12/24/94
11-7-94
501

UCRL-ID-117701

Minuteman III - Stage 3 Propellant Fire Characterization

Julio C. Diaz

June 20, 1994

Lawrence
Livermore
National
Laboratory

This is an informal report intended primarily for internal or limited external distribution. The opinions and conclusions stated are those of the author and may or may not be those of the Laboratory.

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Propellant Fire Characterization Table of Contents

DISCLAIMER.....	1
Abstract.....	2
Introduction.....	3
Diagnostics Development.....	4
Bounding fire temperatures.....	4
Materials for diagnostic tools.....	4
Thermowells.....	6
Sight tubes.....	7
Calorimeters.....	8
Experimental.....	9
Temperature measurements.....	10
Scanning radio spectrometry.....	10
Pyrometry.....	11
Ultrasonic thermometry.....	12
Calorimetry.....	13
Stainless-steel slug calorimeter.....	13
Molybdenum rod calorimeter.....	13
Burn rate.....	13
Data acquisition system.....	14
Propellant.....	15
Test design.....	15
Fire Environment.....	17
Conceptual model.....	17
Temperature measurements.....	18
Emissivity measurements.....	23
Heat Flux measurements.....	24
Burn Rate measurements.....	25
Qualitative observations from propellant fire tests.....	26
Experience with materials in propellant fires.....	28
Conclusions.....	29
Thermal Characteristics of ANB-3066 propellant fires.....	29
Speculation on thermal conditions in a silo fire.....	30
Contributors.....	32
References.....	32

Appendix A: Layouts for propellant fire tests

Appendix B: Photographic records of characterization tests

Appendix C: Report on heat flux calculations performed by Jeff Hendricks

Appendix D: Characteristics of alumina deposits

MASTER

JP

MINUTEMAN III- STAGE 3 PROPELLANT FIRE CHARACTERIZATION*

Julio C. Diaz
Lawrence Livermore National Laboratory
Livermore, CA 94551

ABSTRACT

We have completed an experimental program to diagnose and characterize the thermal environment of a solid rocket propellant fire burning in ambient atmospheric conditions. This work has been conducted as part of the Defense Nuclear Agency's probabilistic risk assessment (PRA) of the Minuteman III (MMIII) weapon system¹. The goals of this study are two-fold; 1) to provide a description of a propellant fire in sufficient detail so as to allow system response models to predict the outcome of various hypothetical accident scenarios and, 2) to identify diagnostics that could be used in a large-scale test fire of MMIII stage 3 motor.

The study has been performed burning SRAM II and MMIII stage 3 propellant (ANB-3066), in chimneys ranging in size from 18 cm (seven inches) to 53 cm (twenty-one inches) in diameter. Several methods have been used to determine and confirm temperature measurements including thermometry, radiometry, and ultrasonic thermal sensing. Temperature profiles with peaks in excess of 2300° C have been measured. Temperature measurements have been used in conjunction with inverse modeling to determine heat flux characteristics. The regression rate for ANB-3066 (under ambient conditions) has also been determined. Finally, at a very cursory level, we have studied the characteristics of aluminum oxide deposits as well as some materials responses to these fires.

We have also addressed the initial efforts on development of diagnostics, problems encountered in controlling the burning of propellants, in taking radiometric measurements, and the survivability of materials in the fire.

* Approved for public release; distribution is unlimited.

¹ W87/W78 Minuteman III Weapon System Safety Analysis.

INTRODUCTION

There has been an expressed interest in the development of models capable of predicting the response of systems to solid rocket propellant fires. Predictive capabilities of this nature would be invaluable in conducting probabilistic risk assessments such as that performed for the MMIII weapon system. Input parameters for such a modeling effort include the boundary conditions that describe the fire-temperature, heat flux, emissivity, and propellant burn rate. The purpose of this study was to develop diagnostics and provide such a description for the aluminized composite propellant used in the MMIII third stage.

A vast amount of work has been done to determine the thermophysical properties of propellants and rocket plumes and to study rocket performance and stability. Where temperatures have been studied, measurements have been made using small laboratory apparatus such as strand burners or large systems such as motors. However, a literature search produced one significant reference- this was to a study of the thermal environment of a solid rocket propellant burning at ambient conditions. This study was performed by Ed W. Price^{1,2} in which Titan IIIC propellant (UTP 3001) was used. In our work, we have adopted some of the concepts proposed by Price to describe propellant fires. A second valuable reference, by W. Eckl and N. Eisenreich³, described a method of estimating propellant fire temperatures by measuring continuous emission spectra.

The propellant used during the initial phase, i.e. during the development of diagnostics had a higher aluminum content than the ANB-3066, so the data collected from those tests would not be applicable for this study. Table 1 shows the nominal formulations of propellants used in this work and that used by Price. The ANB-3066 (MMIII) propellant, the SAA132a (SRAMII) propellant used during diagnostics development, and UTP3001 (Titan IIIC) propellant used by Price. The binder designations CTPB, PBAN and, HTPB, stand for carboxy-terminated polybutadiene, poly(butadiene-acrylic acid-acrylonitrile), and hydroxy-terminated polybutadiene.

Formulation (wt %)	ANB 3066	UTP 3001	SAA 132a
Ammonium Perchlorate	73	68	70
Aluminum	15	16	20
Binder-type	CTPB (12%)	PBAN (11%)	HTPB (10%)
Adiabatic Flame Temperature (C)	2730	3136	2846
Application	MM III, Stg 3	Titan IIIC	SRAM II

Table I. Propellant Formulations

In this study we have used scanning radiospectrometry, pyrometry, and ultrasonic thermal sensors to determine temperature profiles, and thermocouples embedded in metal solids to define heat flux profiles. These diagnostics were used on fires of about 100 second duration, and in chimneys of varying diameters. The diagnostics used in this study performed well and were found to be potentially useful in a large-scale propellant fire.

DIAGNOSTICS DEVELOPMENT

The initial phase of this study required the development of diagnostics that would be capable of surviving extreme temperatures and eroding flow fields. An evolutionary approach was taken to this development. We first wanted to bound the temperature regimes that we were going to deal with and identify materials that would survive exposure to these fires. Then, beginning with simpler forms of diagnostics, we wanted to test their applicability and accuracy in this environment. Realizing that arrays of diagnostics would be needed to perform large-scale tests, a conscious effort was made to reduce the complexity and cost of the diagnostics.

Knowing of the difficulties encountered in other studies we felt it was important to validate measurements through the use of redundant diagnostics. The measurements made by our diagnostics were based on different thermo-physics characteristics of high temperature fires. To this end, most of the early tests were designed to use several forms of diagnostics at the same time. Figure 1 depicts a computer-designed rendition of a test using a molybdenum calorimeter (described later) and two pyrometers.

In developing diagnostics, we also made a conscious effort to design all parts and equipment to be reusable. Knowing that many tests would have to be performed in this study, we wanted to minimize time delays and costs associated with fabrication.

BOUNDING FIRE TEMPERATURES

A simple method was used to bound fire temperatures and determine the survivability of materials. Rods of different types of materials were inserted through the chimney walls to be exposed to the plume at different heights. These rods were 0.125 in. in diameter. Figure B3 and B4 in Appendix B, show how these rods were arranged. Metals and ceramics were tested at different heights and their condition was observed at the end of the test. These materials included alumina, zirconia, tungsten, tantalum, molybdenum, stainless steel, copper, aluminum, and other materials of even lower melting points. For any given height above the initial surface of the propellant, if a material survived the fire we would know that the temperature there had been below the melting point of that material. If the rod was gone we assumed that the temperature there was at least above the melting point of the material.

Given such temperature-bounding observations we were able to qualify the temperature readings of other diagnostics being tested. Additionally, we were also able to identify those materials that were most suitable for use in this environment.

MATERIALS FOR DIAGNOSTIC TOOLS

We needed to identify materials that could be used in the manufacture of tools that would be exposed to the propellant fires. Through the use of different materials to bound the fire temperatures we found that only molybdenum survived the worst conditions in this environment, i.e., the highest temperatures. We found that tantalum softened and deformed too easily and that tungsten and tantalum both oxidized and eroded rapidly, even in tests as short as 100 seconds. Graphites manufactured with fine grain were found to erode less than those that had a coarse

Figure 1. Typical layout for propellant fire tests.

grain matrix. Generally, we would expect graphite parts that were fully exposed to the plume to be usable for as many as ten 100 second-tests. Erosion and pitting of the material would make the part too fragile for continued use.

THERMOWELLS

Thermowells are devices that penetrate a body or stream and reach near-thermal equilibrium with it. The external surface of the thermowell would be exposed to the thermal environment. Inside, the thermowell is hollow and some form of temperature diagnostic is used to measure the temperature at the bottom of the well. We attempted to use thermowells to read plume temperatures. A typical thermowell design is depicted in Figure 2 below. The width of the endwall was reduced as much as possible to minimize its thermal mass. The endwalls of graphite thermowells were generally 0.0625 in. and some molybdenum thermowells had thinner endwalls. The pyrometers were aligned to focus on the endwall. The outer wall of the thermowells were generally reduced to 0.125 in. thickness. The length of the body of the thermowell depended on the size of the chimney used and the depth to which we needed the thermowell to penetrate the plume.

Figure 2. Typical thermowell design.

We found, however, significant problems in using thermowells for this work. First, internal outgassing in graphite thermowells interfered with the field of view of the pyrometers. Figure 3, below, shows the appearance of temperature swings caused by the interference. The gases within the thermowell reduced the amount of light transmitted from the endwall to the single-color pyrometer. These gases accumulated and vented periodically, thus causing the apparent temperature swing. An attempt was made to design a vent hole near the endwall and allow a purge gas to sweep away the gases. This redesign did eliminate the initial problem, but temperatures were observed to be (generally) $\sim 100^{\circ}\text{C}$ cooler. Also, the thermal mass caused a delay of a few seconds in the response of the thermowell temperature. This, however, would not be a significant problem for burns of long duration.

Figure 3. Thermowell temperatures measured with single color pyrometer.

We also found that the thermal mass of molybdenum thermowells was too great and they did not reach thermal equilibrium in tests of approximately 100 seconds duration. It is conceivable, however, that molybdenum thermowells could be used in tests of long duration. Appendix B contains photographs of graphite and molybdenum thermowells before and after tests.

SIGHT TUBES

We developed graphite sight tubes to measure temperatures and emissivity along the center line of the plume. These devices were hollow graphite tubes with one end cut at an angle. The sight tube was inserted into the plume with the slant cut facing upward (in the direction of the plume flow). The angle of the cut was chosen to minimize plume entry to the tube and to help draw out any outgassing from the graphite. This device allowed detectors to view a small internal volume of plume. It is through this means that spectrometry and pyrometry measurements were made. Figure 4 shows the manner in which sight tubes were used.

Figure 4. Sight tubes used to penetrate the plume.

Thermowells and sight tubes were mounted to the pyrometers by the use of alignment tubes. These tubes were 75 cm (30 in) long and approximately 3.5 cm (1.3725 in.) in diameter. The pyrometer heads (threaded) were screwed into one end of the alignment tube and, at the other end, set screws were used to align and support a sight tube or thermowell in place. The alignment tubes were outfitted with an inlet for purge gas (nitrogen or argon) and a low flow of purge gas was maintained during tests to insure that outgassing of the graphite did not interfere with the line-of-sight of the pyrometers.

CALORIMETERS

We determined the heat flux characteristics of the plume based on the temperature rise of objects immersed in the plume. Our approach was to imbed thermocouples in solid objects and track the temperature change over time. Inverse modeling calculations were then performed using a heat transfer model (TOPAZ2D) to duplicate the observed temperature history of the calorimeters.

Several materials were tested as well as different size calorimeters. Primarily, two designs were used. One calorimeter was designed as a cylinder with one end machined into a hemisphere (slug calorimeter). On the other end, a well was drilled to the center point of the hemisphere and a tungsten-rhenium thermocouple (tc) was placed in the center (see Figure 5). The tc was pressed on the center point of the calorimeter by a sleeve and pressure was applied on the sleeve by screwing a support rod against it. Support rods were made from high pressure stainless steel tubing threaded to match the threading on the calorimeter.

Slug calorimeters ranging in size from 1.25 cm (0.5 in) diameter to 5 cm (2 in.) diameter were tested. Tantalum, molybdenum, stainless steel, and graphite were used in their manufacture. Generally, the smaller calorimeters did not have sufficient mass or total heat capacitance so their temperature rise would be very quick. Initial evaluations led us to use only stainless steel-5 cm calorimeters (Figure 5 below). The use of tantalum calorimeters was abandoned because of the oxidation of their surface, their softening and, deformation. The next best material would have been

molybdenum but stock to manufacture a 5 cm slug calorimeter was not available before we started using the second design.

The second calorimeter was designed as a one-dimensional heat flux analog. This was a rod calorimeter that had imbedded tc's along the length of the calorimeter (Figure 6 below). The sidewall of the rod was insulated with an alumina blanket and encased in a graphite container. This was found to be the most dependable design. Appendix B contains photographs of both calorimeters.

Early in these tests an attempt was made to use calorimetry data to estimate the temperature required to drive the observed heat flux. John Creighton^{4,15} analyzed data from a 5 cm (2 in.) stainless steel calorimeter exposed to an unconfined propellant fire to estimate heat flux and plume temperature. Results of his analysis are presented later in this report. His initial success in this analysis led us to use the code TOPAZ2D on data collected in later testing.

EXPERIMENTAL

An experimental program was designed for DNA to escalate from burning single propellant packages of approximately 6 kg (14 lb.) to tests involving as much as 250 kilograms (550 lbs.) of propellant. Unfortunately, new environmental restrictions at our test site forced us to reduce the scale of the test program to burning single cartons of propellant. The propellant was burned in chimneys that ranged from 18 cm. to 53 cm. in diameter. Some of the chimneys were made of graphite and some of steel. For this study, we measured temperatures, emissivities, and heat flux at distances ranging from 8 cm to 135 cm above the initial surface of the propellant

An Operation Safety Procedure (OSP) was obtained to perform the tests. All tests were conducted at the LLNL test facility, Site 300, bunkers 801, 812, and 851. With few exceptions, all tests were video recorded. These recordings are available as additional documentation of this study. Also, most calculations were performed using Microsoft Excel spreadsheets and are also available.

TEMPERATURE MEASUREMENTS

Two spectrometric methods and one form of sensible temperature measurement (using an ultrasonics-based system) were used to determine plume temperature profiles. Classical diagnostics such as thermocouples are not appropriate for plume temperature measurements because of their short lifespans in these conditions, so their use was limited to heat flux measurement devices. Each method that we applied had strengths and weaknesses but we felt that the combined results would provide the most reliable data.

The spectrometric methods operate on the principle that perfectly radiating bodies (blackbodies) at a given temperature will emit energy within a range of wavelengths and at an intensity that is predicted by Planck's Equation. Most real surfaces are not perfect blackbodies but radiate energy at some fraction of the total energy of a blackbody; these are referred to as graybodies and the fraction is referred to as emissivity(ϵ).

W. Eckl and N. Eisenreich³ were able to successfully estimate plume temperatures by analyzing the continuous emission spectra of burning solid propellant. They showed that the plume radiated as a graybody (following Planck's equation) between 360 nm and 560 nm. In that study, a composite propellant consisting of 15% aluminum (Al), 15% glycidyl azide (GAP), and 70% ammonium perchlorate (AP) was used. We decided to apply this method in this study to determine if the plume of the MMIII propellant emitted as a graybody, and if so, measure the emissivity of the plume along with temperature. Additionally, if the emission spectrum resembled a graybody we could then apply pyrometry to determine plume temperatures.

Scanning radio spectrometry. We applied scanning radiospectrometry to determine the emission spectra of the plume between wavelengths (λ) of 400 nm and 900 nm. This was done to determine how well the plume could be represented as a graybody radiator and to validate emissivity and temperature measurements.

The system used was a JY Optical Systems, S.A., CP200 imaging spectrograph fitted with a Princeton Instruments silicon diode array detector of 1024 channels. The grating contained 133 lines per mm and covered a range of 400 nm to 1200 nm. Three exposures of the array were taken per scan (for a total of 100 ms) and, scans were performed every 4 seconds. The spectrometer was calibrated against an Optronics Laboratories Radiometric Calibration Standard, Model 345RP.

Assuming that the plume was a freely radiating body (i.e. graybody), the spectral radiance is modeled from Planck's equation-

$$L(\lambda, T) = \frac{\epsilon C_1}{\lambda^5 (\exp(C_2/\lambda T) - 1)} \quad (1)$$

where $L(\lambda, T)$ = spectral radiance emitted by the plume (mW/cm² nm)
 T = source temperature (K)
 ϵ = emissivity of the plume
 λ = wavelength (nm)
 $C_1 = 37418 \text{ E3 mW mm}^5/\text{cm}^2 \text{ nm}$
 $C_2 = 14388 \text{ mm K.}$

The spectral radiance detected by our apparatus would be predicted by

$$L(\lambda, T) = \frac{\epsilon C_1}{\lambda^5 r^2 (\exp(C_2/\lambda T) - 1)} \quad (2)$$

where r = distance from source to sensor (cm)

In our tests we collected spectral scans during a burn, then superimposed (on the data) a best estimate of the spectral radiance (calculated from equation 2) to estimate temperature and emissivity. An analogous method used to estimate temperature is based on a log function of spectral radiance. The resulting linear equation, the slope of which is a function of temperature, can be written as,

$$\ln(f(L)) = \frac{C_2}{T} \left(\frac{1}{\lambda} \right) \quad (3)$$

where

$$f(L) = \left(\frac{\epsilon C_1}{\lambda^5 r^2} \right) + 1 \quad (4)$$

In our analyses of test results we also plotted the log function (3) of the collected data vs. $1/\lambda$, and estimated temperature by matching the slope of that line using a least squares fit.

Pyrometry. Two pyrometric methods were used to extract temperature and emissivity data for the plume. A two-color commercial pyrometer with narrow bandwidths located between wavelengths of 780 and 1000 nm was used to infer the temperature of the plume. This type of instrument determines temperature based on the ratio of the intensities at each of the two wavelengths and is generally appropriate for use on a graybody or blackbody source. However, the instrument we used has a slope-adjust capability for non-gray bodies. It can determine temperatures for non-graybodies as long as the body produces a continuous spectrum between 780 nm and 1000 nm (however, this does require calibration).

A second, single-color commercial pyrometer with a narrow bandwidth at 950 nm was used to provide a second method of determining ϵ . A color temperature was inferred by the single color pyrometer based on the assumption that the plume radiated as a blackbody ($\epsilon=1$). To estimate emissivity we coupled the measurements of the two-color pyrometer with that of a single color pyrometer by focusing our pyrometers on the same volume-space of the plume. This (ratio radiometry) is an accepted method and its validity has recently been tested by R.B. Johnson and C. Cheng⁵. Assuming that the plume acts as a graybody, then

$$L_1(\lambda, T) = \frac{C_1}{\lambda^5 (\exp(C_2/\lambda T_1) - 1)} = L_2(\lambda, T) = \frac{\epsilon C_1}{\lambda^5 (\exp(C_2/\lambda T_2) - 1)}$$

where subscript 1 refers to measurements of the two-color pyrometer,
subscript 2 refers to measurements of the single-color pyrometer,
and λ = wavelength of single color pyrometer (950 nm).

To solve for ϵ we could rearrange the equations above to,

$$\epsilon = \frac{\exp(C_2 / \lambda T_2) - 1}{\exp(C_2 / \lambda T_1) - 1} \quad (5)$$

The advantage of using a two-color pyrometer is that changes in emissivity and changes in the total amount of light that arrives at the lens do not affect the measurements; the temperature estimates are based solely on the ratio of radiance at the specified wavelengths. However the measurements would be meaningless if the plume did not radiate continuously and in form similar to a graybody.

The two-color pyrometer used was a Mikron pyrometer model 77LS. This pyrometer was calibrated to measure between 1000° C and 3000° C, and had a linear 0 -1 V output. The output from this system was coupled to a digitizer and transferred to the data acquisition system at 1 Hz. The single-color pyrometers (we had 3 units) were products of Accufiber (LUXTRON Corp.) models 900-PY-HF4 (2), and 900-PY-HF5 (1). This system was calibrated to measure between 500° C and 3000° C. The Accufiber pyrometer lenses were coupled to 30 meter steel-clad fiber-optic cables that extended from the burn site to the control bunkers, where the controller was located. The controller operated at 5 Hz, and communicated with the data acquisition system via an RS-232 port. All the pyrometers used in this study focused on a spot size of approximately 6 mm (0.25 in.).

Ultrasonic thermometry. Efforts were also made to measure plume temperature by using an ultrasonics-based thermal sensor. The instrument consists of a controller, a piezo-electric generator, and a tungsten rod that has a groove cut at about 2.5 centimeters from one end. This system is uniquely capable of providing a continuous measurement of temperature between ambient and 3000° C. A schematic of the system is shown on Figure 7. An ultrasonic signal generated by the piezoelectric travels the length of the rod, and is reflected by the groove and the end of the rod. The time difference between the two reflections is a function of the average temperature of that section of the rod. The controller has a calibration curve for the time delays and, displays temperature. This method was selected because of the ability of the sensor to survive the fire environment. The sensor rod is made of potassium-doped tungsten and survived the hot temperatures and abrasive environment, where thermocouples did not. This system provided a third, non-optical method for measuring plume temperature. These measurements were taken to help validate spectral data.

Figure 7. Schematic of Ultrasonic Thermal Sensor

The ultrasonic sensors used in this study are a commercial product manufactured by RMC, Inc. The model used was an RMC 400 UTS, with a 0.317 cm (0.125 in) and a 0.476 cm (0.187 in.) diameter rods. The rods were each 61 cm (24 in) in length and were individually calibrated to provide continuous temperature measurement between 0° C and 3000° C. This system had RS-232 and 0-10 V output for each rod.

CALORIMETRY

Heat fluxes to objects engulfed in the plume were estimated by imbedding thermocouples in solid metal objects and placing them in the plume. Inverse modeling calculations were then performed using a heat transfer model (TOPAZ2D) to duplicate the observed temperature history of the calorimeters. The temperature history was duplicated by establishing a temperature boundary condition and modeling the presence of a thin deposit of aluminum oxide. The heat flux that generated the observed temperature history was extracted from the model calculations. Appendix C contains the report on these calculations. Two devices were used in these studies.

Stainless-steel slug calorimeter. The steel calorimeter was a 5 cm. (2 in.) long cylinder of 5 cm (2 in.) diameter. One end of the cylinder was machined into a hemisphere, and the other end was drilled to the center point of the hemisphere and a tungsten-rhenium thermocouple was placed in the center (see Figure 5). The tc was pressed on the center point of the calorimeter by the sleeve. Pressure was applied on the sleeve by tightening the support rod against it. The support rod was 0.50 in. high pressure stainless steel pipe threaded to match the calorimeter thread.

Molybdenum rod calorimeter. This calorimeter was designed by Jeff Hendricks, Ernie Moor III, and Julio Diaz, to allow us to model a one-dimensional heat transfer process. It was a molybdenum rod of 2.5 cm (1 in.) diameter and 15.25 cm in length (see Figure 6). The rod had two tungsten-rhenium thermocouples (tc's) imbedded on the centerline at 3.18 cm (1.25 in.) and 8.25 cm (3.25 in.) from the exposed end of the rod. Additionally, a thermocouple was placed on the wall of the rod at 8.25 cm from the end. All thermocouples (tc's) were 0.0625 in. OD C-type grounded tc's, tantalum sheathed with beryllium-oxide insulation. The rod was wrapped with an insulating ceramic blanket and placed in a holder that exposed only one face of the rod.

BURN RATE

An estimate of burn rate was made by measuring the height of the propellant cylinders prior to a test and then, timing the duration of the burns. The burn time was assumed to give "good" data if the burn was controlled, i.e. limited to the top surface. There were occasions when the burn engulfed the sides and/or the bottom of the package. These instances were obvious from observations made by the TV monitor and the type of material deposited on the alumina and graphite base plates beneath the propellant. That material would be solid and had a rough texture when burns were uncontrolled (see Appendix B). These tests were not used in determining burn rate.

DATA ACQUISITION SYSTEM

Test data were collected using a Macintosh-II computer running LabView software. Data was collected and logged at a 1 Hz rate. Figure 8 shows the approximate layout of the system. There were two primary data systems, a Wavetek programmable voltage multimeter and the Accufiber controller for the single color pyrometers. The ultrasonic sensor and two-color pyrometry analog data was sampled by the digitizer at 2 Hz and collected by the LabView driver at 1 Hz. The data acquisition system drivers were a modified version of those developed by Mr. Cary D. Long of Oak Ridge National Laboratory. Mr. Long designed that system to collect data from multiple digitizers and the controller for Accufiber pyrometers. His assistance in providing this software saved the project as many as one hundred hours of programming and testing effort.

Thermocouple data were collected on an IBM compatible at 5 Hz. Following the experiments the data were translated and transferred to the Macintosh for analysis. Similarly, spectrometry data were collected using an IBM. The spectra were calibrated, the black-current eliminated and the data were then transferred to the Macintosh for analysis.

Figure 8. Data acquisition system for propellant fire experiments.

PROPELLANT

The propellant of interest for this study was the MMIII stage 3 propellant, ANB-3066. This is an ammonium perchlorate (AP)-based composite propellant. Its composition is (in weight percent) 73 % AP, 15 % Al, and 12% carboxy-terminated polybutadiene binder⁷. ANB-3066 has an adiabatic flame temperature of 2730 °C, but we did not expect to observe that high a temperature due to incomplete combustion of aluminum and expected heat losses to the chimney walls.

The propellant used in this study was produced by Aerojet Corporation, (of Sacramento, CA), and was packaged in heavy-paper gallon cartons. These cartons measure about 15 cm (6 in.) in height and 17 cm (6.75 in.) in diameter. For our tests the carton material was removed and the propellant inspected for irregularities. If accepted, the propellant was weighed and triple-wrapped with a fiber reinforced tape.

Ignition of the propellant was performed by placing an aluminum alloy bridge wire on the top surface. The wire was covered with an approximately 5 cm wide patch of boron potassium-nitrate. The test was initiated by applying a 120 volt source across the bridge. Figure 9 shows a propellant cylinder prepared for ignition.

For our tests, we attempted to control the burn to the top surface only. However, other surfaces would ignite occasionally due to surface irregularities and due to aluminum droplets rolling off the top surface of the propellant and igniting the sides or bottom of the propellant package. When this occurred, the burn duration would be shorter and the fire more violent. We defined such an instance as an 'uncontrolled' burn.

Figure 9. Propellant cylinder prepared for ignition.

TEST DESIGN

Typical layouts of experiments are depicted in Figures 10 and 11. In these tests a 2.5 cm thick graphite plate was used as a base. On it, we placed an alumina plate of 13 cm diameter to support the propellant. This was done to keep liquid aluminum droplets that fall off the burning surface from igniting the bottom surface of the propellant (causing an uncontrolled burn). A chimney was then placed over the

the chimney wall. Measurements given for standoff distances refer to the distance between the diagnostic and the initial surface of the propellant prior to ignition. As a burn progressed, the surface would recede and increase the standoff distance by approximately 15 cm (6 in.).

We conducted many tests to validate and improve the diagnostics and other devices used. Later tests were designed to measure temperature and heat flux profiles and burn rate. Figure 10 shows a test layout designed to measure the heat flux to the molybdenum rod-calorimeter.

Figure 11 shows a test layout designed to collect temperature distribution as well as spectrometry data to compare with 2-color pyrometry data. Figure 12 is a photograph of the actual layout of a test similar to the one shown on Figure 11.

Figure 12 Photo of spectrometry test prior to ignition.

The layouts for the fire characterization tests are compiled in Appendix A. All tests prior to test PFCT40 were conducted either using a surrogate propellant (SRAMII), or for diagnostics development.

A few tests conducted for this study were designed to provide qualitative information on topics associated with heat transfer, oxide deposition, and material response. Tests PFCT67 and PFCT74-77 were for that purpose. The test designs are included in Appendix A and their results are discussed later in this report.

FIRE ENVIRONMENT

More than 50 tests were conducted in support of diagnostics development and determination of plume properties. However, 21 of those tests were conducted using a surrogate propellant while we waited for delivery of ANB-3066. No data are presented for the surrogate material.

CONCEPTUAL MODEL

As noted earlier, the adiabatic flame temperature for ANB-3066 propellant has been calculated to be approximately 2730° C. We would not expect to observe this high a temperature in a fire due to the incomplete combustion of aluminum that would result in these conditions and to the heat losses to the environment. A conceptual model for an ambient pressure-unconstrained propellant fire was presented by Edward Price¹, during a similar study based on the Titan IIIC propellant. We feel that this model (Figure 13, below) is applicable to our geometry and will be helpful in presenting the boundary conditions for modeling efforts.

Figure 13. Propellant fire conceptual model.

The primary cone is assumed to be the hottest region of the fire. It is in this region that the greatest fraction of aluminum is consumed. The cross-section, or width, of the fire is determined by the surface area of propellant that is burning, while the height of this region is determined more by the kinetics of combustion and the flow rate of the plume. That is to say, the hottest region in a fire will be within a relatively short distance of the surface burning and will be minimally impacted by cooling through mixing.

The secondary cone is probably best characterized by the completion of aluminum combustion and, condensation and deposition of aluminum oxide as a viscous liquid on objects immersed in the plume. The dimensions of this region are more strongly dependent on cooling effects such as heat losses and entrainment of air. The temperature in this region is likely to be above the melting point for aluminum oxide (m.p. 2072° C).

In the tertiary cone and the mixing regions the plume cools rapidly due to mixing with entrained air and thermodynamic expansion. These regions are best characterized by powdery deposition of aluminum oxide. The deposits thermally insulate objects in the plume. This phenomena causes a downward bias of temperature measurements made when using classical diagnostics.

TEMPERATURE MEASUREMENTS

Tests were performed using combinations of diagnostics (as depicted in Figure 11) to both collect new data and to validate measurements. The results presented below first review spectrometric results and are followed by pyrometric and ultrasonic sensor observations.

To validate our spectrometric data, the Princeton Instruments system was deployed at our test site and set up to view a portable blackbody source. The source

was set at 1150° C. The spectrum shown on Figure 14 was collected. The dashed line represents the results of equation 2 with $T = 1423\text{K}$ and $\epsilon = 0.98$. The observed data show very good agreement with the predicted spectrum and thus verifies the accuracy of the system calibration. The small divergence in the 600 nm to 700 nm region may be due to calibration factors or a background signal.

Figure 14. Calibration of Radiospectrometer

Tests were conducted with instrumentation at standoffs from the original propellant surface ranging from 8 cm (3 in.) to 135 cm (59 in.). The following series of graphs (Figures 15-20) presents selected spectral radiance data for heights up to 89 cm (35 in.) standoff. For our analysis we have processed the spectrographic data using Equation (3) and have produced graphs as shown in Figure 15. To produce the graphs presented here we took the estimates resulting from the analysis and solved Equation 2 then superimposed the resulting graybody curve on a plot of the collected spectra. Figure 16 is an example of this.

Figure 15. Observed plume spectra processed by Equation (3).

Figure 16 shows the spectrum for a measurement taken at 8 cm standoff in a 35 cm chimney. The data was analyzed using equation 2 to estimate temperature and emissivity. Figure 16 also shows the predicted gray body curve for a temperature of 2400 K, and emissivity of 0.30. This method of analysis was performed on many tests. It was clear that the analytical process provided a means of estimating temperature with relatively good resolution. And, because the spectra was approximated rather well by the graybody radiation predicted by Equation 2, we had a high level of confidence in the results.

Figure 16. Observed plume spectrum and predicted radiance.

As Figure 16 shows, the plume does not radiate as a perfect graybody. Electronic emission lines are visible at approximately 590 nm, 620 nm, and 770 nm¹⁰. These peaks are attributed to sodium, iron oxide, and potassium. These peaks are not thermal and do not contribute significantly to the total optical radiation of the plume, so we feel comfortable representing the plume as a graybody for the spectral region covered by our pyrometers.

Tests were performed in the smaller graphite chimney (18 cm) to maximize the volume of the primary cone and thus make it easier to detect its temperature. Figures 17 and 18, show two typical temperatures detected at 20 cm (8 in.) and 89 cm (35 in.) above the initial surface of the propellant, respectively. The temperatures displayed on the figures are stated in degrees Kelvin (K). Data indicate that temperatures in the primary cone may be as high as 2300° C. The length of the cone is being elongated by restricting the volume of space into which the plume can expand. The temperatures observed at a 89 cm standoff, ranged between 2100° and 2200° C.

Figure 17. Observed plume spectra and predicted graybody radiation.

Figure 18. Observed plume spectra and predicted graybody radiation.

For this confinement, the secondary cone would be considered to end at a height near 89 cm. In a chimney of larger diameter we would expect this temperature to occur at a lower standoff.

Other tests were performed using a 35 cm (14 in.) diameter graphite chimney. Figures 19 and 20 present samples of spectrometry results for measurements at standoffs of 20 cm (7 in.) and 89 cm (35 in.). Based on the interpretation of the spectrum at 20 cm (Figure 19), the temperature observed is nearly 2250° C. This was among the highest temperatures observed in our testing. Generally, higher temperatures have been observed at standoffs between 20 cm and 30 cm. Figure 20 presents the spectrum measured at a standoff of 89 cm, and shows the temperature to have dropped to about 1980° C. At this standoff the temperature in the larger

chimney showed to be lower than in a 18 cm chimney as evidenced by Figures 18 and 20.

Figure 19. Observed plume spectrum and predicted graybody radiation (in a 35 cm chimney at 20 cm standoff).

Figure 20. Observed plume spectrum and predicted graybody radiation (in a 35 cm chimney at 89 cm standoff).

These temperature results are typical but temperature variations of greater than 100° C did occur between tests. The lack of a steady temperature during the progress of the burn made it difficult to quickly establish a temperature profile. For this reason, measurements at each standoff were repeated a number of times.

Temperature estimates were validated by collecting data using different types of instruments while focusing on the same volume-space in the plume. Figure 21 presents a time-temperature plot at a 20 cm standoff, in the smaller graphite chimney. The continuous data were inferred by the two color pyrometer and the asterisks represent data points determined from spectrometric data. It has generally

been the case that the two-color pyrometry data have overstated spectrometry data by about 5% .

Figure 21. Temperatures estimated via spectrometry superimposed on pyrometry data.

Because these differences are relatively small we feel that the systems and methods used have provided valid results for temperature and emissivity. Furthermore, we feel that two color pyrometry is a valid system to use for inferring temperature since the plume radiates very closely as a graybody above 500 nm wavelengths.

Temperatures recorded by the ultrasonic thermal sensors have been biased heavily by the coating of alumina that occurs during a burn. Temperatures detected were about 300° C lower than suggested by spectrometry data. There was a small improvement by masking the deposit of alumina using a 0.635 cm (0.25 in) rod at 2.54 cm (1 in) below the sensor. The sensors then received a very thin coating of alumina, but the temperatures recorded were still as much as 200° C lower than expected. The sensors did produce a continuous temperature measurement from ambient temperature to plume temperatures. This is a unique capability since no one pyrometer or type of thermocouple is able to span the range of temperatures from ambient to 3000° C. If the alumina coating could be controlled, this system would be more applicable for burns of extended duration.

EMISSION MEASUREMENTS

Two methods have been applied to determine the emissivity of the plume. One is via the fit of graybody curves to spectrometric data by using Equation 2, with appropriate values for temperature and emissivity. This was depicted on Figure 16, earlier. A second method that we have applied relies on ratio radiometry. As indicated by Equation 5, the ratio of the exponentials of temperatures observed by the single and two-color pyrometers can be used to determine emissivity. Figure 22 shows the results of such a calculation. In this instance, both the two-color and the single-color pyrometers focused on the same volume of plume. The temperatures measured by each pyrometer are plotted along with the estimated emissivity. These data along with spectrometry data were used to define an emissivity profile for the propellant plume.

Figure 22. Estimates of plume emissivity by ratio radiometry (35 cm chimney).

HEAT FLUX MEASUREMENTS

Heat flux measurements were made by placing the calorimeters at different locations relative to the propellant and in different size chimneys. Inverse modeling calculations have been performed to duplicate the observed temperatures and determine the resulting heat flux. Figure 23 below shows the data collected during a test. Table II summarizes the results of the molybdenum calorimeter tests. A report by Jeff Hendricks on these calculations is included in Appendix C. These estimates included the insulating effects of the alumina coating. Considering the temperature of the plume, it is apparent that the alumina coating produces a significant insulating effect for objects in the plume.

Test	Chimney cm (in)	Standoff cm (in)	Heat Flux (cal/s/cm ²)
PFCT63	35 (14)	83 (33)	13
PFCT65	28 (11.5)	71 (28)	11
PFCT66	18 (7)	25 (10)	19
PFCT71	48 (19)	43 (17)	15
PFCT72	18 (7)	86 (34)	12

Table II. Heat Flux Test Data

Figure 23. Temperatures from thermocouples in molybdenum rod calorimeter.

BURN RATE MEASUREMENTS

Not all tests produced burn durations that were useful in estimating the burn front regression rate. Table III below summarizes the first 16 test durations observed. Based on the data we can state that the propellant front burns at a rate of 0.134 ± 0.005 cm/s (0.053 ± 0.002 in/s). Measurements from later tests did not vary from those summarized here.

Test	Rate (in/s)	Rate (cm/s)	Burn dist. (in)	Duration (sec)
PFCT40	0.048	0.122	5.75	120
PFCT41	0.050	0.127	12	240
PFCT42	0.060	0.152	6	100
PFCT43	0.048	0.122	6	125
PFCT44	0.046	0.117	6	130
PFCT45	0.055	0.139	6	109
PFCT46	0.050	0.127	6.25	126
PFCT47	0.055	0.139	6	110
PFCT48	0.055	0.139	6	110
PFCT51	0.054	0.137	6.25	116
PFCT52	0.054	0.136	6	112
PFCT53	0.057	0.145	6	105
PFCT54	0.053	0.133	6.25	119
PFCT55	0.054	0.136	5.75	107
PFCT56	0.051	0.129	6	118
PFCT57	0.056	0.141	6	108

Table III. Propellant surface regression rates

QUALITATIVE OBSERVATIONS FROM PROPELLANT FIRE TESTS

As indicated earlier, a number of tests were performed to evaluate heat transfer and oxide deposition characteristics. The first such test (PFCT67) (see Appendix A) was designed to give us an impression of how significant heat transfer is downward from a burning surface. For this test a steel canister was outfitted with four C type thermocouples, filled with fine grit silica used in sandblasting and placed below the propellant package. Two tc's were placed at one inch from the top of the canister and opposite each other. Two more tc's were placed at one inch from the bottom of the canister opposite each other. This test simulated the effects on a motor if a separate motor (above it) was on fire.

This test progressed in a controlled manner for approximately 80 seconds, when the remaining propellant fell in the annular space between the canister and the chimney wall. As depicted in Figure 24, temperatures recorded at the canister skin were relatively cool during the controlled portion of the test. Because of the low observed temperatures we may assert that there is very little downward convection of the plume and that radiant heating due to reflection from chimney walls is the most likely source of heat. This being the case, it appears that geometry of the system plays a very important role. The larger the enclosure (relative to the burning surface) the lower the heat flux to objects below. On the other hand, a tighter fit between the burning object and the enclosure will reduce the downward heat reflection but increase the heat flux back to the area near the burning surface.

Figure 24. Wall temperatures of canister below burning solid rocket propellant.

A second test, PFCT74, was designed to observe the plume flow into an inverted conical fixture (see Appendix A). The object was a stainless steel funnel crimped at the funnel exit. Two molybdenum rods pierced the funnel to provide support. The funnel was placed at a standoff of 76 cm (30 in). At this height all deposition was of a powdery nature. However, deposition inside the cone was heavier and included small

droplet-like particles. These particles (aluminum or alumina droplets) are observed flying out of the chimneys regularly during burn tests. The approximate coating thickness inside the funnel ranged between 1.2 mm and 0.6 mm (excluding droplets). The coating on the outside of the funnel was more powdery in nature and averaged only at about 0.2 mm in thickness.

Tests PFCT75 and 76 were designed to observe the deposition at a 76 cm (30 in.) standoff on objects parallel to plume flow. This test was to provide some impression of flow about the components located above the MMIII third stage. Test plates measuring 0.32 cm (1/8 in.) in thickness and 15 cm high by 10 cm wide (6 in. x 4 in.) in size were suspended above the propellant. A stainless steel plate was used for test PFCT75 and an aluminum plate was used in test PFCT76.

The aluminum plate melted away during the test. The steel plate was coated with powdery aluminum oxide and survived the test. The steel plate was coated to approximately 0.6 mm (on each side) at the end nearest the propellant and was coated to approximately 0.4 mm at the end furthest away. The loss of the aluminum sample may serve to indicate the potential for failure of the structures above a motor.

Finally, test PFCT77 was designed to test the thermal transfer to a hollow object placed in the plume of a fire, with an opening located directly in the path of a plume. For this test, a steel box beam 10 cm on each side and 46 cm long (4 in x 4 in x 18 in) was sealed at the ends and a hole was cut on a side measuring 8 cm by 5 cm (3 in x 2 in). The hole was cut midway along the length of the box. Two type K thermocouples were enclosed at one end of the box as shown in Appendix A, with one exposed to the center section of the box and the second tc exposed more to a wall of the box (see Appendix A sketch of box instrumentation).

The temperatures observed are shown in Figure 25. For this test, data collection started about 15 seconds before the burn was initiated. The tc response was, however, very quick once the fire started. The first tc climbed to a temperature of about 300° C and leveled off. This may be due to somewhat of a steady state condition developing as the ends of the box (not exposed to the plume) were able to conduct heat away. This test may point to the significant thermal exposure objects may receive within enclosures such as a trailer or van. However, this also points out that the temperatures are well within a range that one can protect against with common insulating materials.

Figure 25. Temperatures in chamber exposed to a propellant plume.

EXPERIENCE WITH MATERIALS IN PROPELLANT FIRES

As described earlier, many different materials were used in developing diagnostics and support systems. We described below some results of interest that may be helpful to others in future testing.

Graphite- we found high density graphite to be quite suitable for diagnostic components and chimneys. The material used was UCAR CS grade graphite.

Tantalum- even though tantalum has a high melting point we had problems with softening of the metal. Tantalum was first used in calorimeters.

Molybdenum- turned out to be quite useful. It retains its strength and is relatively inert in that environment. Components made from molybdenum suffered very little oxidation, corrosion, or erosion when compared to stainless steel, tungsten, tantalum, etc.

Tungsten- most components used became extremely brittle after exposure to the plume. And, because of the difficulty in machining, it was seldom used. The one exception was in the ultrasonic sensors. This was a potassium doped tungsten. It did corrode but did not lose its strength or become overly brittle.

Stainless steel- some support components were made of steel. This was not a problem if used at long distances from the fire (>100 cm) and where the plume flow was not high.

To obtain a better understanding of the characteristics of the alumina deposits that form during propellant fires two samples were sent for laboratory analysis. The samples included, 1) solid material that had the appearance of being molten on the wall of sight tube and, 2) material that was relatively friable, but appeared as sintered powder. We were interested in the porosity, density, and average pore size for the deposits. These characteristics are associated with heat transfer. Generally, low densities and high porosities are associated with good insulating materials. Appendix D contains the results of these tests. In summary, the deposit was found to vary in density from 2.0 g/cc to 3.5 g/cc and, porosity was observed to vary from 22% to 50%.

CONCLUSIONS

THERMAL CHARACTERISTICS OF ANB-3066 PROPELLANT FIRES

Figures 26 and 27 depict the nominal profiles for temperature, emissivity and heat flux that have been determined from the tests and analysis described above. As previously stated, the methods applied have given us a high level of confidence in our measurements but we have observed widely varying temperatures between tests ($\pm 10\%$). Obviously, the turbulence and thermal characteristics of a propellant fire are highly dependent on the surface area undergoing combustion and the cross-sectional area of the enclosure.

Figure 26. Temperature and emissivity profiles for the plume of ANB-3066 burning in ambient atmospheric conditions.

Figure 27. Temperature and heat flux profiles for the plume of ANB-3066 burning in ambient atmospheric conditions.

The characterization of an ANB-3066 propellant fire may be summarized as in Figure 28, below. This figure presents the conceptual model prescribed by Pierce¹, with our proposed temperature and emissivity value ranges. The values are approximations because there are various factors that affect the characteristics of the plume. These factors include the size of the chimney or chamber that contains the fire, the surface area that is burning and lack of homogeneity in the propellant.

Figure 28. Thermal characteristics of ANB-3066 propellant fire.

SPECULATION ON THERMAL CONDITIONS IN A SILO FIRE

The conditions that may be encountered in a propellant fire within a silo are highly dependent on the manner in which the burn progresses. I can imagine three very different scenarios. One, a relatively well 'controlled' burn, where the stage burns, exhausting freely and not disintegrating. Secondly, the propellant in the burning stage disintegrates and an accelerated burn occurs, leading to higher temperatures, higher plume flow velocities, and greater damage to objects above the fire. Thirdly, (the worst case) a burn where the exhaust from the burning propellant impinges on a second motor and cooks it off, resulting in a catastrophic fire.

If the burning motor were to be able to exhaust the fire plume easily and away from another combustible source (e.g. upward through the thrust termination ports), I would expect that any materials of relatively low melting point (e.g. aluminum) and within a distance of ~100 cm (40 in.) would be melted and swept away with the plume. Objects farther away would be coated with alumina and may be deformed but may still

survive. There may be a problem however, with parts falling into the burning motor as the nearby structure melts away. If the burn is slow enough, the upper components may tilt and fall through the annulus between the missile and the silo wall. As long as the plume exists upward, I would not expect temperatures about the second stage to cause a significant problem. Test PFCT67 (previously discussed) has already shown us that downward heat transfer from the plume is not significant.

For the second case, if the propellant disintegrates I would expect the upper components to collapse into the burning propellant and melt, unless the motor casing also disintegrates, allowing burning pieces of propellant to fall to the bottom of the silo. Such a situation would be best for the upper components as they may fall but on a reduced amount of burning propellant. The propellant that falls will burn but the resulting plume would quickly cool to a temperature where it would not affect objects more than 2 or 3 m (6 to 9 feet) away.

Finally, a cook off of the second motor could jettison the upper components. If the second motor were to disintegrate in the cook off, I can only imagine a complete loss of all upper components.

CONTRIBUTORS

Program Management Ed Farley and Doug Stephens. Direction and help from LCDR Ken Stein/NOSA and Maj. Jack Deplitch/TDTR are also gratefully acknowledged.

Scientific Charles Honodel, Frank Helm, Ernest H. Moor II, Jeff Hendricks, William Shay, Russ Sanborn, John Creighton, and Bob Homsy.

Test Site personnel Douglas Bakker, Frederick Sator, John Rubke, David White, John Elliott, Vince Gase, Jamie Lister, Gary Bertram, and Karen Larson.

REFERENCES

1. Price, E.W., et al. *The Fire Environment of a Solid Rocket Propellant Burning in Air*. Air Force Weapons Laboratory, report # AFWL-TR-78-34. March 1979.
2. Price, E.W., et al. *Further Studies of the Fire Environment of a Solid Rocket Propellant Burning in Air*. Air Force Weapons Laboratory, report # AFWL-TR-79-55, April 1980.
3. W. Eckl and N. Eisenreich, *Determination of the Temperature in a Solid Propellant Flame by Analysis of Emission Spectra*. Propellants, Explosives, Pyrotechnics 17, 202-206 (1992).
4. J.R. Creighton, *Some Estimates of Fire Temperature in the LLNL Propellant Fire of February 11, 1992*. Lawrence Livermore National Laboratory, DDV-92-0018, (May 6, 1992).
5. R.B. Johnson, C. Feng, and J. Fehribach, *On the Validity and Techniques of Temperature Measurement and Emissivity Measurements*. SPIE, Thermosense X, Vol 934, 202-206 (1988).
6. D.P. DeWitt. *Inferring Temperature From Optical Radiation Measurements*. SPIE, Thermosense VI, Vol 446, 226-233 (1983).
7. S.D. Drell, Chairman, *Report of THE PANEL ON NUCLEAR WEAPON SAFETY of the House Armed Services Committee*. Appendix F-39, December 1990.
8. K. Watson. *Spectral Ratio Method for Measuring Emissivity*. Remote Sensing of Environment, Vol 42, No. 2, 113-116 (1992).
9. K. Watson. *Two-Temperature Method for Measuring Emissivity*. Remote Sensing of Environment, Vol 42, No. 2, 117-122 (1992).
10. Personal Communication with Dr. Frank Helm, LLNL. October 1993.
11. R. Dawbarn., et al. *Analysis of the Measured Effects of the Principal Exhaust Effluents from Solid Rocket Motors*. Arnold Engineering Development Center, report # NASA-CR-3136, 1980.

12. J. Powling and W. Smith, *The Surface Temperature of Burning Ammonium Perchlorate*. Combustion and Flame, Vol. 7, 269-275 (Sept. 1963).
13. J. Powling and W. Smith, *Measurement of Burning Surface Temperature of Propellant Compositions by Infra-red Emissions*. Combustion and Flame, Vol 6, 173-181 (Sept. 1962).
14. E.J. Mularz and M.C. Yuen. *An Experimental Investigation of Radiative Properties of Aluminum Oxide Particles*. J. of Quantitative Spectroscopy-Radiative Transfer. Vol. 12, 1553-1568 (1972).
15. J.R. Creighton, *Time Constants for Thermal Probes for Propellant Fires*. Lawrence Livermore National Laboratory, Internal memo, (January 24,1992).

ACKNOWLEDGMENT

Work performed by Lawrence Livermore National Laboratory under the auspices of the U.S. Department of Energy under contract number W-7405-ENG-48, and sponsored by the Defense Nuclear Agency.

Appendix A

Layouts for Propellant Fire Tests

The attached diagrams were used by Test Site personnel to assemble the hardware for the propellant fire characterization tests. During set-up some modifications may have been made. The layouts have been updated if the modifications were significant.

PFCT40 Test
January 27, 1993

Diagnostics:

1. IR pyrometers (2) with sight-tubes for temp. profile
2. Mikron 2-color pyrometer
3. FO. link to spectral radiometer

Test:

7" single carton of MMIII propellant-tape wrapped.

This is the first burn with true MMIII propellant. Collecting spectral data to determine 'gray body' likeness of the plume.

JCD 1/27/93

PFCT41 Test
January 1993

Diagnostics:

1. IR pyrometers (2) with sight-tubes for temp. profile
2. Mikron 2-color pyrometer

Test:

12"- double carton of MMIII propellant- tape wrapped.

This will be an extended burn with true MMIII propellant. The two color pyrometer & Accufiber pyrometer will be used to calculate emissivity.

JCD 1/93

PFCT42 Test
January 26, 1992

PFCT43 Test
January 27, 1993

Diagnostics:

1. IR pyrometers (2) with sight-tubes for temp. profile
2. Mikron 2-color pyrometer
3. FO. link to spectral radiometer at 7" standoff

Test:

7" single carton of MMIII propellant-tape wrapped.

This burn will use MMIII propellant. We will collect spectral data to determine 'gray body' likeness of the plume in a large steel chimney.

JCD 1/27/93

PFCT44 Test
January 1993

This test will use MMIII propellant. We want to compare data to previous tests with SRAMII propellant and attempt the use of argon purge gas in sight tubes.

Diagnostics:

1. Two Accufiber optical pyrometers for plume temperature at 7", and 12" standoffs.
2. Two color pyrometer at 7" standoff.

Test:

One 7" carton of MMIII propellant in graphite chimney.

JCD 1/93

PFCT45 Test
January 1993

This test is designed to continue the determination of 'gray body' likeness of the plume at higher standoffs.

Diagnostics:

1. Two Accufiber optical pyrometers for plume temperature at 3", and 8" standoffs.
2. Mikron two-color pyrometer at 13" standoff.
3. F.O. link to spectral radiometer at 13" standoff

Test:

One 7" carton of MMIII propellant in graphite chimney.

JCD 1/27/93

PFCT46 Test
January 28, 1993

This test is designed to continue the determination of 'gray body' likeness of the plume at lower standoffs.

Diagnostics:

1. Two Accufiber optical pyrometers for plume temperature at 13", and 8" standoffs.
2. Mikron two-color pyrometer at 3" standoff.
3. F.O. link to scanning spectrometer at 13" standoff

Test:

One 7" carton of MMIII propellant in graphite chimney.

JCD 1/93

PFCT48 Test
January 28, 1993

PFCT49 Test
February 1993

PFCT50 Test
February 1993

PFCT51 Test
January 1993

Diagnostics:

1. Mikron 2-color pyrometer
2. FO. link to spectral radiometer
3. Ultrasonic sensor

Test:

7" single carton of MMIII propellant-tape wrapped.

The accuracy and transient response of the ultrasonic thermal sensors will be tested. The spectral data will also be collected at a different height.

JCD 1/93

PFCT52 Test
January 1993

Diagnostics:

1. Mikron 2-color pyrometer
2. FO. link to spectral radiometer
3. Ultrasonic sensor

Test:

7" single carton of MMIII propellant-tape wrapped.

The ultrasonic thermal sensor will be exposed to the most severe conditions. Spectral data is collected at a different height.

JCD 1/93

PFCT53 Test
January 1993

This will be the first graphite chimney burn to use the ultrasonic thermal sensor, the two color pyrometer and the spectrometer will all be used. This completes the collection of spectral data within a 7" graphite chimney.

Diagnostics:

1. Mikron 2-color pyrometer
2. FO. link to spectral radiometer
3. Ultrasonic sensor

Test:

7" single carton of MMIII propellant-tape wrapped.

JCD 1/93

PFCT54 Test
January 1993

This test replicates test PRCT52

Diagnostics:

1. Mikron 2-color pyrometer
2. FO. link to spectral radiometer
3. Ultrasonic sensor

Test:

7" single carton of MMIII propellant-tape wrapped.

JCD 1/93

**PFCT55 Test
January 1993**

The ultrasonic thermal sensor will be protected from oxide deposition by using a moly rod to disturb the oncoming plume flow. The spectral data will be used to validate graybody assumptions.

Diagnostics:

1. Mikron 2-color pyrometer
2. FO. link to spectral radiometer
3. Ultrasonic sensor

Test:

7" single carton of MMIII propellant-tape wrapped.

JCD 1/93

**PFCT56 Test
January 1993**

On this test we will expose a bundle of thermocouples to the propellant fire. We are trying to design a method of protecting such a bundle for an exposure of about 2 to 3 minutes.

Diagnostics:

1. FO. link to spectral radiometer
2. Mikron 2-color pyrometer
3. Single color pyrometer.

Test:

7" single carton of MMIII propellant-tape wrapped.

JCD 1/93

PFCT57 Test

March 1993

Scanning radiospectrometer will be used opposite the 2 color pyrometer to determine gray body-likeness and calibrate temperature measurements. The ultrasonic thermal sensor and single color pyrometers will provide temperatures for calibration and determining emissivity.

Diagnostics:

1. IR pyrometers (2) with sight-tubes for temp. profile
2. Mikron 2-color pyrometer
3. Ultrasonic sensor
4. F.O. link to spectral radiometer

Test:

7" single carton of MMIII propellant-tape wrapped. Using two stacked graphite chimneys (14" ID)

JCD 3/93

PFCT58 Test

March 1993

Scanning radiospectrometer will be used opposite the 2 color pyrometer to determine gray body-likeness and calibrate temperature measurements.

Diagnostics:

1. IR pyrometers (2) with sight-tubes for temp. profile
2. Mikron 2-color pyrometer
3. Ultrasonic sensor
4. F.O. link to spectral radiometer

Test:

7" single carton of MMIII propellant-tape wrapped.

JCD 3/93

PFCT59 Test

March 1993

Scanning radiospectrometer will be used opposite the 2 color pyrometer to determine gray body-likeness and calibrate temperature measurements.

Diagnostics:

1. IR pyrometers (2) with sight-tubes for temp. profile
2. Mikron 2-color pyrometer
3. Ultrasonic sensor
4. F.O. link to spectral radiometer

Test:

7" single carton of MMIII propellant-tape wrapped.

JCD 3/93

PFCT60 Test

April 1993

Scanning radiospectrometer will be used opposite the 2 color pyrometer to determine gray body-likeness and calibrate temperature measurements.

Diagnostics:

1. IR pyrometer with sight-tubes for temp. profile
2. Mikron 2-color pyrometer
3. Ultrasonic sensor
4. F.O. link to spectral radiometer

Test:

7" single carton of MMIII propellant-tape wrapped.

JCD 3/93

PFCT61 Test

April 1993

This test will replicated earlier tests to validate measurements.

Diagnostics:

1. IR pyrometers (2) with sight-tubes for temp. profile
2. Mikron 2-color pyrometer
3. Ultrasonic sensor

Test:

7" single carton of MMIII propellant-tape wrapped.

JCD 3/93

PFCT62 Test

April 1993

Diagnostics:

1. Scanning spectrometer
2. Mikron 2-color pyrometer
3. IR pyrometers with sight-tubes for temp. profile

Test:

7" single carton of MMIII propellant-tape wrapped.

This test will collect temperature data at a high standoff. The spectrometer and pyrometer will look at the same volume space to validate low emissivities.

JCD 3/93

PFCT67 Test

June 1993

JCD 5/93

Diagnostics:

1. Four thermocouples placed on internal surfaces of a tin can. Two near the top of the can and two near the bottom.
2. Mikron 2 color pyrometer

This test is designed to determine the thermal response of objects located beneath burning rocket propellant.

PFCT70 Test

June 1993

JCD 6/93

Diagnostics:

1. Three two-color pyrometers. Only one will record on the data acquisition system

Test:

- 7" single carton of MMIII propellant-tape wrapped.
- 3 graphite chimneys of 14" ID will be stacked for this test.

2 color pyrometers will provide temperatures for the highest standoff yet measured.

PFCT71 Test
June 1993

Diagnostics:

1. Molybdenum rod calorimeter
2. Two color Mikron pyrometer

Test:

7" single carton of MMIII propellant-tape wrapped.

2 color pyrometer will provide temperatures for calorimetry test.

PFCT72 Test
June 1993

Diagnostics:

1. Molybdenum rod calorimeter
2. Mikron two color pyrometer

Test:

7" single carton of MMIII propellant-tape wrapped.

2 color pyrometer will provide temperatures for calorimetry test. This test will use the 7" ID graphite chimney.

PFCT74 Test

June 1993

JCD 5/93

Diagnostics:

1. Conical substrate for oxide deposition

Test:

7" single carton of MMIII propellant-tape wrapped.

2 color pyrometer will provide temperatures to indicate if the test is abnormal

PFCT75 Test

June 1993

JCD 5/93

Diagnostics:

1. Plate substrate for oxide deposition

Test:

7" single carton of MMIII propellant-tape wrapped.

2 color pyrometer will provide temperatures to indicate if the test is abnormal. This test will use the 14" ID graphite chimney. The plate will be a 1/8" steel and measure 6" x 4".

PFCT76 Test

June 1993

JCD 5/93

Diagnostics:

1. Plate substrate for oxide deposition

Test:

7" single carton of MMIII propellant-tape wrapped.

2 color pyrometer will provide temperatures to indicate if the test is abnormal- but its use is not a requirement. This test will use the 14" ID graphite chimney. The plate will be a 1/8" aluminum and measure 6" x 4".

PFCT77 Test

June 1993

JCD 5/93

Diagnostics:

1. Steel 'box' with opening exposed to plume
2. Mikron two color pyrometer
3. Tcs to measure temperatures within enclosure.

Test:

7" single package of MMIII propellant-

2 color pyrometer will provide temperatures to indicate if the test is abnormal- but its use is not a requirement. This test will use the 14" ID graphite chimney. The steel box channel will be sealed at the ends.

STEEL FOR BEAM
2 x 4 x 1/8 INCH

1/4 WALL

TIN CAN 2 1/2 DIA. BY 1 1/4 INCH LONG.
PULLED TIGHT AGAINST BOX BEAM

T-1

T-2

3 x 2 INCH OPENING IN BOX
BEAM FOR FIRE TO ENTER

SECTION AA

TYPE K THERMOCOUPLE, 10 MIL DIA, GLASS INSULATION, SPOTHWELED TO 1/16 IN DIA
OF CAN.

ES
6/16/93

Appendix B

Photographic Records of Characterization Tests

The attached photographs depict topics discussed in the body of this report.

Figure B1. Propellant fire in an 18 cm. (7 in.) chimney. Plume flow velocity is high (though it was never timed). However, the plume does not appear to have much inertia because a mild wind would easily sweep the plume away. Walls of the chimney would be an orange-white hot by the end of a test.

Figure B2. Propellant fire in a 30 cm (12 in.) chimney. The velocity of the plume is reduced significantly (relative to an 18 cm. chimney). Walls of this size chimney would be red-orange hot by the end of a test.

Figure B3 Graphite chimneys could be stacked to provide higher standoffs for instrumentation. (*Photo turned on side*)

Figure B4 Arrangement of rods piercing an 18 cm (7 in.) graphite chimney. The holes for the rods were approximately 4 cm. off center of the chimney and were spaced at 5 cm (2 in.) increments. (*Photo turned on side*)

Figure B5. Graphite thermowell after test in an 18 cm. chimney. Outgassing from the graphite interfered with spectrometry measurements. Longer thermowells were used in the larger chimneys.

Figure B6. Graphite sight tube after test in an 18 cm. chimney. Plume flow impeded deposition of alumina. Alumina did deposit on surfaces facing away from the flow. Deposits did form if tubes were used in the zone of the plume where the alumina was condensing. In such a case the deposit would be solid (instead of powdery), and appeared to have flowed around surfaces.

Figure B7. The two color pyrometer attached to its base and alignment tube. A sight tube attached to the far end of the alignment tube rests on a 1 inch port hole on the chimney wall.

Figure B8 The appearance of a sight tube following a test in a 50 cm (20 in.) chimney. Deposit is relatively uniform except on the surface facing the flow, where it is only slightly thicker and has a 'grainy' appearance. The sight tube had been at a standoff of 20 cm. (8 in.).

Figure B9 Molybdenum thermowell after test in an 18 cm. chimney. The thermowell had been placed at a standoff of 20 cm. (8 in). Some of the deposit appears powdery in nature, but deposits on the side that faced the propellant appear to have been molten at one time.

Figure B10. Molybdenum thermowell after test in an 18 cm. chimney. The thermowell had been placed at a 8 cm standoff. The appearance of bubbling and liquid-like deposits was common at that standoff.

Figure B11 The appearance of a graphite thermowell following a test in a 50 cm. (20 in.) chimney. A patch of deposited alumina may have fallen off during cooling. The walls would generally have been covered evenly.

Figure B12 Diagnostics in place for a propellant fire test in a 52 cm (20 in.) chimney. The molybdenum thermowell extends 10 cm (4 in) into the chimney, the graphite sight tube has been inserted to near the center line of the chimney. The rods on the left side are an ultrasonic thermal sensor and a rod below it, to reduce alumina deposition on the sensor.

Figure B13 Ultrasonic sensor after a test where the sensor had been placed at a 20 cm (8 in) standoff. The deposit is generally distributed thicker near the center. In this case, there appears to be more particulate matter than is commonly observed.

Figure B14 Ultrasonic sensor after a test. The sensor had been placed at a standoff of 8 cm (3 in.). It appeared as if such a quantity of alumina deposited that it was about to drip.

Figure B15 Ultrasonic sensor following a test where the sensor had been placed at a standoff of 110 cm (36 in.). The alumina deposit is evenly distributed, thin, and powdery. On this test the temperature readings were being compared with pyrometer measurements.

Figure B16 Test designed to determine the effect of using a rod to reduce the deposit on an ultrasonic sensor. The molybdenum rod is suspended approximately 2.5 cm (1 in.) below the sensor. The rod intercepts the alumina flow of the plume and thus reduces the deposit on the sensor. However, the rod may have also cast a thermal shadow.

Figure B17 Molybdenum rod and ultrasonic sensor following a test. The rod effectively reduced the alumina deposit on the sensor. The sensor had been placed at 30 cm (12 in.) standoff.

Figure B18. Support system used to suspend calorimeters in the plume. This test used a 2 in. stainless steel calorimeter and a 1 in. graphite calorimeter. The length of the threaded support tube determined the standoff the calorimeters would have from the propellant. The support beam and thermocouple leads would be wrapped with an alumina blanket for insulation.

Figure B19 Stainless steel calorimeter following a test. Irregular deposit on the bottom surface results from impact of droplets of alumina and aluminum, along with powdery deposit.

Figure B20 Molybdenum rod calorimeter suspended in a 30 cm (12 in.) graphite chimney. Sight tube (below) provides temperature data to calibrate results.

Figure B21 Test designed to compare the insulating efficiency of aluminum and molybdenum sheeting on wire bundles. The sheeting would be used to wrap bundles of instrument wiring in a large scale test. The bundles consist of wiring wrapped with alumina blanket followed by the metal sheeting.

Figure B22 Wire bundles following a test. Appearances are misleading. The molybdenum sheeting held up better, but the alumina blanket inside partially melted and burned the wiring. The aluminum sheeting was damaged, but the blanket and wiring inside survived.

Figure B23 Appearance of the base plate following a test where the propellant package did not burn in a controlled manner. The bottom surface of the propellant ignited and shattered the alumina disk beneath it. The caked coating on the graphite base plate appears as sintered powder and is relatively thick in some areas.

Figure B24 Sintered alumina deposit from a 180 second test. This was an extended duration test. The deposit was not solid, had a relatively low density, and was easily broken.

Figure B25 Alumina coating from the bottom surface of a 5 cm (2 in.) stainless steel calorimeter. Rods of different metals had been used in this test. Some of the rods were molten and swept off by the plume, thus contaminating this surface.

Figure B26 Micrograph of the cross section of solid alumina deposit on a calorimeter (12.8X). Liquid deposit appears to have flowed towards the perimeter of the calorimeter, creating the thicker coating there. Note the large gas bubbles within the once-liquid matrix. Not visible in the reproduction are white spots of aluminum droplets caught within the matrix of the deposit.

Figure B27 Alumina disk was used to support the propellant off the graphite base plate. The disk had a smaller diameter than the propellant package to allow aluminum droplets to fall on the base plate, without igniting the bottom surface of the propellant. Note that the propellant package is triple wrapped with black tape.

Appendix C

Report on Heat Flux Calculations Performed by Jeff Hendricks

DEFENSE TECHNOLOGIES ENGINEERING DIVISION

CODTU-94-0211

ENDT-94-005

CALORIMETER NUMERICAL MODELING FOR PROPELLANT FIRE CHARACTERIZATION

Jeffrey T. Hendricks

Applied Mechanics Group

Defense Technologies Engineering Division

Mechanical Engineering Department

June 1993

Distribution:

J. Diaz	L-083
E. Farley	L-084
E. Moor	L-122
D. Schauer	L-122
EIC Library	L-127
DTED Historical File	L-125

SUMMARY

The ability to characterize propellant fires has been paramount in predicting the warhead thermal response subject to propellant fires. The Defense Nuclear Agency and Lawrence Livermore National Laboratory (LLNL) have taken a key role in the characterization of propellant fires for the probability risk assessment of the W87 warhead. Julio Diaz has been leading the testing effort at the LLNL Site 300 facility. Seven tests consisted of burning a propellant sample in a graphite chimney using pyrometry and thermocouples to measure temperature and emissivity parameters. Other parameters of a propellant fire must also be observed in order to characterize the propellant fire. One important parameter of the propellant fire is the heat flux potential at a specific location in the combustion plume. In the Site 300 tests, heat flux was implicitly measured using a thermocoupled molybdenum rod to measure the temperature response. Direct numerical calculations using TOPAZ2D [1] were completed and benchmarked against the experimental data. Time dependent heat fluxes were then extracted from the boundary nodes in the numerical model. Results show that the boundary heat flux is highly dependent on the chimney and propellant sample diameter, and the location of the calorimeter in the fire.

INTRODUCTION

A molybdenum rod 2.54 cm in diameter and 15.24 cm long encased in a kaowool insulator supported by a graphite holder was used to predict the heat flux potential at various elevations and chimney diameters for a series of propellant burn tests (Figures 1a-b). Seven burn tests were conducted by Julio Diaz at the LLNL Site 300. The recovered data consisted of temperature response of the molybdenum rod at two locations, aluminum oxide deposition thickness and density on the face of the rod, and emissivity and temperature of the plume at the elevation of the calorimeter. The data was used in an effort to evaluate the applied heat flux at the boundary of the calorimeter. Post processing capabilities were used to extract the calculated time-dependent heat flux at the surface and through the depth of the rod.

ANALYSIS

The seven tests were completed with the parameters extracted from each test [2, 3]. Table 1 is the list of the parameters used in and extracted from the experiments.

Table 1: Test Parameters

Test	Data	CD (in)	PD (in)	PS (in)	OD (in)	ρ (gm/cc)	T (C)	ϵ
1	PFCT15	11.5	7	27	0.063	0.5	1700	0.9
2	PFCT16	7	7	12	0.250	3.9	2000	0.8
3	PFCT63	14	7	33	0.063	1.9	2000	0.01
4	PFCT65	11.5	7	28	0.063	1.9	2050	0.05
5	PFCT66	7	7	10	0.125	3.9	2250	0.25
6	PFCT71	19.5	7	17	0.125	1.9	2100	0.1
7	PFCT72	7x	7	34	0.063	1.9	2050	0.01

Where:

CD is the chimney diameter used in the experiment

PD is the propellant sample diameter

PS is the propellant standoff from sample

OD is the nominal aluminum oxide deposition thickness

ρ is the approximate aluminum oxide density

T is the measured plume temperature using optical pyrometry

ϵ is the calculated total hemispherical emissivity using Plank's law

The numerical model included the molybdenum rod with adiabatic boundaries were located on the side and the rear face of the rod. An aluminum oxide deposition was added to the surface of the rod with both convection and radiation boundary conditions applied to the deposition surface. Previous work indicated that instantaneous deposition/reaction of the aluminum oxide at the surface yields reasonable results compared to test data. A nominal aluminum oxide density and thickness was obtained by Julio Diaz through inspection and analysis of the post burn materials. Material properties were taken from the TOPAZ2D Trump database based on the density approximations. A numerical model of each test was completed and benchmarked to the experimental data.

RESULTS

The temperature response of the molybdenum rod at the thermocouple locations for the seven tests are given in Figures 2a-g, respectively. The finite element mesh shown in Figure 3a was produced by MAZE [4, 5] and was used in all seven numerical models. The nodal locations corresponding to the thermocouple placement in the rod is shown in Figure 3b. The simulation of Tests 1 and 2 used a radiation boundary condition and the Test 3 simulation included only convective heating due to the low measured emissivity of 0.01. Boundary conditions used in the models are in Table 2 below.

Table 2: Model Boundary Conditions

Test	ϵ	$h(\text{cal/s/cm}^2/\text{K})$	T(C)
1	0.006	0.000	1700
2	0.004	0.000	2000
3	0.009	0.008	2000
4	0.009	0.006	2050
5	0.250	0.004	2250
6	0.100	0.009	2100
7	0.010	0.009	2050

Where:

ϵ is the total hemispherical emissivity

h is the convective film coefficient

T is the measured plume temperature using optical pyrometry

The temperature-time plots that match the data for Tests 1-7 are shown in Figures 4a-g, respectively.

Heat fluxes were obtained through post-processing the nodes on the surface of the aluminum oxide. Figure 5 shows the nodal locations for the heat flux curves. Figures 6a-g show the heat flux versus time at the nodal locations through the depth of the rod for Tests 1-7, respectively.

The nominal heat flux at the surface of the rod for the 100 second burn are in Table 3 below:

Table 3: Nominal Surface Heat Flux

Test	q (cal/s/cm ²)
1	15
2	32
3	13
4	11
5	21
6	15
7	12

The results indicate that heat flux is a function of elevation above the propellant, confinement diameter, propellant type and diameter, aluminum oxide deposition thickness, and more. MAZE [4, 5] input decks for TOPAZ2D models of Tests 1, 2, and 3 are given in Appendix 1, 2, and 3, respectively. Test 5 and Test 2 input decks differ in the oxide thickness and boundary conditions consistent with Table 1. Similarly, Tests 4, 6, and 7 differ with Test 3 input decks.

CONCLUSIONS / RECOMMENDATIONS

Coupling the energy from combustion products to a surface through boundary conditions is difficult in many respects. In order to accurately apply boundary conditions, an understanding of the source must be obtained in order to determine the energy contribution due to radiation and/or convection. The initial data and emissivities used in this report were obtained from Julio Diaz of D-Division based on the propellant fire testing completed at the LLNL Site 300 facility. Further work may provide enhanced data thus the numerical modeling will need to be reworked to provide new solutions to the problem.

REFERENCES

- [1] Shapiro, A. B., Edwards, A. L., *TOPAZ2D - Two Dimensional Implicit Finite Element Computer Code For Heat Transfer Analysis*, Lawrence Livermore National Laboratory, UCID-ID-104558, May 1990, LLNL.
- [2] Diaz, Julio C., *Propellant Fire Characterization Tests PFCT13 14, 15, and 16*, Memo January 6, 1993.
- [3] Shay, B., *Some comments on reduced data for PFCT63*, Memo May 21, 1993.
- [4] Halquist, J. O., *MAZE- An Input Generator for DYNA2D and NIKE2D*, June 1983, LLNL. (MAZE has been extended for use with TOPAZ2D and Chemical TOPAZ2D)
- [5] Hendricks, J. T., *MAZE Commands for TOPAZ2D and Chemical TOPAZ2D*, Rev. May 19, 1993, LLNL, END 93-024, COMDU 93-0028.

List of Figures

- Figure 1a Calorimeter assembly.
- Figure 1b Test apparatus and calorimeter assembly.
- Figure 2a Temperature - time data of molybdenum rod calorimeter at thermocouple locations for test PFCT15.
- Figure 2b Temperature - time data of molybdenum rod calorimeter at thermocouple locations for test PFCT 16.
- Figure 2c Temperature - time data of molybdenum rod calorimeter at thermocouple locations for test PFCT63.
- Figure 2d Temperature - time data of molybdenum rod calorimeter at thermocouple locations for test PFCT65.
- Figure 2e Temperature - time data of molybdenum rod calorimeter at thermocouple locations for test PFCT66.
- Figure 2f Temperature - time data of molybdenum rod calorimeter at thermocouple locations for test PFCT71.
- Figure 2g Temperature - time data of molybdenum rod calorimeter at thermocouple locations for test PFCT72.
- Figure 3a Finite element mesh of molybdenum rod calorimeter with aluminum oxide deposition.
- Figure 3b Select nodes on molybdenum rod corresponding to locations at which temperature is measured with thermocouples.
- Figure 4a Temperature-time plot of both numerical solution and experimental data PFCT 15 (Test 1, MAZE input deck mol1f).
- Figure 4b Temperature-time plot of both numerical solution and experimental data PFCT 16 (Test 2, MAZE input deck mol2a).
- Figure 4c Temperature-time plot of both numerical solution and experimental data PFCT63 (Test 3, MAZE input deck mol3c).
- Figure 4d Temperature-time plot of both numerical solution and experimental data PFCT65 (Test 4, MAZE input deck mol4a).
- Figure 4e Temperature-time plot of both numerical solution and experimental data PFCT66 (Test 5, MAZE input deck mol5a).
- Figure 4f Temperature-time plot of both numerical solution and experimental data PFCT71 (Test 6, MAZE input deck mol6a).
- Figure 4g Temperature-time plot of both numerical solution and experimental data PFCT72 (Test 7, MAZE input deck mol7b).
- Figure 5 Selected nodes on the molybdenum rod corresponding to the locations at which heat flux is measured extracted from the numerical simulation.

- Figure 6a Heat flux - time curves for test PFCT15 (Test 1, MAZE input deck mol1f).
- Figure 6b Heat flux - time curves for test PFCT16 (Test 2, MAZE input deck mol2a).
- Figure 6c Heat flux - time curves for test PFCT63 (Test 3, MAZE input deck mol3c).
- Figure 6d Heat flux - time curves for test PFCT65 (Test 4, MAZE input deck mol4a).
- Figure 6e Heat flux - time curves for test PFCT66 (Test 5, MAZE input deck mol5a).
- Figure 6f Heat flux - time curves for test PFCT71 (Test 6, MAZE input deck mol6a).
- Figure 6g Heat flux - time curves for test PFCT72 (Test 7, MAZE input deck mol7b).

Calorimeter

- Figure 1a - Calorimeter assembly.

Figure 1b - Test apparatus and calorimeter assembly.

Figure 2a Temperature - time data of molybdenum rod calorimeter at thermocouple locations for test PFCT15.

Figure 2b Temperature - time data of molybdenum rod calorimeter at thermocouple locations for test PFCT16.

Figure 2c Temperature - time data of molybdenum rod calorimeter at thermocouple locations for test PFCT63.

Figure 2d Temperature - time data of molybdenum rod calorimeter at thermocouple locations for test PFCT65.

Figure 2e Temperature - time data of molybdenum rod calorimeter at thermocouple locations for test PFCT66.

Figure 2f Temperature - time data of molybdenum rod calorimeter at thermocouple locations for test PFCT71.

Figure 2g Temperature - time data of molybdenum rod calorimeter at thermocouple locations for test PFCT72.

mol7b - molybdenum rod test, pfct-72
time= 0.00000E+00
dsf = 1.00000E+00

Figure 3a Finite element mesh of molybdenum rod calorimeter with aluminum oxide deposition.

mol7b - molybdenum rod test, pfct-72

nodes packed for time history processing

Figure 3b Select nodes on molybdenum rod corresponding to locations at which temperature is measured with thermocouples.

mol1f - molybdenum rod test, pfct15

Figure 4a Temperature-time plot of both numerical solution and experimental data PFCT 15 (Test 1, MAZE input deck mol1f).

mol2a - molybdenum rod test, pfct16

Figure 4b Temperature-time plot of both numerical solution and experimental data PFCT 16 (Test 2, MAZE input deck mol2a).

mol3c - molybdenum rod test, pfct-63

Figure 4c Temperature-time plot of both numerical solution and experimental data PFCT63 (Test 3, MAZE input deck mol3c).

mol4a - molybdenum rod test, pfct-65

Figure 4d Temperature-time plot of both numerical solution and experimental data PFCT65 (Test 4, MAZE input deck mol4a).

mol5a - molybdenum rod test, pfct-66

Figure 4e Temperature-time plot of both numerical solution and experimental data PFCT66 (Test 5, MAZE input deck mol5a).

mol6a - molybdenum rod test, pfct-71

Figure 4f Temperature-time plot of both numerical solution and experimental data PFCT71 (Test 6, MAZE input deck mol6a).

mol7b - molybdenum rod test, pfct-72

Figure 4g Temperature-time plot of both numerical solution and experimental data PFCT72 (Test 7, MAZE input deck mol7b).

mol7b - molybdenum rod test, pfct-72

nodes packed for time history processing

mol7b - molybdenum rod test, pfct-72

nodes packed for time history processing

Figure 5 Selected nodes on the molybdenum rod corresponding to the locations at which heat flux is measured extracted from the numerical simulation.

mol1f - molybdenum rod test, pfct15

Figure 6a Heat flux - time curves for test PFCT15 (Test 1, MAZE input deck mol1f).

mol2a - molybdenum rod test, pfct16

Figure 6b Heat flux - time curves for test PFCT16 (Test 2, MAZE input deck mol2a).

mol3c - molybdenum rod test, pfct-63

Figure 6c Heat flux - time curves for test PFCT63 (Test 3, MAZE input deck mol3c).

mol4a - molybdenum rod test, pfct-65

Figure 6d Heat flux - time curves for test PFCT65 (Test 4. MAZE input deck mol4a).

mol5a - molybdenum rod test, pfct-66

Figure 6e Heat flux - time curves for test PFCT66 (Test 5. MAZE input deck mol5a).

mol6a - molybdenum rod test, pfct-71

Figure 6f Heat flux - time curves for test PFCT71 (Test 6, MAZE input deck mol6a).

mol7b - molybdenum rod test, pfct-72

Figure 6g Heat flux - time curves for test PFCT72 (Test 7, MAZE input deck mol7b).

Appendix 1

PFCT15 (Test 1) Numerical Model Maze Input Deck

mol1f

1

c ***** c

c mol1fm

c ***** c

c maze input deck for:

c Molybdenum Calorimeter Analysis

c

c Dimensions are cm/gm/sec/K

c

c Jeff Hendricks

c AMG

c NEED

c M.E. Dept

c March 1993

c

c ***** c

c define lines

c ***** c

maztl 0.001

lpoff ppoff

para r1 [2.54/2];

para z1 [-.06*2.54] z2 [0.0] z3 [6.*2.54];

para den1 [15] den2 [5];

para x1 [int(%den2*%r1)] y1 [int(%den1*(%z2-%z1))];

para x2 [int(%den2*%r1)] y2 [int(%den2*(%z3-%z2))];

ld 1 lp 2 0.0 %z1 %r1 %z1

ld 2 lp 2 0.0 %z2 %r1 %z2

ld 3 lp 2 0.0 %z3 %r1 %z3

ld 4 lp 2 0.0 %z1 0.0 %z3

ld 5 lp 2 %r1 %z1 %r1 %z3

c ***** c

c define parts

c ***** c

part 1 5 2 4 1 %x1 5 yes c Part 1 al2O3
part 2 5 3 4 2 %x2 %y2 yes c Part 2 Tungsten rod

c ***** c

c assemble and merge parts

c ***** c

assm

m 1 2

c ***** c

c define initial temperature and boundary conditions

c ***** c

lcd 1 3 0.0 310.0

10.0 2000.0

110.0 2000.0

lcd 2 2 0.0 1.354e-12

20000.0 1.354e-12

c *** Radiation on surface of al2o3 ***

p 1 b

rbcs 1 1 1.0 1.0 2 .8

c ***** c

c define slide lines

c ***** c

c ***** c

c set title, control data and timing

c ***** c

title

mol1f - molybdenum rod test, pfct15

c

c

t0 305. c baseline temp of all nodes

alpha 0.5 c time integration parameter 1.0-implicit 0.5-CN

bwmo 1 c bandwidth minimization 1-on 0-off
flux 1 c node heat flux calc 0-off 1-on
phch 0 c phase change calculation 0-off 1-on
nsmd 1 c solution method 0-fissile Cray, 1-actol Sun
anal 2 c analysis type 0-ss 1-trans w/con mm 2- tran w/lump mm
step 1 c time step mode 0-fixed 1-variable
c - nstep c number of time steps
prtt 99999. c time between printing
pltt 1. c time between plotting
iprt 10000 c steps between print output
iplt 2 c steps between plot output
sbrf -1000 c number of time steps between restart files
start 0.0 c initial problem time
term 110. c termination time
delt 0.01 c time step if fixed - initial variable TS
dtmin 0.0001 c minimum time step - set for variable TS
dtmax 0.5 c maximum time step - set for variable TS
tmpmax 10. c max temp change in TS - set for variable TS
tssf 0.1 c time step scaling factor - set for variable TS
nonl 1 c type of problem 0-linear 1-nonlinear
nbsr 1 c number of time steps between stiff matrix ref
msrf 10 c max number ref per time step
nibsr 1 c max number of equil iter per cond matrix ref
tctol 0.001 c convergence tol for equil iterations - def=0.001
relax 0.5 c relaxation parameter - def (1.0-ss 0.5-transient)

c ***** c
c create output
c ***** c

wbcd topaz2d

c ***** c
c define materials
c ***** c

tmat 1
al2o3
mt 5 den 0.5e+00 tlat 2.318e+03 hlat 1.320e+02
tcp5 6
3.732e+02 2.220e-01 4.731e+02 2.450e-01 5.731e+02 2.651e-01 7.731e+02 2.801e-01
1.173e+03 3.107e-01 1.973e+03 3.119e-01

tcn5 2

2.731e+02 1.00e-03 2000. 8.900e-03

tmat 2

molybdenum

mt 5 den 1.020e+01 tlat 2.893e+03 hlat 6.501e+01

tcp5 5

1.615e+01 4.063e-04 9.165e+01 3.107e-02 2.731e+02 5.901e-02 1.373e+03 7.600e-02

2.773e+03 1.050e-01

tcn5 7

0. 0. 3.315e+01 8.499e-01 8.315e+01 5.019e-01 1.432e+02 3.301e-01

2.731e+02 3.301e-01 1.873e+03 2.200e-01 2.893e+03 1.912e-01

c ***** c

c Define chemistry constants

c ***** c

c ***** c

c define reactions

c ***** c

end

Appendix 2

PFCT16 (Test 2) Numerical Model Maze Input Deck

mol2a

```

1
c ***** c
c mol2am
c ***** c
c maze input deck for:
c Tungsten Calorimeter Analysis
c
c Dimensions are cm/gm/sec/K
c
c Jeff Hendricks
c AMG
c NEED
c M.E. Dept
c March 1993
c
c ***** c
c define lines
c ***** c

maztl 0.001
lpoff ppoff

para r1 [2.54/2];
para z1 [-.2*2.54] z2 [0.0] z3 [6.*2.54];
para den1 [15] den2 [5];
para x1 [int(%den2*%r1)] y1 [int(%den1*(%z2-%z1))];
para x2 [int(%den2*%r1)] y2 [int(%den2*(%z3-%z2))];

ld 1 lp 2 0.0 %z1 %r1 %z1
ld 2 lp 2 0.0 %z2 %r1 %z2
ld 3 lp 2 0.0 %z3 %r1 %z3
ld 4 lp 2 0.0 %z1 0.0 %z3
ld 5 lp 2 %r1 %z1 %r1 %z3

c ***** c
c define parts

```

c ***** c

part 1 5 2 4 1 %x1 5 yes c Part 1 al2O3
part 2 5 3 4 3 %x2 %y2 yes c Part 2 Tungsten rod

c ***** c

c assemble and merge parts

c ***** c

assm
m 1 2

c ***** c

c define initial temperature and boundary conditions

c ***** c

lcd 1 3 0.0 310.0
10.0 2300.0
110.0 2300.0

lcd 2 2 0.0 1.354e-12
20000.0 1.354e-12

c *** Radiation on surface of al2o3 ***

p 1 b
rbcs 1 1 1.0 1.0 2 .9

c ***** c

c define slide lines

c ***** c

c ***** c

c set title, control data and timing

c ***** c

title
mol2a - molybdenum rod test, pfct16
c
c
t0 305. c baseline temp of all nodes
alpha 0.5 c time integration parameter 1.0-implicit 0.5-CN

bwmo 1 c bandwidth minimization 1-on 0-off
flux 1 c node heat flux calc 0-off 1-on
phch 0 c phase change calculation 0-off 1-on
nsmd 1 c solution method 0-fissile Cray, 1-actol Sun
anal 2 c analysis type 0-ss 1-trans w/con mm 2- tran w/lump mm
step 1 c time step mode 0-fixed 1-variable
c - nstep c number of time steps
prtt 99999. c time between printing
pltt 1. c time between plotting
iprt 10000 c steps between print output
iplt 2 c steps between plot output
sbrf -1000 c number of time steps between restart files
start 0.0 c initial problem time
term 110. c termination time
delt 0.01 c time step if fixed - initial variable TS
dtmin 0.0001 c minimum time step - set for variable TS
dtmax 0.5 c maximum time step - set for variable TS
tmpmax 10. c max temp change in TS - set for variable TS
tssf 0.1 c time step scaling factor - set for variable TS
nonl 1 c type of problem 0-linear 1-nonlinear
nbsr 1 c number of time steps between stiff matrix ref
msrf 10 c max number ref per time step
nibsr 1 c max number of equil iter per cond matrix ref
tctol 0.001 c convergence tol for equil iterations - def=0.001
relax 0.5 c relaxation parameter - def (1.0-ss 0.5-transient)

c ***** c
c create output
c ***** c

wbcd topaz2d

c ***** c
c define materials
c ***** c

tmat 1
al2o3
mt 5 den 3.98e+00
tcp5 2
3.732e+02 1.020e-01 1.973e+03 1.050e-01
tcn5 2

2.731e+02 1.00e-02 1000. 5.900e-01

tmat 2

al2o3d

mt 5 den 3.98e+00 tlat 2.318e+03 hlat 1.320e+02

tcp5 10

0. 0. 7.315e+01 9.560e-03 2.231e+02 1.400e-01 2.731e+02 1.740e-01

3.732e+02 2.220e-01 4.731e+02 2.450e-01 5.731e+02 2.651e-01 7.731e+02 2.801e-01

1.173e+03 3.107e-01 1.973e+03 3.119e-01

tcn5 10

2.731e+02 9.560e-02 3.732e+02 6.900e-02 4.731e+02 5.301e-02 5.731e+02 4.199e-02

6.731e+02 3.301e-02 7.731e+02 2.801e-02 9.731e+02 2.200e-02 1.173e+03 1.800e-02

1.473e+03 1.912e-02 1.973e+03 2.500e-02

tmat 3

molybdenum

mt 5 den 1.020e+01 tlat 2.893e+03 hlat 6.501e+01

tcp5 5

1.615e+01 4.063e-04 9.165e+01 3.107e-02 2.731e+02 5.901e-02 1.373e+03 7.600e-02

2.773e+03 1.050e-01

tcn5 3

2.731e+02 3.301e-01 1.873e+03 3.200e-01 2.893e+03 3.912e-01

c ***** c

c Define chemistry constants

c ***** c

c ***** c

c define reactions

c ***** c

end

Appendix 3

PFCT63 (Test 3) Numerical Model Maze Input Deck

mol3c

```

1
c ***** c
c mol3cm
c ***** c
c maze input deck for:
c Molybdenum Calorimeter Analysis PFCT63
c
c Dimensions are cm/gm/sec/K
c
c Jeff Hendricks
c AMG
c NEED
c M.E. Dept
c March 1993
c
c ***** c
c define lines
c ***** c

maztl 0.001
lpoff ppoff

para r1 [2.54/2];
para z1 [-.0625*2.54] z2 [0.0] z3 [6.*2.54];
para den1 [15] den2 [5];
para x1 [int(%den2*%r1)] y1 [int(%den1*(%z2-%z1))];
para x2 [int(%den2*%r1)] y2 [int(%den2*(%z3-%z2))];

ld 1 lp 2 0.0 %z1 %r1 %z1
ld 2 lp 2 0.0 %z2 %r1 %z2
ld 3 lp 2 0.0 %z3 %r1 %z3
ld 4 lp 2 0.0 %z1 0.0 %z3
ld 5 lp 2 %r1 %z1 %r1 %z3

c ***** c
c define parts
  
```

c ***** c

part 1 5 2 4 1 %x1 5 yes c Part 1 al2O3

part 2 5 3 4 2 %x2 %y2 yes c Part 2 Tungsten rod

c ***** c

c assemble and merge parts

c ***** c

assm

m 1 2

c ***** c

c define initial temperature and boundary conditions

c ***** c

lcd 1 3 0.0 310.0

10.0 2200.0

110.0 2200.0

lcd 2 2 0.0 .008

20000.0 .008

lcd 3 2 0.0 1.354e-12

20000.0 1.354e-12

c *** Radiation on surface of al2o3 ***

p 1 b

cbcs 1 1 1.0 1.0 2 1.0 0.0

rbcs 1 1 1.0 1.0 3 0.01

c ***** c

c define slide lines

c ***** c

c ***** c

c set title, control data and timing

c ***** c

title

mol3c - molybdenum rod test, pfct-63

c
c
t0 296. c baseline temp of all nodes
alpha 1.0 c time integration parameter 1.0-implicit 0.5-CN
bwmo 1 c bandwidth minimization 1-on 0-off
flux 1 c node heat flux calc 0-off 1-on
phch 0 c phase change calculation 0-off 1-on
nsmd 1 c solution method 0-fissile Cray, 1-actol Sun
anal 2 c analysis type 0-ss 1-trans w/con mm 2- tran w/lump mm
step 1 c time step mode 0-fixed 1-variable
c - nstep c number of time steps
prtt 99999. c time between printing
pltt 2. c time between plotting
iprt 10000 c steps between print output
iplt 2 c steps between plot output
sbrf -1000 c number of time steps between restart files
start 0.0 c initial problem time
term 110. c termination time
delt 0.01 c time step if fixed - initial variable TS
dtmin 0.0001 c minimum time step - set for variable TS
dtmax 2.0 c maximum time step - set for variable TS
tmpmax 10. c max temp change in TS - set for variable TS
tssf 0.1 c time step scaling factor - set for variable TS
nonl 1 c type of problem 0-linear 1-nonlinear
nbsr 1 c number of time steps between stiff matrix ref
msrf 10 c max number ref per time step
nibsr 1 c max number of equil iter per cond matrix ref
tctol 0.001 c convergence tol for equil iterations - def=0.001
relax 0.5 c relaxation parameter - def (1.0-ss 0.5-transient)

c ***** c

c create output

c ***** c

wbcd topaz2d

c ***** c

c define materials

c ***** c

tmat 1

al2o3l

mt 5 den 1.90e+00 tlat 2.318e+03 hlat 1.320e+02

tcp5 10

0. 0. 7.315e+01 9.560e-03 2.231e+02 1.400e-01 2.731e+02 1.740e-01

3.732e+02 2.220e-01 4.731e+02 2.450e-01 5.731e+02 2.651e-01 7.731e+02 2.801e-01

1.173e+03 3.107e-01 1.973e+03 3.119e-01

tcn5 5

4.231e+02 1.250e-02 5.731e+02 9.082e-03 7.731e+02 6.931e-03 1.073e+03 5.201e-03

1.273e+03 4.799e-03

tmat 2

molybdenum

mt 5 den 1.020e+01 tlat 2.893e+03 hlat 6.501e+01

tcp5 5

1.615e+01 4.063e-04 9.165e+01 3.107e-02 2.731e+02 5.901e-02 1.373e+03 7.600e-02

2.773e+03 1.050e-01

tcn5 3

2.731e+02 3.301e-01 1.873e+03 3.200e-01 2.893e+03 3.912e-01

c ***** c

c Define chemistry constants

c ***** c

c ***** c

c define reactions

c ***** c

end

Appendix D

Analysis results for Characteristics of Alumina Deposits

The laboratory results contained in Appendix C detail characteristics of the morphology of the deposited material. The samples included 1) solid material that had the appearance of being molten on the wall of sight tube and, 2) material that was relatively friable, but appeared as sintered powder.

Analysis results for Characteristics of Alumina Deposits

The following laboratory report was produced by the Particle Characterization Lab, of the Chemistry and Material Sciences Department of LLNL. The report describes an alumina sample that appeared to have been deposited as dry particulate matter but, through extended heating, had begun to sinter. The sample held together but was very friable. The report information included measurements of porosity (void vol %), the surface area per unit mass (sq. m / g), and the bulk density (g/cc).

Included with the summary sheet are plots showing the cumulative and incremental distributions of pore volume as a function of pore diameter. The numbers on the left of the page represent pore diameter in micrometers. The numbers on the top represent the appropriate percentage volume corresponding to the pore diameter. These plots help give an indication of the heat transfer characteristics of the material. Large pores and low density may indicate lower heat conductivity relative to a small pore distribution with higher density.

The second set of results are for a sample of alumina deposit that appeared to have been deposited as a liquid and solidified during cooling. The same analysis was performed for both samples.

To summarize:

Sintered alumina deposit:

bulk density -	2.04 g/cc
porosity-	50.2% void
pore area	23.0 m ² /g

Solid alumina deposit:

bulk density -	3.0 g/cc
porosity-	22.1% void
pore area	8.6 m ² /g

.ID DIAZ
192059 SINTERED ALUMINA COATING
R NUMBER +276

LF 10:40:29 3/13/92
HP 11:21:2 3/13/92

LP EQUILIBRATION =	+20.0000 SEC	PNTR CONSTANT =	+10.7900 MICRO-L/PF
HP EQUILIBRATION =	+20.0000 SEC	THETA =	+130.0000
SAMPLE WEIGHT =	+0.3029 G	GAMMA =	+484.0000 DYNES/CM
PNTR WEIGHT =	+70.3877 G	INITIAL PRESSURE =	+1.2747 PSIA
ITR+SAMPLE WEIGHT =	+70.6906 G	STEM VOLUME =	+0.3900 CC
R+SAMPLE+MERCURY =	+117.3130 G	MERCURY DENSITY =	+13.5335 G/CC
PNTR VOLUME =	+3.5935 CC		

TRUSION (PRESSURIZATION) DATA SUMMARY

TOTAL INTRUSION VOLUME =	+0.2460 CC/G
TOTAL PORE AREA =	+23.0998 SQ-M/G
IAN PORE DIAMETER (VOLUME) =	+1.9988 MICROMETERS
IAN PORE DIAMETER (AREA) =	+0.0040 MICROMETERS
AVERAGE PORE DIAMETER (4V/A) =	+0.0426 MICROMETERS
BULK DENSITY =	+2.0391 G/CC
APPARENT (SKELETAL) DENSITY =	+4.0916 G/CC

APILLARY = +19.1051 ****

POROSITY = 50.16 %

ULIO DIAZ
 EQ92059 SINTERED ALUMINA COATING
 NTR NUMBER +276

LP 10:40:29 3/13/92
 HP 11:21:2 3/13/92

CUMULATIVE PORE VOLUME (CC/G) VS. PORE DIAMETER
 100% = +0.2460

JLID DIAZ
EQ92059 SINTERED ALUMINA COATING
NTR NUMBER +276

LP 10:40:29 3/13/92
HP 11:21:2 3/13/92

INCREMENTAL VOLUME (CC/G) VS. PORE DIAMETER
100% = +0.183411E-001

0%	20%	40%	60%	80%	100%
I.....	I.....	I.....	I.....	I.....	I.....
+300-*					
+235-*					
+184-*					
+144-*					
+113-*****					
+88.1-*****					
+69.0-*****					
+54.0-*****					
+42.3-*****					
+33.1-*****					
+25.9-*****					
+20.3-*****					
+15.9-*****					
+12.4-*****					
+9.72-*****					
+7.61-*****					
+5.96-*****					
+4.66-*****					
+3.65-*****					
+2.86-*****					
+2.24-*****					
+1.75-*****					
+1.37-*****					
+1.07-*****					
+0.839-*****					
+0.657-*****					
+0.514-*****					
+0.402-*****					
+0.315-*****					
+0.247-*****					
+0.193-***					
+0.151-*****					
+0.118-***					
+0.0926-***					
+0.0725-*****					
+0.0567-***					
+0.0444-***					
+0.0347-*****					
+0.0272-*****					
+0.0213-*****					
+0.0167-*****					
+0.0130-*****					
+0.0102-*****					
+0.00799-*****					
+0.00626-*****					
+0.00490-*****					
+0.00383-*****					
+0.00300-*****					

JULIO DIAZ
REQ92058 SOLID ALUMINA COATING
PNTR NUMBER +249

LP 10:40:29 3/13/92
HP 11:21:2 3/13/92

LP EQUILIBRATION =	+20.0000 SEC	PNTR CONSTANT =	+10.7900 MICRO-L/PF
HP EQUILIBRATION =	+20.0000 SEC	THETA =	+130.0000
SAMPLE WEIGHT =	+0.7845 G	GAMMA =	+484.0000 DYNES/CM
PNTR WEIGHT =	+68.6044 G	INITIAL PRESSURE =	+1.2747 PSIA
PNTR+SAMPLE WEIGHT =	+69.3889 G	STEM VOLUME =	+0.3900 CC
PNTR+SAMPLE+MERCURY =	+115.6020 G	MERCURY DENSITY =	+13.5335 G/CC
PNTR VOLUME =	+3.6769 CC		

INTRUSION (PRESSURIZATION) DATA SUMMARY

TOTAL INTRUSION VOLUME =	+0.0738 CC/G
TOTAL PORE AREA =	+8.5858 SQ-M/G
MEDIAN PORE DIAMETER (VOLUME) =	+2.8450 MICROMETERS
MEDIAN PORE DIAMETER (AREA) =	+0.0037 MICROMETERS
AVERAGE PORE DIAMETER (4V/A) =	+0.0344 MICROMETERS
BULK DENSITY =	+2.9919 G/CC
APPARENT (SKELETAL) DENSITY =	+3.8401 G/CC

% CAPILLARY = +14.8505 *****

POROSITY = 22.08%

ULIO DIAZ
EQ92058 SOLID ALUMINA COATING
NTR NUMBER +249.

LP 10:40:29 3/13/92
HP 11:21:2 3/13/92

CUMULATIVE PORE VOLUME (CC/G) VS. PORE DIAMETER
100% = +0.0738

JULIO DIAZ
REQ92058 SOLID ALUMINA COATING
PNTR NUMBER +249

LP 10:40:29 3/13/92
HP 11:21:2 3/13/92

INCREMENTAL VOLUME (CC/G) VS. PORE DIAMETER
100% = +0.105857E-001

0%	20%	40%	60%	80%	100%
I.....	I.....	I.....	I.....	I.....	I.....
+300-*					
+235-*					
+184-*					
+144-*					
+113-*****					
+88.1-*****					
+69.0-*****					
+54.0-*****					
+42.3-*****					
+33.1-*****					
+25.9-*****					
+20.3-*****					
+15.9-*****					
+12.4-*****					
+9.72-*****					
+7.61-*****					
+5.96-*****					
+4.66-*****					
+3.65-*****					
+2.86-*****					
+2.24-*****					
+1.75-*****					
+1.37-*****					
+1.07-*****					
+0.839-*****					
+0.657-*****					
+0.514-*****					
+0.402-*****					
+0.315-*****					
+0.247-*****					
+0.193-*****					
+0.151-*****					
+0.118-*****					
+0.0926-*****					
+0.0725-*****					
+0.0567-*****					
+0.0444-*****					
+0.0347-*****					
+0.0272-*****					
+0.0213-*****					
+0.0167-*****					
+0.0130-*****					
+0.0102-*****					
+0.00799-*****					
+0.00626-*****					
+0.00490-*****					
+0.00383-*****					
+0.00300-*****					