Newton, Barry and Chiffoleau, Gwenael J.A. and Steinberg, Theodore and Binder, Christian (2009) ***Adiabatic compression testing - part II : background and approach to estimating severity of test methodology.*** Journal of ASTM International, 6(8).

Symposium: ASTM Twelfth International Symposium on Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres

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ADIABATIC COMPRESSION TESTING II – BACKGROUND AND APPROACH TO ESTIMATING SEVERITY OF TEST METHODOLOGY

ABSTRACT: Adiabatic compression testing of components in gaseous oxygen is a test method that is utilized worldwide and is commonly required to qualify a component for ignition tolerance under its intended service. This testing is required by many industry standards organizations and government agencies; however, a thorough evaluation of the test parameters and test system influences on the thermal energy produced during the test has not yet been performed. This paper presents a background for adiabatic compression testing and discusses an approach to estimating potential differences in the thermal profiles produced by different test laboratories. A "*Thermal Profile Test Fixture*" (TPTF) is described that is capable of measuring and characterizing the thermal energy for a typical pressure shock by any test system. The test systems at Wendell Hull & Associates, Inc. (WHA) in the USA and at the BAM Federal Institute for Materials Research and Testing in Germany are compared in this manner and some of the data obtained is presented. The paper also introduces a new way of comparing the test method to idealized processes to perform system-by-system comparisons. Thus, the paper introduces an "*Idealized Severity Index*" (ISI) of the thermal energy to characterize a rapid pressure surge. From the TPTF data a "*Test Severity Index*" (TSI) can also be calculated so that the thermal energies developed by different test systems can be compared to each other and to the ISI for the equivalent isentropic process. Finally, a "*Service Severity Index*" (SSI) is

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introduced to characterizing the thermal energy of actual service conditions. This paper is the second in a series of publications planned on the subject of adiabatic compression testing.

Introduction:

The compressed gas industry and government agencies worldwide utilize "*adiabatic compression*" test methodologies for qualifying high-pressure valves, regulators, and other related flow control equipment for gaseous oxygen service. This test methodology is known by various terms including adiabatic compression[5] testing, gaseous fluid impact[6] testing, pneumatic impact testing, and BAM[7] testing as the most common terms. The test methodology will be described in greater detail throughout this document but in summary it consists of pressurizing a test article (valve, regulator, etc.) with gaseous oxygen within 15 to 20 milliseconds. Because the driven gas[8] and the driving gas[9] are rapidly compressed to the final test pressure at the inlet of the test article, they are rapidly heated by the sudden increase in their internal energy to sufficient temperatures (thermal energies) to sometimes result in ignition of the nonmetallic materials (seals and seats) used within the test article. In general, the more rapid the compression process the more "adiabatic" the pressure surge has been presumed to be and the more like an isentropic[10] process the pressure surge has been argued to simulate.

Generally speaking, adiabatic compression is widely considered the most efficient ignition mechanism for directly kindling a nonmetallic material in oxygen and has been implicated in many fire investigations. The temperature rise by near-adiabatic compression has commonly been calculated by assuming ideal gas behavior through the polytropic equation[11] considering

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[5] While various terms are used for the type of testing discussed herein, adiabatic compression testing is the term that will be used most frequently in this document. This term is chosen not because it is an accurate description, but because it is used most widely within the industry. It is actually the methodologies irreversibility's and non-adiabacity that this research program is evaluating.

[6] Gaseous Fluid Impact is the official description given by ASTM Committee G04 (see Reference 11)

[7] BAM stands for Bundesanstalt für Materialforschung und – prüfung and is the German Federal Institute for Materials Research and Testing where the test methodology dates back to the 1950s. The test method was also implemented by the National Aeronautics and Space Administration (NASA), in a somewhat different form, after the 1970s; and by such companies as AIRCO, RegO, AGA, and Circle Seal as discussed in the first paper of this series (reference 1).

[8] Atmospheric pressure oxygen originally in the system piping or tubing upstream of the test article;

[9] Oxygen gas originally contained in a high-pressure accumulator and separated from the driven gas by a fast operating valve.

[10] It is noteworthy that while shock wave processes are not discussed in this paper, the faster the pressurization the more likely that shock processes may develop during a pressure surge. Faeth [16] argues that if the time of the event (pressure rise time) is not much slower than the tube length divided by the local speed of sound, (i.e., $t_{rise} >> length/sound_{speed}$) then shock processes are more likely and localized pressure disturbances can be expected.

[11] The temperature produced by adiabatic compression is usually calculated using isentropic relationships assuming that the oxygen behaves like an ideal gas and that the compression process is sufficiently rapid that heat transfer

isentropic behavior (reversible and adiabatic). However, the adiabatic compression process as required by the industry standards has never been thermodynamically modeled and empirically verified, although attempts have been made.
This research evaluates these questions:

1) Can the compression process required by the industry standards be thermodynamically and fluid dynamically modeled so that predictions of the thermal profiles produced be made,

2) Can the thermal profiles produced by the rapid compression process be measured in order to validate the thermodynamic and fluid dynamic models; and, estimate the severity of the test, and,

3) Can a new industry standard be prepared to resolve inconsistencies between various test laboratories conducting tests according to the present standards?

This paper is the second of a series of publications that are planned to evaluate these questions and will present the background and initial testing that has been conducted in the current research. More complete system-to-system comparisons, detailed analysis of the temperature-time histories of the current test systems, modeling of shock-wave processes and testing to evaluate whether shock waves are present in the transient compression will be forthcoming in later publications.

The first paper in this series, "*Adiabatic Compression Testing I – Historical Development and Evaluation of Fluid Dynamic Processes Including Shock-Wave Considerations*" [1] presents the

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does not occur during the short time of the pulse (i.e., essentially adiabatic). The form of the equation normally used to calculate the final temperature is:

$$T_f := T_i \cdot \left(\frac{P_f}{P_i}\right)^{\frac{(k-1)}{k}} \qquad (1)$$

where: T_f = Final Temperature (abs)
T_i = Initial Temperature (abs)
P_f = Final Pressure
Pi = Initial Pressure
k = ratio of specific heats for oxygen (1.4)

author's understanding of the historical development of the current test method and some of the fluid dynamic processes that may influence the temperature of the compressed gas. The first paper introduces the conclusion that shock-wave processes might be present during a pressure surge; but, that neither their presence nor strength is currently understood. The research anticipated in this series will attempt to resolve this question and expects to use both measurement and computational fluid dynamic modeling. This paper, the second in the series, outlines the background of the current test methods that are widely used and the importance of understanding the thermal profiles that are produced by the various test systems. It also presents a measurement scheme that has shown promise in measuring the thermal profiles that are produce by different test systems. The measurements obtained by the time of publication had not resolved whether shock processes are present in a pressure surge conducted according to the standards; but, further testing is currently planned and will be presented in a later publication in this series. Historically, the oxygen safety community has focused its attention on the heating that occurs in the driven gas (i.e., gas being compressed by the high-pressure slug); and, has considered this process to be isentropic. This is the perspective that will be taken in the material presented in this paper.

Testing Background:

Historically adiabatic compression processes are often depicted by the illustration shown in Figure 1. In sequence 1, as illustrated, a volume of low pressure gas at an initial pressure and temperature is isolated from a volume of high pressure gas by a valve (or other isolating element). Another closed valve provides a dead-end to the low pressure volume. If the upstream valve is opened rapidly, as illustrated in sequence 2, then the low pressure gas, hereafter defined as the ***driven gas***, suddenly undergoes a compression process by the high pressure gas, hereafter defined as the ***driving gas***, which flows through the newly opened valve. The "*P-dV*" work done by the driving gas causes a temperature rise in the driven gas. This temperature rise is often considered to be "adiabatic" as long as the pressure rise rate is sufficiently rapid, as compared to the development time for conduction and convective heat transfer. During the compression process, the driving gas also goes through state changes, both expansion and recompression. Therefore an increase in temperature also develops in the driving gas, especially in the gas that flows into the impact tube in the early stages of the compression process. The degree of mixing between the driving and driven gases is an important element influencing the maximum temperature achieved by the compression process.

Statement of Industry Problem:

The test laboratories who commonly conduct this testing worldwide are indicated in Table 1[12]. While each test laboratory meets the requirements of the predominant standards currently in use, subtle differences exist in the test equipment operated at the different laboratories (discussed further below) which is believed to produce variations in the test results. **Significantly, t*hese variations have been argued to result in some components passing the tests at one laboratory while failing at another*.** This disparity in results is of great concern to the industry since the adiabatic compression test is fundamentally a test to ensure that safe and reliable components are placed into the public marketplace.

Table 1 – Laboratories That Carry Out Adiabatic Compression Testing.

Test Laboratory	Location	High-Speed Valve Design	Pressurization Rate Control
BAM	Berlin, Germany	Globe Valve	3.5 mm Orifice
CTE – Air Liquide	Paris, France	Sliding Gate Valve	4.3 mm Orifice
Apragaz	Brussels, Belgium	Sliding Gate Valve	Unknown orifice size
DNV	Norway	Unknown	Unknown
WHA	Las Cruces, NM USA	Ball Valve	Valve Opening Speed
NASA - WSTF	Las Cruces, NM USA	Ball Valve	Valve Opening Speed
NASA - MSFC	Huntsville, AL USA	Ball Valve	Valve Opening Speed

Figure 2 shows a component that “passed” the current test method but was withdrawn from the marketplace by a “safety recall” instituted by the United States Food and Drug Administrations Center for Devices and Radiological Health due to ignitions in service. It is important to understand, however, that the ignitions that occurred in the field were attributed more to design problems on this device than to adiabatic compression testing problems. However, this example does illustrate the importance of high fidelity in the testing methodologies.

One problem with properly defining the test methodology is the lack of a thorough understanding of the state processes that the driving and driven gases go through during actual service conditions or during the testing. To our knowledge, while several attempts have been made, no thermodynamic or fluid dynamic model has been validated by testing that specifies the state conditions of the gas and predicts the thermal profile (e.g., temperature versus time profile) of the driving and driven gases during the compression process. As a consequence, calculation of the thermal energy in the compressed gas has not been utilized in the design of the test method to establish the safety margins provided by the test results. Further, no testing

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[12] It is noteworthy that Western Enterprises, Victor Equipment Company (United States) and the Cavagna Group (Italy) also have the capability of conducting adiabatic compression testing on the components they manufacture. To our knowledge, however, their test systems are not commercially available.

has been able to confirm the thermal energies produced within the cylindrical tube sections upstream of a test article due to the very rapid pressurization rates (~ 15 to 20 milliseconds to full pressure) encountered in this testing, and then relate that thermal profile to the potential for ignition or statistical variations between test laboratories.

An important outcome of this research will be to utilize this research in the preparation of an ASTM International test standard that will specify the critical control elements for test systems conducting adiabatic compression testing worldwide[13].

Test Method Background:

The testing of interest here is conducted in different ways by different test laboratories but the fundamental system requirements are few. For illustration purposes the WHA test system is shown in Figure 3 along with the pressure profile that is required by the predominant standards. The test is typically conducted by pressurizing a test article (valve, regulator, etc.) very rapidly by opening a high-speed valve (impact valve), simulating a sudden pressurization that might occur in service. When the impact valve is opened, high pressure oxygen stored in an accumulator at 1.2 times the test article working pressure and pre-heated to 60 °C pressurizes a test article positioned at the end of an impact tube within 15 to 20 milliseconds. According to the standards, the impact tube (volume of oxygen to be compressed upstream of the test article) is either a 5 mm-ID tube that is 1-meter long or a 14 mm-ID tube that is 0.75-meter long depending on whether the test article is intended for use on a cylinder or on a manifold. As shown in Figure 3, after the rapid pressurization, the test article is held at the test pressure for at least 10 seconds to allow ignition and propagation to develop if the test article nonmetallic materials are vulnerable by this method. After this hold period, the test article is vented to ambient pressure and allowed to cool for a minimum of 3 seconds before the test cycle is repeated within 30 seconds. According to most standards, twenty test cycles are typically performed with the test article closed (regulator reduced or valve closed) and another 20 with the test article open (regulator increased or valve opened) and the discharge port plugged. Successful completion of the 40 cycles completes the test series.

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[13] ASTM International Committee G04 formed a task group to develop a standard that will specify the way adiabatic compression testing is conducted in the future. Most of the test laboratories listed in Table 1 have agreed to participate in this evaluation and in the development of a standard to specify the test system controls to be implemented. Several industry working groups such as the ISO/TC 58/SC 2/WG 6 subcommittee responsible for adiabatic compression testing of compressed gas cylinder valves and their counterparts from the Compressed Gas Association in the United States have requested that the ASTM International standard development efforts be coordinated with these ISO and CGA committees.

Figure 4 shows the relationship between the sensible heat developed by the compression process (Q_{cal} in the driven gas) and the temperature rise developed by a small mass of a nonmetallic material (considering an isentropic process); assuming that all the sensible heat is used to uniformly raise the temperature of the plastic. While near-adiabatic compression is known to readily kindle most flammable nonmetallic materials in oxygen, the actual temperature-rise rate and maximum temperature achieved in real systems has never been measured in real time.

Recently some effort to correlate real-gas behavior to the compression process has been made; but, empirical measurements have not been successful in large part due to the temperature rise occurring over such a small time increment (< 20 msec). Further, since empirical measurements have been largely unsuccessful, no methodology has been developed to compare pressure surges produced by two different test systems that utilize different components to produce the pressure surge. So, the actual correlation of the temperature-rise rate in any test system to the behavior shown in Figure 4 is unknown.

Since adiabatic compression is such a common ignition mechanism in gaseous oxygen systems and has routinely been implicated as the primary reason for component ignition failures, many industry groups including the International Standards Organization (ISO), the United States Compressed Gas Association (CGA), Australian Standards Organization, and ASTM International require the performance of adiabatic compression testing to qualify nonmetallic materials and pneumatic components (primarily high-pressure valves, regulators, flexhoses, etc.) intended for use in high-pressure oxygen systems, as illustrated by Table 2. Table 2 is a summary of some of the international standards requiring adiabatic compression testing of components. This table is not exhaustive and several more standards could be included. As is evident, however, this test methodology has gained very wide subscription through out the world. *It is rapidly becoming one of the most important test methodologies for high-pressure component validation in the oxygen industry*.

The historical development of the test method is traced in the companion paper in this series [1]; but it is noteworthy that early work was performed by companies such as AIRCO, RegO and Circle Seal. The German Federal Testing Institute, BAM, developed a test capability in the 1950s and early 1960s [1-3]. The first German standard in which it was included was DIN 477:

1963-11, which involved conducting 50 repetitive pressure surge (pneumatic impact) cycles. Each pneumatic impact cycle was repeated every 10 seconds and exposed the component to a pressure surge from ambient to its maximum working pressure.

The test method was modified by the Air Liquide Corporation in the 1980's [4-6] for component testing, which led to several changes in the way in which adiabatic compression testing was performed. The most important of these changes was the requirement to use a 5-mm internal diameter impact tube of 1-meter in length. The Air Liquide contributions to the test methodology also led to the incorporation of test criteria into many international standards described in Table 2.

Presently, all prevalent test standards except ASGM G74 require 20 pressure surge cycles be performed. Two test configurations are generally required for each component: closed and open/plugged and generally the test (i.e., required number of cycles in each of two configurations) is repeated with three test articles. The same two configurations are required on cylinder valves with the exception that the pressure surge is applied to the outlet of the cylinder valve, instead of its inlet, in order to evaluate the potential for ignition during cylinder filling operations.

In the 1970's NASA-WSTF conducted adiabatic compression testing of components in oxygen and was responsible for all qualification of oxygen components for ground support and space shuttle operations. During the 1980s and up to the present, NASA required that all gaseous oxygen handling components be qualified by passing adiabatic compression testing [7-10]. The NASA-WSTF test system configuration was used as an example of a suitable system in 1982 by the American Society for Testing and Materials (ASTM, now known as ASTM International) in ASTM Standard G-74, "*Standard Test Method for Ignition Sensitivity of Materials to Gaseous Fluid Impact"* [11, 12]. However, ASTM G74 did not mandate design criteria for any specific system and allowed some variation in the specific configuration.

In 1989, Wendell Hull & Associates, Inc, (WHA) who conducts forensic investigations of fires and explosions, including oxygen equipment fires developed an adiabatic compression test system similar to the NASA-WSTF system; but, was also consistent with the predominant compressed gas industry adiabatic compression test methods that were gaining wide subscription in the industry [13]. At that time, WHA was the only commercially available test laboratory in the United States for this testing.

Table 2 – International Standards that Include Adiabatic Compression Test Requirements (not exhaustive).

Standard	Title of Standard	Date	Test Pressure	Pres Rate	Gas Temp.	Failure / Cycles	Cycle Interval	Impact Line Length	Impact Line ID
ISO 2503	Pressure regulators for gas cylinders used in welding, cutting and allied processes	1983	20 MPa	20 ms	60 ±3 °C	0/20	30 s		
EN 585	Gas welding equipment - Pressure regulators for gas cylinders used in welding, cutting and allied processes up to 200 bar	1994	24 MPa	20 +0,-5 ms	60 ±3 °C	0/20	30 s	1 m	5 mm
CGA E-4	Standard for gas pressure regulators	1994	1.2 times MWP	20 +0,-5 ms	60 ±3 °C	0/20	30 s	1 m	5 or 12 mm
ISO 10524	Pressure regulators and pressure regulators with flow-metering devices for medical gas systems	1995	24 MPa	20 +0,-5 ms	60 ±3 °C	0/20	30 s	1 m	5 mm
AS 4267	Pressure regulators for use with industrial compressed gas cylinders	1995	MWP	20 ms	60 ±3 °C	0/20	30 s	1 m	> 3 mm
EN 849	Transportable gas cylinders - Cylinders valves - Specification and type testing	1996	1.2 times MWP	20 +0,-5 ms	60 ±3 °C	0/50	30 s	1 m	5 mm
EN 738-1	Pressure regulators for use with medical gases - Part 1: Pressure regulators and pressure regulators with flow metering devices	1997	24 MPa	20 +0,-5 ms	60 ±3 °C	0/20	30 s	1 m	5 mm
BS-EN 849	Transportable gas cylinders - Cylinders valves - Specification and type testing	1997	1.2 times MWP	20 +0,-5 ms	60 ±3 °C	0/50	30 s	1 m	5 mm
ISO/DIS 2503	Gas welding equipment - Pressure regulators for gas cylinders used in welding, cutting and allied processes up to 300 bar	1997	1.2 times MWP	20 +0,-5 ms	60 ±3 °C	0/20	30 s	1 m	5 mm
AS 3840.1	Pressure regulator for use with medical gases Part 1: Pressure regulators and pressure regulators with flow-metering devices	1998	1.2 times MWP	20 +0,-5 ms	60 ±3 °C	0/20	30 s	1 m	5 mm
EN 738-3	Pressure regulators for use with medical gases - Part 3: Pressure regulators integrated with cylinder valves	1999	24 MPa	20 +0,-5 ms	60 ±3 °C	0/20	30 s	1 m	5 mm
ASTM G175	Standard Test Method for Evaluating the Ignition Sensitivity and Fault Tolerance of Oxygen Regulators Used for Medical and Emergency Applications	2003	Specifies use of ISO 10524 for adiabatic compression testing						
CGA V-9	Compressed Gas Association Standard for Compressed Gas Cylinder Valves	2004	1.2 x MWP	20 +0,-5 ms	60 ±3 °C	0/20	30 s	1 m	5 mm
ISO 10297	Gas cylinders - Refillable gas cylinder valves - Specification and type testing	1999	1.2 times MWP	20 +0,-5 ms	60 ±3 °C	0/20	30 s	1 m	5 mm
ASTM G74	Standard Test Method for Ignition Sensitivity of Materials to Gaseous Fluid Impact	1982	To 69 MPa	50 +/- 3 ms	20 °C	0/20 or 1/60	12 s	238 mm	7.9 mm

Variability Among Test Systems

A recent effort has begun within standards organizations to generate commonality between all the test methodologies within each of the various test standards. One of the test parameters being changed is the requirement for 50 test cycles for cylinder valves, which is in the process of being reduced to 20 test cycles to be consistent with the regulator requirements. However, the predominant test laboratories that conduct this testing (see Table 1) report variations in the pass/fail performance of identical test articles. ***In other words, test articles that pass the testing at one laboratory sometimes fail the test at another laboratory.*** Consequently, the statistical reliability and associated validity of the test results has been questioned.

In an effort to better understand the test variances, WHA personnel visited all of the test laboratories except DNV (yet to be scheduled) to evaluate whether the test methodology varied from laboratory to laboratory. While all of the laboratories meet the limited standardized requirements for conducting this test, such as pressurization rate and impact tube configuration (length/diameter), significant differences were observed in the hardware utilized and in the system configurations. Some of the more important differences are listed in Table 1.

One important difference observed was the design of the high-speed impact valve utilized to produce the pressure surge (see Table 1). This valve is very rapidly opened at the start of a test cycle to suddenly pressurize a test article (either a nonmetallic material or a component). Most importantly, the pressurization profile could be very different due to the way in which the valve opens, as shown in Figure 5. This figure demonstrates the variability in the percent of flow for different valve configurations and illustrates that since the different laboratories do not use similar valve configurations that the pressurization profiles downstream of the valve should exhibit different pressurization profiles. Further, since the flow coefficients and flow turbulence of these valve types also varies (WHA Ball Valve: Cv ~27; BAM Globe Valve: Cv 4.7 to 8.5), the pressurization dynamics for these two systems would also be expected to be different and produce different thermal events as a function of turbulence and mixing effects.

Indeed, as Figure 6 demonstrates, the pressurization profiles recorded by the dynamic pressure transducers do exhibit differences and the effect on the thermal profiles produced upstream of the test article is the subject of this research. Figure 6 depicts the results of testing performed by WHA to compare the WHA and BAM thermal profiles and also shows the respective pressure profiles for a 200 bar-g pressure pulse obtained on a typical test cycle with a high-speed dynamic (quartz crystal) pressure transducer. The valve used by WHA is a typical ball valve. The valve used by BAM is a typical globe valve. Other test systems, such as CTE and NASA-WSTF have also been characterized but the results of those evaluations are not included herein; and, if permission is received, will be addressed in a future paper in this series. Figure 6 also demonstrates the temperatures that were obtained at four different positions by the WHA Thermal Profile Test Fixture (TPTF) to be described later. The temperatures plotted in this figure were obtained by Type K (chromel-alumel) thermocouples of 0.025-mm (0.001-inch) diameter. It is noteworthy that BAM utilizes an orifice to control the pressurization rate whereas WHA uses a variable speed valve to control pressurization rate. The influence of these two approaches will be more thoroughly discussed in another paper that will compare the thermal profiles of the various test systems.

As is also depicted in Figure 6, the temperatures obtained during the pressure pulse vary from system to system and do not obtain the temperatures calculated by the classical means using isentropic relationships (1241 ^{o}C) [3-6, 13, 15-16]. It is, of course, recognized that the thermocouple response times may not be sufficient to fully represent the transient temperatures present in the pressure pulse (another subject of this research).

As mentioned above, another parameter that varies among the test systems is the method for controlling the pressurization rates, also recorded in Table 1. WHA, NASA-WSTF, and NASA-MSFC use a variable speed ball valve to control flow rate. BAM and CTE use an orifice (of different dimensions) to control the pressure rise. The thermodynamic states undergone by the driving gas (gas from the accumulator) and driven gas (gas initially at 1-atm being compressed to test pressure) is expected to vary from system to system because of these differences, as illustrated in Figure 7. Figure 7 presents an idealized depiction of the state processes (Temperature – Entropy) that the WHA and BAM driving and driven gases undergo during a pressure pulse, if the flow differences between the valves are ignored and only state processes considered.

The WHA and NASA state processes are relatively straight forward. If it is assumed that the perfect gas laws hold, that no heat is transferred in the valves and no mass is stored, then the gas from the accumulator can be idealized to enter the downstream pipe at its initial temperature and at the pressure of the downstream pipe (P_3, 1-atm). It is then recompressed to its original pressure (P_0) and undergoes a corresponding isentropic temperature rise shown from state 2 to state 3. The final idealized temperature is shown at position 3 on the temperature-entropy diagram for the WHA state process in Figure 7.

The BAM and CTE systems, by comparison, go through a similar state change through the valve but recompresses to a new intermediate pressure (state 3) at the orifice before expanding again while flowing through the flow control orifice (states 3 to 4). The recompression process at state 3 could be expected to increase the temperature of the driving gas before it expands through the orifice to recompress again to its original pressure. The final state change is reflected in Figure 7 at position 5 for the BAM state processes. As shown in the idealized diagrams, the temperature increase by the adiabatic compression process in the BAM system could be expected by this analysis to be greater than in the WHA system, even though the pressurization rate requirement is met by both systems.

Another system difference between the WHA and BAM systems is the length of the tubing between the accumulator and the high speed impact valve. The BAM system includes a length of tubing 6-meters long between the accumulators and the impact valve. The WHA system is more closely coupled to the impact valve and incorporates a length of tubing no more than 0.5-meters long. If the gas entering the impact valve decreases in pressure during compression process, due to pressure expansion down the tubing run from the accumulator, then the state changes for the driving gas entering the impact valve can be idealized as shown in Figure 8. If the pressure drops at the inlet to the impact valve then the state processes are shown by the red lines in Figure 8 and lead to a final recompressed temperature of 5’, which could be substantially lower than previously predicted.

At present, these uncertainties are being evaluated; but, the potential change in the outcome of an adiabatic compression test is readily evident by the temperature predictions. ***More importantly, no test standard presently available (Table 2)***

specifies the test system configuration requirements that would be expected to control these potential differences.

It is important to note here that the data we currently have available is generally consistent with Figure 6 and will be presented in detail in another paper in this series. However, the thermal profiles for BAM and WHA do not vary greatly from one another as Figure 6 illustrates and the maximum temperatures are generally within ~50 ^{o}C for these two systems. The data cannot be fully discussed in this paper, but, it should be observed that the influence of the orifice does not seem to predispose the BAM system to higher temperatures, probably due to the close coupling of this orifice at the immediate outlet of the high-speed valve, which minimizes the recompression influence. Mixing of the driving and driven gases might occur downstream of the orifice due to turbulence, but, this influence is still under evaluation. Further, while the BAM tubing length between their primary accumulators and their high-speed valve measures about 6-meters, the inside diameter of this line is large (14-mm or greater) and therefore does not restrict the re-supply of oxygen/pressure to the high-speed valve during a pressure surge. This 6-meter line is also heated, so, for all practical purposes seems to function as similar to a smaller accumulator. The idealized influences that are pointed out in the temperature-entropy relationships of Figures 7 and 8 are nevertheless valid; but, this testing has shown these factors to be of less importance on the BAM system. However, a system that did not closely couple the orifice to the high-speed valve and/or utilized a supply line that choked the flow would be expected to behave very differently, even though the two systems would be schematically identical.

Methodology and Research Approach

This research anticipates that the thermal energy from a rapid pressure surge in oxygen will generate sufficient sensible heat to ignite nonmetallic materials either placed at the dead end of the impact tube or within the seat assemblies of valves and regulators. Consequently, the rate at which this sensible heat is generated by the pressure surge and the maximum temperature that is developed are measurable quantities sufficient to characterize the pressure surge itself and the equipment used to create the pressure surge. Therefore the research described here sought to both thermodynamically model the pressure surge and to measure empirically the temperature rise rate as a function of time (thermal profile) during the period in which the pressure rise was occurring (generally 20 milliseconds according to the predominant test standards).

The challenges that this research encountered were twofold:

1) **Modeling:** One challenge was to determine empirically the processes undergone by the compressed gas (isentropic or shock or a combination of both) and to then model those processes with sufficient fidelity so that predictions of the thermal energy can be made and measured. The background for the fluid dynamic processes considered and the results of the modeling will be discussed in a separate paper.

2) **Measurement:** Another challenge was to develop and validate a way to measure the temperature rise as a function of time during the compression process and thereby to compare the performance of one test system to another. If a method of measuring the thermal profile (temperature vs. time) of a pressure surge could be developed then the thermal energy contained within the pressure surge and the energy development rate could be directly compared between test systems, as illustrated in Figure 9. The 2^{nd} objective, measurement, will be discussed herein since much of this initial research has been focused on developing a measurement approach.

Measurement:

As shown in Figure 9, characterization of the thermal energy in a pressure surge can in principle be achieved by measuring the temperature vs. time changes and the maximum temperature attained. While the figure labels the area under the temperature curve as“energy”, it is understood that the energy is really the summation of the mass compressed (m) times the specific heat of the gas (Cp) times the temperature rise (ΔT) for each increment of time. However, the major contribution to the energy differences is expected to be the temperature rise or thermal profile. Measurement of the thermal profile should allow system comparisons to be made and integration of the total thermal energy required at the time of ignition to be correlated. Regardless of the process that is producing the temperature rise, ultimately, measurement of the thermal profile should allow for system comparisons to be made and process conditions to be evaluated, for systems having sufficiently similar volumes undergoing compression.

The experimental approach that is suggested herein was first attempted by Faeth [16] on systems of larger size and slower pressurization rates than those presently utilized; but was used with good success. Faeth assumed that the temperature response of a thermocouple (rise time) could be considered to be infinitely fast if the thermocouple bead had essentially zero mass.

His approach used was to take repeated measurements with two different sized thermocouples and then extrapolate the temperatures measured in the compression process to zero diameter. This approach was successful and compared favorably to an isentropic model that included heat transfer influences; but Faeth utilized a linear extrapolation between two differently sized thermocouple beads (0.025-mm (0.001-inch) and 0.076-mm (0.003-inch)); each utilized on different test runs. No simultaneous measurements were made and no validation of the extrapolation order (i.e., linear, first order) was attempted.

A similar approach was utilized in this research except that a thermocouple array has been designed to allow for simultaneous measurement of the temperature in the driving and driven gas at three locations (at the same plane) along at least four different planes in the impact tube. A typical thermocouple array is shown in Figures 10 and 11. Each array comprises three thermocouples of 0.025-mm (0.001-inch), 0.051-mm (0.002-inch), and 0.076-mm (0.003-inch) bead diameters. Testing has also been conducted with thermocouple arrays having 0.013-mm (0.0005-inch), 0.025-mm (0.001-inch), and 0.051-mm (0.002-inch); but, due to the fragile nature of the 0.013-mm diameter thermocouples, the 0.025-mm, 0.051-mm, and 0.076-mm array has been preferred for most of the testing. The different sized beads provide different response times to the thermal process at almost the same location; and, indeed, the 0.013 (0.0005-inch) thermocouple does provide faster response and thus measures higher temperatures. Therefore, a means to improve the fragile nature of this thermocouple is still being sought.

Several different types of thermocouple devices have also been evaluated including the NANMAC fast-response (“eroding bead”) thermocouples [17], Paul Beckman Company micro-miniature thermocouples [18], and fine-wire beaded thermocouples. Several research articles describing the development and use of fast-response thermocouples have also been referenced for background [19-24] and aid in the construction of a measurement system. The NANMAC and Beckman fast response thermocouples were utilized and compared to small diameter 0.013-mm, 0.025-mm and 0.050-mm diameter exposed bead thermocouples. For the testing conducted herein, the 0.0005-inch and 0.001-inch exposed bead thermocouples provided faster rise times and reproduced the temperature of a step input signal (short pulse of hot air of known temperature) than either the NANMAC or Beckman thermocouples. Thus, the exposed bead thermocouples were preferred.

The Thermal Profile Test Fixture (TPTF) designed for these arrays is shown in Figures 12 and 13. Each measurement position can collect temperature data on each thermocouple array in real time. Two positions are provided to collect dynamic pressure data during the short time of the pressure surge. The illustrations only show one position for dynamic pressure; but, two positions are actually designed into the TPTF, one at the upstream end and one at the downstream end. A data acquisition system has also been developed capable of taking temperature data every 70 to 100 microseconds on each temperature and pressure channel (total of 12 temperature channels and two pressure channels). Pressure volume calculations confirm that the driven gas will occupy approximately 2.3 cm at the end of the TPT fixture, if mixing is ignored. Therefore, Positions 1 and 2 should provide data pertaining to the driven gas and Positions 3 and 4 should provide data pertaining to the driving gas. If mixing develops, which is expected, then Position 3 will be expected to provide helpful data to evaluate the mixing influences.

The TPTF described here has been recently used to begin characterization of the WHA and BAM test systems in an effort to evaluate the research approach. For these tests an identical TPT fixture was used on these four test systems and the same thermocouple arrays were utilized on each. The position and clocking of each array was maintained during this testing.

Figures 6 and 14 show actual data taken on the WHA and BAM test systems with the TPTF and demonstrate that differences between the test systems is measureable based on the methodology suggested here. Figures 6 and 14 provide actual data taken by the thermocouples in real time. While the temperatures should not be considered as more than indications at this point in time, the methodology does suggest that with sufficient refinement and validation of the measurement that a means of characterizing the thermal profile of various systems and evaluating the effects of the different hardware can be achieved.

Figure 15 symbolically illustrates an extrapolation procedure that is being evaluated to produce an estimate of the temperature for an imaginary "zero-diameter" (infinitely fast response) thermocouple, similar to the method that Faeth utilized. The extrapolation uses the reading of each thermocouple at each time increment to derive a temperature based on an instantaneous rise time from a pseudo zero-mass thermocouple. The extrapolation should in reality be based on how the heat transfer develops an "emf" in the thermocouple bead; but, the form and order of the heat transfer is still being verified by a calibration process. However, the approach shown in Figure 15 illustrates a simple curvilinear fit to the data obtained from each thermocouple at each time increment. Successful tests with the 0.013-mm diameter thermocouple indicated that the temperatures produced momentarily by the adiabatic compression process do produce higher temperatures than measured by the 0.025-mm diameter thermocouple. Further, when the extrapolation scheme is applied to the 0.025-mm, 0.051-mm, and 0.076-mm data, and extrapolations are carried out to predict the temperature of a 0.013 thermocouple, the measured and extrapolated temperatures are within that do approximate the temperatures calculated by the extrapolation method.

Figure 16 shows this procedure applied to the data taken at position 1 (the dead end) for the WHA test results originally shown in Figure 14. As shown, by this procedure the maximum temperatures estimated are exaggerated by the differences in the three thermocouple readings at each time increment, due to the response time of each individual thermocouple. This approach predicts a maximum temperature for an infinitely fast, near-zero mass, thermocouple of 623 ^{o}C, whereas, the maximum temperature measured by the 0.025-mm thermocouple was 391 ^{o}C. Examination of the approach has indicated that the greater the difference in the measurements, at each time increment, the greater the predicted temperature when the extrapolation technique is used. Therefore, additional work on the uncertainty in the temperature measurements must be performed before the technique can be considered valid.

Figures 17 and 18 show the thermal profiles for WHA and BAM for 200 barg tests during one cycle of a 20-cycle test series. The actual temperatures measured and the extrapolation predictions are shown for each of the four positions of the thermal profile test fixture. The clear differences in the pressurization profile dynamics (i.e., pressure transducer response curves) are still under investigation; but, since the same transducer was used for each system, they are believed to be real fluid dynamic differences between WHA and BAM.

The measurements do indicate that thermal energy in the compressed gas can be measured at each of the four TPT fixture locations and that differences between the test systems can be characterized.

Future Work:

This research has shown that a method of characterizing the thermal profile of an adiabatic compression test has been developed which is capable of determining whether differences in the thermal energy between different test systems exist. WHA is currently undertaking to characterize and analyze the thermal profiles of all of the predominant test systems that perform this testing and is developing data analysis routines to deal with the massive amount of temperature data that is produced during these characterization tests. Further, fluid dynamic modeling and shock-wave analysis of the compression process is underway to aid in predicting the actual state processes undergone and the gas temperatures that would be expected from a rapid pressurization test.

The system-to-system comparisons based on the thermal profiles is also underway along with an uncertainty analysis on the thermocouple data. Since the ignition propensity of a test article is ultimately being evaluated by the test, differences in the thermal energy produced by the test systems must be minimized. Therefore, the following approach to estimating the relative severity of the test and the test systems is being proposed as a tool for making the comparisons.

Based on the temperature/energy data available from the WHA TPT fixture, calculation of three severity indices (simple ratios) is proposed. The severity index will be a variable used to relate the standardized test system “results” to idealized compression events and to actual “in-service” circumstances. The following severity indices are proposed:

Idealized Severity Index (ISI) – The idealized severity index will be an index (ratio) calculated to compare purely adiabatic and reversible (i.e., isentropic) compression of a mass of compressed gas to the thermodynamic and fluid dynamic predictions when real-gas properties are considered. This index will establish an idealized limit for the potential thermal energy expected from an isentropic pressure surge on a test system.

Test Severity Index (TSI) – From the TPTF data a “*Test Severity Index*” (TSI) can be derived so that the thermal energies developed by different test systems can be compared to each other on the basis of the ISI as compared to the equivalent idealized process. By this index, a particular test system can be compared to the idealized behavior and then to other test systems that have been evaluated in the same way. The TSI will provide a way to directly compare one system to another.

Service Severity Index (SSI) – A “*Service Severity Index*” (SSI) can also be developed by utilizing the TPTF to characterize the thermal energy of actual service conditions, such as the opening of a cylinder valve with a regulator connected. This is the most common service condition for which the adiabatic compression testing is intended to qualify valves and regulators. The SSI for this application, and potentially others, will be compared to both the ISI and the TSI to help with the prediction of the statistical reliability of the adiabatic compression test results. Once the SSI and TSI are specified for a given service configuration and test system, then a confidence interval for a “passing” result can be more readily derived.

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Figure 1: Simulated Adiabatic Compression Against Closed Valve

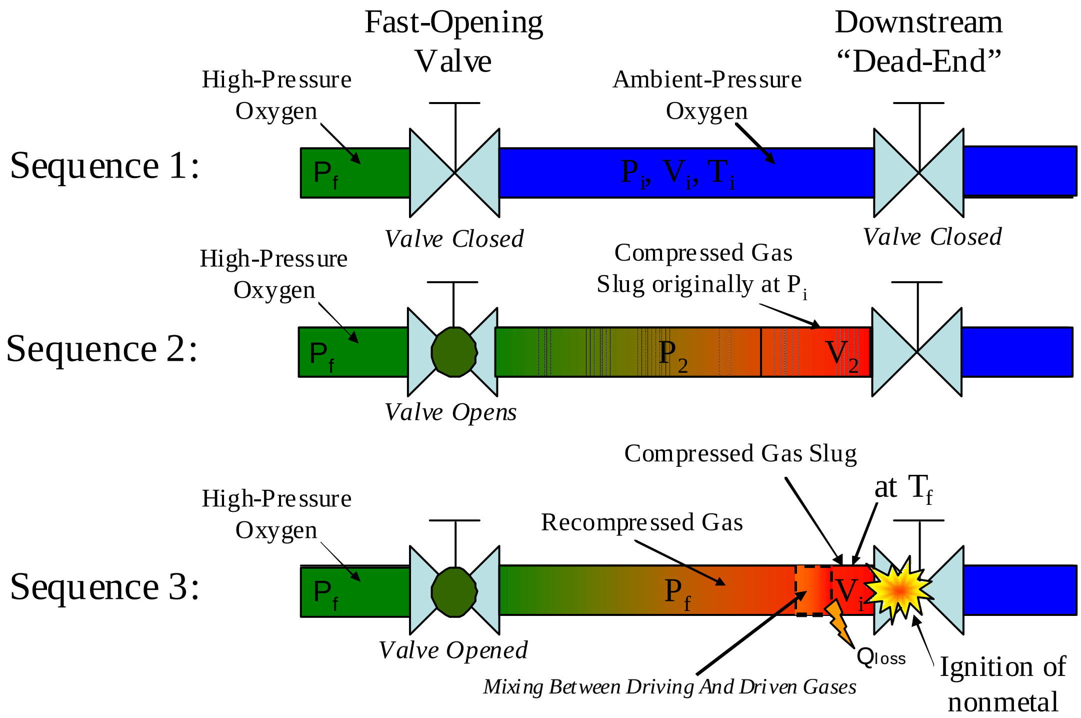


Figure 2 – Regulator Fire Investigated by WHA

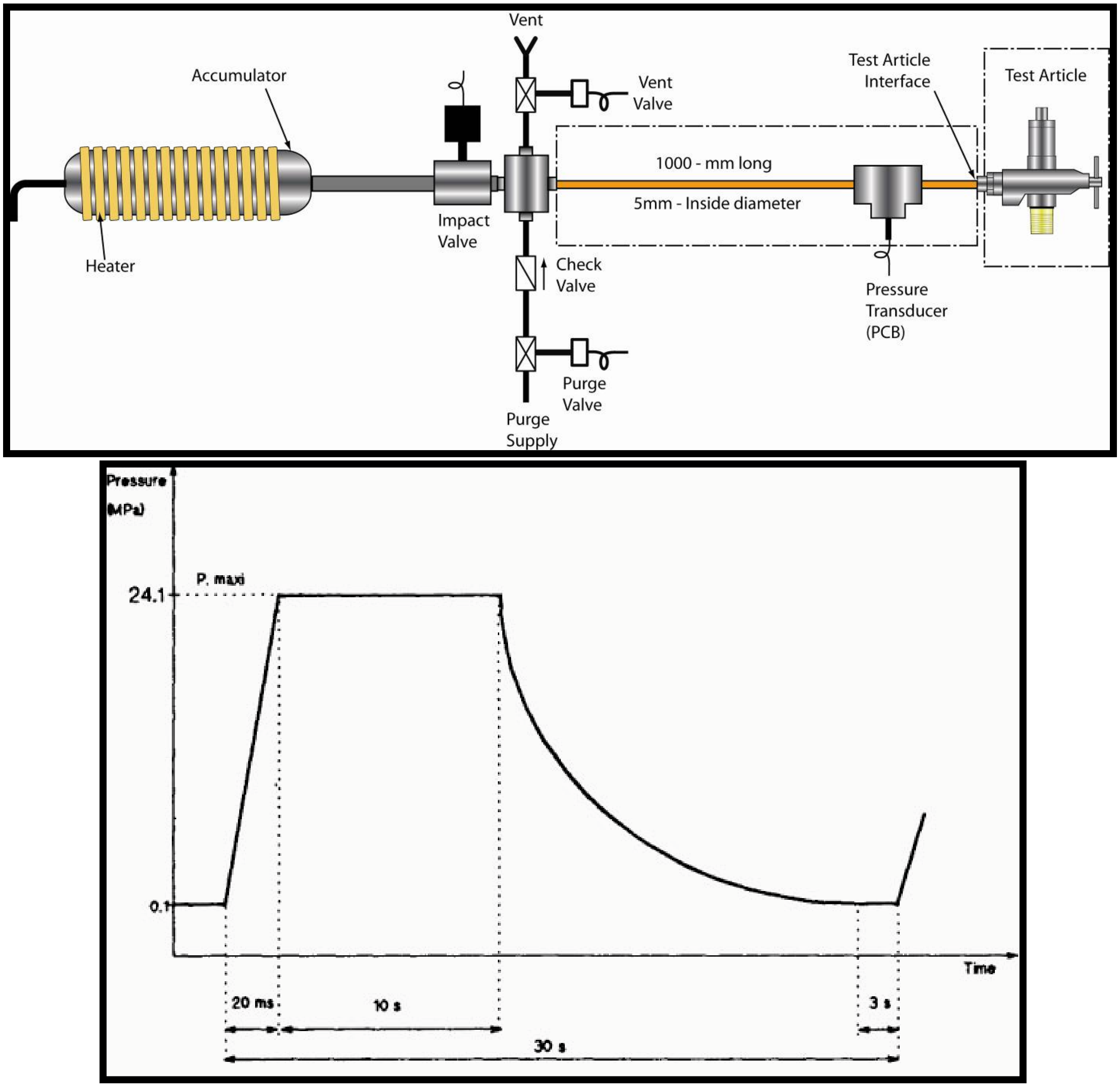


Figure 3 – WHA Adiabatic Compression Test system and Test Cycle

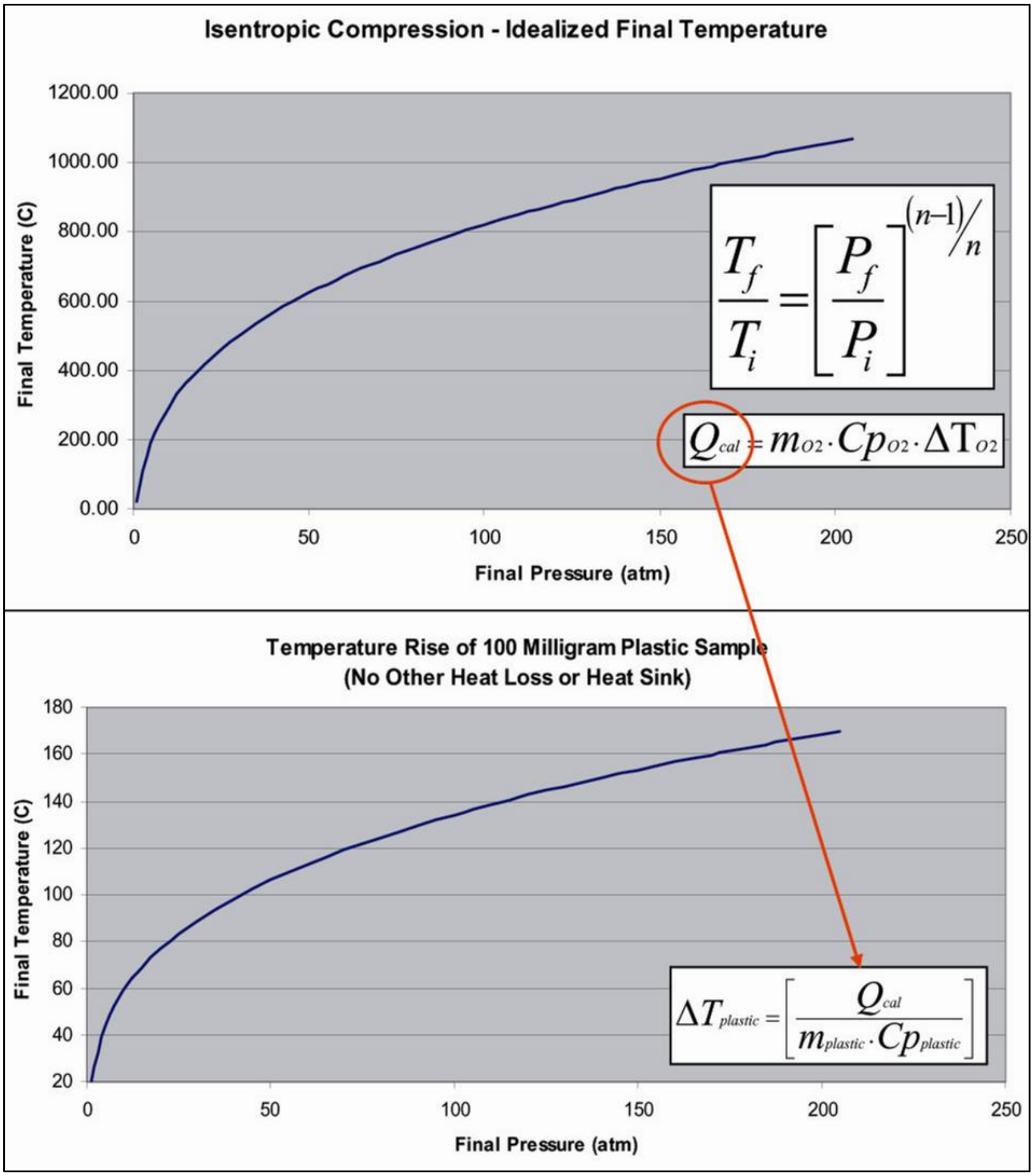


Figure 4: Idealized Temperature Rise of Small Plastic Sample Due to Heat Content in Compressed Slug Originally in 5-mm 1-meter long Impact Tube (n = 1.4 for oxygen)

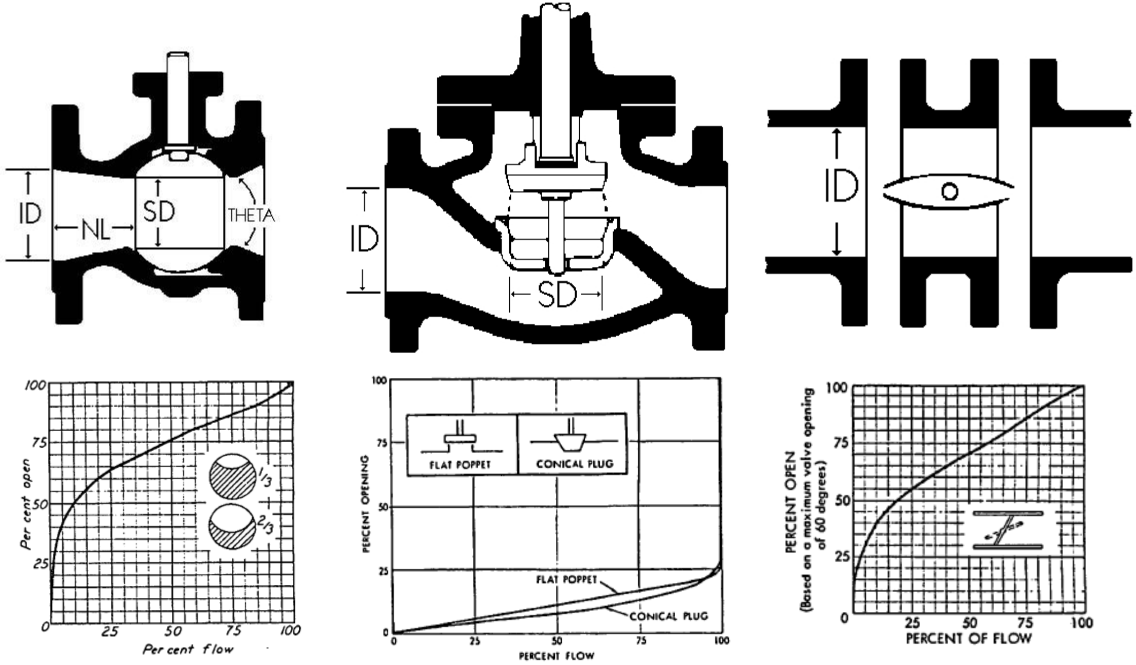


Figure 5 - Flow Characteristics of Valve Configurations (percent flow vs. percent open) [13]

A – Ball Valve Configuration B – Poppet/Globe Valve Configuration C – Butterfly Valve Configuration

(Note that the valve cross-sections are for illustration only and are not intended as accurate engineering drawings)

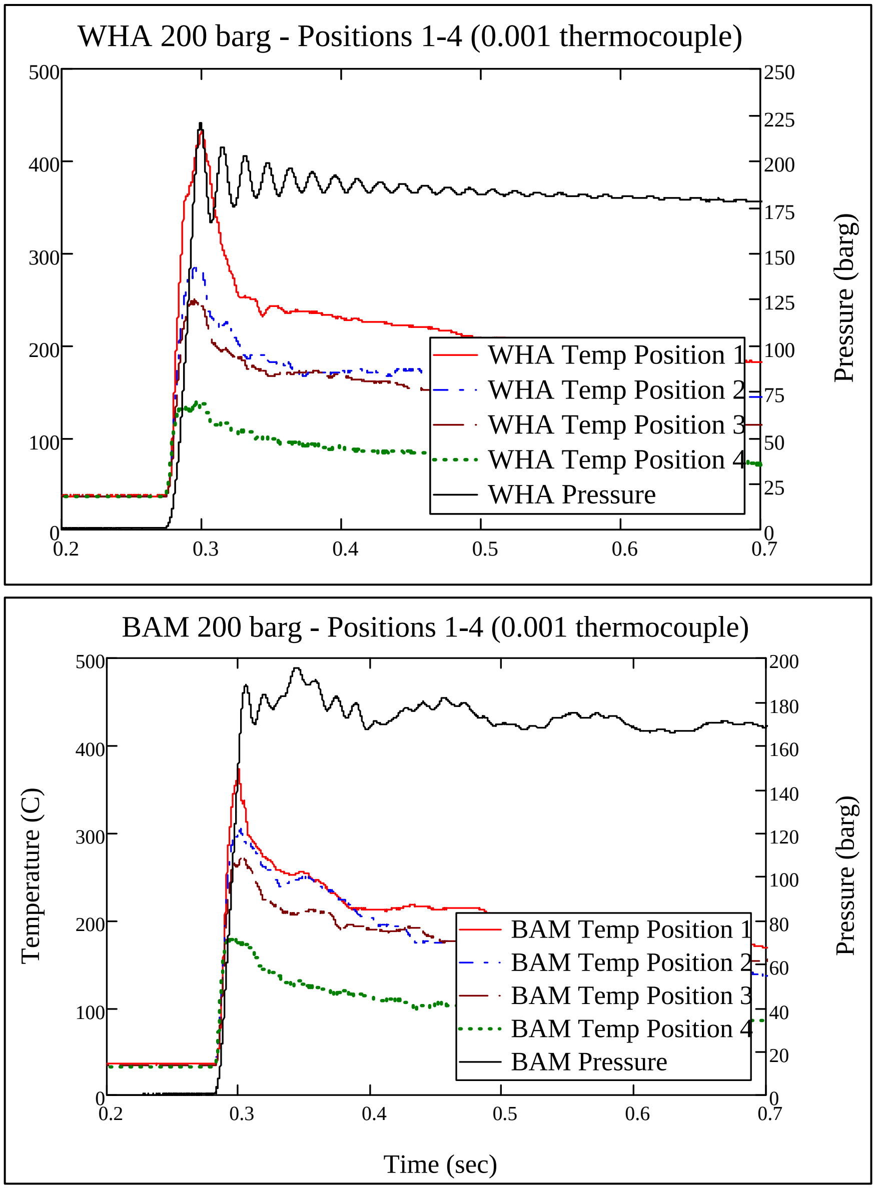


Figure 6 – WHA and BAM Pressure and Temperature Profiles
(test methodology described later)

Figure 7 - Idealized T-S Diagrams

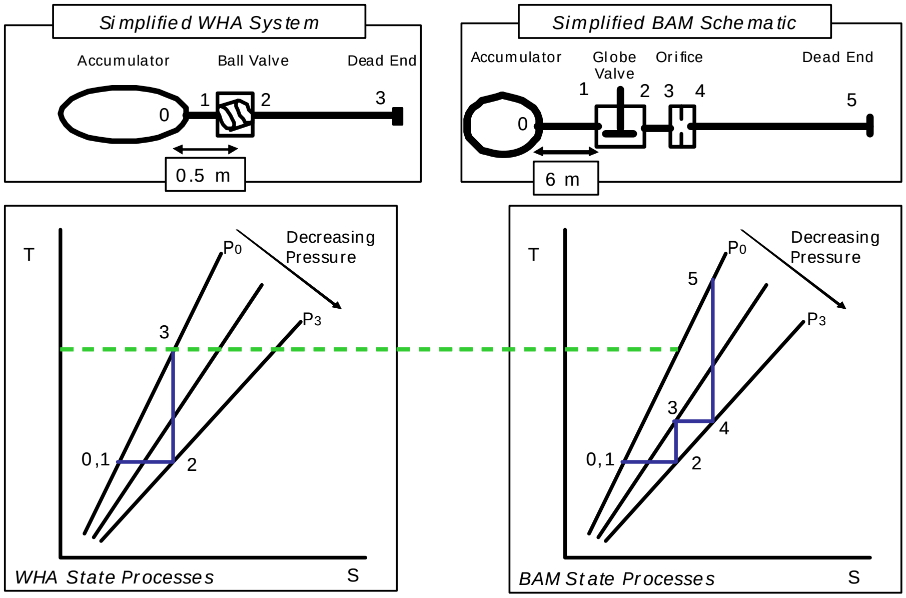


Figure 8 - Idealized T-S Diagram For Pressure Drop Before Impact Valve

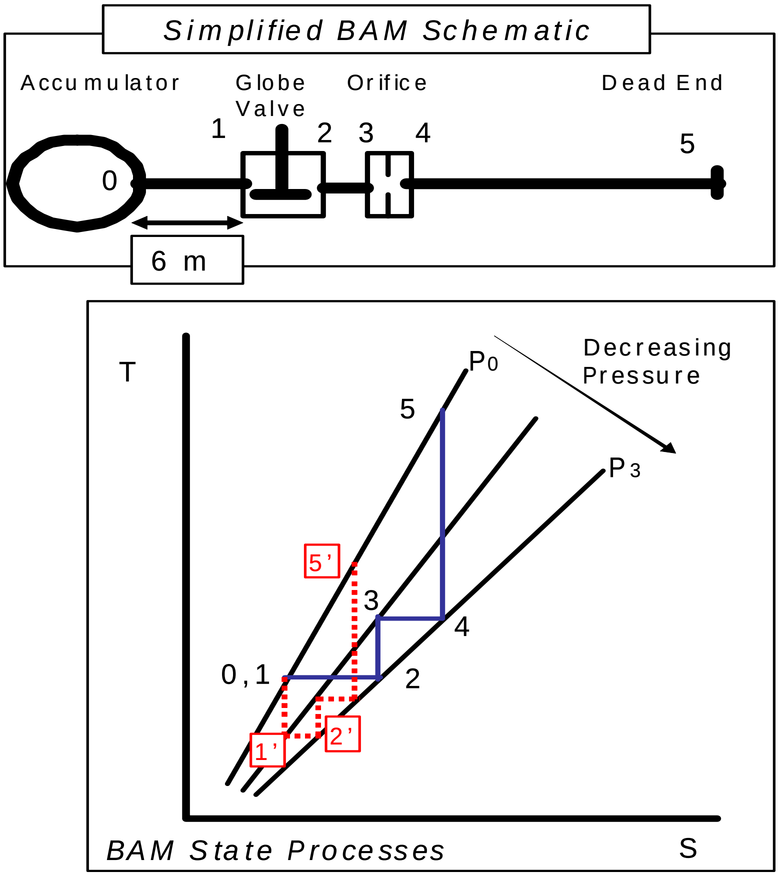


Figure 9: System Specific Thermal Profiles Allow Comparison and Calibration

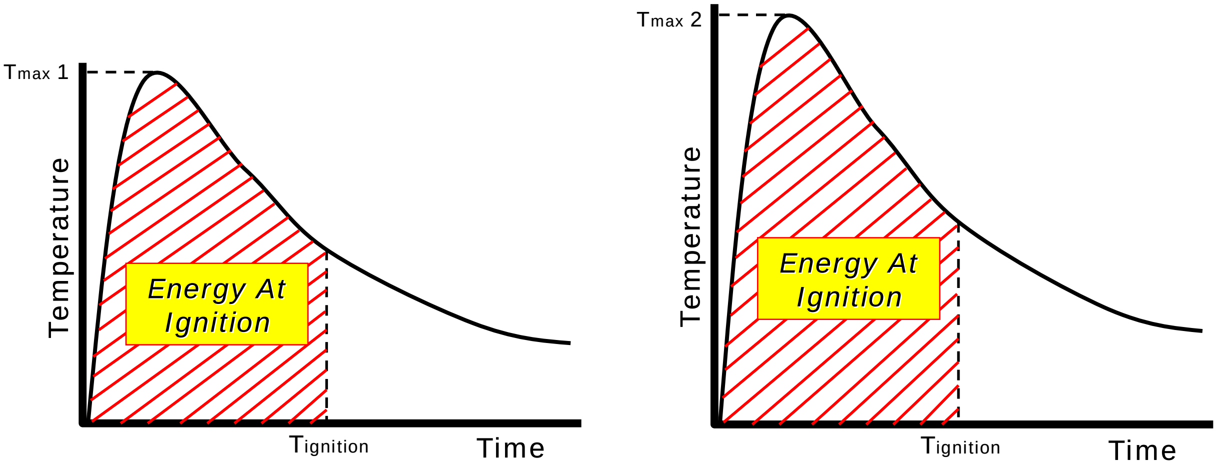
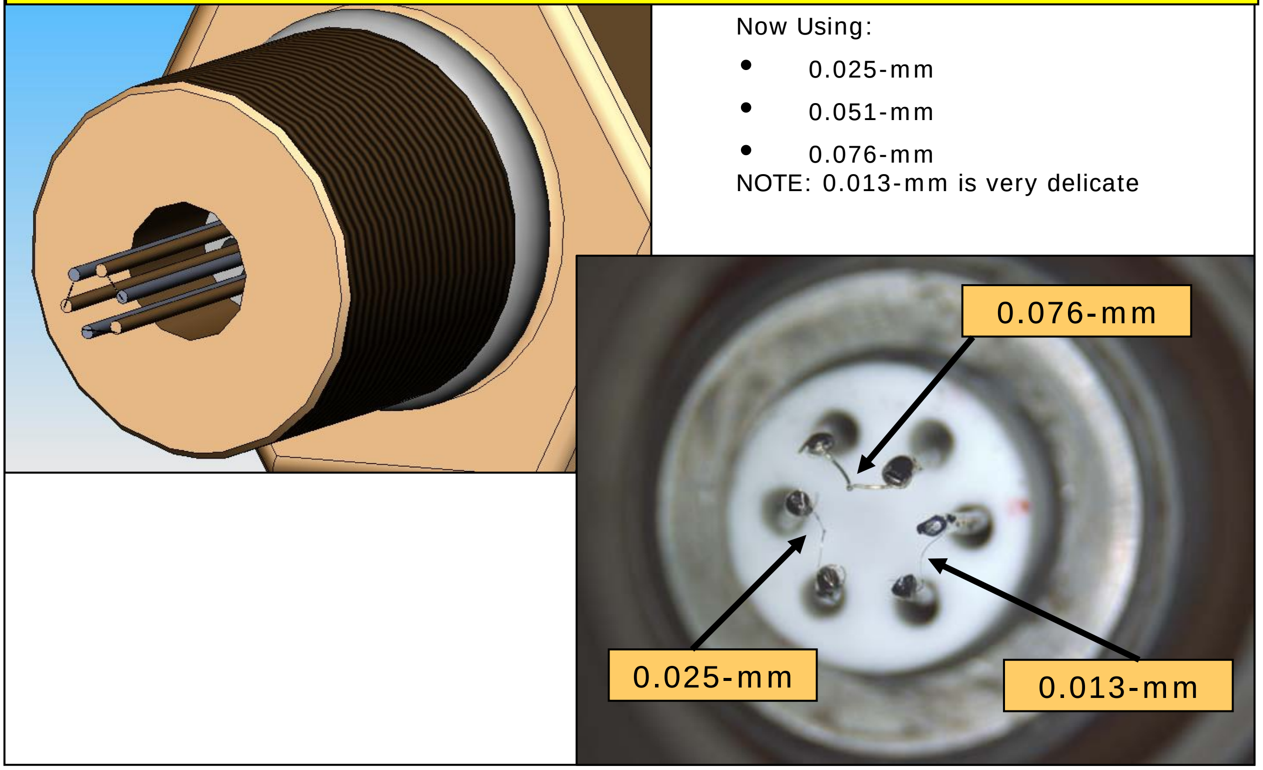


Figure 10: Thermocouple Array – End View

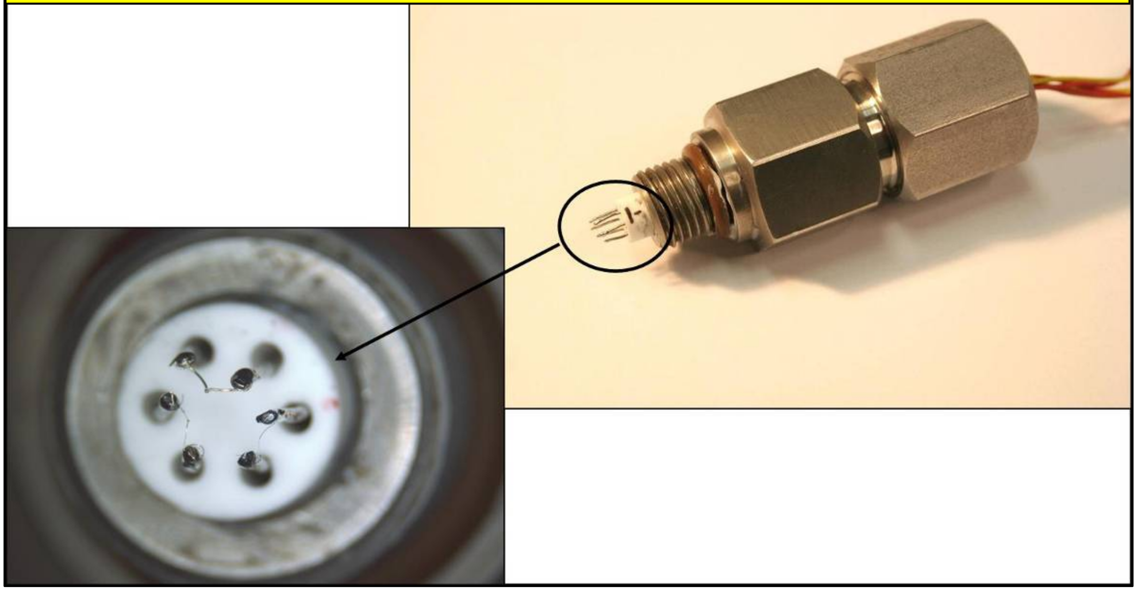


Now Using:

- 0.025-mm
- 0.051-mm
- 0.076-mm

NOTE: 0.013-mm is very delicate

Figure 11: Thermocouple Array – Side View



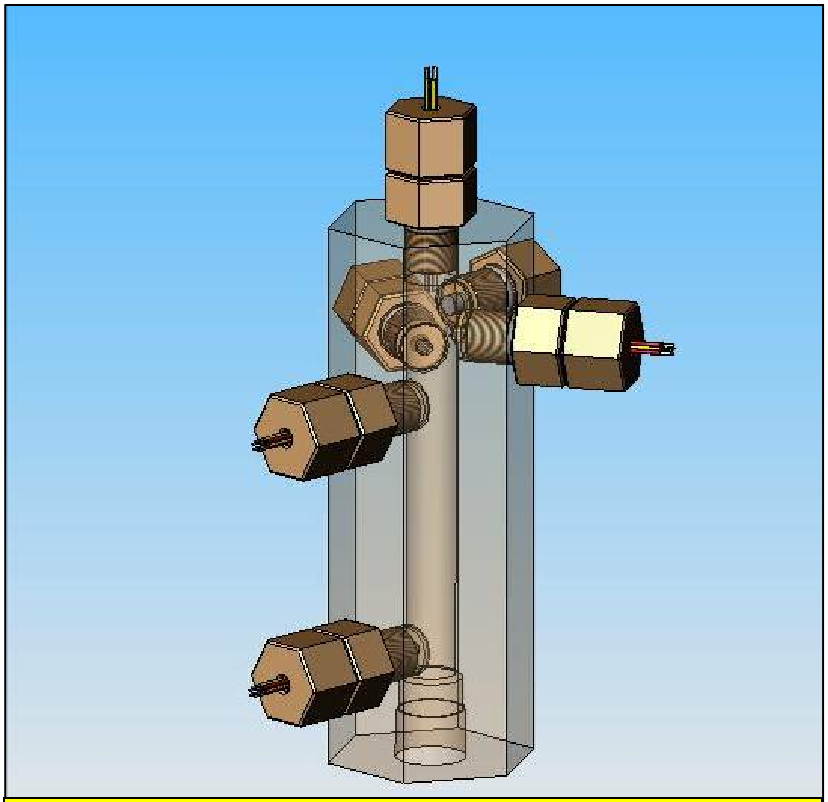


Figure 12 - Thermal Profile Test Fixture (transparent view)

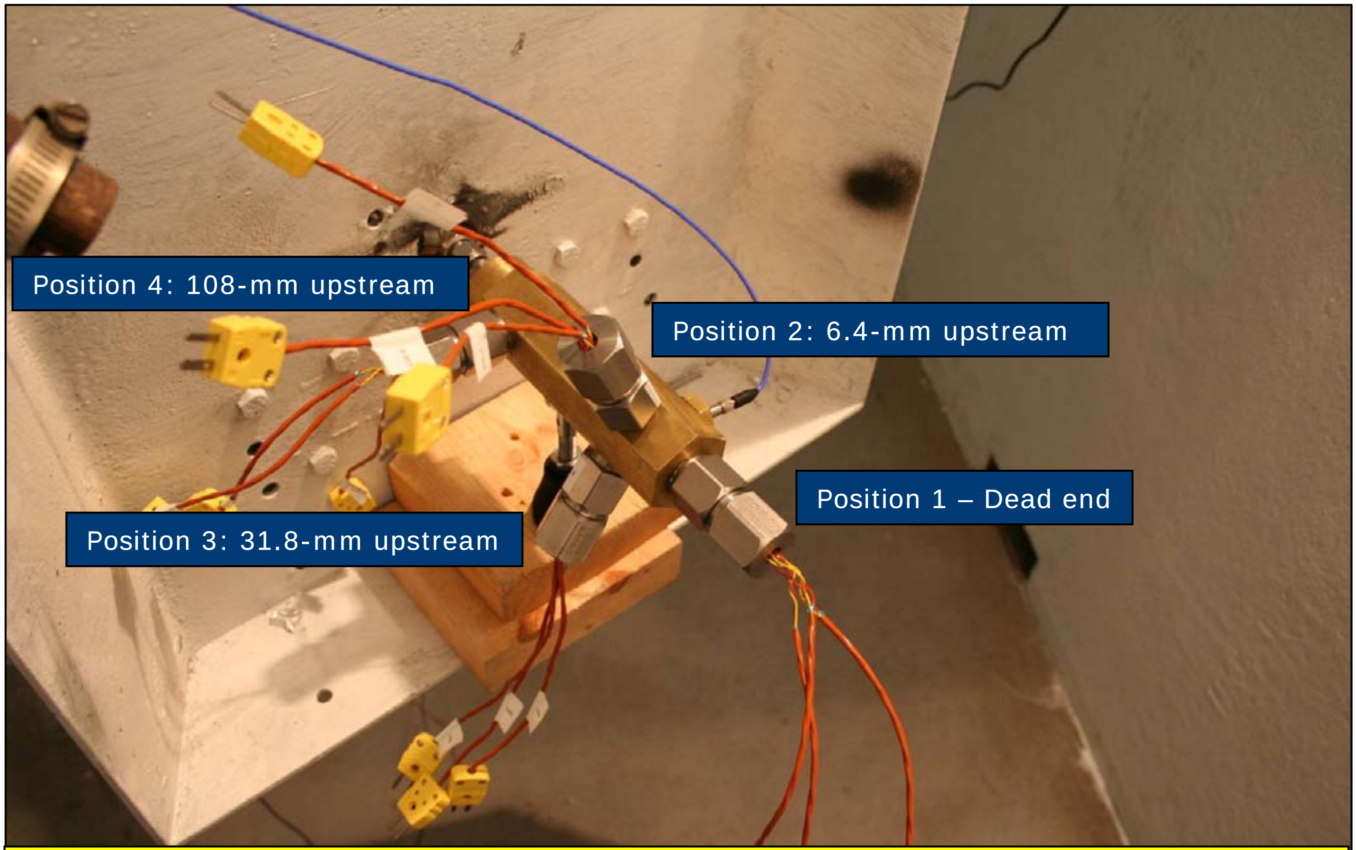


Figure 13 - Thermal Profile Test Fixture Installed on WHA Test System

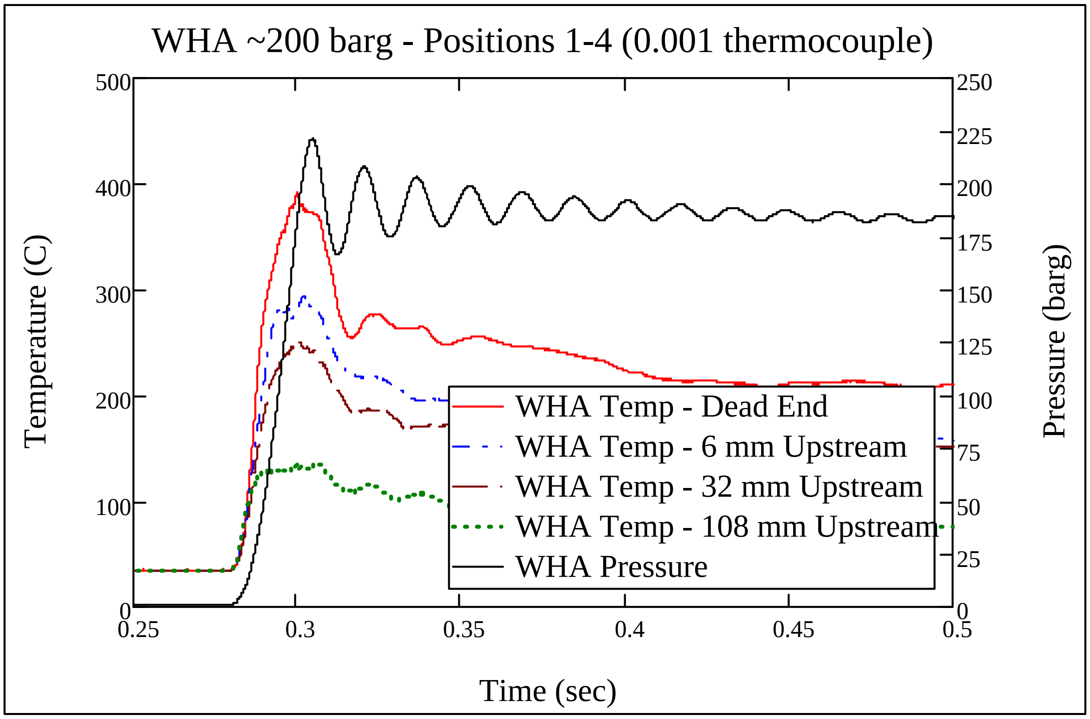


Figure 14 – Temperature Profile in WHA System at 4 Positions (0.025-mm TC)

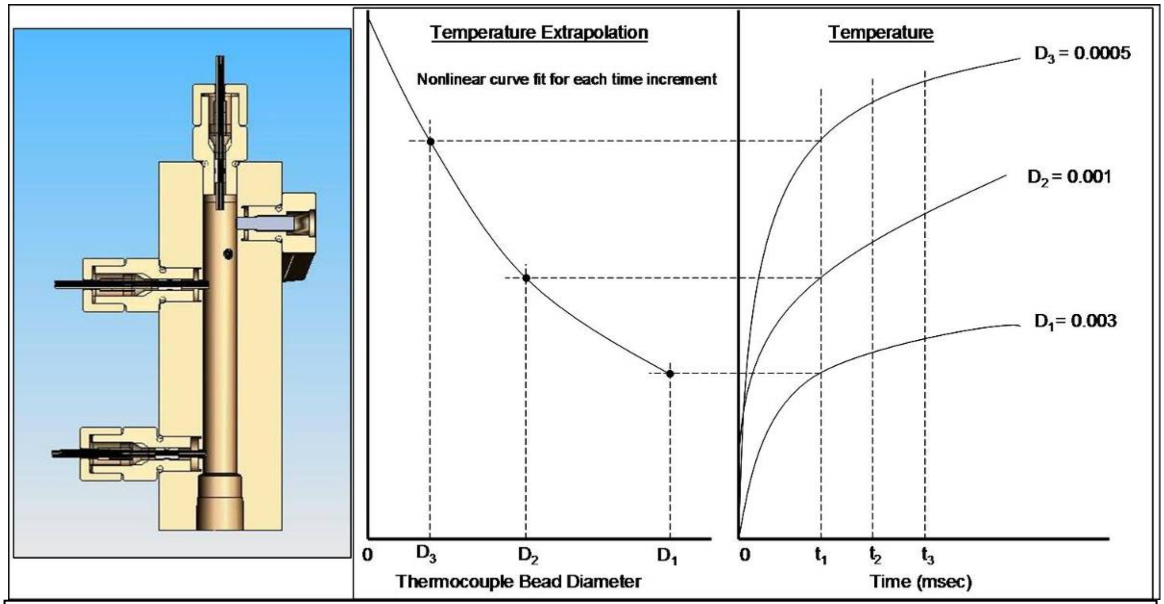


Figure 15: Temperature Extrapolation to Zero Diameter (illustration)
(theoretically instant rise time)

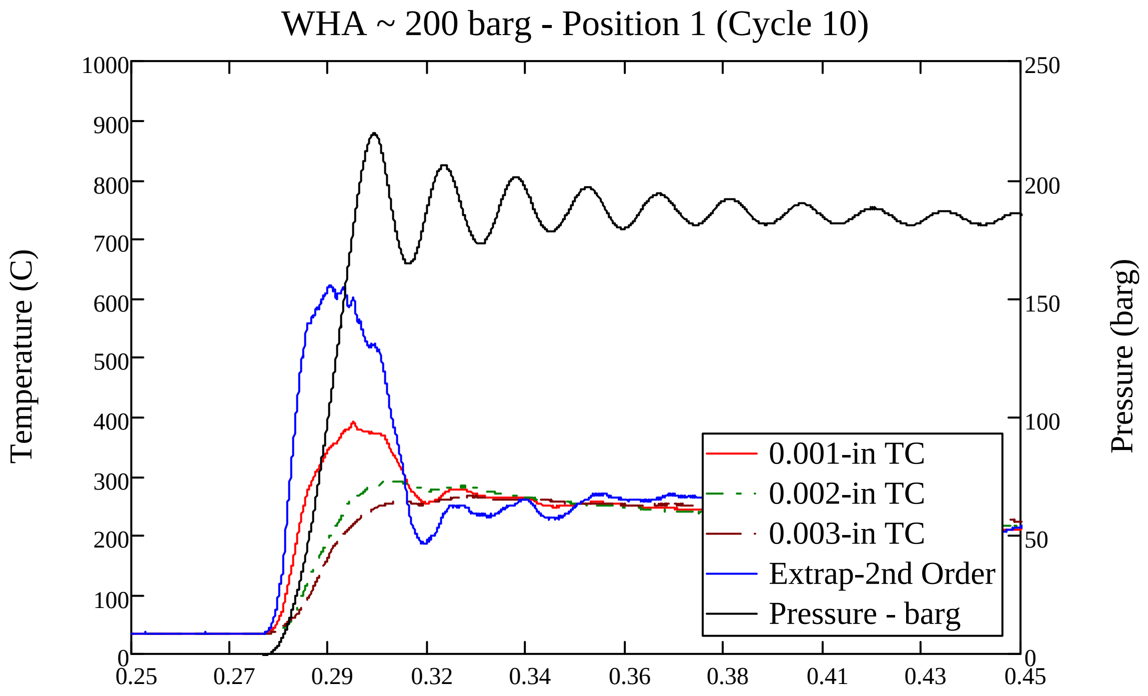


Figure 16 – WHA Test at 200 barg

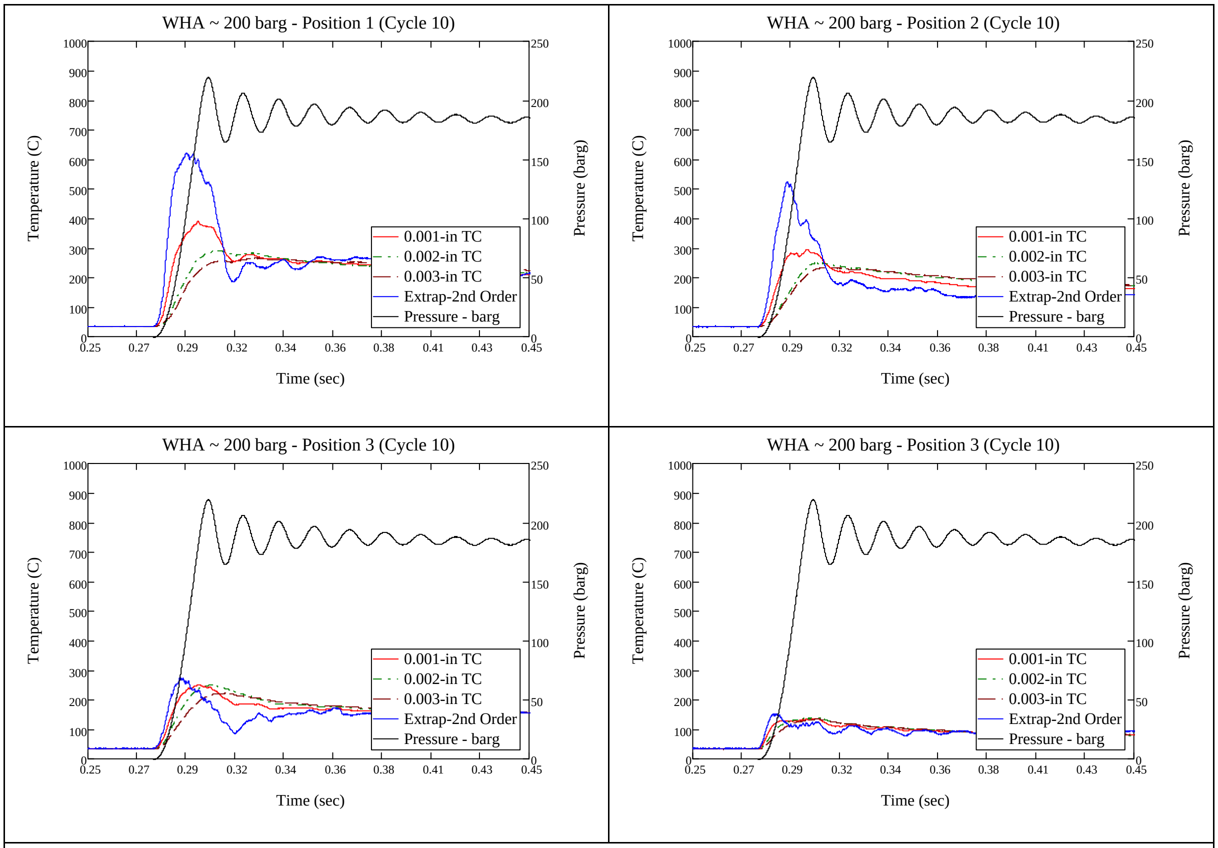


Figure 17 – TPTF Data for all WHA Thermocouples Plus Extrapolations (~200 barg, Cycle 10)

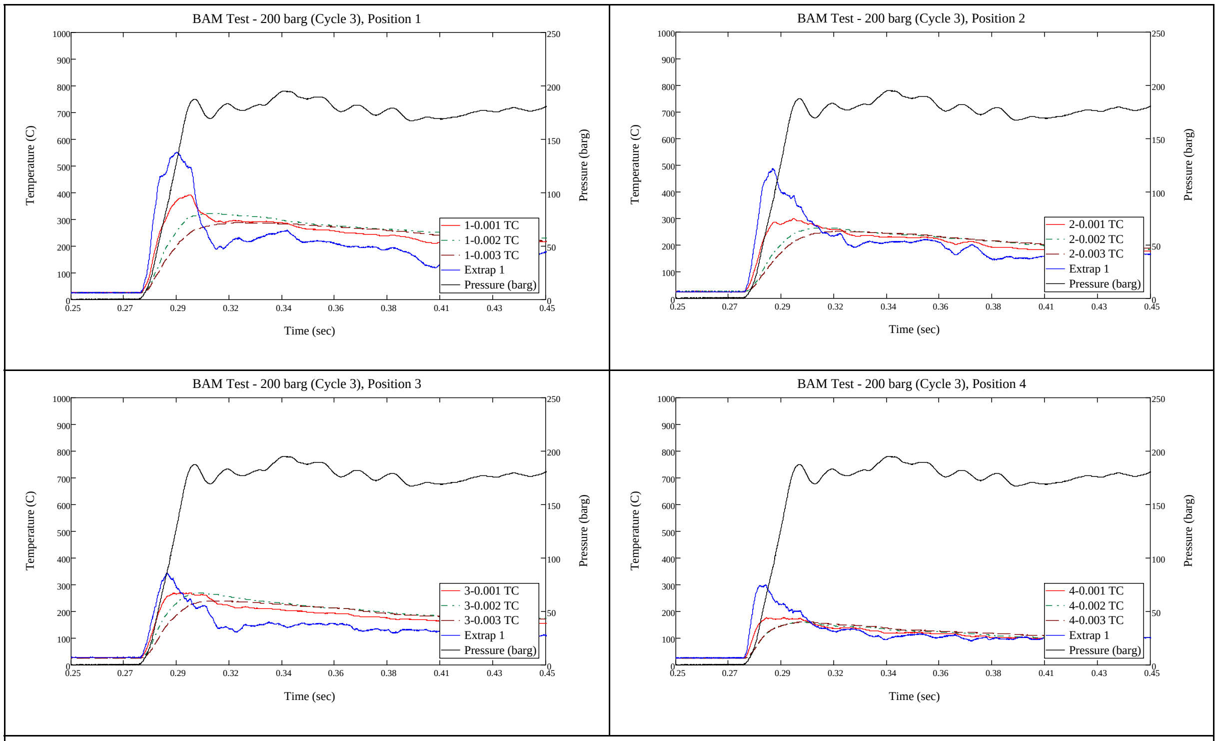


Figure 18 – TPTF Data for all BAM Thermocouples Plus Extrapolations (~200 barg, Cycle 3)