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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This research project is concerned with determining the mechanisms governing the formation and combustion of metal/agglomerate/metal oxide particles throughout the solid rocket motor, that is, propellant surface/near surface, motor cavity, and nozzle regions. Also of concern is the influence these particles have on propellant combustion characteristics and overall motor performance. This		

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past year's efforts have been directed toward developing the experimental equipment and/or techniques required for determining particle size distributions at or near the propellant surface. The approach taken involves making use of a laboratory scale, servo-controlled strand window bomb in conjunction with both an imaging-type particle size analyzer and a high speed, pulse-lit photographic technique. In this report, the servo-controlled strand window bomb is described following a brief review of past research efforts which have employed similar propellant feed mechanisms. Next, the theory and operation of the particle size analyzer is detailed. Finally, the feasibility of employing high speed, pulse-lit photography in the study of metal particle/agglomerate combustion is discussed.

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Interim Report
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**DETERMINATION OF THE COMBUSTION MECHANISMS
OF ALUMINIZED PROPELLANTS**

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I. INTRODUCTION

The use of metalized solid propellants may lead to decreased motor efficiencies due to two phase flow effects as well as incomplete metal particle/agglomerate combustion. To be confident of the two phase flow loss prediction, information must be obtained regarding metal particle/agglomerate size and size distribution throughout the motor chamber and propulsive nozzle. Furthermore, factors controlling the combustion efficiency of metalized propellants are the size of the metal particles/agglomerates, their burning rate characteristics, and their residence time in the rocket motor combustion chamber. Analytical combustion efficiency analyses [1,2] must be based on trajectory calculations for individual metal particles/agglomerates in the combustion chamber flowfield, accounting for gas/particle velocity and thermal lags (two phase flow effects) and metal particle/agglomerate burning behavior.

In order to predict mechanisms for describing metal particle/agglomerate chemical and physical size change in the flowfield of a nozzle, one must be able to accurately specify the initial metal particle/agglomerate size and size distribution at the entrance of the nozzle. Therefore, it is important that the various mechanisms influencing the combustion of metal as well as the physical and chemical characteristics of the burning metal particle/agglomerate as it leaves the propellant surface and traverses the motor chamber be well understood.

Two important aspects of metal particle/agglomerate behavior are currently under investigation. These being: (1) the surface/near surface particle agglomeration mechanism and (2) the metal particle/agglomerate combustion mechanism within the motor chamber flowfield. The surface/near surface behavior is important since the metal particle/agglomerate size and combustion characteristics must be examined in order to observe their relationships with both motor operating conditions and propellant formulation variables. Also, motor chamber flowfield behavior along with (ARAC)

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particle/agglomerate combustion behavior is required for combustion efficiency calculations.

The proposed approach for analyzing the mechanisms involved in metalized propellant combustion makes use of a laboratory scale motor flowfield simulating device in conjunction with both an imaging-type particle size analyzer [3,4] and a high speed, pulse-lit photographic technique [5]. The flowfield device consists of a servo-positioning, high pressure window bomb [5,6] coupled to a PDP-11 minicomputer for data acquisition/reduction. Both the imaging-type particle size analyzer and the pulse-lit photographic technique are unique in their application to solid propellant research in that they should prove to be accurate, non-intrusive diagnostic tools for making metal particle/agglomerate size and size distribution measurements within simulated motor chamber flowfields.

II. RESEARCH OBJECTIVES

The long range objectives of this research program are:

- (a) To gain a thorough understanding of the various mechanisms influencing the combustion of metal; that is, an understanding of the physical and chemical characteristics of the burning metal/agglomerate/metal oxide particle as it leaves the propellant surface and traverses the motor chamber and nozzle. This knowledge will lead to an accurate determination of the metal/agglomerate/metal oxide particle size and size distributions throughout the motor and a detailed description of the changes a particle undergoes as it flows through the nozzle.

- (b) To predict (based on the knowledge gained from the first objective) motor performance and efficiency accurately and a priori based on propellant composition and motor/propellant grain size and geometry.

While the long range goals listed above are the ultimate research-objectives, the effort of this past year has been focused on the more immediate, short term goals. The work has been devoted to tasks that must be completed before accurate experimental data can be obtained. In the following section, the experimental program currently being conducted in an effort to meet the above long range goals is thus described. Since the laboratory scale, servo-controlled combustion bomb is presently the focal point of our metal particle/agglomerate size distribution measurements, it will be described. This however follows a brief review of past solid propellant combustion research efforts which have employed similar propellant feed mechanisms. Following a description of the servo-controlled combustion bomb, the theory and operation of the existing imaging-type, particle size analyzer will be detailed. Finally, brief comments will be made as to the feasibility of employing high speed, pulse-lit photography in the study of aluminum particle/agglomerate combustion.

III. EXPERIMENTAL STUDIES

In an effort to validate theoretical modeling results obtained for aluminum particle surface/near surface agglomeration/ignition/combustion behavior, detailed experimental observations of these processes must be conducted. Especially important is that one must be able to observe and understand the processes occurring on or near the surface during the combustion of aluminized propellants in controlled environments. One such laboratory tool that has been proposed for long duration observation of the burning process is a servo-controlled propellant strand burner. The purpose of such a device is to continuously feed a strand of propellant into a controlled pressure/flow environment at a rate equal to its burning rate. With this constraint satisfied, the propellant surface is held fixed in space for the entire duration of the strand burn, thus permitting ample time for observation. In this section, the limited research efforts directed toward developing such an apparatus over the past three decades are reviewed. In this light, the servo-positioning strand window bomb currently in operation at Purdue University is described [6]. Subsequently, the feasibility of employing both a video-based particle imaging device and a high speed, pulse-lit photographic technique in conjunction with this device for propellant surface and aluminum combustion studies is addressed.

a. Servo-Positioning Strand Window Bomb

The feasibility and fabrication of a servo-positioning device utilized in combustion studies of solid propellants is neither unique nor recent. In 1954, Rekers and Villars [7] employed a servo-positioning strand combustion bomb to conduct spectroscopic studies of solid propellant flames. Their system utilized a lamp light source to provide a tracking beam to be optically directed across the propellant surface and imaged upon the face of two photocells. These two photocells were part of a thyratron control circuit which provided a voltage to drive the DC feed motor at a speed dictated by the

amount of light incident on the pair. A unique feature of this strand positioning device was that the feed motor drove a pinch roller assembly that subsequently fed the propellant into the combustion bomb. The propellant was coiled and loaded into a magazine capable of accommodating strands up to a maximum of 1.83 meters in length. Therefore, for a typical propellant burning rate of 1 cm/s, this maximum length corresponded to a total burning/observation time of over three minutes.

A decade later, Osborn, et al [8], described a servo-controlled combustion system used for the direct and continuous measurement of burning rates of solid propellants under conditions closely approximating those of a solid rocket motor. This device and its subsequent modified versions were part of several research efforts conducted in the sixties at Purdue University dealing with solid propellant combustion. In that work, the surface of a propellant sample (2.5 X 2.5 X 10 cm) could be maintained in a fixed position within a two-dimensional rocket motor. To achieve this control, a collimated beam of gamma rays from a source of ^{137}Cs was passed through the combustion chamber containing the unburned solid propellant. As the propellant regressed due to combustion, the intensity of the collimated beam increased due to the difference in the density of the solid propellant and its combustion products. The intensity of the beam after passing through the test section was measured with a scintillation probe whose output provided the input to a linear ratemeter. The ratemeter's voltage output which is proportional to the propellant's position was then amplified, compared to a standard, or reference, propellant position and then used to excite the field of a rotating amplifier. The output of the rotating amplifier was then supplied to the armature of a .6 Hp DC servo-motor which fed the propellant into the combustion chamber. Instantaneous burning rate versus pressure data for several different propellant formulations were experimentally determined using this servo-positioning system with satisfactory results.

Shortly thereafter, Derr [9] utilized a modified version of that servo-positioning system in his research to determine the structure of the gaseous reaction zone above a burning composite propellant surface. His primary experimental efforts were directed at measuring the temperature profile above the surface of an AP/polysulfide propellant via a modified line reversal technique. In addition, color motion pictures of the surface/near surface region were taken. In his system, Derr employed a tungsten strip lamp source along with focusing optics and a photo-multiplier tube (PMT) as the positioning beam detector. As before in the original design by Osborn [8], the detection of the surface was accomplished with the output of the PMT being proportional to the position of the propellant strand within the combustion chamber of his apparatus. The PMT output was used in conjunction with an SCR amplifier triggering circuit to provide power to drive the DC servo-motor propellant feed system. The light source was chopped at a low audio frequency before passing over the burning surface. By using full wave rectification electronics, discrimination between the radiation from the tungsten strip lamp and the luminosity of the combustion zone could be accomplished. Also, the intensity of a second light beam which passed directly above the first beam was monitored as a reference to determine the possibility of signal error due to attenuation on the light beam by smoke or haze in the gas phase reaction zone and/or window clouding.

More recently, three separate research efforts [6,10,11] have employed a surface position tracking/feed system in the investigation of solid propellant combustion processes. In the first of these efforts, Goetz and Mann [10] at the Air Force Rocket Propulsion Laboratory have developed a high pressure strand window bomb which is coupled to an optical servo-controlled feed mechanism designed to hold the burning surface of a propellant strand at a fixed position within the bomb chamber. The purpose of this experimental device was similar to that of Rekers and Villars [7] described

earlier - to record spectroscopic data from the gas phase reaction zone of both metalized and non-metalized solid propellants. In their surface position tracking design, a He-Ne laser was employed along with a filtered solid state photocell as part of the detector circuitry. For propellant feeding, an electronic pulse activated stepping motor was used, the stepping rate being determined from the difference between the photocell output and a predetermined reference voltage. Although their initial visible spectroscopic results were somewhat disappointing, the servo-positioning system performed satisfactorily. However, due to the stepping nature of the feed system, the surface of the propellant will appear to jerk instead of being smoothly fed upward as is the case with the servo-positioning systems previously discussed. This effect may or may not be desirable depending on the magnitude of the individual step sizes and/or the nature of the experiment being conducted.

The second research effort employing a controlled propellant surface tracking mechanism was that detailed by Caveny, et al [11]. In their design, a digital version of the drive and control system utilized by Derr [9] was used to maintain an LDV control volume at a prescribed position above a stationary burning propellant surface. More precisely, the propellant strand burning within a purged, pressurized combustion bomb remained fixed, while their LDV optics were lowered at the same rate as the propellant regression rate. The feedback control on the lowering rate was achieved by sensing the degree to which one of the reflected laser beams interfered with the burning surface. Their research was directed at measuring the unsteady gas velocities above a burning propellant surface corresponding to the idealized pressure-coupling of burning propellant - the pressure oscillations being forced within the burner chamber by a rotating vent orifice. Maintaining the relative position of the control volume was essential for success, since it permitted a statistically significant data sample to be collected. However, only relatively small propellant strands (and consequently, short observation

times) could be investigated due to the unique features of their LDV positioning system/combustion bomb window arrangement.

The third research effort, that conducted by Lilley [6], utilized the servo-positioning strand window bomb currently in operation at Purdue University by the authors to be used in the observation of solid propellant surface/near surface burning phenomenon. This servo-controlled strand burner is a modified Crawford bomb designed for a maximum pressure of approximately 7 MPa. A schematic of this bomb is presented in Fig. 1. The bomb consists of two separate sections, a pressurization chamber and a test chamber. The chambers are separated by a central flange and the burner is sealed by flanges on the top of the test chamber and the bottom of the pressurization chamber. The pressurization chamber is the lower of the two chambers and includes a flange which forms the base of the burner. The propellant feed shaft enters the burner through this flange. On the bottom flange are two shaft seal plates which form an O-ring seal on the push rod and the bottom plate is in turn sealed to the flange.

The mechanical components for the servo-system are similar to those first used by Osborn [8]. They consist of the .6 Hp servo-motor and drive gears, a feed rod, a propellant push rod and an anti-torque system. The electrical components for the servo-system consist of a photo-detector circuit, a reference voltage circuit, a differential amplifier, a servo-amplifier, a rotating servo-generator, a servo-motor and a servo-motor field voltage supply. The outputs of the photo-detector and reference voltage circuits are fed into the side of the differential amplifier. The output of the differential amplifier provides the input to the remote sensing terminals of the servo-amplifier functioning as a programmable power supply. The output of the servo-amplifier is input across the field of the rotating servo-generator. Finally, the servo-generator output is then used to excite the armature of the propellant feeding servo-motor whose field

voltage is supplied by a 450 VDC power supply. Presently, the servo-amplifier and rotating servo-generator are being replaced by a state-of-the-art, remotely programmable, 200 watt autoranging power supply. This addition should improve the response characteristics of the feedback control system.

The optical system shown schematically in Fig. 2 is used to detect the burning surface of the propellant. The light source is a 2 milliwatt He-Ne laser. This laser beam is passed through a variable, rectangular aperture whose function is two-fold. First the aperture cuts the round laser beam into a rectangular image. The result is that as the beam is blocked, the amount of light striking the photo-detector will be more nearly linear with respect to the amount of beam blocked. The second function of the aperture is to block some of the laser beam since the full output of the laser will saturate the photo-detector. After the laser beam passes through the aperture, it passes through one quartz window into the bomb then across the burning surface and finally out through the quartz window on the opposite side of the bomb. The beam then passes through a .6328 μm narrow band width filter. The purpose of this filter is to assure that only light from the laser strikes the photo-detector. The photo-detector circuit consists of a high speed photo-darlington amplifier placed in series with a 100 Ω resistor. A regulated voltage is placed across the series pair with the output of the detector circuit being the voltage drop across the resistor experimentally determined as being proportional to the amount of laser light striking the photo-darlington amplifier.

To date, the servo-positioning strand window bomb thus described has been shown to operate successfully during the combustion of several AP-based non-aluminized propellants at pressure levels up to a maximum of 2.5 MPa. During a typical test sequence, a PDP-11 minicomputer data acquisition system acquires all pertinent servo-positioning system data along with additional combustion environmental information such as pressure. With the acquisition of servo-motor propellant feed rate versus time

data, an instantaneous propellant surface position can be determined as a function of time. Figure 3 depicts a typical surface position versus time trace of one of the propellant investigated. After an initial start-up transient, the burning propellant surface is shown to be held within $\pm 100\mu\text{m}$ - or on the order of the surface roughness for this 80 μm AP oxidizer propellant formulation. Efforts are currently underway to improve the response of the propellant feed system so that the burning propellant surface can be held even more fixed - a necessary requirement for the experimental investigations of the surface/near surface behavior of aluminized propellants to follow.

As a final note, in experimental aluminum agglomeration studies conducted recently by the Russians [12], a pressurized flow combustion bomb was employed in which the propellant burning surface was also held stationary. Similar to most of the American systems described above, this was accomplished by feeding the propellant into the combustion volume at a rate equal to the propellant's burning rate. However, no details as to the manner in which this was performed or how accurately the surface was held stationary were given.

b. Imaging-Type Particle Size Analyzer

The imaging-type, particle size analyzer currently being employed was originally designed by Southern Research Institute for the Parker-Hannifin Corporation to measure liquid fuel spray concentrations. With this machine, a fuel spray could be sampled 15 times a second with the data obtained with each sample being processed prior to the next sample being taken. The measured concentrations (in droplets per cubic millimeter) were then displayed in 6 binary size ranges from 8 microns to 512 microns after a pre-determined number of samples were taken. The overall imaging system was functionally divided into five major subsystems. These being: (1) droplet detection, (2) video processing, (3) conversion, (4) display, and (5) readout.

Over the past few years, this device has been modified [3,4]. Although the first two subsystems remain almost identical both mechanically and electronically, the functions of the latter three subsystems are now performed by a PDP-11 minicomputer. The minicomputer also controls the positioning and sampling of the droplet detection equipment while storing the processed data after each sample is taken. With this added flexibility, the spray analyzer has thus been modified to have the capability of determining the local variations in droplet size distribution within the fuel spray under investigation. Below is a brief review of the theory of operation for the spray analyzer as it presently exists.

As listed previously, the first major subsystem of the spray analyzer deals with droplet/particle (depending on the application) detection. This subsystem consists of an illuminator, a closed circuit television camera, and a video monitor. The sampling of the test volume is accomplished by means of a high intensity, short duration light source - or illuminator. This light source is a xenon flash lamp powered by a parallel capacitor and is triggered by an external electrode. Since the test volume is positioned between the illuminator and the television camera, droplet/particle images appear dark on a light background projected on the face of the camera vidicon. The operation of the illuminator is synchronized with the camera so that the flash occurs during the vertical retrace of the camera. Images of the droplets/particles detected during the flash are stored on the photosensitive surface of the vidicon. The vidicon surface is then scanned and the droplet/particle images are converted into an electronic signal. This electronic signal is then sent to the second subsystem, the video processing unit, described below. The television camera used is a high performance closed circuit television camera manufactured by Motorola. This camera is equipped with a heterojunction vidicon which is extremely sensitive to low light levels, especially in the near infra-red. The video monitor is a high resolution monitor, also manufactured by

Motorola, and is provided to aid the operator in setting up (calibration and alignment) and using the instrument.

The electronic signal from the scanned vidicon surface is sent to the video processing subsystem where it is analyzed to yield the size of each droplet/particle image and the number of images in each sample. The size of the droplet image is determined by the number of horizontal scan lines intercepted on the face of the vidicon. For the instrument in its present configuration, the combination of optics and vidicon surface area results in each horizontal scan line representing approximately 4 microns. The video processing circuits count the number of scan lines an image intersects and sends this count to the minicomputer where the number is converted to droplet/particle size and subsequently stored. The view volume between the camera and the illuminator is very small, ranging from 2 to 10 cubic millimeters. This view volume is determined by the lens systems of the camera and illuminator and also by the usable area of the vidicon face. As the droplets/particles pass in the vicinity of this view volume, some will be outside this volume and will appear as blurred images on the face of the vidicon. Therefore, a focus detection circuit is employed to sense the images that are out of focus in order to prevent them from being counted. Since this view volume varies with the dimension of the droplet/particle being observed, calibration must be performed prior to operation using known droplet/particle sizes. Such calibration data is then used in the data reduction program in order to compute actual number densities.

When a very dense spray or gas/particle mixture is being observed, many images will be obtained during each sample. Under such conditions, more than one image may intercept one or more common horizontal scan lines. In this event, the information from only one of these images would be used, because the video processing circuits can handle only one bit of information in each horizontal scan line. However, this instrument has been built with three parallel video processing channels, which enables it to

process up to three images which intersect a common horizontal scan.

As stated previously, the PDP-11 minicomputer performs the function of the original remaining three subsystems; the conversion, display and readout. Having taken a predetermined number of samples, the software developed for this machine takes the data obtained and using the prior calibration data, calculates number densities for the spray or gas/particle mixture being observed. Further software developed for this system enables plots of the droplet/particle number densities obtained to be generated on the Printronix printer tied to the minicomputer. Sample number density plots for fuel-type sprays can be observed in Refs. 3 and 4.

c. High Speed, Pulse-Lit Photography

With a servo-positioning window burner such as that described above, the authors believe that the surface/near surface environment of a burning propellant strand can now be investigated photographically in a fashion better than that achieved to date. One of the major drawbacks associated with conventional, non-positioning strand combustion photography has been that the surface quickly burns out of the depth-of-field (DOF) of the optical/camera system employed. This is especially true for high resolution, micro-photographic studies wherein typically the DOF may be on the order of .1 mm, or 100 μm . Under such conditions, the total observation period may be less than .01 second (assuming a typical 1 cm/sec propellant burning rate). Even at very high framing rates, say 10^4 frames/sec, this still only provides on the order of 10^4 frames of in-focus surface burning detail - along with a large amount of out-of-focus frames.

There are four additional areas of concern associated with conventional photographic techniques. The first of these has to do with the mechanical "jitter" associated with high speed rotating prism camera systems. The second concern deals with the

degree of magnification and/or the resolution of the film employed (this is typically defined in terms of the number of line pairs per millimeter). In other words, the limit of the spatial scale that can be resolved with such photographs is important to the study of surface/near surface combustion detail. The third concern deals with the electrical power requirements for continuous front lit photography at high framing rates. Analysis shows that continuous illumination necessary for high speed front lit photography can possibly result in propellant sample heating - thus invalidating the results obtained. Finally, in regard to aluminum combustion photographic studies, an additional concern arises from the appearance of a bright "aureole" surrounding the burning aluminum particle/agglomerate - thus preventing acquisition of true particle/agglomerate size distribution information.

We are currently investigating the feasibility of using a high speed, pulse illumination photographic technique similar to that employed by the Russians [12] to study aluminized propellant combustion, especially within the surface/near surface environment. By using such a system, we intend to eliminate or at least reduce many of the problems listed above. In an effort to eliminate the loss of spatial scale resolution due to the mechanical "jitter" associated with motion compensation techniques employed in rotating prism camera systems, high magnification has traditionally been used. However, increased magnification results in corresponding loss of depth of field as well as substantial increases in required illumination. Therefore, in order to maintain a relatively high DOF so that surface structure as well as particle interaction/agglomeration detail can be discerned, magnification should be kept relatively low. The solution to the mechanical "jitter" problem can then be obtained through the elimination of the motion compensating prism arrangement and the subsequent use of short pulse width/high peak power pulsed illumination to "frame" the images on the photographic film. The short pulse width will virtually freeze any particle and/or surface motion

while avoiding any propellant sample heating that is a distinct possibility in continuous front lit photographic systems. By taking the lead from the Russian system described in Ref. 12 and filtering out combustion generated self-illumination while using the proper pulse wavelength/film sensitivity combination, both back lit "shadow" photography -thus eliminating the aluminum particle combustion "aureole" effect - and front lit photography should be possible. The Russians reported an experimentally determined resolution of at least 15 μm which our calculations seem to verify as being the current lower limit of resolving power typically available with today's camera/lens systems. However, recent photographs taken by Lee Cross at the University of Dayton Research Institute utilizing high resolution holographic film (resolution on the order of 10^3 line pairs per millimeter) provide encouragement to the fact that this lower limit may be reduced. In conclusion, the authors believe that by a judicious integration of the above pulse photographic techniques in conjunction with the existing servo-positioning strand window bomb improvements can be obtained thus improving our understanding of solid propellant combustion.

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VI. PAPERS PRESENTED DURING PROGRAM YEAR

1. Renie, J.P. and Osborn, J.R., "Comments on Aluminum Particle Size, Agglomeration, and Acceleration Effects on Solid Propellant Burning Behavior," *Eighteenth JANNAF Combustion Meeting*, CPIA Publication Number 340, Volume III, October 1981, pp. 111-120.
2. Renie, J.P., Osborn, J.R., Corley, B.M., and Kobbeman, D.D., "Theoretical Analysis and Combustion Modeling of High Burn Rate Propellants to Obtain Low Pressure Exponent Compositions," *Eighteenth JANNAF Combustion Meeting*, CPIA Publication Number 340, Volume III, October-1981, pp. 149-160.--

3. Rennie, J.P., Lilley, J.S., Frederick, R.A., and Osborn, J.R., "Aluminum Particle Combustion in Composite Solid Propellants," AIAA Paper Number 82-1110, AIAA/SAE/ASME Joint Propulsion Conference, Cleveland, Ohio, June 21-23, 1982.

VII. STUDENTS GRADUATING DURING PROGRAM YEAR-

Jay S. Lilley - Master's Program, School of Aeronautics and Astronautics, Purdue University, December 1981. Thesis Topic: "The Design and Operation of a Servo-Controlled Solid Propellant Strand Window Bomb." Currently employed at the Army Missile Command, Redstone Arsenal, Huntsville, Alabama.

Kevin K. Nack - Master's Program, School of Aeronautics and Astronautics, Purdue University, December 1981. Thesis Topic: "A Study of the Aerodynamic Breakup of Molten Aluminum Particles in Two-Phase Flow." Currently employed at the Air Force Rocket Propulsion Laboratory, Edwards, California.

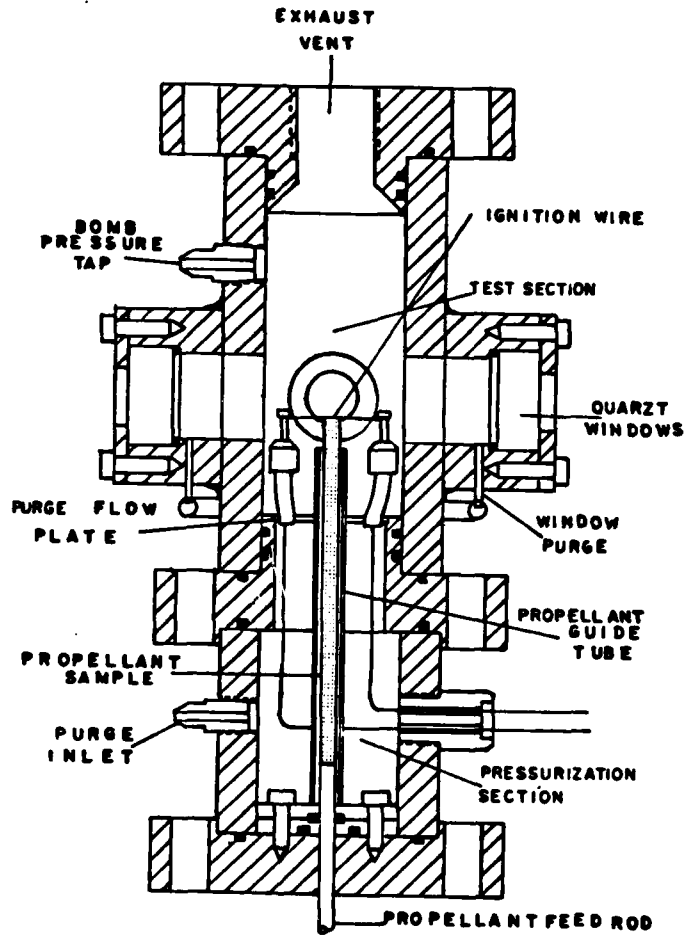


Figure 1. Schematic of Combustion Bomb.

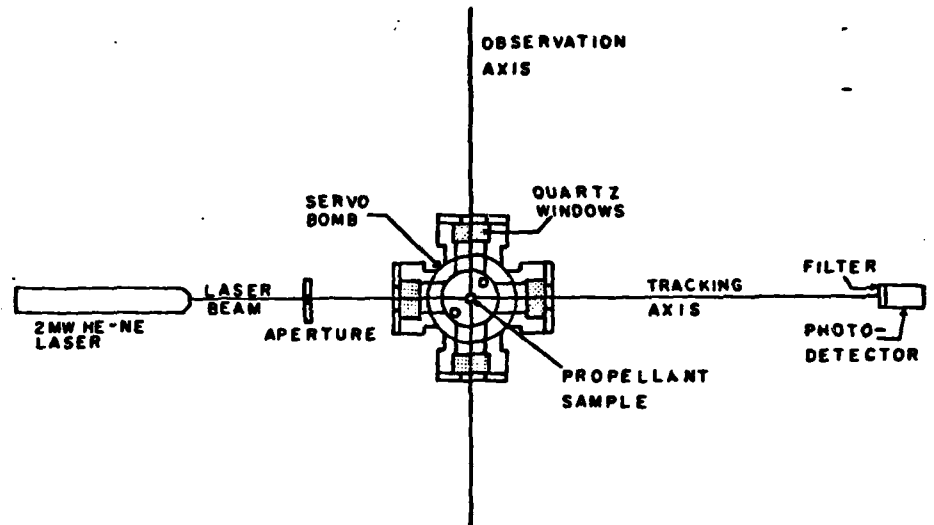


Figure 2. Schematic of Optical System.

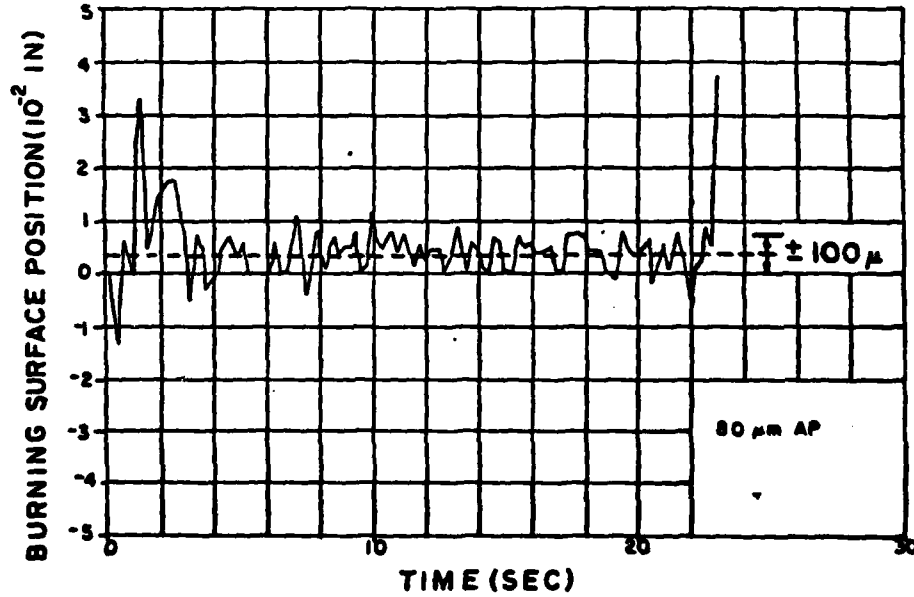


Figure 3. Burning Surface Response.