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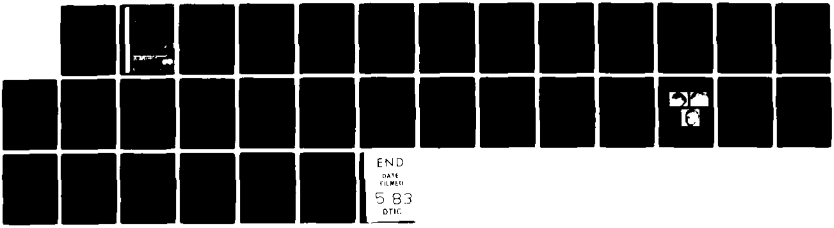

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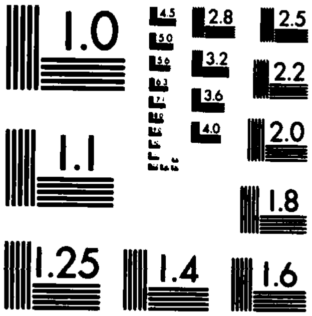

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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

Task I. In the first phase of this program the previously developed impedance tube setup was utilized to determine the dependence of solid propellants pressure coupled response functions and associated gas phase losses upon the

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aluminum content of the propellant. Tests over the 400-1000 Hz frequency range showed that increasing the aluminum content of the propellant increases both the propellant driving and associated gas phase losses. Furthermore, it shifts the frequency at which maximum driving occurs. In the second phase of this task, the modified impedance tube setup has been utilized in the investigation of the characteristics of the velocity coupled response factor. The status of this investigation is summarized in this report.

Task II. The cold flow test facility, which will be used in the first phase of modeling flows in the flame stabilization region, and the two-component LDV system, which will be the main tool for velocity measurements, have been developed and tested to verify that performance is satisfactory and to acquire skills. Also, it has been determined that Rayleigh scattering will be used for measuring species concentration in cold flows and Raman scattering will be used for measuring both species concentrations and temperatures in the combustion tests which come later. The Rayleigh scattering system has been developed and preliminary tests have been completed in order to eliminate problems and develop techniques. Testing in the cold flow facility is being initiated now. In addition, a computer code that uses the k-method to model turbulence has been acquired, tested extensively via numerical experiments, and improved. Further checks and improvements, as required, will be made as cold flow data becomes available.

Task III. Studies of aluminum agglomeration-combustion in AP/Al/HC binder systems were continued, including refinement and extension of experimental methods, extension of the range of test variables, and consolidation of results into a comprehensive qualitative theory of aluminum behavior and summary of experimental results. A family of propellants was contrived to provide a critical test of key elements of agglomeration theory. Test results support the theory.

Task IV. Progress continued in the comparison between theory and experiment in the problem of pressure fluctuation prediction given the state of turbulence in rocket-like interior flows. A breakthrough was made in the prediction of the non-propogational, hydrodynamic component of pressure and the acoustic component continues to be predictable. Four configurations have now been tested, varying length to diameter ratio and side wall impedance. Future tests will concentrate on mass flow and mass flow distribution variations.

AFOSR INTERIM SCIENTIFIC REPORT

AFOSR-TR-82

COMBUSTION DYNAMICS IN ROCKETS

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TASK I

INVESTIGATION OF THE PRESSURE AND VELOCITY COUPLED RESPONSE FUNCTIONS OF ALUMINIZED AND NON ALUMINIZED SOLID PROPELLANTS

BEN T. ZINN BRADY R. DANIEL

A. Research Objectives

The general objective of this study is the determination of the characteristics of the burn rates of different classes of solid propellants under various conditions simulating those observed in unstable solid propellant rocket motors. More specifically, the research conducted during the past year under this task was concerned with the determination of the dependence of propellant driving and damping upon the aluminum content of the propellant and the development of experimental capabilities for investigating the characteristics of velocity coupled response functions of solid propellants.

B. Status of Research

During the initial phase of this reporting period the previously developed impedance tube setup was utilized in the investigation of the effect of aluminum addition upon the response functions and gas phase losses associated with aluminized propellants. To isolate the effect of aluminum content, three different propellant formulations differing primarily in their aluminum content were tested over the 400-1000 Hz frequency range. The tested propellants, UZ7, UZ8 and UZ9 had similar nonaluminized fractions and they contained 0,5 and 18 percent aluminum, respectively. Typical results obtained in these tests are provided in Fig. 1 where y_r, the real part of the admittance, describes the propellant driving and G the associated gas phase losses. Examination of Fig. 2 shows that increasing the aluminum content of the propellant (1) increases the driving capabilities of the propellant; (2) shifts the frequency at which maximum driving occurs; and (3) increases the gas phase damping. Since increasing both the propellant driving and the gas phase damping would exert countering effects on the stability of a rocket motor, one cannot determine the effect of aluminum addition upon a given rocket stability without conducting an analysis capable of properly accounting for the above indicated effects. Furthermore, it remains to establish that the observed effects are due to the aluminum addition only and not due to the slight differences in the compositions of the nonaluminized fractions of the tested propellants.

The experimental configuration developed for the determination of the velocity coupled response functions of solid propellants is shown in Fig. 2 along with the impedance tube wave equations. These equations are similar to those utilized in rocket motor axial stability analyses, the only difference being that in the latter case the length of the sidewall propellant sample is equal to the motor length. In an experiment, the "driver" propellant sample provides a stream of hot combustion products that moves past the "test" propellant samples in an attempt to simulate actual rocket flow conditions. The acoustic driver at the opposite end of the tube is used to excite a standing wave of a desired frequency inside the impedance tube and the

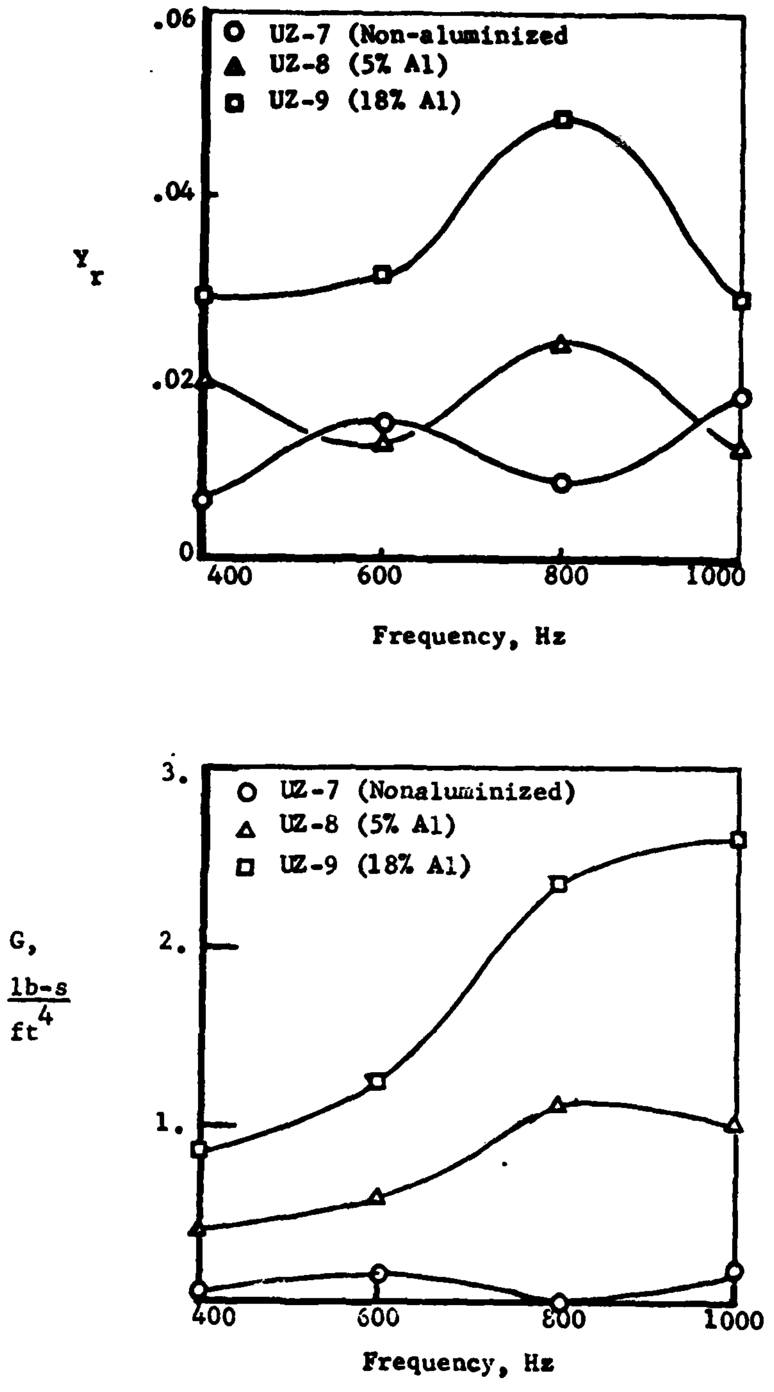
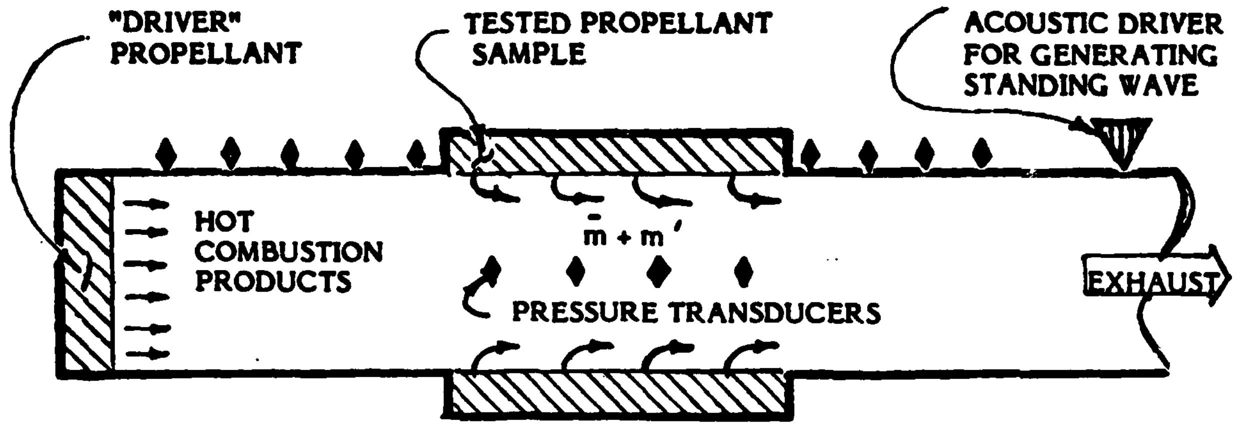


Fig. 1. Dependence of Propellant Driving, Y_r, and Associated Gas Phase Losses, G, upon Frequency and Propellant Aluminum Content.

IMPEDANCE TUBE WAVE EQUATIONS



CONTINUITY: $$i\omega\rho' + \frac{d}{dx}(\bar u\rho' + \bar\rho u') = \frac{b}{A}m_b'$$

MOMENTUM: $$i\omega\bar\rho u' + \bar\rho\bar u\frac{du'}{dx} + \bar\rho\frac{d\bar u}{dx}u' + \frac{dp'}{dx} + \frac{b}{A}\bar m_b u' + F' = 0$$

ENERGY: $$i\omega p' + \bar u\frac{dp'}{dx} + \frac{d\bar p}{dx}u' + \gamma\bar p\frac{du'}{dx} + \gamma\frac{d\bar u}{dx}p' = \frac{b}{A}\bar m_b\bar E\left(\frac{E'}{\bar E} + \frac{m_b'}{\bar m_b}\right) + (\gamma-1)G\bar u u'$$

WHERE

$$E = \gamma RT_F + \gamma R\Delta T + (R/2C_v)(u^2 + u_b^2)$$

THE VELOCITY AND PRESSURE COUPLED RESPONSE FUNCTIONS ARE INTRODUCED BY LETTING

$$R_p = \frac{\left(\frac{E'}{\bar E} + \frac{m_b'}{\bar m_b}\right)}{\left(\frac{p'}{\bar p}\right)} \quad ; \quad R_v = \frac{\left(\frac{E'}{\bar E} + \frac{m_b'}{\bar m_b}\right)}{(u'/\bar a)}$$

OR

$$\frac{m_b'}{\bar m_b} + \frac{E'}{\bar E} = R_p\frac{p'}{\bar p} + R_v\frac{u'}{\bar a}$$

Fig. 2. Set-up and Equations Utilized for the Determination of Velocity Coupled Response Functions.

tested propellant sample is placed in a region experiencing both pressure and axial velocity oscillations. The developed experimental setup permits locating the "test" propellants at any distance downstream of the "driver" propellant. Consequently, the response of the "test" propellants can be investigated at different acoustical environments along the standing wave (e.g., at a pressure node). A stepping motor is utilized to feed the "test" propellant samples inward at the propellant burning rate. This is done in order to maintain the burning "test" propellant surfaces flush with the impedance tube walls.

During a test, the acoustic pressure data are continuously fed, via an analog-to-digital converter, into a minicomputer-disc system for storage. The test duration is divided into a series of data acquisition periods, separated from each other by periods of data transfer. Each data acquisition period, called a block, can be programmed to acquire data over a period whose duration is a multiple of 12 cycles of the test signal.

After the test, the stored data are Fourier-analyzed to obtain the amplitudes and phases of the measured data at the test frequency. A study of the analyzed data shows the existence of ignition and extinguishment transients with a quasi-steady burning period in between. Data obtained during this quasi-steady period is used to evaluate the propellant response. The data reduction procedure developed for the velocity coupled case has been discussed in detail at the 18th JANNAF Combustion Meeting. It is to be noted, however, that the data-reduction procedure presumes a knowledge of the pressure coupled response and it determines only the velocity coupled response function. Consequently, the pressure coupled response function needs to be determined in a separate experiment or by use of a reliable theory.

Since many of the acoustic pressure measurements are performed near the pressure node, the desired signal is often buried in noise from other sources. Signal averaging can be used to separate the signal from the noise. Since the available memory of the minicomputer limits the amount of data that can be recorded in a given block, an estimate of the minimum number of periods of the test signal over which the data should be averaged to sufficiently enhance the signal-to-noise ratio is required. This problem is currently being investigated by comparing data averaged over different numbers of cycles during the quasi-steady burning period.

The spatial amplitude and phase distributions, used to evaluate the velocity coupled response functions, were obtained by averaging the measured signals over 36 cycles. The needed pressure coupled response functions were measured by the use of the previously developed impedance tube method. A comparison between the computed standing wave pattern that provided the "best" agreement and the experimental data is presented in Fig. 2. The determined optimum value of R_v and the measured value of R_p that were used to predict the standing wave pattern are also indicated in the figure.

Examination of Fig. 2 indicates a reasonable agreement between the predicted and measured amplitude distributions. In contrast, some disagreement is noted in the compared phase distributions. These discrepancies could be due to errors in measurements and/or data reduction procedure or due to shortcomings in the wave equations that are currently utilized (see Fig. 1) to model the axial instability problem. Specifically, a rigorous justification for the utilized definitions of R_p and R_v is lacking and there exists no proof that the utilized "one-dimensional" formulation is indeed capable of accounting for the multi-dimensional aspects of the problem where driving of the axial oscillations occurs on the side walls. These problems are currently under investigation under this program.

C. Publications

(1) Zinn, B. T., and Narayanaswami, L., "Application of the Impedance Tube Technique in the Measurement of Provided by Solid Propellants During Combustion Instabilities", Acta Astranautica, Vol. 9, 1982.

(2) Zinn, B. T., Baum, J. D. and Daniel, B. R., "Determination of Aluminized Solid Propellant Admittances by the Impedance Tube Method," AIAA Journal, Vol. 20, No. 3, pp. 417-421, March 1982.

(3) Zinn, B. T., and Narayanaswami, L., "Experimental Determination of the Velocity Coupled Response of Solid Propellants," Proceedings of the 18th JANNAF Combustion Meeting, Pasadena, CA, Oct. 1981.

(4) Sigman, R. K., and Zinn, B. T., "A Finite Element Approach for Predicting Nozzle Admittances," accepted for publication in the Journal of Sound and Vibrations.

D.Personnel

Principal Investigators - Ben T. Zinn and Brady R. Daniel.

Graduate Research Assistants - Lakshmanan Narayaraswami and Koorosh Madnia.

E Professional Activities

(1) Zinn, B. T., "Experimental Determination of the Velocity Coupled Response of Solid Propellants", presented at the 18th JANNAF Combustion Meeting, Jet Propulsion Laboratory, Pasadena, Calif., Oct. 19-23, 1981.

(2) Zinn, B. T., "Investigation of the Driving and Gas Phase Losses Associated with Different Aluminized and Nonaluminized Propellants," presented at the 19th JANNAF Combustion Meeting, NASA/Goddard Space Flight Center, Greenbelt, Md., October 4-7,1982.

(3) Zinn, B. T., "Investigation of the Velocity and Pressure Coupled Admittances of Aluminized and Nonaluminized Propellants", AFOSR Contractors' Meeting, Lancaster, Calif., March 1982.

(4) Member, U. S. Air Force Review Panel for the New Aero Propulsion Systems Test Facility (ASTF) in Tullahoma, Tenn.

TASK II

HETEROGENEOUS DIFFUSION FRAME STABILIZATION

WARREN C. STRAHLE JAMES E. HUBBARTT J. I. JAGODA

A. Research Objective

The overall objective of the program is to understand and be able to predict recirculatory turbulent reacting flows, flame stabilization limits, and fuel regression rates in a flame stabilization region like that for a solid fueled ramjet. The specific goals for the past year were to develop a cold flow test facility, develop the Laser Doppler Velocimeter, make plans and preparations for analysis and testing, and begin cold flow tests.

B. Status of research

During this past year substantial progress has been made toward the overall objective by way of completing preliminary tasks necessary before the integrated experimental and analytical studies. The tasks include the development of test equipment, diagnostic techniques, and analysis. The following paragraphs summarize the major accomplishments.

1. Test equipment. Design, fabrication, assembly, and check-out of the cold flow test facility has been completed. This facility will be used in the first phase of the progressive modeling of flows in flame stabilization zones. It has a rectangular cross-section and draws room air past a rearward facing step which simulates the flameholder with recirculation. The large scale test section is 43 cm long, 40.5 cm wide, and 10.5 cm high. The boundary layer thickness and step height are variable. Flow velocity is variable up to about 100 m/sec. Preliminary tests have shown that the mean flow in the test zone is two-dimensional and is the quality needed for evaluating and developing the analysis. The facility is equipped for making mean flow and turbulent velocity surveys using both Laser Doppler

Velocimeter (LDV) and hot wire anemometer techniques. Furthermore, mean velocity profiles can be evaluated using pressure probes and the surfaces are equipped with numerous static pressure taps for measuring pressure gradients.

Also, during this period, the second channel of the LDV has been acquired and assembled. In addition, the LDV actuator, with stepping motors and remote controller, has been developed. This portable actuator provides the capability of surveying over a total volume 30 x 48 x 70 cm. Finally, facilities for calibrating the LDV and hot wires have been developed.

2. Diagnostics. The program makes use of advanced laser diagnostic techniques for measuring instantaneous velocities, species concentration, and temperatures and for evaluating their spectra and correlations. This year, the work focused on considering and selecting techniques, developing equipment, and preliminary testing in simple flows. The testing has been necessary in order to develop procedures and skills, isolate and eliminate problems, and determine accuracies.

Testing with the two-channel LDV has uncovered serious problems with respect to the electronics, signal to noise ratio, flow seeding, and test section windows. Faulty electronic components have been repaired by the manufacturer. Also, as examples, it has been determined that the nominal diameter of seeding particles must be near 1μm for a satisfactory doppler signal and that the test section window must be clean and made of good quality glass rather than plexiglas to eliminate excessive noise. Now, it is thought that all serious problems have been resolved and that operator skills are adequate for final testing. Thus, testing will begin in the cold flow facility. In parallel, velocities will be measured with hot wires and pressure probes to check and complement the LDV data.

Rayleigh scattering (i.e., molecular scattering) has been selected as the technique for measuring species concentrations for the cold flow case with surface blowing of foreign gases. Since velocity and concentration measurements are to be carried out simultaneously, the LDV beams will be used as the incident radiation for molecular scattering. The gases must be seeded for the LDV measurements and the intensity of light scattered from these seed particles is many orders of magnitude greater than that from molecules. Because this intense light will render the photomultiplier (PM) for Rayleigh scattering measurements inoperative for a long time, the PM must be gated off when particles are in the test volume. The gating circuit has been designed and assembled. Tests have shown that this circuit performs satisfactorily. However, the tests reveal a signal fluctuation of about ± 15% due to photon "shot noise" (i.e., fluctuations due to changes in the number of photons in the test volume) and submicron particles in the air. It has been decided that this will not affect cross correlations because of the randomness of shot and submicron particle noise but will affect auto correlations. For auto correlations it will be necessary to deal with probability density functions which can be corrected by extracting the portion due to noise.

Vibrational Raman scattering has been selected for simultaneous concentration and temperature measurements in flows with combustion. The Candela Dye Laser and spectrometer have been ordered and a polychromator for mounting photomultipliers at the exit plane of the spectrometer is being designed. It is anticipated that considerable experience will be acquired with the Raman scattering system prior to the development of the combustion test facility.

3. Analysis. A computer code that uses the k-ϵ method to model turbulence has been acquired and used for numerical experiments which explored characteristics and capabilities of the k-ϵ approach for predicting flow details in the flame stabilization region with cold flow conditions. The code uses the usual conservation equations for the mean flow variables and two additional equations for evaluating the turbulent kinetic energy, k, and dissipation rate, ϵ, which are

employed as turbulence scales to establish a turbulent viscosity relating Reynolds stresses to mean flow strain rates. Also, a second computer code based on the same k-ϵ model has been written for the one-dimensional, asymptotic solution of fully developed channel flow. This code was developed as a simple method for assessing the other code at the asymptotic limit far downstream of the flame stabilization region.

It has been determined that at least 30 streamwise and 40 cross-stream grid points will be required for satisfactory convergence of the numerical computations in the flame stabilization region. This requires a CPU time of about 700 sec. on the CYBER 74. Also, it has been determined that the numerical solution must be extended to about 100 channel heights downstream of the step expansion before fully developed channel flow conditions are achieved. Because this asymptotic limit, which is easily specified, cannot be obtained in the test configuration it may be necessary to input downstream as well as upstream boundary conditions for accurate predictions in the flame stabilization region. Further studies are being made to determine the sensitivity of the results to the downstream conditions. The flowfield predictions by the two computer codes for the one-dimensional asymptotic limit were in excellent agreement. Also, these predictions agreed with available channel flow data.

Comparisons between predictions with the k-ϵ code and available experimental data for the cold flow version of the flame stabilization region have shown that predicted turbulent stresses and reattachment lengths are in serious error. However, substantial improvements in the predictions have been obtained by including a new velocity-pressure gradient correlation in the turbulent kinetic energy equation. Also it has been shown that additional improvements can be made by adjusting empirical constants in the k-ϵ equations. Justifications for changing constants are still being sought. It is anticipated that further improvements will be made as the experimental data from the cold flow facility becomes available.

C. Publications

1. J. E. Hubbartt and W.C. Strahle, "External/Base Burning for Base Drag Reduction at Mach 3," AIAA Journal, 19, pp. 1502-1504, Nov., 1981.
2. W. C. Strahle, J.E. Hubbartt and R. E. Walterick, "Base Burning Performance at Mach 3," AIAA Journal, 20, pp. 986-991, July, 1982.

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E. Professional Activities

Strahle, W.C., "Base and External Burning for Propulsion," presented at JANNAF Combustion Meeting and AGARD Conference on Ramjets and Ramrockets for Military Applications, Oct., 1981.

Strahle, W.C., "Solid Propellant Airbreathing Combustion Phenomena," presented at AFOSR Contractors Meeting, Lancaster, CA, Feb., 1982.

TASK III
BEHAVIOR OF ALUMINUM IN SOLID PROPELLANT COMBUSTION

E. W. PRICE R. K. SIGMAN

A. Research Objectives

The objectives of this task were to gain understanding and improved control of combustion of the aluminum ingredient in solid propellant, and of the aluminum effect in overall propellant combustion. In practical terms, this relates to attainment and assurance of desired burning rate, combustion efficiency, combustor stability and resistance to detonation while striving for high propellant density and high specific impulse.

Specifically, the objectives were to clarify the accumulation processes that set the stage on the propellant burning surface for formation of "large" agglomerates of aluminum, and to clarify the conditions for ignition-agglomeration, the nature and combustion of agglomerates, and the nature of the oxide product population.

Six areas of investigation were described in the original proposal, and progress in these areas is summarized in the following.

B. Progress and Significant Accomplishments

General.

Because of the complex and varied nature of aluminum combustion behavior in propellants (Fig. 1), the present program has been designed to clarify the qualitative aspects of the combustion. This approach was based on the premise that a rigorous analytical description of the overall behavior would be intractable, and a simple analytical description would be naive. Accordingly, attention was addressed to clarification of the remaining controversial aspects of aluminum behavior.

A variety of experimental studies were undertaken and/or continued from earlier work, studies designed to establish the controlling mechanisms in the various sequential steps characteristic of aluminum behavior in combustion of ammonium perchlorate-aluminum-hydrocarbon binder propellants burning in quiescent atmospheres. In addition, it was proposed that studies be extended to propellants with other formulations, and to combustion with flow environments.

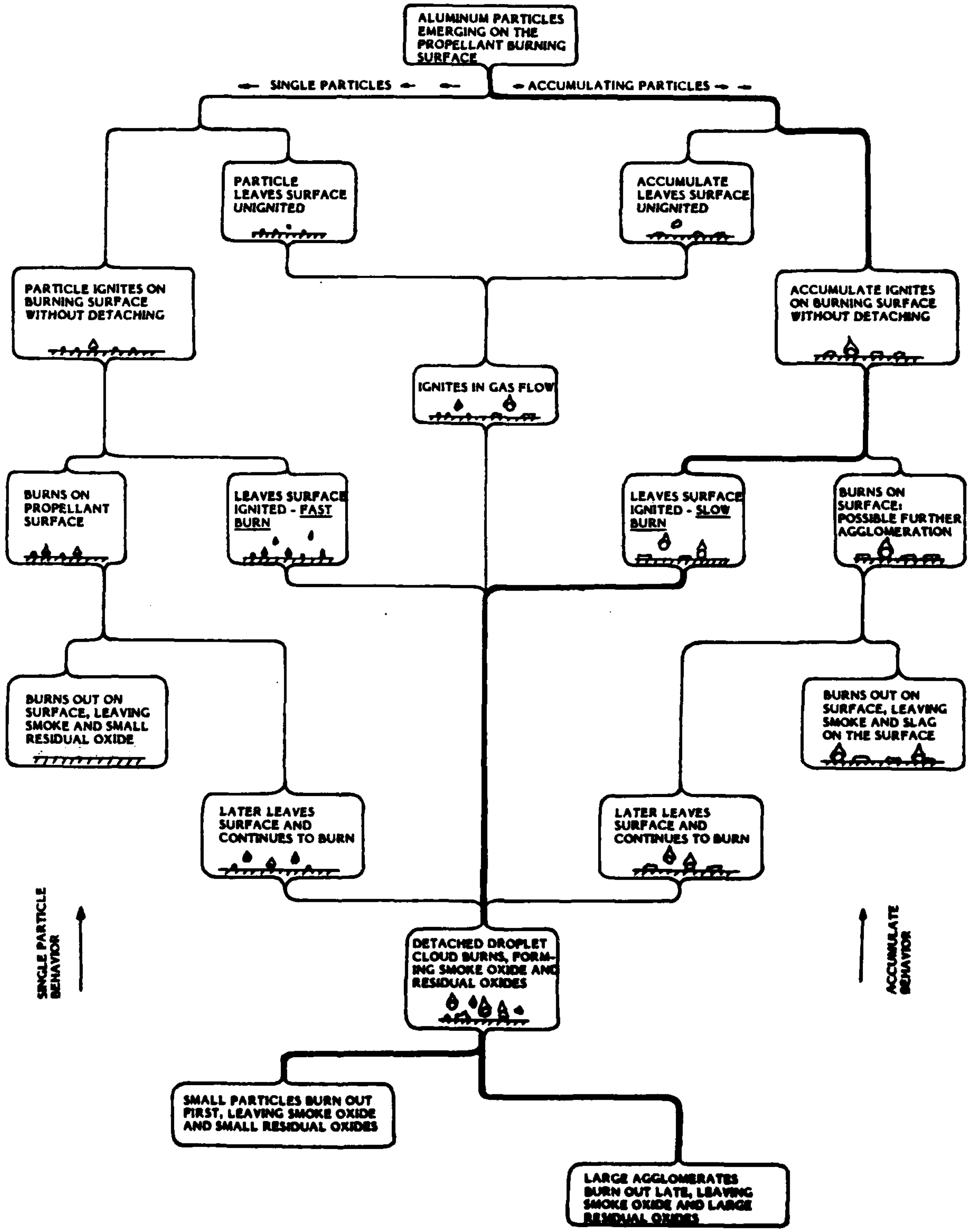

Fig. 1 Diagrammatic representation of the sequences of behavior of aluminum during propellant combustion.

Conditions Conducive to Inflamation of Accumulates.

A crucial aspect of aluminum behavior is the accumulation on the propellant burning surface, a process usually terminated upon local ignition of concentrations of aluminum called "accumulates". A variety of experiments were run that established that aluminum does not readily ignite in the environment of the deflagrating oxidizer alone. The experiments indicate that inflamation of accumulates is induced by exposure to local high temperature flamelets formed in the mixing interfaces between oxidizer and binder vapors. In addition to experiments reported earlier, this interpretation was used to predict the behavior of a series of propellants with bimodal oxidizer particle size distribution. Using particle sizes and pressures chosen specifically to control the availability of flamelets to ignite aluminum, the size of accumulates and resulting agglomerates was observed to follow closely the trends predicted on the basis of proximity of flamelets to terminate local accumulations. These results are partly reported in Ref. 1, and Fig. 2. Results now available indicate not only the dependence of inflamation on oxidizer-binder flamelets, but also a critical condition for existence of such flamelets near the burning surface (Ref. 1, 2). This critical condition was discovered on a companion project (Ref. 2), and explains also certain other singular aspects of propellant combustion such as burning rate trends of bimodal propellants (Ref. 3).

Nature of Agglomerates.

When an accumulate inflames, it usually coalesces into a single droplet called an "agglomerate", which detaches from the burning surface and burns in the combustor flow. These agglomerates often have rather complex structure that reflects the manner of their formation and affects their burning and the nature of the oxide products. In the present studies, agglomerates were quenched in a number of combustion systems, at various times during burning, and studied by a variety of methods. The collected results establish that a fully inflamed agglomerate is a spherical droplet of aluminum with a lobe of molten oxide. The droplet has from 5 to 15% void volume, the amount being dependent on pressure and agglomerate size, and the volume being in one or more unsymmetrically disposed voids that are not ordinarily open to the surface. The agglomerate also contains an irregular interior array of oxide films, remnants of the oxide skins on the original aluminum particles that coalesced into the agglomerate. These

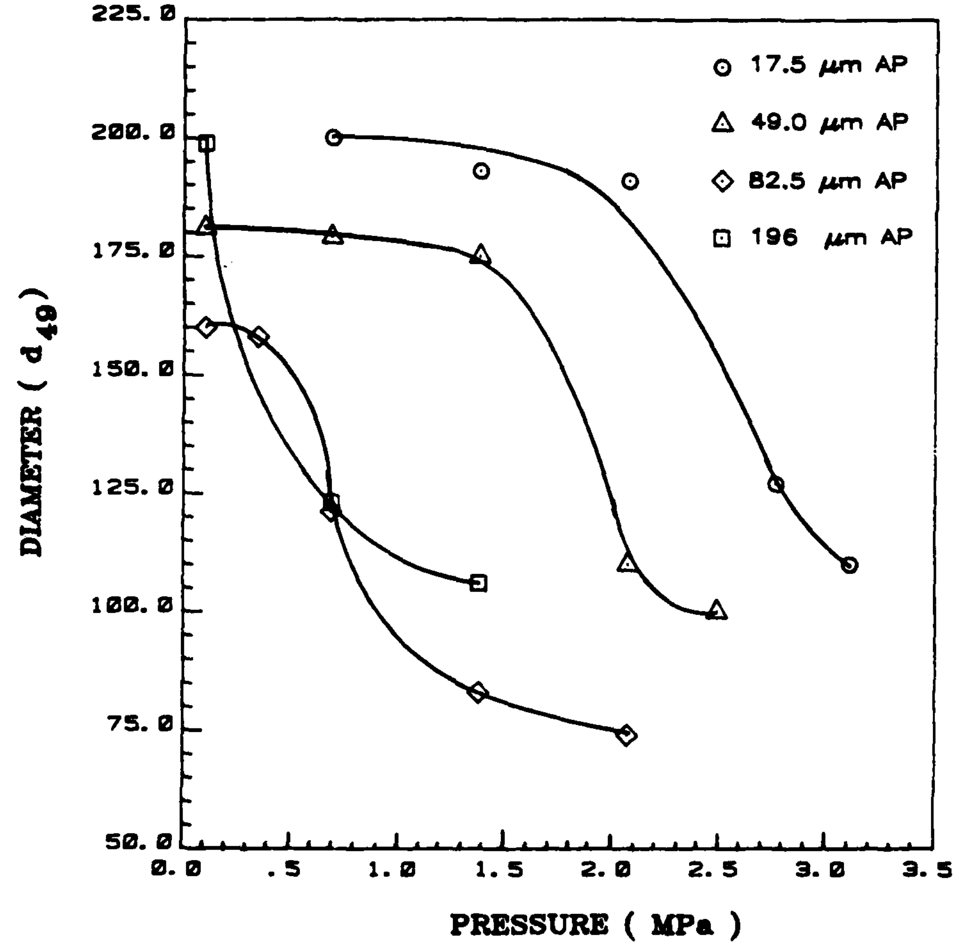

Fig. 2 Effect of pressure and oxidizer particle size on mass-average agglomerate size. Bimodal AP propellant with 4:1 ratio of coarse (400 μm) to fine AP. AP/Al/PBAN binder mass ratio 71/18/11. Transition to small agglomerate size corresponds to establishment of local oxidizer-binder flamelets on individual fine AP particles, and hence earlier ignition of aluminum.

features are revealed by microscopic examination of intact, cleaved, and acid-etched agglomerates, and are described more fully in Ref. 4 and 5.

Burning History of Agglomerates.

In addition to earlier studies by combustion photography, the present studies using quenching of agglomerates at various distances from the burning surface have permitted rather complete characterization of agglomerates and the entire plume as a function of time during burning. Fig. 3 shows the configurations of agglomerates at successively greater distance from the burning surface, and Fig. 4 shows the mass fraction of unreacted aluminum as a function of distance from the burning surface for a typical AP/Al/HC binder propellant. Results are described in greater detail in Ref. 4, 5, 6. Results establish that:

a) Most of the oxide (~ 85%) forms as fine smoke in a detached flame around the agglomerates.

b) Some of the oxide (0 - 5%) forms before agglomeration is complete and is present in and on the burning agglomerate.

c) Some oxide (0-10%) forms by either reaction or condensation on the agglomerate surface during burning.

d) The oxide increasingly dominates the agglomerate as the aluminum is burned away (Fig. 3c).

e) The aluminum droplet cloud is consumed very rapidly as it moves away from the burning surface (Fig. 4), but the consumption rate drops off rapidly, and the last 20% burns slowly enough to affect combustion efficiency in the motor. This problem is aggravated by heavy agglomeration and unusually fuel-rich stoichiometry.

Results to date do not determine the nature of the burnout phase of agglomerates, although they seem to exclude fragmentation events observed in some idealized laboratory experiments on single particle combustion (e.g., in air). Results also do not establish any burning rate law for individual agglomerates. This objective is being pursued, using a propellant that is formulated to form only one agglomerate size.

Oxide Product Populations.

It is generally recognized that, in addition to the fine oxide smoke formed in the flame envelope around the agglomerate, the final reaction products contain

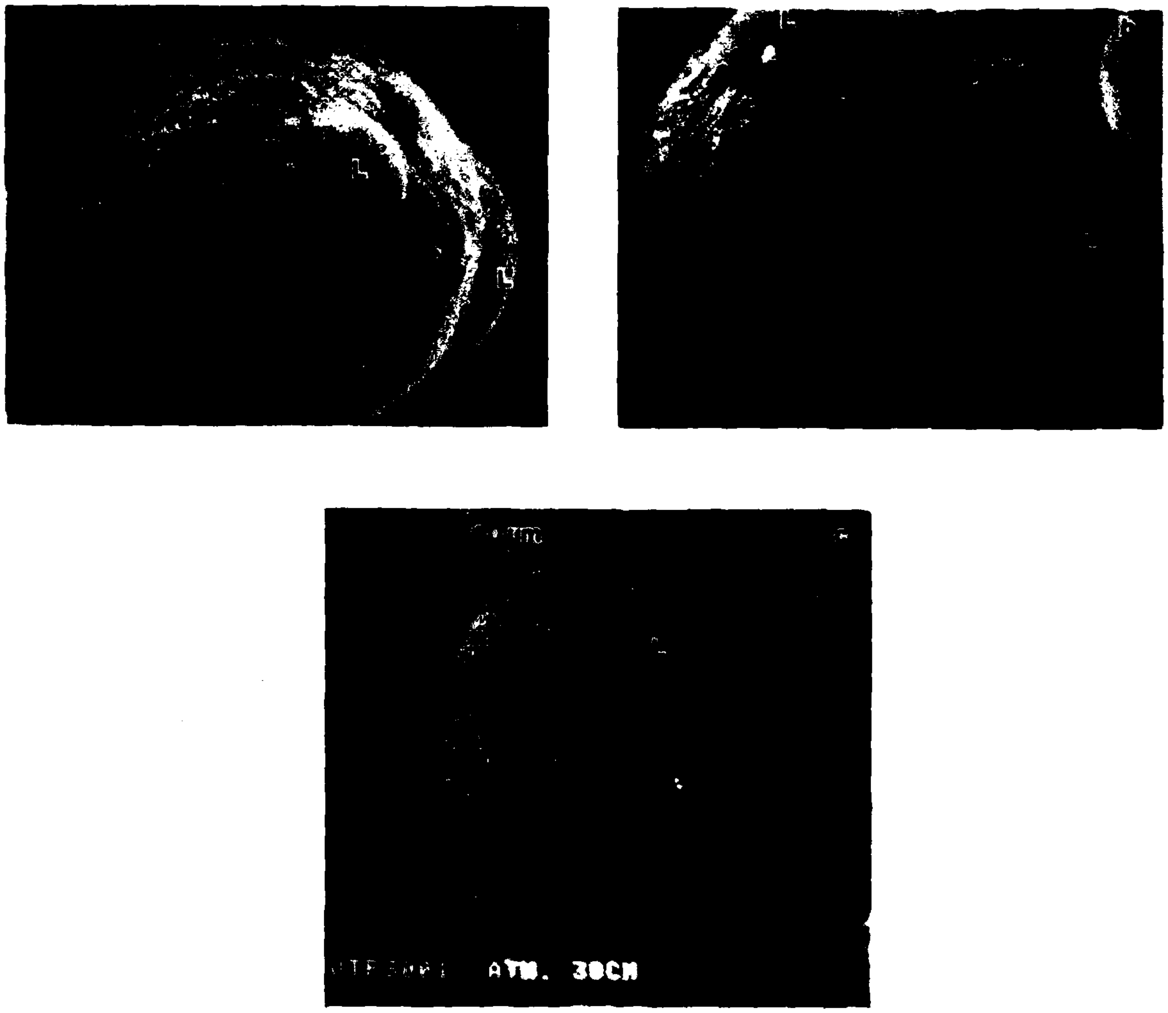

Fig. 3 Configuration of agglomerates at successively later times in burning. "L" designates oxide lobe.

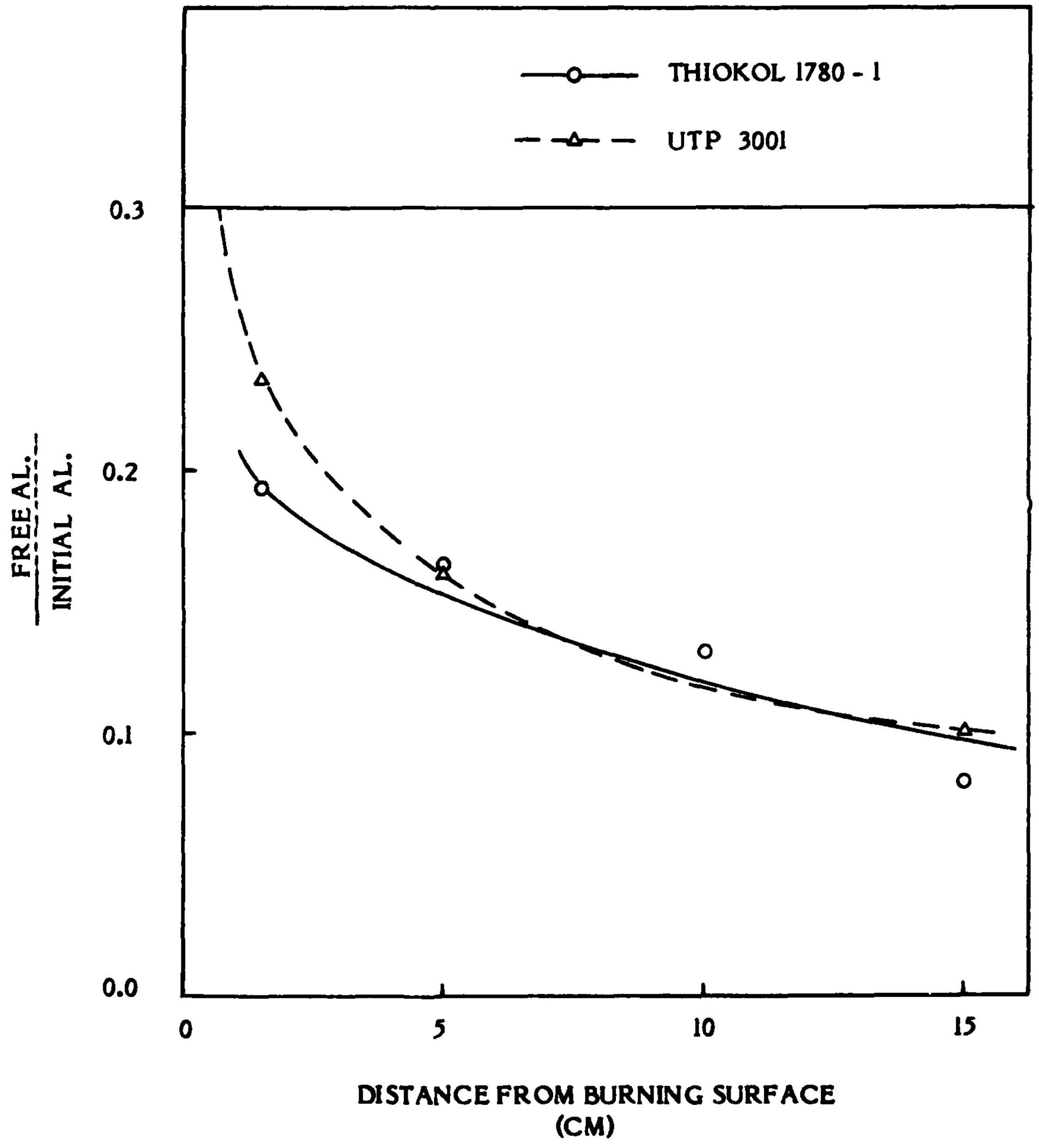

Fig. 4 Unburned aluminum vs quench distance. Tests at 0.7 MPa.

from 5 - 20% of coarser droplets. These are presumed to be the residual oxide left behind when agglomerates burn out. The present results of studies of quenched samples indicate that the size distribution is generally consistent with the trend of oxide accumulation on the parent agglomerates, implying that burnout is "noncatastrophic". However, this coarse fraction of the total oxide particle population (particles > 5 μm) is made up of two different kinds of particles. One kind is relatively small in size (generally < 35 μm) and is present in relatively small mass fraction. The particles are smooth, void-free, and nearly transparent. The second kind is relatively large (> 30 μm), somewhat porous, white opaque, with surface (and sometimes interior) suggestive of crystallization patterns. The size distribution indicates that the coarse fraction represents the bulk of the residual agglomerate oxide. The smaller, transparent particles may be expelled from agglomerates during burnout. Details of the testing and results are reported in Ref. 4-6. The results account qualitatively for the observed oxide distribution in reaction products. Under convective flow conditions the size distribution in the combustion chamber would be modified to the extent that the agglomerate size distribution would be different (Ref. 7).

Combustion Behavior in Flow Environments.

Work on this subject has not been initiated yet. The current objective is to observe photographically the responsiveness of the behavior of aluminum on the burning surface to flow disturbances parallel to the burning surface.

Other Propellants.

It is considered to be important to apply the increased understanding and experimental methods to study of propellants other than the AP/Al/HC binder system. The rather limited efforts to obtain propellants with HMX and/or energetic binders have revealed that there are formidable difficulties in obtaining even very small quantities. The quantities required are so small that hazard can be reduced to zero, but shipping regulations are usually cited as the problem.

Plume quench tests were completed on an AP/Al/HTPB propellant containing 10% fine HMX. Results are reported in Ref. 5. The only visible effect of the HMX was the presence of tiny "blow holes" in the binder, indicating subsurface vaporization of the HMX.

Synthesis of Studies of AP/Al/HC Binder Systems.

A major effort was made to consolidate the results of the studies to date, which provide a fairly complete understanding of aluminum behavior in AP/Al/HCB systems burning under quiescent conditions. These efforts at consolidation are available in Ref. 5, and are reflected in Ref. 6 as well. In addition, much of the work is consolidated in the Ph.D. thesis (Ref. 7) that will be available in the near future.

Development of Experimental Methods.

Several new techniques were developed that have long-term usefulness.

1. A new method was developed for analysis of the content of unoxidized aluminum in quench samples; the method is relatively easy to use and gives accurate results.
2. A method of microscopic observation of the response of particles to heating was contrived using electrical heating of particles in the scanning electron microscope. Response of aluminum particles (in vacuum) was observed successfully.
3. A modification of the plume quench experiment was evaluated at atmospheric pressure. The method provides more precise knowledge of the distance from the propellant surface to quench point. The plume impinges perpendicularly on a porous plate flooded with transpired coolant (ethanol).

Summary.

The work during this year was primarily a continuation of studies of FY 1981 on agglomeration, ignition of accumulates, formation and nature of agglomerates, combustion of agglomerates, and formation and nature of product oxide droplets. Experimental methods (quiescent atmospheres) were improved and systematic tests were run to determine trends with pressure and propellant variables. The available understanding was organized into a qualitative theory, and the experimental results leading to that theory were assembled into a summary report. A family of propellants was devised to demonstrate certain critical features of the theory, and tested over a range of pressures. The observed agglomeration trends were consistent with trends predicted by the theory, and provide an explanation for previously unexplained results by other investigators.

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2. Price, E. W., R. R. Panyam, J. K. Sambamurthi and R. K. Sigman, "Combustion of Ammonium Perchlorate-Polymer Sandwiches," 19th JANNAF Combustion Meeting, October 1982, to be published by CPIA.
3. Miller, R. R., "Effects of Particle Size on Reduced Smoke Propellant Ballistics," AIAA/SAE/ASME 18th Joint Propulsion Conference, June 1982, AIAA preprint AIAA-82-1096.
4. Price, E. W., C. J. Park, R. K. Sigman and J. K. Sambamurthi, "The Nature and Combustion of Agglomerates," 18th JANNAF Combustion Meeting, CPIA Publication 347, October 1981.
5. Price, E. W., R. K. Sigman, J. K. Sambamurthi and C. J. Park, "Behavior of Aluminum in Solid Propellant Combustion," Scientific Report on Contracts AFOSR F 49620-78-C-0003 and AFOSR F 49620-82-C-0013, Georgia Institute of Technology, June 1982.
6. Price, E. W., et al, "Rocket Research at Georgia Tech," Final Scientific Report on Contract AFOSR F 49620-78-C-0003, Georgia Institute of Technology, November 1981.
7. Sambamurthi, J. K., "Behavior of Aluminum on the Burning Surface of a Solid Propellant," Ph.D. Thesis in preparation at Georgia Institute of Technology.

C. Publications and Presentations

The following were published or presented during 1 October 1981 to 30 September 1982.

1. Price, E. W., C. J. Park, R. K. Sigman, and J. K. Sambamurthi, "The Nature and Combustion of Agglomerates," 18th JANNAF Combustion Meeting, CPIA Publication 347, October 1981.
2. Price, E. W., J. K. Sambamurthi, R. K. Sigman and C. J. Park, "Combustion of High Aluminum Content Solid Propellants, 18th JANNAF Combustion Meeting, CPIA Publication 347, October 1981.

3. Price, E. W., W. C. Strahle, B. T. Zinn, J. E. Hubbartt, R. K. Sigman and B. R. Daniel, "Rocket Research at Georgia Tech," Final Scientific Report on AFOSR Contract No. F49620-78-C-0003, Georgia Institute of Technology, November 1981.
4. Price, E. W., Behavior of Aluminum in Solid Propellant Combustion," presented at AFOSR/AFRPL Combustion Contractors Meeting, Lancaster, CA, March 1982.
5. Price, E. W., R. K. Sigman, J. K. Sambamurthi and C. J. Park, " Behavior of Aluminum in Solid Propellant Combustion," Scientific Report on Contracts AFOSR F 49620-78-C-0003 and AFOSR F 49620-82-C-0013, Georgia Institute of Technology, June 1982.
6. Price, E. W., J. K. Sambamurthi, C. J. Park and R. K. Sigman, "Aluminum Agglomeration and Ignition in Propellants with Bimodal AP Size Distribution," presented at 19th JANNAF Combustion Meeting, October 1982, to be published by CPIA.
7. Price, E. W., K. J. Kraeutle, J. L. Prentice, T. L. Boggs, J. E. Crump, and D. E. Zurn, "Behavior of Aluminum in Solid Propellant Combustion," NWC TP-6120, March 1982 (writing of this review was started by the first author in 1969, completed in 1980 under Naval Weapons Center and Georgia Institute of Technology sponsorship; publication completed in 1982).

D. Personnel

Principal Investigators -- E. W. Price, Professor, and R. K. Sigman, Senior Research Engineer.

Graduate Research Assistants -- J. K. Sambamurthi and C. J. Park.

E. Professional Activities

1. Participant, 18th JANNAF Combustion Meeting, presentation of papers 1. and 2. above, October 1981.
2. Organization, chair and report on JANNAF Workshop on Combustion Zone Microstructure, 1981-82.
3. Participant, AFOSR/AFRPL Combustion Contractors Meeting, March 1982.
4. Participant, AIAA Joint Propulsion Specialists Meeting, June 1982.
5. Member, AIAA National Publications Committee.

TASK IV

ROCKET MOTOR AEROACOUSTICS

WARREN C. STRAHLE

A. Research Objectives

The overall objective of this program is to show that a) if the turbulence structure is known within a rocket motor cavity flow and b) if the propellant response characteristics are known, then the pressure fluctuation level within a motor may be predicted with regard to its spectral content and amplitude. The specific goals for the past year have been redevelopment of the theory and addition to the data base.

B. Status of Research

Substantial progress has been made during the past year in meeting the program goal. The following paragraphs summarize the major accomplishments:

1. Hydrodynamic vs Acoustic Pressure. A breakthrough has occurred in prediction of the non-propagational, non-acoustic component of pressure away from the walls. It had previously been found that this component, significantly higher than wall-measured pressure fluctuations, could not be predicted. Moreover, the fact that it was so high was leading to serious doubts about the experimental procedure. A method was found during the past year to line-integrate the momentum equation in a manner to reveal this pressure component, and it is now predictable to within 10% accuracy. In conjunction with the fact that the acoustic component of wall pressure

fluctuations had already been proven predictable, it is now believed that the physics of pressure generation within flow cavities is now well-understood.

2. Theoretical Studies. In conjunction with the work above, the theory of both acoustic and non-acoustic pressure fluctuations has been reformulated to make it somewhat more understandable to the non-practitioner. Preliminary calculations have also been made in rocket motor environments where propellant response is important in determining the pressure level. It is being shown that any pressure level desired can be produced if the propellant and cavity combination is sufficiently near a stability limit.

3. Experimental Studies. Completion of data reduction and comparison of theory and experiment has now been completed on four set-ups. One has been a long pipe terminated with a choked nozzle. Three have been rocket motor simulators made of porous walls, taking in mass from the sides to simulate a center-perforated grain configuration. Variables have been length to diameter ratio and side wall impedance. A fifth configuration to be tested will vary internal velocity.

Agreement between calculated acoustic pressure and experiment have in general been good. A notable lack of agreement has been in the actual amplitude of the pressure fluctuation in the first longitudinal mode. It is believed that insufficient data have been taken on the velocity fluctuation spectrum for a good prediction here, and this deficiency is currently being rectified.

C. Publications

1. U. G. Hegde and W. C. Strahle, "Investigation of Turbulence Generated Pressure Fluctuation in Some Interior Flows" AIAA Paper No. 82-0175.

D. Personnel

Principal Investigator - Warren C. Strahle

Graduate Research Assistant - Uday G. Hegde

E. Professional Activities

Strahle, W. C., "Investigation of Turbulence Generated Pressure Fluctuations in Some Interior Flows", presented at AIAA 20th Aerospace Sciences Meeting, Orlando, FL, January 1982.

Strahle, W. C. "Rocket Motor Aeroacoustics" presented at AFOSR Contractors' Meeting, Lancaster, CA, March 1982.