Contract Report SL-96-2
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JOINT U.S./ROK R&D PROGRAM FOR NEW UNDERGROUND AMMUNITION STORAGE TECHNOLOGIES

FINAL REPORT

IMPROVED TECHNIQUES FOR MEASURING THERMAL EFFECTS OF PROPELLANT BURN TESTS IN CONFINED AREAS

by

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May 1996

Prepared for U.S. Army Engineer Waterways Experiment Station
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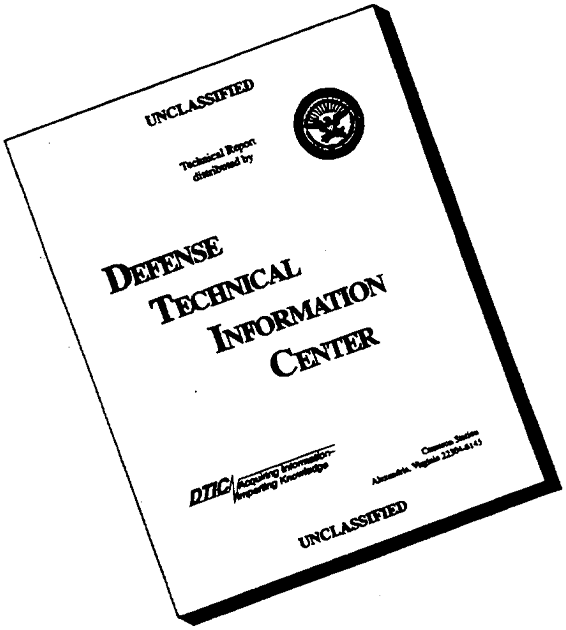
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**US Army Corps
of Engineers**
Waterways Experiment
Station

Joint U.S./ROK R&D Program for New Underground Ammunition Storage Technologies

Improved Techniques for Measuring Thermal Effects of Propellant Burn Tests in Confined Areas

*by E. C. Knox
REMTECH, Inc.*

WES

Prepared for Headquarters, U.S. Army Corps of Engineers

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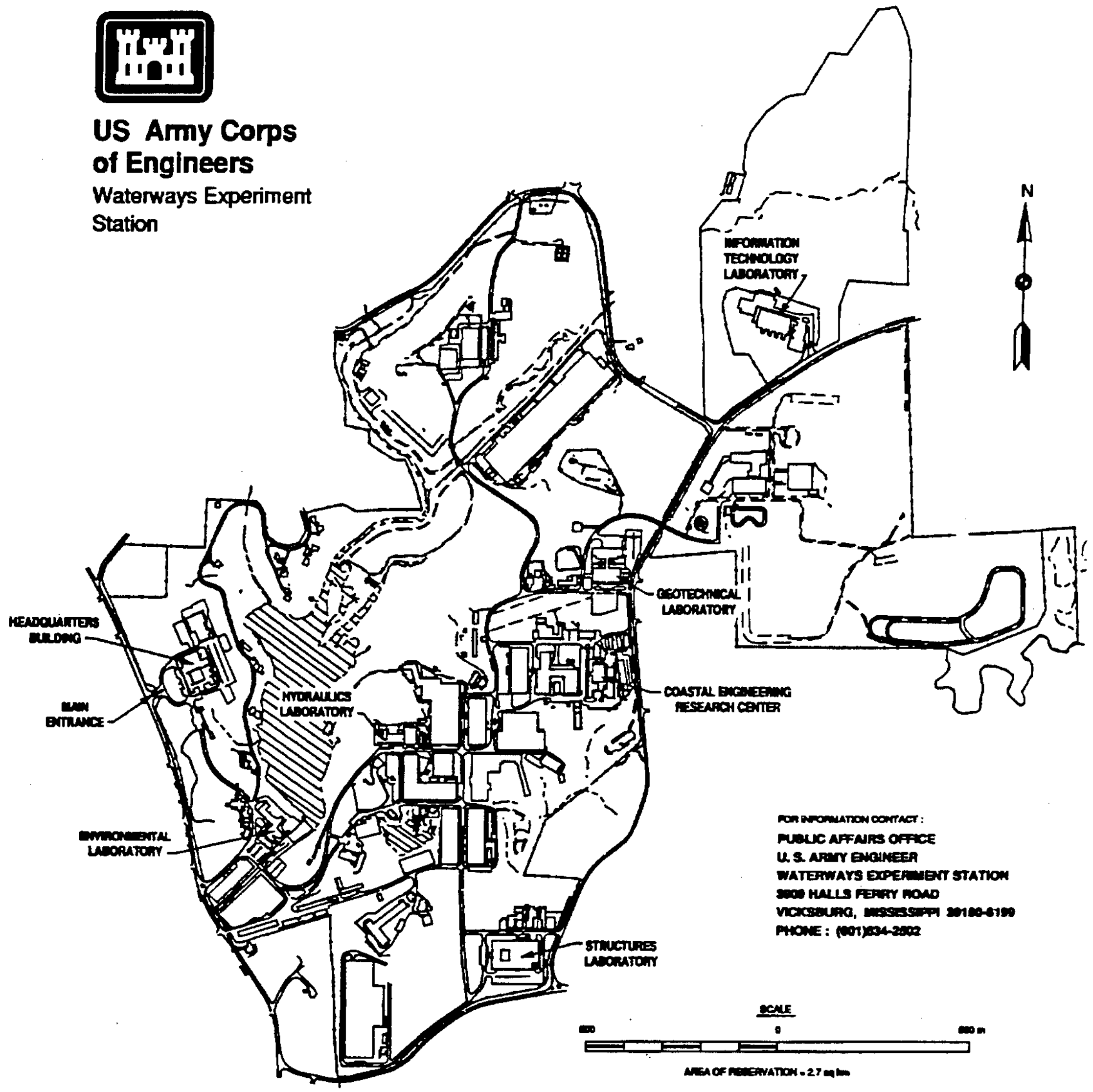

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PREFACE

This study was conducted for the U.S. Army Engineer Waterways Experiment Station (WES) under contract DACA39-92-M-7281 as part of the Joint U.S./Republic of Korea (ROK) R&D Study for New Underground Ammunition Storage Technologies. Technical Managers for the Joint Program were Mr. Landon K. Davis, Geomechanics and Explosions Effects Division (GEED), WES, and Dr. So-young Song, Korean Agency for Defense Development. The Program Managers were Mr. Gary Abrisz, U.S. Army Technical Center for Explosives Safety, and COL Yeon Woo Chung, Logistics Bureau, Korean Ministry of Defense.

Mr. E. C. Knox, REMTECH, Inc., conducted the study reported herein and is the author of this report. The work was monitored by Mr. Charles E. Joachim, GEED, Structures Laboratory (SL), WES. Dr. Jimmy P. Balsara was Chief, GEED, and Mr. Bryant Mather was Director, SL.

At the time of preparation of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

NOMENCLATURE

A^*	Chocked flow area (= vent pipe area)
A_b	Propellant burning area
C_D	Orifice flow coefficient
P_c	Pressure in bunker
R	Propellant combustion gas constant, C_p - C_V
T_c	Measured gas temperature in bunker
V_c	Bunker volume, ~5 m^3
r	Propellant surface burn, or recession rate, in./sec
t	Time for propellant ignition
γ	Ratio of gas specific heats, C_p/C_V
ρ	Density, gas or propellant

Subscripts

b	Denotes burning or propellant characteristic
c	Denotes chamber or bunker conditions/characteristics
p	Denotes peak value, as in peak pressure

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
atmospheres	101.325	kilopascals
BTU per square foot-second	1134.893	joule per square metre-second
calories per square inch-second	0.648521	joule per square centimetre-second
degrees	0.01745329	radians
degrees Fahrenheit	{5/9} {F-32}	Celsius
degrees Celsius	C + 273.15	Kelvins
degrees Kelvin	1.8	Ramkine
feet	0.3048	metres
feet per second	0.3048	metres per second
inches	2.54	centimetres
kilowatts per square metre	1.000000	joule per square metre
litres	0.001	cubic metres
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pound (mass) per cubic inch	27.67990	grams per cubic centimetres
pounds (force) per square inch (psi)	6.894757	kilopascals

Section 1
INTRODUCTION

The U.S. Army Corps of Engineers, Waterways Experiment Station (WES), is conducting a test program to study the effects of the accidental burning of propellants stored in a confined area. This work is a part of a broader program called the Joint U.S./ROK (Republic of Korea) R&D Study for New Underground Ammunition Storage Technologies. The goal of the 5-year U.S./ROK Study is to develop improved designs for underground magazines which will greatly reduce the present external hazard areas that are required by current U.S. and Korean military safety standards to protect against the possibility of accidental fires and explosions.

Documentation of propellant burn tests performed to date is presented in Ref. [1]. Additional tests are planned; however, improvements to the instrumentation for these tests have been deemed necessary before executing them. REMTECH, Inc., was tasked by WES to review the instrumentation performance during the Ref. [1] tests and recommend improvements/additions to the Ref. [1] instrumentation for application to a subscale test scheduled for May 1993 at WES. Instrumentation performance experience during these tests will be factored into the instrumentation selection for full-scale tests to be conducted at a later time.

The results of this review are documented in the subject report.

Section 2
OBJECTIVES AND TECHNICAL APPROACH

The objectives for this review were to:

1. Develop improved instrumentation/techniques for measuring the thermal effects of propellant burn tests in confined areas.

2. Develop empirical methods for estimation of the thermal and fluid dynamic environments of the propellant burns.

The technical approach adopted to accomplish these objectives was divided into several phases: review of the available recorded data from Ref. [1] for each instrument channel in terms of quality and inter-channel compatibility; development of a preliminary one-dimensional model of the flow process; characterization of the propellant thermochemical properties; and comparison of results from the model and propellant characterization with the experimental results.

Section 3
PROPELLANT THERMOCHEMICAL PROPERTIES

As a means of establishing a standard by which the performance of the instrumentation for KA-III, Phase C, tests could be measured in terms of possible total energy release and likely pressure rise times, the thermochemical and burning properties of the propellant used in these tests were examined.

3.1 Propellant Thermochemical Properties

The propellant used in the KA-III, Phase C, tests and planned for use in the WES May '93 tests is, in the U.S. Army notation demoted as M-1. Its chemical composition is defined in Ref [2] and repeated herein as

Ingredient	Percent by weight
Ethanol (C_2H_6O)	0.75
Nitrocellulose ($C_6H_{7.3715}N_{2.6355}O_{10.2715}$)	83.74
Dinitrotoluene ($C_7H_6N_2O_4$)	9.84
Diphenylamine ($C_{12}NH_{11}$)	0.99
Butyl Phthalate ($C_{16}H_{22}O_4$)	4.93
Water (liquid)	0.50

This composition was input to REMTECH's in-house version of the NASA Chemical Equilibrium Composition code (CEC) [3] to determine the propellant combustion product and the amount of energy released upon burning.

Two burning condition were analyzed; adiabatic, representing the maximum possible energy release, and isentropic, representative of the propellant burning at one pressure and expanding isentropically to another pressure (atmospheric in this case). The resultant pressure and temperatures for these cases are tabulated as follows:

Condition	Pressure, atm	Temperature, K
Adiabatic	1810.	2437.
Isentropic	1.00	1919.

The complete CEC code outputs for these conditions are included in Appendices A and B, respectively. Therein the combustion products are listed to be approximately 50 percent CO, 20 percent H_2, 13 percent water, 10 percent N_2, and 6 percent CO_2, with lesser amounts of other constituents.

Determination of the adiabatic properties was aided significantly by the assistance of Dr. A. J. Kotlar, USA Research Laboratory, Aberdeen Proving Ground, MD, which is hereby acknowledged.

3.2 Propellant Burning Properties

Mr. Michael M. Swisdak, Jr., Naval Surface Warfare Center/Dahlgren Division, is hereby acknowledged for his providing the geometry and burning characteristics for the M-1 propellant. Shown in Fig. 1 is the propellant geometry; its density is nominally 0.0566 lb/in.^{3}, and its burn-rate equation is defined as

$$r = A * (Pressure)^N \tag{1}$$

where

r = the propellant burning surface recession rate (in./sec),

A = 0.00161 in./sec/psi, and

N = 0.741.

The time for a propellant grain to be consumed by burning for the conditions of the KA-III, Phase C, tests (Test C-3), using the log-mean pressure from initial to peak and the grain cylindrical surface area (inside and external) with the above equation, was estimated to be 0.40 sec.

Comparing this result with the actual burn time of approximately 10 seconds with the theoretical value of 0.40 seconds has several potential implications which include:

1. The entire surface areas of the pellets are not being ignited simultaneously.

2. The mass of the air in the bunker is significant compared with the burned propellant gas mass during the initial pressure buildup.

3. Stacking methods and container type probably influence the burn history since they may control the amount of surface area available for burning as a function of time.

As will be shown later in the report, the vent pipe exit velocity exceeds the combustion gas speed-of-sound (~2000 ft/sec) for portions of the burn history prior to and after the pressure peak. Considering the average grain burn time, any burning grains that become airborne during the burning process could travel as much as 800 ft while in the burning state, thus giving credence to the likelihood of burning propellant being ejected out of the bunker during the KA-III, Phase C, tests.

Similar effects were observed for tests reported in Ref [4], in which upwards to 80 percent of the combustible material was ejected out of the combustion chamber, depending on the vent diameter. Shown in Fig. 2 is a curve of the observed variation of the ejecta material percent vs. the vent diameter.

The presence of this phenomena in the instant process raises concerns as to the scalability of any subscale results to full-scale applications without an attendant math model of the flow process.

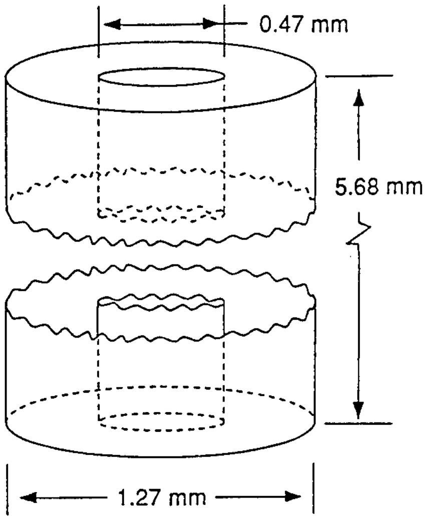


Figure 1. M-1 propellant grain geometry

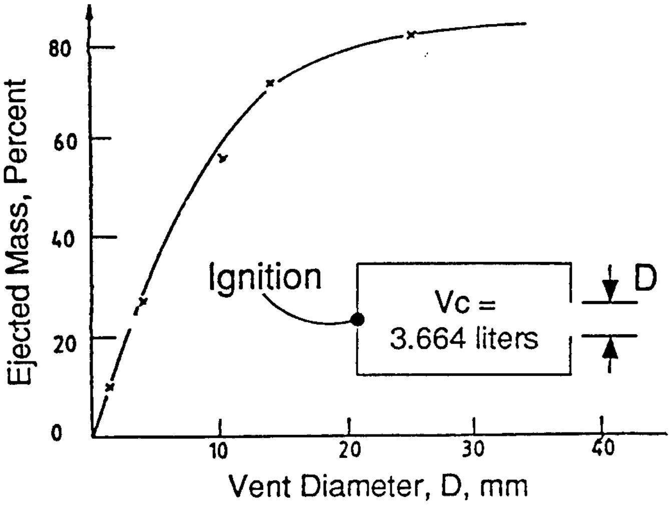


Figure 2. Variation of ejected combustible material with vent diameter, (Ref. [4])

Section 4
ANALYTICAL FLOW MODEL

As a means of establishing a standard by which the performance of the instrumentation for KA-III, Phase C, tests could be measured in terms of pressure histories and related heat transfer variations, a one-dimensional model of the flow process was developed.

4.1 Flow Model Development

Applying the conservation of mass principle to these tests, the combustion gas generated in the process of burning the propellant is accounted for in the accumulation of mass in the bunker and the mass that is vented out the connecting pipe. This balance is expressed in equation form as

$$A_b r \rho_b \quad \frac{d}{dt}(\rho_c V_c) \quad A \; P_c \sqrt{\frac{\gamma}{RT_c}\left(\frac{2}{\gamma \quad 1}\right)^{\frac{\gamma \; 1}{\gamma \; 1}}} \tag{2}$$

assuming the "chocked" flow condition governs the vented mass flow rate, i.e., the condition for which the bunker pressure is greater than 1.9 times atmospheric pressure. Another expression applies for the "unchoked" condition.

4.2 Flow Model Application

Shown in Fig. 3 are the bunker pressure histories for test C-3 of the KA-III, Phase C Tests as measured by instruments ABI180, -181B, and 182. Also shown on Fig 3 is the division between "chocked" and "unchoked" flow; at pressures greater than the division line, the "choked" form of Eq. (2) applies. The comparison temperature (TF190) history is presented in Fig. 4.

The exhibited pressure trends in Fig. 3 are interpreted as propellant burning until the pressure peak, after which pressure decay occurs as the bunker is vented to atmosphere. Then, for the pressure decay portion of the process, the mass generation term goes to zero in Eq. (2) preceding. The reduced Eq. (2) takes the form

$$\frac{dP_c}{dt} \quad \frac{A}{V_c} \sqrt{RT_c \gamma \left(\frac{2}{\gamma \quad 1}\right)^{\frac{\gamma \; 1}{\gamma \; 1}}} \quad P_c \quad 0 \tag{3}$$

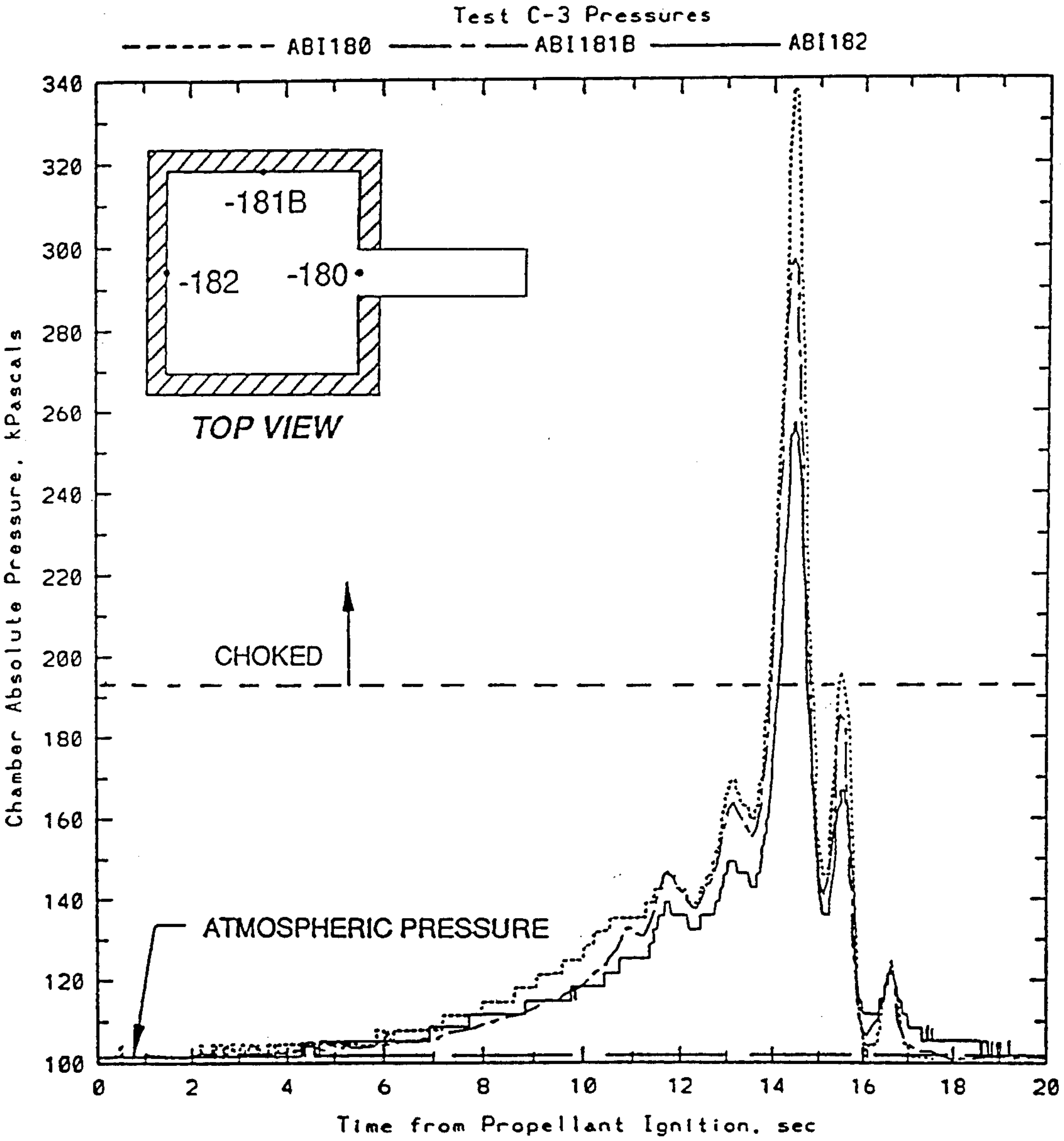


Figure 3. KA-III, Phase C, Test C-3 Bunker Pressure Histories.

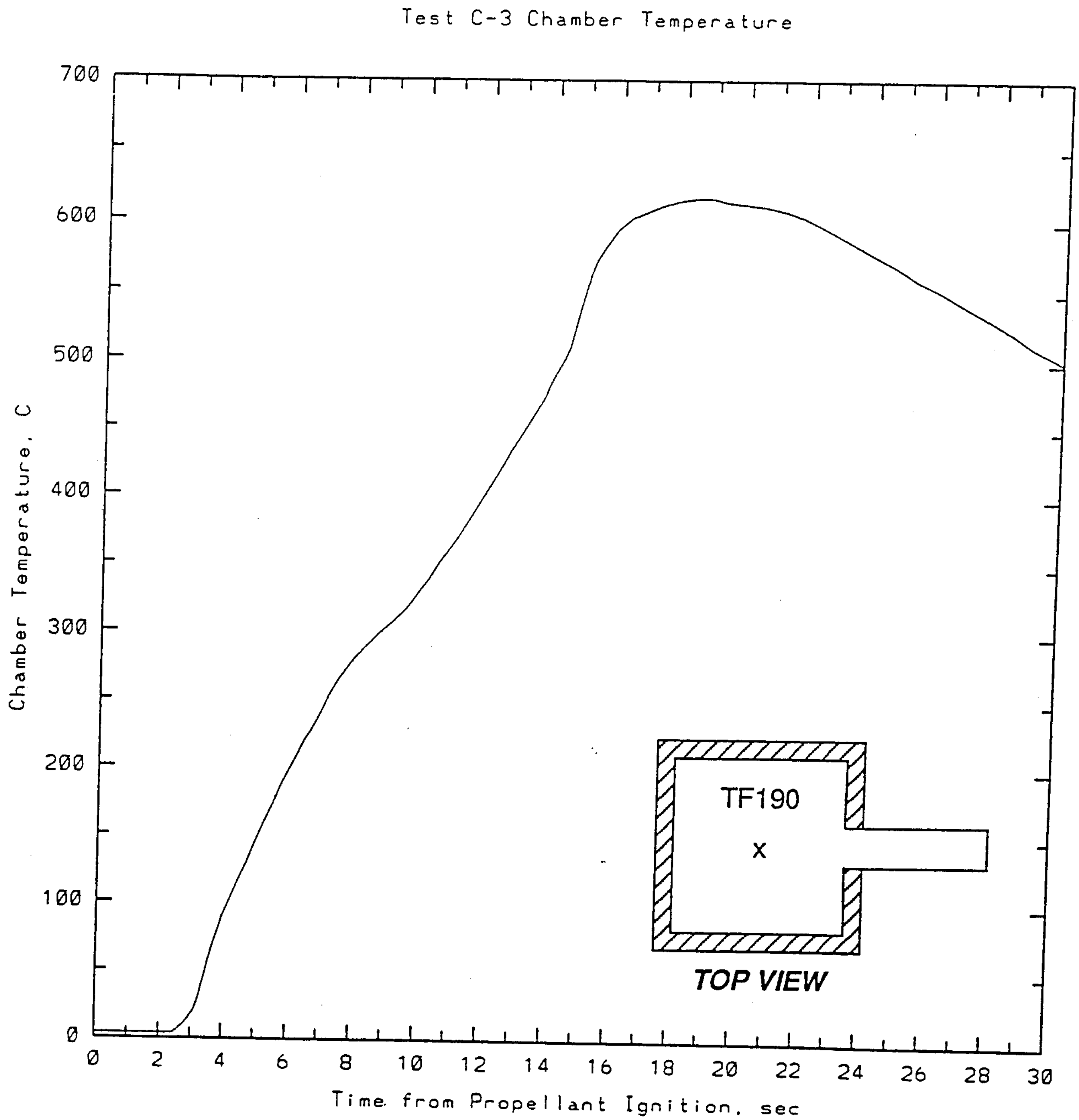


Figure 4. KA-III, Phase C, Test C-3 Bunker Gas Temperature History.

for which the solution takes the form

$$P_c(t) = (P_c)_p \, e^{-Bt}, \; where \; B = \frac{A*}{P_c} \sqrt{RT_c\gamma \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{\gamma-1}}} \tag{4}$$

The instant venting process may be related to venting through an orifice, so the constant, B, is redefined as $B * C_D$, where C_D is the discharge coefficient. C_D is a measure of the resistance offered by the orifice to passing the flow through it; a unity value denotes no resistance, i.e., isentropic flow, and values less than unity, increased resistance, typifying real flow with pressure losses and flow friction. The coefficient, B, was computed for the conditions of Test C-3 to be 5.666, treating the gas temperature as constant during the period of "choked" flow ($\approx$ 14.0 to 15.0 sec). Hence, the particular solution for this case from Eq. (4) is

$$P_c(t) = (P_c)_p \, e^{-5.666 C_{Dt}} \tag{5}$$

The pressure-decay portion of Fig. 3 is expanded in Fig. 5. Also presented in Fig. 5 are the computed pressure decay rates for C_D = 1.0 and 0.18 to illustrate the degree to which the measured decay is non-isentropic and the value of C_D required to match that decay. The normal range for the coefficient, C_D, to account for pressure losses in the orifice is 0.8 - 0.95; the value required to match the measured decay indicates significant other resistance mechanisms in operation. One such mechanism is thermal choking in the vent pipe, caused by heat release with time. This observation is in concert with the likelihood of burning propellant being ejected, and its definition would require the development of a particle transport mechanism model.

In Fig. 3 an apparent acoustical phenomena of the order of 1 Hz is manifested in the pressure history. Attempts to relate this occurrence to any of the geometric or flow parameters of this case have thus far proved unsuccessful, hence, its cause is not currently understood.

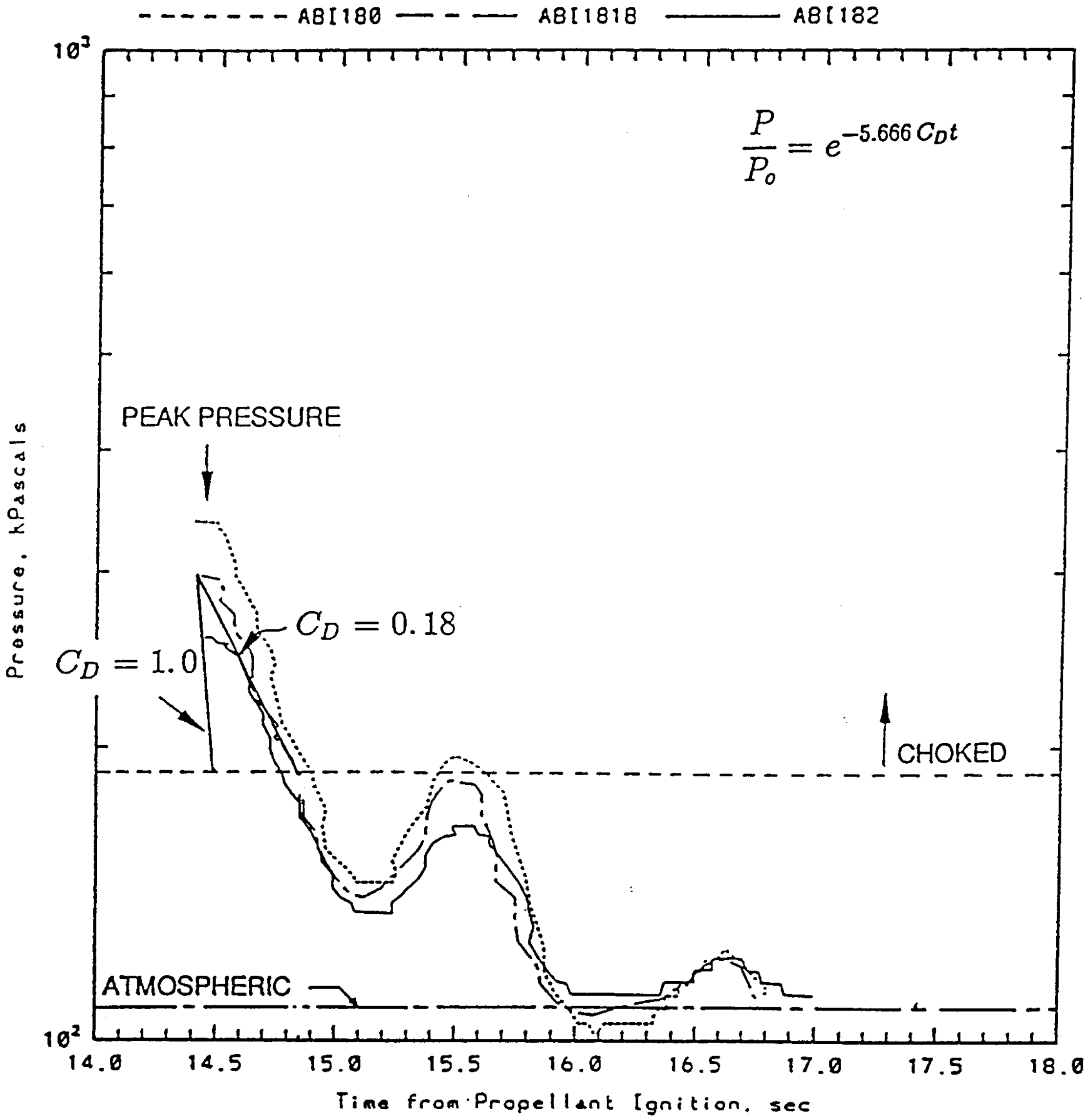


Figure 5. Ka-III, Phase C, Test C-3 Post-peak Bunker Pressure Histories

Section 5
TEST RESULT REVIEW AND COMPARISON WITH ANALYSIS

A review of the KA-III, Phase C Tests and comparison with analytical results based on the information and insights developed in the prior Sections are now presented to gauge the instrumentation performance. Two primary data sources were used: the Test Report [1], and the video footage of the plume history.

5.1 Plume, Bunker Pressure and Temperature Measurements Review

Review of the video coverage of the plume behavior during the propellant burns for all of the tests (C-1 through C-4) showed marked unsteadiness in the plume character, i.e., its shape, radiation intensity, and its apparent mean velocity. Moreover, on one occasion the plume was observed to be completely extinguished only to be subsequently re-ignited.

The observed unsteadiness likely is related to the acoustical phenomena detected in the pressure histories, so understanding this phenomena has more than a causal interest. The re-ignition process could be related to the presence of burning propellant grains or burning of the H_2 produced in the combustion products of the propellant burning process. To gain understanding of these plume characteristics, additional instrumentation to the surface pressures measured in the subject tests is necessary. Recommendations to define the required additional instrumentation are presented in the next Section.

Review of the plotted results presented in Ref [1] provide a better opportunity for direct comparisons and analysis with what one might expect based on fundamental thermochemical and fluid dynamic considerations. Of the four tests presented, the results for Test C-3 provided the better quality plots, hence our review focused on this test exclusively.

Possibly the most surprising aspect of our review was the apparent low amount of energy released in the bunker during the propellant burning compared to the amount theoretically available (See Section 3.1). The comparatively low pressure is possible in view of the vent and/or the slow burning time compared to the fluid dynamic time scale, i.e., the grains can be exhausted well into the plume before burning is completed. Moreover, the pressure histories from three transducers agree well enough to confirm the measurements as being correct.

However, the indicated gas temperature is well below the maximum value one might expect (900K compared to 1900K), suggesting either incomplete combustion in the burning process or very low rate producing little combustion gas. In the latter case the ambient air in the bunker affects measurably the mixture temperature. In addition, the shielded thermocouples may have had significant time lag and conduction loss resulting in lower than actual indicated temperature.

In this vein the one bunker gas temperature measurement was compared chronologically with one of the bunker pressure histories as shown in Fig. 6. The temperature does not peak until about two seconds after the peak pressure occurs. Remembering the inference that the peak pressure indicates the cessation of propellant burning, the continued increase in gas temperature measurement suggests a thermal lag in the temperature measurement device. Future gas temperature instrumentation should be selected to minimize these potential effects.

5.2 Vent Pipe Heat Flux Measurements Review

A means of evaluating the performance of the heat flux instrumentation is the fundamental fluid dynamic relationship between the heat flux and local pressure. This relationship states that the heat flux is proportional to the pressure to an exponent, i.e.,

$$\dot{q} \propto (p)^n \tag{6}$$

where

$n = 0.85$ for turbulent flow.

Since the local pressure is related to the bunker pressure fluid dynamically and the bunker pressures were already digitized, one of the bunker pressure histories was used in the above equation with each of the two heat flux measurements (TF191 and -192). Shown in Figs. 7 and 8 are the heat flux histories for each measurement plotted against the bunker pressure in the log-log domain. Also shown is the 0.85 exponent line paired through the measurements. Good agreement with the fluid dynamic model is clearly evident, indicating the heat flux trends to be as expected and that the instrumentation is performing satisfactorily. It should be remembered, however, that instrumentation was severely overdriven in Test C-4, so for that reason a different type of instrument to measure heat flux is recommended in the following Section for the future tests.

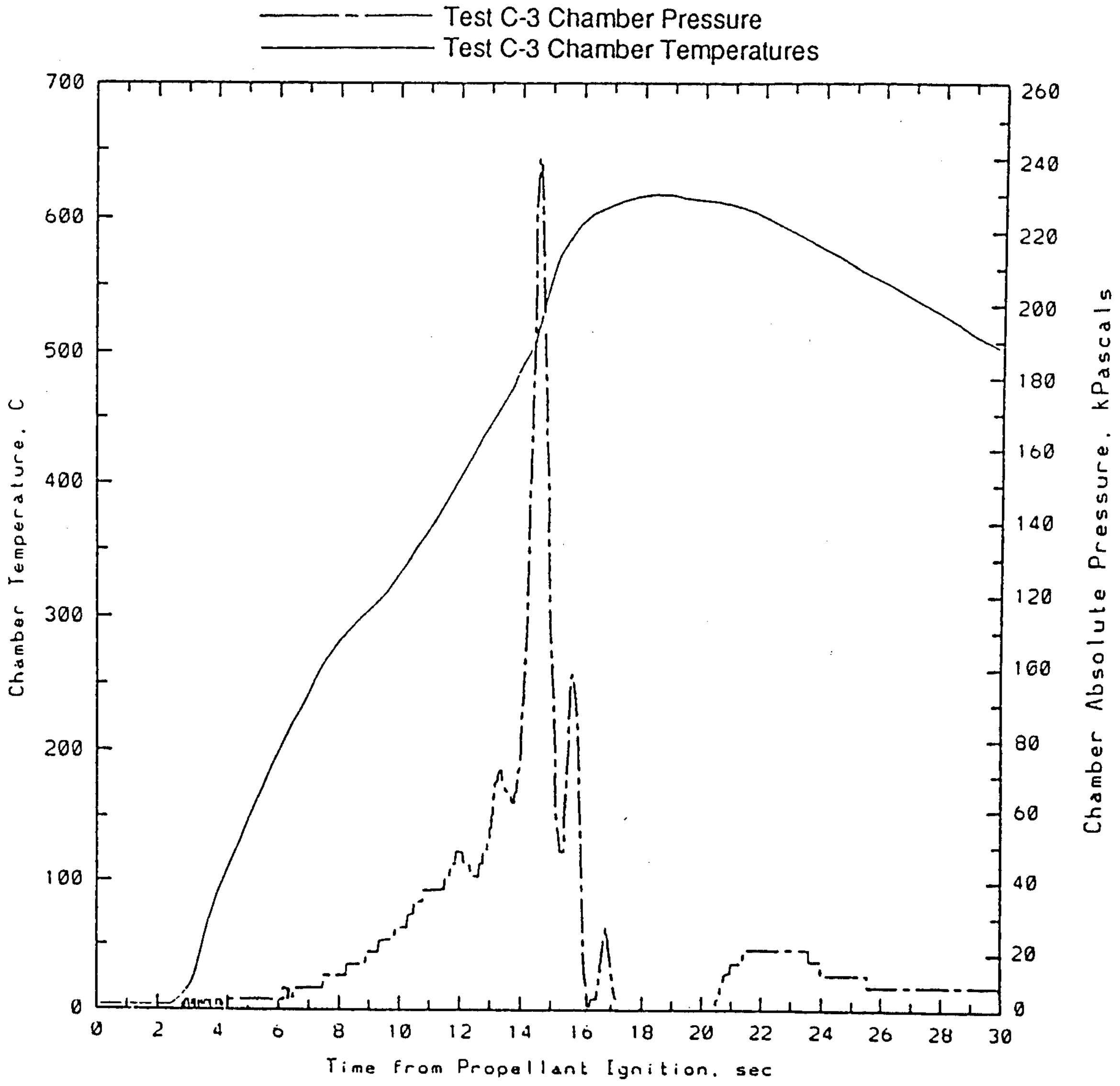


Figure 6. KA-III, Phase C, Test C-3 Bunker Pressure and Gas Temperature History.

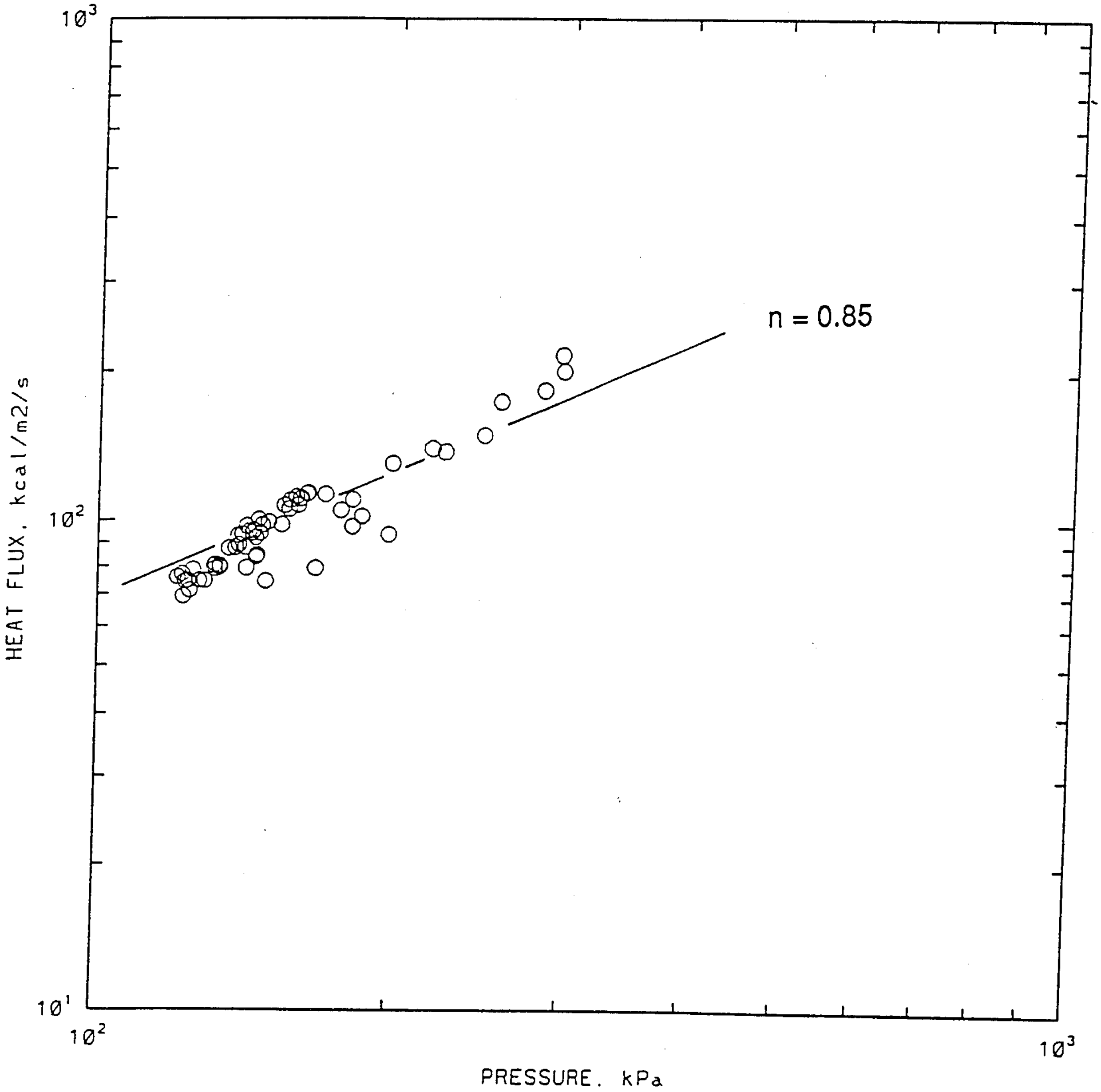


Figure 7. Power-law Correlation of KA-III, Phase C, Test C-3 TF191 Heat Flux History to Bunker Pressure History

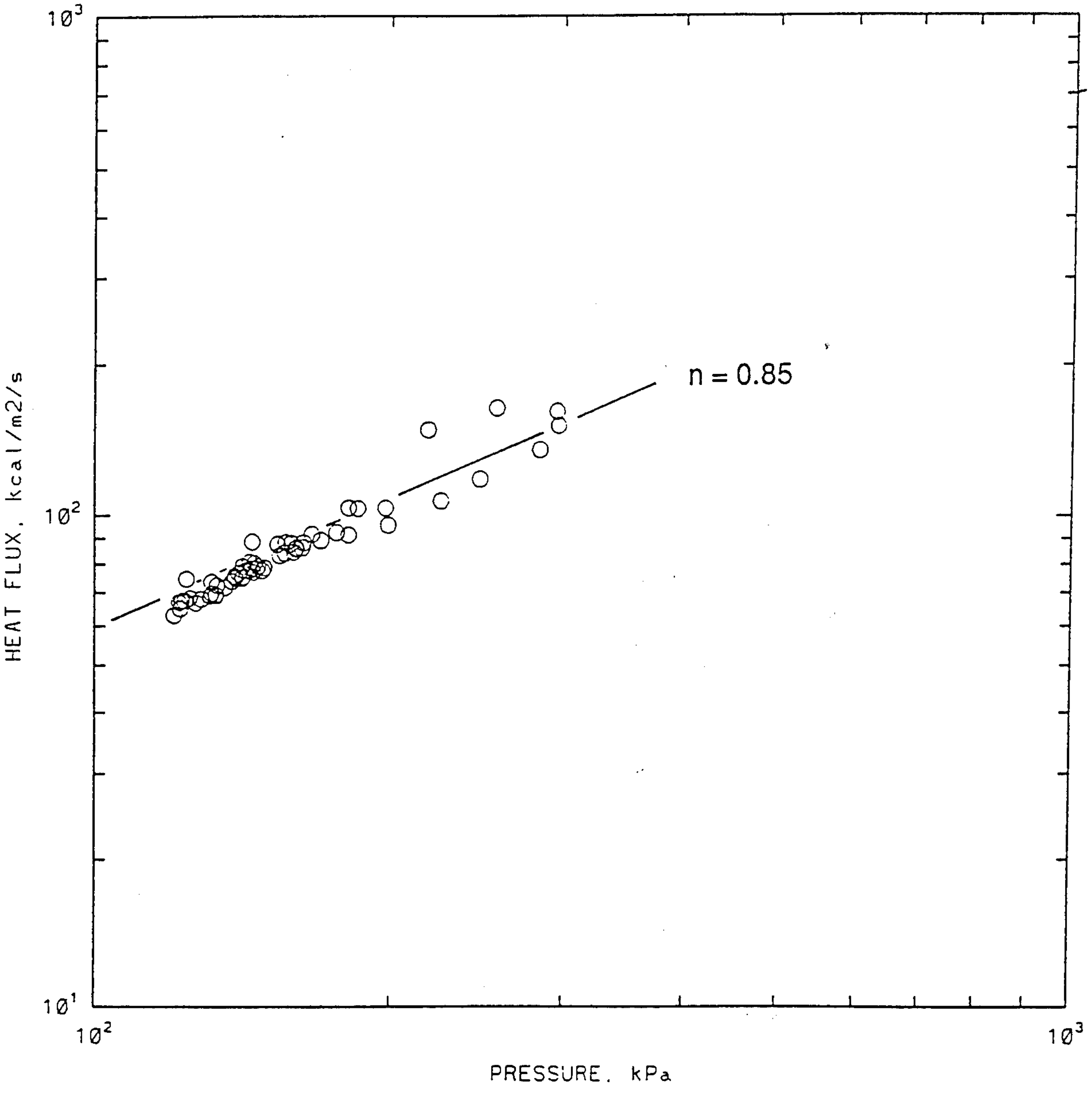


Figure 8. Power-law Correlation of KA-III, Phase C, Test C-3 TF192 Heat Flux History to Bunker Pressure History

Section 6
Recommended Instrumentation for Future Propellant Burn Tests

Based on the review and analysis presented in the prior Sections, the following recommendations are made for instrumentation to be used in future propellant burn-type tests. The recommendations are made to improve the definition of the thermal and fluid dynamic aspects of the propellant burn process with the view to enhancing the understanding and definition of the process environments, particularly the amount of energy released and where it is distributed. The recommendations are presented by a generic subdivision of the regions of interest with a rationale of the need for each measurement. Specification sheets for the recommended thermal instrumentation are given in Appendix C identifying the type and recommended supplier. And a summary of all recommended instrumentation is presented in Table 1.

Table 1: WES May '93 Propellant Burn Tests Recommended Instrumentation Summary

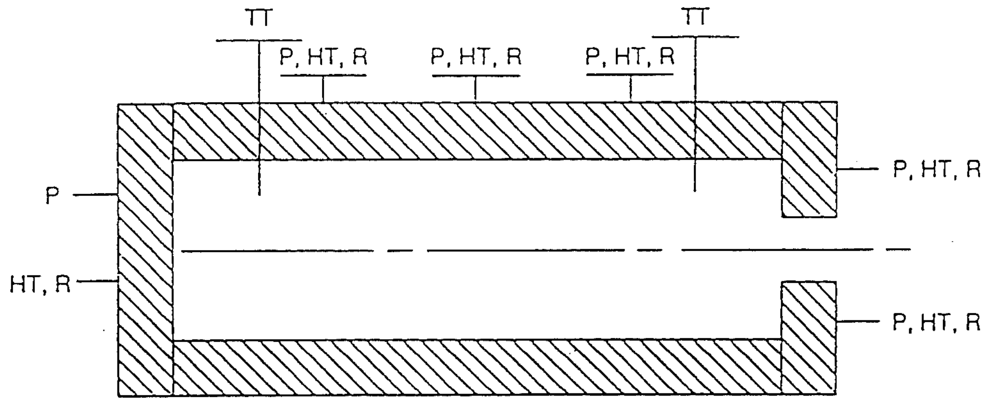
	Specification	Number
Chamber		
Pressures	Selected by WES	6
Total Temperature (T)	TCGT 130 Series-569	2
Total Heat Flux (HT)	TCS-E-YY-ZZ-10196	6
Radiometer (R)	32R-L-XX-140-ZZ-21096	6
Vent Pipe		
Pressures	Selected by WES	7
Total Temperature (T)	T/C-801	2
Total Heat Flux (HT)	TCS-E-YY-ZZ-10196	3
Radiometer (R)	32R-L-XX-140-ZZ-21096	3
Plume		
Pressures	Selected by WES	2+
Total Temperature (T)	T/C-801	1+
Total Heat Flux (HT)	TCS-E-YY-ZZ-10196	3
Radiometer (R)	32-L-XX-140-ZZ-21096	3

Note: Recording channels for T & HT instrumentation may require 10 MHz sampling rate.

6.1 Propellant Combustion Chamber Instrumentation

Shown in Fig. 9 is a geometrically scaled sketch of the combustion chamber hardware to be used in the WES May '93 tests with the recommended instrumentation located. The recommended instrumentation consists of gas total pressure and temperature and chamber wall total and gas radiative heat flux. The pressure instrumentation used in the KA-III, Phase C tests performed quite well and are recommended for use in the future tests. The sensing face of the transducer should be well shielded from the heat effects of gas radiation. Considering the length- to-diameter of the combustion chamber, it is recommended that three (3) pressure measurements be spaced equally along the chamber length to detect any possible gradients. The pressure measurements at each end are placed to detect any acoustical phenomena.

The gas total temperature measurements should be installed near the pressure measurements located at 0.25 and 0.75 of the chamber length. The measurement tip of the thermocouple should extend about 5 in. beyond the chamber side wall. The spec sheet for this transducer is presented as Fig. C-1 (Appendix C).



Pressures (P):	Gas total pressure; six measurements for gradient definition, acoustic effects and redundancy.
Temperatures (TT):	Gas total temperature; two measurements for gradient definition and redundancy.
Heat Flux (HT):	Wall total heat flux gauges; gauge will measure wall surface temperature as well.
Radiometer (R):	Gas radiation gauge; HT-R at each location will provide convection heat flux, allowing definition of local convective heat transfer coefficient, using nearest TT and wall temperature.

Figure 9. Recommended Instrumentation in Combustion Chamber for WES May '93 Propellant Burn Tests

Because of the indication of possible thermal lag of the thermocouple used in the KA-III, Phase C tests, the gauge of the thermocouple wire for this transducer should be as small as possible, consistent with the expected maximum temperature (1900K for the present case). If there is room in the data acquisition system, it would be desirable to add a third thermocouple of a different wire gauge near the bottom of the chamber at the same axial location as one of the top thermocouples to assess the lag effect.

The recommended heat flux measurements in the chamber are designed to allow determination of the amount of energy transferred to the walls before the gas is expelled out the vent pipe. Both total and radiative heat flux instrumentation are recommended to allow the determination of the convective heat transfer (total minus radiative), which may be used in conjunction with the simultaneous gas total and wall temperatures to compute the convective heat transfer coefficient. Having the measurements in this form provides the means to define the thermal environments for other test conditions more readily. The transducer for the total heat flux is actually a surface temperature measurement device; it was selected because it is extremely rugged, provides the direct measurement of the wall temperature, its temperature history can be used in an algorithm to determine the wall heat flux, and it is virtually impossible to overdrive its capability to define the heat flux (as was experienced in the vent pipe for Test C-4 of the KA-III, Phase C tests).

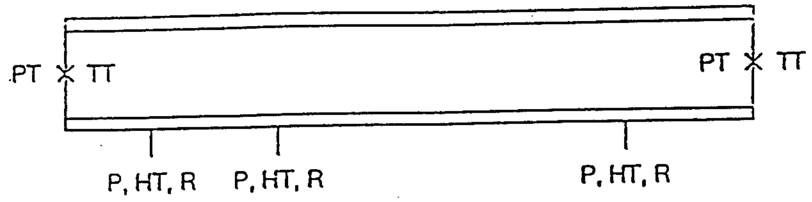
The specs sheets for the surface temperature (total heat flux) and the radiative heat flux gauges are presented as Fig. C-2 and C-3, respectively. The heat flux algorithm is discussed in Subsection 6.4: Recommended Data Reduction and Instrumentation Installation.

6.2 Vent Pipe Instrumentation

The recommended instrumentation in the vent pipe is designed to define the energy and velocity (and mass flow) of the entering and exiting flow, and the distributions with vent-pipe length of static pressure and total and radiative heat flux to the wall.. The placing of the vent-pipe instrumentation is shown in Fig. 10; the locations of the wall static pressure and heat flux transducers should be spaced logarithmically along the length for better definition of any pipe-flow characteristics the flow might exhibit.

The total and radiative heat flux gauges and total and static pressure transducers are the same as those recommended for use in the combustion chamber (See Fig. C-2 and C-3). The installation of the pressure transducers in the pitot probes (PT) is described in Subsection 6.4: Recommended Data Reduction and Instrumentation Installation.

The total temperature transducer recommended for use in the vent pipe is similar to the ones in the combustion chamber but has a different radiation shield. The specs sheet for this transducer is presented in Fig. C-4. The concerns for temperature response with thermocouple wire gauge expressed in the combustion chamber discussion apply here also.



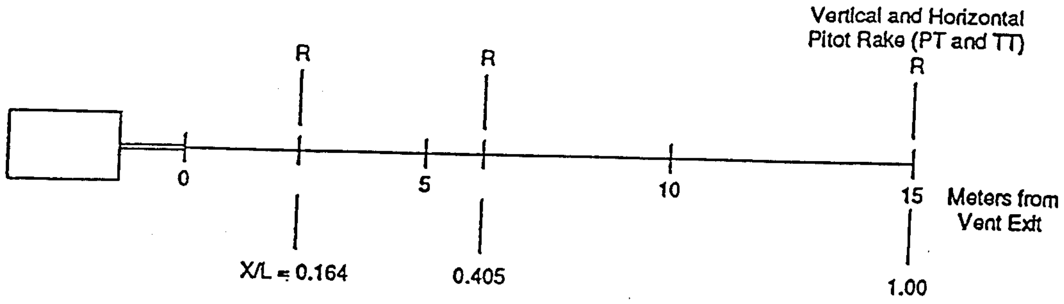
Pressures (P):	Wall static pressures; three measurements are minimum needed to identify pipe flow characteristics.
Heat Flux (HT):	Wall total heat flux gauges to characterize pipe flow and detect any vent pipe burning.
Radiometer (R):	Gas radiation gauge; HT-R at each location will provide convection heat flux, allowing definition of local convective heat transfer coefficient, using nearest TT and wall temperature.
Pitot Tubes (PT):	Probe configured to measure both gas total and static pressures as a measure of these parameters and flow dynamic pressure. Comparisons of entrance and exit values will reveal any in-pipe shock fronts.
Temperatures (TT):	Gas total temperature; used in conjunction with PT measurements to get gas mass flow. Comparisons of entrance and exit values will reveal any in-pipe energy release.

Figure 10. Recommended Instrumentation in Vent Pipe for WES May '93 Propellant Burn Tests.

6.3 Plume Instrumentation

Shown in Fig. 11 is a layout for an instrumentation package to minimally define the thermal/fluid dynamic characteristics of the propellant burn exhaust plume. The package consists of a radiometer positioned at three locations along the plume length (15m shown) and a pitot rake which can be positioned at any location along the plume. The pitot rake should facilitate mounting pitot probes and a total temperature transducer at up to eight (8) adjustable positions both vertically and horizontally plus a center position to provide survey type measurements of the plume cross section.

The pitot probes, total temperature instruments, and the radiometers are the same as those used in the vent pipe application.



Note: Instrument stations spaced equally from vent pipe exit on log scale.

Radiometer (R):	Plume radiation heat flux gauges; measure of far-field radiation effects of plume.
Rake Pitot Tubes (PT):	Probe configured to measure both gas total and static pressures; several locations are desirable to survey plume cross section.
Rake Temperatures (TT):	Plume gas total temperature to measure plume total energy; several locations are desirable to survey plume cross section.

Note: Initial tests should use only one each of the PT and TT instruments. After performance verified, use multiple instruments to define plume profiles.

Figure 11. Recommended Instrumentation in Plume Region for WES May '93 Propellant Burn Tests.

6.4 Recommended Data Reduction and Instrumentation Installation

Data Reduction -- The total heat flux/surface temperature is the only measurement result for which the data reduction procedure is not straightforward multiplication of a gauge constant scale factor, supplied by the instrument vendor, times the instantaneous output of the instrument. Some thermocouple transducers are non-linear and require special digital data reduction.

The surface temperature is obtained by the tabular look-up in the millivolt output tables for Chromel-Constantan taking into account the thermocouple reference temperature, or input of the millivolt output into a curve fit equation of the tables. Computation of the heat flux is more complicated; it requires the time-wise integration of the surface temperature to get the heat flux.

The heat flux algorithm is based on the condition of one-dimensional conduction along the gauge, a condition that is satisfied if the gauge is installed in a material of similar thermophysical properties such that $\sqrt{\rho C_p k}$ for the gauge and the host material are as near the same as possible. For Chromel-Constantan, steel is the best match for these properties. The temperature variation of $\sqrt{\rho C_p k}$ over the range measured by the gauge is required in the data reduction procedure.

The simplest algorithms that for a gauge installed in a semi-infinite slab under a heating load from a time-invariant heat transfer coefficient. This algorithm is available in Ref [5]. However, it is not likely that the heat transfer coefficient for the conditions of the propellant burn tests will be constant with time.

A second algorithm for the time-variant heat transfer coefficient may be developed by solving the inverse of the equation presented in Ref [6] for the wall temperature as a function of the time-variant heat transfer coefficient. This approach requires the computation of the instantaneous slope of the wall temperature with time.

The most direct method of computing the heat transfer coefficient variation with time from the wall temperature time history is by the use if a one-dimensional conduction code which has this capability built in. The EXITS code, developed by REMTECH, Inc., has this capability and can be made available for use in this application.

This type gauge is recommended despite the difficult data reduction procedure required to compute the heat flux in view of the benefits of a very rugged transducer which is virtually impossible to destroy or over-range. Moreover, its use with the radiometer and gas total temperature measurement permits the computation of the convective heat transfer coefficient.

It should be emphasized here that in order to measure the total heat flux, the exposed surface of the gauge must be coated with a paint of known emissivity -- the closer to unity the better for greater accuracy.

Instrumentation Installation -- The installation requirements (hole diameter and thread type, etc.) for all the thermal instrumentation are called out on the spec sheets for each type. Additional installation considerations are discussed below.

The radiometer and heat flux gauge should be installed flush with the internal wall of the test hardware. The heat flux gauges may be contoured to the local radius. The radiometers should not be contoured and should be installed such that no part of the window is protruding into the flow.

In order to avoid the violation of thermal diffusion times, which complicates the data reduction procedure for the heat flux gauges, the minimum wall thickness into which these gauges should be installed is 1.5 in. This criterion is not satisfied in the vent pipe as it is presently designed; methods to effectively increase the local wall thickness around each gauge (1.0 in. radius) should be adopted.

The mounting of the total temperature and pitot probes in the vent pipe should be such as to minimize the interference effects of its presence in the passing flow; how much is too much is difficult to determine -- a rule of thumb is no more than 15 percent blockage area to the unblocked flow area.

The important aspect of the installation of the pressures in the pitot pressure probe is that the static pressure transducer be located sufficiently downstream of the probe front face so that the local pressure has returned to the stream static. A rule of thumb for that distance is 10 probe diameters. For all installations the pressure transducers should be protected from direct radiation from the combustion gases.

Section 7
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[5] Cook, W. J., and Felderman, E. J., "Reduction of Data from Thin-Film Heat Transfer Gages: A Concise Numerical Technique," AAIA J., Vol. 4, No. 3, March 1966.

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Appendix A

ANALYSIS OF ADIABATIC BURNING CONDITION OF M-1 PROPELLANT USED IN KA-III, PHASE C, TESTS (CEC Code Output)

```
1

 REACTANTS
 C    2.0000  H    6.0000  O    1.0000       0.0000     0.0000     0.007500     -66420.00  S    298.300    F
 C    6.0000  H    7.3715  N    2.6355  O   10.2715     0.0000     0.837400    -164700.00  S    298.300    F
 C    7.0000  H    6.0000  N    2.0000  O    4.0000     0.0000     0.098400     -17100.00  S    298.300    F
 C   12.0000  N    1.0000  H   11.0000       0.0000     0.0000     0.009900      31070.00  S    298.300    F
 C   16.0000  H   22.0000  O    4.0000       0.0000     0.0000     0.049300    -201400.00  S    298.300    F
 H    2.0000  O    1.0000       0.0000       0.0000     0.0000     0.005000     -68315.00  S    298.300    F

 NAMELISTS
0   ***INPT2***
0KASE =        1   IDEBUG =  0   TRACE = 0.00000D+00   IONS = F   SIUNIT = F
0TP = F   HP = F   SP = F   TV = F   UV = T   SV = F   RKT = F   SHOCK = F   DETN = F
0TRNSPT = F   TRPACC = 0.999950E+00   NODATA = F
0OF = F   FA = F   FPCT = F   ERATIO = F   PHI = F
0S0 = 0.00000000E+00   U = 0.00000000E+00   H = 0.00000000E+00
0V =   0.50000E+01
0RHO = 0.20000E+00
0T =   0.00000E+00
0NO INPT2 VALUE GIVEN FOR OF, EQRAT, FA, OR FPCT
0MIX = 0.00000E+00
0SPECIES BEING CONSIDERED IN THIS SYSTEM
  J 3/78  C                  J12/67  CH                 J12/72  CH2                J 3/61  FORMALDEHYDE       L 4/85  FORMIC ACID
  J 6/69  CH3                L 9/85  HYDROXYMETHYLENE   L 9/85  METHYLOXIDE        L 5/84  CH4                L 9/85  METHANOL
  J 6/69  CN                 J12/70  NCN RAD            J 6/66  CNN RAD            J 9/65  CO                 J 9/65  CO2
  J12/69  C2                 J 3/67  C2H RAD            J 3/61  ACETYLENE          BUR 84  KETENE             BUR 84  C2H3 RAD
  BUR 84  METHYL CYANIDE     BUR 84  CH3CO RAD          BUR 84  CH2CHO RAD         L 4/85  ETHYLENE           BUR 84  ACETALDEHYDE
  L 4/85  ACETIC ACID        L 4/85  (FORMIC ACID)2     P10/83  ETHYL RAD          BUR 84  ETHYL OXIDE RAD    L 5/84  ETHANE
  BUR 84  AZOMETHANE         BUR 84  DIMETHYL ETHER     BUR 84  ETHANOL            J 3/67  CNC RAD            J 3/61  CYANOGEN
  J 9/66  CCO RAD            J12/69  C3                 DB6/61  C3H3 RAD           BUR 84  CYCLOPROPENE       BUR 84  PROPYNE
  BUR 84  ALLENE             BUR 84  C3H5 RAD           BUR 84  CYCLOPROPANE       L 4/85  PROPYLENE          L 9/85  PROPYLENE OXIDE
  L 9/85  I-PROPYL RAD       L 9/85  N-PROPYL RAD       L 4/85  PROPANE            L 1/84  1-PROPANOL         J 6/68  CARBON SUBOXIDE
  J12/69  C4                 BUR 84  BUTADIYNE          P10/85  CYCLOBUTADIENE     BUR 84  BUTAN-1EN-3YN      P 4/84  1,3-BUTADIENE
  BUR 84  2-BUTYNE           BUR 84  2-BUTENE TRANS     BUR 84  2-BUTENE CIS       BUR 84  ISOBUTENE          BUR 84  1-BUTENE
  L 4/85  (ACETIC ACID)2     L 9/85  T-BUTYL RAD        L 9/85  S-BUTYL RAD        P10/83  N-BUTYL RAD        L 4/85  N-BUTANE
  L 4/85  ISOBUTANE          J 3/61  CARBON SUBNITRID   J12/69  C5                 P10/85  CYCLOPENTADIENE    P12/52  CYCLOPENTANE
  P12/52  1-PENTENE          L 5/87  T-PENTYL RAD       P10/83  N-PENTYL RAD       P10/85  PENTANE            P10/85  ISOPENTANE
  P10/85  CH3C(CH3)2CH3      BUR 84  HEXATRIYNE         L12/84  PHENYL RAD         L12/84  PHENOXY RAD        L12/84  BENZENE
  L12/84  PHENOL             BUR 84  CYCLOHEXENE        P10/83  N-HEXYL RAD        P10/84  TOLUENE            L 6/87  CRESOL
  P12/52  1-HEPTENE          P10/83  N-HEPTYL RAD       P 4/81  N-HEPTANE          P12/52  1-OCTENE           P10/83  N-OCTYL RAD
  P 4/85  OCTANE             P 4/85  ISO-OCTANE         P10/83  N-NONYL RAD        BUR 84  NAPTHLENE          BUR 84  AZULENE
  P10/83  N-DECYL RAD        L12/84  O-BIPHENYL RAD     L12/84  BIPHENYL           L 6/88  JET-A(G)           J 3/77  H
  L12/69  HCN                J12/70  HCO RAD            J12/70  HNCO               RUS 78  HNO                RUS 78  HNO2
  RUS 78  HNO3               L 5/89  HO2                J 3/77  H2                 J12/65  H2N2               J 3/79  H2O
  L 3/85  H2O2               J 3/77  N                  J12/70  NCO                RUS 78  NH                 RUS 78  NH2
  J 6/77  NH3                RUS 78  NH2OH              RUS 78  NO                 RUS 78  NO2                J12/64  NO3
```

```
   J 3/77  N2               RUS 78  N2H2            RUS 78  NH2NO2          RUS 78  N2H4            RUS 78  N2O
  RUS 78  N2O3              RUS 78  N2O4            RUS 78  N2O5            RUS 78  N3              RUS 78  N3H
   J 3/77  O                J 6/77  OH              J 3/77  O2              J 6/61  O3              J 3/78  C(GR)
  P10/80  BENZENE(L)        P10/80  TOLUENE(L)      P10/80  OCTANE(L)       L 6/88  JET-A(L)        L 3/81  H2O(S)
   J 3/79  H2O(L)
 0OF =    0.000000
                              EFFECTIVE FUEL          EFFECTIVE OXIDANT          MIXTURE
  INTERNAL ENERGY                 HPP(2)                  HPP(1)                  HSUB0
  (KG-MOL)(DEG K)/KG        -0.28176266E+03          0.00000000E+00         -0.28176266E+03
 0KG-FORM.WT./KG               BOP(I,2)                BOP(I,1)                 B0(I)
  C                          0.25349588E-01          0.00000000E+00          0.25349588E-01
  H                          0.31067750E-01          0.00000000E+00          0.31067750E-01
  O                          0.33694333E-01          0.00000000E+00          0.33694333E-01
  N                          0.89330269E-02          0.00000000E+00          0.89330269E-02
 0POINT ITN    T       C              H              O              N
    1   13 2437.49    -6.380         -7.089        -20.635        -11.217
 1                                    THERMODYNAMIC EQUILIBRIUM COMBUSTION PROPERTIES AT ASSIGNED
 0                                                             VOLUME

  CASE NO.       1
                                                                                      WT FRACTION     ENERGY     STATE    TEMP
          CHEMICAL FORMULA                                                            (SEE NOTE)     CAL/MOL             DEG K
  FUEL     C  2.00000   H  6.00000   O  1.00000                                        0.007444    -66420.000     S     298.30
  FUEL     C  6.00000   H  7.37150   N  2.63550   O 10.27150                           0.831166  -164700.000     S     298.30
  FUEL     C  7.00000   H  6.00000   N  2.00000   O  4.00000                           0.097667   -17100.000     S     298.30
  FUEL     C 12.00000   N  1.00000   H 11.00000                                        0.009826    31070.000     S     298.30
  FUEL     C 16.00000   H 22.00000   O  4.00000                                        0.048933  -201400.000     S     298.30
  FUEL     H  2.00000   O  1.00000                                                     0.004963   -68315.000     S     298.30
 0               O/F=  0.0000    PERCENT FUEL= 100.0000    EQUIVALENCE RATIO= 1.9657    PHI= 0.0000
 0THERMODYNAMIC PROPERTIES

  P, ATM            1810.19
  T, DEG K          2437.49
  RHO, G/CC        2.0000-1
  H, CAL/G          -340.73
  U, CAL/G          -559.92
  G, CAL/G         -5703.39
  S, CAL/(G)(K)      2.2001

  M, MOL WT          22.099
  (DLV/DLP)T       -1.00334
  (DLV/DLT)P         1.0150
  CP, CAL/(G)(K)     0.4475
  GAMMA (S)          1.2558
  SON VEL,M/SEC      1073.2

 0MOLE FRACTIONS

  FORMALDEHYDE      0.00011
  FORMIC ACID       0.00005
  CH3               0.00001
  CH4               0.00053
```

```
 CO               0.50555
 CO2              0.05351
 H                0.00020
 HCN              0.00036
 HCO RAD          0.00003
 HNCO             0.00003
 H2               0.20902
 H2O              0.13174
 NH3              0.00063
 N2               0.09819
 OH               0.00003
0ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.50000E-05 FOR ALL ASSIGNED CONDITIONS

  C                 CH                CH2               HYDROXYMETHYLENE  METHYLOXIDE       METHANOL          CN
  NCN RAD           CNN RAD           C2                C2H RAD           ACETYLENE         KETENE            C2H3 RAD
  METHYL CYANIDE    CH3CO RAD         CH2CHO RAD        ETHYLENE          ACETALDEHYDE      ACETIC ACID       (FORMIC ACID)2
  ETHYL RAD         ETHYL OXIDE RAD   ETHANE            AZOMETHANE        DIMETHYL ETHER    ETHANOL           CNC RAD
  CYANOGEN          CCO RAD           C3                C3H3 RAD          CYCLOPROPENE      PROPYNE           ALLENE
  C3H5 RAD          CYCLOPROPANE      PROPYLENE         PROPYLENE OXIDE   I-PROPYL RAD      N-PROPYL RAD      PROPANE
  1-PROPANOL        CARBON SUBOXIDE   C4                BUTADIYNE         CYCLOBUTADIENE    BUTAN-1EN-3YN     1,3-BUTADIENE
  2-BUTYNE          2-BUTENE TRANS    2-BUTENE CIS      ISOBUTENE         1-BUTENE          (ACETIC ACID)2    T-BUTYL RAD
  S-BUTYL RAD       N-BUTYL RAD       N-BUTANE          ISOBUTANE         CARBON SUBNITRID  C5                CYCLOPENTADIENE
  CYCLOPENTANE      1-PENTENE         T-PENTYL RAD      N-PENTYL RAD      PENTANE           ISOPENTANE        CH3C(CH3)2CH3
  HEXATRIYNE        PHENYL RAD        PHENOXY RAD       BENZENE           PHENOL            CYCLOHEXENE       N-HEXYL RAD
  TOLUENE           CRESOL            1-HEPTENE         N-HEPTYL RAD      N-HEPTANE         1-OCTENE          N-OCTYL RAD
  OCTANE            ISO-OCTANE        N-NONYL RAD       NAPTHLENE         AZULENE           N-DECYL RAD       O-BIPHENYL RAD
  BIPHENYL          JET-A(G)          HNO               HNO2              HNO3              HO2               H2N2
  H2O2              N                 NCO               NH                NH2               NH2OH             NO
  NO2               NO3               N2H2              NH2NO2            N2H4              N2O               N2O3
  N2O4              N2O5              N3                N3H               O                 O2                O3
  C(GR)             BENZENE(L)        TOLUENE(L)        OCTANE(L)         JET-A(L)          H2O(S)            H2O(L)
0NOTE. WEIGHT FRACTION OF FUEL IN TOTAL FUELS AND OF OXIDANT IN TOTAL OXIDANTS
1
  STOP
0ERROR IN ABOVE CARD.  CONTENTS IGNORED.
```

Appendix B

ANALYSIS OF ISENTROPIC BURNING CONDITION OF M-1 PROPELLANT USED IN KA-III, PHASE C, TESTS (CEC Code Output)

```
1

 REACTANTS
 C    2.0000  H    6.0000  O    1.0000      0.0000      0.0000     0.007500     -66420.00       298.300  F
 C    6.0000  H    7.3715  N    2.6355  O  10.2715      0.0000     0.837400    -164700.00       298.300  F
 C    7.0000  H    6.0000  N    2.0000  O   4.0000      0.0000     0.098400     -17100.00       298.300  F
 C   12.0000  N    1.0000  H   11.0000      0.0000      0.0000     0.009900      31070.00       298.300  F
 C   16.0000  H   22.0000  O    4.0000      0.0000      0.0000     0.049300    -201400.00       298.300  F
 H    2.0000  O    1.0000      0.0000      0.0000      0.0000     0.005000     -68315.00       298.300  F

 NAMELISTS
0    ***INPT2***
0KASE =        1   IDEBUG =  0   TRACE = 0.00000D+00   IONS = F   SIUNIT = F
0TP = F   HP = F   SP = F   TV = F   UV = F   SV = F   RKT = T   SHOCK = F   DETN = F
0TRNSPT = F   TRPACC = 0.999950E+00   NODATA = F
0OF = F   FA = F   FPCT = F   ERATIO = F   PHI = F
0S0 = 0.00000000E+00   U = 0.00000000E+00   H = 0.00000000E+00
0P =   0.15000E+02
0T =   0.00000E+00
0NO INPT2 VALUE GIVEN FOR OF, EQRAT, FA, OR FPCT
0MIX = 0.00000E+00
0SPECIES BEING CONSIDERED IN THIS SYSTEM
  J 3/78  C                 J12/67  CH                J12/72  CH2               J 3/61  FORMALDEHYDE      L 4/85  FORMIC ACID
  J 6/69  CH3               L 9/85  HYDROXYMETHYLENE  L 9/85  METHYLOXIDE       L 5/84  CH4               L 9/85  METHANOL
  J 6/69  CN                J12/70  NCN RAD           J 6/66  CNN RAD           J 9/65  CO                J 9/65  CO2
  J12/69  C2                J 3/67  C2H RAD           J 3/61  ACETYLENE         BUR 84  KETENE            BUR 84  C2H3 RAD
  BUR 84  METHYL CYANIDE    BUR 84  CH3CO RAD         BUR 84  CH2CHO RAD        L 4/85  ETHYLENE          BUR 84  ACETALDEHYDE
  L 4/85  ACETIC ACID       L 4/85  (FORMIC ACID)2    P10/83  ETHYL RAD         BUR 84  ETHYL OXIDE RAD   L 5/84  ETHANE
  BUR 84  AZOMETHANE        BUR 84  DIMETHYL ETHER    BUR 84  ETHANOL           J 3/67  CNC RAD           J 3/61  CYANOGEN
  J 9/66  CCO RAD           J12/69  C3                DB6/61  C3H3 RAD          BUR 84  CYCLOPROPENE      BUR 84  PROPYNE
  BUR 84  ALLENE            BUR 84  C3H5 RAD          BUR 84  CYCLOPROPANE      L 4/85  PROPYLENE         L 9/85  PROPYLENE OXIDE
  L 9/85  I-PROPYL RAD      L 9/85  N-PROPYL RAD      L 4/85  PROPANE           L 1/84  1-PROPANOL        J 6/68  CARBON SUBOXIDE
  J12/69  C4                BUR 84  BUTADIYNE         P10/85  CYCLOBUTADIENE    BUR 84  BUTAN-1EN-3YN     P 4/84  1,3-BUTADIENE
  BUR 84  2-BUTYNE          BUR 84  2-BUTENE TRANS    BUR 84  2-BUTENE CIS      BUR 84  ISOBUTENE         BUR 84  1-BUTENE
  L 4/85  (ACETIC ACID)2    L 9/85  T-BUTYL RAD       L 9/85  S-BUTYL RAD       P10/83  N-BUTYL RAD       L 4/85  N-BUTANE
  L 4/85  ISOBUTANE         J 3/61  CARBON SUBNITRID  J12/69  C5                P10/85  CYCLOPENTADIENE   P12/52  CYCLOPENTANE
  P12/52  1-PENTENE         L 5/87  T-PENTYL RAD      P10/83  N-PENTYL RAD      P10/85  PENTANE           P10/85  ISOPENTANE
  P10/85  CH3C(CH3)2CH3     BUR 84  HEXATRIYNE        L12/84  PHENYL RAD        L12/84  PHENOXY RAD       L12/84  BENZENE
  L12/84  PHENOL            BUR 84  CYCLOHEXENE       P10/83  N-HEXYL RAD       P10/84  TOLUENE           L 6/87  CRESOL
  P12/52  1-HEPTENE         P10/83  N-HEPTYL RAD      P 4/81  N-HEPTANE         P12/52  1-OCTENE          P10/83  N-OCTYL RAD
  P 4/85  OCTANE            P 4/85  ISO-OCTANE        P10/83  N-NONYL RAD       BUR 84  NAPTHLENE         BUR 84  AZULENE
  P10/83  N-DECYL RAD       L12/84  O-BIPHENYL RAD    L12/84  BIPHENYL          L 6/88  JET-A(G)          J 3/77  H
  L12/69  HCN               J12/70  HCO RAD           J12/70  HNCO              RUS 78  HNO               RUS 78  HNO2
  RUS 78  HNO3              L 5/89  HO2               J 3/77  H2                J12/65  H2N2              J 3/79  H2O
  L 3/85  H2O2              J 3/77  N                 J12/70  NCO               RUS 78  NH                RUS 78  NH2
  J 6/77  NH3               RUS 78  NH2OH             RUS 78  NO                RUS 78  NO2               J12/64  NO3
  J 3/77  N2                RUS 78  N2H2              RUS 78  NH2NO2            RUS 78  N2H4              RUS 78  N2O
```

```
 RUS 78  N2O3              RUS 78  N2O4              RUS 78  N2O5              RUS 78  N3                RUS 78  N3H
 J 3/77  O                 J 6/77  OH                J 3/77  O2                J 6/61  O3                J 3/78  C(GR)
 P10/80  BENZENE(L)        P10/80  TOLUENE(L)        P10/80  OCTANE(L)         L 6/88  JET-A(L)          L 3/81  H2O(S)
 J 3/79  H2O(L)
0   ***RKTINP***
0EQL = T   FROZ = T   NFZ =  1   TCEST =  3800.000   FAC = F   MA = 0.00000000E+00   ACAT = 0.00000000E+00   DEBUGF = F
0PCP =   0.10204000E+01
0SUBAR =
0SUPAR =
0OF =   0.000000
                           EFFECTIVE FUEL          EFFECTIVE OXIDANT          MIXTURE
 ENTHALPY                     HPP(2)                  HPP(1)                  HSUB0
 (KG-MOL)(DEG K)/KG       -0.28176266E+03         0.00000000E+00          -0.28176266E+03
0KG-FORM.WT./KG              BOP(I,2)                BOP(I,1)                BO(I)
 C                         0.25349588E-01         0.00000000E+00           0.25349588E-01
 H                         0.31067750E-01         0.00000000E+00           0.31067750E-01
 O                         0.33694333E-01         0.00000000E+00           0.33694333E-01
 N                         0.89330269E-02         0.00000000E+00           0.89330269E-02
0POINT ITN    T       C                H               O               N
   1    21 1927.03  -11.497          -10.417         -23.644         -14.550
   2     4 1703.22  -10.657          -10.505         -25.590         -14.644
 PC/PT= 1.808481    T =  1703.22
   2     2 1702.49  -10.654          -10.506         -25.597         -14.645
 PC/PT= 1.812162    T =  1702.49
   3     4 1919.02  -11.472          -10.420         -23.705         -14.554
1                    THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM COMPOSITION DURING EXPANSION

                                                    FROM INFINITE AREA COMBUSTOR
0PINF =     15.0 PSIA
 CASE NO.       1
                                                                                       WT FRACTION     ENERGY     STATE    TEMP
          CHEMICAL FORMULA                                                             (SEE NOTE)     CAL/MOL              DEG K
 FUEL      C  2.00000    H  6.00000    O  1.00000                                       0.007444    -66420.000            298.30
 FUEL      C  6.00000    H  7.37150    N  2.63550    O 10.27150                         0.831166   -164700.000            298.30
 FUEL      C  7.00000    H  6.00000    N  2.00000    O  4.00000                         0.097667    -17100.000            298.30
 FUEL      C 12.00000    N  1.00000    H 11.00000                                       0.009826     31070.000            298.30
 FUEL      C 16.00000    H 22.00000    O  4.00000                                       0.048933   -201400.000            298.30
 FUEL      H  2.00000    O  1.00000                                                     0.004963    -68315.000            298.30
0               O/F=  0.0000     PERCENT FUEL= 100.0000     EQUIVALENCE RATIO= 1.9657     PHI= 0.0000
0                  CHAMBER    THROAT     EXIT
 PINF/P             1.0000    1.8122    1.0204
 P, ATM             1.0207   0.56324    1.0003
 T, DEG K          1927.03   1702.49   1919.02
 RHO, G/CC        1.4230-4  8.8898-5  1.4004-4
 H, CAL/G          -559.92   -657.06   -563.42
 U, CAL/G          -733.63   -810.50   -736.41
 G, CAL/G         -5904.06  -5378.49  -5885.34
 S, CAL/(G)(K)      2.7732    2.7732    2.7732

 M, MOL WT          22.046    22.050    22.046
 (DLV/DLP)T       -1.00012  -1.00003  -1.00011
 (DLV/DLT)P         1.0034    1.0008    1.0032
```

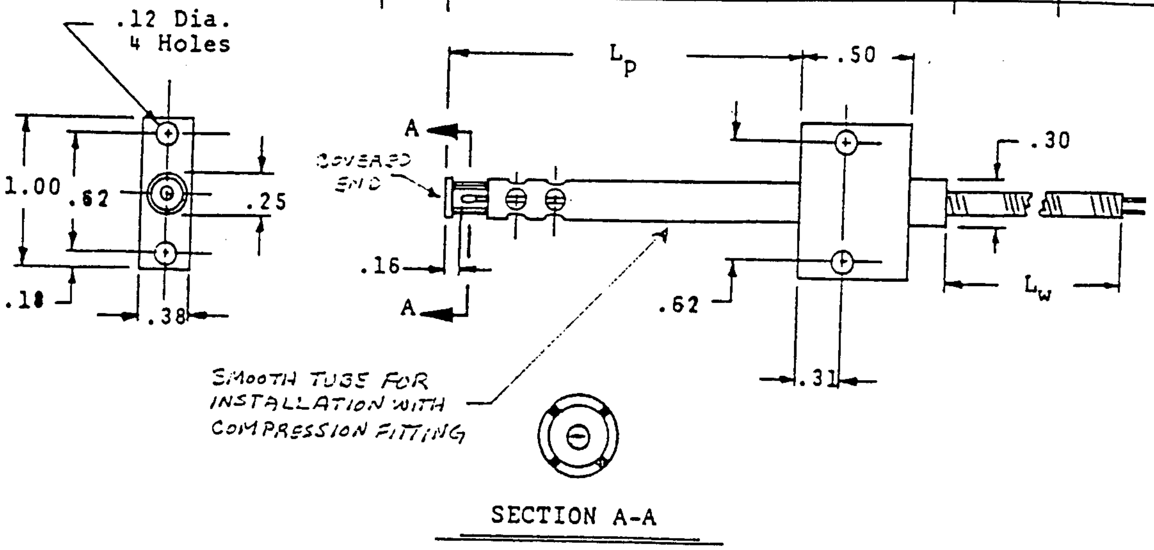
```
 CP, CAL/(G)(K)       0.4387  0.4293  0.4382
 GAMMA (S)            1.2606  1.2662  1.2609
 SON VEL,M/SEC         957.2   901.6   955.3
 MACH NUMBER           0.000   1.000   0.179

0PERFORMANCE PARAMETERS

 AE/AT                        1.0000  3.3440
 CSTAR, FT/SEC                  4233    4233
 CF                            0.699   0.133
 IVAC,LB-SEC/LB                164.5   448.7
 ISP, LB-SEC/LB                 91.9    17.5


0MOLE FRACTIONS

 CO                  0.49571 0.48821 0.49549
 CO2                 0.06313 0.07074 0.06336
 H                   0.00045 0.00010 0.00043
 H2                  0.22141 0.22921 0.22165
 H2O                 0.12081 0.11326 0.12058
 N2                  0.09847 0.09848 0.09847
 OH                  0.00002 0.00000 0.00002
0ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.50000E-05 FOR ALL ASSIGNED CONDITIONS

  C                  CH                 CH2                FORMALDEHYDE       FORMIC ACID        CH3                HYDROXYMETHYLENE
  METHYLOXIDE        CH4                METHANOL           CN                 NCN RAD            CNN RAD            C2
  C2H RAD            ACETYLENE          KETENE             C2H3 RAD           METHYL CYANIDE     CH3CO RAD          CH2CHO RAD
  ETHYLENE           ACETALDEHYDE       ACETIC ACID        (FORMIC ACID)2     ETHYL RAD          ETHYL OXIDE RAD    ETHANE
  AZOMETHANE         DIMETHYL ETHER     ETHANOL            CNC RAD            CYANOGEN           CCO RAD            C3
  C3H3 RAD           CYCLOPROPENE       PROPYNE            ALLENE             C3H5 RAD           CYCLOPROPANE       PROPYLENE
  PROPYLENE OXIDE    I-PROPYL RAD       N-PROPYL RAD       PROPANE            1-PROPANOL         CARBON SUBOXIDE    C4
  BUTADIYNE          CYCLOBUTADIENE     BUTAN-1EN-3YN      1,3-BUTADIENE      2-BUTYNE           2-BUTENE TRANS     2-BUTENE CIS
  ISOBUTENE          1-BUTENE           (ACETIC ACID)2     T-BUTYL RAD        S-BUTYL RAD        N-BUTYL RAD        N-BUTANE
  ISOBUTANE          CARBON SUBNITRID   C5                 CYCLOPENTADIENE    CYCLOPENTANE       1-PENTENE          T-PENTYL RAD
  N-PENTYL RAD       PENTANE            ISOPENTANE         CH3C(CH3)2CH3      HEXATRIYNE         PHENYL RAD         PHENOXY RAD
  BENZENE            PHENOL             CYCLOHEXENE        N-HEXYL RAD        TOLUENE            CRESOL             1-HEPTENE
  N-HEPTYL RAD       N-HEPTANE          1-OCTENE           N-OCTYL RAD        OCTANE             ISO-OCTANE         N-NONYL RAD
  NAPTHLENE          AZULENE            N-DECYL RAD        O-BIPHENYL RAD     BIPHENYL           JET-A(G)           HCN
  HCO RAD            HNCO               HNO                HNO2               HNO3               HO2                H2N2
  H2O2               N                  NCO                NH                 NH2                NH3                NH2OH
  NO                 NO2                NO3                N2H2               NH2NO2             N2H4               N2O
  N2O3               N2O4               N2O5               N3                 N3H                O                  O2
  O3                 C(GR)              BENZENE(L)         TOLUENE(L)         OCTANE(L)          JET-A(L)           H2O(S)
  H2O(L)
0NOTE. WEIGHT FRACTION OF FUEL IN TOTAL FUELS AND OF OXIDANT IN TOTAL OXIDANTS
1                        THEORETICAL ROCKET PERFORMANCE ASSUMING FROZEN COMPOSITION DURING EXPANSION

0PINF =    15.0 PSIA
 CASE NO.       1

          CHEMICAL FORMULA                                                                 WT FRACTION      ENERGY    STATE    TEMP
                                                                                           (SEE NOTE)       CAL/MOL            DEG K
```

```
 FUEL    C  2.00000   H  6.00000   O  1.00000                                     0.007444   -66420.000        298.30
 FUEL    C  6.00000   H  7.37150   N  2.63550   O 10.27150                        0.831166  -164700.000        298.30
 FUEL    C  7.00000   H  6.00000   N  2.00000   O  4.00000                        0.097667   -17100.000        298.30
 FUEL    C 12.00000   N  1.00000   H 11.00000                                     0.009826    31070.000        298.30
 FUEL    C 16.00000   H 22.00000   O  4.00000                                     0.048933  -201400.000        298.30
 FUEL    H  2.00000   O  1.00000                                                  0.004963   -68315.000        298.30
0              O/F=  0.0000    PERCENT FUEL= 100.0000    EQUIVALENCE RATIO= 1.9657    PHI= 0.0000
0                    CHAMBER    THROAT     EXIT
 PINF/P               1.0000    1.8199    1.0204
 P, ATM               1.0207   0.56085    1.0003
 T, DEG K            1927.03   1693.47   1918.73
 RHO, G/CC          1.4230-4  8.8975-5  1.4006-4
 H, CAL/G            -559.92   -657.52   -563.42
 U, CAL/G            -733.63   -810.17   -736.38
 G, CAL/G           -5904.06  -5353.93  -5884.54
 S, CAL/(G)(K)        2.7732    2.7732    2.7732

 M, MOL WT            22.046    22.046    22.046
 CP, CAL/(G)(K)       0.4218    0.4136    0.4215
 GAMMA (S)            1.2718    1.2787    1.2720
 SON VEL,M/SEC         961.4     903.7     959.4
 MACH NUMBER           0.000     1.000     0.178

OPERFORMANCE PARAMETERS

 AE/AT                          1.0000    3.3544
 CSTAR, FT/SEC                    4220      4220
 CF                              0.703     0.133
 IVAC,LB-SEC/LB                  164.2     448.6
 ISP, LB-SEC/LB                   92.2      17.5

OMOLE FRACTIONS

 CO                 0.49571     CO2                0.06313     H                  0.00045     H2                 0.22141
 H2O                0.12081     N2                 0.09847     OH                 0.00002
OADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.50000E-05 FOR ALL ASSIGNED CONDITIONS

  C                  CH                 CH2                FORMALDEHYDE       FORMIC ACID        CH3                HYDROXYMETHYLENE
  METHYLOXIDE        CH4                METHANOL           CN                 NCN RAD            CNN RAD            C2
  C2H RAD            ACETYLENE          KETENE             C2H3 RAD           METHYL CYANIDE     CH3CO RAD          CH2CHO RAD
  ETHYLENE           ACETALDEHYDE       ACETIC ACID        (FORMIC ACID)2     ETHYL RAD          ETHYL OXIDE RAD    ETHANE
  AZOMETHANE         DIMETHYL ETHER     ETHANOL            CNC RAD            CYANOGEN           CCO RAD            C3
  C3H3 RAD           CYCLOPROPENE       PROPYNE            ALLENE             C3H5 RAD           CYCLOPROPANE       PROPYLENE
  PROPYLENE OXIDE    I-PROPYL RAD       N-PROPYL RAD       PROPANE            1-PROPANOL         CARBON SUBOXIDE    C4
  BUTADIYNE          CYCLOBUTADIENE     BUTAN-1EN-3YN      1,3-BUTADIENE      2-BUTYNE           2-BUTENE TRANS     2-BUTENE CIS
  ISOBUTENE          1-BUTENE           (ACETIC ACID)2     T-BUTYL RAD        S-BUTYL RAD        N-BUTYL RAD        N-BUTANE
  ISOBUTANE          CARBON SUBNITRID   C5                 CYCLOPENTADIENE    CYCLOPENTANE       1-PENTENE          T-PENTYL RAD
  N-PENTYL RAD       PENTANE            ISOPENTANE         CH3C(CH3)2CH3      HEXATRIYNE         PHENYL RAD         PHENOXY RAD
  BENZENE            PHENOL             CYCLOHEXENE        N-HEXYL RAD        TOLUENE            CRESOL             1-HEPTENE
  N-HEPTYL RAD       N-HEPTANE          1-OCTENE           N-OCTYL RAD        OCTANE             ISO-OCTANE         N-NONYL RAD
  NAPTHLENE          AZULENE            N-DECYL RAD        O-BIPHENYL RAD     BIPHENYL           JET-A(G)           HCN
  HCO RAD            HNCO               HNO                HNO2               HNO3               HO2                H2N2
```

```
 H2O2          N             NCO           NH            NH2           NH3           NH2OH
 NO            NO2           NO3           N2H2          NH2NO2        N2H4          N2O
 N2O3          N2O4          N2O5          N3            N3H           O             O2
 O3            C(GR)         BENZENE(L)    TOLUENE(L)    OCTANE(L)     JET-A(L)      H2O(S)
 H2O(L)
0NOTE. WEIGHT FRACTION OF FUEL IN TOTAL FUELS AND OF OXIDANT IN TOTAL OXIDANTS
1
 STOP
```

Appendix C
SPECIFICATION SHEETS FOR THE RECOMMENDED THERMAL INSTRUMENTATION

REVISIONS			
SYM	DESCRIPTION	DATE	APPROVAL



Available Options:

1. T/C Mat'l

T/C Mat'l	Order Code
Pt/Pt 10% Rh	S
W/W 26 Re	W/W 26

2. T/C Wire Size (Nominal)

AWG	DIA.	Order Code
36	.005	36
30	.010	30
26	.016	26
22	.025	22

3. Probe Length (L_p)

Probe Length (L_p)	Order Code
Available in 1/8" increments 1-12"	State length in inches

4. Lead Wire

a. Protection

Protection	Order Code
CRES Braid	S
Spiral Armor	X

b. Length (L_w)

Length (L_w)	Order Code
(12" Standard)	State length in inches.

Model No.	T/C Mat'l	T/C Wire	Probe Length	Lead Wire
TCGT 130	①	②	③	④

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCES

FRACTIONS	DECIMALS	ANGLES
—	.01	± 1°

MATERIAL
Sheath Tube-Tantalum
Base-CRES

FINISH
32/ε Polish

HIGH TEMPERATURE
THERMOCOUPLE PROBE
GAS TOTAL
TCGT 130 SERIES

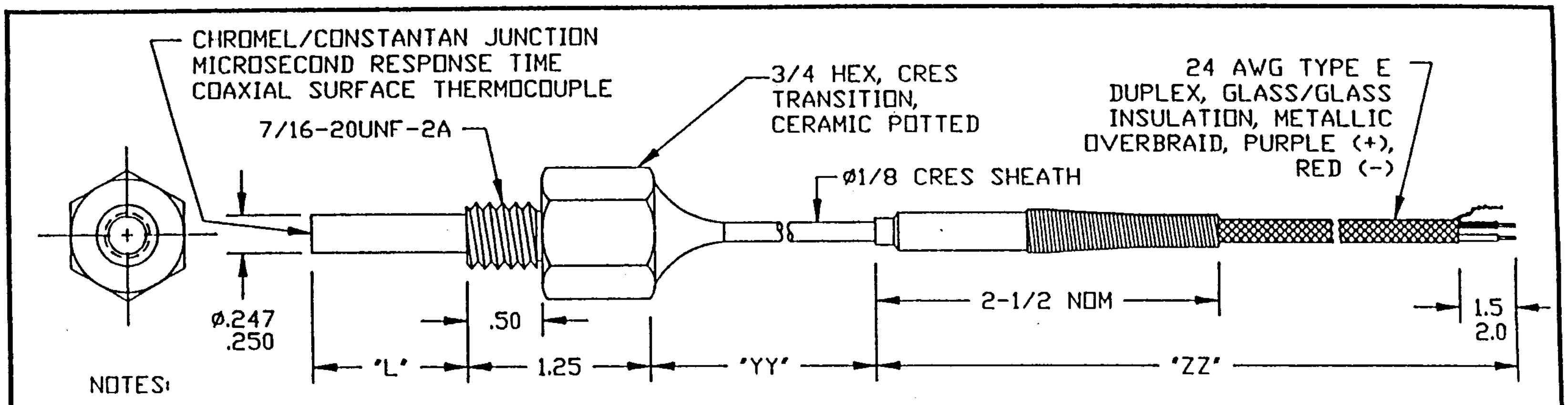
MEDTHERM
CORPORATION
POST OFFICE BOX 412 / HUNTSVILLE, ALABAMA [illegible]

DRAWN: P.W.S.	DATE: 1-18-67
CHECKED:	SCALE: —
APPROVED:	L/M NO: —

DWG SIZE A 569

SHEET OF

Figure C-1: Recommended Chamber Total Temperature Instrumentation for WES May '93 Propellant Burn Tests



NOTES:

1. The TCS-E-'L'-'YY'-'ZZ'-10196 is a chromel/constantan microsecond response time coaxial surface thermocouple in 304 CRES housing.

2. This fast response surface thermocouple is often used to determine surface heat transfer rates from calculations based on the measured surface temperature versus time history, assuming a semi-infinite one dimensional wall.

3. The unit is available with a second in-depth thermocouple for fast response heat transfer measurements when the total test times exceed the time limits of the semi-infinite wall theory.

4. The standard leadwire construction is 'YY' inches (4' std.) of 1/8 inch diameter stainless steel sheathed leadwire with a transition to 'ZZ' inches (36' std.) of flexible 24 AWG fiberglass/fiberglass insulated duplex cable with metallic overbraid.

5. Other mounting configurations, materials, and leadwire options are available.

REVISIONS

SYM	DESCRIPTION	DATE	APP

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCES

FRACTIONS	DECIMALS	ANGLES
± 1/32	2PL ± .01 3PL ± .005	± 30'

MATERIAL NOTED

FINISH 64

MICROSECOND RESPONSE
COAXIAL SURFACE THERMOCOUPLE
TCS-E-"YY"-"ZZ"-10196

SCALE:

ORIG. DWG 12/4 /84

CAD DWG 2/12 /93

DR. GMcc

DES.

CHK.

APP. BeJ

MEDTHERM
CORPORATION
POST OFFICE BOX 412
HUNTSVILLE, ALABAMA 35804

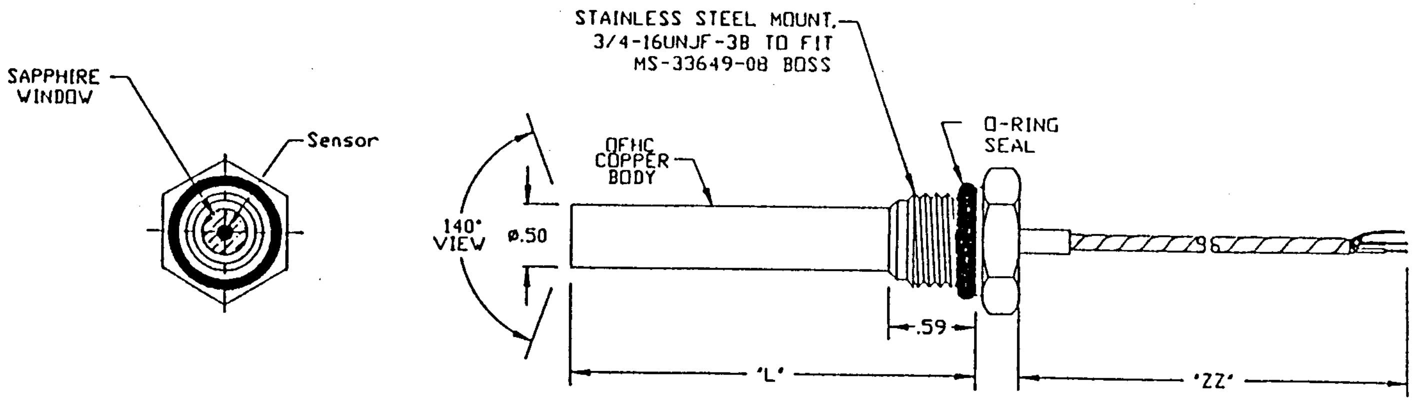
DWG SIZE A

10196

REV

SHEET OF

Figure C-2: Recommended Total Heat Flux/Surface Thermocouple Instrumentation for WES May '93 Propellant Burn Tests



NOTES:

1. The 32R-'L'-'XX'-140-'ZZ'-21096 is an infrared radiometer with sapphire window and 140° view angle. The radiometer will provide a linear output directly proportional to the incident radiant flux within the 0.3 to 5.5 micrometer spectral passband of the window. The standard nominal output is 10 millivolts at the design heat flux level 'XX' in Btu/ft^{2}sec. Other outputs are available. Each unit is supplied with a certified calibration traceable to NIST.

2. The unit is designed to operate at pressures to 3000 psi.

3. The lead wire construction consist of 'ZZ' inches of 24 AWG stranded nickel plated copper duplex wire with teflon over each conductor (White positive, Black negative), nickel plated copper braid over both, teflon jacket overall.

4. To order, specify Model No. by replacing drawing notation dimensions with the appropriate dimensions, in inches, to meet specific installation requirements.

'L' - Length of ø.50 sensing tip, inches

'XX' - Design heat flux level, BTU/ft^{2}sec

'ZZ' - Flexible lead wire length, inches

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCES

FRACTIONS	DECIMALS	ANGLES
± 1/32	2PL ± .015 3PL ± .005	± 30'

MATERIAL
NOTED

FINISH

INFRARED RADIOMETER

32R-"L"-"XX"-140-"ZZ"-21096

MEDTHERM
CORPORATION

POST OFFICE BOX 412
HUNTSVILLE, ALABAMA 35804

SCALE:
ORIG. DWG / /
CAD DWG 2/28/93
DR.
DES.
CHK.
APP.
DWG SIZE B
21096
REV
SHEET OF

Figure C-3: Recommended Radiometer Instrumentation for WES May '93 Propellant Burn Tests

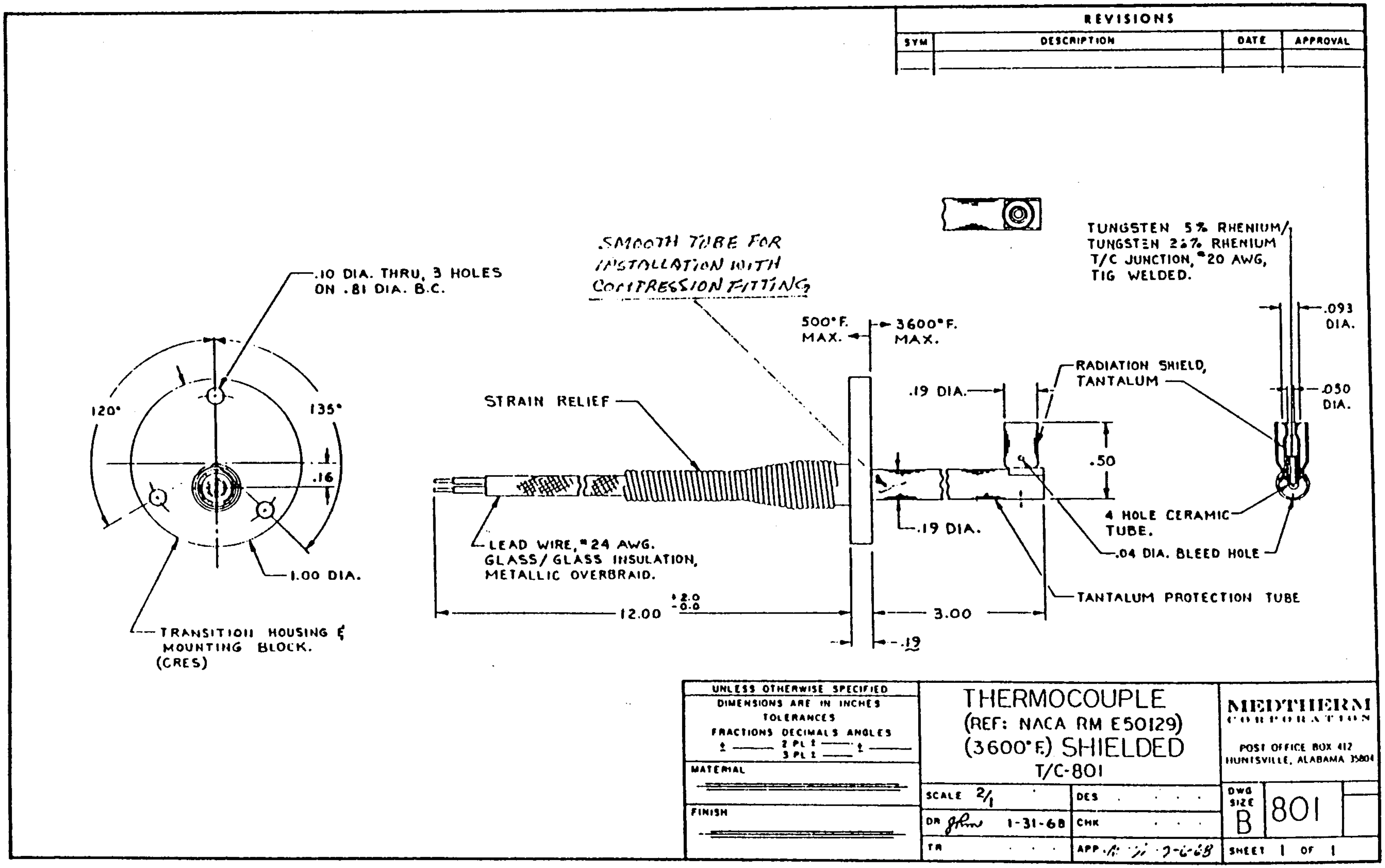


Figure C-4: Recommended Vent Pipe and Plume Total Temperature Instrumentation for WES May '93 Propellant Burn Tests

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13. ABSTRACT *(Maximum 200 words)*

During 1989, WES conducted a series of propellant burn experiments in a partially confined space to evaluate the potential for transition from deflagration to detonation. Pressure, temperature, and thermal flux-time histories were recorded. These data were analyzed in terms of quality and interchannel compatibility to develop improved instrumentation/techniques for measuring the thermal effects of propellant deflagration. In addition, a one-dimensional model was developed characterizing the propellant thermochemical properties and flow processes. This report documents the data analyses, thermal model development, comparison of model and measured data, and recommendations for improved thermal instrumentation.

14. SUBJECT TERMS

Deflagration	Partially confined burn
M-1 propellant	Single perf propellant
Propellant burn	

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