

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Figure 7-14 - 375 metre DN900 Exposed Pipe - Pressure, Ambient and Estimated Creep with Ambient.

The ambient was also plotted in Figure 7-14 (blue with dots) with the scale selected to approximate the ultimate pressure rise. The orange-coloured curve is that of estimated creep which occurred in another buried pipe section during testing but superimposed on a linear rise to approximate the combined effect of creep with ambient rise. During the four-hour strength test the pressure rose over 14800 kPa at 13:00 hrs (4:00 hrs on Figure 7-14). It should rise further since the daytime temperature peak occurred around 16:00 hrs. Subsequent pressure over the next ten days was expected to oscillate with the diurnal ambient cycle with changes of almost 2000 kPa .


Figure 7-15 - DN900 - Possible Creep Curve based on Similar Pipe in Different Test Section.

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During the subsequent period of ten days under pressure Figure 7-15 above indicated the possibility for creep to continue but should only occur when the pressure was within a few percent of the original 14,500 to $14,800 \mathrm{kPa}$.

The following Figure 7-16 provided the acoustic differentials of da/dT, dP/da and the combined $\mathrm{dP} / \mathrm{dT}$ over the temperature range from $15^{\circ} \mathrm{C}$ to $45^{\circ} \mathrm{C}$ needed for the subsequent analysis. Although calculated at $11,000 \mathrm{kPa}$, there was little variation with pressure and was suitable up to $15,000 \mathrm{kPa}$.


Figure 7-16 - DN 900 Pipe - Acoustic Differentials: $d P / d a, d a / d T$ and combined dP/dT at 11000 kPa.

Summary plots for the DN900 velocity measurements are shown in Figure 7-17 and Figure 7-18 below. Figure 7-17 shows pressure and velocity changes which appear similar. Using the two axes results in an approximate dp/da ratio of $6000 / 30=200 \mathrm{kPa} /(\mathrm{m} / \mathrm{s})$ which from the above graph implies an average temperature around $21^{\circ} \mathrm{C}$. This crude estimate appears low. Linear trend lines have been inserted into the pressure and velocity traces of Figure 7-17 with the pressure (blue) dropping and the velocity (red) rising. This could be a consequence of air dissolving which would lower pressure and increase velocity. The above indicative creep curve could support less than 100 kPa drop over 9 days whereas the trend line was indicating 100 kPa per day. For the velocity the rise was $0.5 \mathrm{~m} / \mathrm{s}$ per day which should support an air free pressure rise of around 225 kPa per day. There was effectively a 325 $\mathrm{kPa} / \mathrm{m} / \mathrm{s}$ per day change taking place.

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Figure 7-17 - 375m Above Ground DN900 Pipe - Acoustic Velocity and Pressure Measurements.

Figure 7-18 showed many days of data condensed into 24 hours and superimposed on each other. Again using the ratio of range of axes gives $6000 / 20=200 \mathrm{kPa} /(\mathrm{m} / \mathrm{s})$. Chapter 5 information on the this above ground DN 900 pipe indicated an average internal temperature of around 33 to 35 degrees which using the above graph should have had dP/da factor of around $450 \mathrm{kPa} / \mathrm{m} / \mathrm{s}$.


Figure 7-18 - DN 900 Pipe 375 m. - Superimposed Pressure and Acoustic Velocity Measurements - 24 hour period.

The following chart Figure 7-19 showed the effect of free air on the velocity during final pressure reduction or depressurisation.

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Figure 7-19 - Acoustic Velocity variation with Pressure as Pressure was Reduced.
The readings were taken on final depressurisation and so showed the pressure-velocity trend with air present while ignoring temperature change over 2 days. The power law trendline in Figure 7-19, closely matched the data except for the two points close to 3000 kPa .

The following Figure 7-20 showed as the black dashed line the trendline from Figure 7-19. Also shown were estimated velocities for atmospheric air volumes from 10 to 300 litres for comparison. The best match was for the 80 litre atmospheric air content (orange curve). The top most finely dashed line used Matlab calculated velocities (without air) incorporating the component wall thickness velocity variation and IAPWS water property variation with pressure at a constant $32^{\circ} \mathrm{C}$ temperature. An Excel model estimated the variation in air pocket length with different air volumes at the top of the second air pocket shown in Figure 6-43. This Excel model also provided the central air pocket cross sectional area and air fraction which was used to estimate velocities using an equation to approximate Ruggles' Figure 2-17 and Silberman's Figure 2-18. These air affected velocities were then applied to the air pocket length to determine the time taken to twice traverse the air pocket, regardless of pressure. Another Excel model then for each pressure and atmospheric air volume estimated the air volume at pressure which then provided the estimated air pocket length at pressure and time taken to traverse it. This was then combined with the air free velocity for the remaining pipe length to generate the estimated velocities plotted in Figure 7-20. The dashed trendline generally matched the 80 litre orange line except for pressure below 6000 kPa at 3000 kPa .

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Figure 7-20 - DN 900 Above Ground Comparison of Measued Velocity and Estimated Velocities for Different Air Contents.

This correspondence of estimated velocity with measured (except for 3000 kPa ) demonstrated that the method of only applying reduced air affected velocities to air pockets was valid and such reduced velocities applied only for the length of the air pocket. The balance of the pipeline section was considered air free.

80 litres at atmospheric pressure was compressed to 2.5 litres at 3100 kPa (and 0.6 litres at $13,000 \mathrm{kPa}$ ) which was 2.5 times the estimated air pocket volume acoustically detected at a distance of 248 metres in Figure 6-62 ( 32 litres at atmospheric pressure). The value of 2.5 litres was of a similar order and was much better supported by the data from Figure 7-19 and its comparison with Figure 7-20. The location of 248 metres was still valid. Figure 6-43 used an estimated curve to approximate the pipe shape at the second surveyed high point at 250 metres but positioned the high point 2 metres short of the surveyed high point. The estimate of 1 litre was based on an estimated air pocket length and velocity, both of which were subject to error.

Discussion below Figure 6-63 expected an air volume of 1.9 litres at $13,000 \mathrm{kPa}$ after 10 days solution based on the initial air fraction of 0.0003 and the diameter scaled value of alpha from Figure 4-18. However Figure 6-43 assumed that 67\% of the air was located at the first air pocket and 33\% at the second air pocket so that the estimated 1.9 litres at $13,000 \mathrm{kPa}$ should have been split to around 1.27 litres at the first air pocket and 0.63 at the second which agrees closely with the 0.6 compressed litres at $13,000 \mathrm{kPa}$ from the 80 litres. This exercise using Figure 7-19 and Figure 7-20 highlighted the unexpected total solution of the expected 1.3 litres in the first air pocket probably due to the greater surface area of an almost flat high point. It also confirmed the diameter scaling used to generate

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Figure 4-18 and the concept that the centre of a short air pocket determined the air fraction and reduced velocity with the air pocket length then controlling the resultant section velocity.

This result for a 375 metre long above ground pipe with two isolated air pockets demonstrated that for air solution purposes the air fraction was the total air volume divided by the total pipeline volume. This air fraction was then reduced to the pressure at which solution would take place with Figure 4-18 then providing the alpha value which then needed to be diameter scaled. The evidence that the first air pocket around 200 metres from the instrument end had fully dissolved and that on depressurisation from the opposite end water with dissolved air was observed 125 metres from the second air pocket demonstrated that the pipeline length absorbing the air extended the order of 100 metres from air pocket locations and contributed to the water quantity needed to determine the air fraction. For some of the air solution experiments the initially compressed air pocket was less than the pipe length but with distances less than a metre. However the results in Figure 4-18 appeared to be able to be applied to a DN 900 pipe of 375 metre length with isolated near central air pockets. This represents a ratio of length to internal diameter of around 420.

In the previous Section 7.1 .2 for the DN 150 pipe, distributing 18 litres of air at pressure over a cumulative distance of 60 metres came close to estimating the possible solution rate pressure drop. This length to internal diameter ratio was around 385 which was close to the DN 900 ratio of 420 . Could an average length/internal diameter ratio of 400 represent the realistic extent of pipe contributing to air solution of isolated pockets or is such pure coincidence?

### 7.3 DN 300 - BURIED TEST SECTIONS.

During the DN 300 project numerous acoustic measurements were taken but were generally time limited to the period when the required leak test was carried out as part of the Pipeline Pressure Test. Often two tests were carried out simultaneously with the Test Container central and which only permitted acoustic measurements in one of the sections. This project indicated what this author called the acoustic anomaly which was thought due to air solution and with it an exponential like rise in velocity based on the solution rate published by Chappuis [77] as reported by Dorsey [76]. It was for the purpose of determining the actual solution rate and consequent time dependent pressure rise that the detailed work in Chapter 4 was carried out.

Using the measured or estimated air fractions for the respective test sections with acoustic measurements, the following Table 7-4 was prepared and provided the estimated time for $99 \%$ air solution using the air solution rate experimental data (Chapter 4) while assuming the air fraction was distributed throughout the whole test section.

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Table 7-4 - Test Section Air Content Summary and Air Solution considerations

| Test Secn | Volume <br> $\mathrm{m}^{\wedge} 3$ | $\mathrm{dV} / \mathrm{dP}$ <br> $\mathrm{It} / \mathrm{kPa}$ | Air\% | Initial <br> Pressure <br> kPa | Final <br> Pressure <br> kPa | Recalc <br> Final Press <br> kPa | Alpha | Time to <br> $99 \%$ <br> hh:mm:ss |
| ---: | ---: | :---: | :---: | :---: | :---: | :---: | :---: | ---: |
| 12 | 704 | 0.505 | $0.0040 \%$ | 12800 | 12799.94 | 12799.6 | 102.2245 | $1: 04: 48$ |
| 5 | 2278 | 1.67 | $0.0006 \%$ | 12900 | 12899.99 | 12899.9 | 359.3761 | $0: 18: 26$ |
| 6 | 2169 | 1.56 | $0.0738 \%$ | 12300 | 12298.97 | 12291.6 | 14.54271 | $7: 35: 29$ |
| 7 | 1966 | 1.44 | $0.0027 \%$ | 12500 | 12499.96 | 12499.7 | 130.4581 | $0: 50: 46$ |
| 9 | 892 | 0.646 | $0.0018 \%$ | 12900 | 12899.98 | 12899.8 | 174.0399 | $0: 38: 04$ |
| 10 | 704 | 0.113 | $0.0018 \%$ | 12600 | 12599.89 | 12599.1 | 171.3781 | $0: 38: 39$ |

This table effectively demonstrated that any air would be rapidly dissolved in all sections, possibly during the four hour strength test, except Test Section No. 6 where it would take over seven hours provided it was distributed throughout the section. Chapter 6 showed that Test Section No. 6 had a distinct air pocket close to the end containing all the air in the section which negated the assumption of distribution throughout the section and would likely require an extended time beyond the duration of the leak test for solution. Test section No. 8 was not included in Table 7-4 but contained no measurable air. All test sections were required to commence pressurisation at the lowest pressure possible while maintaining the hydraulic head without vacuum at high points. Hence was ideal for air content assessment.

The following Figure 7-21 compared the differences in measured velocity with start point the beginning of the strength test and considered as zero time.


Figure 7-21 - Comparison of velocity measurements during leak test - Comparative increases in Velocity.

Air was not observed during the pressure-volume plot for test section 8 located in the valley floor and the velocity rise in Figure $6-7$ was estimated at $0.2 \mathrm{~m} / \mathrm{s}$ during the leak test and possibly $0.3 \mathrm{~m} / \mathrm{s}$

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from the strength test start and could not be due to air solution. The highest air content was in test section 6 , mentioned above. The velocity rise in section 6 was the second highest at $1.8 \mathrm{~m} / \mathrm{s}$ during the leak test and $2.2 \mathrm{~m} / \mathrm{s}$ from the strength test start. Sections 8 and 6 provided the extremes in relation to air content. Section 8 had the least velocity anomaly while section 6 had the second worst with test section 12 the worst. Air in test section 6 could be observed acoustically and remained for the duration of the pressure test, 30 hours, and did not dissolve as implied by the above table due to the air being at a very short specific location of length near to one metre. It was the only section where an air pocket was identified and located acoustically.

The general elevation profile for these test sections is shown in the following Figure 7-22.


Figure 7-22 - Ground Profile for Test Sections 4 to 12 - DN 300 Pipeline.
The pipeline route crossed the Great Dividing Range and the Expedition Range geographical features in the above figure and explains the elevations of and exceeding 500 metres above sea level. The water source for testing these sections was obtained from a bore at KP 96 at the start of Test Section No. 4. It was high quality water and potable. The pipe was not internally lines so that oxygen scavenger, biocide and filming agent were added to prevent internal corrosion with the products supplied by Maxwell Chemicals (a specialist supplier to the Pipeline Industry). No assessment has been made of the effect of such chemicals on the acoustic velocity.

The DN300 acoustic differentials are shown in Figure 7-23 below.

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Figure 7-23 - DN300 Acoustic Differentials at $12,000 \mathrm{kPa}$ of $\mathrm{dP} / \mathrm{da}$ and da/dT with resultant $d P / d T$.

### 7.3.1 Leak Test Acceptance Criteria and Acoustic Velocity Equivalent

All of the DN 300 Project Pressure Leak Tests had been accepted on the basis of the pressure and average pipe temperature changes over the 24 hour leak test period. The average pipe wall (top of pipe) temperature changes were converted to equivalent pressure changes and subtracted from the pressure changes. This difference was required to be within the acceptable uncertainty margin based on the minimum of the following three factors:

- $0.1 \%$ of test pressure + equivalent of $0.1^{\circ} \mathrm{C}$ (typically $13 \mathrm{kPa}+27 \mathrm{kPa}=40 \mathrm{kPa}$ )
- Volume loss of 4 litres/hour for sections > 3000 kL and pro-rata for lower (approx. $0.3 \%$ of test pressure per day or for TP of $13000 \mathrm{kPa}-39 \mathrm{kPa}$ /day).
- 45 kPa .

Velocity measurements were ancillary and not used in the test acceptance. However the acceptance criteria of typically around 40 kPa provided a basis for assessing the value of the acoustic velocity measurements as an alternative to pipe wall temperature measurements. Using Figure 7-23, in the temperature range of 15 to $25^{\circ} \mathrm{C}$ the $\mathrm{dP} / \mathrm{da}$ factor varied from 110 to $250 \mathrm{kPa} / \mathrm{m} / \mathrm{s}$. So that 40 kPa range acceptance criterion would correspond to 0.36 to $0.16 \mathrm{~m} / \mathrm{s}$ velocity range acceptance equivalent. Only section 8 would come close to that velocity acceptance criterion within the first 24 hours.

### 7.3.2 DN 300 Pipeline - B.O.M. Data and Below Ground Temperature Modelling.

In Section 5.10 daily weather averages for the year relevant to the pressure tests of the DN 300 Pipeline were analysed and used to produce expected below ground temperatures. The following Figure 7-24 showed the average ambient together with the times when the pressure tests were

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performed. The data are from Roma, Injune and Rolleston with Injune very close to test sections 4 and 5. Rolleston was nearer to test section 12 while Roma was near to the start of the pipeline and more than 60 km away from section 4. Roma's data has the advantage of a continuous data set which made modelling easier. The Figure 7-24 below showed the similarity between the three data source locations and confirmed the usefulness of Roma's data.


Figure 7-24 - B.O.M Data for Roma, Rolleston and Injune during the Pressure Testing of part of the DN 300 Pipeline with Time of Tests identified.


Figure 7-25 - Below Ground Estimates from B.O.M. data with Times of Pressure Tests on DN 300 Pipeline using Diffusivity of $0.8 \mathrm{~mm}^{2} / \mathrm{s}$.

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The above Figure 7-25 incorporated the below ground estimates and repeated the Roma (light blue) average ambient for comparison purposes. The below ground estimates were produced by a Matlab program using signal analysis techniques and based on an assumed soil diffusivity value of $0.8 \mathrm{~mm}^{2} / \mathrm{s}$. Other assumed diffusivities were used in subsequent analysis ranging from 0.4 to 1.2 $\mathrm{mm}^{2} / \mathrm{s}$.

There was only a vague similarity between the Roma average ambient data (light blue) and the below ground estimates. Most of the detail had been removed and only the major features reproduced but also smoothed out. The progressive delay between surface and greatest depth was apparent together with the amplitude reduction.

The above modelling was used when analysing individual test sections starting with test section number 6 which was the worst for air content.

### 7.3.3 Test Section No. 6

Section 6 was a test case in that it had the most air content and if any section had air solution producing a rise in acoustic velocity then section 6 should be the prime example.

The following Figure 7-26 showed the below ground temperature measurements for this test section. The ground probe was trending upwards on average $0.1^{\circ} \mathrm{C}$ per day. Only a couple of pipe wall probes showed a similar trend with the balance showing decay following previous test activities. The two vertical black dashed lines indicated the start and end of the strength test with pressurisation and water movement before causing the general disturbance.


Figure 7-26 - DN 300 Test Section No. 6 - Below Ground Temperatures.
There were no measured temperature trends that could explain the acoustic velocity rise. Air solution had been ruled out by the previous air pocket analysis in Chapter 6. Using the Bureau of Meteorology data for Roma, Injune and Rolleston for the daily maxima and minima and taking their

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progressive averages resulted in the following Figure 7-27 in relation to Test Section No. 6 conducted during the $15^{\text {th }}$ to $16^{\text {th }}$ September.


Figure 7-27 - Test Section No. 6-BOM Averages near time of test. The Roma average was used to generate the estimated below ground temperatures in the following figures.

Besides the below ground estimates in Figure 7-28 were the below ground measured temperatures, pressure (as equivalent velocity) and velocity.


Figure 7-28 - Test Section No. 6-Estimated and Measured Below-Ground Temperatures. Also, Pressure and Acoustic Velocity. Assumed diffusivity $1.2 \mathrm{~mm}^{2} / \mathrm{s}$.

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Figure 7-29 and Figure 7-30 following are for reduced diffusivity values of $0.8 \mathrm{~mm}^{2} / \mathrm{s}$ and 0.4 $\mathrm{mm}^{2} / \mathrm{s}$.


Figure 7-29 - Test Section No. 6-Estimated and Measured Below-Ground Temperatures. Also, Pressure and Acoustic Velocity. Assumed diffusivity $0.8 \mathrm{~mm}^{2} / \mathrm{s}$.


Figure 7-30 - Test Section No. 6 - Estimated and Measured Below-Ground Temperatures. Also, Pressure and Acoustic Velocity. Assumed diffusivity $0.4 \mathrm{~mm}^{2} / \mathrm{s}$.

In Figure 7-28 during the leak test period the estimated below ground temperatures had a combination of falling, rising and changing from falling to rising. These effects were reduced in the

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subsequent Figure 7-29 and Figure 7-30. Of the measured temperatures in Figure 7-30, two are falling, two are rising and two slightly rising. Amongst all three diffusivities there is no particular one which best corresponded to the measured below ground temperature changes. There was no data on which to base diffusivity values. The diversity in below ground measurements pointed to the likelihood of the six measurement locations being at different depths and consequently recording different responses of the pipe wall temperature to the changing ground temperature. This set of three figures with different diffusivities provided possible evidence for the unpredictability of below ground measurements during a pressure test. The major time scale in these figures was 7 days during which the estimated changes in below ground temperature were significant. The extent of these changes severely cast doubt on any attempts to achieve thermal stabilisation prior to pressure tests unless only of the order of degrees but not tenths of degrees Celsius.

The below ground measured temperatures appeared to be converging towards some target. The downward curving appeared as if they would level off within another day and similarly with the rising ones. They appeared to be responding to some thermal disturbance.

For the highest diffusivity values, during the leak test period the shallowest estimated (red) temperatures were the coldest and the deepest (light blue) the warmest which represented inversion of conditions three to four days earlier to which the pipe's contents must respond. This inversion was followed a day or so later by a reversion back to the previous pattern. The only conclusion that can be drawn regarding thermal gradients during the period of acoustic measurements during the leak test was that the test was conducted during a period of thermal instability and luckily the pipe wall temperatures provided acceptable results which the acoustic velocity measurements couldn't provide.

## Pressure and Ambient

The following Figure 7-31 showed that the pressure change generally reflected the ambient.


Figure 7-31 - Test Section No 6 - Pressure and Ambient Temperature comparison.

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The ambient temperature from 15:00 hrs to 21:00 hrs at the end of the trace has been translated to the start as the red squares and appeared to be similar to the subsequent pink squares. The same period for pressure has also been translated in the same manner as the dark orange diamonds and the hand drawn black line was an attempt to trace the pressure to agree with the ambient. This left a decreasing gap between the initial pressure (dark blue diamonds) and the ambient based approximation which was the basis for the following Figure 7-32 estimating the decrease in the gap with time.


Figure 7-32 - $\quad$ Test Section No 6 - Initial Leak Test Pressure decay.
The red curve was based on time with an exponent of 0.5 which better matched the estimated pressure difference. With a pressure/temperature factor of around $207 \mathrm{kPa} /{ }^{\circ} \mathrm{C}$, the initial leak test difference of around 11 kPa would correspond to a temperature difference of $0.053^{\circ} \mathrm{C}$ and implied that the pressure drop was evidence of a temperature drop which would have continued from the end of pressurisation. Extending the red curve back in time to the strength test start would indicate a start difference of around 68 kPa equivalent to $0.33^{\circ} \mathrm{C}$ which is double the estimated adiabatic increase of $0.16^{\circ} \mathrm{C}$ but of the same order. Hence this pressure decay pattern was most likely the recovery from the adiabatic temperature rise but with the estimated points incorrect or other temperature adjustments taking place.

The previous plot of pressure and ambient temperature, Figure 7-31, had a pressure scale ranging 18 kPa and temperature scale of $35^{\circ} \mathrm{C}$ giving a pressure/ambient factor of approximately $0.51 \mathrm{kPa} /{ }^{\circ} \mathrm{C}$ which was 400 times smaller than the estimated $207 \mathrm{kPa} /{ }^{\circ} \mathrm{C}$. The pressure was obviously affected by the ambient but only for $1 / 400$ times the pipe test section length of 28.24 km or 70 metres which would represent two 18 metre exposed pipe lengths at each end of the test section.

Pressure and ambient were never directly related as demonstrated by the exposed tank experiments in Chapter 5 and their plot over time took the form of a broad inclined oval which in the above case would have had a slope of $0.5 \mathrm{kPa} /{ }^{\circ} \mathrm{C}$.

Dead weight tester pressure measurements are limited to a resolution of 1 kPa as evidenced by the previous plot with sometimes two or three readings the same.

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## Acoustic Velocity Measurements

The following Figure 7-33 compared the average buried pipe wall and ground temperatures with the acoustic velocities measured during the test. The measured velocity change over the period of measurements was approximately $1.5 \mathrm{~m} / \mathrm{s}$ while the average pipe wall hardly changed and the ground rose around $0.1^{\circ} \mathrm{C}$. Expected velocity change due to temperature should have been around 2 metre/second per degree C. Hence an anomaly of 7 times the expected.

In Figure 7-33 the average pipe wall temperature was around $0.7^{\circ} \mathrm{C}$ higher than the ground so that with cool surrounding ground and seasonal solar heating from above, thermal layering should have been present in the pipe and could have affected the results.


Figure 7-33 - Acoustic Velocities and buried Temperatures - Test Section No. 6.
The velocities shown in Figure 7-33 were misleading since the velocity scale had been enlarged to fit by around 7 times the equivalent temperature. The true acoustic velocity variation was shown in Figure 7-28, Figure 7-29 and Figure 7-30 by the rapidly rising dark blue line cutting across the below ground measurements.

## Test Section No. 6 Conclusion

The above analysis for Test Section No. 6 has exhausted possible explanations for the significant difference of velocity compared with pressure and pipewall temperature. Air solution has been discounted, predicted ambient induced below ground changes have not been of use, a pressure decay appeared partly due to adiabatic effects. But no identified effect had resolved the acoustic anomaly.

Figure 6-64 of the ground profile showed an elevation range of around 170 metres in the test section which suggested many sections of high slope especially the last drop from the air pocket to the lowest point at the section end. In Chapter 5 for the buried tank during the month of September with surface temperatures rising and the bottom of pipe ground temperatures still cold, thermal layering developed but was in a flat location. Add initial adiabatic effects, ambient induced below ground

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changes to high slope areas to enhance the seasonal thermal layering could probably result in enhanced lack of thermal stability and high convection currents with consequent significant effects on acoustic velocity. Such speculation is without evidence unless other test sections with similar anomalous acoustic velocities have similar features to support a consensus view.

### 7.3.4 Test Section 4 Velocity Measurements

Acoustic velocity measurements taken during the leak test of section 4 are shown in the following Figure 7-34 together with the average pipe wall temperature and the pressure converted to equivalent velocity.


Figure 7-34 - Test Section No. 4 - Pressure, Average Pipe wall Temperature and Acoustic Velocity plotted against time - Pressure converted to equivalent acoustic velocity.

In this figure, while there was similarity between the pressure and pipe wall temperature, there was none with the velocity which has an overall rise of $0.7 \mathrm{~m} / \mathrm{s}$ over a period of around 16 hours. The da/dT factor was around $1.8 \mathrm{~m} / \mathrm{s} /{ }^{\circ} \mathrm{C}$ which then required a temperature change of close to $0.4^{\circ} \mathrm{C}$ to support it. The axes have been scaled to match the da/dT factor. The acoustic velocity change over time did not match pressure or pipe wall temperature changes. This data was repeated in more detail in the following Figure 7-35 which included the other below ground measurements (P2 to P6 and G6) together with the predicted below ground temperatures using the BOM average data.

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Figure 7-35 - Test Section No. 4 - Pressure as acoustic velocity, Acoustic Velocity and Below Ground Measurements and BOM based estimated Temperatures for Diffusivity of $0.8 \mathrm{~mm}^{2} / \mathrm{s}$.

What was surprising was that the average pipe wall temperature (green) matched the slope of the below ground estimates for most depths. The pressure (as velocity - black) has a slight decay with levelling off and starting to rise at the same rate as the estimated below ground. The section was long with little ambient influence on the pressure. The pressure was dropping and converging with the average pipe wall. But only one pipe wall measurement, P 6 , reflected the pressure change and then only in the curvature but not the slope. There was some variation in the measured below ground but not as bad as Test Section No. 6. The estimated below ground temperatures over the previous day had slowly increased the thermal gradient mainly with the shallower depths.

The pressure was dropping relative to the average pipe wall temperature and the velocity was rising at a much higher rate. According to Figure 7-22 there was significant elevation in Test Section No. 4 but not with the high elevation range of Test Section No. 6.

### 7.3.5 Test Section No. 8

For test section 8, the following Figure 7-36 compared pressure and ambient with a similar decay to test section 6

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Figure 7-36 - Test Section No 8 - Pressure and Ambient comparison.
The pressure change from ambient using the pressure and temperature scales was $0.67 \mathrm{kPa} /{ }^{\circ} \mathrm{C}$ which based on an average temperature of $18^{\circ} \mathrm{C}$ should be around $250 \mathrm{kPa} /{ }^{\circ} \mathrm{C}$ indicating that the exposed pipe contributed only $0.27 \%$ to the average pipe wall temperature as expected for a long buried section. The following Figure 7-37 plotted the pressure as velocity, the velocity and the average pipe wall and ground temperatures.


Figure 7-37 - Acoustic velocity and Ambient - TS No 8 - No free air measured.
Even though there was no evidence of air in Test Section No. 8 there was still a rise in acoustic velocity although smaller than test section 6 with evidence of air. The velocity points do not show any

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association with the ambient and the velocity change over the leak test was around $0.23 \mathrm{~m} / \mathrm{s}$ rise which should approximate a $0.13^{\circ} \mathrm{C}$ temperature rise.

The pressure has been converted to equivalent velocity with a combination of offsets and the $\mathrm{dP} / \mathrm{da}$ factor of $150 \mathrm{kPa} / \mathrm{m} / \mathrm{s}$. It was shown touching the average ground temperature at around 7:00 hrs and then rose slightly relative to the ground. The acoustic velocity appeared to be on an exponential rise up to the ground temperature. The blue average pipe wall appeared to follow the pressure for the first 12 hours and then deviated to follow the ambient rise (not shown). The following Figure 7-38 showed the pipe wall measurements with the inevitable scatter in values and patterns made worse by loss of data on some probes and data loggers.


Figure 7-38 - Test Section No. 8 - Below Ground and Ambient Temperatures during Leak Test.
P4 and P5 pipe wall probes appeared to have an initial exponential like decay and P3 a minor version with P3 and P4 ultimately rising in a manner similar to the average ground temperature. The ambient showed an overall fall up until 6:00 consistent with the pressure with the subsequent rise anticipating the pressure rise by around one hour.

There was nothing in this data to provide support for an overall velocity rise but the initial drop in pressure equivalent, P4, P5 and P3 hint that some form of thermal stabilisation was taking place. The alpha value for the acoustic velocity rise of 1.4 differed from the CFD equivalent value of 0.9 and in the opposite direction but was not an order of magnitude different hinting that it could be a partial consequence of adiabatic temperature changes.

Acoustic signals around 14:30 hrs on $12^{\text {th }}$ September had interference from noise and the echoes couldn't be properly isolated for velocity estimation. Shortly after the signals returned to normal as evidenced on Figure 7-37 above. The test point was close to a gravel road which could have generated

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ground vibration with vehicle passage. Data was missing from some of the probes and was probably due to livestock interference.


Figure 7-39 - $\quad$ Test Section No. 8 - Pressure as acoustic velocity, Acoustic Velocity and Below Ground Temperatures compared with Estimated Below Ground Temperatures - Assumed diffusivity $0.8 \mathrm{~mm}^{2} / \mathrm{s}$

According to Figure 7-39 there should be a dissipating thermal gradient in test section 8 during the period of the leak test following a peak the day before. Two of the pipe wall temperatures showed an exponential like reduction and levelling off as if they had been subject to a sudden rise in temperature of the order of $0.2^{\circ} \mathrm{C}$ consistent with expected adiabatic rise of $0.17^{\circ} \mathrm{C}$ at $18^{\circ} \mathrm{C}$. The range of below ground measured temperatures was $1.5^{\circ} \mathrm{C}$ much higher than the estimated range for depths of maximum $0.5^{\circ} \mathrm{C}$ at the start of the leak test. This points to other factors affecting the measured below ground temperatures of the order of $1^{\circ} \mathrm{C}$.

Even with a length of 35 kilometres, section 8 pressure was influenced by ambient and needed both ambient or exposed pipe temperatures and buried pipe wall temperatures for test acceptance. Acoustic velocity did not appear to be influenced by ambient and if used may need to be complemented by exposed pipe wall temperatures.

If the presence of air was responsible for the anomalous rise in acoustic velocity then with no air evident there should be no rise in acoustic velocity. Test Section 8 was therefore the best refutation that air solution was the cause of the velocity rise. The velocity rise was small and was just outside the range needed for use in test acceptance within the first 24 hours of a leak test. It also showed trending towards the ground temperature indicating that the subsequent 24 hours following the leak test would have resulted in an acceptable test result using acoustic velocity.

The elevation range was small and the ground profile was essentially flat so that inclined pipe thermal gradients would not have been present.

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### 7.3.6 Test Section No. 9

Test Section number 9 had the third highest velocity increase or anomaly behind sections 6 and 12. Figure $7-40$ below from 16:00 hrs shows the pressure and ambient changes during the 24 hour leak test period. The end of both of these traces from 9:00 hrs to the end have been duplicated and brought forward one day and were the dashed and dotted traces at the left hand side of the figure.


Figure 7-40 - $\quad$ Test Section No. 9 - Pressure and Ambient Temperature Comparison.
The ambient peaked around 16:00 hrs and where they overlaped the difference was only about 1 to 2 degrees while the pressure differed by around 12 to 13 kPa which would imply that there had been an internal temperature rise in the pipe system which was confirmed by both an average pipe wall increase of $0.1^{\circ} \mathrm{C}$ and ground temperature increase by $0.1^{\circ} \mathrm{C}$ at one end and fall by $0.05^{\circ} \mathrm{C}$ at the opposite end to average a small increase of $0.025^{\circ} \mathrm{C}$. With an average pipe wall temperature of $21.7^{\circ} \mathrm{C}$ the $\mathrm{dP} / \mathrm{dT}$ factor should be around $310 \mathrm{kPa} /{ }^{\circ} \mathrm{C}$ which for a 12 kPa increase requires a temperature increase of $0.04^{\circ} \mathrm{C}$ similar to the average ground but half the pipe wall. Using the $\mathrm{dP} / \mathrm{da}$ factor of around $200 \mathrm{kPa} / \mathrm{m} / \mathrm{s}$ and scaling the axes of the following Figure 7-41 accordingly allowed a pressure and acoustic velocity comparison.

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Figure 7-41 - Test Section No. 9 - Pressure and Acoustic Velocity.
While the previous Figure 7-40 showed reasonable correspondence between the pressure and ambient there was none between velocity and pressure. Acoustic velocity followed an exponential shape with the following equation expressing its shape with time in days and acoustic velocity units of $\mathrm{m} / \mathrm{s}$.

$$
\begin{equation*}
\text { Velocity }=1216.4-2.13 e^{-1.56 t} \tag{7.3.1}
\end{equation*}
$$

Where time, t , started from the commencement of the strength test 4 to 5 hours before the leak test or around $11: 00 \mathrm{hrs}$ on the same day as the leak test. If the velocity change was due to temperature then for a change of $2.13 \mathrm{~m} / \mathrm{s}$ and a da/dT factor of $1.6 \mathrm{~m} / \mathrm{s} /{ }^{\circ} \mathrm{C}$ a temperature change of $1.3^{\circ} \mathrm{C}$ would have been needed to produce such velocity change. The time exponent of 1.56 /day was double the exponents in the table based on the CFD data in Chapter 3 and did not appear to be a direct consequence of pipe response to adiabatic temperature changes and with double the exponent alpha resulted in half the time scale or double the rate at which the asymptote was reached. The $1.3^{\circ} \mathrm{C}$ equivalent was more than 6 times the expected adiabatic temperature rise of around $0.2^{\circ} \mathrm{C}$. Air in the section had been estimated at $0.0018 \%$ of section volume 892,000 litres at atmospheric pressure which when dissolved at pressure would result in a small and hard to detect pressure change of 0.2 kPa based on a compressed volume of around 124 ml and a dV/dP factor of $646 \mathrm{~m} / \mathrm{kPa}$. The solution rate exponent for such small air content had an alpha of 174/day based on the whole section volume which should take only fourty minutes to dissolve. No obvious echoes were detected in the waveform traces but could be hidden if in the first half of the trace since this half was not amplified while the latter half was to enable resolution of the echo from the remote end.

The pressure trace showed the significant influence of ambient while the velocity trace did not within the scatter of data. This may be a consequence of the velocity not detecting the influence of the ambient influenced exposed pipe at each end of the test section which was the cause of the pressure

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changes. Test Section 9 had one exposed end at a low point which the CFD research [11] showed caused warm water to be convected up along the top of the pipe and the return cooler water along the bottom of the pipe which would continue in the spring-summer period. This convected water movement acts as a heat pump warming the pipe section from the exposed low point to the nearest high point where the warmed water would accumulate. From the section elevation figure below can be seen the 4.8 km long section heated by the exposed low point at KP 245 which was also the test point with pressurising water taken from the adjoining end of test section 8. Using Google Earth Pro and estimating the pipeline route of section 9 as mostly straight indicated an intermediate high point at 2 km which would prevent further convection flow. Even this 2 km section was around $17 \%$ of the section length. Test section 8 was tested more than two weeks before 9 so that the water in section 9 and the water from section 8 used to pressurise 9 was very stable and came from the upper end of a sloping section where warm water would have accumulated.

The following Figure 7-42 for the estimated below ground temperatures showed little predicted variation with depth during the test period and slight reduction in thermal gradient in the day prior. The average pipe wall temperature was rising slightly and the component temperatures were variable as usual. Pressure showed the effect of ambient on exposed pipe and differed from the rise in velocity which appeared to rise towards the pressure with the possibility of tracking it if the test was extended another 24 hours. The range of below ground pipe wall measurements was $3^{\circ} \mathrm{C}$ which was surprisingly large and hid the source of such variation which did not appear to be caused by depth of burial. As mentioned above, section 9 had plenty of time for stabilisation prior to test.


Figure 7-42 - $\quad$ Test Section No. 9 - Estimated below ground Temperatures, Measured Pressure (as velocity), Velocity and Pipe wall Temperatures - Diffusivity $0.8 \mathrm{~mm}^{2} / \mathrm{s}$.

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The following version of the previous Figure 7-42 extended the time to better understand what could have occurred before the test.


Figure 7-43- Test Section No. 9 - Estimated below ground Temperatures, Measured Pressure (as velocity), Velocity and Pipe wall Temperatures - Diffusivity $0.8 \mathrm{~mm}^{2} / \mathrm{s}$ - Longer Time.

While the period of the test appeared benign, two days before the below ground temperatures quickly changed from a rising thermal gradient to a rapid reduction and partial reversal. What was not known was the rate at which the pipe water contents could respond to rapid changes. It was unlikely that the water contents could follow such rapid changes without some lag and development of convection currents in inclines. Test Section 8 appeared to be in conditions equivalent to one or two days earlier without adverse effects. Could one day make a significant difference?


Figure 7-44- Test Section No. 9-Ground Profile and Location of Temperature Probes.

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With a gradual upward incline shown in Figure 7-44 from the start at KP 245 and time of year late September, there should be heating of this section from the exposed end as demonstrated by the CFD studies. There was an upward rise in the average pipe wall temperature and also P1 and G1 probes at that end. P2 was steady and matched P3. At the opposite end the last probes P6 and G6 had different trajectories with P6 (green near top) fluctuating and G6 (light blue at top) trending downwards. The elevation of the probes roughly corresponded to their temperature which had no physical basis except for seasonal heating and accumulation of warmer water at higher locations. Atmospheric adiabatic lapse rate reduced at the rate of $0.6^{\circ} \mathrm{C}$ per 100 metres and not increased as applies in Test Section No. 9.

## T.S. 9 Conclusions

Figure 7-41 showed an unusually smooth exponential acoustic velocity rise independent of pressure, ambient and pipe wall and ground temperatures. It appeared to commence at the start of the pressure test. Such rise could not be explained by the usual input variables. The unique feature of this test section was the smooth gradual rise for the first five kilometres and a half kilometre rise at the end with a trapped high point with the first known to produce thermal convection daytime heating of the uphill pipe while the latter can cause night time cooling of the downhill pipe. Such processes would take place regardless of the start of the pressure test. The initiation of the exponential velocity rise had to be caused by some event or activity at the start of the pressure test. One often overlooked process was the injection of water for pressurisation of the order of $1 \%$ of section volume or length. Such water passes through the high pressure pump and is heated in the process. With a length of 11.6 km then around 120 lineal metres of water would have been transferred from the end of Section 8 to Section 9. In the case of Test Section No. 9 with an uphill section at the start, cold water would have accumulated prior to the pressurisation. The end of Test Section No. 8 providing the water would have been a local high point with a higher temperature than the adjoining start (low point) of Test Section No. 9. Transfer of $1 \%$ of the section volume of Test Section No. 9 from 8 would introduce warmer water into 9 which would then by convection travel upwards and take some time to reach thermal equilibrium. Any adiabatic change applies to the whole section and has minimal effect on thermal stability other than a difference relative to the soil whereas an injection of warmer water into a low point has an initially significant impact which takes time to resolve and was likely to generate an exponential like change unlike low point thermal heating which would be an ongoing process.

### 7.3.7 Test Section No. 10

Of the test sections with anomalies, test section No. 10 was unusual in being the shortest at only 2045 metres long and with the longest relative length of ambient exposed pipe, as shown in the following elevation plot Figure 7-45 together with the location of pipe wall temperature probes.

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Figure 7-45 - Test Section No. 10 - Section Profile and Temperature Probe Location.
Of note is that the P1 and P6 probes were located on the exposed test headers at each end and both headers were at low points with the pipe inclined upwards. The following Figure 7-46 showed the temperature measurements from these end probes together with the ambient and the weighted average of the exposed and buried pipe wall measurements. There were two axes in Figure 7-46 corresponding to the weighted average temperature plotted as pressure and pressure using the left axis and the probes P1, P6 and ambient using the right axis to allow for the relative differences in amplitude.


Figure 7-46 - $\quad$ Test Section No. 10 - Pressure, Average Pipe wall (as pressure), Ambient and Exposed Pipe Probes.

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To obtain the average pipe wall temperature, the two exposed pipe probes P1 and P6 were allocated a fraction each of 0.06 or $6 \%$ while the buried pipe wall probes P 2 to P 5 were allocated a fraction each of 0.22 or $22 \%$. Manual probe readings were taken at around four-hour intervals indicated by the sudden changes in slope of the temperatures. (Test section No. 11 was tested at the same time which limited instrument and data logger resources). The average pipe wall temperature has been converted to equivalent pressure using the $\mathrm{dP} / \mathrm{dT}$ factor of $285 \mathrm{kPa} /{ }^{\circ} \mathrm{C}$ since if plotted using the temperature axis would be almost a straight line.

Acoustic measurements were carried out over an extended time longer than the 24-hour leak test so that additional pressure measurements were recorded as a continuous line on $9^{\text {th }}$ October. A copy of the 24-hour leak test pressure has been delayed one day and displayed as the dashed black trace in Figure 7-47 which happened to match the field pressure measurements on the latter part of the second day (continuous black line). These pressure traces were compared with the velocity measurements.


Figure 7-47- Test Section No. 10 - Pressure (as velocity and Velocity Measurements with 24 hour delayed copy of Pressure for comparison purposes.

Although 32 acoustic velocity measurements were taken, five were experimental tests on different input waveform shapes and a significant additional number were adversely affected by noise in the morning of the first day during the period where there was data scatter. Unfortunately there was too much scatter to make any conclusions regarding the ability of the acoustic technique to incorporate or measure the ambient effect on pressure. There was a hint that it had an effect and the range did not appear to have the anomalous behaviour of continual rise.

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Figure 7-48 - Test Section No. 10 - Estimated below ground Temperatures and Measured Pressure (as velocity), Velocity and Below Ground Temperatures - assumed Diffusivity $0.8 \mathrm{~mm}^{2} / \mathrm{s}$.

Of note in Figure 7-48 was that for a guessed ground thermal diffusivity value of $0.8 \mathrm{~mm}^{2} / \mathrm{s}$ the weather and seasonal effect appeared benign with almost no change in the 36 hours before the test and only minor change during the test.The seasonal rise has not been superimposed on the below ground estimated temperatures but the pipe wall and ground probes indicated a rise which was consistent with the slow rise of the deepest especially if a seasonal rise was added. The pressure surprisingly had not shown a rise while the velocity measurements hint at a rise or a minor anomalous rise. Some of the signal processing issues affecting velocity measurements were addressed in Chapter 6

### 7.3.8 Test Section No. 12

The following Figure 7-49 for TS 12 showed the ground profile which had an overall average slope of 0.7 degrees but individual sections had an average slope of 3.3 degrees with the maximum of 10.2 degrees. Both ends were inclined with the upper trapping solar heated water in the exposed pipe but cooling the downhill section in the early morning. The lower end would trap cold water but transfer uphill the solar heated water during the day. Since the time of test was mid-October with both rising average ambient and rising seasonal temperatures, the effect of the exposed pipe at the lowest point will have caused heating of the last section until the nearest high point which would prevent further convection heating. With the test cabin in Figure 7-49 shown at the lowest point adjoining Test Section No. 13, the water source for pressurisation must have been a water tank or tanker since 10,000 litres would probably be sufficient to pressurise the section. Temperature of such water would have been

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unknown but likely to be higher than the water at the lowest point in Test Section No. 12 at the time of year. Temperature probe No. P6 and G6 were unlikely to measure the effects of hotter pressurising water due to the intermediate high point around KP 274. However such hotter water injected into the bottom of the section may have been partly responsible for the highest acoustic velocity exponential rise.


Figure 7-49 - $\quad$ Test Section 12 - Profile with Locations of Temperature Probes and Test Cabin.
In Figure 7-50 pressure appeared to vary similarly with the ambient but with a delay of around 3 hours.


Figure 7-50 - $\quad$ Test Section No. 12 - Pressure and Ambient Temperature plotted against Time.

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Recorded ambient, shown in Figure $7-50$, varied from $12^{\circ} \mathrm{C}$ to $35^{\circ} \mathrm{C}$ during the leak test with the pressure showing a response to the ambient of the order of $2 \mathrm{kPa} /{ }^{\circ} \mathrm{C}$. The $\mathrm{dP} / \mathrm{dT}$ factor was 273 $\mathrm{kPa} /{ }^{\circ} \mathrm{C}$ which implied that the exposed pipe contribution was around $0.7 \%$ of the 9171 metres or around 67 metres. Figure 7-51 showed the below ground temperature measurements.


Figure 7-51 - Test Section No. 12 - Below Ground Temperatures.
All the temperatures measured around the middle of the test period ranged from $21.2^{\circ} \mathrm{C}$ to $22.5^{\circ} \mathrm{C}$ with the lowest pipe and ground (P6 and G6) rising $0.25^{\circ} \mathrm{C} /$ day and $\mathrm{P} 40.3^{\circ} \mathrm{C} /$ day. No probes were installed at high points. Of the three close to low points, P1 was steady, P3 falling and P5 rising. The most upslope probe P 4 was the one rising at $0.3^{\circ} \mathrm{C}$ / day and P 6 and G 6 at $0.25^{\circ} \mathrm{C} /$ day but P 2 was steady. Undissolved air was negligible as indicated by the pressure/volume plot. Average measured pipe wall temperature rose $0.12^{\circ} \mathrm{C}$ per day and the pressure around 23 kPa /day which for the $\mathrm{dP} / \mathrm{dT}$ factor of $273 \mathrm{kPa} /{ }^{\circ} \mathrm{C}$ accounted for 33 kPa of the 23 kPa . The following Figure 7-52 merged the below ground measurements with the BOM based estimated below ground values and pressure (as acoustic velocity) and acoustic velocity.

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Figure 7-52 - Test Section No. 12 - Estimated Below Ground Temperatures based on BOM Data, Pressure (as acousticvelocity), Acoustic Velocity and Measured Below Ground Temperatures. Assumed Diffusivity $0.8 \mathrm{~mm}^{2} / \mathrm{s}$.

The above Figure 7-52 had added the seasonal temperature rise for the estimated below ground temperatures which were the upper four temperature traces and closely matched some of the below ground temperature probe measurements. The BOM estimated temperatures had no thermal gradients prior to the start of the test and only developed during the test period, at least based on the diffusivity value of $0.8 \mathrm{~mm}^{2} / \mathrm{s}$. The following Figure 7-53 extended the time range in the hope that it might provide some evidence. If the diffusivity was higher the BOM below ground temperatures would be shifted to the left resullting in higher thermal gradients of the order of $0.3^{\circ} \mathrm{C}$ across the pipe in horizontal orientation. At an average temperature around $22^{\circ} \mathrm{C}$ the adiabatic rise should be around $0.26^{\circ} \mathrm{C}$ which should increase the thermal gradient to around 0.5 to $0.6^{\circ} \mathrm{C}$. The weather and seasonally induced thermal gradient was changing over time. CFD results were generally for a single temperature change followed by recovery over time. The field situation was of repeated temperature changes without any recovery. Is this sufficient to explain the velocity rise around $1.6 \mathrm{~m} / \mathrm{s}$ during the same period? With the scales in Figure $7-52$ approximating the $1.55 \mathrm{~m} / \mathrm{s} /{ }^{\circ} \mathrm{C}$ da/dT factor for $22^{\circ} \mathrm{C}$, a $1.3^{\circ} \mathrm{C}$ temperature change would be required if only due to temperature change. Other factors must have applied.

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Figure 7-53 - Test Section No. 12 - Estimated Below Ground Temperatures based on BOM Data, Pressure (as acoustic velocity), Acoustic Velocity and Measured Below Ground Temperatures. Assumed Diffusivity $0.8 \mathrm{~mm}^{2} / \mathrm{s}$ - extended time.

The following Figure 7-54 plotted an exponential through the velocity data points and projected the continuation superimposed on the equivalent slope based on average pipe wall temperatures of P4 and P6 (as velocity).


Figure 7-54 - $\quad$ Test Section No. 12 - Acoustic Velocity Data fitted to Exponential with Incline based on P4 and P6 below ground pipe wall Temperatures. Also plotted is difference between the exponential and the Inclined trend line.

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If test acceptance was based on an uncertainty equivalent to $0.1^{\circ} \mathrm{C}$ or around 40 kPa and only acoustic measurements were used, the maximum velocity change per day would be less than $0.2 \mathrm{~m} / \mathrm{s}$ and with the above exponential this would only occur by extending the 24 hour test to 60 hours with the velocity change in the last 24 hours less than $0.2 \mathrm{~m} / \mathrm{s}$.

### 7.3.9 DN 300 Pipeline Acoustic Velocity Measurement Summary

Sections where there was rock permitted the use of 700 to 750 mm cover provided that pipe with factory applied "Rock Jacket" concrete based coating was used which in turn permitted excavated rock to be installed on top of the rock jacketed pipe.

A simple exercise was to check acoustic anomaly amplitude against Rock Jacket distribution to see whether there was any correspondence which was done in the following Table 7-5. The anomaly was considered to start at the start of the strength test which may explain why the values were higher than discussed above during the leak test.

Table 7-5 - DN 300 - Test Sections and Rock Jacket and Acoustic Anomaly Comparison.

| DN 300 - Test Sections and Rock Jacket portion and Acoustic Anomaly |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
| Test Section No. | Length (km) | Rock Jacket Percentage of Length | Acoustic Velocity anomaly ( $\mathrm{m} / \mathrm{s}$ ) from Start Strength Test | Acoustic Velocity anomaly (m/s) Leak Test only |
| 12 | 9.2 | 37\% | 3.6 | 2.3 |
| 6 | 28.3 | 80\% | 2.7 | 1.5 |
| 9 | 11.6 | 55\% | 2.2 | 1.2 |
| 5 | 29.7 | 25\% | 1.6 | 0.6 |
| 10 | 2.05 | 70\% | 1.5 | - |
| 7 | 25.6 | 7\% | 1.0? | 0.6 |
| 4 | 30.7 | 53\% | 0.8 | - |
| 8 | 35.3 | 0.7\% | 0.3 | 0.15 |
| Note: Acoustic Velocity anomaly values from start of Strength Test estimated from the Leak Test Period Measurements. |  |  |  |  |

There was no obvious relationship between the anomaly and the percentage of Rock Jacket or location in low burial depth ground. It is more than likely that the variation was a matter of weather changes which are just as unpredictable. Acoustic velocity measurements were carried out on other test sections and were not reported as they did not appear to have anomalous results. Test sections 4 and 8 were included in these and were recovered to provide some balance and for comparison purposes.

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While there appeared to be no connection in the above Table 7-5, Figure 7-13 showed that the acoustic velocity variation from theoretical increased with rock jacket percentage which was explained by the effective pipe strength increase changing the acoustic velocity. However the figure showed sections 4,9 and 12 with higher values relative to the trend line while sections 5,6 and 7 were lower and section 8 just below. This grouping separation, with the exception of section 6 , placed the most anomalous sections with higher relative velocities. All these tests were carried out during the springsummer period with rising ground temperatures which according to Figures 5-41 and 5-42 the seasonal average temperature rise was around $0.15^{\circ} \mathrm{C} /$ day. The below ground DN 435 tank experiment demonstrated that this time period had the highest thermal gradients. The weather induced changes were superimposed on top of such changes. The test on test section 12 followed, according to Figure $7-53$, a weather induced drop at 0.75 m depth of around $0.7^{\circ} \mathrm{C}$ from which the water in the test section would have been recovering during the test. With multiple short inclined portions in this section and varying temperature drops with depth of burial, thermal convection currents would have been very active in trying to recover from the weather induced changes and thermal stability far from achieved.

### 7.4 CONCLUSIONS OF PIPELINE COMPARISONS

With regard to the effect of air on the acoustic velocity, air solution rates have been studied in detail and has been discounted as the cause of the anomalous rise in velocity by Test Section 6 with an air pocket and Test Section 8 without any air.

Could there be other factors causing the exponential-like rise in velocity over time?
Such could be:

- Acoustic velocity being affected by weather pattern induced below ground temperature changes.
- Test sections not sufficiently thermally stable for the acoustic measurements.
- Some influence on acoustic velocity such as the "needed" temperatures to offset the measured pipe wall temperatures.
- Velocity somehow dependent on and affected by the bottom of pipe delayed response compared to side and top.
- Hot water from adjoining section or tank used to pressurise the colder low point of the test section.
- Sections 9, 6 and 12 with highest anomalies had significant elevation changes.
- Section 8 with least anomaly was almost flat and included a river crossing.
- Any weather pattern induced effects should be in both directions namely a rise or fall.
- All tests were carried out in Spring-Summer with rising ground and pipe temperatures and likely thermal gradients.
- DN 400 acoustic measurements had rising temperatures but no anomaly but were filled with most likely warm water in cold ground causing thermal mixing.

All acoustic anomalies took the form of increasing acoustic velocity in an exponential pattern. None had a falling character. Whatever has caused it must only produce such a rise and without any

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interference or modification. The rise was greatest at the start of the strength test and in most cases took 24 hours or more to approach an asymptote generally corresponding to ground temperature trends. With all the rises having an exponential form it was highly likely that the cause was the start of the pressure test. This Chapter has looked at the possibility of ambient induced below ground temperatures as a potential cause but failed to demonstrate consistent effects. Also ambient induced changes were likely to produce both rising and falling acoustic velocities but not consistent exponential like rises.

Acoustic velocity rises exponentially with air solution and hence was an ideal solution to the anomaly but proved not to be the cause. Any final solution should have a similar characteristic.

## CHAPTER 8 MATLAB MODELLING OF ACOUSTIC PROPAGATION IN PIPE

The CFD studies conducted by the University of Wollongong [11, 115, 116] and reported in Chapter 3 were able to provide thermal gradients within a pipe subject to the input thermal conditions. The run time to produce a temperature pattern was similar to the time modelled due to the extensive calculations required. CFD software was very good at generating such temperature patterns but did not lend itself to modelling acoustic propagation inside a pipe with such temperature patterns.

Note: All Matlab generated code, input data and analysis was carried out by this author.

### 8.1 PURPOSE

No explanation has been found so far to explain the anomalous rise in acoustic velocity of a number of buried DN300 pipeline test sections during the leak test. So far the following possible solutions have been evaluated and eliminated:

- Air solution based acoustic velocity rise.
- Steel creep.

This chapter attempts to determine whether thermal gradients were the cause of these anomalous acoustic velocity changes. If this was found to be the case, this chapter will seek to establish the conditions and circumstances that must apply for the acoustic technique to be used during pipeline pressure testing for leak assessment.

Modelling in Matlab offered a method to calculate the effect of thermal gradients on the acoustic propagation inside a pipe but cannot easily generate the thermal gradients. CFD was able to estimate the thermal gradients generated in a pipe based on external parameters and inputs but did not appear to have a module which could then assess the effect of the thermal gradients on acoustic propagation unless there was some way that the program developed in Matlab could be then run in a CFDgenerated model. Matlab was then a relatively simple way of verifying whether the input thermal gradients could produce the anticipated acoustic velocity changes. The input thermal gradients used were based on a mixture of CFD-estimated gradients, experimentally determined gradients and hypothesised gradients as appropriate. The purpose was not to find an exact solution but to check whether the proposed solution was plausible and an estimate of the proportion of the anomalous result that could be estimated.

### 8.2 METHODOLOGY

This section details the Matlab program modelling the acoustic ray paths inside a pipe with a thermal gradient. Chapter 6 indicated that the transmitter was located on top of the test header (pipe) and generated pressure signals inside the pipe by the vertical movement of the piston. No study had been carried out on the nature of the pressure signal generated inside the main pipe section from this branch flow. The only studies were of the acoustic resonances of the combined transmitter pipe assembly. Signals used in the field were mostly of frequencies below 100 Hz which for a propagation

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velocity around $1200 \mathrm{~m} / \mathrm{s}$ had a shortest wavelength of 12 metres which was an order of magnitude larger than any likely pipe diameter and sufficient to justify plane wave propagation inside the pipe.

### 8.2.1 Initial Ray Locations

Based on an assumed plane wave mode of propagation inside the pipe, the source signal was split up into a number of points representing convenient sized areas. The first model of source areas was that of a square shaped grid of 100 squares with the corners removed to create an octagonal source area to approximate a circular area. This configuration is shown in the following Figure 8-1.


Figure 8-1 - Initial Matlab "Bounce" Program Source Locations based on an Octagon of 100 squares with the corners removed.

Most of the areas, the square ones, were of the same size while the diagonal (triangular) corners were of half the area of the squares they adjoined. These square and triangular areas were then used to represent an array of sources in a plane at one end of the pipeline section with the outgoing rays initially considered to be parallel to the pipe axis. As the rays progressed along the pipe they were subject to:

- refraction due to any thermal gradient which tended to bend the rays down
- reflection when any ray reached the pipe wall boundary
- thermal gradients were considered uniform across the pipe cross section and varied only in the vertical direction.

The resulting ray paths eventually reached the end of the pipe section in what appeared to be a bouncing path and so the program was referred to as the "Bounce" program. The section length was doubled to simulate the returned echo from the end but considered to continue in the same direction for the same length. Any ray approaching a flat end would reflect. The only difference between continuation and reflection was the change of handedness. A ray moving to the left at it touches the end would reflect but continue to the left and return back to the source end. If this pipe were then rotated 180 degrees about a vertical axis through the end plate, what was observed as a continuation

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to the left of the reflection now becomes a movement to the right in the pipe section now continuing. The handedness of all the paths reaching the location of the end plate are reversed. This should have no effect on the resultant rays travelling in the same direction for double the pipe length. What is only of interest is the time taken to reach the end and the consequent effective velocity of each ray. The velocities of all the rays were then averaged based on their source areas to determine the change resulting from the bouncing path and compared with the velocity without the thermal gradients.

Axes used were X for the pipe longitudinal axis, Z for vertical and Y for lateral both at right angles to the pipe centreline. Since all thermal gradients result from gravitational effects they only operate in the vertical or $Z$ direction and furthermore since higher temperatures almost always sit above lower temperatures and velocities increase with temperature, refraction always resulted in a downward bending of any rays but only in the $Z$ direction. The following Matlab Figure $8-2$ generated by the program showed the signal generated near the central top (left side) and propagating by combinations of refraction and reflection progressively to the upper right within the 80 metres shown in this view..


Figure 8-2 - Matlab Program - Three dimensional Acoustic Ray path inside DN 900 Pipe.
The following Figure 8-3 extended the ray path over a longer distance and via an end view of the pipe showed the consequence of the downward refraction as general avoidance of the top segment but even distribution through the remaining part of the cross section.

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Figure 8-3 - Matlab Program - Pipe end view of acoustic Ray paths inside DN 900 Pipe.
Another aspect was the outer almost straight line paths very close to the pipe perimeter but only in the lower two thirds of the pipe cross section.

### 8.2.2 Time and Distance Increment

Distance increment for the ray tracing was 0.2 times the internal diameter. An input velocity was required and was used together with the distance increment to determine the time increment by dividing the distance increment by the velocity. Distance was the signal travel distance which was double the pipe length. All the following results were based on these increments which were much coarser than the above source location separation but justified in that the radius of curvature of rays was quite large and the change of height with axial distance for each successive calculation smaller than the radial source resolution.

Final velocity resolution was dependent on the signal travel distance chosen. Velocities were typically around $1200 \mathrm{~m} / \mathrm{s}$ for pipelines. So a DN 1000 pipe of length of 600 metres and signal travel distance of 1200 metres had a velocity resolution of $1 / 6000$ and a DN 100 pipe of the same length a velocity resolution of $1 / 60000$. Shorter lengths reduced the resolution as would larger diameters. Matlab calculation on a laptop computer took just less than 10 minutes for 500 metre pipe length of DN 200 pipe with nominal velocity $1200 \mathrm{~m} / \mathrm{s}$ and covering seven different velocity gradients.

### 8.2.3 Program Input Geometry Change

The octagonal input was awkward to program and was restricted to the 84 or so rectangular or triangular areas. An alternative approach was later developed in the form of concentric annular rings

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with multiple sectors within each ring all of the same area including a set of central sectors. This restricted the numbers of sectors to what may appear as strange numbers of equal areas of 75,147 , $300,588,1200,2352$ and 4800 . However dividing by 3 results in $25,49,100,196,400,784$ and 1600 which can be generated by the square of the number of radial annuli which in turn are based on half powers of 2 multiplied by 10 . This provides a good range of element numbers and flexibility while simplifying programming.

A further model change was for the thermal input. It was changed from an array of velocity values for specific $Z$ values to an array of equation coefficients to allow for a cubic equation for $Z$ based velocity changes and a quartic equation for X based velocity variation along the pipe axis with the constant of the quartic equation the velocity at zero $X$. The latter modification allowed for the input of upward or downward equivalent inclines and combinations. The differential of the $Z$ based cubic equation provided the thermal gradient for the velocity at that $Z$ value. The variables for the cubic and quartic equations were ratios of $X$ and $Z$ coordinates to respectively pipe length and pipe internal radius which simplified the equation generation and use.

An example of the annular arrangement of input points was shown in the following Figure 8-4 for DN300 pipe with 300 equal area elements:


Figure 8-4 - Matlab Program - Acoustic Source Pattern inside DN 300 Pipe.
Visually there was an even distribution of points. The pattern of points did not change with diameter but only with number of points limited to the strange values detailed above. This model and mode of velocity and gradient entry was used to generate the results detailed below.

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### 8.2.4 Refraction

The program has Function named: Point_Increment_Ann_Eqn.m which had an input vector and produced an output vector. The thermal gradient determined the change from input to output vector based on refraction.

Refraction was the bending of the ray due to changes in velocity or a velocity gradient in accordance with Snell's law which was addressed in Kinsler and Frey [5] for underwater acoustics and provided the following Equation (8.2.1) for the gradient of the sound speed as:

$$
\begin{equation*}
g=\frac{d c}{d z} \tag{8.2.1}
\end{equation*}
$$

where

Co reference or average sound speed at the top of the curve of radius $R$.
sound speed gradient
sound speed varying with height or depth $z$.
vertical height or depth. radius of curvature of ray path the angular position relative to the top of curve of radius $R$.

The radius of curvature, $R$, in a constant gradient sound speed $g$ was given by:

$$
\begin{equation*}
R=-\frac{c_{0}}{g \cos \theta} \tag{8.2.2}
\end{equation*}
$$

For a circle of radius $R$ and a small increment $\Delta x$ along its perimeter there was a change in tangent angle of $\alpha$ which equalled the angle subtended at the centre of the circle. This simple geometric relation was used to determine the ray vector angle change in the vertical plane based on the distance between successive points and the radius of curvature of the ray at the location.

$$
\begin{equation*}
\alpha \approx \frac{\Delta x}{R}=-\frac{g \Delta x}{c} \tag{8.2.3}
\end{equation*}
$$

In the previous Chapter 5 of this document, internal below ground measurements have indicated vertical temperature gradients of around $1^{\circ} \mathrm{C}$ over the diameter of 0.4 metres which approximated a sound speed gradient of around $4 \mathrm{~m} / \mathrm{s}$ per metre while the sound speed should be around $1200 \mathrm{~m} / \mathrm{s}$. Using Equation (8.2.2) indicated a radius of curvature of around 300 metres for below ground. For above ground the gradient can be an order of magnitude higher and the radius of curvature an order of magnitude smaller. The Matlab "Bounce" program used distance increments of $20 \%$ of diameter which for DN 300 pipe was around 60 mm so that angle increments for below ground situations with radii of curvature 300 metres were very small and of the order of 0.0002 radians. For such small angles equivalent $\Delta z / \Delta x$ values adequately approximate ray angle changes due to refraction.

For an initial angle $\theta_{1}$ and the subsequent angle $\theta_{2}$ due to the angle change $\alpha$, the change in $z$ value and $x$ values was given by Kinsler et Al. (page 440) [5]:

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$$
\begin{align*}
\Delta z & =R\left(\sin \theta_{1}-\sin \theta_{2}\right)  \tag{8.2.4}\\
\Delta x & =R\left(\cos \theta_{2}-\cos \theta_{1}\right) \tag{8.2.5}
\end{align*}
$$

In the current version of the "Bounce" program all velocity gradients were assumed to be in a vertical plane due to gravitational influences on thermal convection currents producing such gradients. Hence only the $Z$ axis values were directly affected by the refraction. Since the gradients were assumed to be solely in a vertical plane then for the same $Z$ axis value all points had the same thermal gradient across the pipe width.

A Function for the Matlab program was sent coordinates and other relevant variables together with the velocity equation for the cross section. It calculated for the $z$ coordinate value the velocity and the velocity gradient which was the differential of the velocity variation with respect to $z$ and returned these two values.

Another function then took the $z$ coordinates, velocity and velocity gradient and then calculated the radius of curvature which was then used to determine the refracted ray location using the following equations:

$$
\begin{gather*}
\beta_{v}=\tan ^{-1}\left(\tan \theta_{v} \times \cos \theta_{h}\right)  \tag{8.2.6}\\
R=\frac{c}{g \times \cos \beta_{v}} \tag{8.2.7}
\end{gather*}
$$

where
$\beta_{v}$
$\theta_{v} \quad$ angle of the velocity vector of the ray and the pipe axis in the vertical plane through the axis.
$\theta_{h} \quad$ angle of the velocity vector of the ray and the pipe axis in the horizontal plane through the pipe axis.
c the velocity returned by the velocity function for the input height.
g the velocity gradient returned by the velocity function for the input height.

The new velocity vector of the ray was calculated by a Function "Point_Increment_Ann_Eqn.m" as follows based on refraction:

$$
\begin{gather*}
\text { dist }=c \times d t  \tag{8.2.8}\\
\beta_{v 2}=\beta_{v 1}-\frac{d i s t}{R}  \tag{8.2.9}\\
\Delta x=d i s t \times \cos \beta_{v 2} \times \cos \theta_{h}  \tag{8.2.10}\\
\Delta y=d i s t \times \cos \beta_{v 2} \times \sin \theta_{h}  \tag{8.2.11}\\
\Delta z=\operatorname{dist} \times \sin \beta_{v 2} \tag{8.2.12}
\end{gather*}
$$

The previous coordinates were then incremented by the above values of $\Delta x, \Delta y$ and $\Delta z$.

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The current radius was the Pythagorean combination of the $Y$ and $Z$ coordinates which was used to check whether the pipe radius has been reached.

The new values of $\theta_{\mathrm{h}}$ and $\theta_{\mathrm{v}}$ were given by:

$$
\begin{align*}
& \theta_{v}=\text { Angle_}_{-} A_{-} \operatorname{Tan}(\Delta x, \Delta z)  \tag{8.2.13}\\
& \theta_{h}=\text { Angle_}_{-} A_{-} \operatorname{Tan}(\Delta x, \Delta y) \tag{8.2.14}
\end{align*}
$$

These series of operations were then repeated until the end of the pipe was reached. If the pipe wall was reached then the reflection Function is invoked to provide the new velocity and angles.

The increments were accumulated for each ray together with the total number of time increments of dt . From these values the average velocity along the ray path was calculated. Most important was the signal travel length divided by the total transit time to give the observed velocity which was slower than the ray path velocity.

### 8.2.5 Reflection

The program has a Function titled: Internal_Reflection_Ann_Eqn.m which had an input vector and an output vector. The output vector resulted as if the pipe surface was a mirror and was the reflection of the incoming vector but its length depended on the length prior to reaching the pipe as explained below.

When the ray reaches the pipe wall reflection takes place. Reaching the pipe wall was determined by the radial distance from the pipe axis to the end of the ray exceeding the pipe radius. Since each ray element is a short straight vector, the point of wall contact could then be calculated and in the Figure $8-5$ below is point $P\left(x_{1}, y_{1}, z_{1}\right)$. The start position for such ray prior to hitting the pipe wall was $\mathrm{O}\left(\mathrm{x}_{0}, \mathrm{y}_{0}, \mathrm{z}_{0}\right)$ in the figure. The point P was used to determine the radial vector, $\bar{r}$. The incoming vector was $\bar{u}$ and the reflected vector $\bar{v}$ terminating at point $Q\left(x_{2}, y_{2}, z_{2}\right)$. Angles $\theta_{0}, \theta_{1}$ and $\theta_{2}$ were the angles from the X axis to the respective points $\mathrm{O}, \mathrm{P}$ and Q . The coordinates of the point on the pipe axis where radial vector $\bar{r}$ touched was $R\left(x_{r}, y_{r}, z_{r}\right)$.

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Figure 8-5 - Matlab Program - Reflection Cross Section Geometry and General Axes Orientation.

The following principles determined the location of Q , the end of vector $\overline{\mathrm{V}}$.

1. Incoming vector $\bar{u}$ must be the same length as reflected vector $\overline{\mathrm{V}}$.
2. The radial distance from the pipeline axis to O must be the same as that to Q .
3. The angle from $\theta_{1}$ to $\theta_{0}$ must be the same as that from $\theta_{2}$ to $\theta_{1}$.
4. The Y axis distance from $\mathrm{y}_{0}$ to $\mathrm{y}_{1}$ must equal that from $\mathrm{y}_{1}$ to $\mathrm{y}_{2}$.
5. Any refraction is ignored in the reflection process as the distances are short and the reflection process has far greater effect on ray path than minor refraction.
6. Not shown on the figure was the surface normal vector $\bar{n}$ at point $P$ which was opposite to radial vector $\bar{r}$.

The reflection algorithm worked as follows:
a. Obtain the angle to the start of the incident ray, $O(x o, y o, z o), \theta_{0}$.
b. Obtain the angle to the contact point of the incident ray, $\mathrm{P}(\mathrm{x} 1, \mathrm{y} 1, \mathrm{z} 1), \theta_{1}$.
c. Then use the change in axes: $u=r \cos \left(\theta_{0}-\theta_{1}\right), v=r \sin \left(\theta_{0}-\theta_{1}\right)$ equations to rotate the point O into the point Q using the angle $-2 *\left(\theta_{0}-\theta_{1}\right)$
d. The reflected vector then must be corrected for length based on the residue of the length of the vector which passed through the pipe.

In the Matlab "Bounce" program, the refraction Function identified whether the pipe wall had been reached or passed. It then called the reflection Function with the required input variables and returned the point Q and the vector $\overline{\mathrm{v}}$ with velocity same as for $\bar{u}$ but in a totally different direction. If the pipe wall had been passed then the distance was corrected to match that to the pipe wall and the balance of the distance during the time interval dt used in the reflected ray. So there was no need to program

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for time increments with dt used between any two consecutive points regardless of refraction or reflection. Any reflection at the pipe boundary was counted via a flag for each ray. This meant that the ray approaching the pipe wall represented by vector $\bar{u}$ had a different length from the departing ray represented by vector $\overline{\mathrm{v}}$.

The velocity Function was called and the velocity and velocity gradient returned for the point just before the pipe wall which was the start point. Refraction was not used so that the angles approaching the pipe wall were not changed. The point of pipe wall contact was determined and from it the remaining length during the time dt determined and used to find the end points after reflection.

The reflection equations were as follows with the start point prior to wall contact and end point after reflection. The end point was used twice initially as the end point of the ray approaching and passing through the pipe wall and then reused as the end after reflection:

$$
\begin{align*}
& R_{s}=\sqrt{X_{s}^{2}+Y_{s}^{2}+Z_{s}^{2}}  \tag{8.2.15}\\
& R_{E}=\sqrt{X_{E}^{2}+Y_{E}^{2}+Z_{E}^{2}} \tag{8.2.16}
\end{align*}
$$

Distance between the start and initial end locations was given by:

$$
\begin{equation*}
\text { Dist }_{1}=\sqrt{\left(X_{E}-X_{S}\right)^{2}+\left(Y_{E}-Y_{S}\right)^{2}+\left(Z_{E}-Z_{s}\right)^{2}} \tag{8.2.17}
\end{equation*}
$$

where

| $R_{s}$ | start point radius |
| :--- | :--- |
| $R$ | pipe radius |
| $R_{E}$ | end point radius |
| $X_{S}, Y_{S}, Z_{S}$ | start point $X, Y, Z$ coordinates |
| $X_{P}, Y_{P}, Z_{P}$ | pipe $X, Y, Z$ coordinates |
| $X_{E}, Y_{E}, Z_{E}$ | end point $X, Y, Z$ coordinates |

The following three equations pro-rataed the lengths in the direction of the three axes to determine the point at which the ray hit the pipe wall.

$$
\begin{align*}
X_{p} & =X_{S}+\frac{\left(R_{p}-R_{s}\right)}{\left(R_{E}-R_{S}\right)}\left(X_{E}-X_{S}\right)  \tag{8.2.18}\\
Y_{p} & =Y_{S}+\frac{\left(R_{p}-R_{S}\right)}{\left(R_{E}-R_{S}\right)}\left(Y_{E}-Y_{S}\right)  \tag{8.2.19}\\
Z_{p} & =Z_{S}+\frac{\left(R_{p}-R_{S}\right)}{\left(R_{E}-R_{S}\right)}\left(Z_{E}-Z_{S}\right) \tag{8.2.20}
\end{align*}
$$

New values of $\Delta x, \Delta y$ and $\Delta z$ then become:

$$
\begin{equation*}
\Delta x=X_{p}-X_{s} \tag{8.2.21}
\end{equation*}
$$

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$$
\begin{gather*}
\Delta y=Y_{p}-Y_{s}  \tag{8.2.22}\\
\Delta z=Z_{p}-Z_{s}  \tag{8.2.23}\\
\Delta_{X Y Z}=\sqrt{\Delta x^{2}+\Delta y^{2}+\Delta z^{2}} \tag{8.2.24}
\end{gather*}
$$

The last expression for $\Delta_{x y z}$ is the length from the start point to the pipe along the ray. The length correction according to the current program was given by:

$$
\begin{equation*}
\text { Length }_{\text {corrn }}=\frac{\left(\text { Dist }_{1}-\Delta_{X Y Z}\right)}{\Delta_{X Y Z}} \tag{8.2.25}
\end{equation*}
$$

The equation appeared incorrect in that for very small values of $\Delta_{x y z}$ the correction could exceed Dist1 but was correct. The reflection process simply reflected the start point across the radial line from pipe centre to the point on the pipe. Hence the new end point had the same distance from the pipe as the original start point but this distance needed to be reduced. The new distance of $\Delta_{x y z}$ when multiplied by the length correction factor then became:

$$
\begin{align*}
\text { New }_{\text {Length }}= & \frac{\Delta_{X Y Z}\left(\text { Dist }_{1}-\Delta_{X Y Z}\right)}{\Delta_{X Y Z}}  \tag{8.2.26}\\
& =\left(\text { Dist }_{1}-\Delta_{X Y Z}\right)
\end{align*}
$$

Which is the remaining length of the original Dist $t_{1}$ that was outside the pipe.
The following are the steps in the reflection process using the Matlab format for ease of expression:

```
Angle_Start = Angle_A_Tan(StartY,StartZ);
Angle_Pipe = Angle_A_Tan(PipeY,PipeZ);
EndX = StartX + 2*dX;
EndY \(=\) StartY* \(\cos \left(-2^{*}(\right.\) Angle_Pipe - Angle_Start) \()+\) StartZ * \(\sin \left(-2^{*}\right.\) (Angle_Pipe - Angle_Start));
EndZ \(=\) StartZ* \(\cos \left(-2^{*}(\right.\) Angle_Pipe - Angle_Start) \()-\) StartY * \(\sin \left(-2^{*}\right.\) (Angle_Pipe - Angle_Start));
EndX \(=\) PipeX + (EndX - PipeX) * Length_correction;
EndY \(=\) Pipe + (EndY - PipeY \()\) * Length_correction;
EndZ = PipeZ + (EndZ - PipeZ) * Length_correction;
dX = EndX - PipeX;
dY = EndY - PipeY;
dZ = EndZ - PipeZ;
Start_angle_vert = Angle_A_Tan(dX,dZ);
Start_angle_horiz = Angle_A_Tan(dX,dY);
```

The above start angles and new end points were the starting points for the next refraction calculation.

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### 8.2.6 Angle A Tan Function

The program included a Function titled: Angle_A_Tan.m which took an input of two values and provided the correct angle between 0 and $2 \pi$ radians. The two input values were a horizontal and a vertical value. As can be seen in the reflection algorithm, the ATAN function was important. The ATAN function in Matlab provided an angle but no guidance on the quadrant to which the angle applied. The above Function made up for that deficiency.

### 8.2.7 Velocity Gradient

An important Function was titled: Velocity_Eqn.m which had as input a $Z$ and $X$ coordinate and the velocity function values varying mainly in the vertical direction but with the option of variation in the $X$ or pipe axial direction. It returned the velocity and velocity gradient for those coordinates. The velocity gradient was the differential of the velocity curve. The radius of curvature was calculated in the Function calling program based on the returned values.

### 8.2.8 Thermal Gradient and Velocity Gradient

For calculation purposes, only velocity gradients were used and were generally based on a gradient of $1 \mathrm{~m} / \mathrm{s}$ change per degree Celsius. Referring to Figure 7-9 and Figure 7-10 for da/dT values showed that da/dT for 10 degrees was over 2 while at 40 degrees was just below 1 . This suggests that the Matlab "Bounce" calculations needed to be adjusted for the relevant pipe water temperature with predicted velocity changes doubled for temperatures around 10 degrees and progressively reduced for higher temperatures in accordance with da/dT values from Figure 7-9 or Figure 7-10.

### 8.3 CHALLENGES

Matlab was a very powerful but ideosyncratic program ideal for use with arrays of multiple dimensions but confusing when dealing with vectors. It had traces of $C$ but did not permit some of the C expressions. Error messages were often misleading and confusing when trying to track down the cause of programming problems.

One of the most significant problems was the programming of the reflection from the inclined pipe wall. The other was the initial input locations for the rays which started with the octagonal configuration and then into the annular ring arrangement. Another issue was the atan function which took time to resolve. The method of inputting the velocity gradient was another major issue.

### 8.4 HORIZONTAL PIPE THEORETICAL RESULTS

The following Figure 8-6 showed results for a linear increase in velocity from bottom to top of the pipe cross section and with zero velocity change at the pipe axis. At each $Z$ or height value the velocity was uniform across the width of the pipe at that height. Zero height was at the pipe axis. Besides the result for linear increase in velocity gradient (blue) Figure 8-6 also showed a nonlinear version in red for so called "Cold Bottom" velocity gradient.

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Figure 8-6 - Matlab "Bounce" program results - Linear and Non-Linear thermal gradients and their effect on Velocity Change.

In the above Figure 8-6 the velocity gradient ratio was the ratio of velocity change to pipe radius $(\mathrm{m} / \mathrm{s} / \mathrm{m})$ and was plotted on the horizontal axis while the resultant velocity reduction in metres/second was plotted on the vertical axis. The blue line was obviously linear with $0.5 \mathrm{~m} / \mathrm{s}$ velocity change for a gradient of $1 \mathrm{~m} / \mathrm{s}$ / radius. The red line resulted from a nonlinear gradient with greatest change at the bottom referred to as "Cold Bottom" since such gradients were produced by cooling from underneath. The shape of the gradient in the upper part of the pipe was the same as the linear gradient but the bottom gradient was increased. The resulting velocity change appeared to be a combination of the linear gradient result and a contribution from the more rapidly changing bottom part and surprisingly reached a velocity change of $0.9 \mathrm{~m} / \mathrm{s}$ for $1.0 \mathrm{~m} / \mathrm{s} /$ radius of "Cold Bottom" gradient. This varying gradient will be covered in more detail later.

The following Figure 8-7 plotted the Y and Z coordinates along a pipe length of 1000 m for DN 300 pipe and linear gradient of $\pm 0.6 \mathrm{~m} / \mathrm{s} /$ radius.

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Figure 8-7 - $\quad$ Side (for Z) and Top (for Y) view of Ray Bounces along 1000 m of DN 300 pipe. Vertical gradient $0.6 \mathrm{~m} / \mathrm{s} /$ radius. Path of one ray only with $Z$ and $Y$ axis values plotted against pipe length $X$.

The ray in the above Figure 8-7 started at the top and slightly off pipe centre and bounced along as indicated by the red $(Z)$ vertical value while the lateral $Y$ axis value started to deviate and then after a few reflections ricocheted from side to side. The number of bounces over the 1000 metre length was relatively small and less than 20 while ricochets off the side pipe walls was around 10 . While the ray started at the top of the pipe it rarely returned near the top and so sampled mainly lower gradients. The ray pattern was similar for the other gradients down to $0.15 \mathrm{~m} / \mathrm{s} /$ radius other than a reduction in the number of bounces. For zero gradient there was no bouncing and all rays stayed parallel to the pipe axis. The $Z$ axis value was the only one with curvature since gravity and the thermal gradient was in the vertical plane only. The $Y$ axis value only had straight lines between ricochets or side reflections.

Figure 8-7 and subsequent similar figures were based on tracking one ray starting near the top centre of the pipe. Any observations and conclusions based on these figures were limited since the resultant velocity was the combination of results from all source points as in Figure 8-4. Such results may appear non-intuitive with regard to the single plotted source but may make sense when all component sources were considered.

The model originally used vertical thermal gradients in an array with a set of eight gradient values down the pipe vertical axis which applied to all points across the pipe diameter for each vertical location for velocity calculation. This array input method was changed to allow for quartic equations to approximate the vertical gradients which allowed for more flexibility in thermal gradient input. With heating from the top there was an increase in gradient at the top while for cooling from the bottom there was a higher gradient at the bottom. Such gradients and combinations were considered in Figure 8-8 below.

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Figure 8-8 - Fourth Order Polynomial Velocity Gradients and Fifth Order Convection Approximation.

Figure 8-8 has been oriented with the vertical $Z$ axis vertical on the page to realistically represent the velocity profiles. The blue "Bottom Cooling" or "Cold Bottom" had the same central slope as the red "Top Heating" or "Hot Top". The change was in the lowest or highest third of the Z/R value (fraction of $\pm 1$ ). The black dashed curve was an attempt to approximate longitudinal convection currents in the pipe with flow on the underside of the top and on the bottom in opposite directions. Ideally such shape should not end in a sharp contact with the pipe wall but in a constant velocity. Such modification was not attempted. Convection flow velocity assumed to be the acoustic velocity change for modelling purposes. (Convection flow velocity for the DN 200 above ground pipe in Chapter 7 was estimated at around $30 \mathrm{~m} / \mathrm{hr}$ or $0.008 \mathrm{~m} / \mathrm{s}$ for a slope of around $1: 100$ or 0.6 degrees: a value two orders of magnitude below that of Figure 8-8). This gradient conveniently could be generated by only the fifth order coefficient without interfering with or affecting the fourth order shape of the "Hot Top" or "Cold Bottom" gradients. Thus the combination of "Cold Bottom" and Convection was achieved in the orange dashed curve simply by changing the coefficient of the fifth order term from zero for the "Cold Bottom" polynomial. Since Z/R has value one independent of pipe radius the shape of the gradients using this scaling was then independent of pipe diameter for calculation purposes but would affect the actual gradient as the radius changed. All of the modelling was based on the Z/R range of $\pm 1$ and by changing the coefficients of the $5^{\text {th }}$ order polynomial gradient.

Inputting these gradients into the Matlab "Bounce" program with pipe length of 1000 metres and DN 300, the "Top heating" gradient produced an average velocity reduction of $0.59 \mathrm{~m} / \mathrm{s}$ while the "Bottom cooling" gradient change was $0.89 \mathrm{~m} / \mathrm{s}$ which reflected the greater influence of the lower part of the pipe on the multiple bouncing propagation. The following Figure 8-9 showed the effect of "top heating" or "hot top".

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Figure 8-9 - "Top Heating" or "Hot Top" Thermal Profile for DN 300 pipe.
For the "bottom cooling" or "cold bottom" below in Figure 8-10, there was a significant reduction in the number of reflections and change in their shape. Higher velocity reduction associated with reduced reflections was counter intuitive.


Figure 8-10 - "Bottom Cooling" or "Cold Bottom" Thermal Profile for DN 300 pipe.
For a linear gradient of $\pm 1 \mathrm{~m} / \mathrm{s}$ per radius the resultant velocity reduction was $0.51 \mathrm{~m} / \mathrm{s}$ whereas the "Bottom Cooling" gradient increased that reduction by 75\% while the "Top heating" only increased the reduction by $16 \%$ a factor of five smaller effect. Figure $8-6$ showed the "Bottom cooling" as the blue line while the red line was the "Top heating".

Above discussion and results were based on acoustic velocity gradients resulting from thermal gradients without linking them. The issue of convection currents has been mentioned in regards to the gradients in Figure 8-8 but not tested. Any longitudinal convection current has a particle velocity which will modify the acoustic velocity and can be modelled as an equivalent acoustic velocity but was expected to be sufficiently small to be almost negligible. The two above variable velocity gradients could be combined to reflect the up slope moving warm water at the top of the pipe and down slope cooler water at the bottom. Using the black dashed "convection" gradient from Figure 8-8 with $+/-1$ $\mathrm{m} / \mathrm{s}$ maximum gradient and with zero in the central half, the velocity reduction was $0.314 \mathrm{~m} / \mathrm{s}$. Doubling the maximum to $+/-2 \mathrm{~m} / \mathrm{s}$ produced a velocity reduction of $0.69 \mathrm{~m} / \mathrm{s}$ higher than double $0.314 \mathrm{~m} / \mathrm{s}$. Ideally there should be zero convection velocity when in contact with the pipe wall but would require

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extending the polynomial beyond fifth order. The ray path for the $+/-1 \mathrm{~m} / \mathrm{s}$ convection approximation is shown in Figure 8-11 below and based on the black dashed line in Figure 8-8.


Figure 8-11 - Longitudinal Convection modelled Thermal Profile for DN 300 pipe with maximum gradient at top and bottom of $+/-1 \mathrm{~m} / \mathrm{s}$.

Note that there was curvature in the path only at the top and bottom where there was a gradient but not in the central section without gradient. Curvature was concave down as has been the case for all gradients.

The " S " shaped convection gradient was achieved with all gradient polynomial coefficients zero with the exception of that for the fifth power of Z/R. This made it very easy to superimpose such a gradient on another such as the "cold bottom" which has been done and was the orange dashed curve in Figure 8-8. Using this combined gradient resulted in a velocity reduction of $1.38 \mathrm{~m} / \mathrm{s}$ which was 0.17 $\mathrm{m} / \mathrm{s}$ higher than the addition of the convection value of $0.315 \mathrm{~m} / \mathrm{s}$ to the $100 \%$ "cold bottom" reduction of $0.893 \mathrm{~m} / \mathrm{s}$ which resulted in $1.207 \mathrm{~m} / \mathrm{s}$. A single near central ray propagating under these conditions was shown below in Figure 8-12.


Figure 8-12 - Longitudinal Convection combined with "Cold Bottom" showing unusual pattern of rays merging at the bottom of the pipe.

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Figure $8-12$ showed a very unusual feature of this combination, only slightly perceptible in Figure 8 -10, which was the progressive restriction of the $Z$ component towards the bottom of the pipe at the end of the Figure with the Y component simply consisting of bouncing across the lowest levels of the pipe with progressively shorter paths. This may be a significant contributor to the acoustic anomaly in that the ray path no longer samples the whole pipe and by being confined to the lowest and coolest part of the pipe has very low relative velocities not characteristic of the average of the start cross section average. Field conditions contributing to this situation would be cold ground with heating from the top typical of the rising spring-summer seasonal change combined with slopes sufficient to generate longitudinal convection currents. Such conditions applied to the period in which the anomalous DN 300 acoustic measurements were made especially in Test Section No. 12 with the highest anomaly and highest average slopes. The gradient used to generate Figure $8-12$ effectively had a velocity of $+2 \mathrm{~m} / \mathrm{s}$ at the top and $-3 \mathrm{~m} / \mathrm{s}$ at the bottom (orange dashed curve in Figure $8-8$ ) with combined change across the pipe diameter of $5 \mathrm{~m} / \mathrm{s}$ and achieved the $1.38 \mathrm{~m} / \mathrm{s}$ overall velocity reduction which appeared to be a small reduction of $27 \%$ for the much larger input gradient. This combination of "cold bottom" and convection has shown that such effects were additive.

### 8.5 DIFFERENCES WITH PIPE DIAMETER.

The following table of thermal gradient equation coefficients was used for the seven different thermal gradients for comparison of the effect of the gradients on Pipe Diameter. These seven gradients are the columns in the following table of polynomial coefficients.

Table 8-1 - Polynomial Coefficients of Thermal Gradient Equations for Modified Matlab "Bounce" Program.

| Polynomial Coefficients for Thermal Gradients. |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | $\begin{aligned} & 1.00 \\ & \text { Linear } \end{aligned}$ | Hot Top | $\begin{gathered} 1.00 \\ \text { Cold } \\ \text { Bottom } \end{gathered}$ | 0.25 CB | 0.5 CB | 0.75 CB | +/- Conv | $\begin{aligned} & \text { +/- Conv } \\ & + \text { CB } \end{aligned}$ |
| (z/R)^0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| (z/R)^1 | 1.00 | 0.95 | 0.95 | 0.2375 | 0.475 | 0.7125 | 0 | 0.95 |
| (z/R)^2 | 0.0 | 0.12 | -0.12 | -0.03 | -0.06 | -0.09 | 0 | -0.12 |
| (z/R)^3 | 0.0 | 0.552 | 0.552 | 0.138 | 0.276 | 0.414 | 0 | 0.552 |
| (z/R)^4 | 0.0 | 0.39 | -0.39 | -0.0975 | -0.195 | -0.2925 | 0 | -0.39 |
| (z/R)^5 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |

The gradient polynomial variable was ( $z / R$ ) so that it should be independent of diameter or radius. These same equations were used to construct Figure 8-8 and were the input gradients for Figure 8-6. Figure $8-8$ showed "Hot Top", $100 \%$ "Cold Bottom", "Convection" and "Convection" combined with "Cold Bottom". Figure 8-6 linear gradient (upper blue and lower red line) resulted from only the (z/R)^1 term to provide the gradient while the "Cold Bottom" (blue curve) was based on the coefficients for

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0.25 to 1.0 Cold Bottom (CB). These coefficients were simply the respective fractions of the $100 \%$ "Cold Bottom". To change from "Cold Bottom" to "Hot Top" simply requires a sign change of the coefficients for the squared and quartic variables. As can be seen from the table, addition of "Convection" approximation only required the addition of a non-zero coefficient for the quintic variable (z/R)^5.

Using such thermal gradients normalised with respect to pipe radius was expected to minimise variation with radius or pipe diameter. The following Figure 8-13 showed the variation with diameter of percentage of "Cold Bottom" thermal gradients with pipe diameters varying from DN150 to DN 900. The DN 200, 300, 600 and 900 appeared to be grouped together with DN 150 by itself. All appeared to have an almost linear variation of the resultant velocity change with percentage of the thermal gradient but as the red curve in Figure 8-6 highlighted there was a slight curvature in the data. Due to the bouncing nature of the transmitted rays and variable numbers of bounces along the pipe length the results for multiple rays may not smoothly vary with diameter. The program did not require integral bounces with the path of each ray followed until it reaches the pipe length regardless of where and at what orientation at that position.


Figure 8-13 - Acoustic Velocity Reduction Variation with Diameter for Different Percentages of the "Cold Bottom" Thermal Gradient.

Linear trend lines for the above Figure 8-13 reached the vertical axis slightly below 0.0 velocity unlike the red curve in Figure 8-6. For diameters DN 200 to DN 900 there was slight slope variation with diameter. At 100\% "Cold Bottom" the velocity reduction range was from 0.84 to $1.01 \mathrm{~m} / \mathrm{s}$ over a diameter range from DN 200 to DN 900. A different graph using the same data is shown in the following Figure 8-14.

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Figure 8-14 - Acoustic Velocity Reduction Variation with Diameter for Different Percentages of the "Cold Bottom" Thermal Gradient.

A linear trend line could be used for DN 300 through to DN 900 but DN 150 appeared exceptional as also noticed on the previous Figure 8-13. DN 200 appeared to be borderline in that it generally appeared to be linear with the higher diameters except for 100\% "Cold Bottom".

The number of bounces in the vertical (Z-X) plane were 32, 22, 16 and 13 for the DN 150, 300 600 and 900 respectively. A small change in diameter from DN 300 to DN 150 had resulted in a significant increase in the number of bounces which helped to explain the pattern change relative to the other diameters but not the reduced velocity change which would be expected to increase with increase in the number of bounces. As pointed out earlier the ray traces and bounce numbers were only for one out of 300 component traces and may be unrepresentative of the cause of the reduction in velocity change.

DN 200 appeared to be more similar to DN 300 than DN 150. The above Figure 8-14 and following Figure 8-15 may indicate that acoustic anomalies were less likely for diameters below DN 200 with the lower limit possibly DN 250.

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Figure 8-15 - Acoustic Velocity Reduction with Different Thermal gradient Types and Variation with Pipe Diameter.

In the above Figure 8-15, the highest velocity reduction resulted from combined "convection" and "Cold Bottom" which was almost $0.2 \mathrm{~m} / \mathrm{s}$ higher than if the two were calculated separately and then added (Cold Bottom + Convection). As noted earlier the "Cold Bottom" (light red) was around 0.3 higher than the "Hot Top" (light blue).

The results from the Matlab "Bounce" program have identified different model input thermal gradients and their effect on reducing the acoustic velocity. The assumption was that the acoustic velocity anomaly was a consequence of thermal gradients present at the start of the leak test and which then dissipated and resulted in the acoustic velocity rising in an exponential like manner. In the above Figure 8-15 the maximum combined gradient has produced a velocity reduction of $1.4 \mathrm{~m} / \mathrm{s}$ for DN 300 pipe which was close to the magnitude of most of the anomalies during the leak test and slighty below that of Test Section No. 12 with an anomaly of $1.6 \mathrm{~m} / \mathrm{s}$. The combined 100\% cold bottom and convection in Figure 8-15 used velocity gradients of +2 to $-3 \mathrm{~m} / \mathrm{s}$ with range of $5 \mathrm{~m} / \mathrm{s}$ without addressing such variation with temperature. Average pipewall temperatures for Test Section No. 12 were around $22{ }^{\circ} \mathrm{C}$ which had a da/dT value around $1.6 \mathrm{~m} / \mathrm{s}$ per ${ }^{\circ} \mathrm{C}$ which would then require a temperature gradient acros the pipe of more than $3^{\circ} \mathrm{C}$, much higher than any measured gradient in the DN 435 buried tank experiment.

### 8.6 INCLINED PIPE

Inclined pipe sections have thermal gradients which were likely to cause velocity reductions until they were dissipated. The problem was how to model them (other than convection currents modelled above). A simple longitudinal gradient of increased velocity with elevation was tried but had negligible effect. A last minute attempt at modelling the velocity reduction is shown in the following Figure 8-16.

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Figure 8-16- DN 300 Inclined Pipe - Velocity Reduction variation with Slope Gradient and Fraction of Linear Cross Section Gradient.

One problem encountered in developing this inclined version of the Matlab model was that a simple average of upslope velocity and return downslope velocity returned a smaller reduction than an average based on the combined times for the respective halves of the signal path. This was not an obvious problem since a velocity average of two values appeared to be simply their numerical average. The following Equation demonstrates the incorrectness of such assumption:

$$
\begin{equation*}
V_{A}=\frac{2 L}{T_{U}+T_{D}}=\frac{2 L}{\frac{L}{V_{U}}+\frac{L}{V_{D}}}=\frac{2}{\frac{1}{V_{U}}+\frac{1}{V_{D}}} \neq \frac{V_{U}+V_{D}}{2} \tag{8.6.1}
\end{equation*}
$$

Where

| L | pipeline length |
| :--- | :--- |
| TU | Uphill time |
| TD | Downhill time |
| VU | Uphill velocity |
| VD | Downhill velocity |

The equation is almost like the addition of parallel resistors with an additional factor of 2 and definitely not a linear addition shown by the "not equal" sign before the last ratio in Equation (8.5.1). Not recognising this difference was responsible for the initial failure to model acoustic propagation in inclined pipe as it lead to rediculously low velocity changes and the approach abandoned. Another

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issue was that beyond a certain input slope gradient the Matlab program locked up and in the case of Figure 8-16 was limited to 0.35 for cross sectional gradients up to $\pm 0.75 /$ radius and pipe length 100 m .

CFD Figure 3-25 and Figure 3-26 showed inclined 5 metre lengths of pipe of DN 450 at times of 1 and 10 hours after a sudden temperature change. Regardless of time and temperature, a common feature of the two Figures was that the coloured temperature bands were horizontal and strongly suggested that any modelling of gradients in slopes ensure such horizontal banding. Convection currents move bodies of water of different temperature until they conform to uniform horizontal bands upon which convection stops and conduction takes over. For generation of Figure $8-16$, the $X$ axis was the topographical slope or gradient. The slope in Figure $3-25$ was $15^{\circ}$ with a gradient of 0.27 . Linear gradients were used as in Figure 8-6 and Figure 8-8. Only simple Matlab program changes were needed to achieve Figure 8-16. The Figure was based on a pipe length of 100 metres. Extending the run distance to 500 metres resulted in limiting the cross section gradient to $\pm 0.5 \mathrm{~m} /$ radius and the slope gradient to 0.1 . Higher values resulted in corrupted data with unknown cause.

A surprising feature hidden in the results shown in Figure 8-16 was that the up and down slope velocity changes were an order of magnitude higher than the resultant reduction with for example the slope gradient of 0.3 for 1.0 Linear cross sectional gradient (blue curve) the velocities were $+93 /-99$ $\mathrm{m} / \mathrm{s}$ relative to the reference. If it were possible to measure the upslope velocity only it would be much slower than the downslope velocity. If measurements were taken in one direction only from both ends of a test section then slope effects could more easily be measured and may be one way of better assessing slope contribution to the acoustic anomalies. While not modelled, it was expected that the initial direction of a return signal may affect the outcome as the assumed uniformly distributed source would be deformed mid way which then would subsequently affect the return pattern.

DN 300 Test Section No. 12 had a profile with average slope of 0.7 degrees but had multiple intermediate high points which trapped and limited convection currents. The average slope of these intermediate sections was 3.3 degrees ( 0.06 slope gradient) with the worst 10.2 degrees ( 0.18 slope gradient). Using Figure 8-16 and assuming a linear cross section velocity gradient across the pipe of $\pm 0.5 \mathrm{~m} / \mathrm{s}$ per radius, the 3.3 degree slope would produce a velocity reduction around $0.3 \mathrm{~m} / \mathrm{s}$ while the 10.2 degree slope $1.2 \mathrm{~m} / \mathrm{s}$. The estimated acoustic aomaly for Test Section No. 12 was around 2.3 $\mathrm{m} / \mathrm{s}$ during the leak test period (refer to Table 7-5) and was above both of these Figure 8-16 estimated values. The thermal gradients used to generate Figure 8-16 were the linear gradients on which were based the "cold bottom" gradients in Figure 8-13 and Figure 8-14 and represent the worst case. Addition of "Cold bottom" and "convection" effects were likely to increase the above estimated values based on Figure 8-16.

Water movement and weather pattern changes prior to the test could have thermally destabilised the fill water and produced recovering convection currents during the leak test in these multiple trapped inclined sections. These may have then produced higher thermal gradients than the estimated $\pm 0.5$ $\mathrm{m} / \mathrm{s}$ per radius values and fully explained the highest anomalous velocity results in this test section.

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Figure 8-16 showed high sensitivity to both increased linear cross sectional gradient and pipe slope. Slight increases above the $\pm 0.5 \mathrm{~m} / \mathrm{s}$ per radius used above could produce greater acoustic velocity changes.

### 8.7 MATLAB OUTCOMES

The Matlab "Bounce" model has obtained the following results:
a) For linear gradients across the pipe vertical diameter there was a reduction in acoustic velocity directly proportional to the gradient.
b) The acoustic velocity reduction for linear gradients was approximately $0.5 \mathrm{~m} / \mathrm{s}$ for a gradient of $\pm 1 \mathrm{~m} / \mathrm{s}$ per radius or $2 \mathrm{~m} / \mathrm{s}$ across the diameter.
c) For nonlinear gradients, the "hot top" version only slightly further increased the acoustic velocity reduction compared with a similar linear gradient.
d) For nonlinear gradients, the "cold bottom" significantly further increased the acoustic velocity reduction compared with a similar linear gradient.
e) For an "S" shaped gradient approximating longitudinal convection currents there was a reduction in acoustic velocity with nonlinear increased reduction with increased convection flow.
f) The model made it easy to superimpose convection gradients on other gradients
g) Addition of separately determined velocity reductions underestimated the results from using a combined velocity gradient.
h) Modelling of slope changes on linear gradients produced changes almost an order of magnitude greater than any of those in this list and when combined with the other gradient effects noted above may explain the acoustic anomalies.
i) Because the gradient was based on $Z / R$ values between -1 and +1 , true gradients across the diameter were inversely proportional to diameter so that the velocity reduction was in effect higher for larger diameter pipe for the same thermal. Lower da/dT values for larger diameter pipes would reduce temperature based gradients.

### 8.8 FIELD RELATED SUPPORT

In this section field results are reviewed in relation to the above Matlab Model results.

### 8.8.1 Above Ground DN 200 pipe 108 metres long

As noted in Section 5.3, no internal temperature measurements were taken of the above ground 108 metre long DN 200 pipe. Only external pipe wall temperatures, pressures and acoustic velocities were measured. In addition to pipe wall temperatures at the centre of the pipe length, measurements were taken near the upper end which demonstrated thermal gradients in the longitudinal direction. The DN 200 tank experiments provided typical thermal gradients from internal measurements that could be used for the 108m pipe but could not be used in regard to longitudinal convection currents.

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Estimated incline of the pipe was approximately 1 metre rise in the 108 metre length or $1 \%$ slope. Bottom of pipe temperature at 17 metres from the upper end was 4 degrees higher than the same location at the centre indicating a longitudinal thermal gradient of approximately $0.11^{\circ} \mathrm{C} /$ metre or $11.7^{\circ} \mathrm{C}$ over the 108 metre length when in direct sunlight and with pipe axis orientation east-west. In Section 5.3 the convection rate of hot water was estimated at $30 \mathrm{~m} / \mathrm{hr}$ or $8 \mathrm{~mm} / \mathrm{s}$ which would be difficult to detect acoustically as it is below the velocity resolution of around $0.1 \mathrm{~m} / \mathrm{s}$ or $100 \mathrm{~mm} / \mathrm{s}$. Such convection movement of hot water along the top of the pipe would be countered by flow of cooler water in the opposite direction along the bottom resulting in a convection based gradient across the pipe cross section of $16 \mathrm{~mm} / \mathrm{s}$ over 200 mm diameter or $0.08 \mathrm{~m} / \mathrm{s} / \mathrm{m}$ of diameter. If the da/dT factor was around $2 \mathrm{~m} / \mathrm{s} /{ }^{\circ} \mathrm{C}$ this would equate to $0.04^{\circ} \mathrm{C} / \mathrm{m}$ of diameter and of the same order as the $0.11^{\circ} \mathrm{C} / \mathrm{metre}$ along the length.

No acoustic velocity anomalies were noted on this length of pipe during the short monitoring period. Near constant conditions with uniform rise in pressure and temperature occurred during the period from 11:30 to 15:30. This period was well after the change from night to morning and just before the afternoon maximum. Any thermal gradients affecting velocity may have had a near constant effect during this time without evidence of anomalous acoustic results.

### 8.8.2 Above Ground DN 900 pipe 375 metres long

For the DN 900 above ground 375 metre long pipe, no internal or external temperature measurements were taken on the expectation that the pressure would follow the acoustic velocity. The short length DN 900 experiment provided internal temperature measurements and pressures but no external pipe wall temperatures. These internal measurements were input into the Matlab "bounce" program with results shown in the following Figure 8-17. Examples of central vertical temperature profile variations over time were detailed previously and were used as the thermal profiles to produce the following results.

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Figure 8-17 - Matlab "Bounce" Program results for short DN 900 Pipe at one time point (late afternoon).

Temperature gradient used was the red curve on the right side of the figure which matched the internal probe and external pipe wall perimeter temperature measurements (possibly with an offset of around $4^{\circ} \mathrm{C}$ ). Thermal profile temperature has been converted into equivalent velocity. The left vertical axis was the vertical height in the pipe of either the thermal gradient or location of source for the "Bounce" program. The results of this temperature gradient on resultant velocity were shown as blue diamond shaped dots (off central vertical plane) or circles (on central vertical plane through pipe axis) for the respective heights of the source based on the octangular model of around 84 source locations. For the lower half of the pipe there was little change but nevertheless a slight reduction. For the upper half there was progressive reduction in velocity with the exception of the top constant temperature layer where there was an increase but only for two central (circles) and one lateral point at 0.4 m and 0.45 m heights. For each height increment the central axis velocity was shown as an open circle while the lateral source locations indicated by the blue diamonds showed progressively greater velocity reductions. The average effect of these changes was an overall reduction in velocity relative to a constant temperature/velocity profile. The above model had assumed that for each height within the pipe the same temperature applied to the whole width. Should there have been additional variation in the width superimposed on the central velocity profile then the overall change could be greater especially due to the non central source locations contributing greated reductions..

For DN 900 pipe the average temperature for Figure 8-17 in the late afternoon was around $36{ }^{\circ} \mathrm{C}$ which had a da/dT factor around 0.7 so that a velocity change from bottom to top of $9 \mathrm{~m} / \mathrm{s}$ (red velocity

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profile) represented a temperature change of around $6^{\circ} \mathrm{C}$ which was only possible in an exposed pipe. The average reduction in velocity was around $1.0 \mathrm{~m} / \mathrm{s}$ for an input velocity gradient of $9.5 \mathrm{~m} / \mathrm{s}$ or close to $10 \%$ of the input. The above profile was only one of the profiles from the short DN 900 pipe. Using an hourly sequence of the central vertical thermal profile the following Figure 8-18 was produced.


Figure 8-18 - DN 900 Pipe - Pressure, Estimated Acoustic Velocity from Internal Average Temperature and Matlab "Bounce" Program Velocity results for same Internal Temperature Profiles.

The average central vertical temperature variation over time was converted to equivalent acoustic velocity and shown in red. The thermal profile at the time of each average was then used by the Matlab program and resulted in the light brown bottom trace which varied from a maximum acoustic velocity reduction of around $1.0 \mathrm{~m} / \mathrm{s}$ at the top to around $0.7 \mathrm{~m} / \mathrm{s}$ on the downslope on the right hand side. Added to this figure were the results of continuing the calculations for the equivalent of the second echo or pipe length of 750 m which only slightly differed from the first 375 m length for times (and temperatures/acoustic velocities) away from the peak. There was little variation with time and average temperature.

The pressure was also shown in Figure 8-18 as the black trace using the left axis and which had a shape similar to both. While temperatures were not measured for the 375 metre long above ground DN 900 pipe, a similar relationship should have existed compared to the short pipe. The pressure trace appeared earlier than the internal pipe temperatures/velocities. As mentioned in the above ground temperature experiments there should be a counterbalancing contribution of temperatures earlier than the pressure trace so that when added to the central measured temperatures resulted in an average which was an exact match for the pressure and had a peak and trough coinciding with the pressure. Since the only measurements of the DN 900 pipe were central vertical then the counterbalancing contribution would most likely come from the sides and if so may result in a distortion of the Matlab "bounce" program results.

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The pressure - velocity version of the above Figure 8-18 in Figure 8-19 showed the pattern similar to that observed for the smaller diameters. The pressure and velocity do not move up and down a single line but loop in a manner similar to the electrical Lissajou figure which implies they are out of phase or not synchronised.


Figure 8-19 - DN 900 Pipe - Pressure and Velocity Plots - Initial and Final Velocities.
While the above Figures considered the measured pressure and velocities based on the central vertical temperature measurements, there was a missing contribution to the pressure which had been estimated and presented in the following version of the previous Figure 8-18.


Figure 8-20 - DN 900 Pipe - Pressure and Velocity plotted against Time - Initial Velocity and "Missing" or "Needed" Velocity.

The black is the pressure, red the previous "initial" velocity based on the central vertical temperatures and the blue was the missing velocity or temperature equivalent to balance the

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temperature contributions to the pressure. A pressure velocity version of these curves was shown in Figure 8-21.


Figure 8-21 - DN 900 Pipe - Pressure Velocity Plot - Initial Velocity and "Missing" or "Needed" Velocity.

The two traces were inverted with respect to each other and if added together would result in a straight line (which was effectively how it was calculated). No ambient measurements were taken for the DN 900 pipe used for these tests but were expected to slightly precede the "missing" temperatures which were likely to represent the outer annulus of temperatures next to the pipe performing the function of driving the peripheral convection currents with the counter flow currents passing up or down through the vertical centre of the pipe. The ambient was the driving heat source or sink initiating any thermal changes in the pipe and the input location was the pipe wall with its combination of good thermal radiati
on, conductivity, rigidity and ability to generate convection currents in the liquid fill.

### 8.8.3 DN 300 Below Ground

DN 300 buried Test Sections 4, 5, 6, 7, 8, 9 and 12 had measured velocities rising over the 24 hour leak test period which initially were thought to be the consequence of air solution. CFD research by the University of Wollongong [11, 115, 116] showed the presence of cross sectional thermal gradients generated by the equivalent of rapid adiabatic temperature changes resulting from rapid pressure increase at the start of pressure tests. These gradients then attenuated over time which had been scaled in Chapter 3 and for DN 300 appeared similar to the shape of the observed velocity increases but not the amplitude. These adiabatic temperature changes for the DN 300 test sections were only of the order of $0.2^{\circ} \mathrm{C}$. The pipe was buried, yield strength only X60 ( 413 MPa ) and wall thickness minimum 5.6 mm which resulted in low leak test pressures of the order of $12,000 \mathrm{kPa}$ and most of the mentioned test sections pressure tested in late winter and spring with relatively low ground temperatures all of which limited the adiabatic temperature change.

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While the adiabatic changes were small, these would have been superimposed on the larger weather induced thermal gradients identified by the DN 435 buried tank experiments in Chapter 5 where maximum range of internal temperatures as measured by the eight sensors over a height of 370 mm were 0.8 to $0.9^{\circ} \mathrm{C}$ and four to five times the adiabatic increase. With a da/dT factor of around $1.6 \mathrm{~m} / \mathrm{s} /{ }^{\circ} \mathrm{C}$ for DN 300 pipe at $22{ }^{\circ} \mathrm{C}$ the DN 435 temperature gradients convert to velocity gradients of around $1 \mathrm{~m} / \mathrm{s}$ across the diameter and $0.5 \mathrm{~m} / \mathrm{s}$ across the radius which was $50 \%$ of the linear gradient used in the Matlab modelling (excluding any convection effects).

A linear gradient of $0.5 \mathrm{~m} / \mathrm{s}$ across the 0.15 m radius using Figure $8-6$ can account for velocity reduction of $0.25 \mathrm{~m} / \mathrm{s}$ insuffficient to resolve leak test period anomalies in all sections with the exception of Test Section No. 8. Adding around $0.33 \mathrm{~m} / \mathrm{s}$ for the adiabatic effect could improve the case for Sections 4, 7, 10 and 5. Other additional gradients were needed to explain the Test Section No. 9, 6 and 12 anomalies. The differences only needed a single digit factor improvement and not an order of magnitude and as such were likely to be resolved by addition of other potential contributing factors such as those associated with sloping sections.

### 8.8.4 Sloping Pipe Results

A further consideration was the effect of an inclined pipe with its own longitudinal thermal gradient which then needed to be considered together with the abovementioned gradients. Test sections were mainly limited by pressure range and section volume. Pressure range in turn limited elevation changes to typical values of 120 metres up to 200 metres. Section volume affected length based on pipe cross sectional area. Meteorological consequences of elevation change were atmospheric temperature changes usually referred to as the adiabatic lapse rate (Ahrens and Henson [130]) which was nominally $6^{\circ} \mathrm{C}$ per 1000 metres elevation change and which for the above mentioned elevations can represent differences of 0.75 to $1.2^{\circ} \mathrm{C}$ between the lowest point and highest point in a test section as regards the ambient temperature. For the DN 300 pipe and a da/dT factor of $1.6 \mathrm{~m} / \mathrm{s}$ per ${ }^{\circ} \mathrm{C}$ this range translated to 1.2 to $1.9 \mathrm{~m} / \mathrm{s}$ reduction with elevation. This atmospheric gradient was opposite to pipe internal thermal gradients and although small, the differences may be greater due to being opposite. Solar radiation changes with such elevation changes were considered negligible. Soil depth and type with consequent effects on diffusivity would alter temperatures at pipe depth.

Movement of water inside the test section, especially the pressurising water, resulted in convection currents once the water became stationary due to differences in temperature between soil and water on slopes, especially long inclined slopes. These convection currents generated thermal gradients in these slopes. Actual convection based flow velocities identified by the CFD work were millimetres to micrometres per second and unlikely to affect the acoustic velocities but the thermal gradients they induced were likely to be long lasting and significantly affect velocities.

A thermal gradient has most effect on velocity when it extended over long distances and affected a significant portion of the test section length. Section No. 12 would be an ideal candidate for such convection currents as discussed in Section 7.3 .8 with the section consisting of multiple inclined sections of average incline 3.3 degrees and many short sections of slopes up to 10.2 degrees. The

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almost order of magnitude higher effect of slopes on velocity reduction shown in Figure 8-16 and high occurrence of slopes in Section 12 pointed to slope effects as the dominant contributor to the acoustic anomalies.

### 8.8.5 Needed or Missing Gradients

The DN 900 above ground measurements using only the central vertical temperatures appeared to be inadequate and "Needed" or "Missing" data of the order of 60\% were needed to be added to then match the pressure changes. A similar observation related to the DN 900 pipe submerged in the tank. Similar observations have been made regarding the DN 435 tank both above ground and buried. The nature of the "Missing" or "Needed" temperatures could not be specified but may relate to the near vertical sides of the pipe which were in the ideal location to impart via convection ambient and radiant heat to the pipe contents. It was also the ideal location for ambient temperature to transfer heat to the pipe. The DN 435 above ground central horizontal probe identified temperature changes which in turn implied convection currents near to the side pipe wall. CFD Figures hinted at a peripheral difference after the establishment of the thermal gradients but relied initially on convection currents to build up and generate the thermal gradients

Using the Matlab "Bounce" program there was enhanced velocity reduction when a "cold bottom" was added to a linear thermal gradient but not to the same extent with a "hot top" the following questions can apply:

- If such enhancement could be added to the sides what would be the outcome?
- Extend such effect around the whole lower half of the pipe and what would the outcome be?

The current Matlab "Bounce" model cannot address the issue without significant modification to the thermal gradient input method and then modification of the refraction function to address both vertical and radial bending of the rays. What was needed was a full pattern of temperatures across the whole pipe cross section on which to base the model calculations. The only source of such information was via CFD computer modelling which was not initiated.

The CFD comparison between PHOENICS and ANSYS CFX showed significant differences in the internal patterns for inclined slope convection affected temperatures. The heat transfer and diameter/diffusivity modelling of Chapter 3 mostly relied on PHOENICS results which had almost uniform gradients across the pipe width. Any CFD work needed to resolve the differences between the two sets of patterns and then provide the resolved pattern to be used by a modified version of the Matlab "Bounce" program and especially the effect of inclined slopes.

### 8.8.6 Verification and Testing for Thermal Gradient Types

Any proposed model needs some means of verification or testing to confirm that it was correct. The only outcome of the Matlab "Bounce" model was demonstration of a velocity reduction of similar order to the observed anomalies. What was needed was a method of checking which types of thermal gradients had been in operation. Only one method was tried so far which was that of determining whether there would be any effect on input frequencies from a linear gradient such as interference

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effects when the peak of one ray corresponded to the trough of another to cause partial cancellation or amplitude reduction. For the range of frequencies that can currently be detected, the delays of individual rays were insufficiently small to result in any effect on the detected frequencies of combined rays. Only with improved signal generation, detection and noise reduction can higher frequencies and improved methods be considered. Velocity was temperature dependent but also viscosity dependent so that using signals of different frequencies may be able to detect thermal gradient types. Signals with special combinations of amplitudes and frequencies that were found to be sensitive to particular gradients could be tested. This was similar to the "Catch 22 " situation in that improvements in technique can lead to greater sensitivity which then enables better use of the improvements. Without the initial improvements the circular or better a spiral process cannot start.

The starting point would be a CFD study equivalent to the DN 435 buried tank experiment but with mapping of the complete cross section temperatures resulting from weather induced below ground temperatures. These cross section temperatures then would be used in the Matlab program to determine the effect on velocity propagation. Finally field tests where acoustic measurements were carried out together with below ground diffusivity type measurements to confirm the CFD/Matlab results. Such work should extend to that of inclined buried pipes with measurements taken both upslope and downslope to confirm the Matlab slope based velocity reductions.

### 8.8.7 Acoustic Technique Improvements.

So far only one end of each test section has been used for signal generation and detection. With improved communications it should be possible to install detection instruments at the opposite end from the transmitter with the communications used to relay the measured signals to the opposite end. By detecting the signal half way on its return path the dB attenuation was halved which can represent an order of magnitude change in signal strength and perrmit higher frequencies to be used. An additional transmitter could be located at the opposite end further enhancing possible improvements.

With use of feedback techniques in signal generation to eliminate transients it should be possible to transmit multiple signals during the time taken for the round trip of the initial signal thus allowing for the accumulation of multiple signals to enhance noise elimination and improve echo amplitude. Sequences of signals could incorporate phase changes, frequency modifications and other techniques that on reassembly can enhance noise elimination and velocity resolution improvement.

Use of more than one transmitter and transducer could also be trialled to produce and detect oriented signals. Investigation of other pressure or pipe movement measuring devices such as accelerometers, velocity transducers and surface displacement transducers could be trialled and could lead to detection of oriented signals caused by specific types of thermal gradients.

### 8.9 KNOWLEDGE GAPS ADDRESSED

Ray curvature in layered medium is well known in underwater acoustics. Such effects inside cylindrical horizontal and inclined pipes is not known. This Chapter has demonstrated the reduction in average velocity of input rays subject to thermal gradients in such pipes. It has demonstrated that the

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nature of the gradient, whether linear or non linear has effects with higher bottom gradients increasing the velocity reduction. Presence of thermal gradients in inclined pipe was also modelled and showed a non linear response to both thermal gradient slope and increased topographical pipeline slope. These findings were of the same order of magnitude as the observed acoustic anomalous measurements made during field pressure testing but could not be specifically used to confirm their effects as the cause of the anomalies.

The outstanding knowledge gap from these results was the linking of modelled thermal gradient reductions to either field measurements or CFD predictions of complete thermal gradient patterns across the pipe cross section.

### 8.10 MATLAB MODELLING CONCLUSIONS

The above Matlab modelling has confirmed a reduction in acoustic velocity as a result of thermal gradients as anticipated in this document's topic and has provided almost sufficient thermal gradient based velocity changes to resolve completely the anomalies identified.

Potential causes of thermal gradients likely to affect velocities were:
a) Adiabatic temperature increase generated thermal layering which had a time decay feature and affected all the pipe in the test section.
b) Weather and seasonal induced thermal layering which varied over time and affected all pipe in the test section dependent on burial depth.
c) Water movement events prior to leak test including filling, transferring, depressurising to atmospheric pressure, pressurising to test pressure and partial depressurising to leak test pressure produce convection currents and thermal gradients. While these affect direcly around $1 \%$ of test section length, almost all the section is affected except the far end. Such require time to return the thermal system back into equilibrium and has a time decay character. This affects the whole section but more so the section nearest the pressure pumps for pressurisation.
d) a), b) and c) above contributing to inclined sections with consequent effects on increasing acoustic velocity reduction.
e) Internal parts of the pipe not measured by the central vertical multisensor probes and inferred by the "Needed" temperatures.
f) Spring-summer period with enhanced thermal gradient inside the pipe.

Field acoustic and temperature measurements were never envisaged to support the investigation of water movement events. The likely presence of convection based thermal layering could increase the amount of velocity change especially in slopes. "Needed" temperatures were suspected and could only be identified by subsequent CFD study.

## CHAPTER 9 CONCLUSIONS, RECOMMENDATIONS AND FUTURE RESEARCH

The main purpose of this study was to resolve the acoustic anomalies identified decades ago. At the same time the intention was to determine accurate models for calculating velocities in pipes with and without air present and determine the thermal effects on pipeline test pressure and acoustic velocity. As has been emphasised throughout this document, surrounding soil and ambient have significant influence on such thermal effects.

### 9.1 AIR EFFECTS

Air solution was initially considered the cause of the acoustic anomalies and required experimentation and assessment of field acoustic measurements to resolve whether it was the cause.

### 9.1.1 Free Air - Acoustic Velocity

In Chapter 2, Literature Review, equations for the effects of air on acoustic velocity were examined in detail and found to be deficient in addressing horizontal pipes. There was also inadequate treatment of the effect of air pockets even in research published in the last few years. The present study has provided an example of DN 150, DN 300 and DN 900 pipeline section with air pocket(s) which provided support for such sections being treated as air free for all the pipeline with the exception of the air pocket location where the equations for air affected velocity could be used and the resultant velocity for the pipeline section the length weighted average of the velocities. The same examples provided support for treatment of air solution rate as being localised.

### 9.1.2 Air Solution Rate and Bubbles

Air solution rate experiments have confirmed Adeney et al. [78-81] modelling of air solution rate as dependent on area of the air/water interface and have shown that quiescent solution rates are orders of magnitude slower than mixed. They have identified changes in solution rate with air bubble volume, width and relative length.

The research has greatly extended the limited work by others especially in terms of establishing modelling of quiescent solution rate coefficients scaled with air content at pressure and pipe diameter and provided the background and basis for more accurate and extensive modelling once bubble shape volume and surface areas were finalised.

Constant bubble width in a horizontal pipe was an unexpected finding of the research and was partly instrumental in producing an Excel model of the bubble perimeter contact with the underside of the upper pipe surface. The model was then able to closely approximate the bubble width experimental data over a pipe diameter range from 100 to 1000 mm . The finding was also important in better understanding the solution rate changes as the bubble constant width length changed and at one extreme widened when pipe length
was reached and at the other contracted into a pseudo elliptical shape and ultimately into a reducing semi-spherical bubble.

### 9.1.3 Dissolved Air - Acoustic Velocity, Partial Molar Volume and Fluid Properties

Free air in a water filled pipe resulted in reduced velocity compared with an air free pipe. Work by Harvey et al., [74], Kell [96] and Bignell [90] have confirmed the effect of dissolved air on density. Greenspan and Tschiegg [104] determined the effect of dissolved air on acoustic velocity at atmospheric pressure. No other references have been found regarding other fluid properties with dissolved air at atmospheric pressure. No references have been found for the effect of substantial dissolved air volume at pressure.

An additional air solution rate experiment was carried out to assess whether fluid properties would be changed by air solution. Air solution experiments were sensitive to the pipeline pressure test differentials of $d p / d V$ and $d p / d T$. The $d p / d V$ differential was dependent on fluid bulk modulus while the dp/dT differential was dependent on the fluid bulk modulus and thermal expansion coefficient. The experiment concluded that the dp/dT factor had increased very slightly with fully dissolved air but not sufficient to support a change in thermal expansion coefficient.

Acoustic velocity was dependent on density which is highly dependent on the dissolved air content due to its lower density. Large volumes of dissolved air should significantly increase velocity which can be measured with a velocimeter.

The above experimental results highlighted the need for experimental determination of the actual velocity increase with dissolved air at pressure. The increased acoustic velocity with fully dissolved air at pressure could create an unusual situation either side of a large air bubble. Within the section of pipe with the air bubble the velocity will be almost an order of magnitude lower than the air free pipe but next to the air bubble at pressure will be zones of air saturated water with increased velocity with the velocity reducing with distance away from the air pocket as the level of dissolved air would also reduce.

The DN 900 above ground ten day solution and acoustic velocity experiment showed a difference in solution rate of two air pockets with the one located in a flat section of pipe completely dissolving early and leaving the other one undissolved. This highlighted the effect of pipe curvature on solution rate. Dissolved air detected up to 200 metres from the air pockets provided evidence of the lateral distribution of water with dissolved air over a ten day period and raised questions as to the mechanism and time scaling.

Air pocket results supported the method of estimation of air effects on acoustic velocity as limited to the location of the air pocket with the velocity at that location estimated from the air pocket cross sectional area fraction at pressure and using the graphs or equations for the same fraction at atmospheric pressure.

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### 9.2 SOIL TEMPERATURES AND LEAK TESTING

Unavailability of soil thermal diffusivity data lead to field measurements which in turn produced some surprising results.

### 9.2.1 Diffusivity Probe Measurements

The soil diffusivity probe near the buried DN 435 tank demonstrated that the tank pressure closely followed the diffusivity probe measurements at a depth similar to a location around 100 mm to 150 mm above the tank bottom. This demonstrated that such probes could provide guidance as to the likely pressure fluctuations during a pressure test. They also provided the diffusivity values needed to model thermal ground penetration of weather. A simple set of soil water content measurements demonstrated the effect on diffusivity of soil water content. Diffusivity results differed over a distance of 5 metres due to soil type demonstrating the need for such probes to be installed at representative soil locations.

Data from the probes showed that the main factor affecting the below ground measurements was the average ambient temperature changes a week or so earlier. The probes could monitor such information for use in predicting the expected temperature changes during a pressure test.

### 9.2.2 Weather Bureau Data

Analysis of the DN 300 below ground pipe measurements showed the value of the Weather Bureau daily maximum and minimum temperatures over time to predict the below ground temperatures. Predictions using such data were still dependent on diffusivity values for the prediction. Hence the need for typical diffusivity values for the pipeline test section location and the Weather Bureau data for the predictions.

Such predictions ahead of the proposed pressure test can then be used to optimise schedules and avoid adverse periods identified by the predictions.

### 9.2.3 Soil Temperature Measurements

The Australian Standard AS2885.5:2020 recommended soil temperature measurements near to the pipe centre height but off to the side and still in the backfill. The diffusivity probe and buried tank showed that the better location was slightly lower than this level. If soil temperature probes were to be used then diffusivity probes would be a better alternative by supplying more useful data

### 9.3 PIPE WALL TEMPERATURE MEASUREMENTS FOR LEAK TESTING

### 9.3.1 CFD Recommendations on Sensor Positions and Scaling

The CFD Uncertainty study focussed on the then known temperature input of the adiabatic temperature rise from pressurisation at the start of the strength test. Such changes were best measured by sensors attached at the side (3:00 or 9:00 O'clock
positions) or the top of the pipe. The time, diffusivity and diameter modelling developed in Chapter 3 could provide guidance on the expected difference between such sensor measurements and the pressure which reflected the bulk water temperature. Such modelling was only of value if the only change in temperature was the adiabatic rise.

### 9.3.2 Weather Related Effect on Sensor Position

The present study has identified weather related changes that can be of similar or higher magnitude than the adiabatic effect and can be up or down which rendered the above CFD based scaling only applicable for all changes for the side location. As pointed out in this document the time scaling for the bottom of pipe response was four times longer than the top or side. If there was a weather induced reduction in temperature then the CFD results for the pipe sensor locations and scaling needed to be reversed with the top response now four times longer and the bottom similar to the side.

What must be considered were the combined effects of adiabatic changes and the weather related changes. When the combined result was a fall then the above problem arose and top of pipe probe measurements had limited value.

This likelihood of temperature reduction can be determined from the predicted adiabatic change and weather or diffusivity probe predicted changes.

### 9.4 THERMAL STABILITY FOR PRESSURE TESTS

Early versions of the Australian Standard for Pipeline Pressure Testing [12, 131] only required consideration of water thermal stability prior to the start of the pressure test. Subsequent versions recommended that due to the disturbance of adiabatic effects that stabilisation be extended to include such disturbance. Stabilisation is difficult to measure, quantify and consequently specify. Ultimately the residual temperature changes of all the water in the test section should be no greater that that produced by the adiabatic rise during pressurisation. The CFD scaling indicated that smaller diameters more quickly recovered from adiabatic changes. Weather effects on water temperature were better avoided in any assessment of stabilisation but could affect test duration. Pressure Test Acceptance Criteria should allow for the adiabatic changes and if not then a delay should be mandated until it was possible to achieve the criteria. Such stability is "Thermal Stability" to ensure a successful test in the specified time period within the acceptance criteria (without leaks present)

### 9.5 ACOUSTIC ANOMALY RESOLUTION PROPOSAL

Attempts in Chapter 7 to resolve the acoustic anomaly for the DN 300 test sections did not succeed when trying to rely on potential thermal gradients resulting from seasonal and weather based below ground estimates. Air solution and creep effects had been discounted in earlier Chapters. Chapter 8 Matlab modelling provided a possible mechanism in the
effect of inclined pipe with large thermal gradients of significantly reducing the acoustic velocity. The test sections with highest anomalies had common features namely:

- Spring-summer period (mid August to mid October).
- Rugged terrain.
- Highest anomaly in most inclined section.
- Similar exponential like rise in acoustic velocity but with different amplitudes.
- Negligible effect of exposed ambient.
- Large variation of patterns and range of buried pipewall and ground temperature measurements during the pressure test with ranges from around 1.5 to $3.0^{\circ} \mathrm{C}$.

Other important considerations relate to the extent of contribution as evidenced by the lack of exposed pipe temperature effects where such effects generally only apply to a small fraction of the test section and although large made a very small contribution. Adiabatic temperature rise following pressurisation affects the whole of the water in the section and while relatively small in magnitude affects the whole section. Prior movement of water through the section has extensive and potentially high magnitude effects. While the pressurising water only represents approximately $1 \%$ of the pipe volume it affects almost all of the test section by the diminishing displacement of the water and exposing most of the pipe to temperatures to which it had not previously stabilised. The large range of measured buried pipe wall temperatures supports such disturbance.

A third feature related to the exponential like rise in that the time of rise commencement was never measured before the start of the leak test but was assumed to start from the pressurisation and progressively reduced during the leak test monitoring period and always rose and never reversed nor changed in trending. This supports the importance of the pressurising water movement and prior water movement especially since following pressurisation all water movement ceases until the leak test has been approved after a period of time not less than 24 hours. Furthermore, for relatively flat sections movement of water has little effect as depth of pipe is very consistent and changes in water location do not greatly affect buried temperatures. This is not the case for test Sections like DN 300 No. 12 with overall incline and multiple included subsections of higher incline resulting from trench in rock of variable depth and nature of backfill from loose rock to sand. Water movement in such locations can result in significant temperature changes and large thermal gradients.

Matlab modelling showed the greatest reduction in acoustic velocity resulted from a combination of high thermal gradient and high topographical gradient both of which may have applied to the worst anomaly in Test Section No. 12.

The acoustic anomaly resolution proposal is that it is a consequence of lack of thermal stability prior to the leak test and is most likely an accurate measurement of the ongoing thermal stability process during the subsequent leak test period.

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This proposal, if correct, would be difficult to verify experimentally as any short experimental buried pipe section could never be subject to adequate pressurisation movement disturbance nor would it be able to easily incorporate a combination of overall incline with multiple subsections of different incline and soil depths while conducting the experiments during the spring-summer period. The anomalous acoustic behaviour may itself be anomalous in that it may only apply to a small unique set of pressure tests and not the bulk.

### 9.6 EVALUATION OF ACOUSTIC TECHNIQUE FOR LEAK TESTING

For the DN 200 above ground pipe of 108 m length, there was good correlation between acoustic velocity and pressure which was consistent with measured pipe wall temperatures during the daytime monitoring period.

For the DN 400 buried pipe test section there was rising velocity consistent with rising pressure with circumstances suggesting that the section was filled with cool water in warm ground which was ideal for thermal mixing and minimal or no thermal gradients. Also the location was relatively flat with no inclines to enhance acoustic velocity reduction. There was still merging of acoustic velocity and pressure over time but close to satisfying acceptance criteria during the 24 hour leak test duration.

The DN 300 buried pipe sections had mixed results. All measured velocities were above the theoretical and were consistent with the extent of "Rock Jacket" concrete coating and probable manufacturer's wall thickness allowance. The anomalous rising velocities ranged only over a few metres per second from 0.3 to $3 \mathrm{~m} / \mathrm{s}$. The affected sections were in ranges with difficult terrain with the exception of No. 8 in a relatively flat valley and with the lowest anomaly. All these sections were tested in the spring-summer period where seasonal thermal gradients were greatest. As concluded in Section 9.5 it appeared that the anomaly was mainly applicable to a minority of test sections in rugged areas with inclined pipe sections during the spring-summer period and unlikely to apply to most other sections. It was further proposed that it was a consequence of lack of thermal stability in those sections.

Presence of the acoustic anomaly was unlikely to falsely indicate a leak free pipe. The DN 300 test section with the worst anomaly needed the leak test period extended for another 36 hours to enable the test to be accepted on the basis of acoustic measurements and pressure without temperature measurements.

The technique identified the air pocket location in Test Section No. 6 of the DN 300 pipe at a distance of around 30 km from the instrument location. Detection of air pockets is valuable in that location identification can then assist in assessment of its hazard effects.

The acoustic measurements used in this study had limited resolution in both amplitude and time. Improvements in instrumentation, equipment, technique, noise removal and signal analysis are easily achieved and would significantly improve the techniques' capabilities.

Based on these results the acoustic technique represents a viable supplement or alternative to the current use of multiple pipe wall temperature probes but during the springsummer period in rugged terrain may be subject to possible time extensions. With all measurements taken from one location (pressure and velocity) it lends itself to test sections with difficult access such as water crossings, swamps and offshore. It may prove ideal for circumstances where more rapid temperature measurements of the system temperature were required such as hot water in cold or frozen ground.

### 9.7 RECOMMENDATIONS TO PIPELINE INDUSTRY

While the above focus has been on the acoustic technique, a number of issues have been highlighted during this study which may be of benefit to the Pipeline Industry.

### 9.7.1 Correction to B and $\overline{\mathrm{B}}$ Factors for Temperature

Equations for B and $\overline{\mathrm{B}}$ factors in the appendices of Australian Standard AS2885.5 from the 2002 edition onwards [10, 37, 124] had errors and need correction as highlighted in this document. The correction process has been initiated with the publisher Standards Australia. Once corrected the Pipeline Industry needs to become aware of them. Use of the far more complicated IAPWS equations to generate bulk modulus and thermal expansion coefficients were better than the AS2885.5 corrected equations which were only intended to be good approximations for field calculations.

### 9.7.2 Below Ground Temperature Prediction

Below ground pipe wall temperature measurement has been essential in the conduct of Pipeline Pressure Tests using current methodology. The study has found that below ground multi sensor temperature probes can provide forward information days and possibly up to a week before a pressure test as to the expected below ground temperatures in the locality during the test. Such information can also be generated from past recent Weather Bureau data. Such data and forward projections can be valuable in predicting the likelihood of issues with below ground temperatures during pressure testing. It would be valuable in deciding whether to delay or reschedule a test should unfavourable conditions be anticipated.

### 9.7.3 Below Ground Diffusivity Measurement

Associated with prediction of below ground temperature was knowledge of typical soil diffusivity which is used in the prediction.

### 9.7.4 Temperature Probe Improvement

Currently pipeline temperature probes are designed to measure the top of pipe temperature based on ease of installation and of checking whether still in contact with the pipe (push down). A temperature probe with additional sensors above the bottom sensor

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but below the ground surface can double as a diffusivity probe and provide additional information regarding weather induced effects on the pipe. Such probes could change the lottery like results of single measurements at multiple locations along the test section into sources of useful information on below ground temperature changes to better understand the top of pipe measurements.

The below ground tank experiment demonstrated that below ground measurements by diffusivity probes of backfill temperature at the level of the lower quarter of the pipe matched the pressure changes. Use of such probes either in addition to the pipe wall probes or supplementary may prove to be an improvement in temperature measurement and avoid the pipe wall measurement problems should the weather induced changes cause a fall in temperatures.

### 9.7.5 Use of Acoustic Technique as Supplementary Measurement System

Until the acoustic technique becomes the preferred method of temperature measurement and leak test acceptance, it can be valuable in providing supplementary information on temperature changes during pressure tests such as:

- Mixed test sections with above and below ground portions.
- River and lake crossings.
- Shore approaches of offshore pipelines.
- Confirmation of section length and average pipe wall thickness.
- Identification of reflector locations such as heavy wall pipe, major valves and fittings.
- Location of air pockets and extent - information needed for Safety and Hazard Assessment.
- Carry out measurements of sub sections between detected reflectors as a check against below ground temperature measurements, thermal stabilisation and as data for technique improvement.
- Information as to presence of anomalies indicating lack of stabilisation.
- As a measure of thermal stabilisation and acoustic stabilisation.


### 9.7.6 Assessment of Ambient Creep

Repeated pressurisation during the strength test was regarded by hydrotesters as an unpredictable inconvenience because the initial pressure has to be carefully monitored to determine the next pressurisation while the pressure measurements were affected and disturbed by the pressure surges resulting from the end of initial pressurisation. Then during the repressurisation the pressure had to be monitored and the pump(s) stopped when the required value was reached while the surge continued to interfere. The surge dissipated over the first half to one hour of the strength test. Repressurisation can continue during the strength test and in the past the results were recorded but the data never put to use other

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than confirming that the required range had been maintained and the pipe had sufficient strength for its proposed use.

Following Wyatt's [113] and Gajdos et al. [28] work on room temperature creep and as shown in this document, such data can be combined into a creep curve which may be useful information on the average test section pipe material mechanical properties especially when pipe steels were being pushed to higher yields and lower ductility to achieve higher operating pressures. The creep curve data can also be used to confirm or reassess the minimum pressure reduction to leak test pressure to avoid continuing creep effects during the leak test.

### 9.8 FUTURE RESEARCH

The following is a brief summary of suggested areas of future research. Prior details have been presented in the relevant chapters.

### 9.8.1 Weather induced below ground Temperatures

a) Check the effect of weather induced below ground temperatures for different diameters especially larger than DN 435.
b) Carry out CFD analysis for the above.
c) Apply the above to both horizontal and inclined pipe.

### 9.8.2 Acoustic Technique Related

d) Use CFD studies to find the "Missing" or "Needed" portions of the cross sectional temperatures that were not available during the current study and input such data into the Matlab modelling program.
e) Investigate whether acoustic velocity can determine the internal thermal gradients or thermal cross section of the pipe.
f) Investigate effect of inclined pipe on acoustic velocity variation with thermal gradients especially by separate measurements uphill and downhill.
g) Carry out acoustic measurements over longer time periods to confirm whether stabilisation was measured by the acoustic anomaly and whether the anomaly continued to reduce exponentially.
h) Extend and refine air solution rate findings especially for larger diameters.
i) Investigate air solution rate variation with bubble surface area as the bubble size changed.
j) Investigate acoustic velocity variation in pipe sections with air pockets.
k) Investigate improvements in acoustic technique equipment, instrumentation and software.

### 9.8.3 High Pressure Air dissolved Water Fluid Properties

I) Measure acoustic velocity of water with high air content at pressure to determine dissolved air effect on density and partial molar volume.

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## APPENDICES

## APPENDIX A - EQUATIONS

The following equations are based on versions developed by this author [20]. Acoustic velocity in water filled pipe is given by equations (2.3.3) and (2.1.7) repeated below:

$$
\begin{gathered}
a=\sqrt{\frac{B_{P A}}{\rho}} \\
B_{P A}=\frac{B_{A}}{\left(\frac{C_{1} B_{A} D}{E t}+1\right)}
\end{gathered}
$$

A complete differential relating acoustic velocity to pressure and temperature is as follows:

$$
d a=\frac{d a}{d p} d p+\frac{d a}{d T} d T
$$

To obtain da/dT, the above acoustic velocity equation is differentiated with respect to temperature resulting in:

$$
\frac{d a}{d T}=\frac{1}{2} \sqrt{\frac{\rho}{B_{P A}}}\left\{\frac{1}{\rho} \frac{d B_{P A}}{d T}-\frac{B_{P A}}{\rho^{2}} \frac{d \rho}{d T}\right\}
$$

Water thermal expansion coefficient, $\beta$, is given by:

$$
\beta=-\frac{1}{\rho} \frac{d \rho}{d T}
$$

The differential $\frac{d B_{P A}}{d T}$ is obtained as:

$$
\begin{gathered}
\frac{d B_{P A}}{d T}=\frac{d}{d T}\left\{\frac{B_{A}}{\left(\frac{C_{1} B_{A} D}{E t}+1\right)}\right\} \\
=\frac{d B_{A}}{d T} \frac{1}{\left(\frac{C_{1} B_{A} D}{E t}+1\right)}-\left\{\frac{B_{A}}{\left(\frac{C_{1} B_{A} D}{E t}+1\right)^{2}} \frac{C_{1} D}{E t} \frac{d B_{A}}{d T}\right\} \\
=\frac{d B_{A}}{d T}\left\{\frac{\left(\frac{C_{1} B_{A} D}{E t}+1\right)-\frac{C_{1} B_{A} D}{E t}}{\left(\frac{C_{1} B_{A} D}{E t}+1\right)^{2}}\right\} \\
\frac{d B_{P A}}{d T}=\frac{d B_{A}}{d T} \frac{1}{\left(\frac{C_{1} B_{A} D}{E t}+1\right)^{2}}
\end{gathered}
$$

Resulting $\frac{d a}{d T}$ is given by:

$$
\begin{gathered}
\frac{d a}{d T}=\frac{1}{2} \sqrt{\frac{\rho}{B_{P A}}}\left\{\frac{1}{\rho} \frac{d B_{A}}{d T} \frac{1}{\left(\frac{C_{1} B_{A} D}{E t}+1\right)^{2}}+\frac{B_{P A}}{\rho} \beta\right\} \\
\frac{d a}{d T}=\frac{1}{2} \sqrt{\frac{\rho}{B_{P A}}} \frac{B_{P A}}{\rho}\left\{\frac{1}{B_{P A} B_{A}{ }^{2}} \frac{d B_{A}}{d T} \frac{B_{A}{ }^{2}}{\left(\frac{C_{1} B_{A} D}{E t}+1\right)^{2}}+\beta\right\}
\end{gathered}
$$

$$
\begin{gathered}
\frac{d a}{d T}=\frac{1}{2} \sqrt{\frac{B_{P A}}{\rho}}\left\{\frac{1}{B_{P A} B_{A}{ }^{2}} \frac{d B_{A}}{d T} B_{P A}{ }^{2}+\beta\right\} \\
\frac{d a}{d T}=\frac{a}{2}\left\{\frac{B_{P A}}{B_{A}{ }^{2}} \frac{d B_{A}}{d T}+\beta\right\}
\end{gathered}
$$

To obtain $\frac{d a}{d p}$ the following relationship is used:

$$
\frac{d a}{d p}=\frac{d a}{d T} \frac{d T}{d p}
$$

The previous equation for $\mathrm{dp} / \mathrm{dT}$ used the isothermal bulk modulus. For acoustic applications the adiabatic or isentropic bulk modulus needs to be used so that $\mathrm{dp} / \mathrm{dT}$ becomes:

$$
\frac{d p}{d T}=-\frac{B_{A}\left(\beta-C_{2} \alpha\right)}{\left(\frac{C_{1} B_{A} D}{E t}+1\right)}=-B_{P A}\left(\beta-C_{2} \alpha\right)
$$

Using and inverting this equation for $\mathrm{dT} / \mathrm{dp}$ together with the da/dT equation results in:

$$
\frac{d a}{d p}=-\frac{a}{2}\left\{\frac{\frac{1}{B_{A}^{2}} \frac{d B_{A}}{d T}+\frac{\beta}{B_{P A}}}{\left(\beta-C_{2} \alpha\right)}\right\}
$$

with its invert:

$$
\frac{d p}{d a}=-\frac{2}{a}\left\{\frac{\left(\beta-C_{2} \alpha\right)}{\frac{1}{B_{A}{ }^{2}} \frac{d B_{A}}{d T}+\frac{\beta}{B_{P A}}}\right\}
$$

The complete differential then becomes:

$$
\begin{gathered}
d a=-\frac{a}{2}\left\{\frac{\left.\frac{1}{B_{A}{ }^{2}} \frac{d B_{A}}{d T}+\frac{\beta}{B_{P A}}\right\} d p+\frac{a B_{P A}}{2}\left\{\frac{1}{B_{A}{ }^{2}} \frac{d B_{A}}{d T}+\frac{\beta}{B_{P A}}\right\} d T}{d a=\frac{a}{2}\left\{\frac{1}{B_{A}{ }^{2}} \frac{d B_{A}}{d T}+\frac{\beta}{B_{P A}}\right\}\left\{B_{P A} d T-\frac{1}{\left(\beta-C_{2} \alpha\right)} d p\right\}} .\right.
\end{gathered}
$$

The previous equations for $\mathrm{dp} / \mathrm{dT}$ and $\mathrm{dV} / \mathrm{dp}$ used the isothermal bulk modulus. For acoustic applications the adiabatic or isentropic bulk modulus needs to be used so that $\mathrm{dp} / \mathrm{dT}$ and $\mathrm{dV} / \mathrm{dp}$ respectively become:

$$
\begin{gathered}
\frac{d p}{d T}=B_{P A}\left(\beta-C_{2} \alpha\right)=\rho a^{2}\left(\beta-C_{2} \alpha\right) \\
\frac{d V}{d p}=\frac{V_{0}}{B_{A}}\left(\frac{C_{1} B_{A} D}{E t}+1\right)=\frac{V_{0}}{B_{P A}}=\frac{V_{0}}{\rho a^{2}}=\frac{V_{0}}{B_{A}}\left(\frac{a_{0}}{a}\right)^{2}
\end{gathered}
$$

The last result links the pipeline $\mathrm{dV} / \mathrm{d}$ p measure during pressurisation to the square of the acoustic velocity.

## APPENDICES

## APPENDIX B - ADIABATIC TEMPERATURE CHANGES.

The following tables have been calculated using IAPWS equations with pressure in kPa (gauge) and temperatures in degrees Celsius.

| PURE WATER - ADIABATIC TEMPERATURE CHANGE AT TEMPERATURE FOR PRESSURE CHANGE |  |  |  |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| PR | TEMPERATURE ${ }^{\circ} \mathrm{C}$ |  |  |  |  |  |  |  |  |  |  |
|  | 0 | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 |
| 1000 | -0.004 | 0.001 | 0.006 | 0.010 | 0.015 | 0.018 | 0.022 | 0.026 | 0.029 | 0.032 | 0.036 |
| 2000 | -0.008 | 0.003 | 0.012 | 0.021 | 0.029 | 0.037 | 0.044 | 0.051 | 0.058 | 0.065 | 0.072 |
| 3000 | -0.012 | 0.004 | 0.019 | 0.032 | 0.044 | 0.056 | 0.067 | 0.077 | 0.087 | 0.097 | 0.107 |
| 4000 | -0.016 | 0.006 | 0.025 | 0.043 | 0.059 | 0.074 | 0.089 | 0.103 | 0.117 | 0.130 | 0.143 |
| 5000 | -0.019 | 0.008 | 0.032 | 0.054 | 0.074 | 0.093 | 0.111 | 0.129 | 0.146 | 0.163 | 0.179 |
| 6000 | -0.022 | 0.010 | 0.039 | 0.065 | 0.089 | 0.112 | 0.134 | 0.155 | 0.175 | 0.195 | 0.215 |
| 7000 | -0.025 | 0.012 | 0.046 | 0.076 | 0.104 | 0.131 | 0.156 | 0.181 | 0.204 | 0.228 | 0.251 |
| 8000 | -0.027 | 0.015 | 0.053 | 0.087 | 0.119 | 0.150 | 0.179 | 0.207 | 0.234 | 0.260 | 0.286 |
| 9000 | -0.030 | 0.018 | 0.060 | 0.099 | 0.135 | 0.169 | 0.201 | 0.233 | 0.263 | 0.293 | 0.322 |
| 10000 | -0.032 | 0.020 | 0.067 | 0.110 | 0.150 | 0.188 | 0.224 | 0.259 | 0.292 | 0.325 | 0.358 |
| 11000 | -0.034 | 0.024 | 0.075 | 0.122 | 0.166 | 0.207 | 0.247 | 0.285 | 0.322 | 0.358 | 0.394 |
| 12000 | -0.035 | 0.027 | 0.083 | 0.134 | 0.182 | 0.227 | 0.270 | 0.311 | 0.351 | 0.391 | 0.429 |
| 13000 | -0.037 | 0.030 | 0.091 | 0.146 | 0.198 | 0.246 | 0.293 | 0.337 | 0.381 | 0.423 | 0.465 |
| 14000 | -0.038 | 0.034 | 0.099 | 0.158 | 0.214 | 0.266 | 0.315 | 0.363 | 0.410 | 0.456 | 0.501 |
| 15000 | -0.039 | 0.038 | 0.107 | 0.171 | 0.230 | 0.285 | 0.338 | 0.390 | 0.440 | 0.488 | 0.537 |
| 16000 | -0.040 | 0.042 | 0.116 | 0.183 | 0.246 | 0.305 | 0.361 | 0.416 | 0.469 | 0.521 | 0.572 |
| 17000 | -0.040 | 0.046 | 0.124 | 0.195 | 0.262 | 0.325 | 0.385 | 0.442 | 0.499 | 0.554 | 0.608 |
| 18000 | -0.041 | 0.051 | 0.133 | 0.208 | 0.278 | 0.345 | 0.408 | 0.469 | 0.528 | 0.586 | 0.644 |
| 19000 | -0.041 | 0.055 | 0.142 | 0.221 | 0.295 | 0.364 | 0.431 | 0.495 | 0.558 | 0.619 | 0.679 |
| 20000 | -0.040 | 0.060 | 0.151 | 0.234 | 0.311 | 0.384 | 0.454 | 0.522 | 0.587 | 0.652 | 0.715 |
| 21000 | -0.040 | 0.065 | 0.160 | 0.247 | 0.328 | 0.404 | 0.478 | 0.548 | 0.617 | 0.684 | 0.751 |
| 22000 | -0.039 | 0.070 | 0.169 | 0.260 | 0.345 | 0.425 | 0.501 | 0.575 | 0.647 | 0.717 | 0.786 |
| 23000 | -0.039 | 0.076 | 0.179 | 0.273 | 0.361 | 0.445 | 0.525 | 0.601 | 0.676 | 0.750 | 0.822 |
| 24000 | -0.038 | 0.081 | 0.188 | 0.287 | 0.378 | 0.465 | 0.548 | 0.628 | 0.706 | 0.783 | 0.858 |
| 25000 | -0.036 | 0.087 | 0.198 | 0.300 | 0.395 | 0.486 | 0.572 | 0.655 | 0.736 | 0.815 | 0.894 |
| 26000 | -0.035 | 0.093 | 0.208 | 0.314 | 0.413 | 0.506 | 0.595 | 0.682 | 0.766 | 0.848 | 0.929 |
| 27000 | -0.033 | 0.099 | 0.218 | 0.328 | 0.430 | 0.527 | 0.619 | 0.708 | 0.795 | 0.881 | 0.965 |
| 28000 | -0.031 | 0.105 | 0.228 | 0.341 | 0.447 | 0.547 | 0.643 | 0.735 | 0.825 | 0.914 | 1.001 |
| 29000 | -0.029 | 0.112 | 0.239 | 0.355 | 0.465 | 0.568 | 0.667 | 0.762 | 0.855 | 0.946 | 1.036 |
| 30000 | -0.027 | 0.118 | 0.249 | 0.370 | 0.482 | 0.589 | 0.691 | 0.789 | 0.885 | 0.979 | 1.072 |
| 31000 | -0.024 | 0.125 | 0.260 | 0.384 | 0.500 | 0.609 | 0.714 | 0.816 | 0.915 | 1.012 | 1.108 |
| 32000 | -0.022 | 0.132 | 0.271 | 0.398 | 0.517 | 0.630 | 0.738 | 0.843 | 0.945 | 1.045 | 1.143 |
| 33000 | -0.019 | 0.139 | 0.281 | 0.413 | 0.535 | 0.651 | 0.763 | 0.870 | 0.975 | 1.078 | 1.179 |
| 34000 | -0.016 | 0.146 | 0.293 | 0.427 | 0.553 | 0.672 | 0.787 | 0.897 | 1.005 | 1.110 | 1.215 |
| 35000 | -0.012 | 0.154 | 0.304 | 0.442 | 0.571 | 0.694 | 0.811 | 0.924 | 1.035 | 1.143 | 1.250 |
| 36000 | -0.009 | 0.161 | 0.315 | 0.457 | 0.589 | 0.715 | 0.835 | 0.951 | 1.065 | 1.176 | 1.286 |
| 37000 | -0.005 | 0.169 | 0.327 | 0.472 | 0.607 | 0.736 | 0.859 | 0.979 | 1.095 | 1.209 | 1.322 |
| 38000 | -0.001 | 0.177 | 0.338 | 0.487 | 0.626 | 0.757 | 0.884 | 1.006 | 1.125 | 1.242 | 1.357 |
| 39000 | 0.003 | 0.185 | 0.350 | 0.502 | 0.644 | 0.779 | 0.908 | 1.033 | 1.155 | 1.275 | 1.393 |
| 40000 | 0.007 | 0.193 | 0.362 | 0.517 | 0.662 | 0.800 | 0.933 | 1.060 | 1.185 | 1.308 | 1.429 |
| 41000 | 0.012 | 0.202 | 0.374 | 0.532 | 0.681 | 0.822 | 0.957 | 1.088 | 1.215 | 1.341 | 1.464 |
| 42000 | 0.016 | 0.210 | 0.386 | 0.548 | 0.700 | 0.844 | 0.982 | 1.115 | 1.246 | 1.374 | 1.500 |
| 43000 | 0.021 | 0.219 | 0.398 | 0.564 | 0.718 | 0.865 | 1.006 | 1.143 | 1.276 | 1.407 | 1.536 |
| 44000 | 0.026 | 0.228 | 0.411 | 0.579 | 0.737 | 0.887 | 1.031 | 1.170 | 1.306 | 1.440 | 1.571 |


| 45000 | 0.032 | 0.237 | 0.423 | 0.595 | 0.756 | 0.909 | 1.056 | 1.198 | 1.336 | 1.473 | 1.607 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| SEAWATER - ADIABATIC TEMPERATURE CHANGE AT TEMPERATURE FOR PRESSURE CHANGE |  |  |  |  |  |  |  |  |  |  |  |
| TEMPERATURE ${ }^{\circ} \mathrm{C}$ |  |  |  |  |  |  |  |  |  |  |  |
| PRESSURE | 0 | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 |
| 1000 | 0.004 | 0.008 | 0.012 | 0.015 | 0.018 | 0.022 | 0.025 | 0.028 | 0.031 | 0.033 | 0.036 |
| 2000 | 0.007 | 0.016 | 0.023 | 0.030 | 0.037 | 0.043 | 0.050 | 0.056 | 0.061 | 0.067 | 0.072 |
| 3000 | 0.011 | 0.024 | 0.035 | 0.046 | 0.056 | 0.065 | 0.075 | 0.084 | 0.092 | 0.100 | 0.107 |
| 4000 | 0.016 | 0.032 | 0.047 | 0.061 | 0.074 | 0.087 | 0.100 | 0.112 | 0.123 | 0.134 | 0.143 |
| 5000 | 0.020 | 0.040 | 0.059 | 0.077 | 0.093 | 0.109 | 0.125 | 0.139 | 0.154 | 0.167 | 0.179 |
| 6000 | 0.025 | 0.049 | 0.071 | 0.092 | 0.112 | 0.131 | 0.150 | 0.167 | 0.184 | 0.200 | 0.215 |
| 7000 | 0.029 | 0.058 | 0.084 | 0.108 | 0.131 | 0.153 | 0.175 | 0.195 | 0.215 | 0.234 | 0.251 |
| 8000 | 0.034 | 0.066 | 0.096 | 0.124 | 0.150 | 0.175 | 0.200 | 0.224 | 0.246 | 0.267 | 0.287 |
| 9000 | 0.039 | 0.075 | 0.109 | 0.140 | 0.169 | 0.198 | 0.225 | 0.252 | 0.277 | 0.301 | 0.323 |
| 10000 | 0.045 | 0.085 | 0.121 | 0.156 | 0.188 | 0.220 | 0.250 | 0.280 | 0.308 | 0.334 | 0.359 |
| 11000 | 0.050 | 0.094 | 0.134 | 0.172 | 0.208 | 0.242 | 0.276 | 0.308 | 0.339 | 0.368 | 0.395 |
| 12000 | 0.056 | 0.103 | 0.147 | 0.188 | 0.227 | 0.265 | 0.301 | 0.336 | 0.370 | 0.401 | 0.430 |
| 13000 | 0.061 | 0.113 | 0.160 | 0.204 | 0.246 | 0.287 | 0.326 | 0.364 | 0.400 | 0.435 | 0.466 |
| 14000 | 0.067 | 0.123 | 0.173 | 0.221 | 0.266 | 0.310 | 0.352 | 0.392 | 0.431 | 0.468 | 0.502 |
| 15000 | 0.074 | 0.133 | 0.186 | 0.237 | 0.285 | 0.332 | 0.377 | 0.421 | 0.462 | 0.502 | 0.538 |
| 16000 | 0.080 | 0.143 | 0.200 | 0.254 | 0.305 | 0.355 | 0.403 | 0.449 | 0.493 | 0.535 | 0.574 |
| 17000 | 0.087 | 0.153 | 0.213 | 0.270 | 0.325 | 0.377 | 0.428 | 0.477 | 0.524 | 0.569 | 0.610 |
| 18000 | 0.093 | 0.163 | 0.227 | 0.287 | 0.345 | 0.400 | 0.454 | 0.506 | 0.555 | 0.603 | 0.646 |
| 19000 | 0.100 | 0.174 | 0.241 | 0.304 | 0.364 | 0.423 | 0.479 | 0.534 | 0.586 | 0.636 | 0.682 |
| 20000 | 0.107 | 0.184 | 0.255 | 0.321 | 0.384 | 0.446 | 0.505 | 0.562 | 0.618 | 0.670 | 0.718 |
| 21000 | 0.114 | 0.195 | 0.269 | 0.338 | 0.404 | 0.469 | 0.531 | 0.591 | 0.649 | 0.703 | 0.754 |
| 22000 | 0.122 | 0.206 | 0.283 | 0.355 | 0.425 | 0.492 | 0.557 | 0.619 | 0.680 | 0.737 | 0.790 |
| 23000 | 0.129 | 0.217 | 0.297 | 0.372 | 0.445 | 0.515 | 0.582 | 0.648 | 0.711 | 0.771 | 0.826 |
| 24000 | 0.137 | 0.228 | 0.311 | 0.390 | 0.465 | 0.538 | 0.608 | 0.676 | 0.742 | 0.804 | 0.862 |
| 25000 | 0.145 | 0.239 | 0.326 | 0.407 | 0.485 | 0.561 | 0.634 | 0.705 | 0.773 | 0.838 | 0.899 |
| 26000 | 0.153 | 0.251 | 0.340 | 0.425 | 0.506 | 0.584 | 0.660 | 0.734 | 0.804 | 0.872 | 0.935 |
| 27000 | 0.161 | 0.262 | 0.355 | 0.442 | 0.526 | 0.607 | 0.686 | 0.762 | 0.836 | 0.905 | 0.971 |
| 28000 | 0.170 | 0.274 | 0.370 | 0.460 | 0.547 | 0.631 | 0.712 | 0.791 | 0.867 | 0.939 | 1.007 |
| 29000 | 0.178 | 0.286 | 0.385 | 0.478 | 0.567 | 0.654 | 0.738 | 0.819 | 0.898 | 0.973 | 1.043 |
| 30000 | 0.187 | 0.298 | 0.400 | 0.496 | 0.588 | 0.677 | 0.764 | 0.848 | 0.929 | 1.007 | 1.079 |
| 31000 | 0.196 | 0.310 | 0.415 | 0.514 | 0.609 | 0.701 | 0.790 | 0.877 | 0.961 | 1.040 | 1.115 |
| 32000 | 0.205 | 0.322 | 0.430 | 0.532 | 0.630 | 0.724 | 0.816 | 0.906 | 0.992 | 1.074 | 1.151 |
| 33000 | 0.214 | 0.335 | 0.445 | 0.550 | 0.651 | 0.748 | 0.843 | 0.934 | 1.023 | 1.108 | 1.187 |
| 34000 | 0.223 | 0.347 | 0.461 | 0.568 | 0.671 | 0.772 | 0.869 | 0.963 | 1.055 | 1.142 | 1.224 |
| 35000 | 0.233 | 0.360 | 0.476 | 0.587 | 0.693 | 0.795 | 0.895 | 0.992 | 1.086 | 1.176 | 1.260 |
| 36000 | 0.242 | 0.372 | 0.492 | 0.605 | 0.714 | 0.819 | 0.921 | 1.021 | 1.117 | 1.209 | 1.296 |
| 37000 | 0.252 | 0.385 | 0.508 | 0.624 | 0.735 | 0.843 | 0.948 | 1.050 | 1.149 | 1.243 | 1.332 |
| 38000 | 0.262 | 0.398 | 0.524 | 0.642 | 0.756 | 0.867 | 0.974 | 1.079 | 1.180 | 1.277 | 1.368 |
| 39000 | 0.272 | 0.412 | 0.540 | 0.661 | 0.777 | 0.890 | 1.001 | 1.108 | 1.212 | 1.311 | 1.405 |
| 40000 | 0.283 | 0.425 | 0.556 | 0.680 | 0.799 | 0.914 | 1.027 | 1.137 | 1.243 | 1.345 | 1.441 |
| 41000 | 0.293 | 0.438 | 0.572 | 0.698 | 0.820 | 0.938 | 1.054 | 1.166 | 1.275 | 1.379 | 1.477 |
| 42000 | 0.304 | 0.452 | 0.588 | 0.717 | 0.842 | 0.962 | 1.080 | 1.195 | 1.306 | 1.413 | 1.513 |
| 43000 | 0.314 | 0.465 | 0.605 | 0.736 | 0.863 | 0.987 | 1.107 | 1.224 | 1.338 | 1.447 | 1.550 |
| 44000 | 0.325 | 0.479 | 0.621 | 0.756 | 0.885 | 1.011 | 1.133 | 1.253 | 1.369 | 1.481 | 1.586 |
| 45000 | 0.336 | 0.493 | 0.638 | 0.775 | 0.907 | 1.035 | 1.160 | 1.282 | 1.401 | 1.515 | 1.622 |
| 50000 | 0.394 | 0.564 | 0.722 | 0.872 | 1.016 | 1.157 | 1.294 | 1.428 | 1.559 | 1.685 | 1.804 |

## APPENDICES

To use the above tables for example to calculate the temperature increase at $25^{\circ} \mathrm{C}$ when the pressure is raised from 15000 to 21000 kPa for seawater the values in the table for these two pressures are subtracted from each other so that the change is ( $0.469-0.332$ $\left.=0.137^{\circ} \mathrm{C}\right)$ and is not the same as the value at $6000 \mathrm{kPa}(21000-15000)$ which is $0.131^{\circ} \mathrm{C}$. For changes at higher pressures the difference is greater.

## APPENDICES

## APPENDIX C - GLOSSARY

| TERM | MEANING |
| :---: | :---: |
| A/D converter | Analog to Digital Converter |
| Adiabatic | Without heat transfer or with no change in entropy. Applies when there are sudden changes in pressure such as during transmission of acoustic signals. |
| Attenuation | Acoustic term referring to the reduction in signal amplitude with travel distance for a particular frequency. |
| Backfill | The excavated material or other similar material used to surround the below ground pipe and fill the excavation. |
| Backpressure | Pressure in a pipe section in front of a moving pig for the purpose of preventing hydraulic heads behind the pig from causing the pig to accelerate and create a vacuum pocket behind. This usually applies when the hydraulic head behind a pig on a down slope is greater than the gravity head less the vapour pressure or around 9.5 metres. Any slope with elevation difference of more than this value requires backpressure when the pig has water behind and air in front. |
| Bidi pig | Pig fitted with flat disc shaped perimeter seals. Also commonly fitted with guide discs for additional support and to minimise wear on the sealing discs. |
| Brush pig | Pig with metal wire or nylon fibre bristles intended for brushing the internal surface of the pipe. |
| Bulk modulus | Liquid material property. Ratio of applied pressure to volume strain with units the same as pressure. Changes with temperature. Has different values dependent on thermal conditions under which the material is compressed either adiabatic or isothermal. |
| Bulk Viscosity | Time dependent resistance of fluid to overall volume changes. |
| Caliper pig | Special pig designed to follow and measure the inside radius or diameter of the pipe continuously along the length of the section inspected. Can produce a single minimum result or a two dimensional result at consecutive locations along the pipeline. Commonly with mechanical arms in contact with the pipe surface. Non mechanical techniques have been used based on magnetic flux, eddy currents or acoustics. |
| Clean and Gauge | Passage of pigs or scrapers from one end to the other of a pipe section to remove debris. If pig is fitted with a gauge plate it is referred to as a gauge pig. Brushes and magnets may be used to enhance cleaning. |
| Clean up | Process of removal of residual construction materials from the pipeline right of way, re-establishing the original ground contours and spreading the original soil back across the disturbed ground. |
| Constant pressure | Without change in pressure but can be achieved by changing temperature and/or volume. |
| Constant volume | Without addition or removal of fluid but can be achieved by changing temperature and/or pressure. |
| Creep | Permanent stretching which increases with time with usually constant applied stress such as a pipe stretched by added water with water continually added to maintain the same pressure and stress. |
| Cup pig | Pig fitted with mainly cup shaped perimeter seals. |
| D/A converter | Digital to Analog Converter |
| dB | deci Bel. A logarithm based measure of attenuation. The logarithm to base 10 of the ratio of the attenuated signal to the source signal taken and then multiplied by a factor of 20 with 20 |


|  | dB corresponding to a ratio of 0.1 and 40 dB to a ratio of 0.01 and 60 dB to a ratio of 0.001 . Hence an exponent based measure of signal reduction or attenuation. |
| :---: | :---: |
| Dead Weight Tester (DWT) | Dead Weight Tester. Pressure measuring device consisting of a hydraulic piston on which weights are supported to balance and measured the pressure by dividing the supported weight by the known piston area. Usually a primary pressure standard but used for pipeline pressure testing due to their rugged construction and very high measurement accuracy, repeatability and resolution. |
| Dewater | Process of water removal following pressure test. Usually using the same or spare pigs from filling. Compressed air is used to drive the pigs. |
| Diffusivity probe | Special temperature probe with multiple below ground sensors at known separations that can record the measurements and times for later use in calculating the soil diffusivity. |
| Dispersion | Acoustic term referring to the change in propagation velocity with frequency usually resulting from viscous and thermal properties of the transmitting fluid. |
| DN | Nominal Diameter is the approximate metric diameter to the nearest 50 mm for steel welded pipe in "Imperial" or inch sizes. Pipeline sizes have the peculiarity of using the approximate internal diameter up until 12 inch ( 323.9 mm outside diameter) and then flipping over to the use of external diameter for 14 inch ( 355.6 mm outside diameter) and larger. For pipelines constructed onshore the external diameter is usually constant with the internal wall thickness changing. Subsea pipes commonly have varying external diameters and constant internal diameters |
| dP/dT | Theoretical or measured change in pressure resulting from small changes in temperature, usually average pipe wall or internal water temperature. Mathematically referred to as a differential quantity when referring to very small quantities. |
| dP/dV | The theoretical or measured change in pressure resulting from small changes in pipe volume as measured by injected water. Mathematically referred to as a differential quantity when referring to very small quantities. |
| Dry | Removal of residual water after dewatering to a specified level usually expressed as a dew point of discharged air. Different techniques are available including dry air blowing, vacuum drying and use of desiccating liquids such as methanol or mono, di or tri-ethylene glycol. The techniques can be supplemented by foam pig runs of water absorbent foam which also function to spread the water and improve evaporation. |
| DWT | Dead Weight Tester. Pressure measuring device consisting of a hydraulic piston on which weights are supported to balance and measured the pressure by dividing the supported weight by the known piston area. Usually a primary pressure standard but used for pipeline pressure testing due to their rugged construction and very high measurement accuracy, repeatability and resolution. |
| Elastic deformation | Temporary stretch or reduction in size which disappears as soon as the cause is removed. Such as a pipe tested well below yield. |
| End cap | A domed piece of steel with outer section formed into a cylindrical shape to enable welding to a piece of pipe. |
| Factory bend | Usually a length of pipe which has been bent in a factory by a combination of induction heating a narrow ring of the pipe and applying a bending force once the required temperature has been reached. This can be an continuous process or carried out |


|  | in stages. The pipe wall thickness chosen is usually greater than required to allow for the reduction in thickness on the outside of the bend. Thickening on the inside is usually ignored. Unbent sections are left at each end for field welding purposes. |
| :---: | :---: |
| Fill | Introduce water into a pipe section. Usually done behind one or two pigs to remove air and remaining fine debris. |
| Fill valve | Large valve of sufficient opening size to minimise pressure loss when filling, transferring or removing water from the test sections. A DN 900 pipe will usually have a DN 150 or larger valve. Such valves are not used to separate sections during the pressure test but must have sufficient strength not to fail when the body is subjected to strength test pressure. They are usually left in the partly open position during the pressure test and are terminated by a blind flange or some other means of sealing designed for the pressure. |
| Fittings | Permanent or temporary devices welded, flanged or threaded to the pipe and used for attaching instruments, hoses, other fittings and equipment to the pipeline. |
| Foam pig | Plug of expanded foam in a cylindrical shape of sufficient diameter to compress against the inside of the pipe. Can be coated with wear resistant materials, brushes and abrasive materials dependent on the internal pipe surface and intended use. Have some form of seal on the rear surface to ensure that pressure differential can drive them through the pipe. |
| Gauge Plate | Usually a flat plate of specified internal diameter mounted on a pig or trolley to check the minimum clear internal diameter of the pipe section. Commonly 90, 92.5 or $95 \%$ of the smallest internal pipe diameter. |
| Guide disc | Flat disc of external diameter slightly less than the pipe internal diameter for the support of the pig and not for sealing purposes. Usually thicker than the sealing discs. Usually installed at both extremities of the pig and can be in multiple numbers depending on likely travel distance and abrasive nature of the pipe. |
| Hydrotest | Pressure test using water as the test fluid. |
| Intelligent pig | Any pig capable of recording internal pipeline measurements such as size, presence of corrosion or cracks, leaks and route geometry as some examples. |
| Internal temperature probe | Temperature probe designed to operate in water at pressure but with a threaded or flanged fitting to enable the cables or wires to remain sealed to internal pressure but connected to an external recording device at atmospheric pressure. The probe may have multiple sensors at separations. |
| Isentropic | Constant entropy or adiabatic. |
| Isothermal | Constant temperature achieved by continuous heat transfer. Not applicable to sudden changes in pressure or most acoustic propagation. |
| Leak | Loss of liquid or gas from a system under pressure. Usually measured by a consistent reduction in pressure and then linked to volume using the above differential quantity $\mathrm{dP} / \mathrm{dV}$ or its inverse dV/dP. Temperature changes may cause pressure reduction falsely interpreted as leakage. |
| Leak Test | Following a successful strength test, the pressure is usually reduced by a pressure sufficient to ensure no subsequent yielding or creep occurs. Pressure is recorded at regular time intervals together with relevant temperatures of the pipe and/or water inside the pipe. Usually addition of water is avoided unless to ensure pressure limits are not exceeded or reduced below. Success is assessed by comparison of pressure changes corrected for measured temperature changes against an acceptance criterion such as pressure range, pressure range |


|  | comparable to a volume loss or pressure range comparable to a combination of pressure and temperature changes. Any observed leaks in permanent fittings or pipe must be fixed. Leaks in temporary fittings for test purposes are usually measured and used in the test acceptance but are not detrimental to the test performance unless of sufficient size as to make the leak test difficult to conduct such as requiring intermittent or continuous pumping. |
| :---: | :---: |
| Low pressure header | A cylindrical assembly with end cap or flanged end closure designed for pressures likely when launching and receiving cleaning and gauging pigs or drying pigs. Has branch fittings for attachment of instruments, compressor hoses and discharge lines. May have a full bore valve and may have a hinged flanged door for quick isolation and rapid opening |
| Lower-in | Process for transferring the welded and coated pipe from temporary supports above ground to its final position below ground. Usually carried out with sidebooms capable of lifting the pipe weight and installing below ground while moving without overbalancing or overloading similar units before and after in a line of machines. |
| LVDT | Linear Variable Differential Transformer used for small rapid movement without contact with the moving member. |
| Magnet pig | Pig fitted with magnets near to the pipe surface to attract and retain ferrous debris such as metal brush materials, weld spatter and grindings and parts of devices and pigs lost inside the pipe. |
| Mainline valve | Valve of the same diameter as the pipe and can be of ball or gate type and with sufficient bore to permit unobstructed pig passage (full bore) or with slight reduction (reduced bore). |
| NdFeB | Neodymium Iron Boron material used for high strength permanent magnets. |
| Neper | Measure of attenuation whereby the amplitude has changed by the reciprocal of the mathematical constant e or 2.718 equivalent to a reduction to $37 \%$ of the original signal. |
| Nominal Diameter (DN) | Pipe diameters below 14 inches have sizes in inches approximately corresponding to internal diameter while 14 inches and above are the outside diameter. Metric equivalent are sometimes given but are mostly conversions from imperial inches which is the legacy standard size measurement for pipeline diameter. |
| P/V | Pressure/Volume. Measurement of volume added for pressure increase, usually carried out during the increase in pressure to reach strength test pressure. Used to measure air content in a pipe section, confirm the elastic properties of the pipe and measure any deformation or yielding of the pipe. |
| Pig | A tight fitting assembly that can be pushed through a pipe by pressure behind it. Can be made of foam, plastic materials and central metal body. Can have discs or cup shaped perimeter replaceable seals. Can be fitted with additional devices such as gauge plates, brushes, magnets and scraping blades |
| Pipe wall | External part of the pipe usually including factory applied corrosion coating but not concrete coating. |
| Plastic deformation | Permanent stretch of reduction in size. Applies to any deformation beyond the elastic limit usually classified as yield. |
| PMV | Partial Molar Volume |
| Pneumatic Test | Pressure test using a gas such as air or nitrogen as the test medium. Generally avoided due to the high safety risks to persons, property and the pipe if rupture occurred. |
| Poisson's ratio | Measure of the change in one axial direction from a change in another. Usually for strain in a direction orthogonal to an applied |


|  | stress with resulting strain. Value for steel is around 0.3 and for <br> pipe steel 0.27. Rubber like materials have a value close to 0.5 <br> as also steel when in the plastic state at stresses above yield. |
| :--- | :--- |
| Pressure gauge | A pressure measuring device with a visual display of the <br> pressure such as a dial indicator on a disk or chart. More <br> recently an electronic device with digital or analogue display of <br> the measured pressure. |
| Pressure transducer | An electrical device which produces an electrical output when <br> subjected to a pressure change. Electrical output can be a <br> resistance, current, voltage change or charge. Most have some <br> sensitivity to temperature and some have temperature <br> compensation. Have operating ranges that require selection to <br> cover maximum expected pressure with some margin for error. <br> Can be gauge or absolute. |
| Relaxation | Permanent stretching which increases with time with usually <br> constant strain such as pipe initially stretched by added water <br> without any further addition which then remains fixed in volume. |
| Scraper | Alternative name for pig in locations where the term is avoided. <br> Time based resistance of fluid to the relative movement of two <br> parallel plates immersed in the fluid. |
| Shear Viscosity | Specified Minimum Yield Stress. |
| SMYS | Mathematical ratio of the specific heat at constant pressure to <br> the specific heat at constant volume. Identified by the Greek <br> symbol y or gamma. |
| Specific heat ratio | Sample of a material or product intended for testing purposes. |
| Specimen | A white above ground (1.2 metre) louvered box with access door <br> and double roof used for measuring weather parameters such as <br> ambient temperature and designed to minimise solar radiation <br> influence and ground re-radiation and heating on the measuring <br> instruments. |
| Stephenson box reduction in size of material subject to some |  |
| Test | The stretch or red <br> applied force or pressure. |
| The speed at which stretch of pipe material takes place. |  |
| Strain | A period of time in which the pipe section is held between <br> pressure limits. Pressure is usually recorded at regular time <br> intervals and also when water is added or removed to maintain <br> the pressure range. The purpose of the strength test is to <br> confirm that the pipe is capable of maintaining the pressure <br> range without rupture or failure. Leaks during the strength test <br> are usually noted but not rectified. |
| Strain rate the required minimum pressure. |  |


| Test header | A length of pipe thicker than the section to be tested with welded <br> end cap and multiple branch fittings of different sizes for <br> purposes of filling, dewatering and pressure testing. |
| :--- | :--- |
| Thermistor | A semiconductor metallic oxide material which changes <br> resistance siginificantly with temperature. Some have reduced <br> resistance wwith increased temperature and are called negative <br> temperature coefficient thermistors. |
| Tie-in | Welding together two pipe sections usually using manual <br> welding techniques. Such welds if following pressure tests are <br> called "Goldden Welds" as they are only subject to Non <br> Destructive Testing but not to another pressure test. |
| Trench | The continuous excavation intended for pipe installation below <br> ground. |
| Uncertainty | Term can be applied to measurements where it becomes <br> measurement uncertainty or can be applied to the lack of <br> correlation between two different parameters such as pressure <br> and temperature. |
| Valves | Fitting which can be used to separate one part from another by <br> movement of a sealing element. Can be of different type such <br> as ball, gate, plug, needle and choke. |
| Viscosity | Term describing the resistance of a fluid to relative movement. <br> The permanent stretch of pipe material usually defined as 0.5\%. <br> Yield strain stressUpper limit of elastic steel behaviour. Stress beyond which <br> results in permanent stretch usually in pipe diameter. Usually <br> defined as 0.5\% permanent stretch. |
| Young's modulus | The ratio of applied stress to resultant strain in a specimen <br> subject to a stress in one direction only and below the yield <br> stress. It only applies to stresses and strains in the elastic <br> region below the yield stress and strain. For pipe steel has a <br> value of 2.06 x 1011 Pa or 2.06 x 105 MPa. Varies only slightly <br> with temperature but usually considered constant. |

## APPENDIX D - TRANSMITTER DESIGN.

The following figures show the cross sectional views of the small (Figure 9-1) and large (Figure 9-2) transmitters used to generate the signals reported in this document. Both were designed, machined, assembled and pressure tested by this author including the magnet circuit and pitson wire coils. Others performed the hard chrome plating, honing and magnetising.

Small Transmitter


Figure 9-1 - Small Transmitter Cross Section Drawing
Small piston diameter 35 mm . Male thread at top $3 / 4$ " BSPP. Female thread at bottom $1 / 2$ " BSPT or $1 / 2$ " NPT. Coarse diagonally hatched parts carbon steel as part of the magnetic field structure. Dotted area is ceramic magnetic material with the finer diagonal hatching inside it of stainless steel. Piston was of aluminium with copper coil. Central equalising valving and hole through piston not shown. After the pressure containing upper half of the
magnetic circuit was machined it was hard chrome plated and honed for minimal friction with the piston. This was carried out prior to magnetising as once assembled and magnetised it could not be disassembled. The top part was removable for piston changeout and for electrical connections from the coil to the power amplifier via specially designed and made (by this author) high pressure insulated electrical connectors.

Large Transmitter


Figure 9-2 - Large Transmitter Cross Section Sketch
The large transmitter used threads to join the respective component sections so that the two halves could be assembled and magnetised separately and then joined together with the central piece providing the electrical connections to the double coil piston of diameter 50 mm (double the pressure area of the 35 mm piston). As for the small transmitter the central elements were hard chromed and honed. Both ends had 1" NPT female threads which required nipples to connect to the pipeline below and accumulator above. High pressure insulated electrical connections for the piston coils were centrally located with one shown on the right side.

