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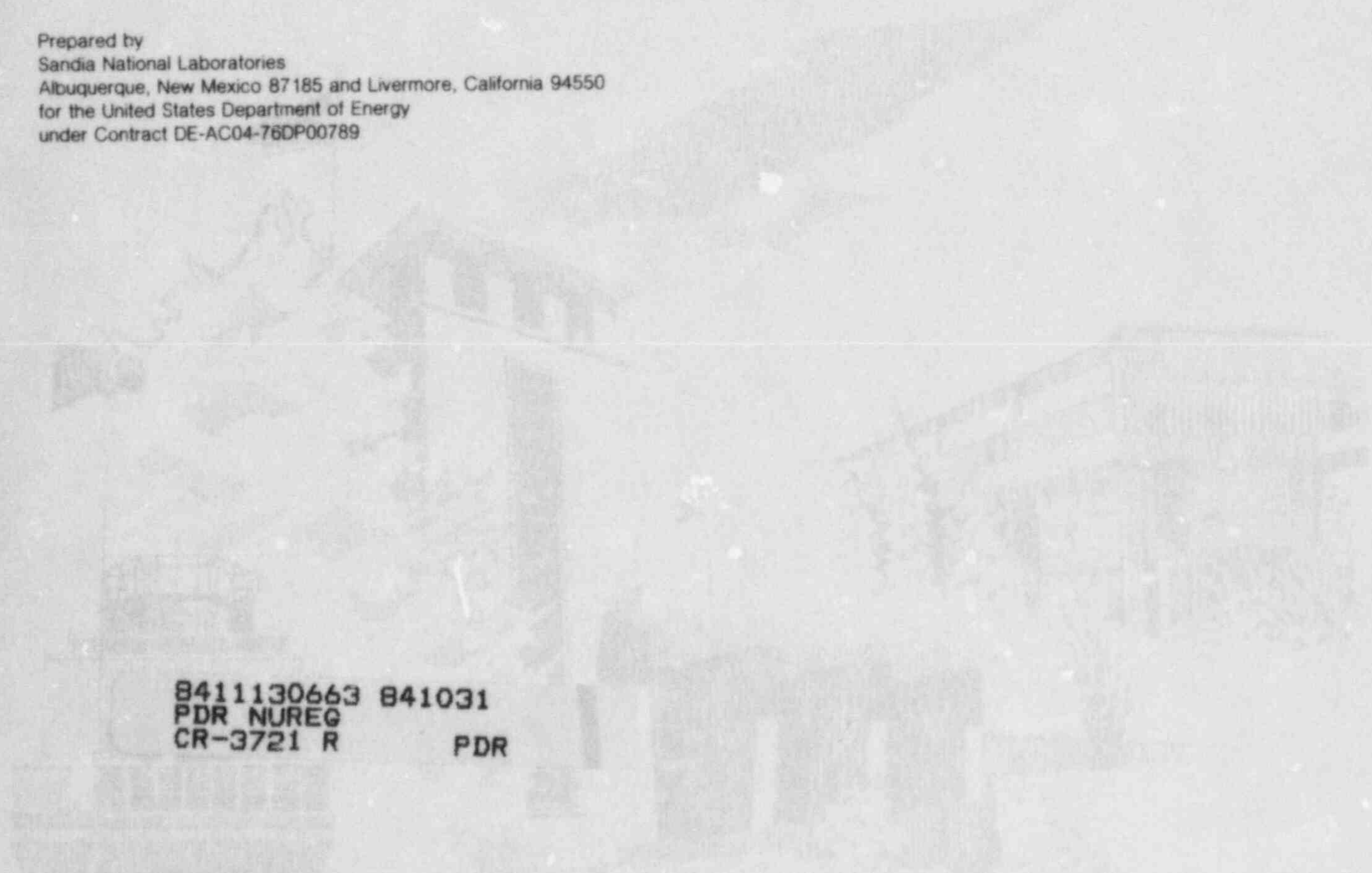

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PRESSURE MEASUREMENTS IN A HYDROGEN COMBUSTION ENVIRONMENT: AN EVALUATION OF THREE PRESSURE TRANSDUCERS

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Abstract

A series of hydrogen:air combustion tests were performed at the Fully Instrumented Test Site (FITS), located at Sandia National Laboratories in Albuquerque, New Mexico, to evaluate the performance of three strain-gage-type pressure transducers in a combustion environment. The three types of gages were Precise sensor models 111-1 and 141-1 and Kulite model XT-190. The evaluation was required since these three types of pressure transducers had been used in previous combustion test series at the FITS facility and the results were inconsistent. During this evaluation testing, Brunswick 1101 stainless steel felt metal was used to provide thermal protection for the transducer diaphragms. The objective of this work was to determine experimentally whether such shielding alters the dynamic pressure response of a transducer during a combustion experiment.

Results of the sixty tests indicated that the three pressure transducers, when thermally shielded with felt metal, recorded peak combustion pressures that were generally within 5% of the statistical mean for each test. The pressure profiles and associated burn times obtained from all of the protected transducers were also comparable. The Precise Sensor model 111-1 gages, when unprotected, were affected significantly by the hot gases of combustion and must be thermally protected with felt metal to obtain accurate measurements. However, thermally unprotected Precise Sensor 141-1 gages recorded transient combustion pressure traces that compared well with those recorded by the thermally protected gages. The Kulite sensor was always used with thermal protection as recommended by the manufacturer. These tests also showed that the Brunswick 1101 felt metal serves as an effective thermal barrier without affecting the magnitudes of the peak pressures, the rise times, or the composite shape of the transient combustion pressure response.

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Acknowledgements

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List of Abbreviations

Amp	Amplifier
AICC	Adiabatic Isochoric Complete Combustion
BT	Burn time (rise time from base to peak)
C.F.	Correction factor applied to the amplifier gain setting
CFM	Cubic Feet per Minute
DEVIATION	Standard Deviation associated with the mean reading
FITS	Fully Instrumented Test Site
ID	Test identification used during experimental program
LPM	Liters per Minute
Mean	Statistical mean of the gages during a test
Name	Test identification used in this report
PORT	Port location of gages in the FITS vessel
PR	Ratio of the pre-ignition pressure to the peak combustion pressure
Range	Pressure gage range
SENS	Pressure gage sensitivity (calibration)
SN	Serial Number of the pressure gage
SNLA	Sandia National Laboratories, Albuquerque, NM
TR	Ratio of initial to the peak gas temperature
% DIFF	Compares a gage response to the mean reading in the following ways: ($\lvert$READING - MEAN$\rvert$ / MEAN) x 100
% H2	Volume percentage of hydrogen before ignition
% MAX	((Maximum - Minimum Reading)/Mean) x 100 of all readings during a test
% RATIO	The ratio of the standard deviation to the mean reading (x 100)
RTI	Resistor Trim Input
RTO	Resistor Trim Output

Executive Summary

A series of hydrogen:air combustion tests has been performed at the Fully Instrumented Test Site (FITS), located at Sandia National Laboratories in Albuquerque, New Mexico, to evaluate the performance of three strain-gage-type pressure transducers in a combustion environment. The three pressure transducers evaluated in this report were the Precise Sensor model 111-1 and 141-1 gages and the Kulite model XT-190 gage. The effects of a thermal barrier on the accuracy of each transducer were of primary interest since these three transducers had been used without thermal protection in previous combustion testing at the FITS facility. In conjunction with this work, the effectiveness of Brunswick 1101 stainless-steel felt metal as a thermal barrier was evaluated. For deflagration experiments, the felt-metal was expected to thermally shield the sensing diaphragm of the transducer without significantly affecting the response of the gage to the transient pressure pulse.

Sixty hydrogen:air combustion tests were conducted at FITS, resulting in the following conclusions about the importance of a thermal barrier to the response of each transducer model. The Kulite model XT-190 and Precise Sensor models 111-1 and 141-1 gages, when thermally protected with felt metal, recorded peak combustion pressures that were within 5% (based on the standard deviation percentage) of the mean response obtained during a test. The Precise Sensor 111-1 and Kulite XT-190 gages required thermal protection for accurate pressure measurements during a combustion test. A thermally unprotected 111-1 transducer recorded peak combustion pressures that were 20-40% higher than did the thermally shielded 111-1. Further, the composite shape of the pressure trace recorded by an unprotected 111-1 gage and the resulting associated burn time were substantially different than those of the protected gage. The performance of the Kulite XT-190 gage was only evaluated with thermal protection, since the manufacturer indicated that the transducer would most likely fail in a combustion environment if not protected. The thermally protected and unprotected 141-1 gages yielded comparable peak pressures, burn times and transient pressure profiles. The insensitivity of the 141-1 gage to the thermal environment was attributed to the transducer design (i.e., the sensing diaphragm is recessed approximately 5 cm from the front surface of the gage). These results also indicate that the Brunswick 1101 felt metal acted as an effective thermal barrier in deflagration type combustion experiments. The felt metal did not affect the magnitudes of the peak pressures, the rise times, or the composite shapes of the transient pressure response.

As a result of this study, it is recommended that the pressure transducers be thermally shielded for all future combustion testing at FITS. In addition, this series of combustion tests pointed out the importance of analyzing each experiment performed at FITS shortly after it has been conducted. This procedure would insure that the results from different kinds of instrumentation are consistent as well as consistent with previous experiments and analytical predictions. Unexpected differences could identify problems that need correcting and prevent the test series from proceeding with invalid instrumentation. Additionally, if each component of the data acquisition system is not calibrated frequently, the quality of the resulting data may not be of the highest possible standard. Therefore, it is recommended that the data acquisition system, and particularly the pressure measurement system, be calibrated frequently and systematically on-site.

1. Introduction

A series of hydrogen:air combustion tests was performed at the Fully Instrumented Test Site (FITS), located at Sandia National Laboratories in Albuquerque, New Mexico (SNLA), which compared the responses of three different kinds of pressure transducers, with and without thermal protection. The three types of pressure transducers evaluated during these combustion tests were those which had been used in previous combustion testing at FITS. Increasing speculation and concern about the validity of pressure data from past combustion experiments using particular transducer designs emphasized the need for such an experimental evaluation. In previous testing, for example, peak combustion pressures measured by a particular transducer exceeded the Adiabatic Isochoric Complete Combustion (AICC) predictions while another type of transducer design under-predicted the AICC calculation as hydrogen:air concentrations approached stoichiometry. The goal of this study was to evaluate the response of each transducer model relative to analytical trends and the responses of the other transducers. From these evaluations, the validity of the past experimental pressure data recorded by each different transducer model could be determined. Finally, definitive conclusions could be drawn about the past instrumentation and experimental procedures used at FITS.

A second motive of this study was to evaluate Brunswick 1101 felt metal as a flame arrestor and thermal shield in a combustion environment. In a previous analytical study which evaluated this type of thermal protection [1], it was concluded that:

> "For pressure rises of the order of 0.01 seconds or slower, the use of moderately permeable felt metal shields in front of a pressure transducer will not significantly degrade transient response of a pressure transducer. The felt metal shield will act as a flame arrestor."

The objective of this part of the study was to show experimentally that these felt metal pads eliminated any thermal effects that an unprotected transducer might otherwise experience, without affecting the transient response of the gage.

2. Experimental Apparatus

Three different pressure transducer models, the 111-1 and 141-1 gages manufactured by Precise Sensor Inc. and the XT-190 gage manufactured by Kulite Inc., were evaluated in this study. The pertinent manufacturer's specifications for each of the transducers are shown in Table 1 [2,3]. Schematics of the three pressure transducer designs are shown in Figure 1 for direct comparison. The sensors of the Kulite XT-190 and Precise Sensor model 111-1 gages are flush-surface diaphragm designs while the Precise Sensor model 141-1 has its sensing diaphragm recessed from the front surface of the gage.

The Precise Sensor model 141-1 is a bonded strain-gage-type transducer with the sensing element positioned approximately 5.0 cm (2 in.) from the front surface of the gage housing. The sensing element consists of a stainless-steel diaphragm and strain-cylinder combination with a four-active-arm strain gage permanently bonded to the cylinder. The model 141-1 is gas cooled to remove any thermal energy transmitted through the front diaphragm which may affect the output of the sensor. The Precise Sensor model 111-1 is also a bonded strain-gage transducer. The sensing element and gas-cooling features incorporated in the model 111-1 design are identical to those described for the model 141-1. The model 111-1 is rated for higher operating temperatures than either the 141-1 or the Kulite XT-190, which would be advantageous in combustion applications.* The third transducer type, the Kulite model XT-190, is a solid-state pressure transducer in which the sensor circuit consists of a wheatstone bridge bonded to a miniature silicon diaphragm. The Kulite XT-190 transducer has a perforated screen over the silicon diaphragm for protection, but it is not designed for operation in severe thermal environments unless additional thermal protection is provided.

During this testing program, the Precise Sensors were internally air-cooled through a baffle arrangement shown schematically in Figure 2. A nominal inlet gage pressure of 69 kPa (0.68 ATM) was provided to the cooling manifold in all tests except for a short series of tests performed to assess the importance of this cooling mechanism. The 69 kPa inlet pressure resulted in a volumetric flow rate of 14.2 liters per minute (LPM) (0.5 CFM) to each gage, which although less than the

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* Note that this is a static temperature rating and not necessarily an indication of the gage's characteristics when exposed to a transient temperature pulse. Generally, most pressure transducer specifications do not directly address the performance of a gage when exposed to a rapidly changing thermal condition, although this is important when measuring pressures in a combustion environment with a thermally unprotected transducer.

Table 1
Pressure Transducer Manufacturers' Specifications [2,3]

Manufacturer	Precise Sensor	Precise Sensor	Kulite
Model	141-1	111-1	XT-190
Natural Freq.	32 KHz	22 KHz	270 KHz
Resolution	Infinite	Infinite	Infinite
Range	0-6.81 atm 0-13.61 atm	0-13.61 atm.	0-20.41 atm.
Operating Temp.	0-600 C	0-1093°C	-20 to 80°C
Compensated Temp Range	NA	NA	25 to 80°C
Cooling Pressure	1.02-1.36 atm.	1.02-1.36 atm.	NA
Cooling Flow	56.6 LPM (2 CFM)	56.6 LPM (2 CFM)	None

1 atm = 14.696 psia = 101.325 KPa
LPM ....Liters per Minute
CFM ....Cubic Feet per Minute
NA ....Not Applicable

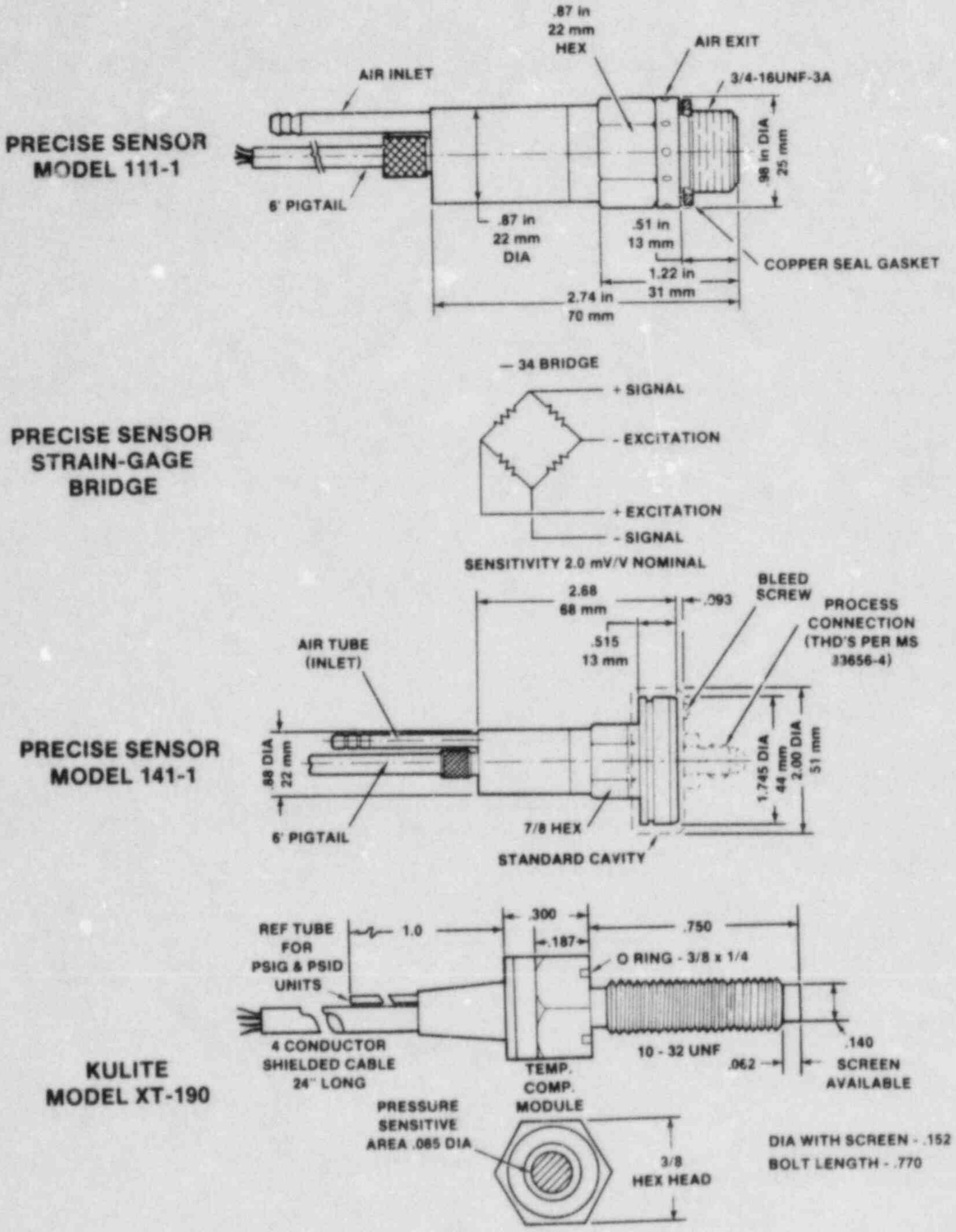


Figure 1. Schematic of the Three Transducers

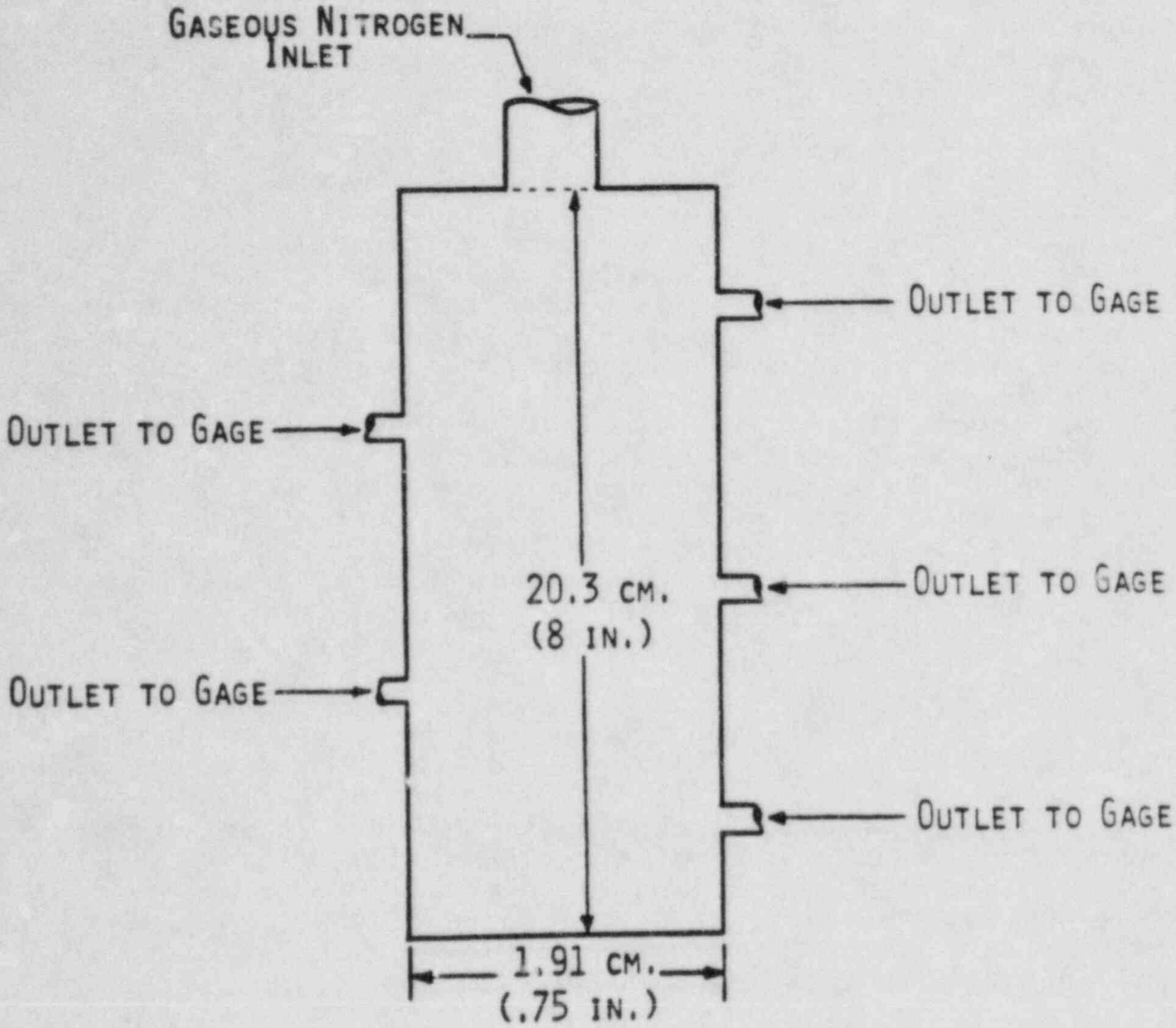


Figure 2. Cooling Baffle

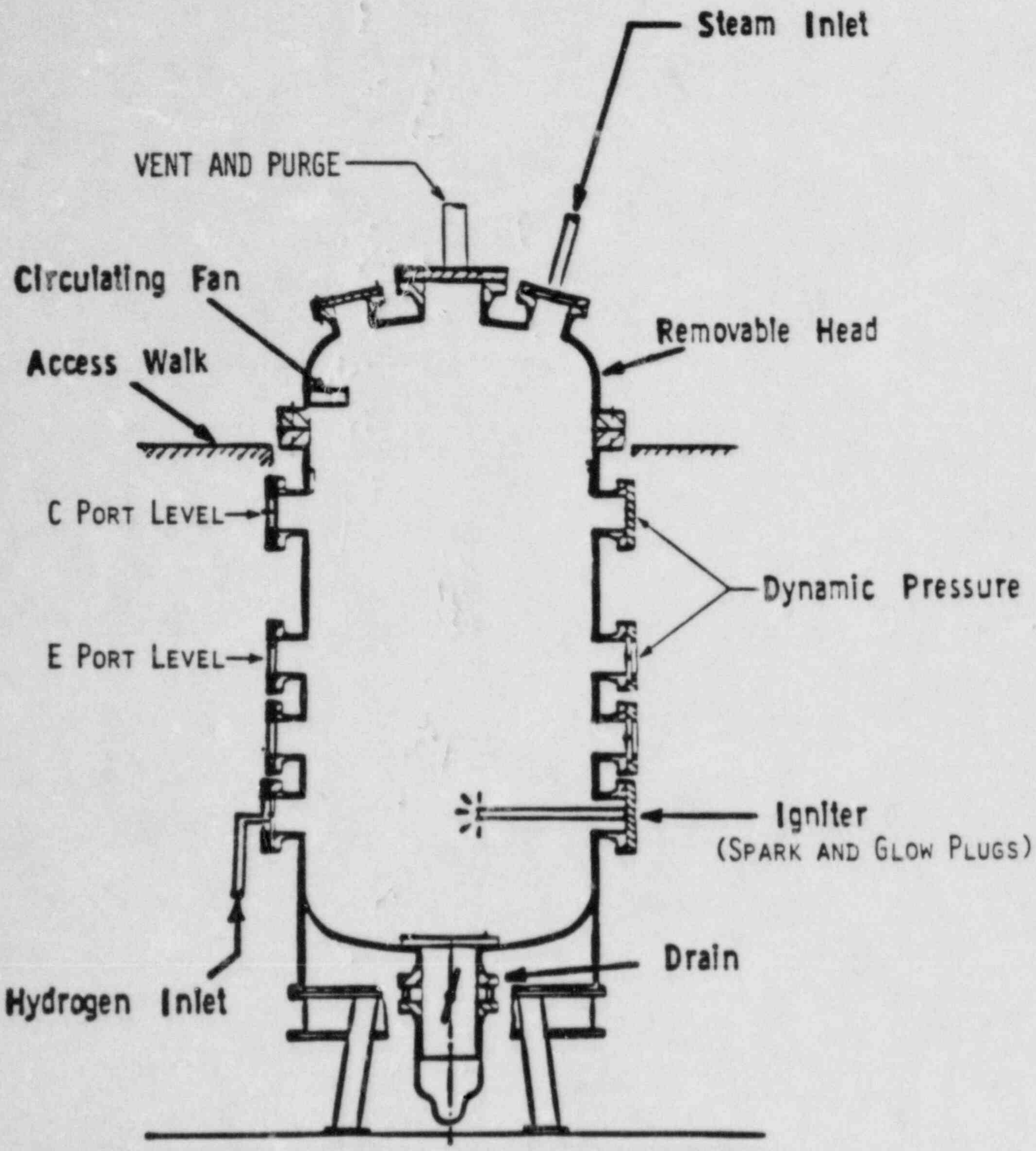
manufacturers' specifications, was still expected to provide sufficient cooling to the sensing elements.

All combustion testing discussed in this report was performed at the SNLA-FITS 5.6 cubic meter vessel, shown schematically in Figure 3. Pressure transducers were positioned at the E and C elevations in the FITS tank, approximately 1.57 m and 2.35 m, respectively, above the spark plug (and glow plug) igniter location.

The port locations and gage setup selections were made to duplicate previous combustion testing conducted at FITS. The Precise Sensor model 111-1 gage, with no thermal protection, was used almost exclusively in the Hydrogen Behavior Program's (HBP) first series of combustion experiments, as well as in the first series of tests performed for the Hydrogen Burn Survivability (HBS) program [4]. Port E-1 in the FITS vessel was the major pressure gage instrumentation port used during these HBS and HBP combustion experiments. Precise Sensor model 141-1 gages were used, with no thermal protection, in the second and third test series (designated FITS-2 and FITS-3) for the HBP and were mounted primarily in Ports E-2 and C-2. The Kulite model XT-190 gage has been used periodically during all of the combustion testing, at each of the C and E port elevations. This latter gage type was not thermally protected during the early test series, and has been used only recently with shielding to obtain reasonable pressure measurements.

Recessed flange inserts were installed in ports E-2 and C-2 before the FITS-2 combustion experiments began in order to position the front surface of a pressure transducer approximately flush with the inner tank wall. Port E-1 does not have a recessed insert, resulting in the front surface of a pressure transducer being approximately 18 cm from the inner tank wall. The positioning of a pressure transducer in port E-1 was expected to provide some slight thermal shielding (less direct exposure to hot combustion gases) without significantly affecting the combustion pressure measurement.

The data acquisition system at FITS, shown in a flow diagram in Figure 4, employs LeCroy ten-bit (model 8210) and twelve-bit (model 8212) transient Analog-to-Digital Converters (ADC) in a Kinetic Systems model 1500 Camac crate which is controlled by an LSI-11/23 microprocessor using RT-11 as an operating system. Generally, the ten bit ADCs were used to record the voltage output of the pressure transducers, since these modules were set up to record approximately 8200 points of data over about thirty seconds. The period of data acquisition for each ADC module was controlled by a LeCroy 8501 programmable 3-speed clock generator, allowing sample rates of 20 Hz to 20 MHz (in two ranges). Approximately four percent of the available module memory was allocated to pre-ignition data and the remainder of the memory was used to record the post-ignition data. The ADC modules were triggered using a



1.5 m (4.9 ft) diameter 3.4 m (11.2 ft) length
5.6 m^3 (195 ft^3) volume

Figure 3. Schematic of FITS Tank

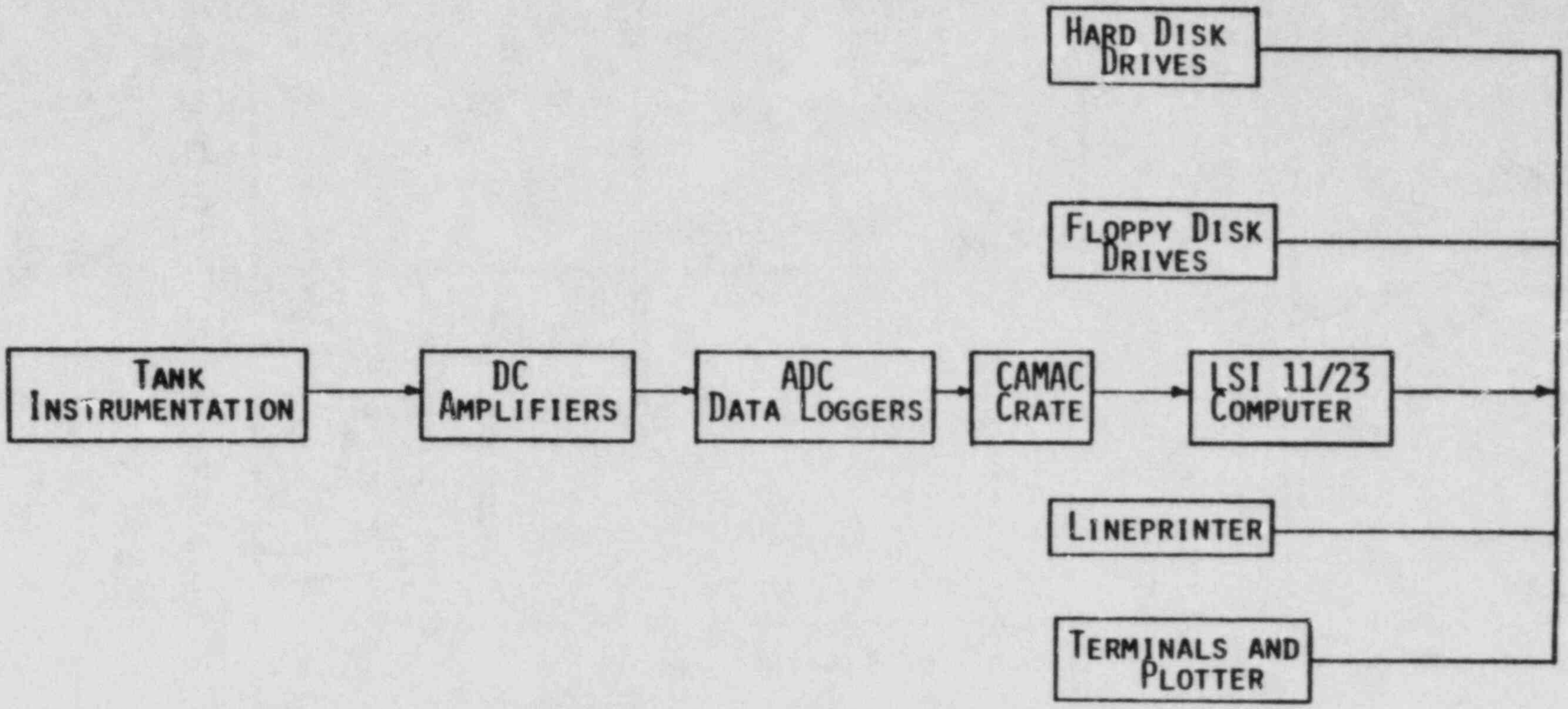


Figure 4. Flow Chart of the Data Acquisition System

Transiac model 1020 amplifier/trigger source. This trigger was accomplished by monitoring (through the transiac) the output voltage of a pressure transducer. When a pre-set voltage level was achieved, a "trigger signal" was sent to the clock generators and the ADC modules and the remainder of the combustion data was recorded.

The voltage signals generated by a pressure transducer during a combustion test were amplified using Dynamic series 7600 differential amplifiers which incorporate model 7860-A strain-gage conditioners. These amplifiers have a variable gain switch in addition to a multi-turn variable gain control which allows the exact gain to be set. The pertinent manufacturer's specifications for these amplifiers are shown in Table 2 [5].

The combustion experiments were performed in the FITS facility in the following manner: The tank was preheated with steam, if it was a "hot" wall test, to the desired temperature. A prescribed quantity of hydrogen, determined using partial pressure calculations, was introduced and allowed to equilibrate with the air already in the vessel. Two 14,200 LPM (500 CFM) fans were used to mix the gas and were either turned off 10 minutes prior to ignition for "quiescent" tests or were left on throughout the experiment for "turbulent" tests. Once the gas was mixed, a spark or glow plug located in the lower part of the volume was energized, igniting the mixture. The data acquisition system recorded the pressure signals for approximately 30 seconds after ignition. Additional information on the experimental procedures, data acquisition system and instrumentation are available in [6].

Table 2
Dynamic Amplifier Specifications [5]

Frequency Response	1% DC to 7.5 kHz 2% DC to 7.5 kHz to 10 kHz 1 dB 10kHz to 35 kHz
Settling Time	Less than 50 sec. to 0.1% of final value
Temperature Coefficient of Drift	0.4 V/°C RTI 100 V/°C RTO
Gain	Front-panel gain switch selects gains of 1, 2, 5, 10, 20, 50, 100, 200, 500, and 1000. Multi-turn variable gain control settings from x1 to x2.5.
Gain Accuracy	0.1%
Gain Stability	0.005% per 200 hours 0.005% per °C
Linearity	0.005% at DC
Output Filter	Five-position front-panel switch selects cutoff frequencies of 10 Hz, 100 Hz, 1 kHz, 10 kHz and WB (Wideband). The filter is a two pole, low pass type with a damping factor of 0.7.
Multichannel Isolation	Fully insulated plug-in modules; no cross-channel connections.
Operating Temperature	0°C to 50°C

3. Initial Tests

The two goals of the early studies were (1) to evaluate the three different transducers at two different locations in the FITS tank and (2) to evaluate Brunswick 1101 felt metal as a thermal barrier on the Precise Sensor transducers. All of the Kulite transducer results were obtained using felt metal thermal shielding as recommended by the manufacturer.

3.1 Experimental Setup

The initial test sequence conducted in this study was divided into two parts. The first of these was an evaluation of two felt metal-protected Kulite transducers and four Precise Sensor model 141-1 gages. Two of the Precise Sensor gages were thermally protected with felt metal and two were unprotected from the hot gases. Two ports (the E-2 and C-2 ports) in the FITS vessel were instrumented each with a protected Kulite, a protected 141-1 and an unprotected 141-1 gage. Thus, the responses of each gage could be compared directly to the others in that port. Comparisons between pressure measurements recorded at the upper and lower ports could also be made with this type of arrangement. The specific gages used, as well as their locations in the FITS vessel and the thermal protection employed, are outlined in Table 3 for this first segment of testing. The six gages were exposed to eight hydrogen:air combustion tests, using equipment setup A of Table 3. These tests were performed with varying initial compositions of hydrogen and air, with the gas temperature approximately equal to the tank wall temperature and with fans operational. The gages were removed and statically calibrated after these experiments and then eleven additional burns were performed with the sensors positioned in the tank as shown in equipment setup B of Table 3. Two different Kulite gages were installed for this latter set of tests. During testing, the Kulite gage C2-42 failed and was replaced with the previously tested Kulite C2-31 gage.

In the second part of testing, one Kulite transducer with felt metal protection, two Precise Sensor model 141-1 gages, with and without thermal protection, and two Precise Sensors model 111-1 gages, with and without thermal protection, were compared. The various gage locations and thermal protection for this second series of tests (equipment setups C through F) are shown in Table 4. In these tests, the major objective was to determine whether felt metal was needed to shield the Precise Sensor model 111-1. Note that in setups E and F, the Precise Sensor 111-1 gages were positioned in port E-1 as in the HBS-1 and FITS-1 test series. In setups C and D, the Precise Sensor 111-1 gages were positioned in the E-2 port, so that the sensing elements were flush with the inner tank walls.

Table 3
Location of Transducers for Setups A and B

Setup A

Transducer Type:Model	SN	Range, atm.	Amp.	Location	Thermal Protection
Kul:XT-190	C2-31	20.41	D-6	Port C-2	Felt Metal
Kul:XT-190	C2-41	20.41	D-5	Port E-2	Felt Metal
PS:141-1	20379	6.81	D-3	Port E-2	None
PS:141-1	20898	6.81	D-1	Port E-2	Felt Metal
PS:141-1	20212	13.61	D-2	Port C-2	None
PS:141-1	20901	13.61	D-4	Port C-2	Felt Metal

Setup B

Transducer Type:Model	SN	Range, atm.	Amp.	Location	Thermal Protection
Kul:XT-190	C2-34	20.41	D-5	Port C-2	Felt Metal
Kul:XT-190	C2-42	20.41	D-6	Port E-2	Felt Metal
PS:141-1	20379	6.81	D-3	Port E-2	None
PS:141-1	20898	6.81	D-1	Port E-2	Felt Metal
PS:141-1	20212	13.61	D-2	Port C-2	None
PS:141-1	20901	13.61	D-4	Port C-2	Felt Metal
*Kul:XT-190	C2-31	20.41	D-6	Port E-2	Felt Metal

*... This gage was installed in port E-2 when Kulite C2-42 malfunctioned.

Table 4
Location of Transducers for Setups C through F

Setup C

Transducer Type:Model	SN	Range, atm.	Amp.	Location	Thermal Protection
Kul:XT-190	C2-33	20.41	D-5	Port E-2	Felt Metal
PS:141-1	20379	6.81	D-3	Port E-2	Felt Metal
PS:111-1	21086	13.61	D-2	Port E-2	Felt Metal
PS:111-1	21087	13.61	D-1	Port E-2	None
PS:141-1	20901	13.61	D-4	Port C-2	None

Setup D

Transducer Type:Model	SN	Range, atm.	Amp.	Location	Thermal Protection
Kul:XT-190	C2-33	20.41	D-5	Port E-2	Felt Metal
PS:141-1	20898	6.81	D-3	Port E-2	Felt Metal
PS:111-1	21086	13.61	D-2	Port E-2	None
PS:111-1	21087	13.61	D-1	Port E-2	Felt Metal
PS:141-1	20901	13.61	D-4	Port C-2	None

Setup E

Transducer Type:Model	SN	Range, atm.	Amp.	Location	Thermal Protection
Kul:XT-190	C2-33	20.41	D-5	Port E-2	Felt Metal
PS:141-1	20898	6.81	D-3	Port E-2	Felt Metal
PS:111-1	21086	13.61	D-2	Port E-1	None
PS:111-1	21087	13.61	D-1	Port E-1	Felt Metal
PS:141-1	20901	13.61	D-4	Port C-2	None

Setup F

Transducer Type:Model	SN	Range, atm.	Amp.	Location	Thermal Protection
Kul:XT-190	C2-33	20.41	D-5	Port E-2	Felt Metal
PS:141-1	20898	6.81	D-3	Port E-2	Felt Metal
PS:111-1	21086	13.61	D-2	Port E-1	Felt Metal
PS:111-1	21087	13.61	D-1	Port E-1	None
PS:141-1	20901	13.61	D-4	Port C-2	None

3.2 Results From Initial Testing

The ratios of the peak combustion pressures to the pre-ignition pressures, along with the corresponding burn times for each of the 19 hydrogen:air combustion experiments performed in the first part of the initial testing sequence are summarized in Table 5. Note that each combustion test presented in Table 5 has a unique test ID (shown as "Name") consisting of a number and letter. All of the tests performed in this study are numbered consecutively, followed by a letter which designates the equipment setup used for that particular test. For simplicity and consistency, this identification scheme will be used to cross match particular combustion tests throughout this text. Summaries of the initial conditions and analytical predictions obtained for each of the combustion tests described in this report are tabulated in Appendix A and B, respectively. Included in Appendix A are the pre-ignition temperatures and pressures, the date and time of ignition, and the FITS 'burn [illegible]' for each test.* Adiabatic isochoric complete combustion (AICC) predictions for the tests are given in Appendix B using the initial conditions provided in Appendix A. The theoretical pressure ratio using the AICC code is also provided in Table 5 for direct comparison and evaluation of the trends.

Review of the data in Table 5 indicates that the unprotected 141-1 Precise Sensors generally recorded lower peak pressures than did the shielded Precise Sensors. The data also indicate that the protected Precise Sensor agreed well with the protected Kulite gage in port E-2 nearest the ignition source. Peak pressures recorded by Precise Sensor gages in port C-2, however, generally were greater than the Kulite readings, and in a few cases even exceeded the AICC values. Overall, the Kulite gages recorded peak pressures that were essentially independent of port location, as one might expect in the FITS vessel. The mean pressure ratio and standard deviation for the six gages used in this test segment are shown in Table 6. The statistical variation from the mean of the six pressure measurements ranged from approximately 3% to 7% for hydrogen burns of 10% to 30% by volume, respectively.

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* The identification system used in this report was established during the assembly of the text. Different test designators were assigned during the testing process, and are provided in the appendices to avoid later confusion when accessing the experimental data.

Table 5
Initial Testing Results for Gages XT-190 and 141-1

		PORT E-2						PORT C-2						
	MODEL:	XT-190		141-1		141-1		141-1		141-1		XT-190		
	SN:	<C2-41>		20379		<20898>		20212		<20901>		<C2-31>		THEO
NAME	%H2	PR	BT	PR	BT	PR	BT	PR	BT	PR	BT	PR	BT	PR
1-A	9.7	4.01	.44	3.86	.44	3.90	.44	4.07	.43	4.26	.47	4.02	.44	4.23
2-A	10.0	3.47	.37	3.40	.40	3.38	.42	3.53	.40	3.69	[illegible]	3.47	.37	4.14
3-A	20.0	6.07	.06	5.63	.08	5.94	.06	6.28	.07	6.47	.08	6.08	.07	6.49
4-A	18.8	6.14	.08	5.72	.09	5.95	.08	6.34	.08	6.56	.10	6.14	.09	6.40
5-A	24.6	7.33	.03	6.64	.04	7.19	.03	7.54	.03	7.88	.04	7.31	.03	7.38
6-A	24.3	7.43	.02	6.73	.04	7.37	.01	7.74	.03	7.82	.05	7.54	.03	7.55
7-A	30.3	7.92	.02	7.26	.03	7.87	.02	8.40	.02	8.81	.03	8.06	.02	8.11
8-A	29.5	7.69	.02	7.07	.04	7.59	.02	7.93	.03	8.23	.03	7.69	.02	7.92

		PORT E-2						PORT C-2						
	MODEL:	XT-190		141-1		141-1		141-1		141-1		XT-190		
	SN:	<C2-41>		20379		<20898>		20212		<20901>		<C2-31>		THEO.
NAME	%H2	PR	BT	PR	BT	PR	BT	PR	BT	PR	BT	PR	BT	PR
9-B	11.2	3.80	.34	3.74	.33	3.72	.35	3.94	.34	4.11	.33	3.81	.33	4.57
10-B	31.1	7.61	.02	7.10	.03	7.40	.02	NA	NA	8.04	.04	7.64	.02	8.06
11-B	34.3	7.73	.02	7.33	.03	7.56	.02	8.17	.02	8.12	.04	7.73	.02	7.90
12-B	10.3	3.28	.25	3.14	.28	3.15	.25	3.29	.25	3.46	.29	3.27	.25	3.65
13-B	50.0	5.26	.04	4.87	.05	5.24	.04	5.53	.04	5.75	.05	5.31	.04	5.74
14-B	60.0	4.55	.08	4.36	.09	4.48	.08	4.73	.08	4.97	.10	4.60	.08	5.04
15-B	68.0	3.68	.25	3.62	.24	3.59	.24	3.79	.24	3.95	.24	3.71	.24	4.29
16-B	29.9	6.49	.03	6.11	.03	6.51	.01	6.80	.03	7.49	.02	6.62	.03	6.79
17-B	39.9	6.12	.03	5.89	.03	6.12	.03	6.44	.03	6.86	.03	6.27	.02	6.64
18-B	19.6@1	NA	NA	4.21	.14	4.57	.12	4.80	.12	5.04	.13	4.68	.12	5.02
19-B	19.1@2	NA	NA	4.23	.12	4.49	.11	4.73	.10	4.95	.11	4.60	.10	4.99

@1..... 20.8% steam (by volume) in the initial composition.
@2..... 14.0% steam (by volume) in the initial composition.
PR..... the ratio of the peak pressure to the pre-ignition pressure.
BT..... the burn time (time from baseline to peak pressure) in seconds.
< >.... the gage is thermally protected.

Representative pressure transducer traces obtained for a nominal 10% by volume hydrogen deflagration (test 12-B) during the initial phase of testing are provided in Figures 5 and 6. The six pressure transducer responses are overlayed in Figure 5, while the three transducers in each port are compared in Figure 6. All sensors appear to have tracked the pressure transients, although there is about a 0.2 to 0.4 atmosphere* pressure difference between the extremes of the peak pressure measurements as noted between transducers in the C-2 and E-2 ports. It is not obvious from either the tabulated results presented in Table 6 or from Figures 5 and 6 that one gage type is superior since neither type of gage read consistently high or low. It should be noted, however, that the Kulite gages were less affected by location in the FITS tank. Even the advantage of using the felt metal on the Precise Sensor model 141-1 for thermal shielding is not obvious, although it appears from the tabulated results that the shielded sensors read slightly higher than do the unshielded sensors. One additional trend can be noted from results obtained during this initial testing. The felt metal was expected to limit the thermal effects without altering the transient combustion pressure response of the transducer. It is evident from Figures 5 and 6 and from the burn time results presented in Table 5, that there is very little difference between the response of the thermally protected Precise Sensor model 141-1 and that of the unprotected 141-1. The felt metal does not appear to alter the shape of the transient combustion pressure trace or the burn time.

The results of the eleven hydrogen:air combustion tests performed during the second part of testing are outlined in Table 7. It is obvious from these results that the Precise Sensor model 111-1 is extremely sensitive to the severe thermal environment during combustion. As indicated previously in the Experimental Apparatus section, the model 111-1 had been used in past combustion testing, and is advertised as being capable of operating in gas temperatures up to 1093°C. This temperature rating is somewhat misleading since the manufacturer's temperature ratings are generally based on static temperature conditions and not on a transient temperature condition imposed on the transducer diaphragm. The unprotected Precise Sensor model

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* Pressures presented in graphical or tabulated form in this text are given in units of atmospheres instead of the more standard SI units (Pascals), for ease of interpretation of the results.

Table 6
Statistical Analysis of the Results Given in Table 5

Name	% Hydrogen	Mean	Deviation	% Max.
1-A	9.7	4.02	.14 (3.48%)	9.95
2-A	10.0	3.49	.11 (3.15%)	8.88
3-A	20.0	6.08	.29 (4.77%)	13.82
4-A	18.8	6.14	.29 (4.72%)	12.21
5-A	24.6	7.32	.41 (5.60%)	16.94
6-A	24.3	7.44	.39 (5.24%)	14.65
7-A	30.3	8.05	.52 (6.46%)	19.25
8-A	29.5	7.70	.39 (5.06%)	15.06
9-B	11.2	3.85	.15 (3.83%)	10.13
10-B	31.1	7.56	.35 (4.57%)	12.43
11-B	34.3	7.77	.32 (4.16%)	10.81
12-B	10.3	3.27	.12 (3.56%)	9.79
13-B	50.0	5.33	.30 (5.57%)	16.51
14-B	60.0	4.62	.21 (4.61%)	13.20
15-B	68.0	3.72	.13 (3.53%)	9.68
16-B	29.9	6.67	.46 (6.91%)	20.69
17-B	39.9	6.28	.34 (5.35%)	15.45
18-B	19.6@1	4.66	.31 (6.57%)	17.81
19-B	19.1@2	4.60	.27 (5.84%)	15.65

@1......... 20.8% steam (by volume) in the initial composition.
@2......... 14.0% steam (by volume) in the initial composition.
Mean....... is the mean pressure ratio of the gages.
Deviation.. is the standard deviation of the calculated mean.
% Max. .... ((Maximum - Minimum) / Mean) x 100

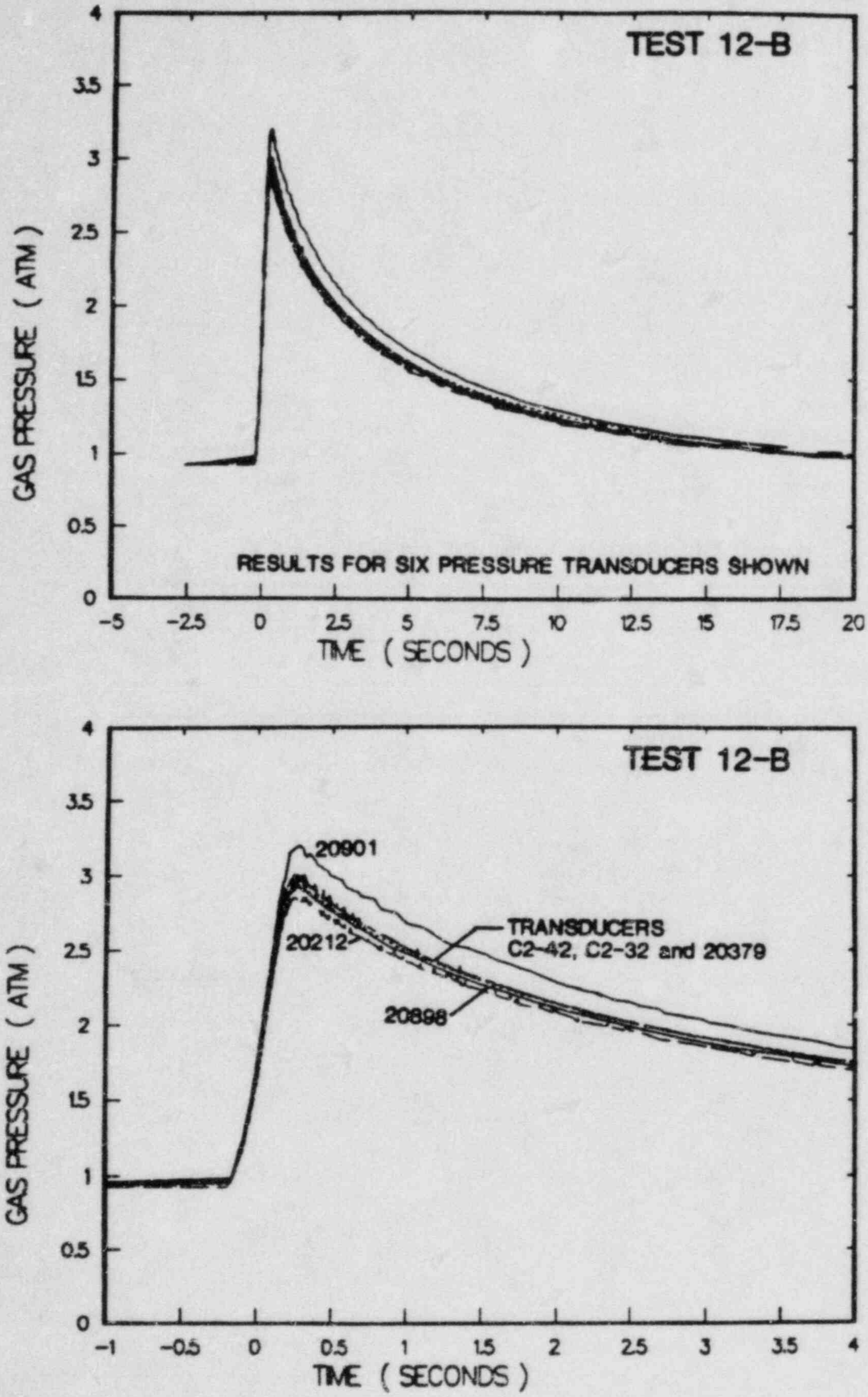
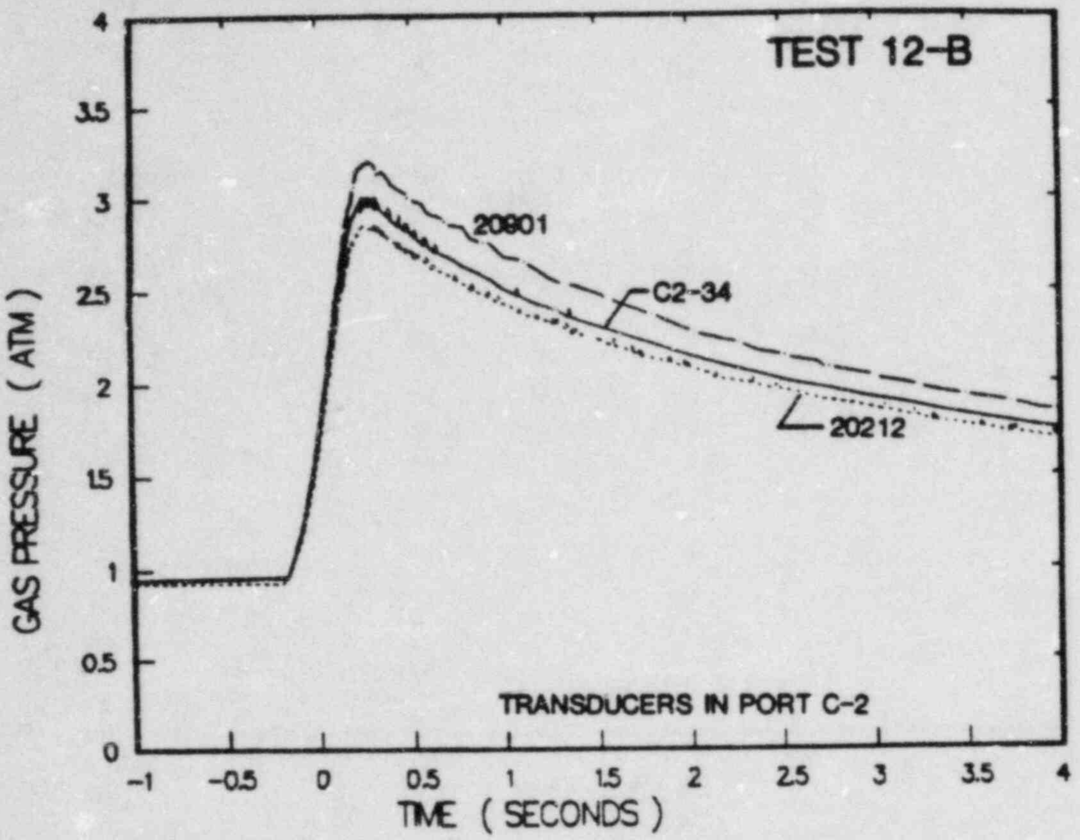


Figure 5. Gage Comparisons for Test 12-B



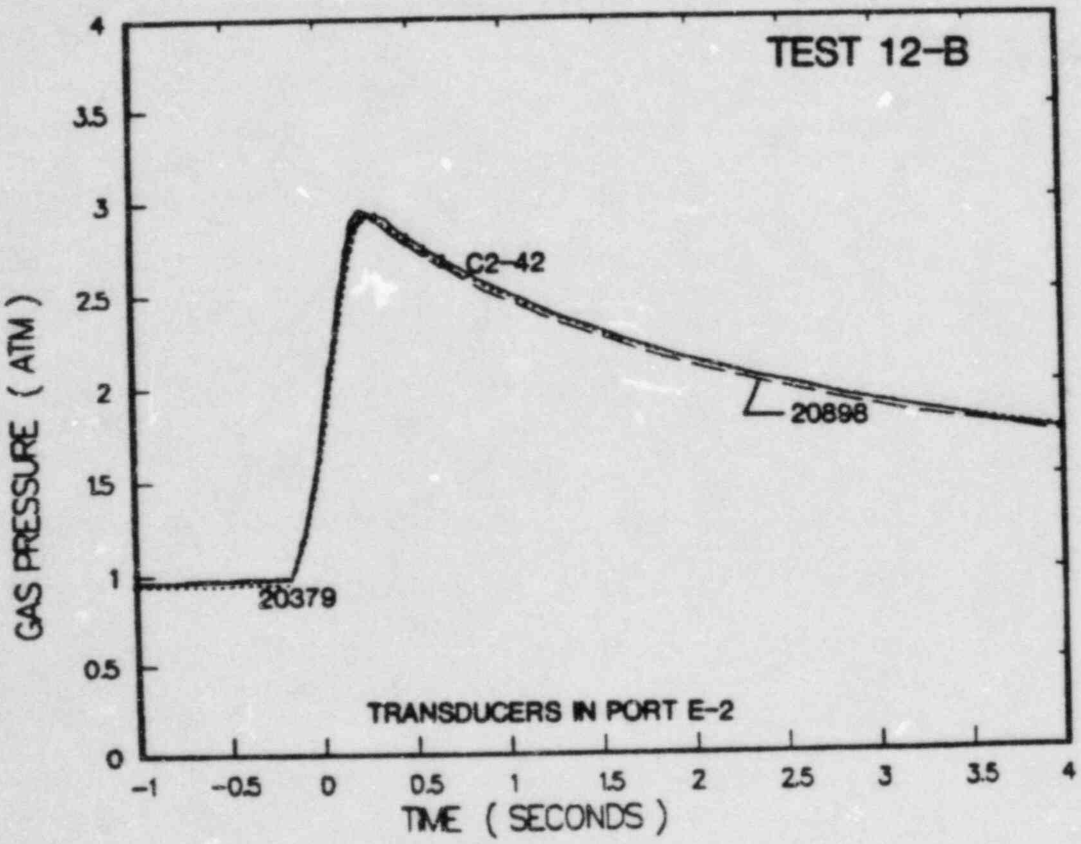


Figure 6. Port Comparisons for Test 12-B

Table 7
Initial Results for the 111-1 Gage

		PORT E-2								PORT C-2		
MODEL:		XT-190		141-1		111-1		111-1		141-1		
SN:		<C2-41>		<20379>		<21086>		21087		20901		THEO.
NAME	%H2	PR	BT	PR	BT	PR	BT	PR	BT	PR	BT	PR
20-C	9.8	3.77	.49	3.68	.51	3.80	.48	6.24	1.23	3.92	.49	4.24
21-C	20.2	6.28	.07	6.27	.09	6.31	.07	10.32	.25	6.25	.08	6.72
22-C	30.1	7.74	.03	NA	NA	7.95	.03	12.61	.11	7.88	.03	8.06

		PORT E-2								PORT C-2		
MODEL:		XT-190		141-1		111-1		111-1		141-1		
SN:		<C2-41>		<20379>		21086		<21087>		20901		THEO.
NAME	%H2	PR	BT	PR	BT	PR	BT	PR	BT	PR	BT	PR
23-D	9.5	3.66	.46	3.64	.49	5.25	.62	3.63	.46	3.73	.49	4.05
24-D	19.6	6.27	.07	6.12	.08	8.83	.18	6.17	.07	6.24	.08	6.43

		PORT E-2				PORT E-1				PORT C-2		
MODEL:		XT-190		141-1		111-1		111-1		141-1		
SN:		<C2-41>		<20898>		21086		<21087>		20901		THEO.
NAME	%H2	PR	BT	PR	BT	PR	BT	PR	BT	PR	BT	PR
25-E	9.4	3.63	.67	3.62	.67	4.42	.73	3.61	.66	3.71	.69	4.11
26-E	20.8	6.21	.12	6.08	.13	8.49	.35	6.33	.12	6.26	.13	6.85
27-E	30.2	7.79	.04	7.55	.06	10.88	.18	8.16	.04	7.85	.06	8.08

		PORT E-2				PORT E-1				PORT C-2		
MODEL:		XT-190		141-1		111-1		111-1		141-1		
SN:		<C2-41>		<20898>		<21086>		21087		20901		THEO.
NAME	%H2	PR	BT	PR	BT	PR	BT	PR	BT	PR	BT	PR
28-F	10.1	3.64	.57	3.64	.56	3.64	.57	5.04	1.04	3.74	.57	4.21
29-F	10.2	3.49	1.82	3.49	1.9	3.53	1.89	4.69	2.07	3.63	1.82	4.24
30-F	19.7	6.05	.15	5.94	.16	6.24	.15	8.21	.40	6.13	.16	6.46

< >..... the gage is thermally protected.
PR...... the ratio of the peak pressure to the pre-ignition pressure
BT...... the burn time (or rise time).

111-1 gage recorded a thermally induced response which was superimposed upon the response induced by the combustion pressure. The thermally protected model 111-1, on the other hand, compared well with the pressure responses of the Kulite and Precise Sensor model 141-1 gages throughout the tests.

The mean combustion pressure ratios calculated from the Kulite and Precise Sensor 141-1 results are compared to the protected and unprotected Precise Sensor model 111-1 results in Table 8. The peak pressure responses of the two model 111-1 gages are compared to the mean of the responses for the Kulite and 141-1 gages, shown on a difference percentage (%DIFF). Note that the protected 111-1 gage is generally within 3% of the mean pressure ratio. For tests in which the unprotected Precise Sensor 111-1 gages were positioned in port E-2, gage 21086 read approximately 40% higher than the other gages while gage 21087 read approximately 60% higher. When the gages were in the E-1 port, gage 21086 recorded pressures which were 20-40% higher, while gage 21087 recorded pressures approximately 30% higher. Thus, the E-1 port provided a slight amount of thermal protection as expected, although the response of the gages was still affected by the thermal environment. The burn times, as determined by the rise time to peak pressure, were also substantially longer, ranging from 30% longer for the leaner burns to over 150% longer for hydrogen concentrations near stoichiometry, when compared to the burn times determined by the protected gages.

The effects of not thermally shielding the 111-1 gages are clearly illustrated in Figure 7. This is a typical 10% hydrogen:air deflagration (test 28-F) in a "cold" tank with the fans operational throughout the data acquisition period. It appears from the longand short-time comparisons in Figure 7 that the thermally protected model 111-1 tracked the transient combustion pressure, while the unprotected gage recorded a thermally induced overpressure. The long time comparison in Figure 7, illustrates that the unprotected model 111-1 approaches the response of the protected transducers at times around twenty seconds after ignition, which would be expected since the combustion gases have cooled considerably by this time. The unprotected model 111-1 gage typically deviates from the protected gage shortly after ignition, achieves a higher apparent peak pressure and "rolls" through the peak. The protected 111-1 (as well as the other gages) rapidly reach the peak (appearing as a step-function for richer combustion tests) and then decay in an exponential manner to the approximate pre-ignition pressure. Additionally, there is no evidence of acoustically induced over-pressures in port E-1, since both gages would have responded to such a phenomenon. The differences between the two types of pressure traces are again clearly shown in Figure 8 for test 26-E, which is a 20.8% hydrogen:air combustion test. The short-time comparison shows

Table 8
Protected and Unprotected Model 111-1 Comparisons*

Name	% H2	Mean	21086	%DIFF	21087	%DIFF
20-C	9.8	3.79	3.80	0.26	6.24	64.64
21-C	20.2	6.30	6.31	0.16	10.32	63.81
22-C	30.1	7.81	7.95	1.79	12.61	61.46
23-D	9.5	3.68	5.25	42.66	3.63	1.36
24-D	19.6	6.18	8.83	42.88	6.17	0.16
25-E	9.4	3.65	4.42	21.11	3.61	1.10
26-E	20.8	6.18	8.49	37.38	6.33	2.43
27-E	30.2	7.73	10.88	40.75	8.16	5.56
28-F	10.1	3.67	3.64	0.82	5.04	37.33
29-F	10.2	3.54	3.53	0.28	4.69	32.49
30-F	19.7	6.04	6.24	3.31	8.21	35.93

*.......... Refer to Table 7 to determine which gage is protected for each test.
Mean....... is the mean pressure ratio of the Kulite XT-190 and Precise Sensor 141-1 gages.
Deviation.. is the standard deviation of the mean pressure ratio.
% DIFF..... implies the following equation was used: (|READING - MEAN|) / MEAN) x 100.

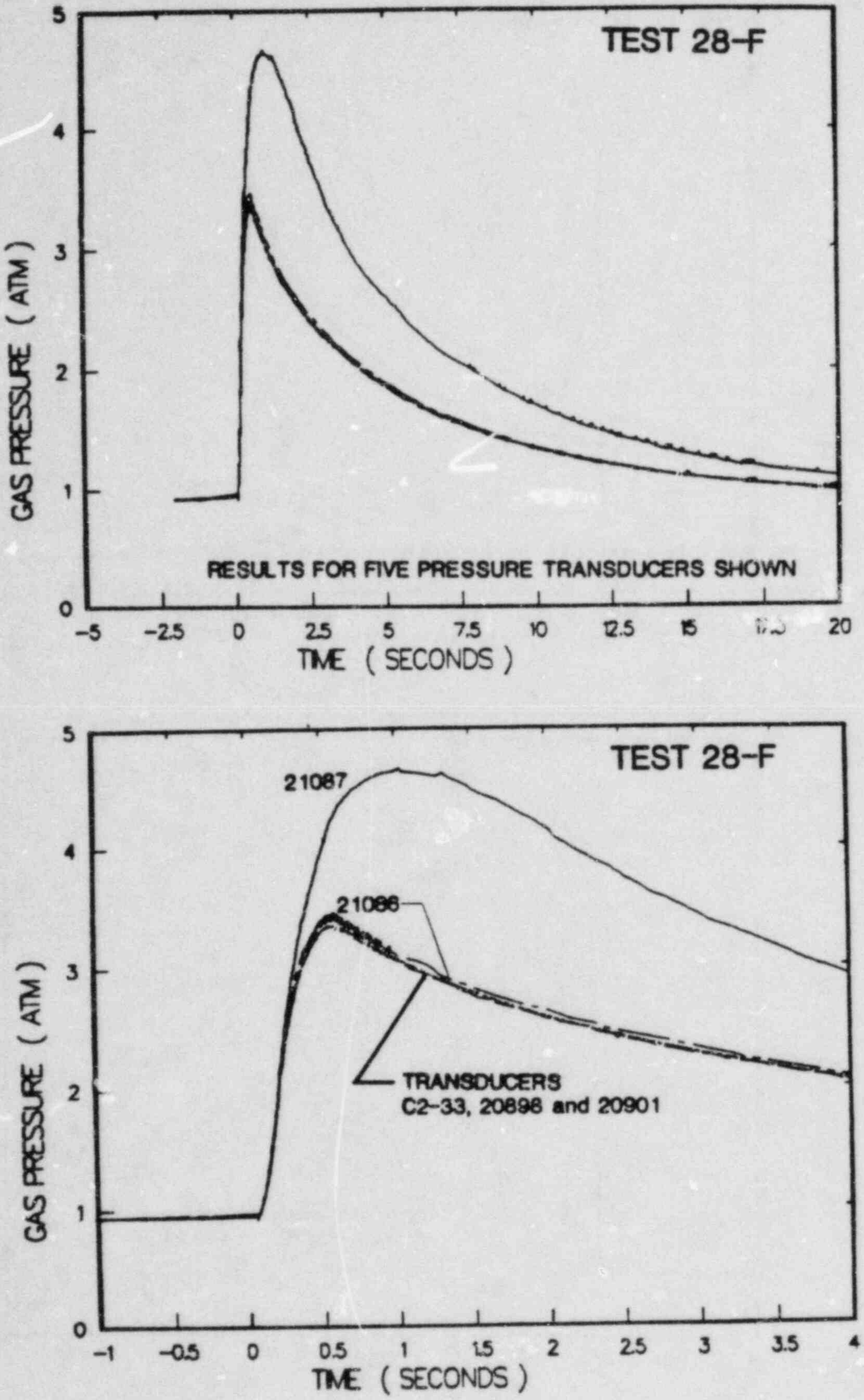


Figure 7. Gage Comparisons for Test 28-F

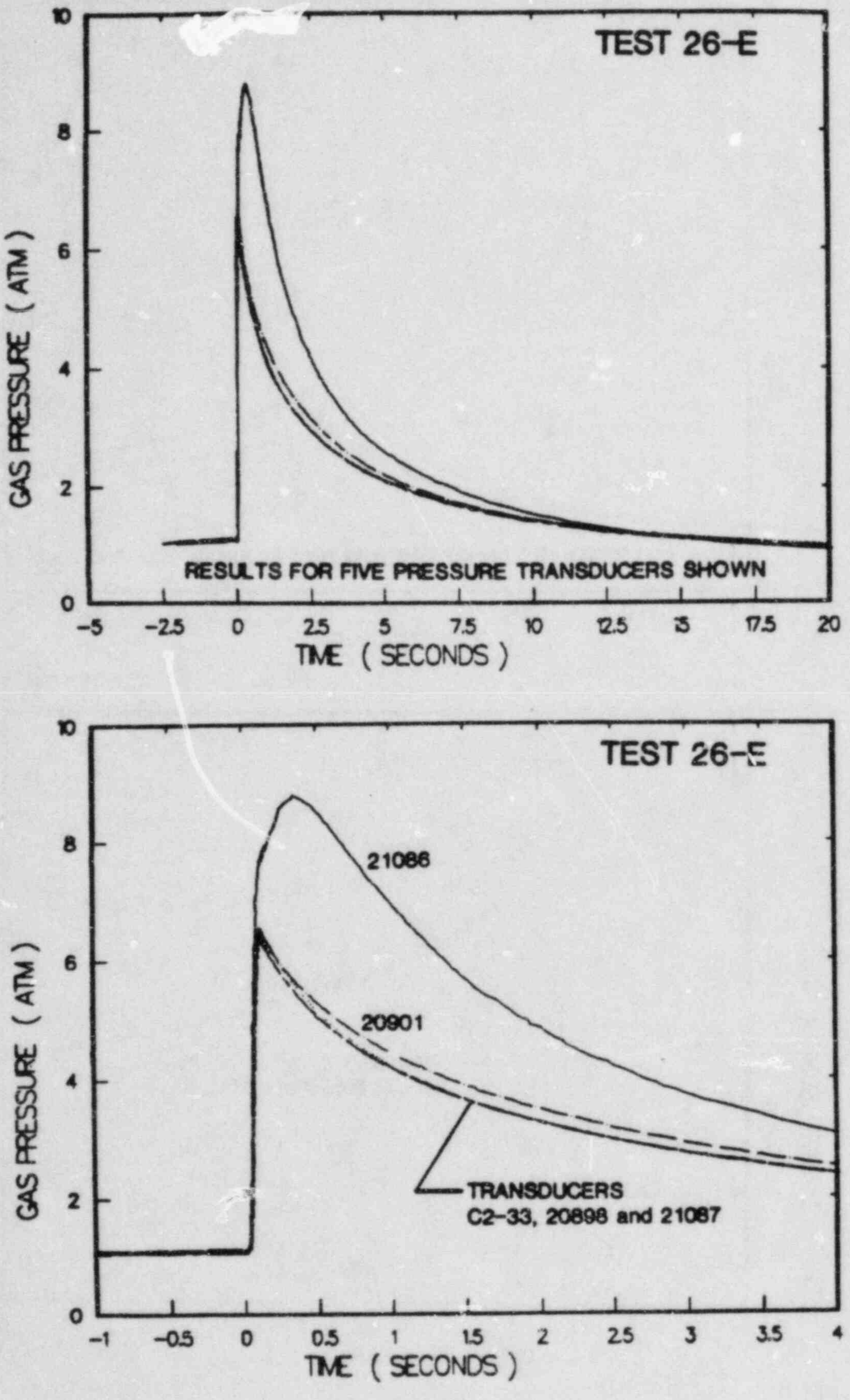


Figure 8. Gage Comparisons for Test 26-E

that the unprotected gage is affected by the thermal environment of combustion. The unprotected gage "rolls" through the peak instead of appearing as a step-function to the peak value. As a result of these studies, then, it is evident that the pressure data recorded by a thermally unprotected Precise Sensor model 111-1 exposed to a transient thermal environment such as combustion, should not be used.

3.3 Initial Conclusions

As a result of these initial studies, we concluded that the response of an unprotected air-cooled Precise Sensor model 111-1 gage is significantly affected by the severe thermal environment associated with combustion. These gages should not be used in any transient thermal environment without felt metal or comparable thermal protection. Further, the reduction and presentation of past combustion pressure data taken with thermally unprotected Precise Sensor model 111-1 gages should probably be avoided. The unprotected Precise Sensor model 141-1 gages, on the other hand, recorded results that were not noticeably affected by the combustion thermal environment. These gages did, however, record results that appeared to be dependent upon location in the FITS chamber. This was contrary to the results recorded by the thermally protected Kulite model XT-190 gages. The Kulite gages recorded combustion pressures that were relatively independent of tank location as would be expected since the combustion-induced gas velocities are subsonic. Therefore, no definitive conclusions could be drawn from this work about the past and future performance of the Precise Sensor 141-1 or the Kulite XT-190 gages. We concluded that additional testing was needed to resolve the port dependency question.

4. Diagnostics Testing

Evaluation of the initial testing results raised two further uncertainties about the performance of the Precise Sensor gages which could not be answered from data obtained in the initial testing. The first uncertainty concerned the importance of gas cooling to the performance of the Precise Sensors. If the diaphragm of either type of Precise Sensor was sensitive to the inlet conditions of the cooling gas, then the transducer response during a combustion test could be affected by the thermal environment due to a lack of proper cooling. Further, since the thermal environment induced by combustion is generally more severe in the upper portion of the volume (where the burn is generally terminated) than in the lower portion, the Precise Sensor gages positioned in the upper ports might record pressures significantly different from those located in lower regions of the chamber as a result of insufficient gas cooling. The second uncertainty, also related to the port-dependency recorded by the 141-1 Precise Sensors, addressed the accuracy and performance of the FITS data acquisition system. That is, was the pressure port-dependency recorded by the 141-1 gages a physical phenomenon or was it an error induced by some component of the data acquisition system? Given that the 141-1 Precise Sensors recorded a port dependency while the Kulite transducers recorded combustion pressures that were relatively independent of location, this was a major concern. It was imperative, for future combustion testing as well as in interpreting the pressure results from past combustion testing at FITS, that these questions be addressed in detail. Thus, a series of diagnostic tests which specifically addressed these two questions was performed. The following sections describe these studies and summarize the conclusions obtained from the diagnostics results.

4.1 Cooling Evaluation

The poor performance of the unfelted Precise Sensor 111-1 gage was surprising to the Precise Sensor representative, M. Lacey, who had recommended this particular transducer for the initial testing at FITS. Following several discussions with him [7], it was decided that additional tests were needed to assess the importance of the gas cooling on the performance of the two Precise Sensor gage types. All of the previously described combustion tests were performed using an inlet (gaseous nitrogen) gage pressure to the cooling baffle (previously shown in Figure 2) of 68.95 kPa (0.68 atm) resulting in a volumetric flow rate of 14.2 LPM (0.50 CFM). Although the Precise Sensor specifications for these transducers recommended inlet pressures of 103.4 to 137.8 kPa gage pressure, it was realized that the volumetric flow rate of the gas was the important criterion for effective gage cooling. A series of combustion tests with different inlet cooling pressures (resulting in different volumetric flow rates) was performed with the transducers arranged as shown in setup F in Table 4. The inlet cooling conditions and number of gages cooled during this testing are outlined in Table 9. Note that when only two gages were cooled through the baffle arrangement, the remaining three cooling lines from the baffle were closed.

Seven combustion tests, mostly in the 10% hydrogen (by volume) range, were performed and are summarized in Table 10. These results indicate that increasing the gas cooling condition (i.e., increasing the volumetric flow rates) does not appreciably improve the performance of the thermally unshielded Precise Sensor model 111-1 or 141-1 gages, although peak pressure responses of the unprotected gages did decrease slightly. Further, tests such as the 10.1% hydrogen combustion test (test 37-F6) again illustrated that the unprotected model 111-1 recorded a thermally induced response, even at a volumetric flow rate well above the recommended 56.6 LPM (measured at 80.0 LPM to each gage) at an inlet pressure of 138 KPa. The Precise Sensor model 111-1 with felt metal, on the other hand, reproduced the response of the Kulite gages and 141-1 Precise Sensor gages as reported during the initial test series. This indicates that thermal shielding, rather than the gas cooling, is crucial to the performance of a Precise Sensor model 111-1 when exposed to a combustion environment. It was also apparent that the gas cooling was not critical to the performance of the Precise Sensor model 141-1. For tests in which there was no gas cooling to the 141-1 gages, measured peak pressures and burn times compared reasonably well with the Kulite transducer and with the thermally shielded 111-1 gage (refer to tests 33-F3, 34-F4, 35-F4, and 36-F5).

4.2 System Evaluation

Although the peak pressure results shown for the model 141-1 gages in the cooling diagnostics section indicated that there might still be a slight port dependency, there was no reason to believe that this result was dependent upon the gas cooling conditions. Therefore, it became even more important that an evaluation of the data acquisition system be performed before any definitive conclusions about particular gage responses could be made. This evaluation concentrated on the individual gages and the associated amplifiers used to enhance the pressure signal.

The direct current (DC) voltage generated by a strain gage type pressure transducer is generally calibrated against the reference pressure (generally either atmospheric pressure or absolute zero), over the full range of the gage in units of pressure per millivolt (mV). Thus, a small change in voltage

Table 9
Cooling Evaluation
(Using Transducer Setup F in Table 4)

Cooling SetUp	* Inlet Gage Pressure	LPM/Gage	Gages Cooled	Description SetUp
1	137.9 KPa	21.2 LPM	5	All of the Precise Sensors cooled.
2	206.8 KPa	28.3 LPM	5	All of the Precise Sensors cooled.
3	68.9 KPa	28.3 LPM	2	Only the Precise Sensor model 111-1s were cooled.
4	137.9 KPa	47.3 LPM	2	Only the Precise Sensor model 111-1s were cooled.
5	206.8 KPa	61.4 LPM	2	Only the Precise Sensor model 111-1s were cooled.
6	137.9 KPa	80.1 LPM	4	All of the Precise Sensors, except the trigger source, had separate nitrogen bottles for cooling.

* .... these pressures are gage and not absolute pressures.

Table 10
Cooling Diagnostics Results

		PORT E-1								PORT C-2	
	MODEL:	XT-190		141-1		111-1		111-1		141-1	
	SN:	<C2-33>		<20902>		<21086>		21087		20901	
Name*	%H2	PR	BT	PR	BT	PR	BT	PR	BT	PR	BT
31-F1	24.3	7.16	.08	7.11	.08	7.23	.09	10.37	.40	7.34	.09
32-F2	11.2	3.12	.54	3.10	.53	3.20	.53	3.59	.59	3.19	.53
33-F3	10.0	2.84	2.04	2.78	2.09	2.86	2.01	3.26	2.16	2.80	2.06
34-F4	10.4	2.85	2.04	2.85	2.01	2.92	2.01	3.34	2.16	2.89	1.99
35-F4	19.7	5.02	1.70	5.06	1.71	5.02	1.70	6.62	1.84	5.08	1.69
36-F5	10.1	3.14	.15	3.14	.14	3.27	.14	3.86	.40	3.17	.14
37-F6	10.1	2.86	1.73	2.77	1.75	2.88	1.75	3.19	1.88	2.77	1.75

* .... specific gage cooling setups for these tests are defined in Table 9.

< >.... gage is thermally protected with felt metal.

PR...... the ratio of the peak pressure to the pre-ignition pressure

BT...... the burn time (or rise time).

would represent a corresponding change in pressure. Since the maximum voltage output of a strain-gage-type transducer is generally less than 50 mV, depending upon transducer sensitivity, amplifiers must be used to enhance the signal of a transducer to an acceptable voltage range for the ADCs (i.e., voltage levels sufficiently high such that the resolution of the ADC is not important to the result). Equation (1) is used to convert the DC signal into a corresponding pressure signal and requires that the gage calibration and amplifier gain settings be known.

$$\text{Pres.} = \frac{\text{SENS.(units of pres./mV)} \times \text{(1000mV/V)}}{\text{AMPLIFIER GAIN}} \times \text{(ADC VOLTAGE)} + \text{(Pres.@0mV)} \qquad (1)$$

Errors in either the calibration of the pressure gage or the amplifier will strongly affect the pressure result. Thus, the actual gains and linearity of the amplifiers are just as crucial to the measurement of pressure as are the sensitivities of the pressure gages.

To isolate any amplifier dependencies, six combustion tests were performed. The amplifiers were switched from transducer to transducer during these tests to determine whether the results recorded by the Precise Sensor 141-1 gages were amplifier dependent or transducer dependent. If a particular transducer recorded peak pressures that were higher than the other gages, then the gain used on that particular amplifier might be incorrect. This would become even more apparent if a particular amplifier, when used with different pressure transducers, caused the different transducers to over-predict (or significantly under-predict) the combustion gas pressure. This would indicate that the amplifier gain used in Eq.(1) to calculate the pressure was incorrect. On the other hand, if a particular gage consistently over-predicted the peak gas pressure with several different amplifier modules, then the gage calibration (or gage itself) would be suspect.

The details of the pressure sensor/amplifier setups and the peak pressure results of the six combustion tests performed in this series are shown in Tables 11 and 12, respectively. All tests conducted in this series were cold-wall combustion experiments with hydrogen concentrations approximately equal to 30% (by volume). These tests consisted of positioning the four 141-1 gages (two range types) in different ports using the same amplifiers to assess any dependence upon gage ranges. In the latter two tests, amplifier-gage combinations were altered to address the performance of the amplifiers.

Table 11
Experimental Setup for Amplifier Testing

MODEL:	XT-190		XT-190		141-1		141-1		141-1		141-1	
SN:	<C2-46>		<C2-50>		20898		<20379>		20901		<20212>	
Name	AMP	PORT	AMP	PORT	AMP	PORT	AMP	PORT	AMP	PORT	AMP	PORT
38-G	D-5	E-2	D-6	C-2	D-1	E-2	D-3	E-2	D-4	C-2	D-2	C-2
39-G	D-5	E-2	D-6	C-2	D-1	E-2	D-3	E-2	D-4	C-2	D-2	C-2
40-H	D-5	C-2	D-6	E-2	D-1	C-2	D-3	C-2	D-4	E-2	D-2	E-2
41-H	D-5	C-2	D-6	E-2	D-1	C-2	D-3	C-2	D-4	E-2	D-2	E-2
42-I	D-5	C-2	D-6	E-2	D-2	C-2	D-4	NA	D-1	E-2	D-3	E-2
43-J	D-5	C-2	D-6	E-2	D-4	C-2	D-2	NA	D-3	E-2	D-1	E-2

< >.... the gage was thermally protected with felt metal.
NA..... a system malfunction and the data is not available.

Table 12
Results of the Amplifier Testing

MODEL:		XT-190	XT-190	141-1	141-1	141-1	141-1
	SN:	<C2-46>	<C2-50>	20898	<20379>	20901	<20212>
Name	%H2	PR	PR	PR	PR	PR	PR
38-G	29.9	7.70	7.72	7.92	7.50	9.03	8.25
39-G	29.8	7.33	7.33	7.31	7.27	8.44	7.90
40-H	29.9	7.54	7.47	7.92	7.45	8.47	7.96
41-H	29.9	7.41	7.34	7.61	6.98	8.50	7.84
42-I	29.9	7.33	7.28	8.49	NA	7.38	7.35
43-J	30.2	7.09	7.06	7.31	NA	7.13	7.13

< >.... the gage was thermally protected with felt metal.
NA..... a system malfunction and the data is not available.

Precise Sensor gages 20901 and 20212 (located in port C-2) recorded peak pressures that were consistently higher than the other four gages in tests 38-G and 39-G. These same trends had been noted previously in the initial test series described in Section 3. In tests 40-H and 41-H, the three gages located in the C-2 port (20212, 20901 and C2-46) were switched with those located in the E-2 port (20898, 20379, and C2-50) to verify that the results were gage/amplifier dependent and not location dependent. As shown in Table 12, the higher peak pressures were again recorded by Precise Sensors 20901 and 20212 indicating that this pressure variation was gage/amplifier dependent. The amplifiers used with Precise Sensors 20901 and 20212 were then switched with the amplifiers used with 20898 and 20379 gages, respectively, for test 42-I. For this test, Precise Sensor gage 20898 recorded a peak pressure which was high, comparable to values measured with gage 20901 (using Dynamic amplifier D-2) in tests 38-G through 41-H. Further, Precise Sensors 20901 and 20212 recorded peak combustion pressures which closely compared to the two Kulite transducers indicating that these sensors were not malfunctioning. In test 43-J, amplifiers were again switched, resulting in the same general trends. Precise Sensors 20901 and 20212 predicted peak pressures that were comparable to the two Kulite gages. The combination of Gage 20898 and amplifier D-4, on the other hand, recorded a peak pressure that was obviously higher than the other gages.

From these results, it appeared that Dynamic amplifiers D-2 and D-4 had gain values that were substantially different from those which had been obtained from calibrations performed during the course of testing. This finding was somewhat surprising since all six of the amplifier gains had been checked periodically throughout this testing. After extensive review of the Dynamic amplifier manuals and suggested calibration procedures, it was concluded that no obvious procedural error would account for this difference and thus further evaluation of the calibration equipment was necessary. In the course of this check-out, it was found that the power supply (a Fluke Model 515-A Portable Calibrator) used to calibrate the amplifier gain was not functioning properly, affecting the actual gain set. When a different power supply was used to check the gains, the gains were actually higher than those indicated using the Fluke power supply. The differences in gains for each module used during this test series are shown in Table 13, along with the corresponding correction factors. These correction factors were applied to the initial testing data and with the six tests conducted in this diagnostics series (shown in Table 14), and the peak pressures recorded then appeared to be much more consistent than was first concluded. To further illustrate this finding, the results shown previously in Figure 5 (Test 12-B) have been replotted in

Figures 9 and 10 with the amplifier correction factors employed. In Figure 9, the new long time comparison is shown along with the long time comparison previously shown in Figure 5. In Figure 10, the same comparison for four transducers from Figure 9 and the corrected data are shown for the short time base. Pressure results for all of the protected gages located at the two levels are given in this figure. From these two Figures, it is evident that the pressure traces are in better agreement than was previously noted. In particular, the short time comparisons of the two sets of results show that the corrected data compares better.

4.3 Diagnostics Conclusions

As a result of this diagnostics testing, it was concluded that the performance of the Precise Sensor 111-1 and 141-1 gages were not noticeably sensitive to the inlet pressure and volumetric flow conditions of the cooling gas. It was also found that the Precise Sensor 141-1 gage could operate without any gas cooling and would still record data which compared well with the Kulite gages and with the protected Precise Sensor 111-1 gages. The port dependency noted in the initial testing was found to have resulted from a faulty power source used to calibrate the Dynamic amplifier gains. A correction factor was used to correct the initial data, which resulted in more consistent data with no apparent port-dependencies.

Table 13
Amplifier Correction Factors

MODULE	SET GAIN	ACTUAL GAIN	C.F.	SET GAIN	ACTUAL GAIN	C.F.
D-1	100	100.1	1.00	200	202.1	0.99
D-2	200	203.4	0.98	500	505.6	0.99
D-3	100	97.4	1.03	200	195.3	1.02
D-4	200	216.3	0.93	500	536.3	0.93
D-5	100	100.5	1.00	200	201.2	0.99
D-6	100	101.6	0.98	200	204.0	0.98

C.F. .... the correction factor for each module which is applied to the pressure data.

Table 14
Corrected Data from the Initial Testing

		PRESSURE RATIOS					
Name	%H2	<C2-41>	20379	<20898>	20212	<20901>	<C2-31>
1-A	9.7	3.99	3.98	3.86	4.00	3.94	3.94
2-A	10.0	3.45	3.47	3.35	3.47	3.41	3.40
3-A	20.0	6.04	5.80	5.94	6.21	6.03	5.98
4-A	18.8	6.11	5.89	5.95	6.27	6.11	6.04
5-A	24.6	7.29	6.84	7.19	7.46	7.34	7.19
6-A	24.3	7.39	6.93	7.37	7.65	7.29	7.42
7-A	30.3	7.88	7.48	7.87	8.31	8.21	7.93
8-A	29.5	7.65	7.28	7.59	7.84	7.67	7.57
9-A	11.2	3.72	3.81	3.68	3.90	3.83	3.79
10-B	31.1	7.49	7.31	7.40	NA	7.44	7.60
11-B	34.3	7.61	7.55	7.56	8.03	7.51	7.69
12-B	10.3	3.21	3.20	3.12	3.25	3.22	3.25
13-B	50.0	5.18	5.02	5.24	5.44	5.32	5.28
14-B	60.0	4.48	4.49	4.48	4.65	4.60	4.58
15-B	68.0	3.62	3.73	3.59	3.73	3.65	3.69
16-B	29.9	6.39	6.29	6.51	6.68	6.93	6.59
17-B	39.9	6.02	6.07	6.12	6.33	6.35	6.24
18-B	19.6@1	NA	4.34	4.57	4.72	4.66	4.66
19-B	19.1@2	NA	4.36	4.49	4.65	4.58	4.58

		PRESSURE RATIOS					
Name	%H2	<C2-46>	<20379>	20898	<20212>	20901	<C2-50>
38-G	29.9	7.62	7.65	7.84	8.17	8.40	7.57
39-G	29.8	7.26	7.42	7.24	7.82	7.85	7.18
40-H	29.9	7.46	7.60	7.84	7.88	7.88	7.32
41-H	29.9	7.34	7.12	7.53	7.76	7.91	7.19
42-I	29.9	7.26	NA	8.41	7.50	7.31	7.13
43-J	30.2	7.02	NA	6.80	7.06	7.06	6.92

@1.... 20.8% steam (by volume) in the initial composition.
@2.... 14.0% steam (by volume) in the initial composition.
NA.... system malfunction and the data is not available.

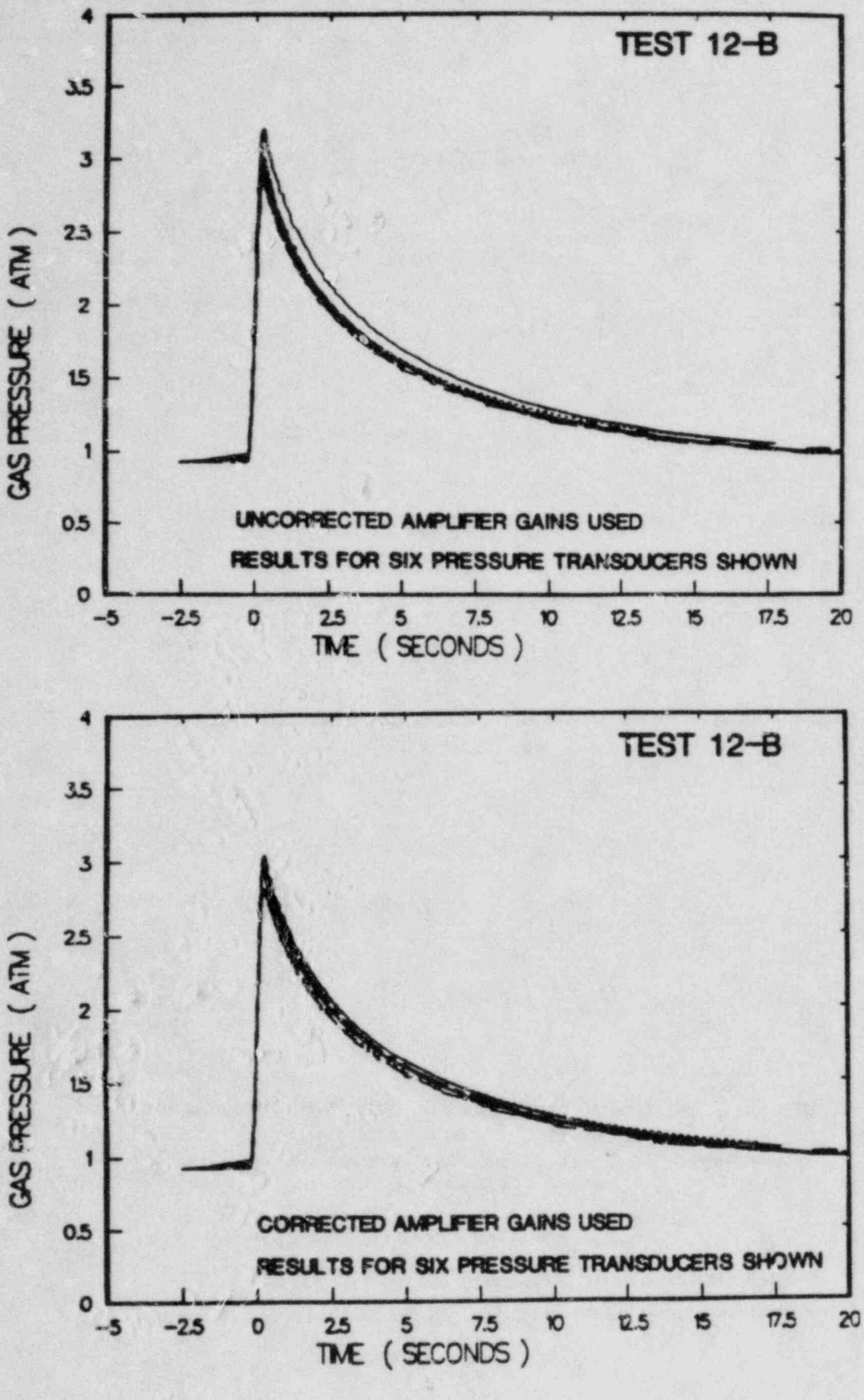


Figure 9. Corrected Long-Term Comparisons for Test 12-B

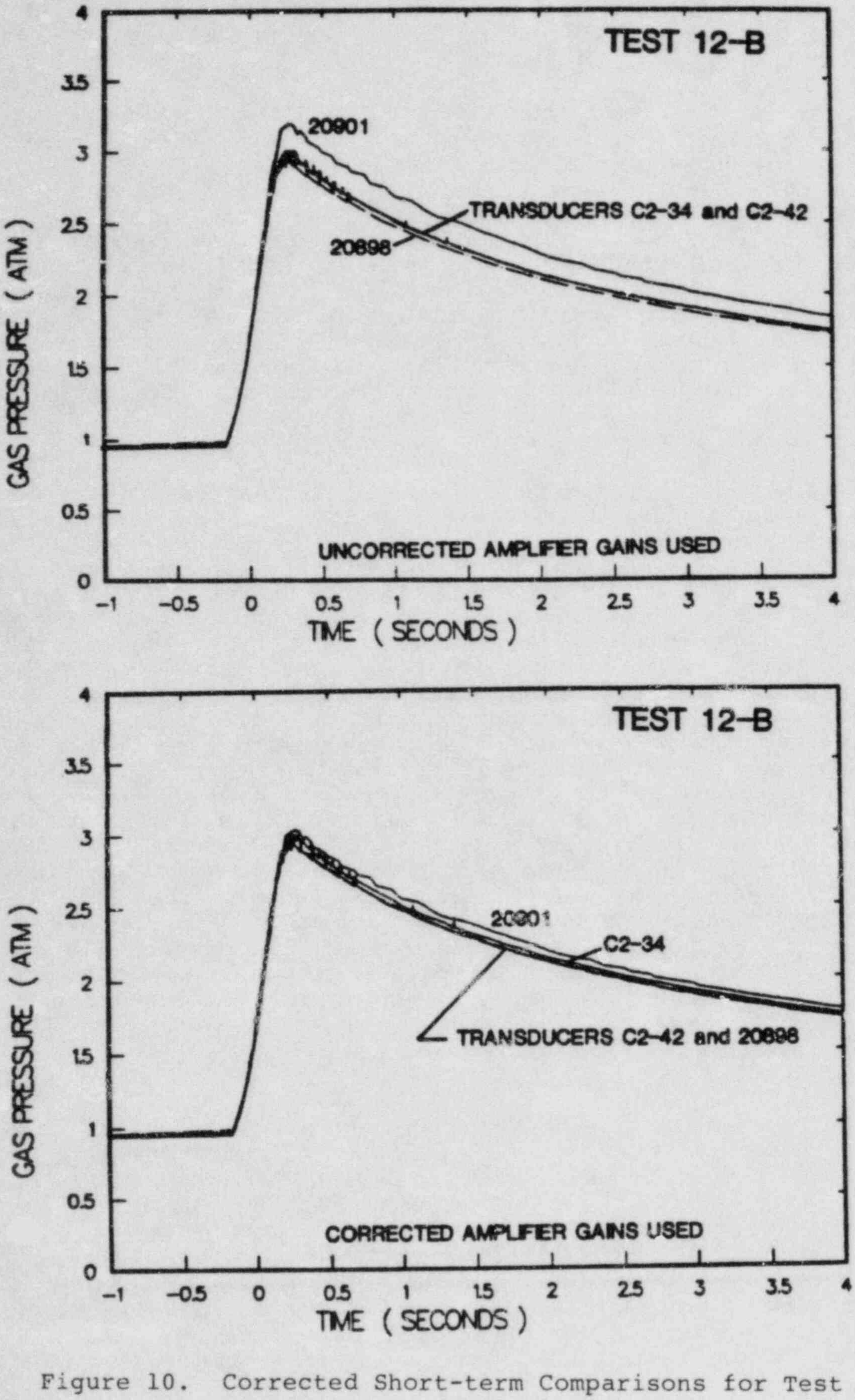


Figure 10. Corrected Short-term Comparisons for Test 12-B

5. Final Testing

A final series of combustion tests similar to the initial test series were conducted to substantiate the conclusions drawn in the initial and diagnostics testing (Sections 3 and 4). The Precise Sensors used in this series of tests had gas cooling conditions of 68.95 kPa (gage pressure) with a flow rate of 14.2 LPM. The amplifiers were also recalibrated with the accurate power supply before this test series began. The intent of this series of tests was to show conclusively which transducers must be thermally protected and to emphasize the importance of this thermal protection. These conclusions are important for future testing as well as in the evaluation of the past experimental combustion studies conducted at FITS.

5.1 Experimental Setup

The final pressure gage comparisons consisted of tests using six different pressure sensor setups. The same three transducer types were again directly compared, as in the initial testing. The first two of these setups (setups A and B, given previously in Table 3) compared the protected Kulite XT-190 gages with four 141-1 Precise Sensors, two protected and two unprotected as before. Setups K and L, given in Table 15, were also used to compare the 141-1 gage and XT-190 gage performances. In these latter tests, the performance of 141-1 gages having different gage ranges (0 - 6.81 atm. and 0 - 13.61 atm. gage ranges) were also compared, with one of each pressure range positioned in each of the two ports. The 0 - 13.61 atm. Precise Sensors were thermally protected in setup K, and were unprotected in setup L as shown in Table 15. The last two setups were identical to Setups E and F (shown in Table 4), which had been used to evaluate Precise Sensor 111-1 performance. In these final tests, two Kulite and two 141-1 Precise Sensor gages, one of each type in the E-2 and C-2 ports, were compared with unprotected and protected model 111-1 gages. This final test series was purposely designed to repeat equipment setups and test sequences previously described in the initial testing.

5.2 Results

The results of the final combustion testing for each setup are shown in Table 16. Evaluation of these results revealed the same conclusions reported during the diagnostics testing. The port dependency problem noted in the initial testing was much less obvious in these combustion tests. Again, as in all tests described in this report, the results recorded by the Kulite gages were found to be relatively independent of port location. Further, Precise Sensors 20379, 20898 (both 0 - 6.81 atm. gages) and 20901 (0 - 13.61 atm. gage) generally recorded data that compared well with the two Kulites. Precise Sensor

Table 15
Final Testing Setups

Setup K

Transducer Type:Model	SN	Range, atm.	Amp.	Location	Thermal Protection
KUL:XT-190	C2-46	20.41	D-6	Port C-2	Felt Metal
KUL:XT-190	C2-50	20.41	D-5	Port E-2	Felt Metal
PS:141-1	20379	6.81	D-3	Port C-2	None
PS:141-1	20898	6.81	D-1	Port E-2	None
PS:141-1	20212	13.61	D-2	Port C-2	Felt Metal
PS:141-1	20901	13.61	D-4	Port E-2	Felt Metal

Setup L

Transducer Type:Model	SN	Range, atm.	Amp.	Location	Thermal Protection
KUL:XT-190	C2-46	20.41	D-6	Port C-2	Felt Metal
KUL:XT-190	C2-50	20.41	D-5	Port E-2	Felt Metal
PS:141-1	20379	6.81	D-3	Port C-2	Felt Metal
PS:141-1	20898	6.81	D-1	Port E-2	Felt Metal
PS:141-1	20212	13.61	D-2	Port C-2	None
PS:141-1	20901	13.61	D-4	Port E-2	None

Table 16
Results of the Final Gage Evaluations

		--------- PORT E-2 -------			------- PORT C-2 -------		
	Model:	XT-190	141-1	141-1	XT-190	141-1	141-1
	SN:	<C2-50>	<20379>	20898	<C2-46>	<20212>	20901
Name	%H2	PR	PR	PR	PR	PR	PR
44-A	10.2	3.73	3.73	3.68	3.72	3.82	3.72
45-A	19.6	**	6.02	5.88	6.00	6.21	6.04
46-A	30.0	**	7.66	7.62	7.74	7.89	7.95

		--------- PORT E-2 -------			------- PORT C-2 -------		
	Model:	XT-190	141-1	141-1	XT-190	141-1	141-1
	SN:	<C2-50>	20379	<20898>	<C2-46>	20212	<20901>
Name	%H2	PR	PR	PR	PR	PR	PR
47-B	10.2	3.43	**	3.42	3.43	3.48	3.44
48-B	20.3	5.53	**	5.53	5.58	5.69	5.62

		--------- PORT E-2 -------			------- PORT C-2 -------		
	Model:	XT-190	141-1	141-1	XT-190	141-1	141-1
	SN:	<C2-50>	20898	<20901>	<C2-46>	20379	<20212>
Name	%H2	PR	PR	PR	PR	PR	PR
49-K	9.7	3.68	3.65	3.68	3.65	3.61	3.71
50-K	20.0	5.72	5.82	5.98	5.84	5.75	6.11
51-K	29.6	7.42	7.39	7.46	7.42	7.22	7.64

		--------- PORT E-2 -------			------- PORT C-2 -------		
	Model:	XT-190	141-1	141-1	XT-190	141-1	141-1
	SN:	<C2-50>	<20898>	20901	<C2-46>	<20379>	20212
Name	%H2	PR	PR	PR	PR	PR	PR
52-L	9.7	3.91	3.90	3.91	3.92	3.93	3.98
53-L	19.8	5.55	5.53	5.47	5.54	5.50	5.67
54-L	29.9	6.22	6.25	6.26	6.23	6.22	6.43

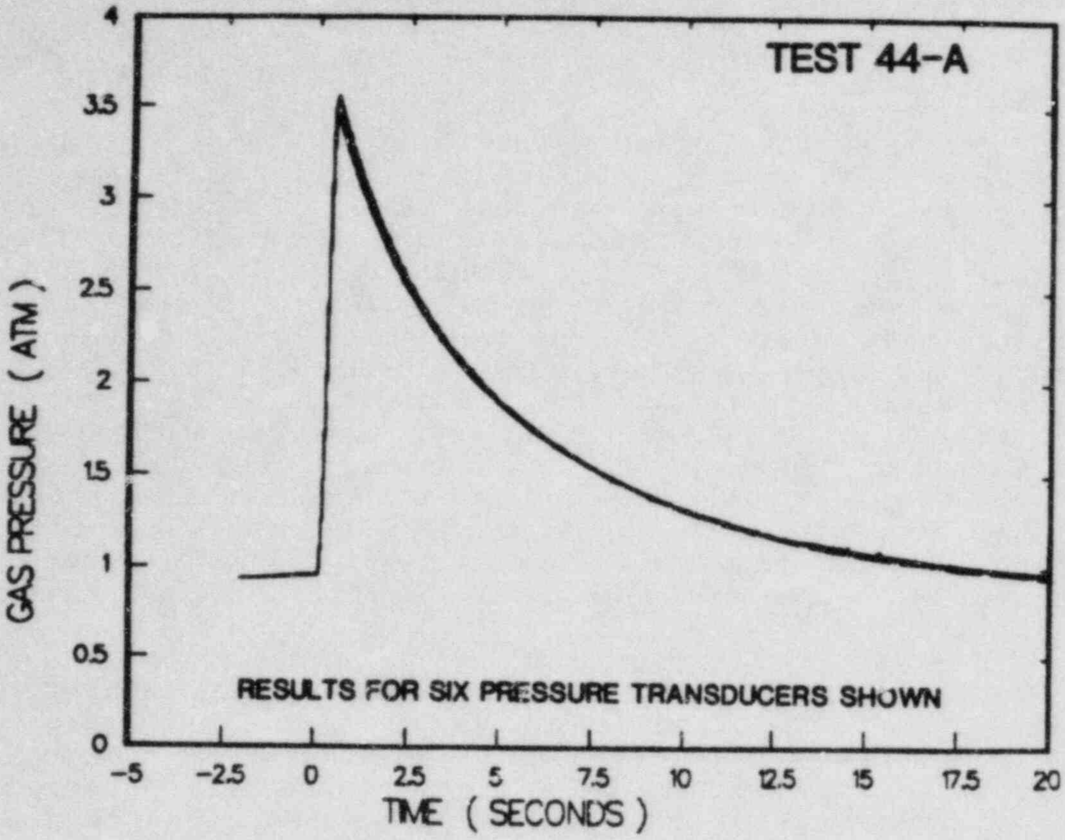
		--- PORT E-2 --		--- PORT E-1 --		--- PORT C-2 --	
	Model:	XT-190	141-1	111-1	111-1	XT-190	141-1
	SN:	<C2-50>	<20379>	21086	<21087>	<C2-46>	<20212>
Name	%H2	PR	PR	PR	PR	PR	PR
55-E	9.7	3.41	3.41	4.21	3.38	3.40	3.44
56-E	19.8	5.69	5.65	7.76	5.67	5.71	5.75
57-E	30.2	7.38	7.31	10.92	7.65	7.46	7.72

		--- PORT E-2 --		--- PORT E-1 --		--- PORT C-2 --	
	Model:	XT-190	141-1	111-1	111-1	XT-190	141-1
	SN:	<C2-50>	<20379>	<21086>	21087	<C2-46>	<20212>
Name	%H2	PR	PR	PR	PR	PR	PR
58-F	10.2	3.46	3.47	3.46	4.51	3.47	3.52
59-F	20.3	5.58	5.57	5.78	7.52	5.60	5.68
60-F	30.2	8.64	8.61	8.96	12.70	8.76	9.02

20212, on the other hand, appeared to measure peak pressures that were consistently higher than the other five gages, although these differences were not large. In comparing results of the first and second setups (A and B) with those of the third and fourth setups (K and L), it was found that gage 20212 generally recorded the highest peak pressure of the six gages. Further, this appeared to hold whether or not the Precise Sensor 141-1 gages were thermally protected. In Figure 11, the long and short time comparisons are shown for a 10% hydrogen:air deflagration (test 44-A). These pressure traces show the relative consistency between the six gages during this combustion test. In this test, gage 20212 recorded a peak combustion pressure approximately 0.13 atmosphere greater than the lowest reading of the remaining five gages. Each of these gages recorded peak pressures that were within 0.05 atmospheres of one another.

The final tests conducted in this series (tests 55-E through 60-F) confirm the findings reported throughout this report about the 111-1 gage operation. That is, the thermally unprotected Precise Sensor 111-1 gages substantially over-predict the peak pressure and time to peak pressure while the protected 111-1 gages record results consistent with the other gage types. Further, the pressure traces obtained from unprotected 111-1 gages are clearly different from traces predicted by the other transducers, as shown previously in Figs. 7 and 8. As mentioned previously, the unprotected 111-1 pressure traces are characterized by a roll through the peak instead of a sharp increase and an apparent exponential decay. The protected 111-1 compared well with the two Kulite gages and two 141-1 Precise Sensor transducers.

The mean and standard deviations of the six gages for the final combustion tests are provided in Table 17. For tests 44-A through 54-L, the XT-190 and 141-1 comparisons, the standard deviation is generally less than 2% of the mean pressure reading. Further, the percent difference between the maximum and minimum reading (shown as %MAX), when compared to the mean value, are generally less than 6%. For tests 55-E through 60-F, the mean value of the two Kulites and the two Precise Sensor model 141-1 gages are compared to the protected and unprotected model 111-1 Precise Sensors. Note that when the model 111-1 is unprotected, it records peak pressures ranging from 23% to 46% higher (shown as %DIFF in Table 17) than the mean peak pressure obtained for the Kulite and 141-1 gages, while the protected gage records peak pressures that are within 3% of this mean value. Therefore, the conclusions drawn in the initial testing series (Section 3) about the model 111-1 Precise Sensors still hold true. The unprotected gage diaphragm is affected substantially by the thermal environment during and after ignition. The thermally protected 111-1 gage, on the other hand, records data that compare well with that of the two Kulites and the two Precise Sensor model 141-1 gages.



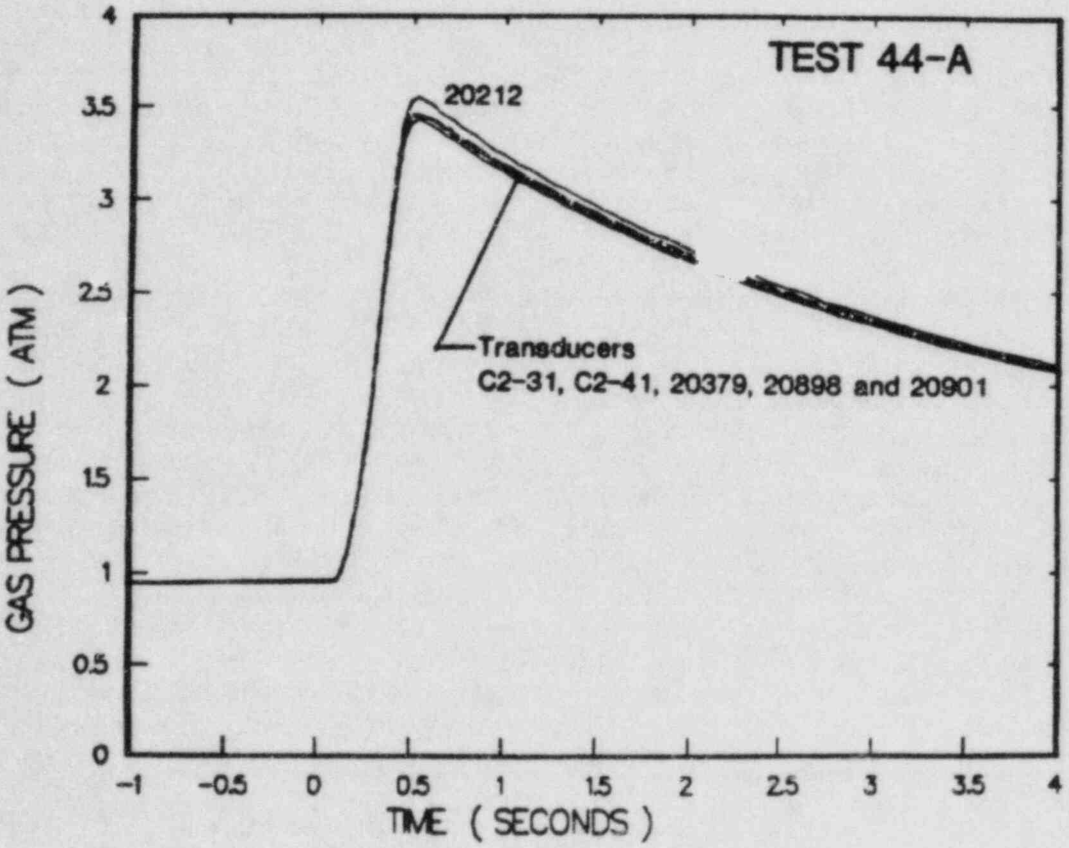


Figure 11. Gage Comparisons for Test 44-A

Table 17
Statistical Evaluation of the Final Tests

Gage XT-190 and 141-1 Evaluations

Name	%H2	MEAN	DEVIATION	% RATIO	% MAX
44-A	10.2	3.73	.05	1.34	3.75
45-A	19.6	6.03	.12	1.99	5.47
46-A	30.0	7.77	.14	1.84	4.25
47-B	10.2	3.44	.02	0.67	1.74
48-B	20.3	5.59	.07	1.20	2.86
49-K	9.7	3.66	.03	0.93	2.73
50-K	20.0	5.87	.15	2.56	6.64
51-K	29.6	7.43	.14	1.88	5.65
52-L	9.7	3.93	.03	0.76	2.04
53-L	19.8	5.54	.07	1.26	3.61
54-L	29.9	6.26	.08	1.28	3.35

Gage 111-1 Evaluation

Name	%H2	MEAN	21086	% DIFF	21087	% DIFF
55-E	9.7	3.42	4.21	23.28	3.38	1.02
56-E	19.8	5.70	7.76	36.14	5.67	0.53
57-E	30.2	7.47	10.92	46.18	7.65	2.41
58-F	10.2	3.48	3.46	0.57	4.51	29.60
59-F	20.3	5.61	5.78	3.03	7.52	34.05
60-F	30.2	8.76	8.96	2.28	12.70	44.98

MEAN..... The mean of the six transducers.
% RATIO.. Implies the equation (DEVIATION / MEAN) x 100 was used.
% MAX.... Implies the following equation was used:
((MAX. - MIN.) / MEAN) x 100
% DIFF... Implies the following equation was used:
(ABS(READING - MEAN) / MEAN) x 100.

5.3 Conclusions Obtained From Final Testing

As a result of this study, we would expect the thermally protected Kulite gages and model 141-1 Precise Sensors to record accurate combustion pressure data. Additionally, the model 141-1 appears to provide reasonable pressure traces with or without thermal protection, although the felt metal protection would be advantageous in all future testing. The Kulite model XT-190 gages should never be used to measure combustion pressures without employing an effective thermal barrier such as felt metal, as suggested by the manufacturer. Similarly, unprotected Precise Sensor model 111-1 gages should not be used to measure combustion pressures. It has become evident throughout the course of this study that the model 111-1 Precise Sensors are significantly affected by the thermal environment of combustion. If the gage is thermally protected with felt metal, or a comparable thermal barrier, then the response is relatively consistent with those of the Kulite and 141-1 gages.

Based on the Precise Sensor model 141-1 results obtained with and without felt metal shielding, it is apparent that felt metal flame arrestors do not significantly change the shape of the transient pressure pulse, the peak magnitude, or the burn times. It should be noted that this conclusion has been verified only for deflagration-type combustion experiments (i.e., subsonic flame speeds relative to the unburned gas), and is not necessarily true for detonations (i.e., supersonic flame speeds) or accelerated flames (flame Mach numbers > 0.5). The felt metal additionally appears to serve as an effective thermal barrier, based on the results recorded by protected and unprotected model 111-1 gages, and should be used whenever possible to shield all transducer designs used in a combustion application.

6. Recommendations

Based on the results obtained during this experimental study, we recommend that combustion pressure data previously recorded at FITS with a thermally unprotected Precise Sensor model 111-1 or Kulite XT-190 not be used, since thermal bias is present in the signals. Whenever combustion pressures are to be measured with these two gage types, it is imperative that the diaphragm of the transducer be thermally shielded to obtain accurate results. On the other hand, the results reported for the Precise Sensor model 141-1 gages indicate that the diaphragms of these gages are not substantially affected by the thermal environment of combustion. Therefore, all of the past combustion pressure data recorded with a Precise Sensor model 141-1 gage should be usable and further should be accurate to within the calibration of the entire data acquisition system (i.e., amplifiers, ADC, etc.). It is recommended, however, that in future combustion tests performed at FITS, all gages should be thermally protected with felt metal or a comparable thermal shield to eliminate any thermally induced signals not evident from this testing.

It is also concluded from the 141-1 and 111-1 results that felt metal pads perform satisfactorily as thermal shields (i.e. provide thermal protection). Further, this type of shielding does not appear to affect the peak pressure magnitudes, the burn times, or the shape of the transient pressure pulse. Therefore, felt metal should serve as an excellent thermal barrier in all deflagration-type combustion studies at FITS or any other similar combustion facility. Whether this type of shielding would be appropriate for detonation work is unclear at this time, and would require verification through additional testing.

At the onset of this work, the response of three thermally unprotected pressure transducers was of interest. However, before quantitative conclusions could be made about the response of the different transducers, the entire data acquisition system had to be evaluated. Therefore, a final recommendation is that sufficient time be allotted during experimental studies to permit adequate documentation and data evaluation between tests. The calibration of the amplifiers and transducers should be checked frequently on-site and documented during the testing program. This documentation (i.e., thermal protection, amplifier calibrations, etc.) is crucial to the use and interpretation of all experimental data. The combustion test data should be analyzed, at least in a preliminary sense, shortly after each test to ensure that the results are internally consistent as well as being consistent with analytical predictions and results obtained from past combustion testing. These evaluations would minimize the number of combustion tests required and would provide guidance during the testing program. Significant cost savings would likely result from these procedures.

References

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5. Dynamic Incorporated, Operating Instructions for Universal Amplifier Model 7600/7860-A, 1980.

6. S. F. Roller, "Hydrogen-Air Combustion Test Series 1 and 2 in the FITS Tank," Sandia National Laboratories, Albuquerque, New Mexico, SAND83-2141, 1983.

7. Private telephone communications with M. Lacey of Precise Sensor Inc. during period of June through July, 1983.

Appendix A

Initial Conditions of the Combustion Tests

NAME*	ID	DATE (1983)	TIME	%H2	P(0) (ATM)	P(air) (ATM)	T(0) (°C)	FANS
1-A	PRH10B	5/25	11:52:59	9.7	.844	.776	21.9	ON
2-A	PRH10C	5/26	13:27:23	10.0	.776	.851	35.5	ON
3-A	PRH20C	5/26	14:56:26	20.0	1.102	.898	34.3	ON
4-A	PRH20B	5/25	14:33:38	18.8	.925	.769	27.2	ON
5-A	PRH25A	5/25	15:35:57	24.6	1.000	.769	30.2	ON
6-A	PRH25B	5/26	09:22:44	24.3	1.027	.796	20.7	ON
7-A	PRH30A	5/26	10:53:41	30.3	1.109	.796	25.4	ON
8-A	PRH30B	5/26	12:16:55	29.5	1.150	.823	30.2	ON
9-B	PRH10D	6/06	12:20:39	11.2	.953	.830	28.4	ON
10-B	PRH30C	6/06	13:55:34	31.1	1.218	.844	28.4	ON
11-B	PRH35A	6/06	15:17:30	34.3	1.320	.851	33.7	ON
12-B	PRH10H	6/07	10:56:41	10.3	.925	.823	97.0	ON
13-B	PRH50A	6/08	10:12:28	50.0	1.647	.823	109.4	ON
14-B	PRH60A	6/08	11:42:26	60.0	2.021	.817	105.9	ON
15-B	PRH70A	6/09	15:16:09	68.0	2.552	.830	118.3	ON
16-B	PRH30D	6/08	13:27:54	29.9	1.164	.823	85.2	ON
17-B	PRH40A	6/08	15:16:31	39.9	1.375	.830	82.8	ON
18-B	PRH20S	6/07	13:33:24	19.6	1.388	.823	109.4	ON
19-B	PRSH20	6/07	15:55:51	19.1	1.204	.803	111.8	ON
20-C	PRES1	7/12	11:21:56	9.8	.905	.810	23.7	ON
21-C	PRES2	7/12	12:31:25	20.2	1.000	.817	24.9	ON
22-C	PRES3	7/12	13:26:39	30.1	1.123	.810	27.2	ON
23-D	PRES4	7/12	14:23:41	9.5	.878	.810	33.1	ON
24-D	PRES5	7/12	15:07:25	19.6	1.014	.823	33.7	ON
25-E	PRES6	7/13	08:55:25	9.4	.912	.817	23.7	ON
26-E	PRES7	7/13	09:52:32	20.8	1.034	.823	24.3	ON
27-E	PRES8	7/13	11:06:23	30.2	1.164	.810	26.6	ON
28-F	PRES9	7/13	12:06:39	10.1	.925	.817	32.5	ON
29-F	PRES10	7/13	13:17:11	10.2	.891	.817	31.9	OFF
30-F	PRES11	7/13	14:29:51	19.7	.993	.817	33.1	OFF
31-F1	PRES16	7/18	10:26:55	24.3	.959	.823	22.5	OFF
32-F2	PRES17	7/18	13:53:02	11.2	.946	.851	97.6	ON
33-F3	PRES19	7/19	10:45:48	10.0	.912	.844	107.7	OFF
34-F4	PRES18	7/18	15:10:22	10.4	1.055	.864	100.6	OFF
35-F4	PRES21	7/19	15:19:15	19.7	1.000	.851	85.8	OFF
36-F5	PRES20	7/19	14:13:19	10.1	.898	.837	82.2	OFF
37-F6	PRES22	7/20	09:37:19	10.1	.919	.844	128.4	OFF
38-G	LAST3	8/19	12:00:17	29.9	1.123	.830	20.7	OFF
39-G	LAST4	8/19	15:10:17	29.8	1.123	.823	33.1	OFF

Appendix A (continued)

NAME*	ID	DATE (1983)	TIME	%H2	P(0) (ATM)	P(air) (ATM)	T(0) (°C)	FANS
40-H	LAST6	8/22	10:58:14	29.9	1.116	.817	29.0	OFF
41-H	LAST7	8/22	12:38:37	29.9	1.116	.817	32.5	OFF
42-I	LAST8	8/22	13:39:32	29.9	1.123	.830	37.3	OFF
43-J	LAST9	8/22	14:49:46	30.2	1.157	.830	40.8	OFF
44-A	RANG13	9/08	09:03:07	10.2	.932	.830	23.1	ON
45-A	RANG14	9/08	12:21:01	19.6	1.034	.817	23.1	ON
46-A	RANG15	9/08	13:03:05	30.0	1.177	.817	27.2	ON
47-B	RANG16	9/08	14:09:30	10.2	.946	.817	32.5	ON
48-B	RANG17	9/08	14:51:51	20.3	1.062	.817	33.1	ON
49-K	RANG10	9/07	11:32:40	9.7	.912	.823	31.4	ON
50-K	RANG11	9/04	13:28:35	20.0	1.034	.823	30.8	ON
51-K	RANG12	9/07	14:39:30	29.6	1.184	.823	33.7	ON
52-L	RANGE7	9/06	14:36:14	9.7	.912	.823	23.1	ON
53-L	RANGE8	9/07	09:10:18	19.8	1.000	.817	24.3	ON
54-L	RANGE9	9/07	09:51:30	29.9	1.136	.817	27.8	ON
55-E	RANG18	9/09	11:41:55	9.7	.939	.817	22.5	ON
56-E	RANG19	9/09	12:37:29	19.8	1.055	.823	23.7	ON
57-E	RANG20	9/09	13:20:44	30.2	1.198	.823	27.8	ON
58-F	RANG24	9/12	09:59:18	10.2	.953	.823	26.6	ON
59-F	RANG22	9/09	15:02:27	20.3	1.055	.823	33.7	ON
60-F	RANG23	9/12	09:10:22	30.2	1.204	.823	19.5	ON

* .... Tests conducted in this program included air cooling for the Precise Sensor gages, with nominal gas flow rates of 14.2 LPM at the baffle (see Figure 2). For tests with numbers appearing after the set-up letter, the gas cooling was modified according to Table 9.

All Combustion tests were ignited using a Champion RN12Y spark plugs with a 4 kV capacitor discharge power supply.

Hydrogen percentages are given on a total volume basis. The .457 m diameter fans nominally rotate at approximately 2500 RPM.

Appendix B

Adiabatic Isochoric Complete Combustion Predictions

NAME*	ID	DATE (1983)	TIME	P(0) (ATM)	P(max) (ATM)	PR	T(0) (K)	T(max) (K)	TR
1-A	PRH10B	5/25	11:52:59	.844	3.572	4.23	294.9	1313	4.45
2-A	PRH10C	5/26	13:27:23	.776	4.028	4.14	308.5	1346	4.36
3-A	PRH20C	5/26	14:56:26	1.102	7.152	6.49	307.3	2213	7.20
4-A	PRH20B	5/25	14:33:38	.925	5.927	6.40	300.2	2117	7.05
5-A	PRH25A	5/25	15:35:57	1.000	7.383	7.38	303.2	2537	8.37
6-A	PRH25B	5/26	09:22:44	1.027	7.757	7.55	293.7	2514	8.56
7-A	PRH30A	5/26	10:53:41	1.109	8.996	8.11	298.4	2793	9.36
8-A	PRH30B	5/26	12:16:55	1.150	9.111	7.92	303.2	2771	9.14
9-B	PRH10D	6/06	12:20:39	.953	4.355	4.57	301.4	1460	4.84
10-B	PRH30C	6/06	13:55:34	1.218	9.819	8.06	301.4	2805	9.31
11-B	PRH35A	6/06	15:17:30	1.320	10.431	7.90	306.7	2787	9.09
12-B	PRH10H	6/07	10:56:41	.925	3.375	3.65	370.0	1423	3.85
13-B	PRH50A	6/08	10:12:28	1.647	9.452	5.74	377.2	2416	6.41
14-B	PRH60A	6/08	11:42:26	2.021	10.186	5.04	378.3	2082	5.50
15-B	PRH70A	6/09	15:16:09	2.552	10.949	4.29	391.3	1802	4.61
16-B	PRH30D	6/08	13:27:54	1.164	7.900	6.79	358.2	2802	7.82
17-B	PRH40A	6/08	15:16:31	1.375	9.125	6.64	355.8	2690	7.56
18-B	PRH20S	6/07	13:33:24	1.388	6.968	5.02	382.4	2125	5.56
19-B	PRSH20	6/07	15:55:51	1.204	6.008	4.99	384.8	2120	5.51
20-C	PRES1	7/12	11:21:56	.905	3.838	4.24	296.7	1325	4.47
21-C	PRES2	7/12	12:31:25	1.000	6.723	6.72	297.9	2227	7.48
22-C	PRES3	7/12	13:26:39	1.123	9.050	8.06	300.2	2792	9.30
23-D	PRES4	7/12	14:23:41	.878	3.552	4.05	306.1	1303	4.26
24-D	PRES5	7/12	15:07:25	1.014	6.519	6.43	306.7	1913	6.24
25-E	PRES6	7/13	08:55:25	.912	3.749	4.11	296.7	1280	4.31
26-E	PRES7	7/13	09:52:32	1.034	7.084	6.85	297.3	2270	7.64
27-E	PRES8	7/13	11:06:23	1.164	9.404	8.08	299.6	2795	9.33
28-F	PRES9	7/13	12:06:39	.925	3.892	4.21	305.5	1355	4.44
29-F	PRES10	7/13	13:17:11	.891	3.777	4.24	304.9	1364	4.47
30-F	PRES11	7/13	14:29:51	.993	6.417	6.46	306.1	2193	7.16
31-F1	PRES16	7/18	10:26:55	.959	7.199	7.50	295.5	2509	8.49
32-F2	PRES17	7/18	13:53:02	.946	3.634	3.84	370.6	1509	4.07
33-F3	PRES19	7/19	10:45:48	.912	3.198	3.51	380.7	1406	3.69
34-F4	PRES18	7/18	15:10:22	1.055	3.851	3.65	373.6	1438	3.85
35-F4	PRES21	7/19	15:19:15	1.000	5.532	5.53	358.8	2219	6.18
36-F5	PRES20	7/19	14:13:19	.898	3.355	3.73	355.2	1397	3.93
37-F6	PRES22	7/20	09:37:19	.919	3.116	3.39	401.4	1433	3.57
38-G	LAST3	8/19	12:00:17	1.123	9.227	8.22	293.7	2788	9.49
39-G	LAST4	8/19	15:10:17	1.123	8.873	7.90	306.1	2789	9.11

Appendix B (continued)

NAME*	ID	DATE (1983)	TIME	P(0) (ATM)	P(max) (ATM)	PR	T(0) (K)	T(max) (K)	TR
40-H	LAST6	8/22	10:58:14	1.116	8.923	8.00	302.0	2790	9.24
41-H	LAST7	8/22	12:38:37	1.116	8.826	7.91	305.5	2790	9.13
42-I	LAST8	8/22	13:39:32	1.123	8.757	7.80	310.3	2791	8.99
43-J	LAST9	8/22	14:49:46	1.157	8.928	7.72	313.8	2797	8.91
44-A	RANG13	9/08	09:03:07	.932	4.049	4.34	296.1	1356	4.58
45-A	RANG14	9/08	12:21:01	1.034	6.866	6.64	296.1	2178	7.36
46-A	RANG15	9/08	13:03:05	1.177	9.499	8.06	300.2	2794	9.31
47-B	RANG16	9/08	14:09:30	.946	4.001	4.23	305.5	1363	4.46
48-B	RANG17	9/08	14:51:51	1.062	6.975	6.57	306.1	2238	7.31
49-K	RANG10	9/07	11:32:40	.912	3.763	4.13	304.4	1321	4.34
50-K	RANG11	9/04	13:28:35	1.034	6.784	6.56	303.8	2211	7.28
51-K	RANG12	9/07	14:39:30	1.184	9.329	7.88	306.7	2789	9.09
52-L	RANGE7	9/06	14:36:14	.912	3.851	4.22	296.1	1315	4.44
53-L	RANGE8	9/07	09:10:18	1.000	6.655	6.65	297.3	2192	7.37
54-L	RANGE9	9/07	09:51:30	1.136	9.139	8.04	300.8	2791	9.28
55-E	RANG18	9/09	11:41:55	.939	3.953	4.21	295.5	1309	4.43
56-E	RANG19	9/09	12:37:29	1.055	7.022	6.66	296.7	2192	7.29
57-E	RANG20	9/09	13:20:44	1.198	9.642	8.05	300.8	2797	9.30
58-F	RANG24	9/12	09:59:18	.953	4.096	4.30	299.6	1358	4.53
59-F	RANG22	9/09	15:02:27	1.055	6.920	6.56	306.7	2238	7.30
60-F	RANG23	9/12	09:10:22	1.204	11.057	9.18	292.5	2795	9.56

* .... Tests conducted in this program included air cooling for the Precise Sensor gages, with nominal gas flow rates of 14.2 LPM at the baffle (see Figure 2). For tests with numbers appearing after the set-up letter, the gas cooling was modified according to Table 9.

Hydrogen percentages are given on a total volume basis.

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A series of hydrogen:air combustion tests was performed at the Fully Instrumented Test Site (FITS), located at Sandia National Laboratories in Albuquerque, NM, to evaluate the performance of three strain-gage-type pressure transducers in a combustion environment. Results of the sixty tests indicated that the three pressure transducers, when thermally shielded with felt metal, recorded peak combustion pressures that were generally within 5% of the statistical mean for each test. The pressure profiles and associated burn times obtained from all of the protected transducers were also comparable. The Precise Sensor model 111-1 gages, when unprotected, were affected significantly by the hot gases of combustion and must be thermally protected with felt metal to obtain accurate measurements. However, thermally unprotected Precise Sensor 141-1 gages recorded transient combustion pressure traces that compared well with those recorded by the thermally protected gages. The Kulite sensor was always used with thermal protection as recommended by the manufacturer. These tests also showed that the Brunswick 1101 felt metal serves as an effective thermal barrier without affecting the magnitudes of the peak pressures, the rise times, or the composite shape of the transient combustion pressure response.

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