AN INTEGRATED DESIGN STRATEGY FOR A RANGE OF INDUSTRIAL ELECTRONIC PRESSURE INSTRUMENTATION.

SUBMISSION FOR THE AWARD OF:
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SUMMARY

This portfolio details the design, construction and testing of three high accuracy digital pressure indicators. A discussion of old and contemporary pressure measurement technologies is included, as well as a comprehensive market survey of electronic pressure measurement instruments currently available.

An integrated design strategy is adopted for the three separate digital pressure instruments, namely a battery - powered stand alone unit, a retransmitting version and an intrinsically safe version of the battery powered unit. Their implementation takes into account many design issues including ease of manufacturing, low power circuit design and electromagnetic compatibility.

Novel features available upon all three instruments resulting from the design strategy adopted are high accuracy measurements, typically ±0.2% of full scale, a battery life of over 12 months, push button zeroing and linearisation, electromagnetic compliance with minimum design changes and an intrinsically safe power supply design that may be used not only in the instrument for which it was designed but for future instruments.

Individual design issues with respect to each instrument are in the three project sections which complete this portfolio.

GLOSSARY OF TERMS

µA	-	Micro-amps.
ADC	-	Analogue to digital converter.
BSP	-	British Standard Pipe Thread
DAC	-	Digital to analogue converter.
EEPROM	-	Electrically erasable read only memory.
EMC	-	Electromagnetic compatibility.
fs	-	Full scale deflection.
kΩ	–	Kilo-ohms.
mA	-	Milli-amps.
MOSFET	-	Metal oxide semiconductor field effect transistor.
ms	-	Milli-seconds.
mV	-	Milli-volts.
NPT	-	National Pipe Thread.
PCB	-	Printed circuit board.
V	-	Volts.
Ω	–	Ohms.
µF	-	Micro-farrad
C	-	Capacitor
mBar	-	Milli-Bar
LVDT	-	Linear Variable Differential Transformer
IP	-	Ingress Protecttion
P1	-	Pressure 1
P2	-	Pressure 2
N	-	Newtons
Pa	-	Pascal
psi	-	Pounds Per Sqaure Inch
N/m^2	-	Newton Metre Squared
BASEEFA	-	British Approvals Service For Electrical Equipment In Flammable Atmosphere.
EECS	-	Electrical Equipment Certification Service
F	-	**Force**
SMT	-	Surface Mount Technology

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OVERVIEW

AN INTEGRATED DESIGN STRATEGY FOR A RANGE OF INDUSTRIAL ELECTRONIC PRESSURE INSTRUMENTATION.

INTRODUCTION

The British Rototherm Company is a well established manufacturer of high quality mechanical and electronic instrumentation such as bi-metallic thermometers, conventional mechanical pressure gauges, electronic pressure transmitters, microprocessor based electronic thermometers and chart recorders.

A Teaching Company Scheme of two years duration was established between British Rototherm Company Ltd and The University of Glamorgan. This was an integrated programme of work which had the single aim of developing design strategies for a new range of electronic instruments for pressure measurements. The key aspects of the program were as follows:

1. Design and development of a battery-powered, microprocessor based digital pressure gauge for industrial applications.

2. Design and development of a microprocessor based industrial digital pressure gauge with 4-20mA current loop interface.

3. Adaptation of the digital pressure gauge to produce an intrinsically safe design, which is suitable for use (or installation) in hazardous environments where flammable atmospheres exist. This work took full cognisance of the powerful European Union ATEX directive.

The symbiosis between the three Projects meant that the implications for strategies adopted in **Project Two** and **Project Three** were kept under continual review.

Consequently, design and development decisions for **Project One** were made with a clear regard to their impact upon the proceeding projects.

This overview aims to provide the philosophy behind the design strategy which was adopted, following a detailed market survey of currently available pressure instrumentation. A number of issues had to be considered, including low power analogue and digital circuit design, design for electromagnetic compatibility and design for intrinsic safety.

The design also had to be modular, so that many of the modules (both hardware and software) could be reused in variants of the digital pressure gauge. Details of each project are contained in the respective portfolio while this overview provides the broader context in which specific design decisions were made and the general performance evaluation of each digital pressure instrument.

1 PRESSURE MEASUREMENT DEFINITIONS

The measurement of pressure is one of the largest fields in industrial process instrumentation. Common applications involve the connection of a mechanical analogue pressure gauge to a pipe or tank to give a local indication of the pressure of the liquid or gas contained inside.

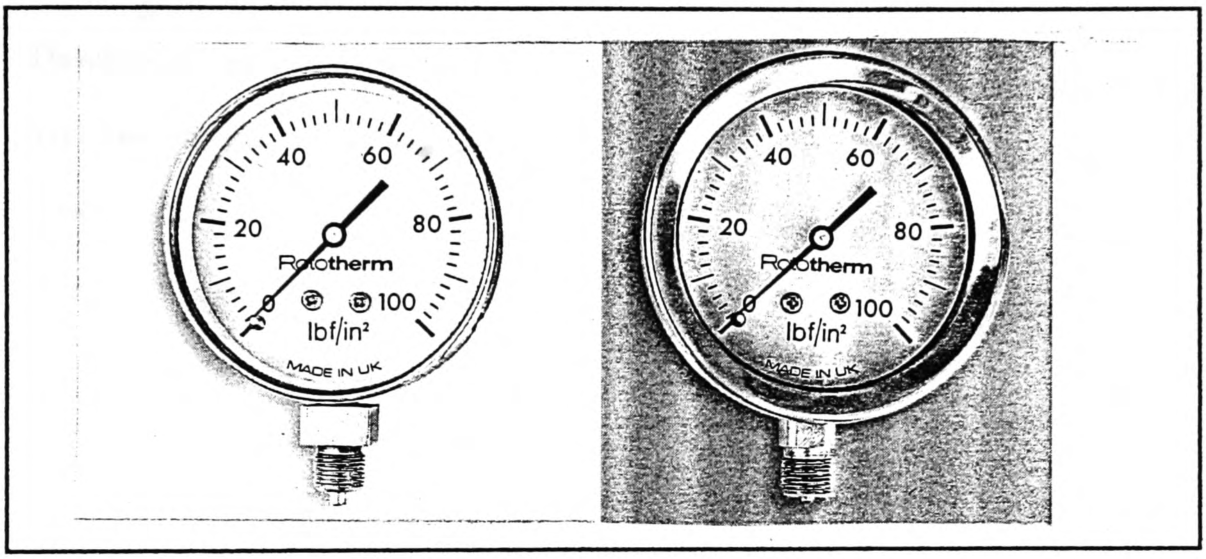


FIGURE 1: Rototherm mechanical pressure gauges.

FIGURE 1 shows a typical Rototherm analogue pressure gauge. Mechanical analogue pressure gauges can also be connected to the regulators on the top of gas cylinders and bottles. In this application the pressure gauge provides a local indication of the pressure of the gas being released from the cylinder, thus enabling the pressure of the released gas to be set to a level required by adjusting pressure control valve on the regulator attached to the gas cylinder.

A mechanical analogue pressure gauge has the inherent limitation of providing only a visual indication of local pressure. There is no possibility to control pressure with a mechanical analogue pressure gauge because there is no feedback available.

However, a mechanical analogue pressure gauge has the advantage that it may be installed in hazardous environments where potentially explosive atmospheres may be present.

Pressure is defined as:-

The force per unit area that a fluid exerts on its surroundings. If the media being measured is a gas, then the pressure of a gas is the force per unit area that the gas will exert on the walls of the housing in which it is contained.

Therefore the pressure of the media being measured is mathematically represented as the force per unit area having the SI units of Newtons Per Square Metre - N/m^2. This unit is named the Pascal, and so 1 N/m^2 = 1 Pa. Other common units of pressure are Pounds Per Square Inch lb/in^2, usually written psi, and the Bar. 1 psi is equal to 6.895 kPa and 1 Bar is equal to 100 kPa.

Further definitions relevant to this overview are:-

Relative (Gauge) Pressure:	*That which is relative to atmospheric pressure. Therefore, a gauge pressure measurement is an expression of the pressure difference between the pressurised medium and the atmosphere.*
Absolute Pressure:	*The sum of atmospheric pressure and applied pressure. With no pressure applied, the gauge would read standard atmospheric pressure. Standard atmosphere pressure = approx. 1.0132 bar, but changes with atmospheric (weather) conditions. With a vacuum applied, the gauge would read 0.*
Static Pressure:	*The pressure where there is no movement of the liquid or gas.*
Dynamic Pressure:	*The pressure when there is movement. In other words, the pressure exerted on the surroundings by the media depends on the movement of the pressure.*

2 AN OVERVIEW OF CURRENT PRESSURE MEASUREMENT TECHNOLOGY

The importance of pressure measurement has led to the development of a number of different pressure measurement technologies. The most common method of measuring pressure is achieved by monitoring the degree of deformation from a mechanical device exposed to a pressure. The mechanical devices are diaphragms, Bourdon tubes and bellows. All of these methods work on the principle that the application of pressure causes a physical displacement which is proportional to the applied pressure.

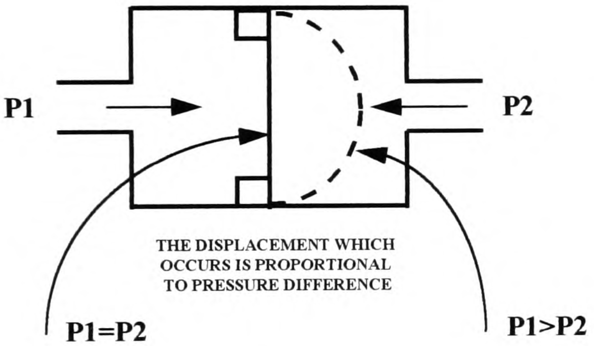


FIGURE 2: DIAPHRAGM

Diaphragm: A pressure **P1** is applied to one side of the diaphragm, and a pressure **P2** on the other. The force exerted is defined as $kx=(P2-P1)A$, where **P1, P2** are pressures in N/m^2 and **A** is the area of the diaphragm in m^2. **FIGURE 2** shows a diaphragm.

The behaviour of the diaphragm is similar to that of a spring, expanding or contracting until such a point that a Hookes Law force is developed across the diaphragm which will balance the pressure force. A diaphragm will be used up to 5000 psi.

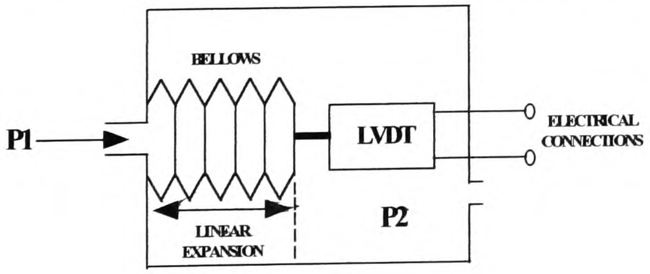


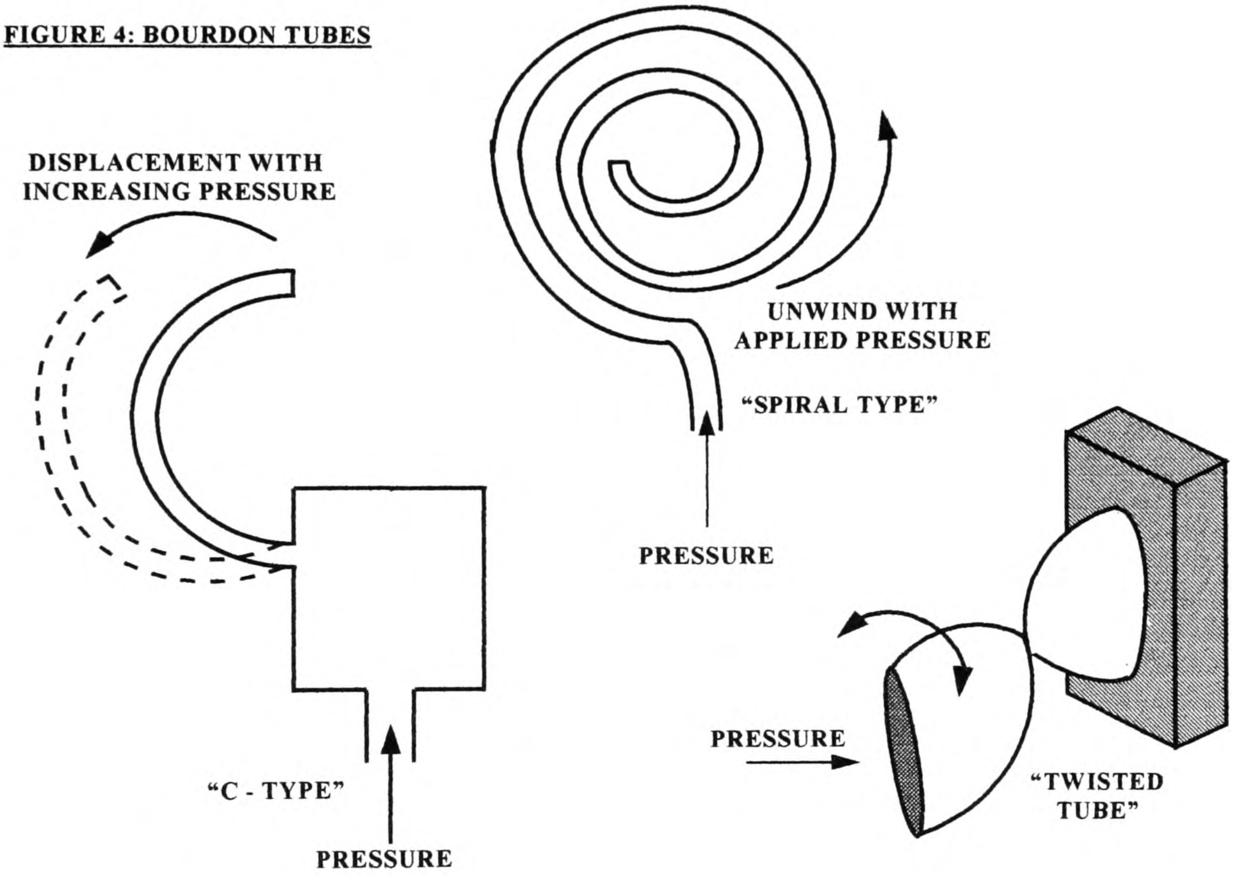
FIGURE 3: BELLOWS

Bellows: When pressure is exerted upon the bellows, the result is a straight line expansion. Bellows are used at low pressure, from 0 to 15 psi, and are also often used on 3 -15 psi control lines.

Though bellows have a fine resolution, they are not very robust.

Bourdon Tube: This is a section of tube which is specially constructed, usually by being flattened and coiled. When pressure is applied to the inside, the tube will begin to uncoil. The most common types of Bourdon Tubes are the spiral, c-type and twisted tube. These are illustrated in **FIGURE 4.**

FIGURE 4: BOURDON TUBES



Conventional mechanical pressure gauges which employ bellows or Bourdon tubes will amplify the displacement at the free end of the tube. This is due to applied pressure by mechanical means known as "a movement." The movement consists of levers and gears in conjunction with a hair spring which removes backlash and counteracts freeplay. The movement rotates a needle or pointer which, in turn moves over a fixed scale graduated with units of pressure. Bourdon tubes are used on pressure ranges up to thousands of psi.

3 INSTRUMENTATION TECHNOLOGY EVOLUTION

Mechanical analogue pressure gauges have been manufactured for over one hundred and fifty years. Advances in manufacturing technology and increased levels of sophistication in production engineering have resulted in the price of even high accuracy mechanical analogue test gauges being low (around £100 January 1999).

A mechanical pressure gauge is also perfectly safe for use in hazardous environments where explosive and flammable dusts, gases and liquids are present. This is because no part of the mechanical pressure gauge will heat up or cause a spark which, in normal operation, might lead to ignition of the surrounding atmosphere. It is "intrinsically safe" - see "**Intrinsically Safe Instrumentation.**"

Once installed, a mechanical analogue pressure gauge is also totally maintenance free; the one exception being the possibility of removal of the pressure gauge for re-calibration, and the end of its stated working life. A mechanical analogue pressure gauge will only give a localised indication of pressure. With no form of feedback present, there is no facility for any form of process control to be derived. The accuracy of a mechanical analogue pressure gauge is typically ±1 - 2 % f.s. but may only be of the order of ±10% in the case of a simple low cost gauge.

The resolution of a mechanical analogue pressure gauge can be low, depending on the maximum pressure range of the instrument and the physical size of the instrument (these factors present the possibility of a mistake being made when a reading is taken from the pressure gauge). For example, a mechanical analogue test gauge which has an accuracy of ±0.25% of full scale and a fine resolution may well have a dial of up to 300 mm in diameter, compared with a standard mechanical analogue pressure gauge which will have a dial of approximately 100 mm diameter.

As industrial processes become increasingly more complex - often with more stringent safety requirements and standards being imposed upon these processes - so the need for industrial process instrumentation with greater levels of complexity and functionality is expanding. Higher levels of complexity and functionality can be substantiated as a need for greater accuracy and resolution together with the need for process control of the media (for which the conditions are being monitored.) Hence the instrument needs to have a feedback facility so that it will not only provide an indication of the state of the media which it is monitoring, but will be able to actuate change on the media conditions. This evolution is also evident in British Rototherm's range of industrial thermometers. Traditional mechanical thermometers work on a similar principle to mechanical pressure gauges, using the amplified expansion / movement of a mechanical element to give a temperature indication. As a result, a market opened up for a temperature indicator with greater accuracy and resolution; with a parallel market for a version certified as intrinsically safe for use or installation in hazardous environments. These market circumstances led to the development of the “Digitemp” range of electronic thermometers.

It is logical that these market conditions should dictate that the company’s range of high accuracy digital thermometers would be complemented by a corresponding range of digital pressure indicators; offering similar advantages in terms of accuracy and resolution over their mechanical counterparts. The need for process control justifies the development of a transmitting version of the stand alone instrument.

4 INTRINSICALLY SAFE INSTRUMENTATION

Intrinsic safety is a technology which ensures that the available electrical energy in a circuit is too low to ignite the most easily combustible mixtures of gas and air, or dust and air.

These ignition mechanisms are electrical, caused by spark energy and thermals from hot surfaces. The design of the circuit and equipment is developed such that it will always remain safe in normal use and under fault conditions within that circuit or equipment. Some categories of apparatus are designed to be intrinsically safe even when multiple faults are present.

As some equipment or circuits (apparatus) will have connections to apparatus outside of the hazardous environment, another consideration is the possibility of an unacceptable amount of power being fed through from the apparatus in the safe area. Hence intrinsic safety can be defined as a system concept in which the apparatus in the hazardous area, the apparatus in the safe area, and the combination of both of these must be considered to create an intrinsically safe set of apparatus.

No official definition of intrinsic safety exits, but EN50020, the relevant CENELEC standard, defines an intrinsically safe circuit as:-

A circuit in which no spark or any thermal effect produced in the test conditions prescribed in this standard (which include normal operation and specified fault conditions) is capable of causing ignition of a given explosive atmosphere.

A detailed discussion of intrinsically safe design is presented in **Project Three**.

5 ELECTRONIC PRESSURE TRANSDUCER TECHNOLOGY

All of the aforementioned mechanical pressure measurement devices may be used to convert the mechanical displacement due to a change in pressure into an electrical signal. The straight line expansion of bellows can be converted into an electrical signal by connecting the end of the bellows to a linear differential variable transformer (LVDT.) The deformation of a Bourdon tube can be monitored by fitting foil strain gauges.

The diaphragm is the most common mechanical element which is monitored for its ability to convert a physical displacement due to applied pressure into an electrical signal. This is normally achieved by measuring the change in resistance of electrical conductors bonded onto or diffused into the diaphragm. These conductors are connected in a bridge configuration. Hence, the resistance of the conductors changes with physical deformation of the diaphragm. This is as a result of an applied pressure on the diaphragm.

The following table details the construction of the most commonly used diaphragms and the monitoring of the resistance changes used with them.

DIAPHRAGM	**MEASUREMENT SYSTEM**
Stainless Steel	Bonded on foil strain gauges
Silicon	Semi-conducting diffusion layer
Ceramic	Thick film resistors

Less common methods of measuring small deflections on diaphragms use inductive, capacitive or quartz crystal methods.

With a capacitve pressure sensor, one plate is a fixed metal disc, the other is a flexible flat circular diaphragm, clamped around its circumference; the dielectric material is air[2]. The deformation of the diaphragm means that the average separation of the plates is reduced, resulting in an increase in capacitance.

With a piezoelectric crystal, if a force is applied to any crystal, then the crystal atoms are displaced slightly from their normal positions in the lattice[3]. The displacement is proportional to the applied force and a piezoelectric crystal gives a direct electrical output which is proportional to the applied force.

6 MARKET SURVEY OF ELECTRONIC AND DIGTAL PRESSURE INDICATORS

At the beginning of Project 1, an extensive market survey of electronic pressure measurement indicators was undertaken using books, instrumentation journals, papers, manufactures data sheets, internet searches and Rototherm's own collection of competitors data sheets.

A general summary of results is outlined in the following table:

SPECIFICATION	FINDINGS	COMMENTS
Accuracy:	Best ±0.1% of full scale Worst ±2% of full scale	Some mechanical gauges have better accuracy than ±2% (typ±1)
Measurement Range:	Absolute and relative available Widest ranges: vacuum to 690 bar. Smallest ranges: 0 to 60 bar	A variety of pressure ranges are available in between zero and maximum pressure range.
Resolution:	Not stated in manufacturers data sheets.	It is assumed that this is dependant on the pressure range selected.
Power Supply:	Lithium cells Nickel-Cadmium cells 9 volt PP3 type battery Sockets for adapters Mains powered	Some instruments were powered from the 4-20mA current loop - thus they were also transmitters, enabling control of the process.
Displays:	Liquid crystal display Light emitting diode	One manufacturer, AMV[4] of Germany, offered a choice of either.
Price:	Lowest £360 Span Instruments[5] Highest £1000 - Dynisco USA[6]	Quoted at one off prices.
Battery/Cell Life:	Worst 2 months - constant use Best 2 years - switching on / off	Those instruments which were fitted only with cells had an on / off switch to extend battery life.
Wetted Parts:	Stainless steel Nylon Plastics Viton Ceramics Silicon	Wetted parts are those which come into contact with the media being measured.
Ingress Protection:	Least protection IP65 Greatest protection IP68	Ingress protection is the level of protection the instrument has against the intrusion of water and dust.
Construction:	Stainless Steel Impact plastics	A combination of both. Square, circular, rectangular appearances
Process Connections:	BSP Both in various sizes NPT	All were direct process mounting types

Over twenty manufacturers of direct process mounting electronic pressure indicators were identified, with these and many more producing electronic pressure transmitters, hand-held pressure measurement devices, calibrators, panel mounted and instrument cased pressure indicators. Of the large amount of data collected from the search, that of direct relevance to the Projects was information on direct process mounting electronic pressure measurement instruments with local display.

7 A COMPARISON OF THE PROPOSED DIGITAL PRESSURE GAUGE AND THE EXISTING MARKET.

An equitable conclusion from this survey was that no product on the market exactly matched the specification for the range of digital pressure gauges presented in this portfolio.

The level of sophistication which was necessary to enable the three proposed digital pressure gauges to be accurate, have fine resolution, be low maintenance and versatile instruments was reasonably complex, and required the three proposed pressure instruments to be micro-processor based. From the results collected from the market survey, it became clear that there was a niche for the proposed range of Rototherm digital pressure gauges. The proposed range of digital pressure instruments specifically was to include:

1. A stand alone, battery-powered, microprocessor based digital pressure gauge for industrial applications.
2. A microprocessor based re-transmitting industrial digital pressure gauge with 4-20mA current loop interface.
3. Adaptation of the digital pressure gauge to produce an intrinsically safe design, which is suitable for use (or installation) in hazardous environments where flammable atmospheres exist.

These instruments offered many advantageous features. The key was low power operation and low maintenance of the gauge. No other electronic pressure gauge was identified that required just two standard alkaline "AA" cells; standard alkaline "AA" cells being the most widely available and low cost cells on the market.

Due to the type of cells used in the digital pressure gauge, and the proposed 12 months continuous use that would be provided from one set of two "AA" cells, the Rototherm digital pressure gauge would be one of the lowest maintenance gauges on the market.

The digital pressure gauge would normally be calibrated at Rototherm, and all that would be required to commission the gauge would be to screw it into its application. As the gauge would run continuously for 12 months, there would be no need for an on/off switch. Moreover, this design would allow an immediate pressure reading to be taken and allow the gauge to be positioned in a place where an operator would not be able to reach it should this be required.

Once the gauge had been installed into its application, absolutely no maintenance would be required until the cells needed changing after 12 months; at which point the display would alternate between "BATT" and the pressure reading, giving a clear indication that a cell change was necessary.

Low maintenance would also be advantageous for the intrinsically safe digital pressure gauge which would be designed and certified safe for use in a hazardous environment; the digital pressure gauge only having to be removed once from the hazardous environment to a safe zone every 12 months for the replacement of the two "AA" cells.

Design of the digital pressure gauge would aim for a works (manufacturing) cost of around £80, enabling the one off selling price for a British Rototherm Digital Pressure Gauge to be around £255; a price significantly cheaper than competitors' pressure gauges.

8 JUSTIFICATION FOR CHOOSING AN INTEGRATED DESIGN STRATEGY

To begin the development of the proposed range of Digital Pressure Gauges, careful consideration had to be given as to whether to pursue one of two options for the implementation of the instruments.

Option 1:	Start from scratch and design each instrument individually with a different system and new components specifically appropriate to the instrument function.
Option 2:	Re-use as many of the hardware and software systems and components of the first instrument (The Stand Alone Digital Pressure Gauge of **Project One**) as possible, but without compromising the target specification of each subsequent instrument.

The following factors were considered in making the choice between Option 1 and 2:

- Total development time.
- Component availability.
- Development tools available.
- Cost of new components and documentation time for these.
- Cost of new software development.
- Ease of system interfacing.

Basing the decision on the above criteria, Option 2 was deemed as being the more suitable choice for beginning the development of the proposed range of Digital Pressure Gauges. Also, as a measurement system which matches the target specification of the Projects 2 and 3 was to be fully tested and implemented in the Stand Alone Digital Pressure Gauge of Project 1, the need and reason for choosing an ***Integrated Design Strategy*** was clearly justified.

9 THE INTEGRATED DESIGN STRATEGY

The design of the three instruments would utilise a generalised modular design process. This modular design approach could be classified as each instrument system consisting of the following three sections:

1. **MECHANICAL DESIGN**
2. **ELECTRONIC HARDWARE DESIGN**
3. **SOFTWARE DESIGN**

Though the above modules were listed and appeared as separate entities, the design of each module would impact on the subsequent module. Consequently, each design stage had to be carried out with a forward looking approach. These design requirements once more justified the adoption of an ***Integrated Design Strategy***.

9.1 Mechanical Design

The mechanical design of the digital pressure gauge required close attention during the early stages of the project. This was because a number of elements and system parameters of the mechanical design would impact upon the electronics.

It was a requirement that the digital pressure gauge should bear a close resemblance to another of British Rototherm's products - the "Digitemp" digital thermometer. This was to give the appearance of a "family of instrumentation products."

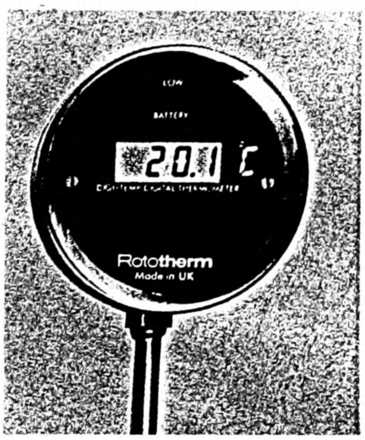


FIGURE5: TheRototherm "DigiTemp".[7]

With this requirement in mind, the stainless steel case used for the instrument was the same as that used for the "Digitemp" digital thermometer.

This type of case would also be used for a mechanical analogue pressure gauge; the economics of using the same case dictating that which is used. Consequently, the first limitation on the design was that of internal space and the shape of the case (round) in which the electronics would be housed. The pressure block of the digital pressure gauge, housing the pressure transducer, was mounted on the rear of the case. This mounting continued into the case, reducing the amount of space for the electronics still further. A great deal of consideration was given to the positioning and housing of the two "AA" cells. It was essential that these could be accessed easily, without any tampering or removal of printed circuit boards. The cells, however, had to be held securely at all times.

After obtaining samples of a number of clips and cell holders, the option chosen was a dual "AA" cell holder. This was because this particular cell holder gave spacing and some electrical insulation between the two cells. Consequently it was impossible for a short circuit to appear across both of the cells due to mechanical failure of the cell holder; an essential feature for the design to meet with approval for intrinsically safe operation.

Due to the space on the printed circuit board occupied by the cell holder, two printed circuit boards were required to accommodate the electronics.

These were mounted directly above one another, the top printed circuit board being secured to the lower board by bolts and spacers. An electrical connection was made between the two boards by a rigid 16 pin header and box connector. The dual cell holder was positioned at the bottom of the instrument.

The 4-20mA loop transmitting digital pressure gauge obtained its power supply from the current loop, and therefore cells were not required.

The space formerly occupied by the battery holder in the stand alone digital pressure gauges became free, and this space was used for an EMC filter and connection socket to the two wire loop in the transmitting digital pressure gauge. Thus the need for total printed circuit board re-design was overcome.

The liquid crystal display and the user interface switches were mounted on the top printed circuit board. The two reasons for choosing this layout were:

1. The ease of manufacture of the instrument was always a prime consideration, and this design was deemed most suitable for uncomplicated and efficient manufacture and assembly.
2. It would allow the user easy access to the cells and the switches, without any need to remove printed circuit boards or tamper with electrical connections or electronic connections. The front bezel could be twisted off and the front dial removed by unscrewing two screws, allowing for a quick change of cells or access to switches.

Due to the space limitations within the case, the possibility of using all surface mount components was considered, but rejected on the grounds that the company did not possess the production facilities for populating surface mount printed circuit boards in large quantities. The above choices amounted to a minimisation of the changes needed for the designs of the three instrument versions. The only change required for the mechanical design of the case was the punching of a hole to accept a plug for the introduction of a cable on the transmitting digital pressure gauge of **Project 2.**

9.2 Electronics Design

A systems approach was adopted for the electronics design of the digital pressure gauges. These systems areas could be defined as:

1. The pressure transducer and analogue signal processing electronics.
2. The power supply.
3. The analogue-to-digital converter and microcontroller.

4. The display.
5. Data storage and data entry.

9.2.1 The Pressure Transducer and Analogue Signal Processing Electronics

It was necessary to design and implement a pressure measurement system that once tested and approved was compatible with all three pressure instruments. The transducer chosen was a Bourdon Sedeme thick film strain gauge deposited on the reverse of a insulating ceramic diaphragm. This transducer had already been used in other Rototherm products. An investigation of a number of pressure transducers was undertaken and a great deal of time was spent testing and selecting a transducer for use in the pressure transmitter. This transducer was suitable for use on most pressure media, and was available in a number of pressure ranges. Although other types of transducer were available, as described earlier, these were deemed too expensive and consumed too much power.

The Bourdon Sedeme transducer was also available in a temperature compensated version, which was a direct replacement for the standard transducer and could be fitted if customers required a gauge which was more accurate over a greater temperature range.

The analogue signal processing electronics consisted of a low-power, precision operational amplifier configured in non-inverting mode, which was used to amplify the signal from the pressure transducer. The excitation voltage to the pressure transducer and the power supply voltage for the operational amplifier were switched on and off using a MOSFET activated by the microcontroller.

9.2.2 The Power Supply

The power consumption of both the stand alone digital pressure gauge and the intrinsically safe digital pressure gauge was of prime importance as these two instruments were the battery powered versions.

A highly efficient power supply section which would provided regulated supply voltages of the correct magnitude was required. The design made provision for, and included, components that were necessary for the instrument to be passed as being intrinsically safe. A very attractive reason for adopting this strategy was that a certified intrinsically safe power supply design could be replicated in all current and future Rototherm products (The provision for these can be seen in the design of the printed circuit board. There is space and tracking on the printed circuit board for two pairs of clamping diodes and a series fuse.)

A supply voltage of +5v was chosen. Energising the pressure transducer from a supply of less than 5v would result in reduced output from the pressure transducer. Such a reduced output would lead to a poorer instrument accuracy due to lower signal level approaching the noise floor of the ADC. Although the analogue and digital electronics could be powered from lower regulated voltage, this would have involved extra circuit components and complexity and thus an increased cost. So a supply of +5V enabled the analogue and digital electronics and the pressure transducer to be powered from the same supply rail.

9.2.3. The Analogue to Digital Converter and Micro-controller

The analogue-to-digital converter and micro-controller formed the heart of the system for all three pressure instruments. These were chosen for their low power operation and their ability to run at a low operating speed while still being able to execute the required routines, and providing the option for programmable sleep modes.

Low quiescent current and low speed operation of the circuit was advantageous for all three circuits for the following reasons:

i) Low quiescent current operation of the circuit enabled a battery life of 12 months to be available for the stand alone digital pressure gauge and the intrinsically safe digital pressure gauge.

ii) It also meant less likelihood of excessive power or energy storage being available in the circuit during normal operation or faulty operation; occurrences which would require reduced circuit changes before the instrument could be certified as intrinsically safe.

iii) Such objectives also aid in meeting electromagnetic compatibility standards as the chances of emissions would reduced. Conversely, the extra capacitance and inductance required to protect the circuit from radio frequency interference (as specified by EMC standards) meant that extra energy storage components were now in the circuit. This made meeting intrinsic safety standards more difficult. The design strategy therefore needed to balance two contradictory requirements.

9.2.4. The Display

A four digit 12.7 mm high liquid crystal display was used for all three instruments, allowing for resolutions from 1 mBar to 100 mBar, depending on the maximum pressure range selected. Using a common display reduced software development while retaining a familiar appearance and minimising costs.

9.2.5. Data Storage and Data Entry

The data storage and entry used dual-in-line switches and push button switches as the user interface to the instruments. Keeping these switches as similar as possible for all instruments significantly reduced software development and made calibration for the instruments easier, as there is as much commonalty between all three instruments as possible because of the integrated strategy adopted for the design process.

9.3 Software Design

The integrated design strategy enabled a modular approach to be taken to the software development, with creation of reusable routines which are common to all three instruments. All the software was written in PIC Assembler, with no high level languages used.

The software was therefore written in a very structured way, with many routines, such as those used for serial communications, addition, subtraction, multiplication and division being frequently called routines. This enabled maximum use to be made of the system resources of the microcontroller. Timing for the power supply switching was controlled by the software, as was the programmable sleep mode of the ADC. Close attention to system timings, such as sensor energisation time, allowed savings on current consumption. Obvious benefits from the software were the linearisation and auto-zero features. The linearisation software increased the accuracy of the instrument to ±0.2%.f.s. The auto-zero software eliminates potentiometer zeroing of the instrument. Using the dual-in-line and push-button switches the instrument is set to calibration mode and zeroed respectively.

Using a push-button mechanism to zero the instrument is not only easier and less time consuming for the user, but the result is a reduced zero shift due to changes in temperature. The software for the stand alone digital pressure gauge and intrinsically safe pressure gauge is identical. This software is also used in the transmitting digital pressure gauge, but with some extra routines to allow scaling of the pressure reading to be communicated to a digital to analogue converter to modulate the current in the two wire transmission loop.

One of the most time consuming operations of the design process was the creation of software and having to write independent software for all three instruments would have greatly increased the development time.

10 TESTING REQUIREMENTS FOR THE RANGE OF PRESSURE INSTRUMENTS

Testing of all the instruments was necessary to ensure that they met the original specifications and conformed to necessary British and European standards governing their operation and installation.

To ensure accuracy, all the instruments were tested in British Rotothems calibration laboratory. This calibration was carried out on a Budenberg dead weight tester. This was a recognised pressure standard, using a combined system of weights and hydraulics to generate very accurate pressures. The accuracy of the Budenberg tester was certified as it was regularly calibrated and tested by an external calibration laboratory, and gave an accuracy of better than 0.1% at all the pressure ranges for which it was designed.

All of the instruments had to conform to the generic standards for electromagnetic-compatibility; which are:-

For Immunity: BS EN 50081-1 : 1992

For Emissions: BS EN 50082-2 : 1995

Electromagnetic compatibility compliance was of prime importance (and is detailed further in **Project Two**.) This was because the introduction of a cable to the instrument required conducted immunity testing. As the instruments of Projects One and Three had no external connections, only tests for radiated immunity and emissions were required.

Project 3 was specifically designed to conform to the requirements of the following standards for intrinsically safe design:

EN50 014 (1992)

EN50 020 (1994)

These were standards to which equipment must comply in order to meet the ATEX directive and gain intrinsically safe certification.

11 EVALUATION OF DESIGNS

All three pressure instruments functioned correctly and satisfactorily met with the original specifications to which they were designed.

The integrated design strategy enabled the core pressure measurement system to be used in all three instruments, which, together with the linearisation software, achieved a very high accuracy for all the digital pressure gauges of ±0.2% of full scale. This ensured that the digital pressure gauges ranked top of the market for accuracy. The accuracy of the digital pressure gauges was equivalent to that of an analogue test gauge, enabling the digital pressure gauges to be sold to test laboratories. The digital pressure gauges were also calibrated externally by NAMAS laboratories, and accuracies of better than ±0.2% were recorded. These results are fully detailed in **Project One**.

The integrated design strategy also produced many advantageous features which were reusable on all three pressure instruments, including; the push button zero feature, which eliminates the need for potentiometer adjustment; a choice of pressure units on the display which can be selected by a change of switch position; a push button linearisation system; a choice of update rates, selected by changing a switch position; and an automatic low battery indication on the display.

The battery powered stand alone digital pressure gauge detailed in Project One had an extremely low quiescent current consumption of only 270μA, guaranteeing a battery life of over 12 months from two standard "AA" alkaline cells. The low cost and wide availability of these cells allowed maintenance of the instrument to be kept to a minimum.

The loop powered transmitting digital pressure gauge detailed in **Project Two** had a transmission accuracy over the 4/20mA current loop, matching the high ±0.2% full scale accuracy of the measurement system. The high accuracy of this instrument enabled it to be used in applications where very fine control of a process was required.

The focus on intrinsically safe design following a full consultation with BASEEFA enabled a redesign of the Digital Pressure Gauge of **Project One** to produce an intrinsically safe version; as detailed in **Project Three**. The redesign was completed and a certificate of approval expected by the end of March 1999. Due to the integrated design strategy a key advantage was the minimum number of amendments needed for the redesign and the decoupling of the power supply and measurement system for certification, to enable the intrinsically safe power supply design to be used on future instruments without having to reapply for another BASEEFA certificate.

12 FUTURE DEVELOPMENTS

It is envisaged that an obvious future development of the range of digital pressure instrumentation described in this portfolio will include an intrinsically safe version of the re-transmitting digital pressure gauge. Other possible enhancements to the range of instruments include a microprocessor with integral display driving capabilities which would reduce component counts, and a change to the use of surface mount technology (SMT) would reduce printed circuit board size, allowing for more components with increased benefits and features. However, this would require considerable investment by the company, which do not have SMT facilities available.

13 CONCLUSION

This overview has detailed all aspects of the integrated design strategy for a range of microprocessor based digital pressure instruments. The results of the Projects in the following portfolio show that such a design approach has produced a number of novel features while broadening the product base for British Rototherm considerably. Benefits accruing from the strategy include:

- High accuracy measurement systems, ±0.2% f.s.
- Reusable hardware modules.
- Reusable software routines and modules.
- Reduced development time.
- Low power circuits and long battery life, 12 months minimum.
- EMC compliance for all instruments with minimum design changes.
- Intrinsically safe designs with separation of power supply and measurement systems for certification purposes, thus providing a further extension of the integrated strategy adopted in this portfolio.

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PROJECT ONE

THE DESIGN AND DEVELOPMENT OF A BATTERY POWERED, MICRO-PROCESSOR BASED PRESSURE GAUGE FOR INDUSTRIAL APPLICATIONS.

DESIGN AND DEVELOPMENT OF A DIGITAL PRESSURE GAUGE

The objective of this project was to design and implement a prototype digital pressure gauge. The project was the core design on which the subsequent projects were based. This project was a stand alone, battery powered, micro-processor-controlled instrument with a liquid crystal display. The instrument was to provide an alternative to the conventional mechanical "Bourdon" type pressure gauges. The key challenge was to ensure that the battery life of the instrument was at least one year, based upon using two standard "AA" alkaline cells. This phase involved the following activities.

The first challenge was the design of low powered analogue electronic circuits to enable maximum life to be obtained from two "AA" cells. Following on from this, there was embedded micro-processor design and software development of the mathematical functions needed for signal processing and the displaying of the measured pressure. To ensure efficient management of time and resources, maximum use was made of available computer aided design (CAD) tools. All work was carried out in accordance with Rototherms quality control procedures, while the designing of the instrument complied with British and International Standards ISO9001 and European Standard EN29001.

On completion of each prototype, a schedule of design verification was undertaken. This involved temperature cycling tests in an environmental chamber, which assessed operation and accuracy over a wide range of temperatures and electro-magnetic compatibility (EMC) testing. Measurement accuracy was defined by using dead-weight testers to apply pressures accurate to better than ±0.1% to the instrument.

A) TARGET SPECIFICATION

Function: A digital pressure indicator for industrial process pressure measurement. A stand alone digital pressure indicator deriving its power from two standard alkaline "AA" cells.

Measurement Ranges:

PRESSURE RANGE	RESOLUTION
-1 to +1 bar	1 mbar
0 to 0.5 bar	1 mbar
0 to 1 bar	1 mbar
0 to 2 bar	1 mbar
0 to 5 bar	1 mbar
0 to 10 bar	10 mbar
0 to 20 bar	10 mbar
0 to 50 bar	10 mbar
0 to 100 bar	10 mbar
0 to 200 bar	100 mbar
0 to 350 bar	100 mbar
0 to 400 bar	100 mbar

Accuracy:
Reading: ±0.2% fs.

Sensors:
Alumina ceramic (Al2O3) diaphragm strain gauges.
Below 2 bar: 42 mm diameter.
Above 2 bar 34 mm diameter.

Wetted Parts:
316 Stainless steel, alumina ceramic (Al2O3), Viton.

Overpressure:
Applied pressure must not exceed 1.25 times normal full scale pressure.

Power Supply:
3Volt DC battery, 2 x 1.5volt alkaline "AA" cells.

Battery life:
12 months at 2 second update rate.

Low power warning:
Display will alternate between pressure reading and BATT.

Temperature Stability:

Uncompensated:	Zero ±0.05% fs/°C, span ±0.04% fs/°C.
Compensated:	Zero ±0.01% fs/°C, span ±0.01% fs/°C.

Linearisation:
Sensor linearisation standard via software.

Protection:
Reverse polarity battery insertion protected by MOSFET functioning as active series diode.

EMC:
Immunity: BS EN 50081-1 : 1992.
Emissions: BS EN 50082-2 : 1995.

Adjustments:
Zero : Push Button to zero.
Span : Multiturn Potentiometer.

Display:
4 digit liquid crystal display, 12.7 mm character height.

Display Units:
Bar and psi as standard, other units to order.

Temperature Limits:
Storage: -20 to +85°C.
Ambient operating: -10 to 60°C.
Pressure Medium: -20 to +100°C.
Internal Case: -10 to +60°C.

Pressure Connections:
1/4" BSP male standard, other units to order.

Stem entry options:
Co-axial (rear), bottom, top, left side (9 o'clock) right side (3 o'clock).

Case Venting:
Dual purpose gas-permeable membrane and pressure relief device.

Case material:
Stainless steel 304 with acrylic window.

Finish:
Case - natural. Bezel - polished.

Dimensions:
Case diameter: 99 mm.
Bezel Diameter: 113mm.
Overall depth including bezel and pressure block: 66 mm.

Ingress Protection:
IP67.

Mountings:
Directly supported by process connection.

Intrinsically-safe versions:
To follow.

Works cost:
Circa £80 to £85 (without temperature compensation.)

B) THE STAND ALONE DIGITAL PRESSURE GAUGE -"DIGI-GAUGE"

The British Rototherm Digital Pressure Gauge is a high accuracy, high resolution, stand alone digital pressure indicator. The digital pressure gauge is suitable for making highly accurate measurements of the pressures of liquids or gases in critical process areas. The accuracy of the instrument also enables it to be used as a digital standard test gauge, replacing less accurate and more fragile analogue mechanical test gauges.

The instrument is housed in a stainless steel case which is sealed to IP67. The digital pressure gauge is designed for direct mounting via a 1/4" BSP male process connection, with pressure ranges available from vacuum to 400 bar. The instrument can be used with liquids or gases (media); NB:- should these be particularly corrosive, diaphragm seals can be fitted.

The wetted parts of the instrument (namely, those parts of the instrument which come into direct contact with the pressure media) comprise of 316 stainless steel, viton and ceramic. The pressure sensor is an Alumina ceramic (AL2O3) diaphragm strain gauge and the resistive strain gauge is a thick film hybrid type. The power source for the instrument is a 3V DC battery comprising of 2x"AA" alkaline cells.

The instrument is micro-processor controlled. Throughout the electronics of the instrument, a combination of low power circuits and power shutdown techniques are used to achieve one years' continuous operation from a pair of cells.

The pressure applied to the instrument is shown on a 4 digit liquid crystal display and, depending on the position of DIL switch SW1, the applied pressure will be displayed either in units of bar or pounds per square inch (psi). The pressure is updated every 2.1 seconds, but if DIL switch SW2 is closed, the update rate is increased to once every 0.5 second, but with reduced battery life.

Dual-in-line switches SW3 and SW4 are used for the initial set up of the instrument and enter the digital pressure gauge into linearisation and calibration modes respectively.

Push button switches are provided for entering and storing data into non-volatile memory whilst the instrument is in linearisation and calibration modes. This stored data is then used by the micro-processor for calculations which ensure a pressure reading accurate to +/- 0.25% of full scale during normal operation.

C) INSTRUMENT OVERVIEW

The block diagram of FIGURE 1 details the final design of the stand alone digital pressure gauge.

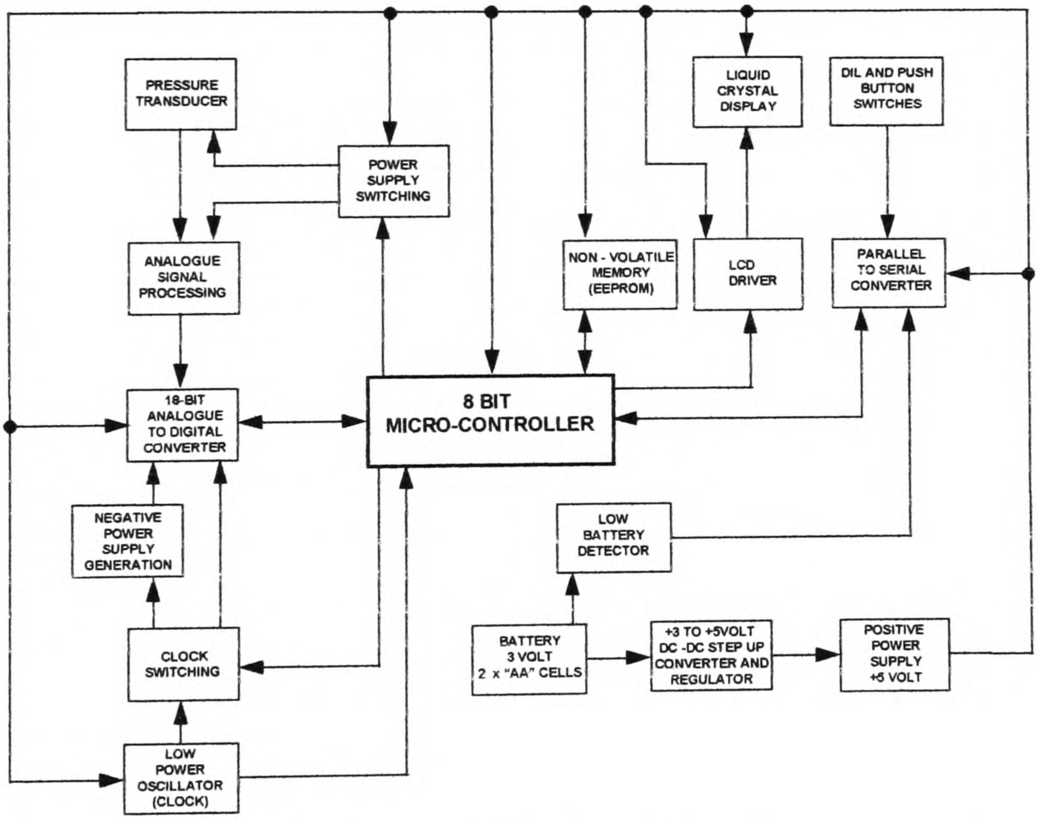


FIGURE 1: Block Diagram Of The Stand Alone Digital Pressure Gauge

The digital pressure gauge obtains its power from a 3 volt battery, comprising of two "AA" cells.

A step up DC-DC converter increases the voltage from the battery to a regulated 5 volts to power the analogue and digital circuits. A low voltage indicator is used as a low battery detector and gives an indication of when the battery voltage falls below 2.0 volts.

A low power oscillator circuit provides the clock for the micro-controller and the analogue to digital converter. This clock is also used in the generation of a negative (-5 volt) power supply for the analogue to digital converter.

The pressure transducer is a thick film strain gauge deposited on the reverse face of the insulating diaphragm. An excitation voltage of approximately 5 volts is applied to the pressure transducer, which gives an output voltage that is proportional to the applied pressure. The output from the sensor is amplified by the analogue signal processing section and fed to the input of the analogue to digital converter.

A binary representation of the input voltage to the analogue to digital converter is the output of the analogue to digital converter; this is processed by the micro-controller, and an indication of applied pressure is output from the microcontroller to the LCD driver and liquid crystal display.

A serial to parallel converter is used to expand the number of input lines to the micro-controller. The parallel to serial converter acts as an interface to the micro-controller for information from the low battery detector along with the direct-in-line and push-button switches which are used for setting the digital pressure gauge into calibration and linearisation modes and entering and storing linearisation and calibration data in the non-volatile memory. The non-volatile memory is used for the storage of instrument set-up, calibration and linearisation data.

Power supply switching is used as a power saving technique in the instrument and shuts down power to the analogue signal processing and the pressure transducer once a pressure reading has been taken and processed by the analogue to digital converter. Power is switched on to the analogue signal processing and the pressure transducer for 65 milli-seconds every 2.1 seconds.

Clock switching is also used as a power saving techniques. The clock switching not only disables the clock to the analogue to digital converter but also the negative power supply for the analogue to digital converter.

The micro-controller forms the heart of the digital pressure gauge and controls the serial interfaces to the parallel-to-serial converter, the analogue to digital converter, the liquid crystal display driver, the non-volatile memory (EEPROM) and also controls the power supply and clock switching. It also carries out all necessary mathematical functions to produce an accurate and high resolution pressure indication for viewing on the liquid crystal display.

C) MECHANICAL DESIGN

The case used for the instrument is a 100 mm stainless steel type. This type of case was chosen because it is an industry standard sized case for analogue pressure gauges. The market dictates that this type of case is used. It was also a requirement that the digital pressure gauge should bear a close resemblance to the Rototherm "Digitemp" digital thermometer, which also uses this type of case, so as to create the appearance of a family of instrumentation products.

The electronic circuit is implemented on two double sided, through hole printed circuit boards. These boards are mounted one above the other.

MECHANICAL
DIAGRAM.

Mechanical connections between the boards are made by metal pillars, and electrical connections are completed by a 16 pin header and box connection, allowing for easy removal of the top printed circuit board. The printed circuit boards are secured into the case by means of three bolts which attach the lower printed circuit board to three studs welded to the inside of the steel case. The upper and smaller printed circuit board accommodates the liquid crystal display, push button switches and direct in line switches. The lower and larger printed circuit board accommodates the majority of the electronics, and also the dual "AA" cell holder.

The dual "AA" cell holder is of plastic construction, with electrical connections being made via two pin contacts. It is mounted directly on the lower printed circuit board by soldering the pin connections to the underside of the printed circuit board with a pair of M2.5 nuts and bolts providing additional secure mounting to the printed circuit board.

The pressure block, which is mounted on the rear of the instrument case, houses the ceramic pressure transducer. It comprises of two parts, the pressure block itself and the stem. The end of the stem has a 1/4" BSP connection machined onto it so that it may be directly fitted to a process connection.

The same pressure block is used over the entire range of digital pressure gauge pressures and must withstand pressures up to 500 bar. This is overpressure, which is 1.25 x upper pressure limit, and the maximum in the digital pressure gauge range is 400 bar. So that the required strength is achieved, the complete pressure block arrangement (i.e. the pressure block and the stem) is machined from two pieces of solid stainless steel. The pressure block and the stem are machined separately on a computer numerically controlled (CNC) lathe. Once this operation is complete the stem and pressure block are forced together and then welded.

A hole in the case allows mounting of the pressure block via four M3 bolts. Strength is maintained by means of a steel re-enforcing ring, and sealing is achieved using a rubber gasket.

An advantageous feature of the instrument is the option of mounting the pressure block to the case in four different ways, corresponding to 0°, 90°, 180°, 270° respectively, thus allowing the instrument to be easily mounted in the most unusual of positions with the display still being in an upright and readable position.

The pressure transducer is mounted in the pressure block as follows. Firstly a Viton o-ring is placed in a groove in the pressure block. The pressure transducer is then placed on top of this, and is secured by screwing down a locking ring by means of threads cut into the pressure block. Electrical connections are made to the pressure transducer via flying leads which are soldered onto pads on the back of the pressure transducer and passed through the centre of the locking ring and soldered to the lower printed circuit board.

An important feature in the mechanical design of the digital pressure gauge is the breather. This is essential for correct and safe operation of the instrument. This device is mounted at the bottom of the case for two reasons. Firstly the breather contains a gas permeable membrane, which allows the pressure inside the case to be equal to that outside the gas. If the pressure in the case was not equalised, the reading shown on the gauge would be incorrect. Though the breather is permeable to gas, it does not allow any liquid to enter into the gauge. Secondly, should the pressure transducer be over pressurised to such an extent that it shatters - allowing a sudden intrusion of high pressure liquid or gas into the case - the breather acts as a pressure release system, and will burst and allow the safe escape of the pressurised media. If this device was not incorporated, then the dangerous possibility of the instrument exploding exists.

The breather is designed to burst at a pressure of 1 bar. This burst pressure was used as intrinsic safety standards allow for pressure of a flammable medium of only 1.1bar. The breather is screwed into bottom of the case and is easily replaced.

The dial for the instrument is a punched aluminium plate, onto which is glued an acetate sheet with instrument information printed on it. This is screwed to pillars on the top printed circuit board. The instrument is sealed finally with a clear acrylic window, rubber gasket and chrome finished bezel.

The ingress protection (IP) rating of instrument is IP67. The ingress protection rating system describes to what level an item is sealed against the intrusion of solid objects and liquids. The digital pressure gauges rating IP67 means that it is sealed so that it is dust tight and protected against the effects of immersion in a liquid.

E) PRELIMINARY DESIGN AND EVALUATION

E.1) Power Supply Requirements

The specification for the power source for the digital pressure gauge states that the instrument will run from a 3 volt DC battery, comprising of 2 x 1.5V “AA”, 2.7 Ah alkaline manganese cells and the battery life of the instrument is 12 months. The battery end point voltage is taken to be 1.8 volts, the end point voltage of each cell being 0.9 volt.

With these specifications, the maximum current consumption of the instrument is calculated as follows:

365 (days) x 24 (hours) = 8760 hours.

2.7 amp hours / 8760 hours = 308uA.

Therefore the maximum current consumption of the instrument has to be no more than 308 micro-amps in order to obtain a battery life of 12 months.

Running the electronic circuits directly from the battery was not considered to be a viable option as the choice of pressure transducer, analogue and digital circuits needed to meet the target specifications of the instrument required a split rail power supply of +5 volts and -5 volts. To obtain these voltages, DC-DC converters were required.

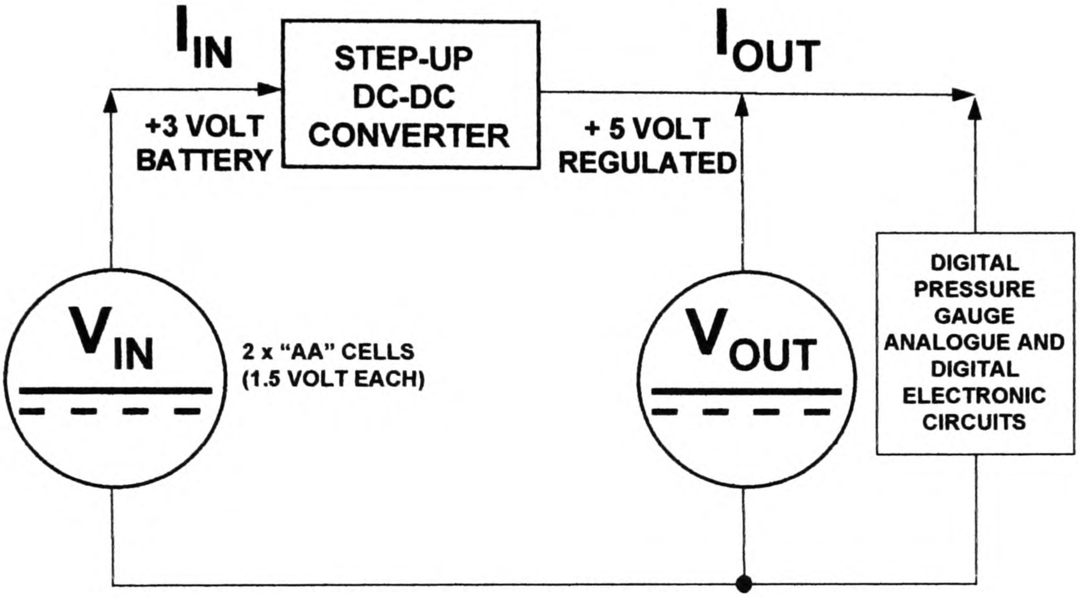
There were elements of the instrument which required permanent energisation, and so the DC-DC converter had to be powered constantly. Consequently the load current on the battery will increase with falling battery voltage in order to maintain constant power.

For the positive supply, a Ricoh RF5RD501 step up converter and voltage regulator was used. This increased the battery voltage to 5 volts +/- 5%. This device was chosen as its performance is exceptional. It has a very low quiescent current of only 4 uA and is capable of a high conversion efficiency. The efficiency of its operation in this application was measured at being between 70 and 80%. These were both essential features when designing a power supply to maintain the maximum life of the cells.

FIGURE 2 shows the relationship between the current drawn from the battery and current drawn by the circuit when using the DC-DC converter.

The negative supply, at -5 volts, was required for the analogue to digital converter. The negative voltage source was provided by a LTC7660 voltage converter. The LTC7660 converter inverts the +5 volt output from the RF5RD501 to give -5 volts. After testing the power supply section it was concluded that changes were necessary as the current consumption of this arrangement was too high, and when the analogue signal processing circuitry was connected the ripple on the +5volt/-5 volt supply rails exceeded 100mV.

An alternative negative power supply was required, and this was constructed using 2 Schmitt NAND gates from a quad, 2 input Schmitt NAND gate CMOS 4093BE.



$V_{IN} \times I_{IN} = P_{IN}$

$V_{OUT} \times I_{OUT} = P_{OUT}$

$P_{OUT} = (P_{IN} / 100) \times$ EFFICIENCY OF CONVERTER %

FIGURE 2: Operating currents of the DC-DC converter

The circuit used two Schmitt NAND gates wired as inverters. These were connected as a CMOS stable circuit. The output from this square-wave oscillator was coupled to a capacitor diode network which acted as a rectification and smoothing network. The negative output from this converter was switched on or off by taking the enable input high or low.

E.2 The Pressure Transducer

The pressure transducer is a thick film strain gauge bridge deposited on the reverse face of an insulating ceramic diaphragm.

These transducers are manufactured by Bourdon Sedeme, and are already in use in another Rototherm product, a 4-20mA pressure transmitter.

Their performance has been thoroughly tested and verified and they are deemed the most suitable transducer available for use in the digital pressure gauge range of products. They are available in a range of maximum rated pressures. These are 0.5, 1, 2, 5, 10, 20, 50, 100, 200, 350 and 400 bar. The transducers are also available in temperature compensated versions, for applications where a greater accuracy over a wide temperature range is required. The uncompensated version of the transducer is fitted as standard in the digital pressure gauge. The temperature compensated transducer is a direct replacement for the uncompensated sensor and can be fitted if specifically required by a customer.

The strain gauge bridge has an input impedance of 6kohms, and an output impedance of 10 - 15 kohms. The excitation voltage can be 30 v ac / dc maximum. FIGURE 3 details the circuit diagram of the uncompensated transducer.

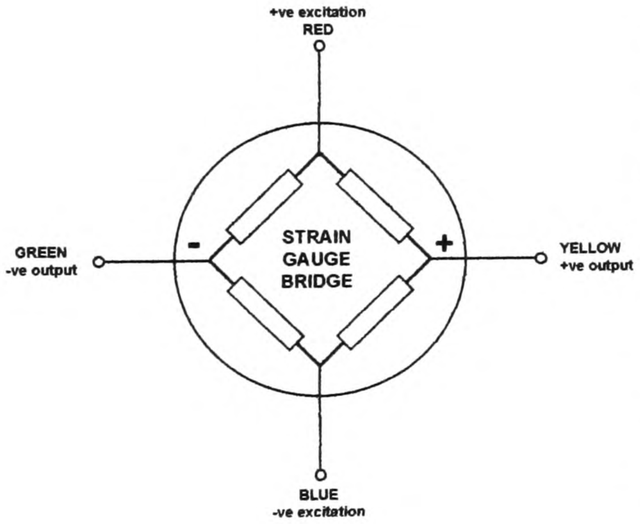


FIGURE 3: Circuit schematic of pressure transducer without temperature compensation.

In order to keep current consumption to a manageable level, an excitation voltage of 0 to +5 volts was chosen for this application.

With an excitation voltage of +5 volts, the current drawn by the transducer when permanently energised will be 5volts / 6kohms = 833 micro-amps.

Using an excitation voltage of less than +5 volts would have resulted in an output from the transducer which was too low in magnitude to enable the specified accuracy and resolution of the instrument to be obtained. A higher excitation voltage would have resulted in too large a current consumption.

With zero pressure applied to the transducer, and a +5 volt excitation voltage, the output of the bridge is no more than +/- 1 mV. With maximum rated pressure applied to the transducer, and an excitation voltage of +5 volts, the output of the bridge will be approximately +30 mV.

E.3 Analogue Signal Processing

The pressure transducer has a differential output which was connected to a low power precision operational amplifier (OP-90G), configured as a non-inverting amplifier, powered from supplies of +5 V and -5 V. The negative output arm of the bridge acted as a virtual 0 volts and the positive output arm of the bridge applied a voltage which increased in direct proportion to the pressure applied to the transducer, to the positive input of the operational amplifier. Theoretically, with no pressure applied to the transducer, its output should be zero volts, but this is not the case. As described earlier a correctly functioning transducer will have an offset voltage of -1 to +1 mV. The system would see this as an applied pressure, and so a zeroing system was included in the signal processing section to eliminate this small offset voltage. The zeroing system consisted of a series resistor network comprising of a resistor, a potentiometer and another resistor connected between the positive 5 volt supply and 0 volts. The wiper of the potentiometer was connected to the positive arm of the bridge and positive input to the operational amplifier.

Adjusting the potentiometer with no pressure applied to the transducer will apply a voltage to the positive arm of the bridge cancelling out the offset of the bridge; this would enable the instrument to display a reading of zero when there was no pressure applied. This is known as zero adjustment.

E.4 The Analogue to Digital Converter

A review of analogue to digital converters was undertaken, the choice of analogue to digital converters being dependent on the following:

1. Power requirements.
2. Supply voltages.
3. Sampling rates.
4. Resolution.
5. Cost.
6. Interface.

A Maxim MAX132 18-bit ADC. This is a multi-slope, integrating ADC. This was selected because it has a low reference voltage, low power supply current, a programmable sleep mode and a choice of sampling rates set by the choice of operating frequency. The MAX132 was also being used on other Rototherm products, so a number of software routines were also already available, thus reducing the software development time.

The multi-slope design of the converter, rather than the conventional dual type, meant that additional resolution was available through secondary, tertiary and quaternary de-integration phases on the voltage remaining after the initial part of the conversion. Prior to the second and third and forth phases the remaining voltage is scaled by a factor of 8 to increase the resolution.

Due to the power constraints of the system, the availability of a programmable sleep mode was of prime importance.

Once the conversion and communication cycle was complete, the ADC could be put into sleep mode. Whilst operating, the ADC had a current consumption of 60uA, and in sleep mode this was reduced to a consumption of 1 uA. The MAX132 ADC required a power supply of 0, +5V and -5V.

The next stage was to select the operating frequency of the ADC. With an operating frequency of 196,608 Hz the MAX132 can complete 96 conversions a second, which is the maximum number of conversions per second that the ADC can perform. A trade off between operating speed and current consumption determines the choice. Running the MAX132 at its maximum conversion rate will enable the pressure transducer (which is the system component with the highest current consumption) to be energised for a shorter period of time thus reducing the current consumption for this component, but whilst the current consumption with time is reduced for the transducer, the higher operating speed of the ADC will mean a significant increase in the current drawn by the ADC.

The specification of the digital pressure gauge required the instrument to update the pressure reading once every two seconds; so using the MAX132 at its highest conversion rate of 96 conversions a second is totally unnecessary. The lowest Crystal frequency at which the ADC will operate is 32,768 Hz. This will allow for a maximum of 16 conversions per second, which is more than adequate for the operation of the instrument. At this speed each conversion will take 1 second / 16 conversions = 62.5 ms per conversion. The energisation time therefore required for the transducer is 62.5 ms.

The MAX132 ADC also required a reference voltage for its operation. This consisted of a series resistor network connected between +5 volts and 0 volts to form a potential divider.

The reference voltage set the analogue input range, and included in the series resistor network was a potentiometer for adjustment of the reference voltage. This adjustment formed the span control for the instrument. The ADC was ratiometric and this was a virtue as any fluctuations in the supply voltage to the instrument would not lead to inaccurate conversions.

The nominal full scale input range for the MAX132 was +/-512 mV. Though the MAX132 was 18-bit ADC, for the nominal +/- 512 mV input range, only bits 3 -18 were used. Hence 32,768 counts represented 512 mV. Bits 0, 1 and 2 were located in the ADC status register used only for hard and soft over-range values, where the analogue input voltage exceeded that set by the reference.

The recommended reference voltage for the ADC was 500 -700 mV. Using references outside of this range would result in a degradation of linearity. Using a reference voltage of 200-500 mV would result in a lower signal to noise ratio: a reference voltage from 700mV to 2V would increase the rollover error. The reference used by the digital pressure gauge was in the range of 500 - 700 mV.

E.5 Setting The Input Voltage To The ADC

The ADC had a maximum input range of +/-512 mV. This was represented by 32,768 counts, hence the least significant bit would be 15.6 uV. The output from the pressure transducer with maximum rated pressure applied was approximately 30 mV, but this was not of sufficient magnitude to maximise the resources of the ADC as it was only 5.8% of the full scale input of the ADC.

The output of the pressure transducer had to be amplified so that the smallest signal present at the output of the bridge was proportional to an increment / decrement in pressure of the smallest reading available; for a given rated maximum pressure proved greater than the smallest increment of the ADC. So the smallest input to the ADC had to be greater that 15.6 uV, and hence be above the noise floor of the system. An amplifier with a gain which provided an input to the ADC close to the maximum full scale input of 512 mV had to be avoided as this could result in over-range and overflow; requiring the development of unnecessary software. To allow for the future developments of the instrument, and to avoid over-range and overflow at all costs, it was decided that the maximum input to the ADC should be 128 mV. This is a quarter of the full scale of the maximum input of the ADC.

The amplifier circuitry required a gain of approximately 4.3 (128 mV / 30 mV) to achieve this. A low gain also reduced the magnitude of any amplified noise in the system, eliminating the possibility of signal clipping, amplifier saturation and instability, and reducing the possibility of interference due to radio frequency noise.

The maximum input of 128 mV is equal to 8192 system counts. 8192 counts equal full scale output from the pressure transducer and this figure is used when calculating the scaling factors required in software to display whatever the maximum rated pressure of the instrument happens to be.

E.6 The Micro-controller

The micro-processor selected for the instrument was the Arizona Microchip PIC16C71. The selection of the processor was determined for a number of reasons.

The rapid instruction execution speed of the processor allowed all the necessary calculations to be completed in a short time period, even at low clock speeds; an essential factor as a low clock speed would give a reduced current consumption of the device.

The PIC also has four separate clock operating modes. The availability of an LP (low power oscillator mode) was an important feature allowing for power saving when operating the device.

There were already CAD development tools available to aid software and hardware development and there was a library of mathematical software routines available to speed up software development. The CAD tools for the PIC16C71 consisted of a PC operated simulator, emulator and 16C71 emulator pod which connected directly into the hardware in which the final one-time programmable processor would operate. These tools greatly reduced software development time as the contents of all registers and memory locations could be viewed on the PC, and it was also possible to single step through programs or force instructions and alter register contents. This greatly aided the debugging of programs. Another tool which was available was a number of windowed PIC16C71 devices which were re-programmable after the program memories had been erased by placing them in an ultra-violet light box.

Some features of the PIC16C71 are:-

i) High Performance RISC (Reduced Instruction Set Computer) like CPU, with only 35 single word instructions. Harvard architecture.

ii) All single cycle instructions except for program branches which are two cycle.

iii) Operating speed DC to 20Mhz.

iv) Interrupt capability.

v) Eight level deep hardware Stack.

vi) Direct, indirect and relative addressing modes.

vii) The device has 36 bytes of RAM and 13 I/O ports.

viii) PIC16C71 addresses 1k x 14 of program memory. All program memory is internal, can directly or indirectly address its register files, contains an 8-bit ALU and working register.

In order to keep the current consumption to a minimum, the PIC16C71 was operated at 40 kHz. This speed was chosen as it enabled the micro-controller to perform the mathematical software routines at sufficient speed, resulting in a 2 second / 0.5 second update rate but not running at such a speed as to compromise current consumption. It also minimised the risk of RF emissions. The external components needed for the oscillator were a 40kHz crystal oscillator, a 47 pF ceramic capacitor, a 15 pF ceramic capacitor and a 220 kΩ resistor which reduced current consumption.

The micro-controller operated from power supplies of 0 volts and +5 volts. The other external components required to operate the device were a 39 kΩ resistor, a 1N4148 signal diode and a 1 uF capacitor; forming a power-on-reset function. On the application of power to the device, the capacitor was discharged and the active low MCLR pin 4 was pulled low, actuating a reset of the device. The capacitor then charged up through the 39 kohm resistor while pin 4 remained high (+5 volt) during normal operation. The diode provided a discharge path for the capacitor during power down.

The PIC16C71 had 5 connections to the ADC. Three of these ports were configured outputs RA0, RA1, RA2 and two were inputs RA3, RB1.

Three ports configured as output connections were used to communicate with the driver for the liquid crystal display, RB2, RB5, RB7. Port RB4 was configured as an output and used as the control line to the CMOS 4053 multiplexer which switched +5,-5 volt power supplies on and off to the analogue signal processing electronics. Port RB3 was also configured as an output and used to switch the negative supply generator on and off. This feature was essential as the ADC required a -5 volt supply for a longer period of time than the analogue electronics and hence cannot be switched from the CMOS multiplexer.

Ports RA4, RB0 and RB6 are unused. Ports are configured as input or output in software by setting bits in the TRISA and TRISB registers.

Communications with the analogue to digital converter and the liquid Crystal display driver were established by using industry standard 4 and 3 wire serial interfaces respectively.

E.7 The Liquid Crystal Display

The display for the instrument is a 4 digit liquid crystal display with 12.7 mm high characters. The display driver used can be either the EM6003 or the Arizona Microchip AY0438. These two devices are directly interchangeable and have very low current consumption, typically 30 uA.

The liquid crystal display driver will operate up to 32 LCD segments of arbitrary configuration. It is a CMOS device and has a wide supply voltage range, low power operation, high noise immunity. There is electrostatic discharge protection on all pins. The device has an on chip oscillator. The only external component is a capacitor to set the oscillator frequency, requiring only three control lines from the micro-processor due to its serial input construction. It latches the data to be displayed and relieves the micro-processor of the task of generating the required waveforms.

E.8 Power Saving Strategies

The current consumption for the time when the pressure transducer was permanently energised (833uA) way exceeded the current consumption budget for the complete system (which was to be no greater than 308 micro-amps), and so power saving strategies had to be employed to meet the specifications of the maximum instrument power consumption. To achieve this each section of the circuit was energised for the minimum period of time necessary for which its operation is required per measurement cycle of the instrument. The transducer was the section of the circuit accounting for the largest current consumption and so had to be energised for as little time as possible. This meant that it was only to be energised for the time it took for the analogue to digital converter to complete one conversion. The switching of the power supply to the pressure transducer, analogue signal processing electronics, and the analogue to digital converter was required in order to reduce the current consumption of the instrument. The switching of the positive and negative supply rails was achieved using a CMOS 4053 triple two channel multiplexer. The control for the CMOS switch was connected to a port on the micro-controller and the on / off timing was set by software.

The analogue to digital converter had the availability of a programmable sleep mode. This feature allowed the ADC to be put into a "sleep mode" condition once it had completed the conversion of the voltage input and serial communications with the microprocessor. Once in sleep mode, the quiescent current consumption of the ADC was reduced from 60uA to 1uA, offering a massive power saving when not in use. As a pressure measurement was only required once every 2 seconds, the ADC remained in sleep mode for the majority of this time.

The microprocessor is operated in LP (low power) oscillator mode, with a clock speed of 40 kHz to minimise current consumption.

Another method of minimising the energisation time of the pressure transducer was to use a flying capacitor amplifier configured as a sample and hold circuit. This was in order to retain the voltage reference to ADC and the amplified output voltage of the pressure transducer, enabling the energisation time of the reference resistor network and pressure transducer to be reduced from over 100ms to 10ms; offering large power savings. However, after careful consideration, this method was deemed unsuitable as the major component - the flying capacitor amplifier - in the sample and hold circuit was considered too costly. This component was necessarily a high quality part, hence its unsuitable cost. It was also felt that whilst this solution offered useful power savings, it was unnecessarily complex.

F) SOFTWARE DESCRIPTION

FIGURE 4 shows a flow chart of the software.

The pressure transducer used in the first test was a 5 bar type. When maximum pressure is applied to the transducer, the liquid Crystal display had to show 5.000. Therefore, the number which came from the ADC at this pressure was 8192; which converted to 5000. A scaling factor in software was required to convert the number of counts from the ADC into a pressure reading equal to that of the pressure applied to the transducer. The equation to do this was implemented in software and was represented as follows:-

$$\frac{\text{Number of counts from ADC} \times 7996}{13{,}100} = \text{pressure applied.}$$

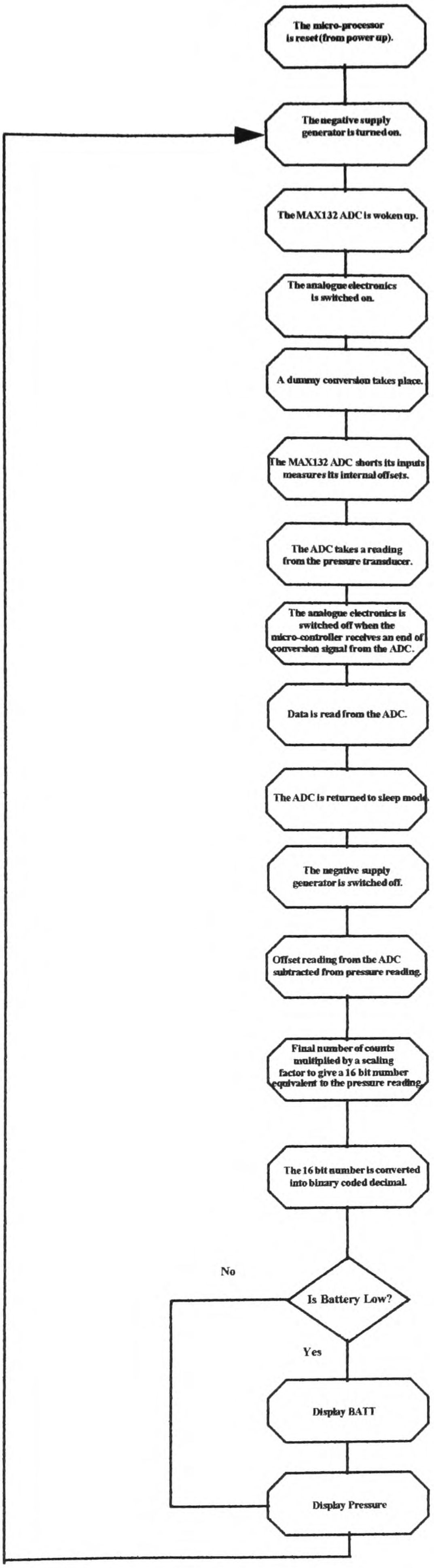


FIGURE 4: Software Flow Chart

Example: $$\frac{8192 \times 7996}{13{,}100} = 5000$$

A decimal point is added to the display so that 5.000 is shown. The large vulgar fractions are used as the PIC microcontroller is only capable of fixed point multiplication and division. The software for the digital pressure gauge is constructed from a number of frequently called sub-routines. These consist of serial communications, multiplications, divisions, subtractions and additions. Power saving is achieved by switching using ports on the microcontroller to energise circuits of the instrument for the period for which they are required to be powered up to complete a pressure reading. The software will turn off power to these circuits when end of conversions and read/write routines are complete. Instrument features that were implemented in software and interface the user to the instrument are push-button zeroing and push-button linearisation.

G) PROTOTYPE PCB CONSTRUCTION OF PRELIMINARY DESIGN

Initial testing of software routines and circuits was completed with a circuit emulator. The electronic circuits were constructed on breadboard and well spaced to allow for swift circuit modifications and ease of taking measurements of circuit performance. Tests on breadboard confirmed that the instruments' electronics and software were functioning correctly, but in order to carry out a more comprehensive set of tests and to progress the instrument towards production, the next stage was to design and implement a prototype printed circuit board.

The prototype mechanical parts of the instrument had been manufactured and tested. The construction of the printed circuit board would allow for complete testing of a fully assembled instrument.

The artwork for the prototype printed circuit boards was designed using the CAD PCB design package EASYPC. The printed circuit boards were double sided while the components used were through hole types. On completion of the design for the printed circuit board artwork, a printed circuit board was constructed using Rotothems in house facility for producing small quantities of prototype printed circuit boards. The PCB was populated and tested for correct operation, and then assembled with the pressure transducer into the stainless steel case and pressure block ready for the necessary tests.

H) TESTING OF THE PRELIMINARY DESIGN

A schedule of design verification was undertaken, involving:-

- Measurement accuracy, defined by using known standards in the form of dead-weight testers to apply pressures accurate to better than ±0.1% to the instrument.
- Temperature cycling tests in an environmental chamber to assess operation and accuracy over a wide range of temperatures.
- Current consumption tests to determine battery life.

To assess accuracy, the instrument was placed on the Budenberg dead weight tester, as shown in FIGURE 5, and pressures from 0 bar to 5 bar were applied.

Results from the pressure tests are shown in the table of FIGURE 6.

FIGURE 6: Results of pressure tests on dead weight tester

PRESSURE APPLIED TO INSTRUMENT	PRESSURE DISPLAYED	ERROR - AS A PERCENTAGE OF FULL SCALE
0 bar	0.000 bar	0 %
1 bar	0.988 bar	-0.225 %
2 bar	1.983 bar	-0.33 %
2.5 bar	2.482 bar	-0.35 %
3 bar	2.984 bar	-0.32 %
4 bar	3.989 bar	-0.21 %
5 bar	5.000 bar	0%

FIGURE 5: Testing the accuracy of the digital pressure gauge on a dead weight tester.

The graph of FIGURE 7 shows the error as a percentage of full scale pressure applied as observed on the instrument.

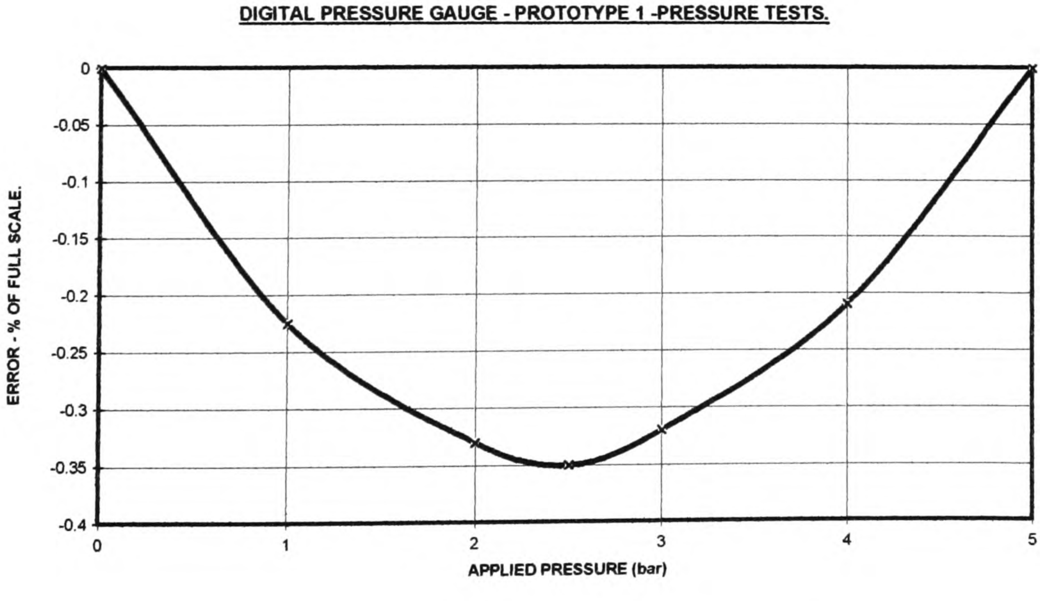


FIGURE 7: Graph showing error as a percentage of full scale pressure.

The non-linearity seen here was due to the performance of the pressure transducer. This was demonstrated when a number of tests were carried out on the complete range of pressure transducers; all of which displayed this characteristic.

H.1 High Temperature Performance Tests

The digital pressure gauge was placed in the environmental test chamber and the temperature of the test chamber was increased to 80 degrees Celsius. Two problems resulted from this test:-

1. As the temperature reached 60°C and above, the CMOS 4053 multiplexer failed to operate correctly. The CMOS switches inside the device would not switch over, and hence no power was available to the analogue electronics.

   Such failure at these temperatures was due to the device having to switch a voltage which was derived from its own supply.

2. As the temperature reached 70°C and above, the instrument display would suddenly read 0.000 and would not change until the temperature was decreased. At these higher temperatures the MAX132 ADC was unable to start its internal oscillator when being awoken from sleep mode.

H.2 Circuit Current Consumption

As the specification requires the battery life of the instrument to be one year of continuous operation, it was essential to test whether the circuit current consumption stayed within the power budget of 308uA.

Testing was carried out by placing an integrating current meter between the positive terminal of the battery and the step up power supply circuit. As the current drawn from the circuit varied over a measurement cycle, the current meter did not integrate the total current consumed over one complete cycle and display this. The current consumption for the prototype was measured as 500 uA. This clearly exceeded the power budget allowed to run the circuit continuously for one year. In order to define the circuit components which were contributing to the excessive current consumption, closer analysis of the individual sections of the circuit was undertaken by making breaks in the circuit and measuring the current consumption of individual components and systems. The actions taken to reduce current consumption in response to the findings of the analysis are detailed in the following section.

I) ACTIONS TAKEN AS A RESULT OF THE TESTING

Following analysis of the test results on the first prototype for current consumption and high temperature performance, it became clear that a number of changes to the circuit were necessary.

The circuit had three separate oscillator sections: the clock for the MAX132 ADC, the astable circuit for the negative supply generator and the clock for the micro-controller PIC16C71. These contributed significantly to the current drawn by the circuit. All three oscillator sections were replaced by one ultra-low power Crystal oscillator clock circuit.

The ultra-low power clock circuit consisted of a CMOS 4007 complementary pair plus inverter integrated circuit, a 40 kHz crystal, three resistors and two capacitors.

The frequency of the oscillator was 40 kHz and the circuit had a current consumption of 6 micro-amps. This oscillator ran permanently and formed the clock for the micro-controller, the analogue to digital converter and the negative supply generator.

Due to the low gain of the operational amplifier, and low signal levels compared to the power supply voltage of the operational amplifier OP-90G, it was deemed unnecessary to operate the op-amp from dual supplies of + / - 5 volts as there was no risk of saturation. Therefore the OP90G need only be powered from +5 volts and 0 volts. The only circuit component which then required a -5 volt supply was the analogue to digital converter.

During the time in which the analogue to digital converter was asleep, it did not require a clock to be running. This time period was identical to that which required a -5 volt supply voltage to be present. As the - 5 volt supply was generated using a clock, the clock for the ADC and the negative supply generator could be the same. They could also be switched on and off at the same time and by the same method.

The circuit was thus modified so that the clock from the ultra-low power oscillator was connected to the PIC16C71 micro-controller and to one input of a logic AND configured from two dual input schmitt NAND gates on a CMOS 4093. The output of the logic AND was the gated clock which was connected to the capacitors and diodes forming the negative supply generator, and also to the oscillator input of the ADC. The other input to the logic AND was connected to the port RB3 on the micro-controller and when this port was set high, the clock to the ADC and negative supply generator was enabled, setting the port low switches off the clock to the ADC and the negative supply generator.

In Prototype 1, the series resistor reference network for the analogue to digital converter was connected to the same +5 volt switched power supply line as the pressure transducer and the analogue electronics. As the analogue to digital converter required its reference to be energised for the period of time for which it is in the awake state - 70 ms longer than it required for the completion of the conversion of the input voltage - this meant that excessive current was being drawn by the instrument. This was because the pressure transducer and analogue electronics were being energised for far longer than required. For this reason the series resistor reference network was also connected to the micro-controller port RB3, and was energised from this, dictating the awake period for the analogue to digital converter.

Due to the failure of the CMOS 4053 multiplexer to operate at high temperatures, another form of power supply switching for the +5 volt power supply to the analogue electronics and pressure transducer was required. The most suitable and simple solution to this problem was to use a low threshold P-Channel MOSFET, and LP0701. This three terminal device was connected and the source terminal connected to +5 volts. The gate was connected to port RB4 on the micro-controller and the drain terminal connected to the analogue electronics and the pressure transducer. The supply to the analogue electronics was switched on taking the gate terminal of the MOSFET low, and switched off by taking the gate high; these operations being carried out by port RB4 of the micro-controller.

The instrument also required additional circuitry in order to meet original specifications and increase the number of functions belonging to the instrument. The additional circuitry consisted of the following:-

1. A low battery detection circuit and software to indicate a low battery condition on the liquid crystal display.

2. Non-volatile memory (an EEPROM) for storage of calibration data. This also prevented the re-calibration of the instrument after battery changes.

3. A set of direct in line single-pole-single-throw switches so that the instrument could be placed into different modes of operation.

4. A set of non-latching push button switches for the entering of calibration data.

5. As extra ports on the PIC16C71 to support the low battery detector and additional switch inputs were required, a parallel to serial converter was needed to expand the number of inputs available to the micro-controller.

A 74HC165 parallel to serial converter was used for the switch inputs and battery low detector. The low battery detector chosen was a RICOH RX5LA20A. This is a three terminal device which gives a high output on terminal 1 when the battery voltage drops below 2.0 volts. The non - volatile EEPROM chosen was an Arizona Microchip 93LC56 serial eeprom.

The addition of these extra components required some re-organisation of the port designations of the micro-controller.

These were finalised as follows:-

PORT No.	I / O	CONNECTION AND DESCRIPTION
RA0, pin 17	output	MAX132, pin 1. Chip enable
RA1, pin 18	output	MAX132, pin 4. Serial clock output. 93LC56, pin 2. Serial clock output 74HC165, pin 2. Serial clock output AY0438, pin 40. Serial clock output.
RA2, pin 1	output	MAX132, pin 2. Data output. 93LC56, pin 3. Data output. AY0438, pin 34. Data output
RA3, pin 2	input	MAX132, pin 3. Data input.
RA4, pin 3	output	74HC165, pin 15. Chip enable
RB0, pin 6	input	Push button switches for external interrupt. (not connected)
RB1, pin 7	input	MAX132, pin 11. End of conversion
RB2, pin 8	output	93LC56, pin 1. Chip enable.
RB3, pin 9	output	On / off control line for negative supply generator, MAX132 clock and MAX132 reference energisation.
RB4, pin 10	output	On / off control line for the analogue electronics power supply switching.
RB5, pin 11	input	93LC56, pin 4. Data input
RB6, pin 12	input	74HC165, pin 9. Data input
RB7, pin 13	output	AY0438, pin 2. Chip enable.

The resulting effect of incorporating these changes was that the current consumption for the second prototype was 270 μA, within the power budget of 300 μA and enabling the instrument to run for 12 months on two "AA" cells. A saving of 330μA has been effected by careful refinement of the design and exploiting some novel features such as minimising circuit energisation time, refining serial communications in software and removing excessive delays in software routines.

K) ELECTROMAGNETIC COMPATIBILTY TESTING

It is a legal requirement that the digital pressure gauge be free from either causing or susceptibility to electromagnetic interference. The relevant generic standards for compliance within the EEC are BS EN50082-2 for emissions and BS EN50081-1 for immunity.

The digital pressure gauge was placed in a stripline and radio frequency waves with an electro-magnetic field strength of 10 volts per metre at frequencies from DC to 1 200 Mhz were applied. No deterioration in operation was observed. As the electronic circuit of the digital pressure gauge was completely enclosed in a stainless steel case, it proved well shielded against radio frequency interference. The low power operation and low clock frequencies used within the digital pressure gauge meant that the likelihood of the instrument emitting radio frequency interference was minimal. EMC is specifically addressed in **Project Two** where immunity issues are to the forefront.

L) IMPROVING THE INSTRUMENT ACCURACY

From the thermal tests on the digital pressure gauge, it could be seen that as temperature increases, a zero error occurs. This was due to voltage offsets within the analogue circuitry increasing with a rise in temperature. To eliminate this, a DG419 analogue switch IC was added to the circuit. This was effectively a single pole double throw analogue switch. The purpose of this component was to disconnect the output of the pressure transducer from the input of the operational amplifier and to short the inputs of the analogue to digital converter to ground (in the first prototypes only the analogue to digital converter was zeroed.) The result of this was that the sum of any voltage offsets within the amplifier and the analogue to digital converter were measured and the value stored in non-volatile memory for use in calculations by the micro-controller. This prevented any error in pressure reading due to thermal drift in the analogue electronics.

This "auto zero" took place as before, with the zero of the ADC once every 30 measurement cycles, which was approximately once every thirty seconds.

The analogue switch was enabled and disabled by output port P0 on the analogue to digital converter. This in turn controlled by a serial code issued by the micro-controller.

When the instrument is calibrated, the first task in the calibration procedure is to "ZERO" the instrument. Due to offsets within the pressure transducer, the instrument display does not read 0.000 The zero process ensures that with no pressure applied to the pressure transducer, the instrument display will read 0.000. This is achieved by adjusting a miniature potentiometer until the display reads 0.000. As the miniature potentiometer is a resistive electromechanical component, it is susceptible to thermal drift. Precise adjustment of this component can also be time consuming. A more suitable solution for the zeroing of the instrument, and one that is not susceptible to thermal drift is to have a push button zero adjustment. This works as follows. With no pressure applied to the instrument, the gauge is put into a "zero mode" by pushing across one of the direct in line switches. One of the push button switches is held down and the instrument takes a pressure reading. The value of this reading is equal to the offset of the pressure transducer, and is stored in non-volatile memory. This value is then added or subtracted (depending on whether it is negative or positive respectively) by the micro-controller from every subsequent pressure reading. The zero resistance network need no longer be fitted to the instrument, though tracks and space for it are left on the printed circuit board should a user specifically request a manual zeroing option. At this point it was decided that the digital pressure gauge should have the accuracy of an analogue test gauge, that is better than +/- 0.25 % of full scale.

Due to the non-linearity characteristic of the pressure transducer, errors of up to -0.45% of full scale are present when the instrument displays the pressure reading.

To obtain an instrument accuracy of + /- 0.25% of full scale it was necessary to write a mathematical linearisation program into the software which would detect what pressure was applied and adjust the reading to give the correct pressure.

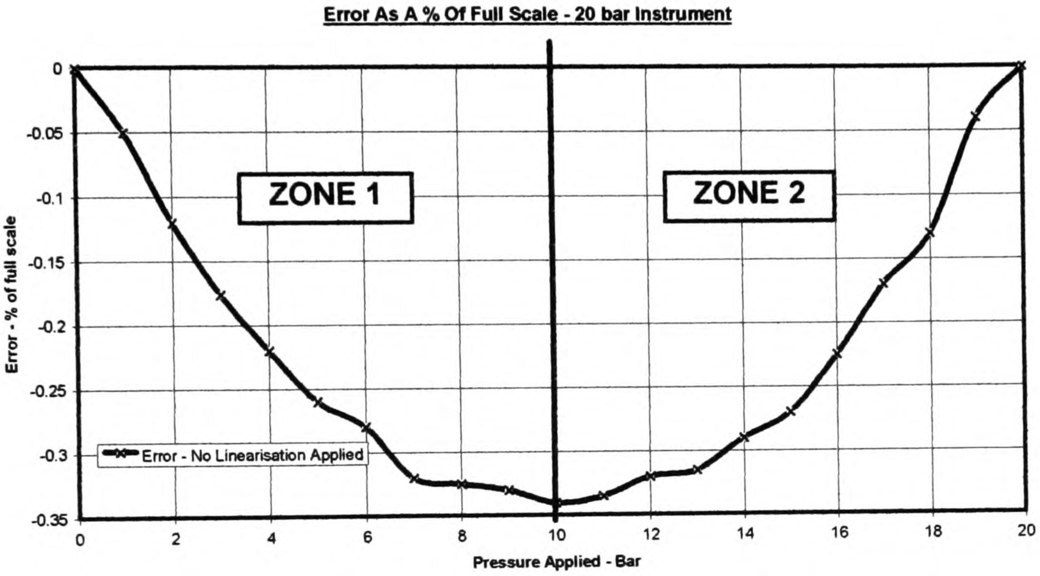


FIGURE 8: 20 bar instrument test results with no linearisation software.

The graph of FIGURE 8 shows the results after testing a 20 bar instrument with no linearisation software. In order to produce linearisation equations in software it was necessary to divide the error characteristic into two pressure zones as shown in FIGURE 8, and write a separate equation for each. Software was also calculated to discover in which pressure zone the pressure reading was given so that the correct equation can be applied.

The equations for the linearisation are as follows:

$$\text{LINEARISATION CHARACTERISTIC} = \frac{\text{MAXIMUM ERROR AS A \% OF FULL SCALE}}{0.05} + 1$$

L.C. = LINEARISATION CHARACTERISTIC

FOR ZONE 1:

$$\text{ZONE 1} = \frac{(\text{PRESSURE READING} \times \text{1/2 FULL SCALE PRESSURE}) + \text{L.C.}}{\text{1/2 FULL SCALE PRESSURE}}$$

FOR ZONE 2:

$$\text{ZONE 2} = \frac{(\text{PRESSURE READING} \times \text{1/2 FULL SCALE PRESSURE}) - \text{L.C.}}{\text{1/2 FULL SCALE PRESSURE}} + (2 \times \text{L.C.})$$

The graph of FIGURE 9 shows the result of the linearisation software, which improves the instruments accuracy to greater than +/-0.25% of full scale.

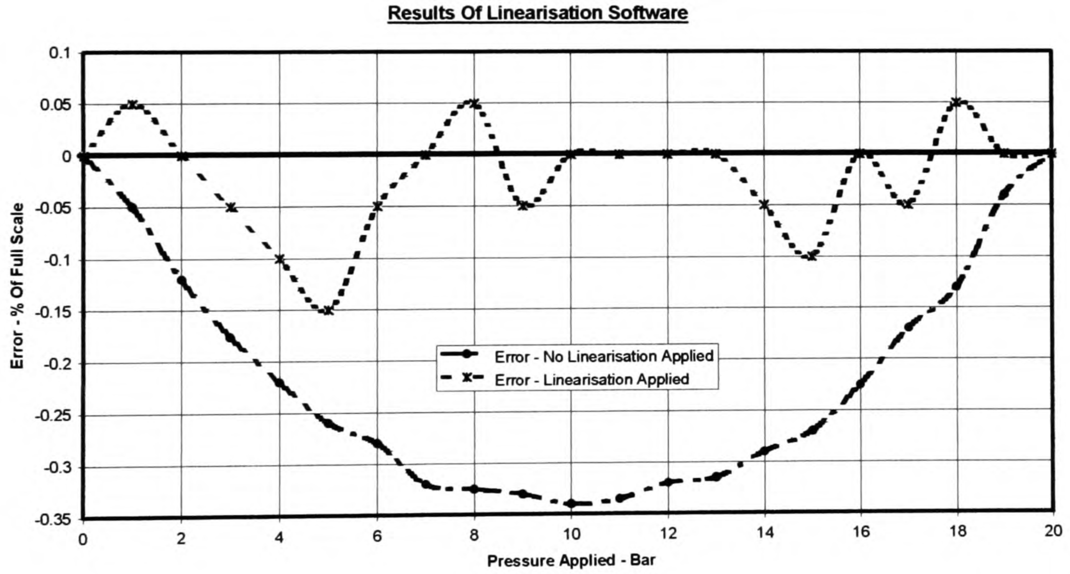


FIGURE 9: Results of linearisation software for a 20 bar gauge.

To ensure the linearisation software was valid, it was tested on all the pressure ranges available for the pressure transducers. An example of the results of the linearisation software on a 400 bar gauge is shown in the graph of FIGURE 10:-

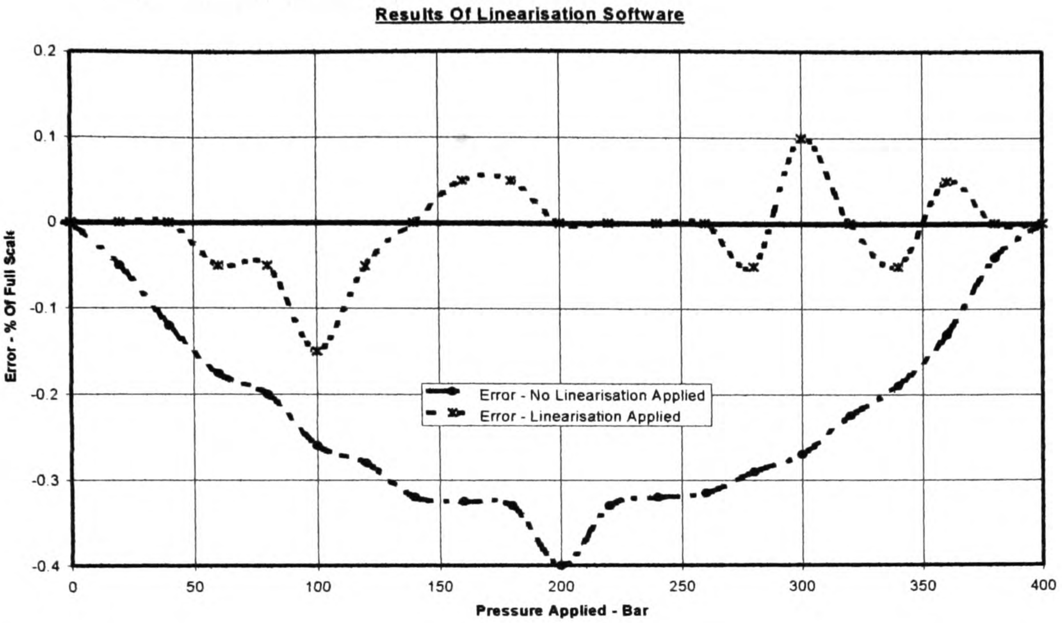


FIGURE 10: Results of linearisation software for a 400 bar gauge.

Linearisation is carried out during instrument calibration. After the instrument has been "zeroed" and then "spanned", it must be "linearised." First, exactly half full scale pressure of the particular instrument must be applied. The instrument is then entered into the linearisation mode by pushing across one of the direct in line switches. One of the push button switches is then held down and the instrument takes a reading at half full scale and calculates the linearisation characteristic for that particular pressure instrument and stores this in non-volatile memory. The instrument can then be returned to the normal mode of operation.

As improved accuracy was required over the complete range of pressures available with digital pressure gauge, it was necessary to investigate and characterise the performance of the -1 bar to 1 bar pressure transducer. From 0 - 1 bar the linearity characteristic of the pressure transducer was the same as that described earlier. However, the linearity characteristic from -1 bar to 0 bar, i.e. when applying a vacuum to the gauge, was considerably different.

A graph of the linearity characteristic of a -1 bar to 1 bar pressure transducer is shown in the graph of FIGURE 11:-

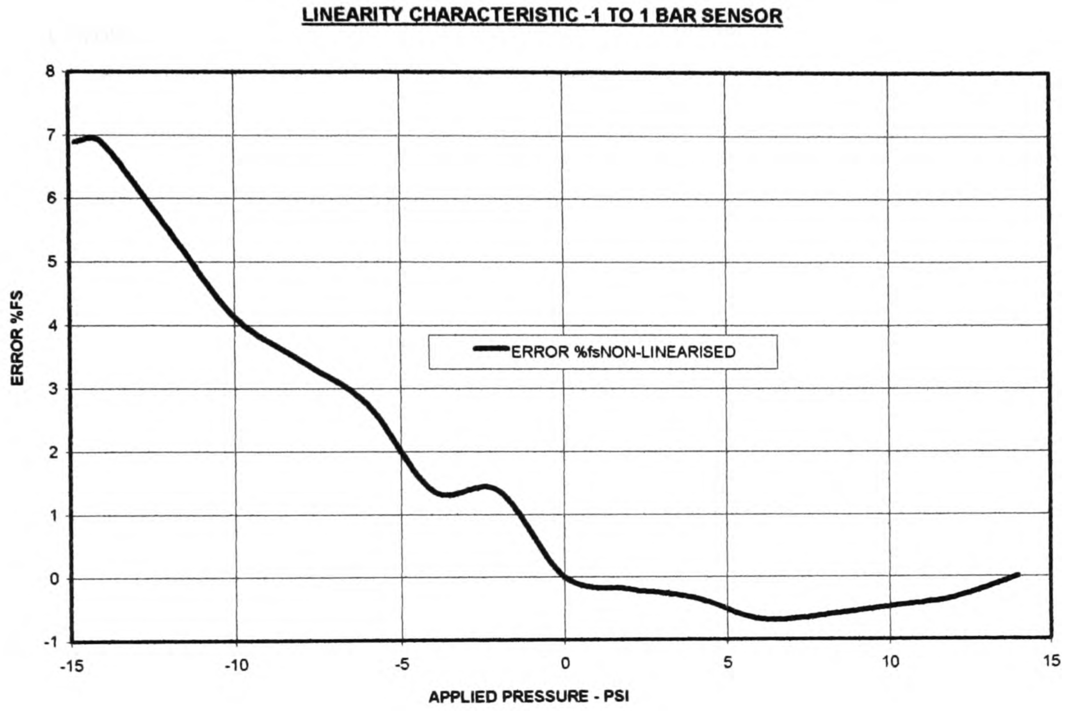


FIGURE 11: Linearity characteristic of -1 bar to 1 bar pressure transducer.

Due to the linearity characteristic of this pressure transducer with a vacuum applied, it was necessary to implement a separate linearisation software routine for the pressures of -1 bar to 0 bar.

Equations used in software for 0 psi to -7.25 psi:

y = 1000 - displayed pressure (mbar)

V2 = (y/3) x 2 + 1000

$$\text{Corrected pressure(linearised)} = \frac{\text{displayed pressure (unlinearised)} \times V2}{1000}$$

For -7.25 psi to -14.504 psi

$$C = 1000 - \frac{\text{displayed pressure(unlinearised)} \times 100}{3}$$

$$X = \frac{(1000 + C/100) \times 1000}{\text{displayed pressure(unlinearised)}}$$

$$V = C/100$$

$$\text{corrected pressure (linearised)} = \frac{(\text{displayed pressure(unlinearised)} \times X)}{1000} - V$$

The graph of FIGURE 12 shows the result of applying the linearisation software to the transducer for pressures of 0 to -14 psi. This clearly shows that a large improvement in accuracy was achieved, so enabling the gauge to meet the specification objective of ±0.25%f.s.

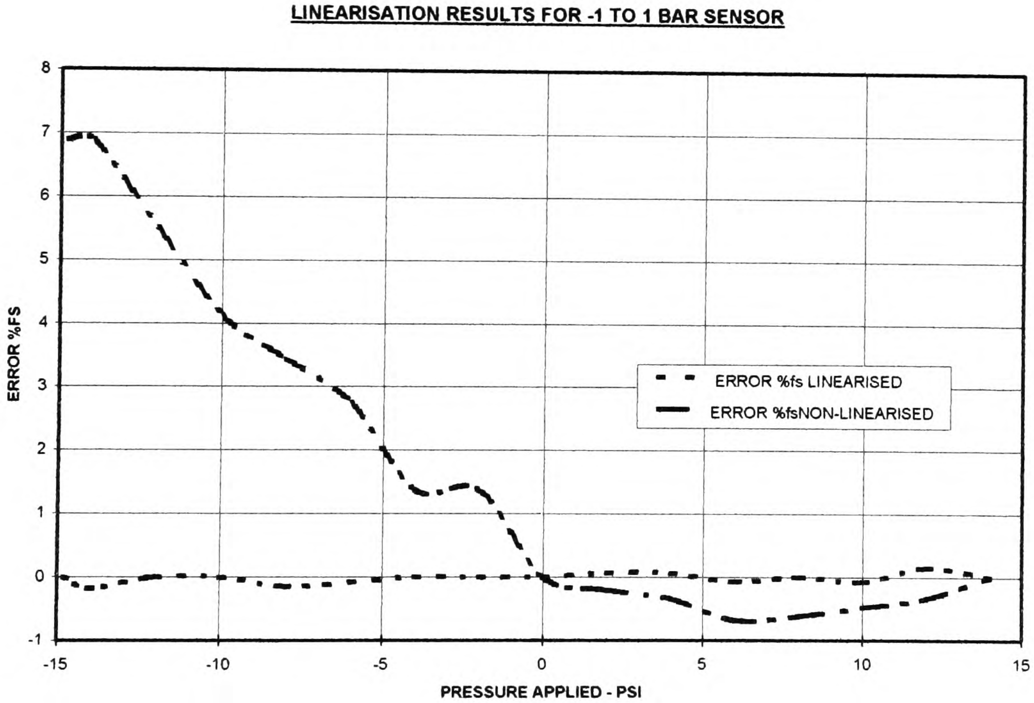


FIGURE 12: Graph of linearisation results of -1 to 1 bar pressure transducer.M)

M) PRODUCTION ISSUES

A final printed circuit board layout was designed for the instrument, and this was sub-contracted out to printed circuit board manufacturer for a batch of boards to be made. Once these boards were received, the insertion of all components was then carried out at British Rototherm.

A completed set of circuit boards, along with the pressure transducer and "AA" cells is shown in the photograph of FIGURE 13.

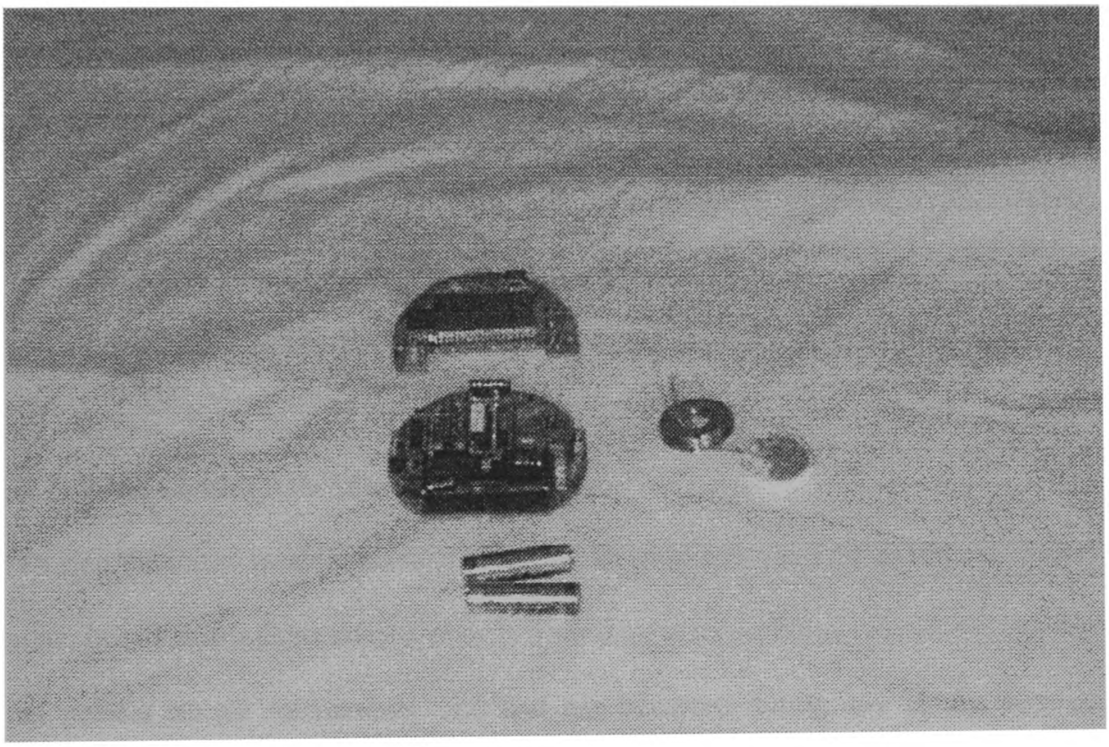


FIGURE 13: Digital pressure gauge PCBs

FIGURE 14: A completed digital pressure gauge.

The complete assembled instrument is shown in the photograph of FIGURE 14.

M.1) Final Circuit Amendments

During the initial production runs of the digital pressure gauge following calibration, a number of instruments started to drift from their zero positions. However, this was not present on all instruments, and had not occurred during any of the tests on prototypes or on any of the earlier production instruments. After temperature cycling tests and careful bench test analysis of the faulty instruments, the cause of the problem was identified. Due to the common mode voltage at the input of the analogue to digital converter being switched on and off every conversion, large transient spikes were present at the input to the analogue to digital converter. These spikes had a magnitude of up to 600 mV.

The spikes were being capacitively coupled through the MAX132 analogue to digital converter (which is a CMOS device) from junction to junction and from gate to substrate, and as a result, these spikes were causing an erroneous reading. This problem was cured by implementing the following changes in hardware and software to all digital pressure gauges produced.

M1.1 Hardware:-

1. Resistor R6, which is part of the series resistor reference network for the analogue to digital converter, is tied high to a permanent +5 volt supply.

2. Pin 16 (analogue ground) of the analogue to digital converter is disconnected from 0 volts and reconnected to the low differential input, INLO pin 15 (which is a virtual 0 volts) of the analogue to digital converter.

3. The analogue switch IC DG419 which was used for eliminating offsets in the analogue electronics and ADC was removed and a link placed between pins 1 and 2 of this device.

M1.2 Software:

1. The analogue electronics is switched on for an extra 10 mS. This allows the analogue electronics more time to settle to the correct voltage levels for an accurate conversion to take place.

2. Maxim MAX132 reads its own internal zero.

Though the analogue signal processing electronics and ADC were zeroed together and their combined offsets added to give the total offset due to thermal drift, the lnger energisation of the analogue electronics and permanent energisation of the ADC reference network resulted in a much reduced thermal drift in the measurement electronics and thus the only measurement of thermal drift now required was that of the ADC.

3. The first reading after the zero is displayed. Due to the hardware changes implemented and extended transducer and analogue electronics energisation period, the initial conversion after a zero reading was now valid.

N) VALIDATION OF INSTRUMENT ACCURACY

The very high accuracy of the digital pressure gauge was confirmed by an external NAMAS accredited standards laboratory, with accuracies of better than ±0.06% of full scale being recorded. The test certificates for this are included at the end of this project. Also included is the current data sheet produced by The British Rototherm Company, which details the specifications of the instrument, along with a circuit diagram of the completed instrument.

O) CONCLUSION

This section has detailed the design phases, both hardware and software that were undertaken to develop a high accuracy, battery powered digital pressure instrument. With suitable linearisation the instrument has a guaranteed accuracy of ±0.25%f.s. and a battery life of a minimum of twelve months. Its novel features include push button linearisation and zeroing. The target specification was comfortably exceeded.

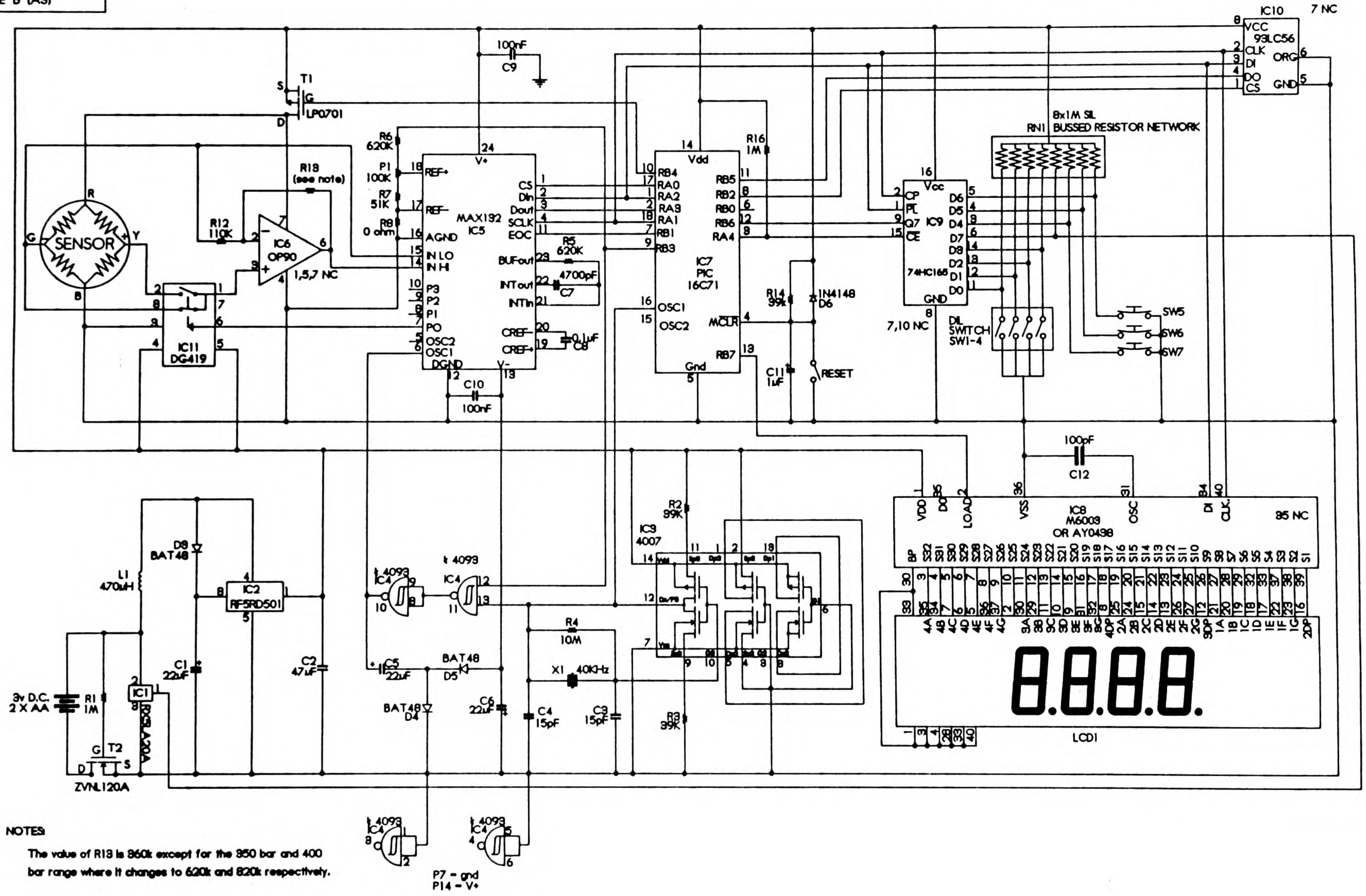
DRG. No. DG0103-Q

SHEET SIZE 'B' (A3)

IF IN DOUBT ASK

REMOVE ALL BURRS AND SHARP EDGES

DO NOT SCALE



NOTES:

The value of R13 is 860k except for the 850 bar and 400 bar range where it changes to 620k and 820k respectively.

PROJECTION

DIMENSIONS IN MM UNLESS OTHERWISE STATED

SURFACE FINISH μm

USED ON

MATERIAL N/A

FINISH N/A

SCALE N/A

ISSUE	MOD. No.	DATE	ISSUE	MOD. No.	DATE
6		16/9/97	3		16/7/97
5		1/9/97	2		8/7/97
4		28/7/97	1		2/6/97

TOLERANCES
NO DECIMALS ± 0.4
DECIMALS ± 0.1
UNLESS OTHERWISE STATED

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TITLE
DigiGauge
Circuit Schematic

DRAWN	TJC
CHECKED	
DATE	16/9/97
DRAWING No.	DG0103-Q

DG - 97

DIGIGAUGE DIGITAL PRESSURE GAUGES

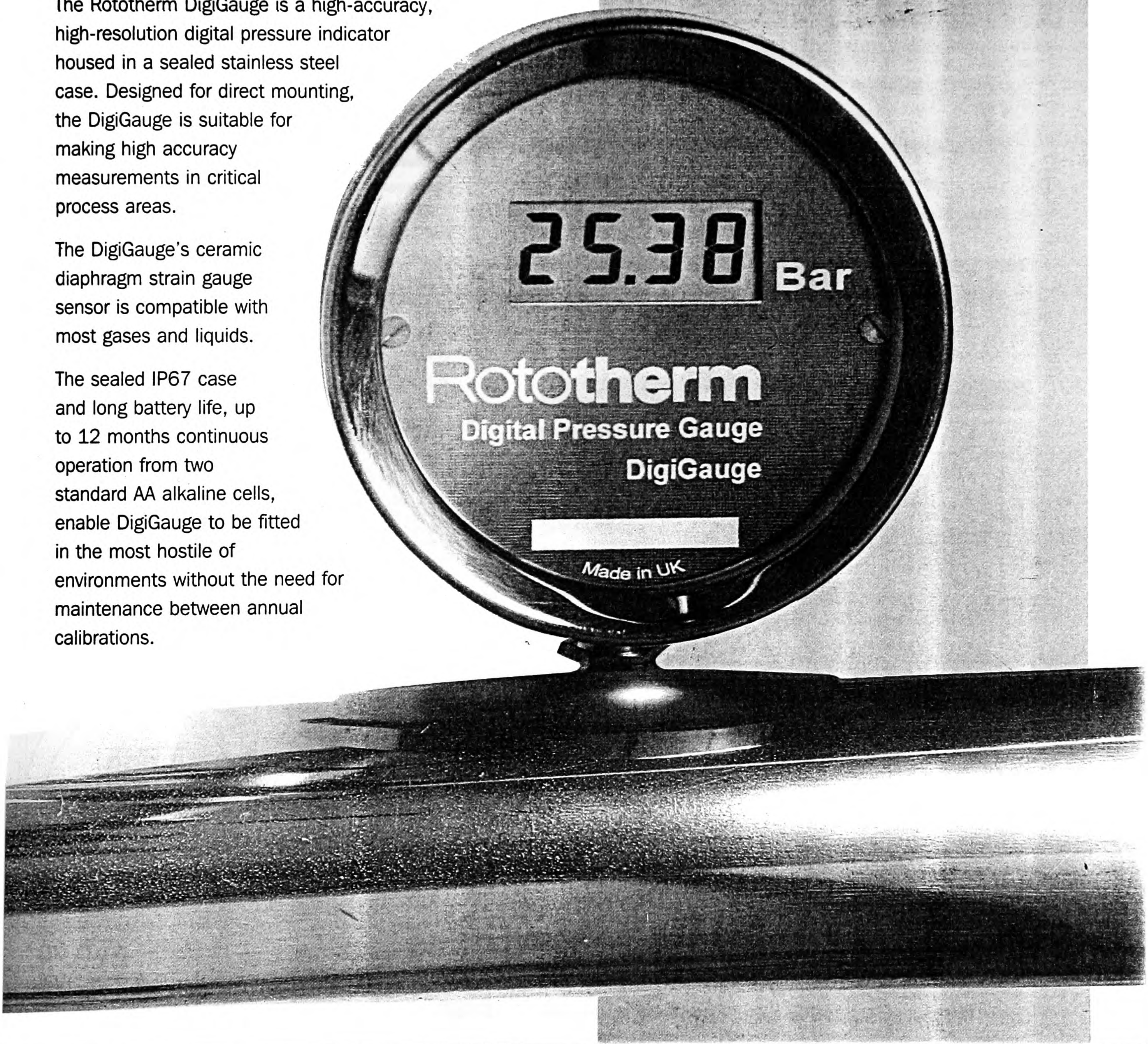
- ***High accuracy ±0.2% f.s.***
- ***Stainless steel case IP67 sealed***
- ***Long battery life - 1 year continuous operation from 2 AA alkaline cells***
- ***Wide selection of pressure ranges from vacuum to 400 bar***

Introduction

The Rototherm DigiGauge is a high-accuracy, high-resolution digital pressure indicator housed in a sealed stainless steel case. Designed for direct mounting, the DigiGauge is suitable for making high accuracy measurements in critical process areas.

The DigiGauge's ceramic diaphragm strain gauge sensor is compatible with most gases and liquids.

The sealed IP67 case and long battery life, up to 12 months continuous operation from two standard AA alkaline cells, enable DigiGauge to be fitted in the most hostile of environments without the need for maintenance between annual calibrations.



Rototherm
instrumentation and control

DIGIGAUGE - DIGITAL PRESSURE GAUGE

APPLICATIONS

igh accuracy and a four digit display enables the DigiGauge to be used as digital standard test-gauge, replacing less accurate, fragile analogue test auges. Factory calibration certificates and NAMAS calibration certificates an be supplied as required.

overing a wide range of test and measurement applications with pressure anges available from vacuum to 400 bar, DigiGauge can be supplied with ygienic fittings for food applications or with diaphragm seals where articularly corrosive media is present.

ustom calibrations can be applied to enable indication of tank/vessel ontents displayed in any units of your choice, a drawing of the tank/vessel ill be required at the time of order placement. Note: applies to regular haped tanks/vessels, please also advise the S.G. of the contents.

TEMPERATURE COMPENSATION

ll standard DigiGauges are calibrated at 20°C, instruments which will be in onstant use at higher or lower temperatures can be calibrated at a user efined temperature. Instruments which will be regularly working across a ignificant temperature range can be supplied with temperature ompensated sensors to correct zero and span drift.

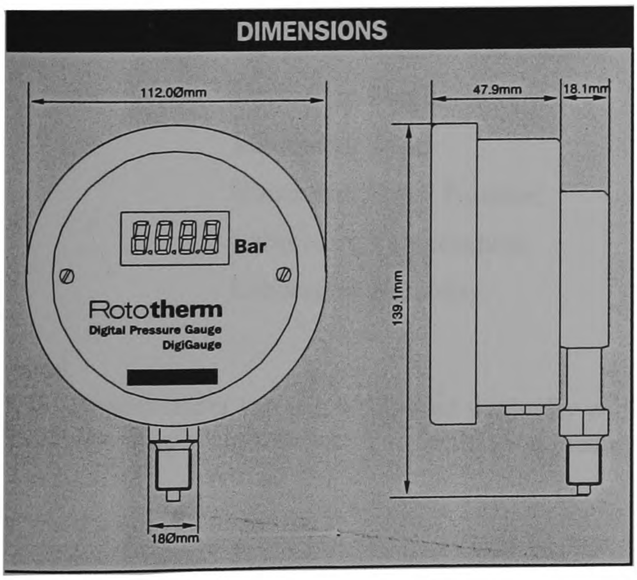
PRESSURE RANGES & PERFORMANCE SPECIFICATION

ressure Range	Display Resolution	Accuracy*
1 to 1 bar	1 mbar	±0.25% fs
to 0.5 bar	1 mbar	±0.25% fs
to 1 bar	1 mbar	±0.20% fs
to 2 bar	1 mbar	±0.20% fs
to 5 bar	1 mbar	±0.20% fs
to 10 bar	10 mbar	±0.20% fs
to 20 bar	10 mbar	±0.20% fs
to 50 bar	10 mbar	±0.20% fs
to 100 bar	100 mbar	±0.20% fs
to 200 bar	100 mbar	±0.20% fs
to 350 bar	100 mbar	±0.20% fs
to 400 bar	100 mbar	±0.20% fs

Note: Accuracy includes non linearity + hysteresis + repeatability

bove figures are for instruments operating at the calibration temperature of 20°C. For temperature ompensated instruments working outside of this range please add ±0.01%fs/°C zero drift and 0.01%fs/°C span drift, for uncompensated sensors add ±0.05%fs/°C zero drift and ±0.04%fs/°C pan drift

DIMENSIONS



SPECIFICATIONS

Case:	100mm dia. 304 s/s case and bezel with ¼"BSP(male) process connection.
Protection:	IP67
Display:	4 digit LCD with 12.7mm high characters.
Display update rate:	2 seconds/0.5 seconds - user selectable
Sensor:	Alumina ceramic (AL_2O_3) diaphragm strain gauge.
Overpressure:	Maximum applied pressure must not exceed 1.25 x upper pressure limit
Compensated Range:	-10 to 60°C*
Wetted Parts:	316 stainless steel, viton and ceramic.
Temperature Limits:	Storage: -20 to +85°C
	Ambient Operating: -10 to +60°C
	Pressure Medium -20 to +100°C
	Internal case: -10 to +60°C
Power Source:	3V DC battery, 2 x 1.5V "AA" alkaline cells.
Battery Life:	12 months at 2 second update rate.
Low Power Warning:	Display will alternate between pressure reading and BATT
EMC Compatibility:	BS EN 50081-1: 1992 & BS EN 50082-2: 1995
Weight:	900g

*Temperature compensation is an optional feature.

ORDER CODE

DIGIGAUGE DG1 ☐ ☐ ☐ ☐ ☐

Mounting	
Direct vertical	V
Direct back	B
Other (specify)	X
Pressure Range *1	XXX
Units of Pressure *2	XXX
Certification	
None	X
Factory Calibration Cert.	F
NAMAS Calibration Cert.	N
Temperature Compensation	
Required	1
Not Required	2

*1 see range table

*2 standard is Bar.

EXAMPLE ORDER

DG1/V/0TO20/BAR/N/1

DigiGauge, direct vertical mounting, ranged 0 to 20 bar supplied complete with a NAMAS calibration certificate and temperature compensated sensor.

Rototherm
nstrumentation and control

The British Rototherm Co. Ltd.,
Kenfig Industrial Estate, Margam, Port Talbot,
West Glamorgan, SA13 2PW United Kingdom.
Tel: +44 (0)1656 740551
Fax: +44 (0)1656 745915 & 741275
email: rototherm@netwales.co.uk

BSI REGISTERED FIRM
NATIONAL ACCREDITATION OF CERTIFICATION BODIES

BS EN
ISO 9001
Registration
no: FM11958

CERTIFICATE OF CALIBRATION

ISSUED BY THE STANDARDS LABORATORY OF HAVEN AUTOMATION LTD
DATE OF ISSUE 30 March 1998 SERIAL NUMBER 1513/P

Haven™

Haven Automation Ltd.
Measurement House
Kingsway
Fforestfach
Swansea SA5 4EX

Tel: 01792 588722
Fax: 01792 582624

NAMAS
CALIBRATION
No. 0295

PAGE 1 OF 2 PAGES

APPROVED SIGNATORY

C. B. Jones

C B Jones
J P Vaughan

Customer:	The British Rototherm Limited
Address	Kenfig Industrial Estate Margam Port Talbot SA13 2PW
Customer Order Number:	021466
Date Instrument Received:	26 March 1998
Date of Measurement:	28 March 1998
Haven Automation Job Number:	RE10745
Instrument Manufacturer:	The British Rototherm Co. Limited
Instrument Type:	0 to 50 bar Digital Pressure Gauge
Instrument Serial Number:	645465/1
Laboratory Temperature:	20°C ± 2°C
Laboratory Humidity:	<75% RH

Method
The instrument under test was calibrated vertically with the input pressure port level with the reference mark on the dead weight tester. The calibration medium used was oil.

Range: 0 to 50 bar

Resolution: 0.01 bar

Serial Number: 645465/1

Before the commencement of test, the pressure was increased to the maximum pressure and decreased to zero. The instrument was calibrated for rising and falling pressures.

Applied Pressure Units: bar	Instrument Readings Units: bar		
	Rising Pressure	Falling Pressure	
0.000	00.00	00.00	0%
13.792	13.73	13.73	0·124%
20.689	20.63	20.63	0·118%
30.138	30.06	30.06	0·156%
40.001	39.91	39.90	0·182%
48.278	48.18		0·196%

The uncertainty of the applied pressure does not exceed ± (0.02%).

The total uncertainty of measurement will be the uncertainty of the applied pressure plus the resolution of the instrument under test.

bove uncertainty refers to the measurements and is not intended to indicate the specification of the rument.

Orientation: vertical

Test Engineer: D Woodman

CERTIFICATE OF CALIBRATION

ISSUED BY THE STANDARDS LABORATORY OF HAVEN AUTOMATION LTD
DATE OF ISSUE 30 March 1998 SERIAL NUMBER 1514/P

NAMAS
CALIBRATION
No. 0295

Haven
Haven Automation Ltd.
Measurement House
Kingsway
Fforestfach
Swansea SA5 4EX

Tel: 01792 588722
Fax: 01792 582624

PAGE 1 OF 2 PAGES

APPROVED SIGNATORY
C.B. Jones

C B Jones
J P Vaughan

Customer:	The British Rototherm Limited
Address	Kenfig Industrial Estate Margam Port Talbot SA13 2PW
Customer Order Number:	021466
Date Instrument Received:	26 March 1998
Date of Measurement:	28 March 1998
Haven Automation Job Number:	RE10746
Instrument Manufacturer:	The British Rototherm Co. Limited
Instrument Type:	0 to 400 bar Digital Pressure Gauge
Instrument Serial Number:	645465/2
Laboratory Temperature:	20°C ± 2°C
Laboratory Humidity:	<75% RH

Method
The instrument under test was calibrated vertically with the input pressure port level with the reference mark on the dead weight tester. The calibration medium used was oil.

CERTIFICATE OF CALIBRATION

ISSUED BY THE STANDARDS LABORATORY OF HAVEN AUTOMATION LTD
Measurement House, Kingsway, Fforestfach, Swansea SA5 4EX U.K.
NAMAS ACCREDITED CALIBRATION LABORATORY No. 0295

SERIAL NUMBER **1514/P**

Range: 0 to 400 bar

Resolution: 0.1 bar

Serial Number: 645465/2

Before the commencement of test, the pressure was increased to the maximum pressure and decreased to zero. The instrument was calibrated for rising and falling pressures.

Applied Pressure Units: bar	Instrument Readings Units: bar		
	Rising Pressure	Falling Pressure	
0.00	000.0	000.0	
51.76	052.0	051.9	-0.06
100.07	100.3	100.3	-0 0575
200.13	200.3	200.7	-0·0425
301.56	301.5	301.9	0 06
379.54	379.5		0·01

The uncertainty of the applied pressure does not exceed ± (0.06 bar).

The total uncertainty of measurement will be the uncertainty of the applied pressure plus the resolution of the instrument under test.

[illegible] above uncertainty refers to the measurements and is not intended to indicate the specification of the [illegible]ument.

Orientation: vertical

Test Engineer: D Woodman

The uncertainties are for a confidence probability of not less than 95%

PROJECT TWO

DESIGN AND DEVELOPMENT OF A MICRO-PROCESSOR BASED INDUSTRIAL DIGITAL PRESSURE GAUGE WITH 4-20mA CURRENT LOOP INTERFACE.

DESIGN AND DEVELOPMENT OF A TRANSMITTING DIGITAL PRESSURE GAUGE

Closely linked to the first project, the objective of **Project Two** was to design and implement a transmitting digital pressure gauge, which derived its power and communication link from the industry standard signalling system; the 4 - 20 mA current loop.

To complete this design phase a review of low power digital to analogue converters, comparison of static and pulse width modulated types was undertaken, with evaluation of these devices as appropriate. A prototype design of a combined pressure transmitter with local display was then constructed and evaluated in a thorough design verification schedule. Design verification involved comparison against pressure measurement standards, temperature cycling tests in an environmental chamber to assess operation and accuracy over a wide range of temperatures, EMC testing as well as checking for accurate transmission over the 4/20mA loop..

A) TARGET SPECIFICATION

Function:-

A range of digital pressure indicators with 4 - 20 mA loop interface for industrial process pressure measurement. An evolution of the existing battery-powered DigiGauge range as discussed in **Project One**, whereby these variants derive power from the 4 - 20 mA loop and provide a local display of pressure. The variation of specification from **Project One** is listed:-

Accuracy:

Local reading: ±0.2% fs.

Loop transmission: ±0.2% fs.

Loop Supply:

12 to 32 V d.c.

4/20 mA loop ranging:

Digital, set up stored in non-volatile EEPROM memory. Partial or Full range transmission.

4/20 mA loop resolution:

12 bits (0.0244% fs)

Protection:

Current loop reverse polarity protected.

EMC:

Immunity: BS EN 50081-1 : 1992.

Emissions: BS EN 50082-2 : 1995.

Electrical Connections:

Minature PG7 cable gland or Lumberg IP68 miniature plug and socket.

Works cost:

Circa £80 to £85 (without temperature compensation).

B) THE TRANSMITTING DIGITAL PRESSURE GAUGE

The Transmitting Digital Pressure Gauge operates from the industry standard 4-20mA current loop. Its power supply is derived from the 4-20 mA loop, which directly modulates this current in proportion to the pressure applied to it. FIGURE 1 details the connections to the Transmitting Digital Pressure Gauge and gives an example of how the current in the 4-20 mA loop varies with the pressure applied to the instrument; which, in this instance, has a full scale pressure of 400 bar.

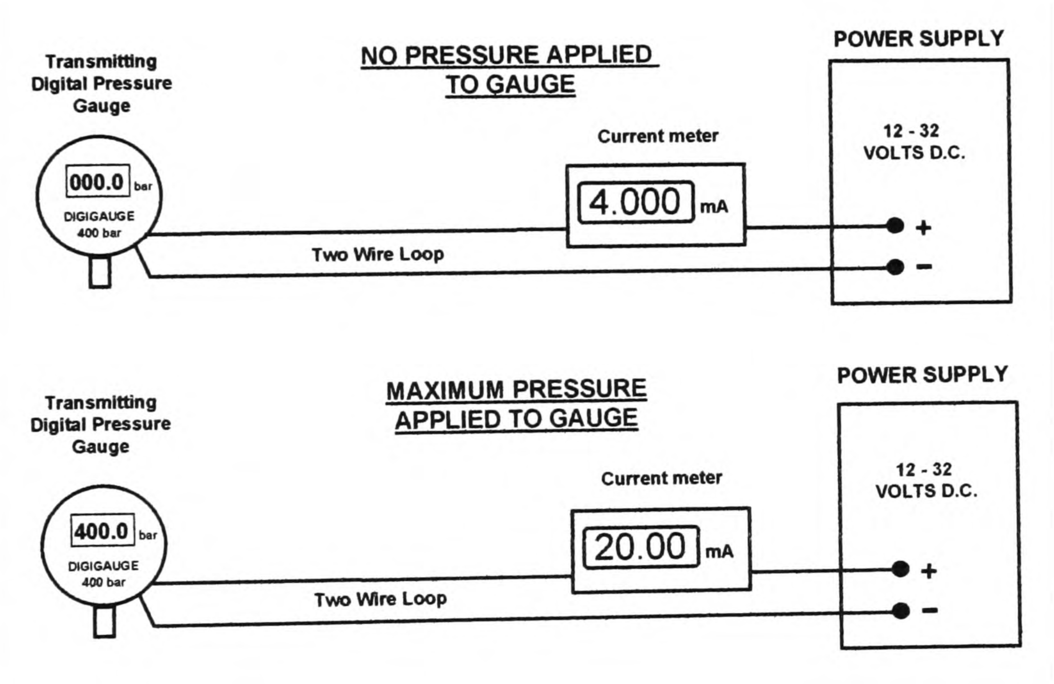


FIGURE 1: **Connections to the transmitting digital pressure gauge, with examples of how current in the transmission loop varies with pressure applied to the gauge.**

This instrument can be placed in a remote location in a factory or plant, where it will give a local display of the pressure of the medium which it is measuring, and also transmit the pressure reading in the form of a modulated current back to a control centre where the power supply for the instrument is derived.

For example, with reference to FIGURE 1, the instrument is calibrated so that, with no pressure applied to the instrument, the current in the two wire loop is 4 mA. With the maximum rated pressure of 400 bar applied to the instrument the current in the two wire loop is 20 mA.. For simplicity, FIGURE 1 shows the pressure indication at the control end of the system to be a current meter. However, with a series resistor in the current loop, a voltmeter can be used as pressure indication at the control point. Other recording instruments such as chart recorders may also be configured for this purpose. The Transmitting Digital Pressure Gauge could also form part of a control system, where the medium being measured is controlled with valves set to operate depending on the current level detected in the two wire loop.

C) INSRUMENT OVERVIEW

As the system derives its power from the two wire loop, the need for micro-power design no longer exists. The maximum current available from the two wire loop to power the instrument is 4 mA. Should the current consumption of the circuit rise above 4 mA however, the instrument will fail to work correctly. Therefore a more conservative figure for the current available from the two wire loop to power the instrument is 3 mA. This lower level of current is taken to be the maximum current available. The reason for this is that when the instrument is in production, some electronic components may consume more current than typical figures state.

Figure 2 shows a block diagram of the Transmitting Digital Pressure Gauge.

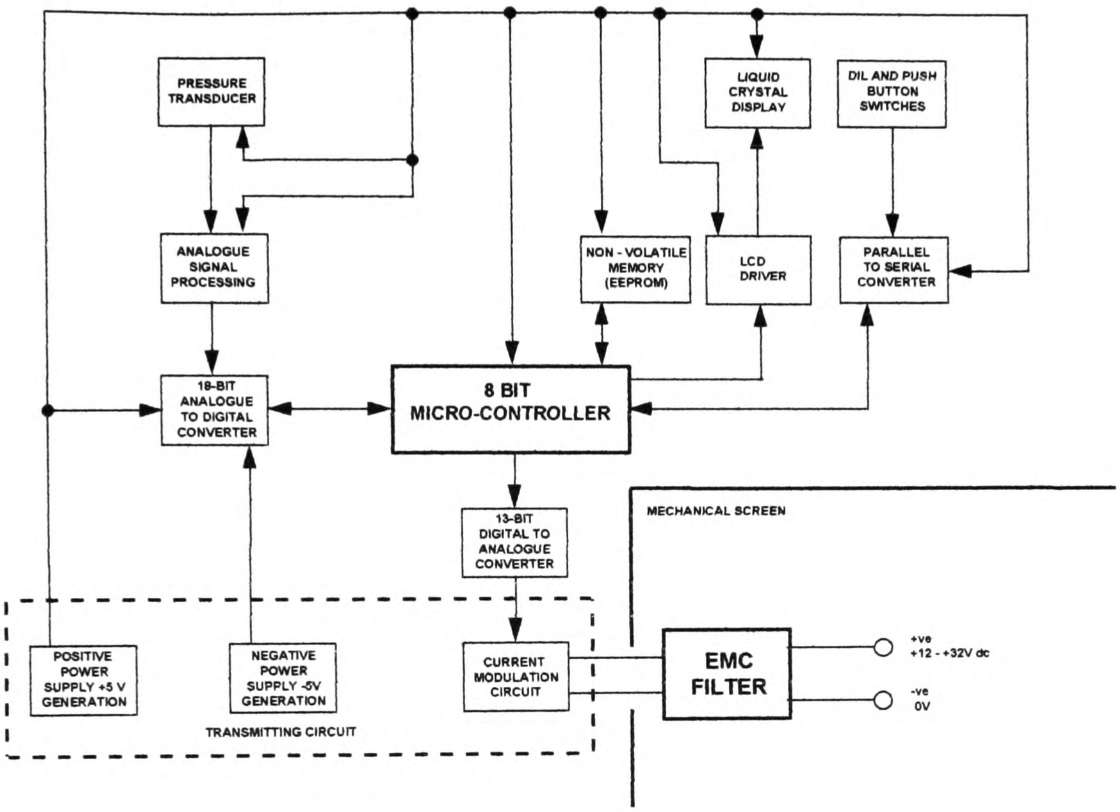


FIGURE 2: Block diagram of transmitting digital pressure gauge.

The pressure measurement system for the Transmitting Digital Pressure Gauge is virtually identical to that used on the Stand Alone Digital Pressure Gauge. The pressure transducer, analogue signal processing and the analogue to digital converter remain configured in the same way as they are for the battery powered digital pressure gauge. This is because it was not necessary to implement the power-saving features if the battery powered gauge (due to the increased supply current available) and any components therefore associated with the switching of the power supplies, were removed. The microcontroller, calibration switches, LCD and driver, and the EEPROM also remained the same.

The low-power oscillator was omitted and the oscillator circuit of the microcontroller was used; and also provided the clock for the MAX132 ADC.

New systems and components which were required consisted of the following:-

I. A transmitting circuit which modulated the current in the two wire loop in proportion to the pressure was applied to the instrument. This circuit also generated the regulated ±5 volt power supplies for the instrument.

II. A digital-to-analogue converter which interfaced the microcontroller to the transmitting circuit. This converted digital pressure information from a serial binary code to an analogue voltage representative of this binary code.

Due to the introduction of a cable to the instrument, an essential requirement was the utilisation of an electro-magnetic-compatibility filter at the input of the instrument. This ensured that the instrument functioned correctly in the presence of radio frequency interference.

D) THE TRANSMITTING CIRCUIT

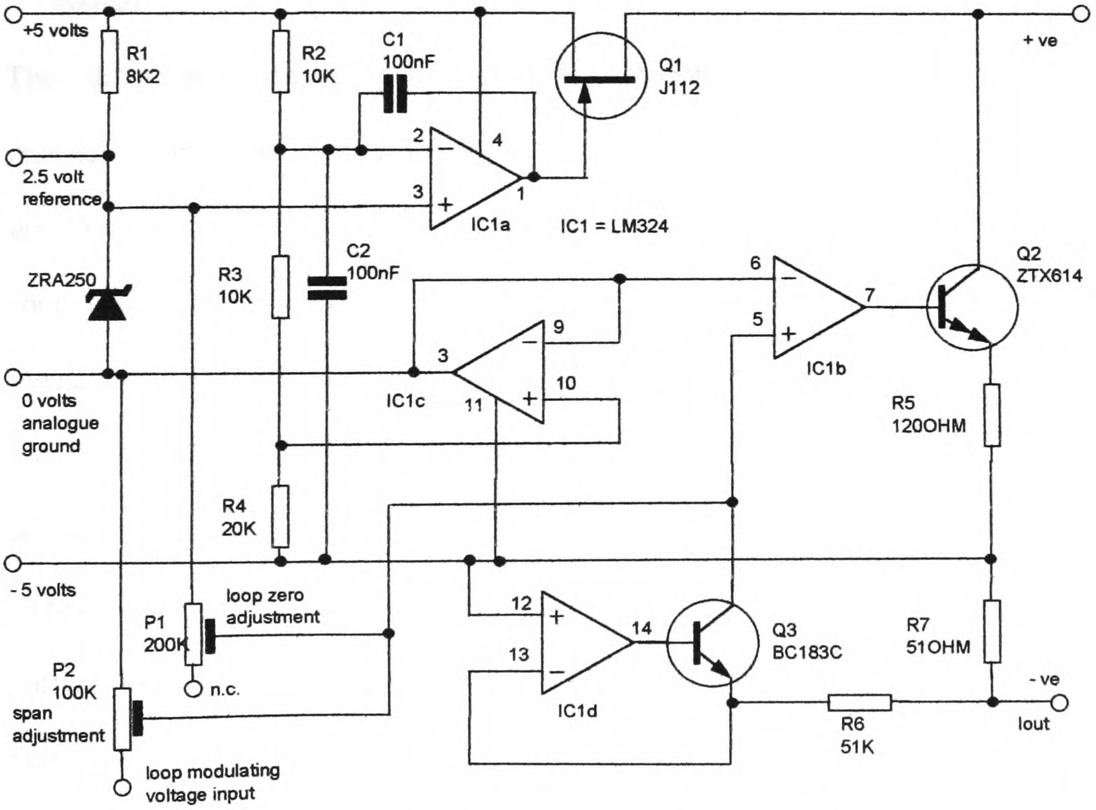


FIGURE 3: Transmitting circuit schematic

The transmitting circuit shown in FIGURE 3 is the interface between the instrument and the two wire connection from the control centre.

With reference to FIGURE 3, the voltage applied to the two wires to energise the instrument is as follows:- on the input line -ve, the voltage applied is 0 volts. On the input line +ve, the voltage applied is anywhere in the range +12 to +32 volts d.c.

The transmitting circuit performed the following functions:-

- Generated regulated power supplies of ±5V, 0V, for a voltage input range of +12 to +32 V d.c., using operational amplifiers, precision voltage references, stabilising capacitors and potential divider networks.
- Modulated the current in the two wire loop in direct proportion to the displayed pressure. Raised the quiescent current of the circuit to 4.00 mA. This was achieved using a combination of operational amplifiers and transistors to form current mirrors.
- Operated with an accuracy and linearity to match that of the instrument measuring system.

The calibration procedure for the Transmitting Digital Pressure Gauge is a two stage process. Firstly, the instruments measurement system is calibrated, in exactly the same way as the stand alone digital pressure gauge would be calibrated. Once this is completed, the transmission loop is calibrated. With no pressure applied to the instrument, the zero potentiometer P1 is adjusted until the current in the loop is 4.000 mA. Then with full pressure applied to the instrument, the span potentiometer is adjusted until the current in the loop is 20.00 mA. The calibration is then complete.

The circuit of FIGURE 3 was constructed, with a current meter to monitor the loop current, a supply of 20 volts and a milli-volt source connected to the loop modulating voltage input; to apply a range of precise input voltages to the transmission circuit. The circuit was calibrated as described above for full scale modulating input voltages of 1V, 2.5V and 5V, and linearity tests conducted for these inputs.

The results are shown in the graphs of FIGURES 4, 5, and 6 respectively. As can be seen from the graphs, the smallest error was less than 0.04% of full scale. These results prove that the transmitting circuit is within the error requirements of the target specification and suitable for use in the instrument. The fact that the transmitting circuit remains within specification for a wide range of input modulating voltages, allows the option for different DACs with varying output voltages to be used, should this be required in the future.

TRANSMITTING CIRCUIT LINEARITY TESTS
MODULATING INPUT VOLTAGE = 0 - 1 VOLT

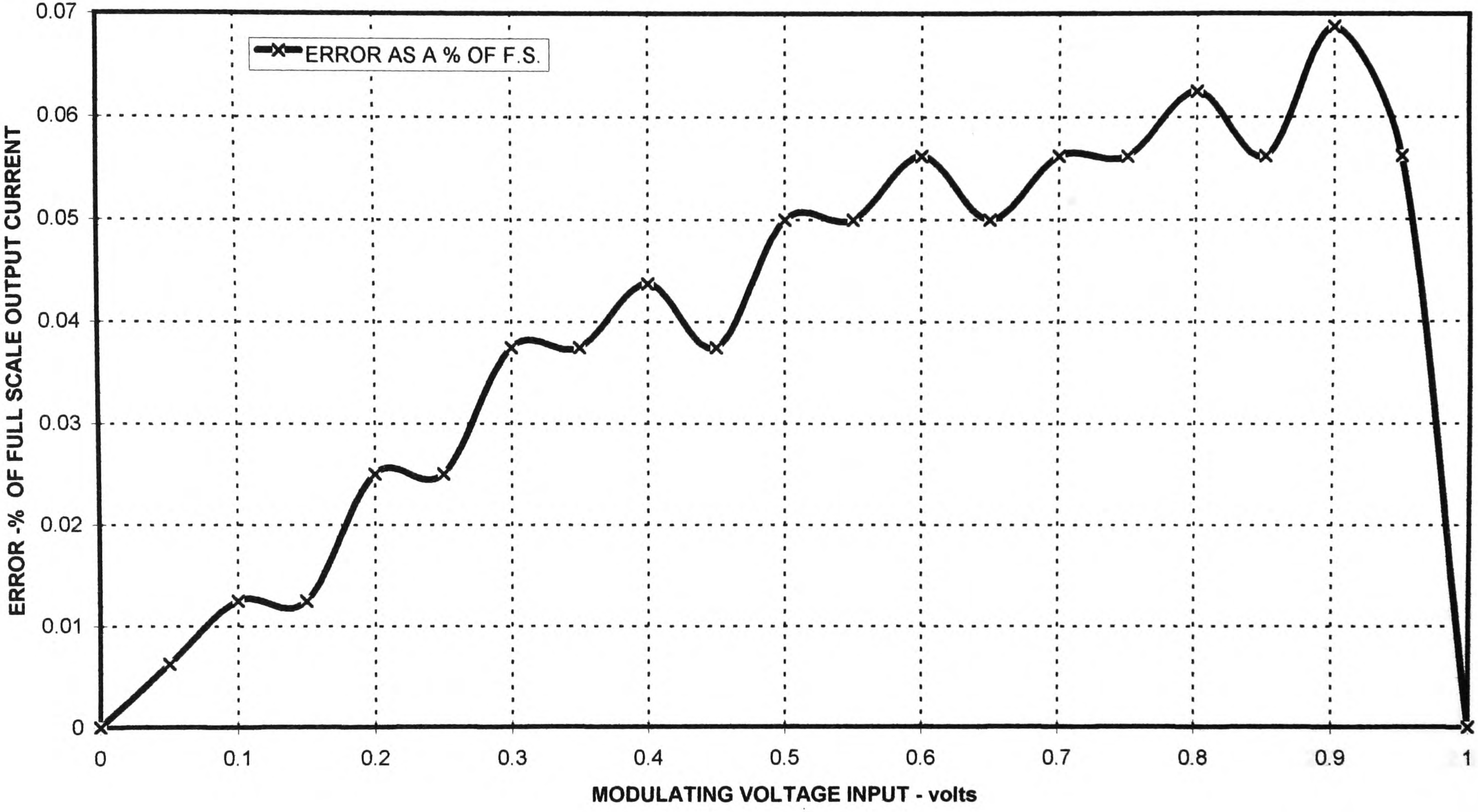


FIGURE 4

TRANSMITTING CIRCUIT LINEARITY TESTS
MODULATING INPUT VOLTAGE - 0 TO 2.5 VOLTS

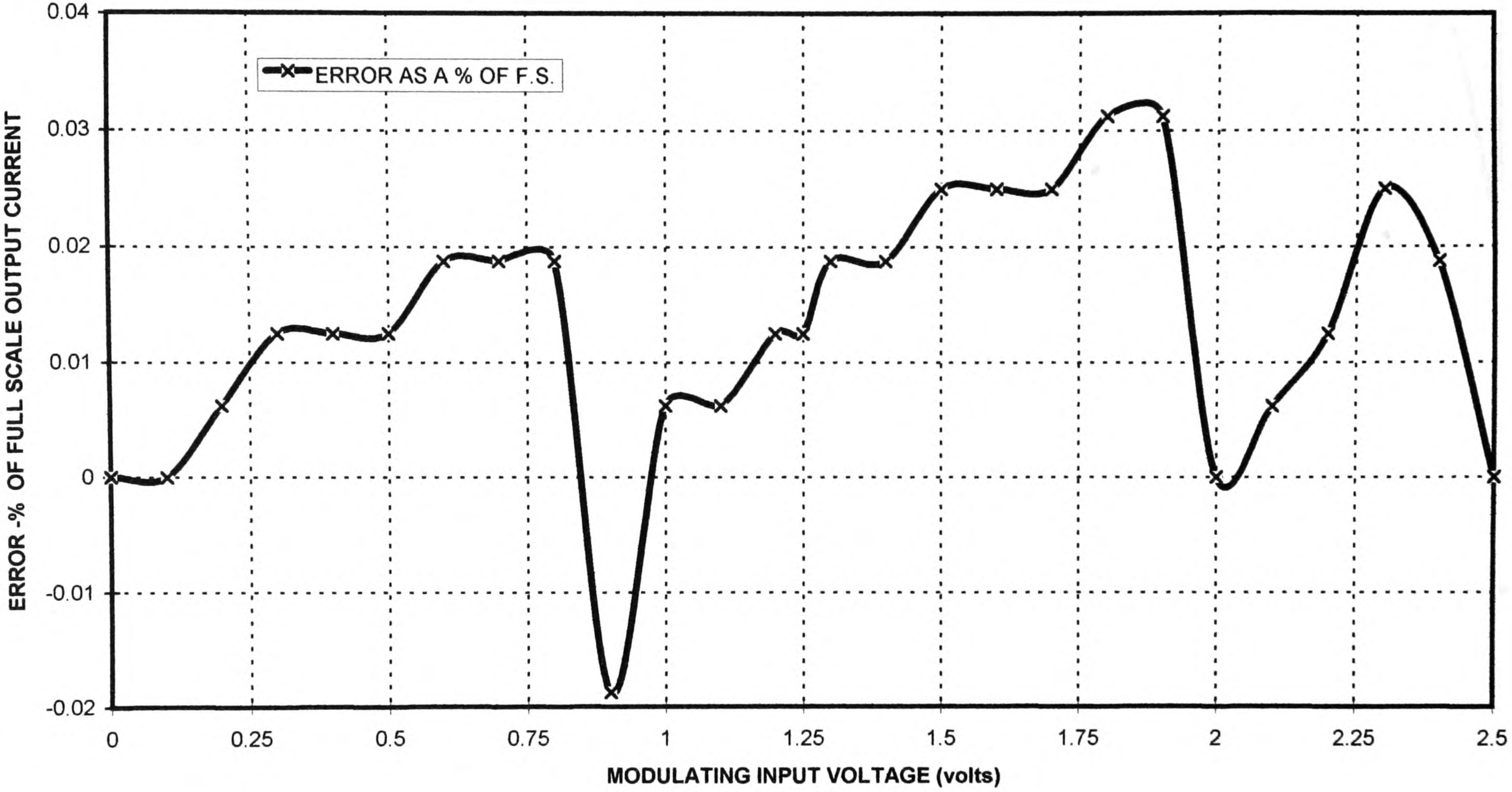


FIGURE 5

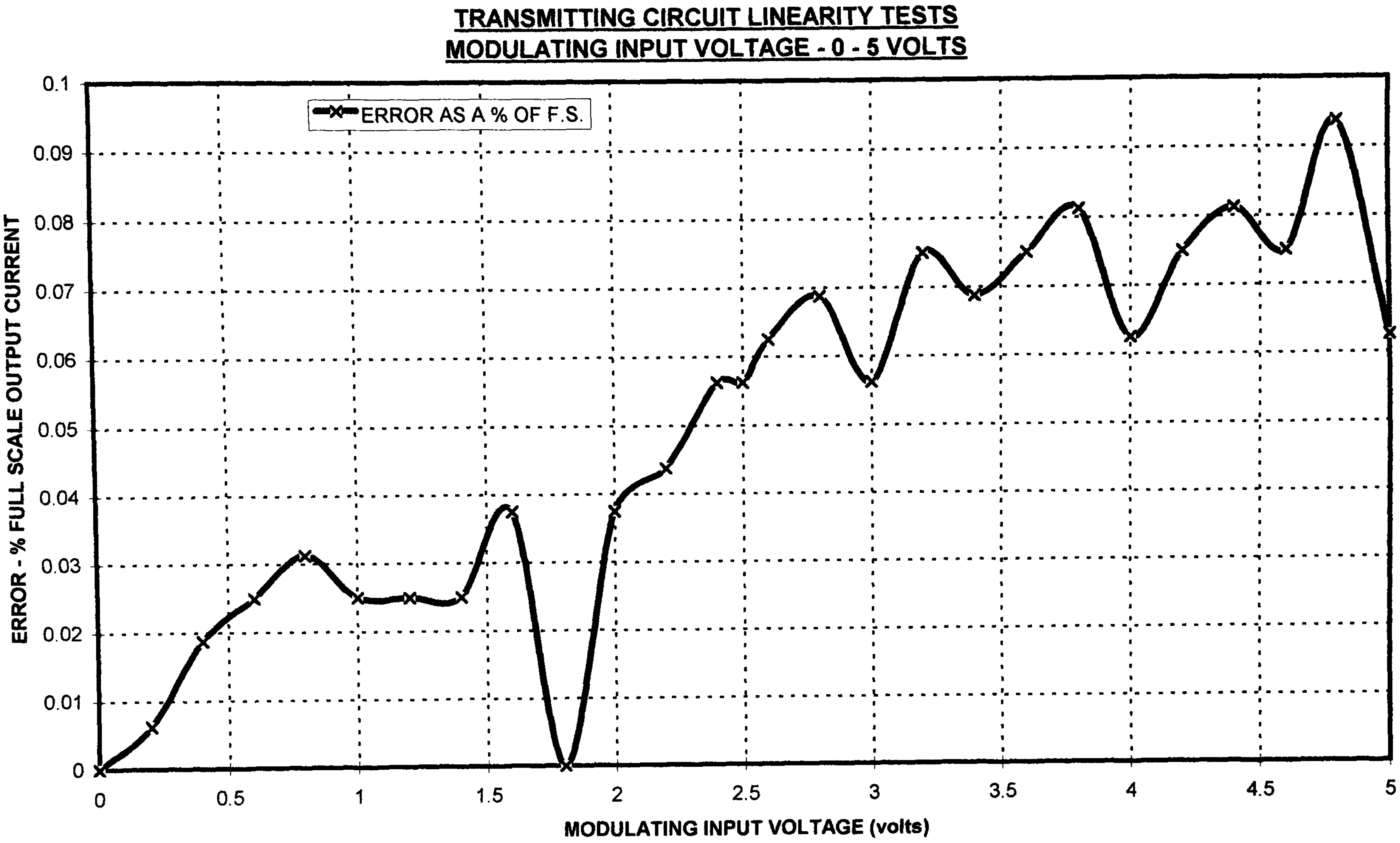

TRANSMITTING CIRCUIT LINEARITY TESTS
MODULATING INPUT VOLTAGE - 0 - 5 VOLTS
ERROR AS A % OF F.S.
ERROR - % FULL SCALE OUTPUT CURRENT
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
MODULATING INPUT VOLTAGE (volts)

FIGURE 6

E) THE DIGITAL TO ANALOGUE CONVERTER

The digital to analogue converter is the interface between the micro-controller managed measurement system and the transmitting circuitry. The micro-controller scales the final linearised pressure reading and this binary number, which is an exact representation of the pressure applied to the instrument, is communicated to the digital to analogue converter over a serial interface. The digital to analogue converter produces an output voltage which is proportional to the binary number. This output voltage is then applied to the loop modulating voltage input, and hence the current in the loop is a proportional representation of the displayed pressure. For ease of integration into the instrument, a digital-to-analogue converter with the following specifications was required:-

- 12 / 13 bit resolution.
- Serial interface for compatibility with other serial devices.
- Configurable output amplifier.
- +5 volt operation.
- Low supply current.
- Integral Non-Linearity error of no greater than ±1 bit.
- Cost to be as low as possible.

After reviewing a number of DACs, the device deemed most suitable for the application was the Maxim MAX535BCPA.

This was a low power, 13 bit voltage output digital-to-analogue converter with a serial interface and integral non-linearity of ±1 bit.

A superior grade device, the MAXIM MAX535ACPA, offering an integral non-linearity of ±½ bit will be available in the future, but was not considerable during the design phase.

E.1) DAC Linearity and Accuracy Tests

The MAX535 DAC was connected to the micro-controller emulator system. A test program was written that would allow the PIC16C558 micro-controller to communicate with the MAX535 digital-to-analogue converter. The program also allowed different binary words to be written to the DAC, so that the output voltage could be measured on a voltmeter and its performance assessed.

The digital-to-analogue converter was configured using external resistors for a gain of two, thus the output of the converter with a binary input value of zero would be 0 volts, and with a binary input value of 8191 would be 5 volts. Results showed that the accuracy and linearity of the DAC would meet the specification of ±0.2 % f.s.

DAC INPUT: (Value - Binary Counts)	**DAC OUTPUT: (Volts)**	**THEORETICAL OUTPUT: (Volts)**	**ERROR - %fs**
0	0	0	0
128	0.07828	0.07751	0.0154
255	0.15642	0.15563	0.0158
512	0.3133	0.3125	0.016
1024	0.626	0.625	0.02
2048	1.2513	1.250	0.026
4096	2.499	2.500	-0.02
8191	5.001	5.000	0.02

The above test was then repeated but with the addition of the transmitting circuitry of FIGURE 3. The output the DAC was connected to the modulating input of the transmitting circuit, and the current in the loop was measured.

DAC INPUT: (Value - Binary Counts)	CURRENT OUTPUT: (mA)	THEORETICAL OUTPUT: (mA)	ERROR - %fs
0	4.000	4.000	0
128	4.248	4.248	0
255	4.498	4.498	0
512	5.000	5.000	0
1024	6.001	6.000	0.0125
2048	8.002	8.000	0.00625
4096	12.005	12.000	0.03125
8191	20.00	20.00	0

Again, the results of the tests proved that the combined digital-to-analogue converter and transmitting circuitry were within the target specification requirements and were suitable for the instrument.

F) ELECTROMAGNETIC COMPATIBILITY

As mentioned in the system overview, the digital pressure gauge had to conform to electromagnetic compatibility standards. A definition of electromagnetic compatibility is as follows:-

> ***A characteristic of products that allows the product to function in the presence of electromagnetic interference and ensures the product does not add to the environments electrical interference levels.***

A comparison between the battery powered digital pressure gauge and the transmitting digital pressure gauge revealed why there were more EMC issues associated with the transmitting digital pressure gauge - this was due to the introduction of cables into the design.

The electronics of the battery powered digital pressure gauge were almost completely shielded within the stainless steel case of the instrument, with no external electrical connections. Thus EMC tests for that instrument were concerned only with radiated radio frequency interference.

As the transmitting digital pressure gauge had external electrical connections via a cable passing through the stainless steel case, the cable provided an entry point for radio frequency interference to be conducted into the electronics. The digital pressure gauge therefore had to undergo conducted immunity testing.

The digital pressure gauge was likely to be installed in industrial environments where high intensity electromagnetic interference might be present. Therefore the transmitting digital pressure gauge had to be designed so that it was immune to such interference.

In order to be sold in the European Union, an electrical product must demonstrate *immunity* in accordance with the British and European Standards for electro-magnetic-compatability compliance. Immunity is defined as the extent to which equipment can operate in a defined electromagnetic environment. Upon demonstration of immunity with these standards the product may display the CE denoting electromagnetic compatibility. These generic standards are:-

For Immunity:	BS EN 50081-1.
For Emissions:	BS EN 50082-2.

U.K. legislation denotes that emissions will consist of the following test criteria:-

- **Conducted magnetic and electric fields.**
- Radiated magnetic and electric fields.
- Electromagnetic fields.

- Supply voltage harmonics.
- Supply voltage fluctuations and interruptions.
- Electrostatic discharge.

As mentioned previously, of fundamental importance to the design of the transmitting digital pressure gauge was such testing for immunity and design against **conducted magnetic and electric fields.** Therefore, this section concentrates solely on this test; though other tests are required for certification purposes - these would be undertaken as part of the certification process.

Test requirements, such as those detailed above, are governed by the following "Standards Bodies":-

- **IEC** (International Electrotechnical Commission) - World-wide EMC standards.

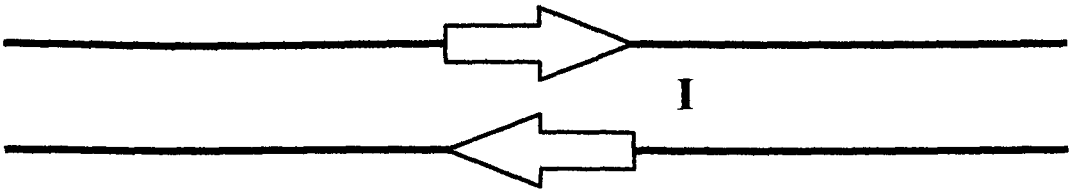
- **CISPR** - EMC test methods and levels, reports to IEC.

- **CENELEC** - produces European harmonised (EN) standards.

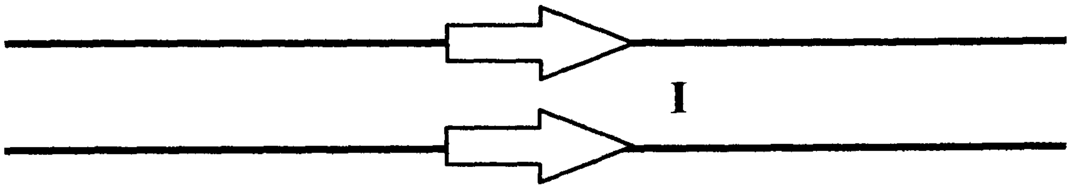
- **BSI** (British Standards Institute) - adopts EN standards as BS EN.

To achieve immunity for the transmitting digital pressure gauge, the objective was to prevent electromagnetic interference from being coupled to the electronics via radiation or conduction from the two wire loop. Electromagnetic signals could propagate along the two wire connection to the transmitting digital pressure gauge in following ways:

DIFFERENTIAL MODE



COMMON MODE



In **differential mode** currents flow in equal and opposite directions.

In **common mode** currents flow in the same direction.

The two wires might also radiate electromagnetic interference where they entered the stainless steel case.

Two systems were required to enable the transmitting digital pressure gauge to achieve the correct immunity levels. These were as follows:-

- An EMC filter - to prevent conducted common and differential mode electromagnetic interference.
- Mechanical screens - to create clean and dirty signal areas, and to prevent radiated electromagnetic interference.

A clean signal area was an area where no electromagnetic interference was present. This area contained the pressure transducer and measurement electronics. FIGURE 7 shows the circuit schematic for the filter used to reject conducted common and differential mode electromagnetic interference.

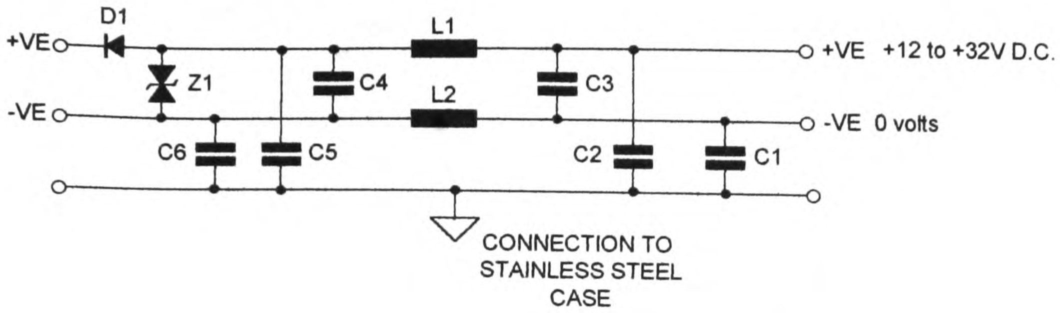


FIGURE 7: EMC filter circuit schematic.

A dirty signal area was an area where electromagnetic interference might be present. This area contained the electromagnetic compatibility filter and the connection to the plug on the wall of the case for the two wire connection.

FIGURES 8 and 9 detail the arrangement of mechanical shields and show clean and dirty signal areas within the transmitting digital pressure gauge.

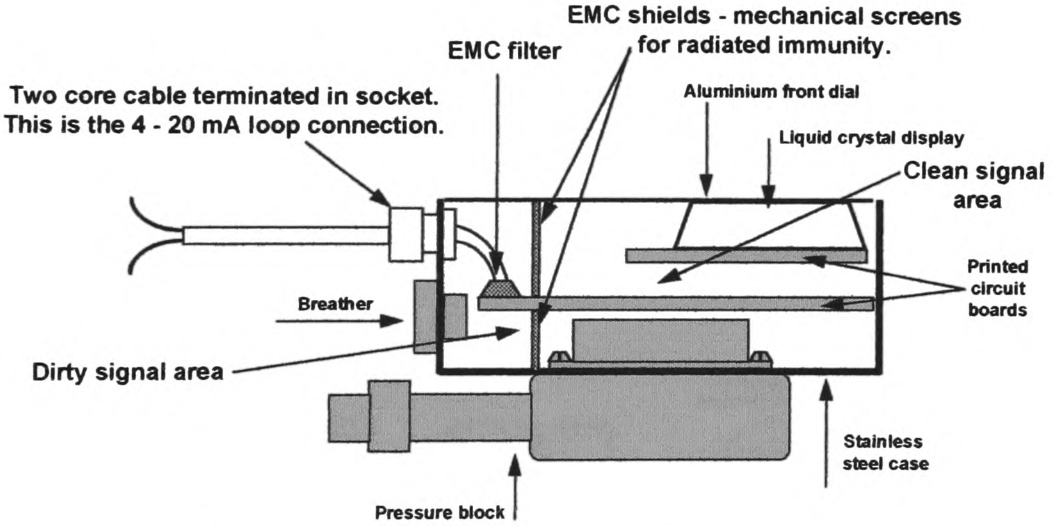


FIGURE 8: Side view - internal layout of the transmitting digital pressure gauge

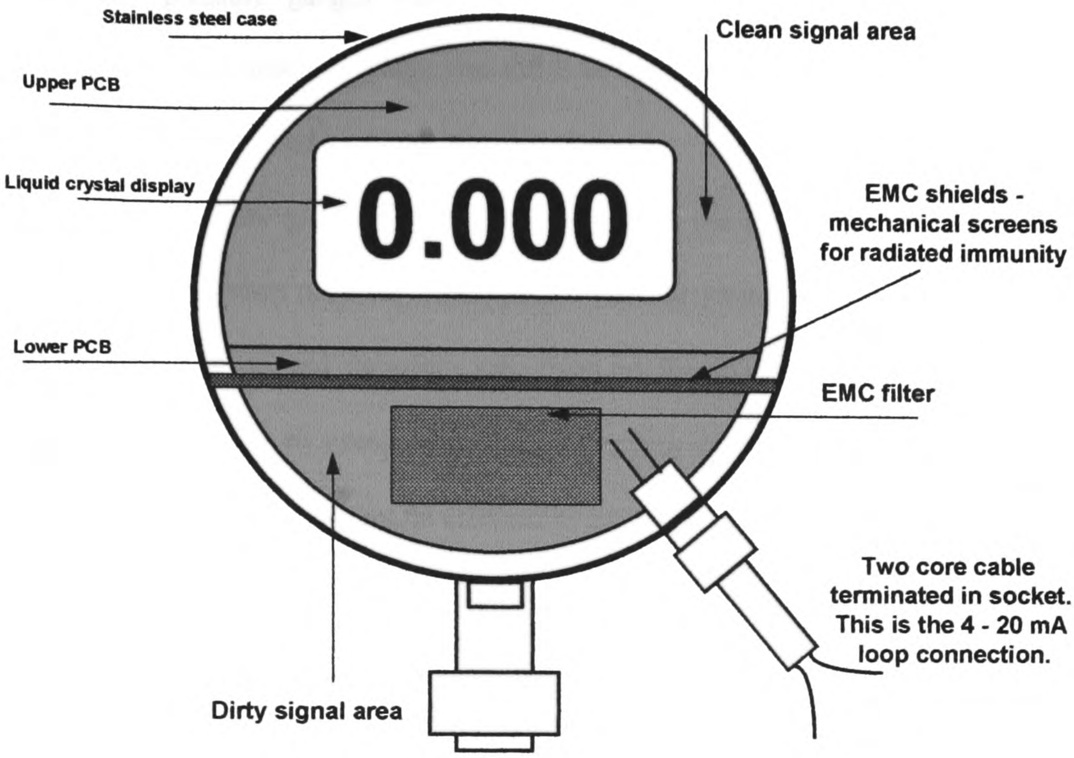


FIGURE 9: Top view - internal layout of the transmitting digital pressure gauge

The next stage was to undertake conducted immunity testing. FIGURE 10 details the test equipment configuration for conducted immunity tests on the re-transmitting digital pressure gauge.

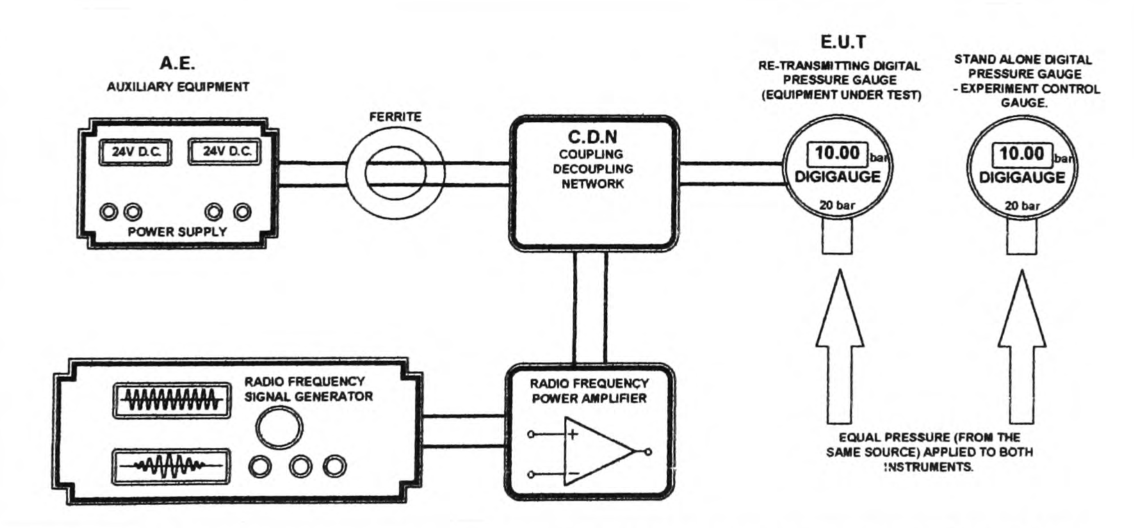


FIGURE 10: Conducted immunity tests - test equipment configuration

Two digital pressure gauges were used in the conducted immunity test. The transmitting digital pressure gauge was the E.U.T - equipment under test. A battery powered digital was used as a control in the tests.

Both digital pressure gauges had been calibrated on the same equipment and gave identical readings when pressure was applied. The instruments were connected to the same pressure source and therefore any error on the transmitting digital pressure gauge was easily seen by comparing it to the reading of the battery powered digital pressure gauge which would not be effected by conducted immunity testing.

The A.E. - the auxiliary equipment, was a DC power supply used to energise the transmitting digital pressure gauge.

The radio frequency generator produced signals of a frequency up to 500 Mhz. These frequencies were associated with electromagnetic interference. The radio frequency amplifier raised the magnitude of these signals to that required for EMC testing.

The C.D.N. - a Coupling Decoupling Network was used to connect the transmitting digital pressure gauge to the power supply and to the output of the radio frequency amplifier. This piece of equipment coupled the electromagnetic interference to the two wire connection of the transmitting digital pressure gauge, but stopped this interference reaching and effecting the auxiliary equipment and its operation.

Conducted immunity tests are strictly limited to frequencies up to 80 Mhz[1]. Above 80 MHz, radiated immunity tests are required (up to 1 GHz). However, Rototherm did not possess the radiated immunity test facilities, so extended conducted immunity tests were undertaken; at up to 230 MHz.

The results of the conducted immunity tests are presented in the graph of FIGURE 11.

This graph shows that the design of the EMC filter and mechanical screens which act as radio frequency shields was successful and provided immunity well above the required test levels.

G) CONCLUSION

In accordance with the analysis of test results presented in this project, it is clear that the transmitting digital pressure gauge succeeded in meeting the requirements of the target specification. The design functioned correctly under the stringent test requirements for electromagnetic compatibility, and the accuracy of pressure reading and transmission current remained well within the ±0.2% of full scale.

H) REFERENCES

1. BS EN 50081-1 : 1992, EMC LIGHT INDUSTRIAL, IMMUNITY
BS EN 50082-2 : 1995, EMC INDUSTRIAL, EMISSIONS

EMC TESTING - CONDUCTED IMMUNITY

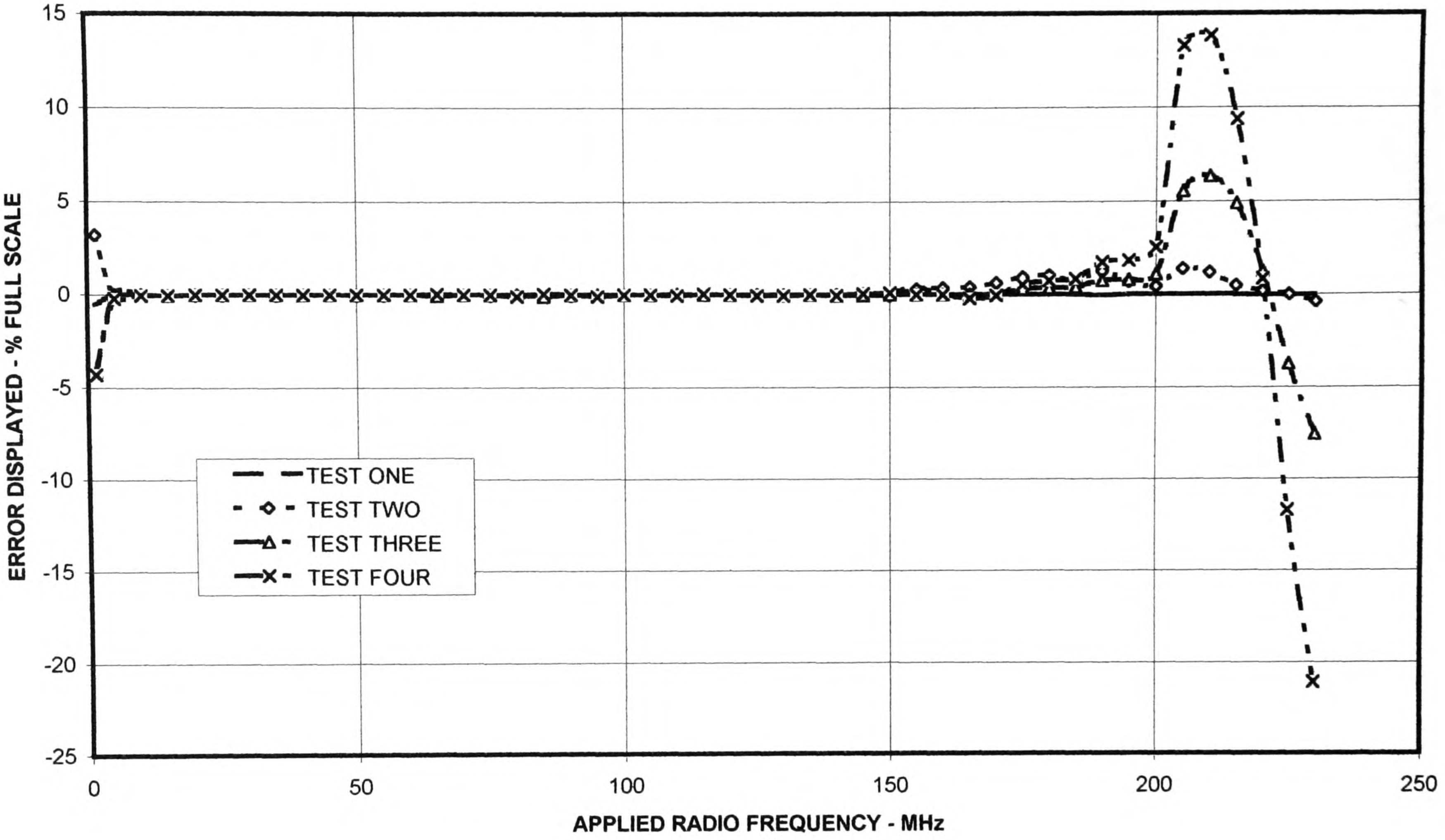
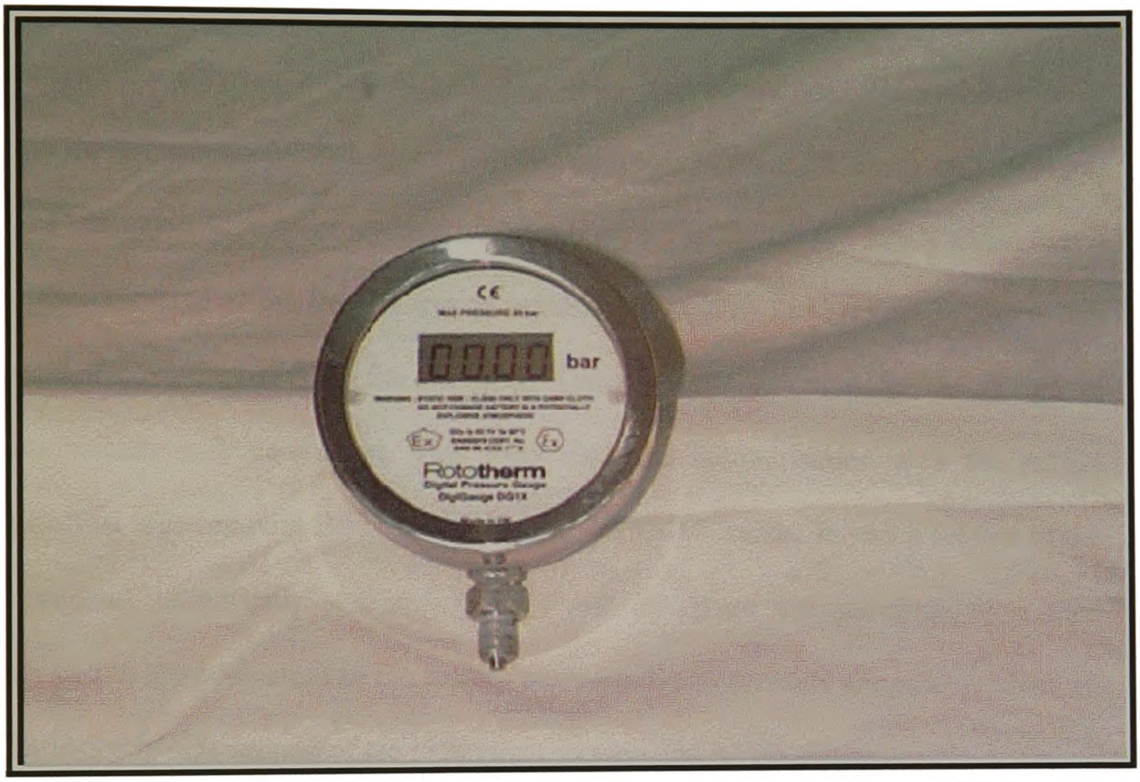


FIGURE 11

PROJECT THREE



ADAPTATION OF THE DIGITAL PRESSURE GAUGE TO PRODUCE AN INTRINSICALLY SAFE VERSION FOR USE IN HAZARDOUS ENVIRONMENTS WHERE FLAMMABLE ATMOSPHERES EXIST.

PROJECT THREE

ADAPTATION OF DIGITAL PRESSURE GAUGE TO PRODUCE AN INTRINSICALLY SAFE VERSION FOR USE IN HAZARDOUS ENVIRONMENTS WHERE FLAMMABLE ATMOSPHERES EXIST

Intrinsically safe apparatus can be defined as that which has been certified safe for use in industrial installations where potentially flammable atmospheres are present. The design of intrinsically safe apparatus is such that it cannot ignite a flammable atmosphere either in normal operation or under fault conditions. The certification of the design was undertaken by the British Approvals Service for Electrical Apparatus in Flammable Atmospheres - BASEEFA, a body of the Health and Safety Executive.

The objective of the Project was to refine the design of Project One so that it met with the requirements of the European Union ATEX directive for the design of intrinsically safe equipment. This work involved familiarisation with the ATEX directive together with BSEN50020 and BSEN 50014 standards which related to the design of intrinsically safe apparatus. These directives and standards were then applied to the adaptation of the battery powered digital pressure gauge to produce an intrinsically safe version of the instrument meeting the ATEX directive.

A) INTRODUCTION TO INTRINSIC SAFETY

On the 14th October 1913, a serious explosion occurred in the Senghenydd colliery, Glamorganshire, South Wales, resulting in the death of 439 Welsh miners. The findings of an official report on the disaster gave the cause as being an explosion of firedamp (the miners name for methane), ignited by "sparking from electric signalling apparatus or from falling rocks."[1] Due to this disaster, the concept of "intrinsic safety" emerged, though it was not known by this name initially.

At the time, the bare wire signalling system used to instruct the winch operator to pull back the full trucks of coal consisted of two galvanised steel wires suspended along the tunnels to the coalface. These wires were connected to a trembler bell or relay positioned by the winch operator. As a miner connected the two wires together by hand, with a shovel or steel T-bar, the bell would ring and the winch operator would pull back the coal.

This method of signalling was considered safe until the disaster investigations were undertaken by the British Home Office Experimental Station in Northumberland. These investigations proved that "break flash", which occurred at the contacts inside the bell or when the signalling wires were separated, could ignite flammable mixtures of methane and air. The "break flash" was largely due to energy stored in the inductive solenoid of the bell. It was discovered this could be reduced to a safe level by suppressing the coil, limiting the voltage to 25V, and restricting the energising current by a non-inductive resistor.

Subsequent signalling systems following these rules were tested and certified, and in 1917, were installed in British mines - where similar systems are still in use today. For the next 18 years this technique was used exclusively in the mining industry, and during this period of time the technique became known as "INTRINSIC SAFETY."

The first certificate was issued in 1936, with the first formal standard being issued in 1945. However, it was not until the 1960's that the technique of intrinsic safety came into its own for process measurement and control.

The basic objectives of intrinsically safe design are to:-

1. Limit current.
2. Limit voltage.
3. Limit stored electrical energy.

The CENELEC (European Committee for Electrotechnical Standardisation) standard EN 50 020 defines an intrinsically safe circuit as:-

> ***A circuit in which no spark or any thermal effect produced in the test conditions prescribed in this standard (which include normal operation and specified fault conditions) is capable of causing ignition of a given explosive atmosphere.***[2]

Two standards of intrinsic safety exist: as the higher standard, "ia" is where safety is maintained with up to two faults while "ib" is where safety is maintained with up to one fault. Equipment certified to "ib" standards is generally acceptable in all zones except Zone 0, and "ia" equipment is suitable for use in all zones. Zones are areas classified according to the probability of a potentially explosive atmosphere being present and the length of time for which it is likely to exist. These are:-

ZONE 0:	in which an explosive gas-air mixture is continuously present or present for long periods (more than 1000 hours a year.)
ZONE 1:	in which an explosive gas-air mixture is likely to occur in normal operation.
ZONE 2:	in which an explosive gas-air mixture is not likely to occur in normal operation, and if it does occur, it will exist only for a short time (less than ten hours a year.)

The ATEX Directive 94/9/EC is a directive adopted by the European Union to facilitate free trade in the EU by aligning the technical and legal requirements in the Member States for products intended for use in potentially explosive atmospheres. A product may only be certified as being intrinsically safe after it has been tested and passed as being intrinsically safe by a Notified Body, who can issue a certificate of conformity. A Notified Body is independent of the supply of the products and has the necessary technical competence and administrative structure to assess the conformity of products and manufacturers to the requirements of the Directive and standards.[3]

The Notified Body to which the digital pressure gauge was submitted for certification was BASEEFA (EECS) - British Approvals Service For Electrical Equipment in Flammable Atmospheres (Electrical Equipment Certification Service.) The level of certification for which the digital pressure gauge was submitted was **EEx ia IIC T4.** This breaks down as:-

EEx: Certified to the CENELEC standard.

ia: Protection concept of intrinsic safety (two faults, Zones 0, 1 and 2).

IIC: Apparatus group (gas group- IIC is acetylene)

T4: Temperature classification - T4 = 135°C. This relates to the maximum surface temperature of a piece of apparatus (normally assuming a 40°C ambient) to the ignition temperature of a gas.

B) BASEEFA / EECS CONSULTATION

On the 25 March 1998, a meeting was attended to seek the advice of EECS (BASEEFA) certifying officers regarding the intrinsically safe Digigauge (battery-powered version.)

Any aspects of the design which would cause difficulties during certification would be changed as required at an early stage; that is, prior to the submission of a formal application for ATEX certification. Consultation with EECS continued throughout the duration of the project. Those present at the meeting were:

Mr Tony Deaves, Certifying Officer EECS.

Mr Brian Parkinson, Certifying Officer EECS.

Dr Stuart Rowlands, British Rototherm.

Mr Chris Hutchens, University of Glamorgan (TCA, British Rototherm)

The principle aspects of the digital pressure gauge design that required the greatest analysis - in order to eliminate the possibility of ignition of the hazardous atmosphere due to sparking or thermal effects - were as follows:-

I. Electrical storage components, namely the inductance and capacitance present in the pressure transducer, power supply and non-volatile memory.

II. Mechanical layout issues to reduce the possibility of short circuits such as sleeving wires and insulating resistors.

A list of 22 explicit design recommendations were made as a result of the meeting. A summary of these recommendations was as follows:-

1. It is sensible to divide the digital pressure gauge circuit into two sections: i) an intrinsically safe power supply including the negative converter and protection components, ii) the pressure measurement circuit. By receiving BASEEFA/EECS approval for the power supply, this power supply can then be replicated in all other Rototherm instruments if required; an example being the Rototherm Digitemp digital thermometer.

Further intrinsic safety certification need only be sought on measurement circuitry. This provides a further extension of the integrated strategy adopted throughout this portfolio.

2. The BS EN 50014 and BS EN 50020 standards only cover apparatus for explosive atmospheres at standard pressure (up to 1.1 Bar.) The strategy adopted for the digital pressure gauge range of instruments ensured that these standards would not be compromised. This is because the pressure relief device (the breather) detailed at the beginning of **Project One** was specifically designed to operate when pressure inside the case reached 1 bar; in other words, the explosive atmosphere within the case cannot rise above the limits for safe operation detailed in the aforementioned standards.

3. The essential safety requirements (ESRs) that one must satisfy are listed in Annex 1 of BASEEFA's guide PO25. The ESRs are also listed in the schedule of the ATEX certificate for that apparatus. It is in fact the ESR which is the only significant difference between ATEX and BASEEFA certificates, so BASEEFA certificate at the same time as the ATEX certificate for a small additional charge.

4. If the pressure transducer used was a temperature compensated type, then a formal declaration from the manufacture of the transducer specifying the inductance and capacitance values is required. If a thermistor is used in the temperature compensation circuit then this may impact upon the maximum surface area allowed for small components.

5. The nominal rating of the series fuse was set according to surface temperature and power supply requirements.

6. Fault conditions associated with the inductor in the power supply in lieu of energy storage are reduced to safe level by fitting a series resistance to dissipate energy.

7. The level of energy storage possible within the charge-pump of the non-volatile memory (EEPROM) is low enough not to require changes or protection.

8. All resistors placed in series with capacitors are infallible resistors and those infallible resistors with PCB tracks passing underneath them must be insulated with a sleeving of minimum 0.5mm^2.

9. The leads to the pressure sensor must to be sleeved with additional insulation (having the usual minimum radial thickness of 0.5mm) to ensure that there is no risk of a short circuit as a result of a component tail on the underside of the PCB piercing the sensor lead insulation.

10. The dial will need to carry a warning that the battery must be changed outside the hazardous zone. If the battery is intended to be changed within the hazardous zone the battery and its protective safety devices must be replaceable as a single assembly.

11. No problems are expected with the 2 x AA battery holder as it is only possible to short circuit one cell in the event of a fault in the holder (faults in some types of 4 cell holders can short circuit two series-connected AA cells.)

12. BASEEFA will test a batch of ten cells of each type. If the maximum temperature rise permitted is 95°C, the rises recorded in the practical tests should be less than 90°C to allow a small extra margin of safety.

13. If axial electrolytic capacitors are specified check that the components have adequate (2mm) creepage distance at the positive lead.

14. When assessing the safe levels of capacitance, the capacitors should be lumped together to form an equivalent circuit. If it is necessary to do practical spark tests a separate equivalent network would be assembled - the tests would not be on the sample apparatus submitted to BASEEFA.

15. The ATEX directive requires the manufacturer to submit suitable quality documentation regarding apparatus operation.

16. Mechanical variations. Provided that the pressure sensor is always mounted in the pressure block, mechanical variations which do not affect intrinsic safety will be possible if a suitably worded warning is provided.

17. When certifying an I.S. design BASEEFA are primarily concerned with the values of safety-critical resistors such as those in the intrinsically safe power supply.

Other resistors may be given a wide value range, or indeed no value may be specified.

18. Printed circuit board track creepage distances will be assessed by BASEEFA.

C) ACTIONS TAKEN

As a direct result of the consultation with the certifying officers of BASEEFA/EECS, the following design changes were implemented:-

I. All capacitor values in the power supply circuit were reduced and infallible resistors were fitted in series with every capacitors. For example, capacitor C5 of the negative supply generator was reduced in value from 22μF to 4.7μF and an infallible resistor of value 10Ω was fitted in series with it.

II. An infallible series resistor was fitted in series with the power supply inductor to reduce energy storage.

III. A BASEEFA/EECS series fuse was fitted.

IV. A redesign of the PCB was completed to ensure creepage and clearance distances fully met the standards.

V. Sleeving was fitted to infallible resistors with PCB tracks passing underneath them and to transducer wiring.

VI. Temperature testing of "AA" cells under short circuit condition was undertaken, so that a list of cells deemed suitable for use in the intrinsically safe instrument could be submitted to BASEEFA/EECS for approval.

D) CURRENT STATUS

All 22 specific recommendations have been incorporated in a redesign of the battery powered digital pressure gauge and this, together with all circuit diagrams, gerber files (PCB layout files), documentation and prototype PCBs, has been submitted to BASEEFA/EECS.

A dialogue has continued with BASEEFA/EECS on a number of minor issues and full BASEEFA/EECS and ATEX certification of the digital pressure gauge is confidently expected by the end of March 1999.

E) CONCLUSION

Though still not formerly approved, this project has provided the background required to amend the battery powered stand alone digital pressure gauge instrument to one which is intrinsically safe and fully underscores the integrated design strategy adopted at the outset of the Project and discussed in the overview.

F) REFERENCES

1. Measurement Technology Limited, An Introduction To Intrinsic Safety, Seminar Notes, March 1997.
2. EN50020: 1977, Apparatus for potentially explosive atmospheres, CENELEC.
3. EECS, "ATEX Directive - Introduction", Issue 1 March 1996.