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BASE FLOW
SUPERSONIC FLOW

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Progress is reported on four distinct projects which are administered as a group The individual projects are identified as tasks and reported on separately. A summary for each task follows:

TASK I. During the reporting period, the impedance tube setup was utilized in the determination of the admittances of two aluminized solid propellants. Both the pressure coupled response and the gas phase losses have been determined over the frequency range of 400-1200 Hertz. In a separate study, the feasibility of utilizing either quartz or piezocermic crytals in the direct measurement of

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) of the mass loss of burning solid propellants has been investigated. Finally studies aimed at the adaptation of the impedance tube setup for the measurement of the velocity coupled response of burning solid propellant has been initiated.

TASK II. Studies were continued on burning in and around the near wake of an axisymmetric model at Mach 3. Burning tests with radiant and axial injection of pure hydrogen have been completed. Burning tests with axial injection of diluted hydrogen, simulating heating values for practical propellants, have been started. Attractive performance values with large reductions in base drag have been obtained with base burning using both base and combined base and radial injection. Also, base thrust has been obtained with radial injection but it has been determined that the results are affected by wind tunnel interference.

TASK III. Further studies were made of aluminum accumulation and agglomeration on the propellant burning surface and droplet combustion in the gas flow from the surface. Modification of the aluminum powder to control agglomeration were evaluated by propellant combustion studies and found to be highly effective. The role of the binder in accumulation was studied with tests on aluminized "sandwiches". The limits of high aluminum content in propellants were explored by a variety of tests with aluminum content up to 35% with ~~acceptable~~ combustion being achieved at 30% ~~aluminum content~~. The nature of aluminum agglomerates, of their combustion, and of the Al_2O_3 product droplets were studied by quenching the combustion plume and analysis of collected particles.

TASK IV. Experimental and analytical studies were continued on the subject of turbulence-induced pressure flucuations in a rocket-like cavity. An advanced theory has provided closure between theory and experiment on one experimental facility. A fuel rocket motor simulator was built and preliminary results were attained to show the separation between propagational sound and local hydrodynamic noise.

AFOSR INTERIM SCIENTIFIC REPORT

AFOSR-TR-80-

ROCKET RESEARCH AT GEORGIA TECH

Prepared for

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TABLE OF CONTENTS

General Introduction

Progress is reported for the third year effort of four distinct projects under contract AFOSR F49620-78-C-0003. The individual projects are identified as distinct tasks; this distinction being preserved because it also reflects distinct test facilities and personnel assignments. Each task report contains its own abstract, introduction, and progress report.

Task I is concerned with combustion instability in solid propellant rocket motors with particular emphasis on the measurement of the response of solid propellant combustion to oscillatory flow environments. Studies conducted under this task included the application of the impedance tube method in the measurement of the pressure response and the gas phase losses associated with the unsteady burning of aluminized propellants. Other efforts were concerned with (1) the modification of the impedance tube method for the measurement of the velocity response of solid propellants and (2) the determination of the feasibility of utilizing crystals in the direct measurement of propellant mass loss during burning.

Task II is concerned with external and base burning as means for reducing base drag or providing base thrust with minimum weight and volume demands on the propulsion system. A facility was developed previously for injection and combustion of pure hydrogen in and around the near-wake shear flow of an axisymmetric body. The facility has been modified for burning diluted hydrogen which simulates heating values for practical propellants. This report discusses results of tests with both pure and diluted hydrogen.

Task III is concerned with the role of the aluminum powder ingredient in propellant combustion and 2-phase product flow. The steps in the metal "metablolsm" are traced through the phase of accumulation on the burning surface, the melting and coalescing of particles into relatively large droplets, the ignition and combustion of the droplets, effect of combustor gas flow on these steps, and their response to gas oscillations. The present report summarizes tests evaluating methods of modifying aluminum powder to control agglomeration; test of the role of binders in accumulation-agglomeration; study of the combustion of propellants with up to 35% aluminum; and study of the nature of aluminum agglomerates, their combustion, and nature of the oxide product droplet population.

Task IV is concerned with the prediction of pressure fluctuations, as caused by turbulence, in rocket motors. Several facilities have been used for illustration and measurement of this effect. Advanced theoretical methods have shown agreement between theory and experiment. Preliminary testing with a full rocket motor simulator has been accomplished.

TASK I
INVESTIGATION OF THE UNSTEADY BURNING CHARACTERISTICS OF SOLID PROPELLANTS

BEN T. ZINN BRADY R. DANIEL

A. Research Objectives

The general objective of the research conducted under this task is the experimental determination of the unsteady burn rates of different classes of solid propellants under different experimental conditions simulating those observed in unstable rocket motors. More specifically, the research conducted during the past year under this task was concerned with the utilization of the impedance tube setup in the measurement of the admittances and gas phase losses associated with the unsteady burning of aluminized solid propellants, the investigation of the feasibility of utilizing piezoelectric crystals in the direct measurement of the mass loss of burning solid propellants and the adaptation of the impedance tube technique for the measurement of the velocity coupled response of burning solid propellants.

B. Status of Research

In the initial phase of this reporting period the impedance tube setup was utilized to check the repeatability of pressure response and gas phase loss data that had been obtained earlier in tests conducted with a UTP-3001 and a UTP-19360 propellant. These tests were conducted over the frequency range 400 to 1100 Hz and they verified the reproducibility of the data. This series of tests with aluminized solid propellants has clearly demonstrated that the impedance tube technique can be utilized in the measurement of the admittances of aluminized solid propellants. Furthermore, it appears that data measured in impedance tube tests with aluminized solid propellants are more accurate than corresponding data measured in tests conducted with nonaluminized solid propellants. This improvement in the accuracy of the data can be attributed to (1) the presence of higher gas phase losses in tests conducted with aluminized propellant which, in turn, result in higher amplitudes at the standing wave minima points (than in the nonaluminized case). These higher amplitudes at the pressue minima can be measured with greater accuracy; and (2) the amplitude of the standing wave in the impedance tube in tests conducted with aluminized propellant was observed to be considerably more stable than the corresponding standing wave amplitudes observed in tests conducted with nonaluminized propellants. The decrease in the unsteadiness in the measured standing wave amplitude also results in more accurate data.

The second effort conducted under this task investigated the feasibility of measuring the mass loss of burning solid propellants by utilizing piezoelectric crystals. The basic idea is to load a crystal, which is part of an electronic circuit, with a sample of a solid propellant and then monitor the change in the natural frequency of one of the modes of the crystal as the mass of the propellant decreases due to burning. The initial phase of this program investigated the suitability of utilizing quartz crystals for performing the planned experiment. This investigation had shown that quartz crystals stop responding (i.e., oscillating) when loaded with weights which are considerably lower than any practical mass of a solid propellant test sample. Consequently, the use of quartz crystals was abandoned and this investigation proceeded to test the feasibility of utilizing ceramic crystals for the needed mass loss measurement. To accomplish this objective, a number of ceramic crystals were acquired and a special electronic circuit for determining the natural frequencies of these crystals has been developed. Initial tests with this circuit have shown that the actual properties of the acquired crystals differ considerably from the crystal properties specified by the supplier. Tests are currently under way to characterize the natural frequencies of the acquired ceramic crystal. Once these tests are completed, the feasibility of utilizing ceramic crystals in the direct determination of the unsteady mass loss of burning solid propellants will be investigated.

The third effort conducted under this task was concerned with the adaptation of the impedance tube technique for the measurement of the velocity response of solid propellants. To date, these efforts have been theoretical in nature and they have been concerned with (1) the determination of an optimum experimental configuration for performing the desired tests; (2) the development of an appropriate data reduction procedure that would utilize the measured acoustic pressure data to obtain the desired propellant velocity response data and (3) the determination of the accuracy of the velocity response data measured in the proposed experimental setup.

The experimental configurations investigated in these studies are similar to those discussed in our most recent proposal. These theoretical studies are currently in their last stages and as soon as the optimum experimental setup configuration is arrived at, the design and development of the actual experimental setup will begin.

C. Publications

(1) Salikuddin, M. and Zinn, B. T., "Adaptation of the impedance Tube Technique for the Measurement of Combustion Process Admittances", Journal of Sound and Vibrations, 68(1), 1980.

(2) Baum, J. D., Daniel, B. R. and Zinn, B. T., "Determination of Solid Propellant Admittances by the Impedance Tube Method" AIAA Paper No. 80-0281, January 1980. Also, accepted for publication in the AIAA Jr.

(3) Baum, J. D. , Daniel, B. R., and Zinn, B. T., "Experimental Determination of Solid Propellant Admittances by the Impedance Tube Method," Published in the Proceedings of the 16th JANNAF Combustion Meeting, Naval Postgraduate School, Monterey, CA., Sept 1979. Also CPIA Publication No. 308, pp. 325-341, December 1979.

(4) Salikuddin, M. and Zinn, B. T., "Experimental Observations of the Dependence of the Impedance Tube Behavior Upon Gas Phase Losses and Propellant Self-Noise," AIAA Paper No. 80-1020, June 1980.

(5)* Powell, E. A. and Zinn, B. T., "Application of the Galerkin Method in the Analysis of Combustion Instability Problems," Published in the Proceedings of the Second International Symposium on Innovative Numerical Analysis in Applied Engineering Science, pp. 213-222, June 1980.

(6)* Padmanabhan, M. S., Powell, E. A., and Zinn, B. T., "On the Applicability of the Method of Averaging in Solid Rocket Stability Analysis, Published in Combustion Science and Technology, Vol. 20, No. 5 and 6 (1979) pp. 179-184.

(7) Baum, J. D., Daniel, B. R., and Zinn, B. T., "Application of the Impedance Tube Technique for the Measurement of the Admittances of Aluminized Solid Propellants," in preparation, paper accepted for presentation at the 19th AIAA Aerospace Sciences Meeting, St. Louis, Missouri, January 1980.

D. Personnel

Principal Investigator - Ben T. Zinn

Senior Research Engineer - Brady R. Daniel

Graduate Research Assistants - Joseph D. Baum, Lakshmanan Narayanaswami and Peter J. Erbland.

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* Partially supported by this AFOSR Grant.

Ph.D. Thesis completed under this program:

Joseph D. Baum, " Experimental Determination of the Admittances of Solid Propellants by the Impedance Tube Technique", May 1980.

E. Professional Activities

(1) Zinn, B. T., "Determination of Solid Propellant Admittances by the Impedance Tube Method," Presented at the AIAA 18th Aerospace Sciences Meeting, Pasadena, California, January 14-16, 1980.

(2) Zinn, B. T., "Measurements of Unsteady Burn Rates of Solid Propellants," Presented at the AFOSR Contractors' Meeting, Lancaster, California, March 1980.

(3) Saliduddin, M. "Experimental Observations of the Dependence of the Impedance Tube Behavior Upon Gas Phase Losses and Propellant Self-Noise," Presented at the AIAA 6th Aeroacoustics Conference, Hartford, Connecticut, June 1980.

(4) Zinn, B. T., Chairman, Session on "Propellant Combustion" 18th Symposium (International) on Combustion, University of Waterloo, Canada, August 1980.

(5) Zinn, B. T., Chairman, Session on "Combustion Instability" 17th JANNAF Combustion Meeting, NASA Langley Research Center, Hampton, Virginia, September 1980.

(6) Zinn, B. T., "Experimental Determination of Solid Propellant Admittances by the Impedance Tube Method," Presented at the 17th JANNAF Combustion Meeting, NASA Langley Research Center, Hampton, VA., September 1980.

TASK II

BASE BURNING FOR PROPULSION

JAMES E. HUBBARTT WARREN C. STRAHLE

A. Research Objective

Burning in or around the near wake of blunt base bodies in flight elevates the pressure force on the base, thereby reducing drag or providing thrust. The objective of this research is to experimentally evaluate the performance potential using these modes of burning for a Mach 3 projectile. An axisymmetric, blunt-base model of the projectile is tested under burning conditions in a wind tunnel.

B. Status of Research

Three modes of operation have been tested during this program year. These are

1. supersonic radial injection of pure hydrogen,
2. combined supersonic radial and subsonic base injection of pure hydrogen, and
3. subsonic base injection of diluted hydrogen.

25 actual burning tests, each with several fuel flow rates, were completed. In addition, due to ignition difficulties under extreme operating conditions, many unsuccessful runs were made. Results and accomplishments for this period are summarized in the following paragraphs.

1. Supersonic radial injection of pure hydrogen. Hydrogen was injected over a range of supersonic speeds into the air stream through six radial nozzles equally spaced around the periphery of the forebody upstream of the base plane. The nozzles were recessed in a circumferential channel cut in the

forebody, serving as a flameholder and a cavity for pyrotechnic igniter compound. Sustained burning could not be achieved with this mode of injection due to the low stagnation temperature (approximately ambient) of the tunnel air stream. After several unsuccessful ignition attempts, using different igniters and hydrogen flow rates, this mode of operation was abandoned in favor of combined supersonic radial and subsonic base injection.

2. Combined supersonic radial and subsonic base injection of pure hydrogen. A porous base plate was adapted to the radial-jet, base configuration to permit simultaneous radial and base injection of pure hydrogen. It was thought and later shown that base burning, associated with base injection, would support combustion of the hydrogen jets. Initial tests with this mode of operation were plagued with erratic ignition problems. It was determined that these ignition problems were due to the lower air temperature during the colder weather and that the operating conditions for this test facility are marginal. The ignition problem was finally overcome by developing hotter igniters and pumping to slightly higher air temperatures. Following this, successful burning tests were completed, covering ranges in total hydrogen flow rate, in the ratio of the jet to base flow rates, and in the jet Mach number. For the higher hydrogen flow rates, base thrust (base pressure higher than the free stream static pressure) was achieved with high fuel specific impulse. However, it was determined from wake pressure surveys and wind tunnel surface pressures that there was tunnel wall interference for all flow conditions which yielded base thrust. For the lower hydrogen flow rates, which yielded base drag reduction, the performance data scattered significantly probably due to differences in combustion for these marginal test conditions. However, the best performance values were comparable with the high performance values reported last year with base injection alone. For example, a base drag reduction of 80% was obtained with a specific impulse

in excess of 5000. This is an encouraging indication that base thrust might be achieved efficiently with combined radial and base injection. It is concluded that this possibility should be pursued but cannot be further explored with this facility, because of the interference problem. It is recommended that either flight tests or tests in a large scale wind tunnel be conducted next.

3. Subsonic base injection of diluted hydrogen. The facility was modified for porous base injection of combustible mixtures of hydrogen and inert gases which control the molecular weight and effective heating value of the injectant. The diluted hydrogen mixtures partially simulates practical propellants. Base burning tests have been made using helium, nitrogen, and carbon dioxide as diluents. To date, five burning tests, each covering a range in hydrogen to diluent mass ratios, have been completed. These tests have shown that for a given hydrogen flow rate (i.e., for a given chemical energy input rate) helium and nitrogen diluents tend to reduce the base pressure while carbon dioxide diluent had no effect on the base pressure. It is known that base pressure increases with cold mass injection. Therefore diluting the hydrogen, thereby increasing the injectant flow rate, evidently causes a significant reduction in the flame speed and/or temperature. For all cases studied to date the effect of the diluent on the base pressure is small and, as an approximation, the specific impulse for a given base pressure elevation is directly proportional to the effective heating value of the injectant. The present results show that an 80% reduction in base drag can be obtained at a specific impulse of from 800 to 900 sec. using base burning with a fuel having an effective heating value of about 10,000 BTU/lb. This investigation using diluted hydrogen is in progress and will be terminated following two additional tests and the subsequent data analysis.

C. Publications

1. Hubbartt, J. E., Strahle, W. C., and Neal, D. H., "Mach 3 Hydrogen External/Base Burning," resubmitted, after review, for publication as paper in AIAA J.

2. Strahle, W. C., Hubbartt, J. E., and Leary, R. N., "Combined External and Base Burning for a Mach 3 Projectile," in preparation for publication as technical note in AIAA J.

D. Personnel

Principal Investigators - Warren C. Strahle
James E. Hubbartt

Research Engineers - Douglas H. Neale (first 3 months)
Richard N. Leary (last 9 months)

Graduate Research Assistant - Johnny C. Richardson

E. Professional Activities

Neale, D. H., Hubbartt, J. E., and Strahle, W. C., "Mach 3 Hydrogen External/Base Burning," AIAA Paper 80-0280 presented at the 18th AIAA Aerospace Sciences Meeting, at the AFOSR Contractor's Meeting, and at JANNAF Propulsion Conference.

Strahle, W. C. and Hubbartt, J. E., "Base and External Burning for Propulsion," submitted for presentation at AGARD Meeting on Ramjets and Ramrockets in Military Applications, Oct., 1981.

TASK III
BEHAVIOR OF ALUMINUM IN SOLID PROPELLANT COMBUSTION

E. W. PRICE R. K. SIGMAN

A. Research Objectives

The practical objectives of this Task are to improve the effectiveness of aluminum as a fuel in solid rocket propellants. Improved effectiveness will be measured by less lead time and cost in propellant development, higher performance, more reliable performance and lower cost. The short term practical objectives are higher specific impulse, more latitude and control of burning rate, control of combustion instability, reduction of detonation hazard (DDT), and more meaningful quality control on ingredient aluminum.

The immediate research goals have been to achieve:

1. Better understanding of the aluminum accumulation-agglomeration process that occurs on propellant burning surface, and how to predict and control the process.

2. Understanding and control of the processes that interrupt local growth of accumulated material by detachment from the burning surface, including specifically onset of ignition of the accumulations.

3. Understanding of the nature and burning history of agglomerated aluminum, how they depend on propellant formulation and combustion environment, and how to predict and control burning history.

4. New experimental methods needed for 1 to 3.

B. Status of Research

Investigations were conducted on the following topics using the experimental methods noted, and described later:

1. Modification of aluminum powder to control agglomeration. Method: evaluation of "pre-stretching" and "pre-oxidation", using hot stage microscope and combustion photography.

2. Sintering and agglomeration, the effect of type of aluminum and type of binder. Methods: sandwich burning, photography of the combustion zone of sandwiches and propellants, and controlled electrical heating of aluminum powders.

3. Nature and combustion of agglomerates; effects of pressure, types of aluminum and binder, propellant formulation. Methods: combustion photography, quench-collection of the combustion plume, chemical and microscopic study of quench samples (including sectioned agglomerates).

4. Combustion characteristics of highly aluminized propellants (up to 35%). Methods: combustion photography, quench burn, sample quench-collection from the plume.

The status of the experimental methods noted above is as follows:

1. A new combustion window bomb was completed that provides for more flexibility in type of experiment and test of larger samples.

2. Controlled electrical heating used the microscope hot-stage reported in earlier progress reports Ref. (1). A much more suitable microscope has been acquired.

3. Quench-collection from the combustion plume involves percolation of the combustion plume through an alcohol bath. The apparatus has been adapted to testing above atmospheric pressure, up to 3 MPa.

4. Chemical and microscopic study of quenched plume samples includes sieve-size grading; free aluminum analyses by acid solution and weight change; particle characterization by microscopy (optical and scanning electron beam system). Microscopic methods were used on quenched propellants, sandwiches, agglomerates, oxide products, and sectioned or broken agglomerates and oxide particles.

A summary of results of the above items of research is presented in the following.

Modification of Aluminum Powder

Further evaluation was made of a "heat treatment" of aluminum powder intended to reduce its tendency towards agglomeration in the propellant combustion zone. This method, referred to as "pre-stretching" the oxide skin on the particle (Ref. 2), was evaluated by comparison with unmodified aluminum and aluminum modified by a more difficult method called "pre-oxidation".

The present evaluation of pre-stretched aluminum involved.

1. Heating particles in a platinum surface, which shows the effectiveness of the oxide skin in preventing metal flow above the metal melting point (Fig.1).

2. Photography of combustion of propellants

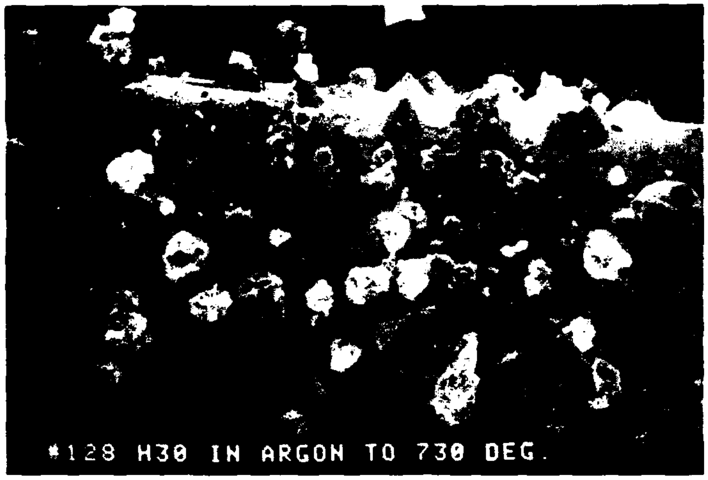
3. Evaluation of aluminum agglomeration - combustion, by study of material quenched in plumes above the propellant surface.

All evaluation methods supported the conclusion suggested by Fig. 1, in which incidence of contact point flow is seen to be drastically reduced by either pre-oxidation or pre-stretching. Propellants using the pre-treated powders were seen to have much more vigorus metal combustion, and higher burning rates. In plume quench tests, the pre-treated powders gave fewer, smaller agglomerates, higher aluminum consumption rates, and finer product oxide droplets, Good combustion was achieved in formulations with up to 30% aluminum. This is illustrated in Fig. 2, which compares the unreacted aluminum remaining in plume quench tests with untreated and treated aluminum.

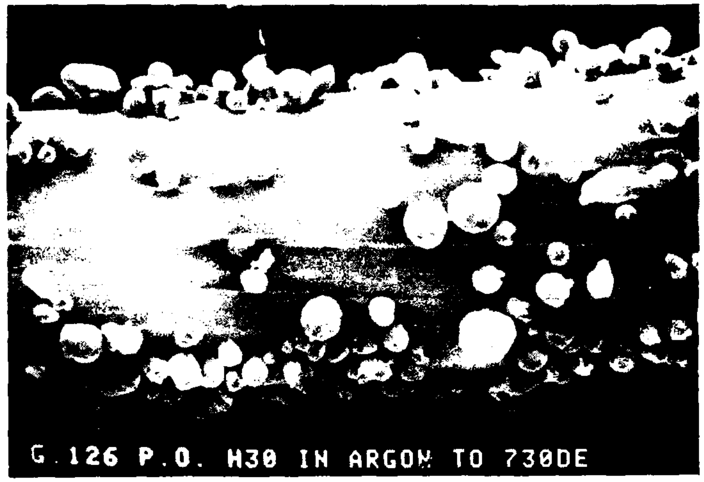
Sintering and Agglomeration

Aluminum that accumulates on the propellant burning surface is retained there by adhesion, apparently due to molten or sticky material. The particles concentrate and adhere to each other, apparently initially by

Fig. 1 Contact-point flow of molten aluminum when heated on platinum: comparison of (a) H-30 Al, (b) pre-stretched Al, (c) Pre-oxidized Al.



a



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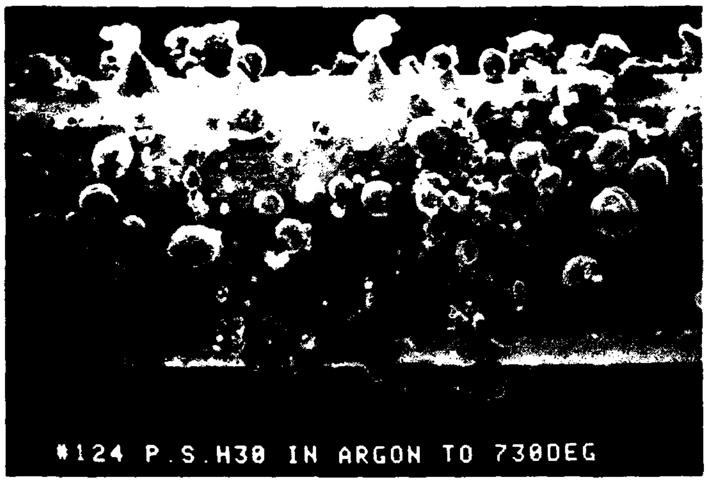


c

Comparision Of Coning Of Aluminum Particles On Platinum Wire During Heating To 730°c In An Argon Atmosphere.

a. Standard H30 Aluminum ; b. Preoxidized H30 ; c. Prestretched H30.

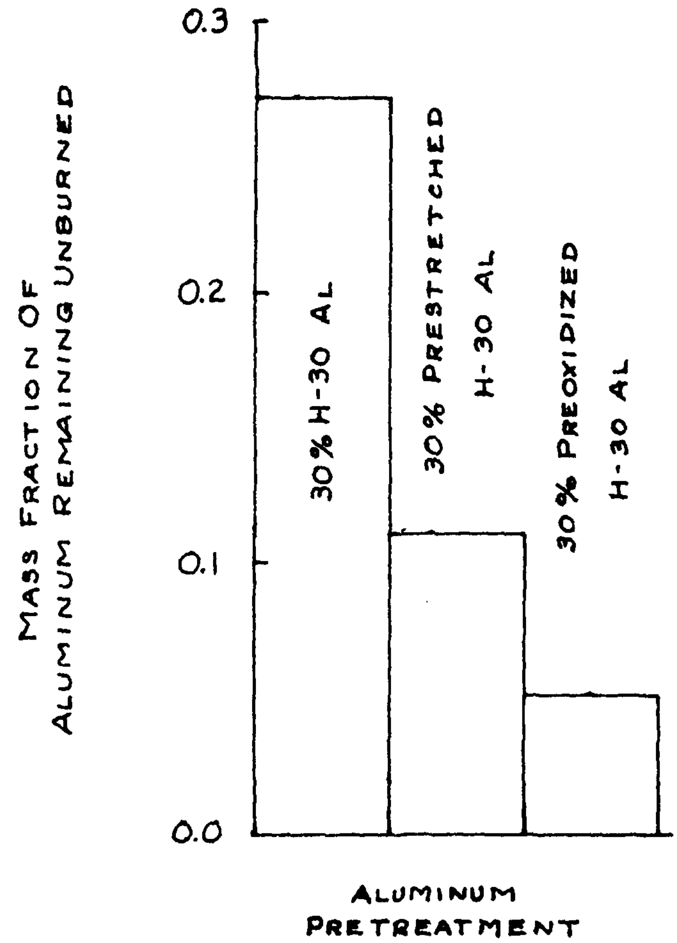


Fig. 2 Effect of aluminum pre-treatment on consumption of aluminum Data points show free aluminum remaining 5.1 cm from the burning surface. Tests were at 1.38 MPa, samples with AP/wax mass ratio 88/10, 100 μ m AP.

action of binder residue and then by inter-particle sintering. This process is very difficult to observe or characterize in detail, especially in the context of the chaotic state of affairs on the burning surface of a propellant. Recourse was taken to the simpler geometry of laminated, or "sandwich" configurations using a 60 m lamina of 50% aluminized binder between two laminae of dry-pressed ammonium perchlorate. Aluminized binder laminae were made as thin as was practical in order to more closely simulate the microstructure of propellant combusiton zones. These samples are burned edge-on and observed by combustion photography and by quenching-burning followed by microscopic examination (photographic results are not completely available yet). Tests were run using H-15 aluminum in three different binders polybutadiene acrylonitrile , and hydroxyterminated polybutadiene: PS, PBAN, HTPB). Pressures of 1.4, 4.1 and 6.9 MPa were used. The test series is summarized in Table 1 and 2. A set of quench samples is shown in Fig. 3, which illustrates the quench profiles, state of the accumulated aluminum, and effect of binder for tests at 6.9 MPa. Table 2 is a summary of the features of the quenched sandwiches. A detailed report of test results is being prepared, and the interpretation of results is being compared with comparison tests of binder effects on propellant combustion. From the quench test results it is evident that this experiment dramatizes the effect of the binder, and shows the tendency of the aluminum to concentrate in or on the pyrolizing binder surface. It shows that the quality of the aluminum accumulation is highly binder-dependent, as is the manner of the "presentation" of this accumulation to the rest of the combustion zone. From the limited motion picture coverage of tests to date it is evident that combustion photography will provide evidence of the effect of the

Table I

SUMMARY OF TESTS ON ALUMINIZED SANDWICHES

TEST VARIABLES \ PRESSURE	1.39 MPa (200 psi)	2.77 MPa (400 psi)	4.13 MPa (600 psi)	5.52 MPa (800 psi)	6.95 MPa (1000 psi)
AP/PBAN/AP	X		X		X
AP/PBAN-10% H-15/AP	X		X		X
AP/PBAN-30% H-15/AP	X		X		X
AP/PBAN-50% H-15/AP	X	X	X	X	X
AP/PS-H-15/AP	X				X
AP/HTPB-H-15/AP	X		X		X
AP/CTPB-H-15/AP	X				X
AP/PBAN-H-5/AP	X		X		X
AP/PBAN-Al_2O_3/AP			X		X
AP/PBAN-5% Fe_2O_3/AP			X		X
AP/PBAN-5% Fe_2O_3-H-15/AP	X		X		X
AP/PBAN-10% Fe_2O_3-H-15/AP	X		X		X

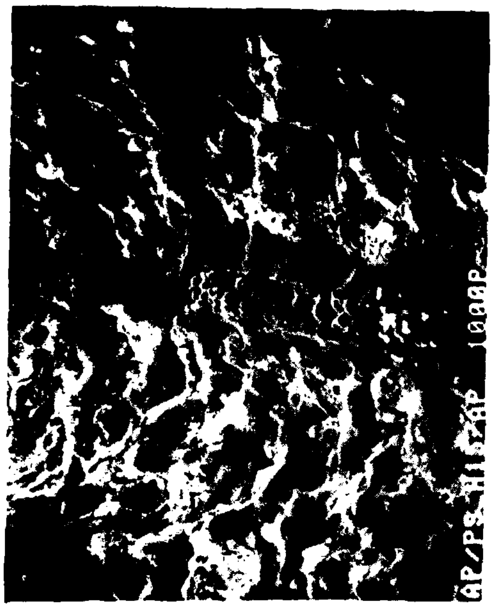
Nominal thickness of binder layer 60 μm
AP laminae dry-pressed at 170 MPa for 20 min. from 100 μm AP

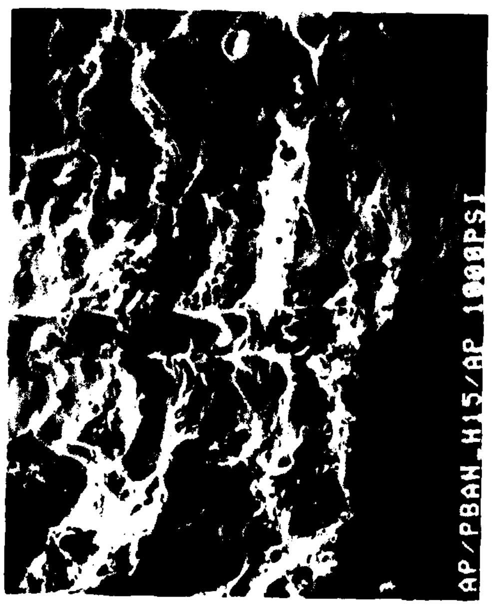
Table 2

CHARACTERISTICS OF QUENCHED SANDWICHES

	Binder		Aluminum Accumulation			Oxidizer Protrusion
	Height	Condition	Extent	Height	Condition	
PBAN						
200	recessed	light melt	moderate	neutral	clumps on melt layer, lightly "wetted"	slight
400	recessed	light melt	moderate	neutral		slight
600	recessed	light melt	moderate	neutral		slight
800	neutral, varies	light melt	moderate	neutral		moderate
1000	neutral, varies	light melt	moderate	variable		moderate
PS						
200	recessed	dry	very large	large, variable	dry sintered	nil
1000	recessed	light melt	moderate	moderate	dry on melt	moderate
HTPB						
200	recessed	light melt	large	neutral	even, lightly wetted by binder	moderate
600	protrudes	melt, no flow	medium	protrudes		large
1000	protrudes, variable	wet	low	protrudes	shows minimally through binder melt	extreme
CTPB						
200	recessed	melt, no flow	uneven	neutral	clumps	moderate
1000	protrudes slightly	melt, no flow	low	protrudes	partially submerged in binder	moderate
Figure 3	recessed	---	large	protrudes	---	moderate

Fig. 3 Sandwiches with 50% aluminized binder laminae quenched from 6.9 MPa: (a) PS binder; (b) PBAN binder; (c) HTPB binder.





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rather versatile accumulation behavior in agglomerate formation (in general, the effect of different binders has emerged as a critical factor in comparison propellant tests). From the combustion photography it is anticipated that characteristic accumulation times will be obtained, along with measures of the linear extent of the agglomerate-forming accumulates that "peel-off" from the sandwich interface. Such information is essential to determination of the dominant factors in agglomerate formation during propellant combustion.

Nature and Combustion of Agglomerates

While it is well recognized that the aluminum droplets in the propellant combustion zone form from coalescence of the accumulates that are produced there, the coalescense process is incredibly complex and the nature of the resulting agglomerate remains somewhat uncertain, as does its subsequent combustion history. It is not likely that the combustion efficiency, combustion dynamics, or role of the resulting two phase flow will be clarified without more complete information about the agglomerates. Plume quench tests (Ref. 4) offer the most direct means to such information, and have continued this year, with most tests being at elevated pressure. A summary of the tests and test conditions is shown in Table 3. Variables investigated included effect of pressure, distance from the propellant surface, % aluminum, type of aluminum powder, type of hydrocarbon fuel, and ingredient particle size.

Table 3 Part 1
Summary of Plume Quench Tests
Effect of Pressure

Pressure Test Variable		0.10 MPA 15 psi	.34 MPa 50 psi	.52 MPa 75 psi	.69 MPa 100 psi	1.04 MPa 150 psi	1.38 MPa 200 psi	2.77 MPA 400psi
Quench Distance (cm)	5	0 1 2	0	0 4 5	0	0 5	0 4	3
	10	0			0			
	15	0			0			
H-30 Al	15% Al 9% wax						0	0
	25% Al 7.7% wax					0	0	
Alcoa 100 µ m Al	12% Al						0	
	15% Al					0	6	
	7.6 cm	0						
	16.2 cm	0						
	27.9 cm	0						
	30.5 cm	0						

* Each symbol in the table denotes a test. A symbol "0" denotes no deviation from standard test conditions except as indicated. Tests with other symbols have further variants as noted below.

"0" Reference state: AP/wax in ratio 88/10, 100 µ m AP; 15% Alcoa 123 Al; quenched at 5 cm
"1" 12% Al, 3.8 cm quench dist.
"2" 12% Al, cm quench dist.
"3" 25% Al, 10% wax
"4" 20% Al
"5" 25% Al,
"6" 14 cm quench distance

Table 3 Part 2
Summary of Plume Quench Tests
Effect of Type of Aluminum

Test Conditions Aluminum	% Al	Quench Distance (cm)	Test Pressure (MPa)	Type of H.C. Fuel	% H.C. Fuel	Type of AP	% AP
H-30	30	5	1.38	wax	7.15	100 m	62.2
	25	5	1.38	wax	7.65	"	66.6
	25	5	2.76	wax	10.00	"	65
Pre-oxidized H-30	30	5	1.38	wax	7.15	"	62.2
Pre-stretched H-30	30	5	1.38	wax	7.15	"	62.2
Alcoa 123	30	5	1.38	wax	7.15	"	62.2
	25	5	1.04	wax	7.65	"	66.6
	15	5	0.68	wax	9.20	"	75.5
	15	5	1.04	wax	9.20	"	75.5
	15	5	1.38	wax	9.20	"	75.5
Alcoa 100 μm	15	6.4	1.04	wax	9.20	"	75.5
	15	14.6	1.35	wax	9.20	"	75.5
H-15	25	5	2.76	wax	10.00	*	65.0

* Blend of 100 μm/10 μm in 3/1 mass ratio

Table 3 Part 3
Summary of Plume Quench Tests
Effect of Aluminum Concentration*

% Al / Variant	5	10	12	15	20	25	30
Standard Condition	0	0	0	0	0	0	0
Alcoa 123, 0.52 MPa							
8.7% wax				0			
8.2% wax					0		
7.65% wax						0	

* Test conditions are standard except as noted. Standard conditions are AP/Wax in ratio 89/10, 100 μm AP; H-30 Al; quenched at 5 cm; pressure 1.38 MPa.

Evaluation of the test samples involves microscopic examination and characterization of quench samples, screening and weighing for size distribution, chemical determination of free aluminum constant, and sectioning of selected particles. By such evaluation it is sought to reconstruct the combustion history of agglomerates. Some trends revealed by the results to date are:

1. Agglomerates (quenched 1 cm or more from the propellant surface) contain varying amounts of oxide, usually ~ 10% in a single oxide lobe. Although not conclusive, tests to date do not suggest presence of unmelted impurities in the agglomerate while burning. Exceptions are agglomerates formed under adverse combustion conditions (very fuel-rich formulations or in flame regions with high heat loss). Such agglomerates are brittle, and often porous.

2. Agglomerates exhibit oxide lobes that are usually porous, suggestive of "out-gassing". The extent of the lobe is dependent on distance from the propellant surface, and on propellant formulation.

3. The free aluminum content in the plume at a given distance from the propellant surface is down to 25% of the original aluminum at a distance of 5 cm from the surface. Variables that gave the appearance of more vigorous aluminum combustion in motion pictures also gave higher propellant burning rate and showed a correspondingly rapid drop-off in free aluminum content.

4. Aluminum oxide in the plume consists of a variety of droplets in addition to the familiar majority constituent, i.e., spherical smoke particles in the 2 μm range. Larger spheres range from black-to-white-to-translucent. The most common is the white sphere in the 20-60 μm diameter range, with 30 μm most typical. Those quenched oxide droplets have about 20% voids in the form of small spherical pores. Other kinds of oxide spheres are found in the same samples, but the majority are white spheres under the more favorable combustion conditions (elevated pressure, favorable mixture ratio, treated aluminum powders, etc.). Other oxide spheres range from zero to 60% void.

5. Under unfavorable combustion conditions large ingredient aluminum particles (100 μm) often do not spheroxidize, and appear to burn slowly by surface oxidation (under conditions where the metal would be melted but the oxide skin may not melt).

Further studies of samples will be done selectively with the objective of quantifying trends as they relate to aluminum agglomerate burning rates and establish qualitative trends in kind and size or amount of each particle as needed to reconstruct agglomerate burning history. Specifically, it is necessary to distinguish what trends are a consequence of the kinds of agglomerates formed, and what trends are a consequence of the mode of burning of the agglomerate, once formed.

High Aluminum Content Propellants

Aluminum as a fuel ingredient in propellants is ordinarily used in concentrations much lower than the optimum predicted by equilibrium combustion-flow theory, primarily because of inability to obtain efficient combustion and control of Al_2O_3 product droplet size. However only minimal study has been made of combustion of the high aluminum formulations. The advances in understanding and control of aluminum combustion are applicable to the high aluminum content situation; accordingly the range of variables in the present studies was extended to aluminum contents of up to 30%, and combustion behavior was examined by combustion photography, quench burning and plume quench studies. Most of the work in this contract period was done with dry-pressed "propellant" samples, i.e., mixtures of ammonium perchlorate, aluminum and carnuba wax pressed at 100 MPa or more in an arbor press. Results of the study were reported at the JANNAF aluminum combustion workshop in Sept 1980, and the combustion photography is available in an edited motion picture.

The test work consisted of a systematic evaluation of the effect of aluminum concentrations, pressure, type of aluminum powder, type of hydrocarbon fuel, and oxidizer particle size. These variables were changed one at a time around a standard formulation-test state consisting of 7% wax; 30% H-30 aluminum; 63%, 100 μm ammonium perchlorate; 6.9 MPa (1000 psi). The actual test conditions are summarized in Fig. 4.

In general, it was found that combustion was satisfactory even at 30% aluminum. However it was quite sensitive to nearly all test variables, and this should be considered in any propellant development work. In general,

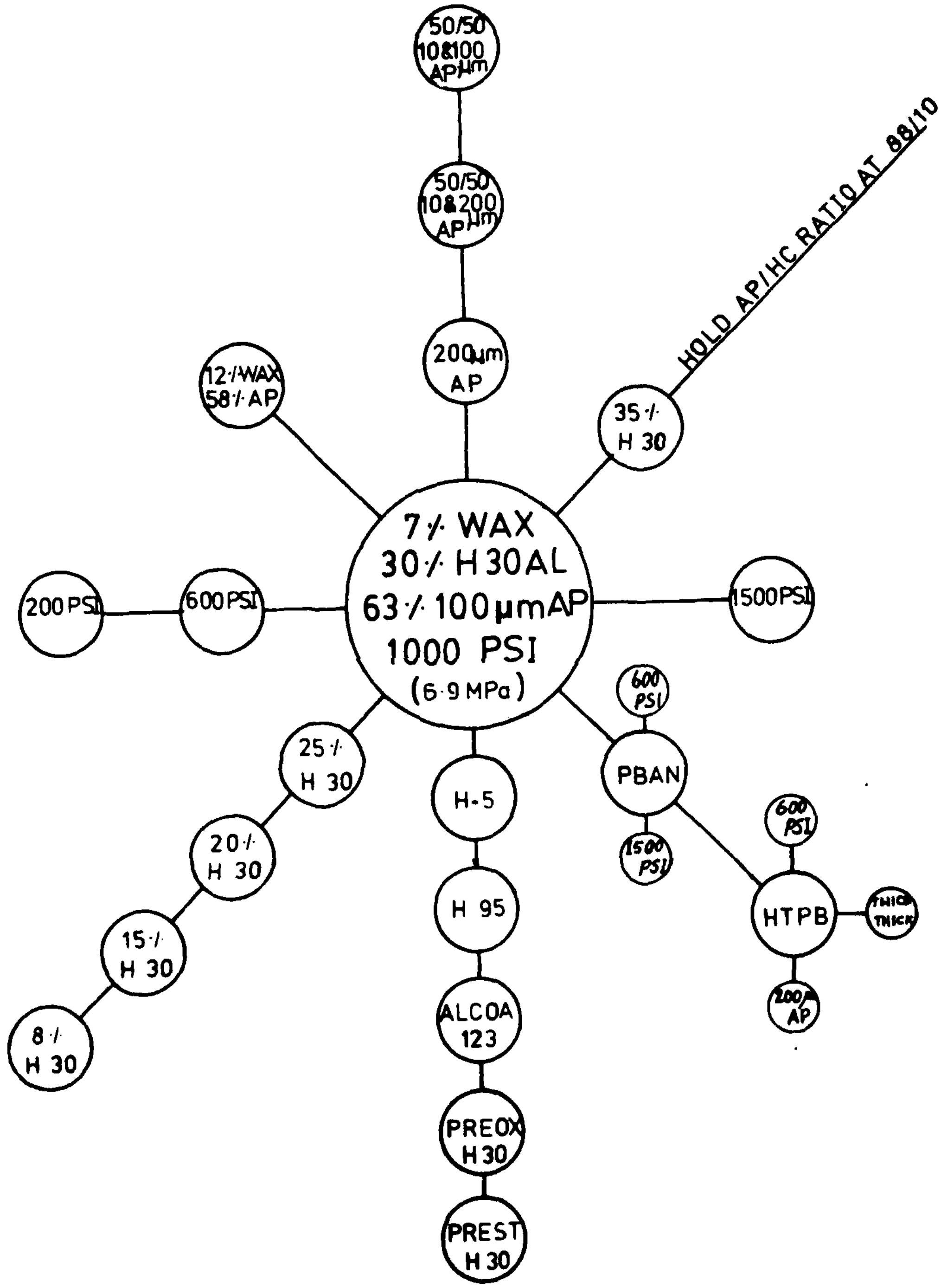

Fig. 4 Diagram showing test conditions used in study of combustion of high aluminum content propellant.

conditions (including use of pre-treated aluminum as noted above) that favored vigorous combustion as determined by high luminosity and product smoke density in combustion photography also gave high burning rates (Fig. 5), and smaller residual oxide droplets. Under adverse conditions (low pressure, high aluminum content), poor combustion could be remedied by use of pre-treated aluminum. Combustion was sensitive to the type of hydrocarbon fuel, and its mass fraction in the range 7-12%. Combustion was better with polymeric binders than with carnuba wax (which was used in most tests).

C. Publications

The following publications are being prepared:

1. Combustion of Metalized Propellants: a chapter in the AIAA book "Combustion of Solid Propellants".

2. Combustion of Aluminized Propellant Sandwiches for AIAA Propulsion Conference.

3. Combustion of High Aluminum Content Propellants, for AIAA Journal.

D. Personnel

Project management (Task III) was shared by Prof. E. W. Price and Dr. R. K. Sigman. Graduate Assistants were Mr. J. K. Sambamurthi and Mr. C. J. Parks (partially supported by a grant from the Aluminum Company of America).

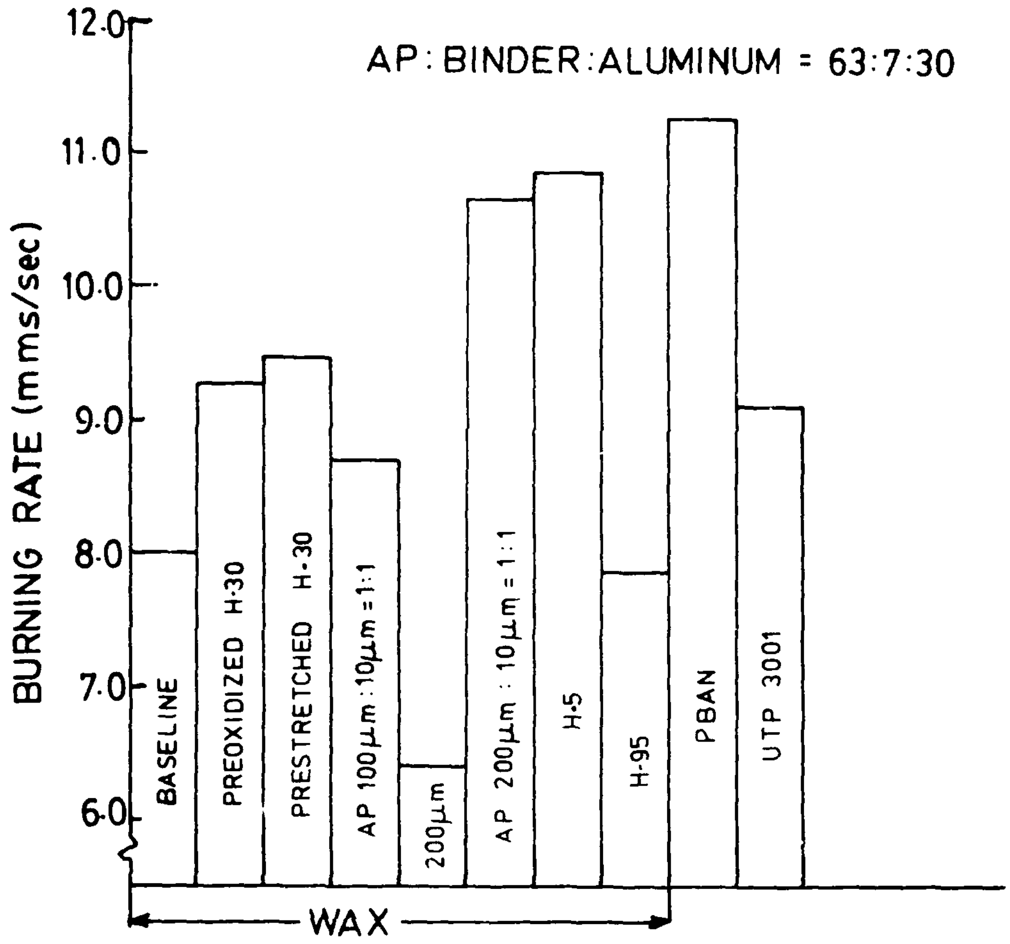

Fig. 5 Burning rate comparison for various modifications of the reference state propellant (6.9 MPa tests): (a) General comparisons;

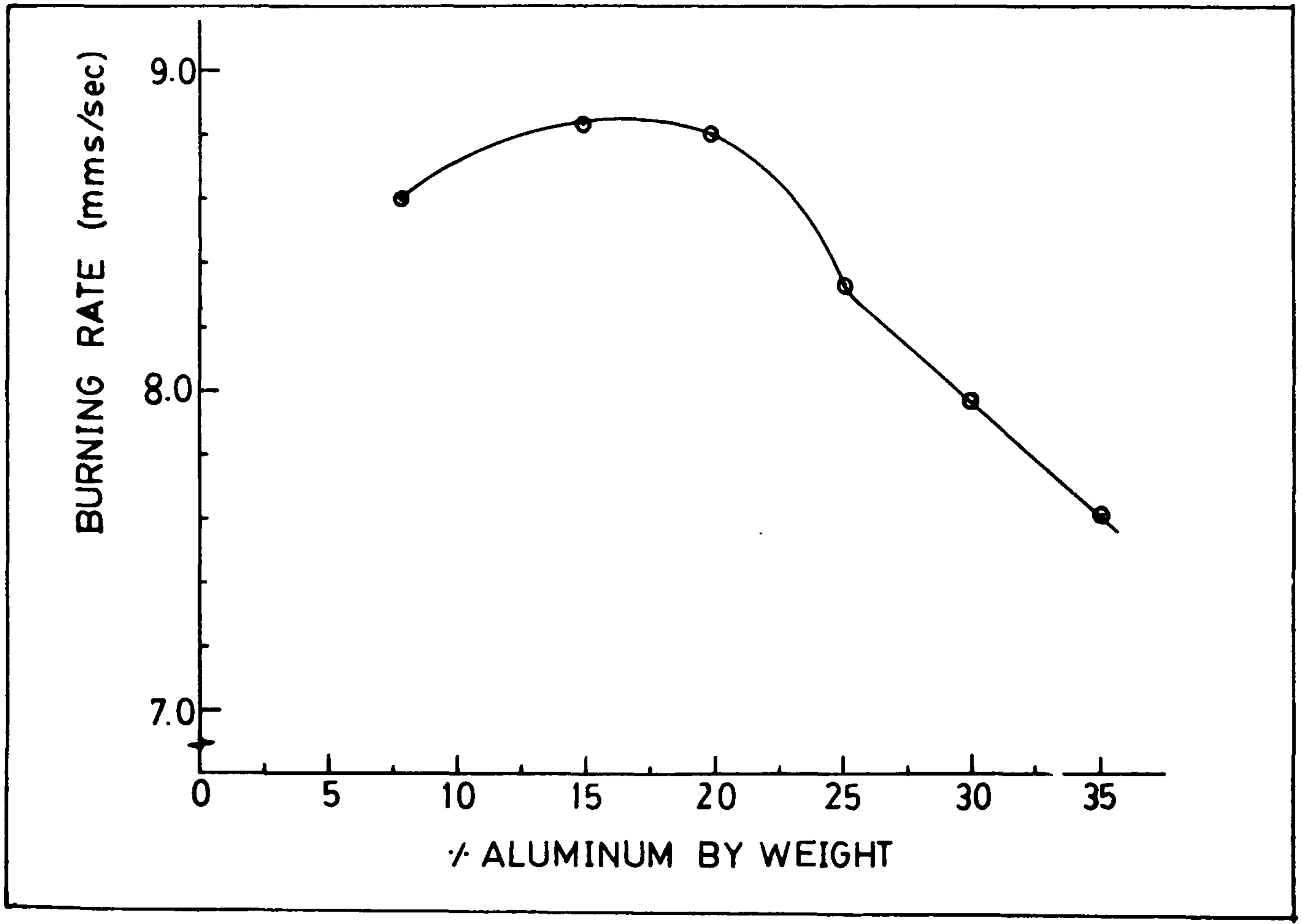

Fig. 5 Burning rate comparison for various modifications of the reference state propellant (6.9 MPa tests): (b) Effect of % aluminum;

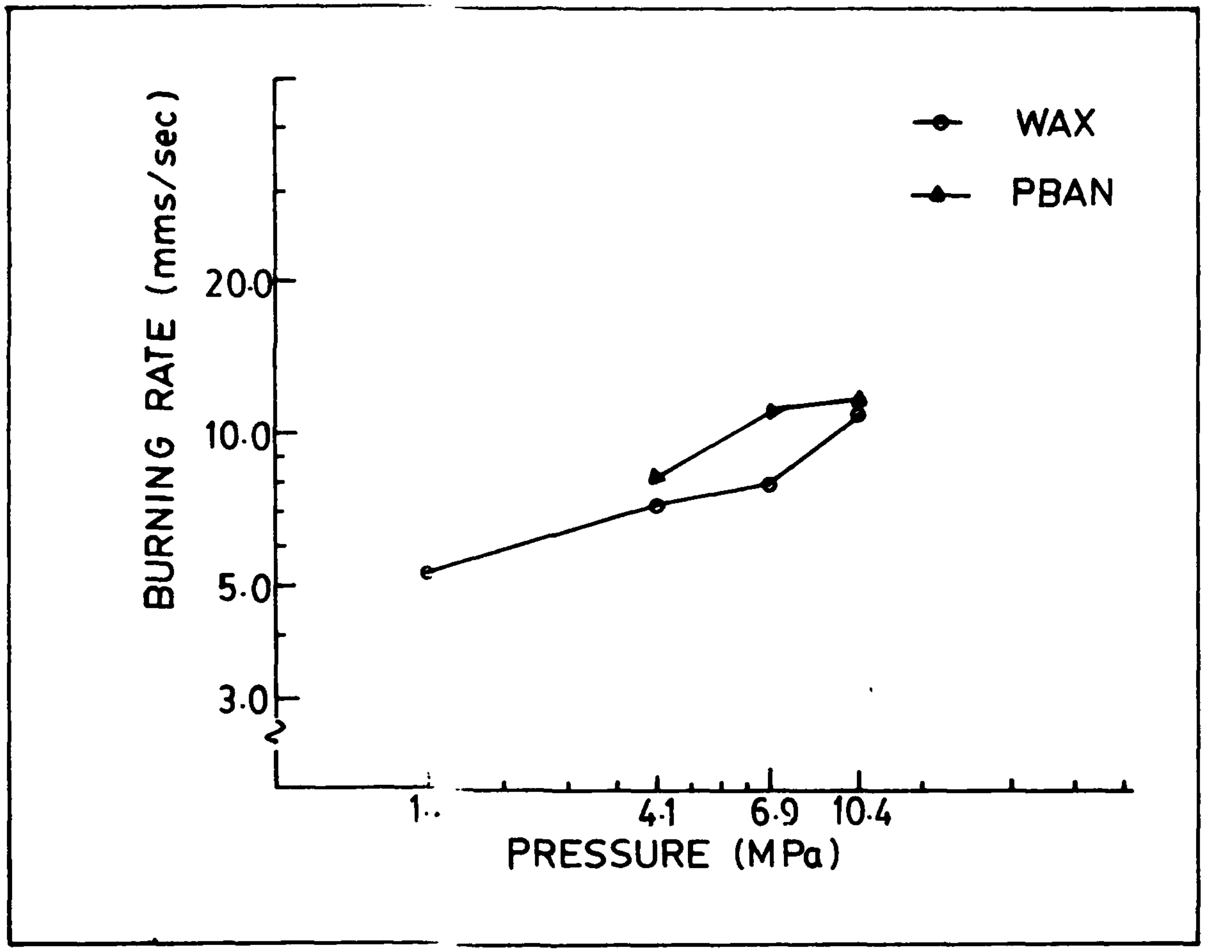

Fig. 5 Burning rate comparison for various modifications of the reference state propellant ([illegible] MPa tests): (c) Effect of pressure.

E. Professional Activities

The following presentations were made at meetings:

1. "Behavior of Aluminum in Solid Propellant Combustion" at the AFOSR Combustion Meeting, Mar. 1980.

2. "Combustion of High Aluminum Content Propellants", at the JANNAF Second Aluminum Combustion Workshop of Sept. 1980.

3. "Review of the 1st Aluminum Combustion Workshop", at the JANNAF Second Aluminum Combustion Workshop, Sept. 1980.

Consultations were held with the following persons on the subject of combustion of metals in solid propellants and/or related combustion instability problems.

1. Mr. Jolly, Australian Defense Ministry, Sept. 1980 (combustion instability)

2. Dr. J. F. Kincaid, U.S. Navy Special Projects Office, May, July, Aug. 1980 (high aluminum propellants).

4. Prof. F.E.C. Culick, California Institute of Technology, Oct. 1979 (review of Part II of the JANNAF "Manual" on Combustion Instability in Solid Propellant Rocket Motors").

5. Mr. Ralph Robinson, Air Force Weapons Laboratory, Jan. 1980 (fire environment in launch failures).

Committee services included:

1. Publication Committee, AIAA
2. Pendray Award Committee, AIAA
3. Solid Propellant Workshops Sub-committee, JANNAF.

4. JANNAF Panel membership, workshop and panel meetings a) Ramjet Oscillations b) Velocity Coupling, c) Aluminum Combustion Workshop.

F. References

1. Price, E. W. and R. K. Sigman, "Behavior of Aluminum in Solid Propellant Combustion", AFOSR-TR 77-0050, Nov. 1976.

2. Price, E. W., et al "Rocket Research at Georgia Tech", Interim Scientific Report to AFOSR on Contract No. F49620-78-C-003, Nov. 1979 pp III-11 to III-13.

3. Kraeutle, K. J. "Method to Test Adhesion of Aluminum Particles During Sub-ignition Heating: Dependence of Adhesion on Particle Properties", CPIA Publication 281, Vol. II Dec. 1976.

4. Price, E. W., E. A. Powell and R. K. Sigman "Further Studies of the Fire Environment of a Solid Rocket Propellant" Air Force Weapons Laboratory-TR-79-55, April 1950.

Figure Captions

Fig. 1 Contact-point flow of molten aluminum when heated on platinum: comparison of (a) H-30 Al, (b) pre-stretched Al, (c) Pre-oxidized Al.

Fig. 2 Effect of aluminum pre-treatment on consumption of aluminum Data points show free aluminum remaining 5.1 cm from the burning surface. Tests were at 1.38 MPa, samples with AP/wax mass ratio 88/10, 100 μ m AP.

Fig. 3 Sandwiches with 50% aluminized binder laminae 3 quenched from 6.9 MPa: (a) P5 binder; (b) PBAN binder; (c) HTPB binder.

Fig. 4 Diagram showing test conditions used in study of combustion of high aluminum content propellant.

Fig. 5 Burning rate comparison for various modifications of the reference state propellant (6.9 MPa tests): (a) General comparisons; (b) Effect of % aluminum; (c) Effect of pressure.

TASK IV

ROCKET MOTOR AEROACOUSTICS

WARREN C. STRAHLE

A. Research Objectives

For this task there is a single dominant research objective. It is to demonstrate that if the state of the turbulence may be measured or calculated for the interior flow in a rocket then the resultant pressure fluctuation field may be calculated.

B. Status of the Research

Substantial progress was made toward the main objective during the past year. Three experimental configurations were used, two of which were constructed during the past year. The first configuration was the old straight pipe which was instrumented in impedance tube fashion to determine the sidewall and entrance plane damping to acoustic waves. The second system consisted of the old straight pipe fitted with a porous sleeve section. This was used for exploratory experiments on the effect of side wall blowing on the noise generation. The third configuration was a rocket motor simulator consisting of completely porous walls feeding a cylindrical cavity terminated by a de Laval nozzle. This is the final configuration to be tested.

Excellent closure between theory and experiment was achieved on the old straight pipe. The measurements allowed determination of the sidewall and entrance plane impedances, which were necessary for insertion into the theory. Moreover, the theory was critically examined with respect to some approximations previously introduced. The result was an excellent prediction of the pressure field from the turbulence measurements.

The exploratory runs on the porous sleeve device showed the expected trends. That is, with side wall blowing the noise level increased because the turbulence was shown to increase. Interestingly, however, the split between local hydrodynamic noise (carried by the turbulence) and the coherent acoustic noise (propagational sound pumped up by the entire volume of turbulence) changed. The propagational sound decreased relative to the local noise as opposed to the runs with the straight pipe.

Construction of the rocket motor simulator was completed and exploratory runs were made to deduce some gross noise characteristics. At the head end the noise is basically propagational acoustic noise. This is as expected since there is very little turbulence there. On the other hand, at the nozzle entrance plane the noise is mainly the local hydrodynamic noise, since this is where the maximum flow velocity (and turbulence) occurs. Work was initiated on the theory of this device, which will require some substantial modification of the original theory, due to the more complex flow field.

C. Publications

1. Strahle, W. C. and Neale, D. H., "Turbulence Generated Pressure Fluctuations in a Rocket-Like Cavity," accepted for publication, AIAA J., February or March, 1981.

2. Hedge, U. and Strahle, W. C., "Pressure Generation by Turbulence in Rocket-Like Internal Flows," preparation just beginning for publication in the AIAA J. via the next AIAA Fluid and Plasmadynamics meeting.

D. Personnel

Principal Investigator - Warren C. Strahle

Research Engineers - Douglas H. Neale (first 3 months) Richard N. Leary (last 9 months)

Graduate Research Assistant - Uday M. Hedge

E. Professional Activities

Strahle, W. C. and Neale, D. H., "Turbulence Generated Pressure Fluctuations in a Rocket-Like Cavity," AIAA Paper 80-0208 presented at the 18th AIAA Aerospace Sciences Meeting and at the AFOSR Contractor's Meeting.

Appointment to JANNAF Panel on Pressure Oscillations in Ramjets with first meeting held 22 Sept. 1980 in Hampton, VA.

Associate Editor for Combustion and Aeroacoustics, AIAA J.

Member of AIAA Propellants and Combustion TC

Editorial Board Member of Combustion Science and Technology

Session Co-Chairman at 18th International Combustion Symposium

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