NASA TECHNICAL MEMORANDUM

NASA TM X-52252

GPO PRICE $ ______

CFSTI PRICE(S) $ ______

Hard copy (HC) 1.00

Microfiche (MF) .50

ff 653 July 65

NASA TM X-52252

FACILITY FORM 602

N67 11335 (ACCESSION NUMBER)

(THRU)

15 (PAGES)

1 (CODE)

TMX-52252 (NASA CR OR TMX OR AD NUMBER)

27 (CATEGORY)

PARTICULATE DAMPING IN SOLID PROPELLANT COMBUSTION INSTABILITY

by Louis Povinelli
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at Fifth Aerospace Sciences Meeting sponsored by the American Institute of Aeronautics and Astronautics
New York, New York, January 23-25, 1967

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION · WASHINGTON, D.C. · 1966

PARTICULATE DAMPING IN SOLID PROPELLANT COMBUSTION INSTABILITY

by Louis A. Povinelli

Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at

Fifth Aerospace Sciences Meeting
sponsored by the American Institute of Aeronautics and Astronautics
New York, New York, January 23-25, 1967

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

PARTICULATE DAMPING IN SOLID PROPELLANT COMBUSTION INSTABILITY

by Louis A. Povinelli

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

Abstract

The effect of aluminum powder in damping solid propellant instability had been investigated in a vortex burner developed previously. The combustor was composed of a main chamber having a shallow center-perforated grain and a hot gas generator. The generator fed combustion gases tangentially into the main chamber causing transverse mode combustion instability. Aluminum powder was added either to the main propellant or to the gas generator charge. Measurement of the amplitude of the pressure oscillations indicated the effectiveness of the metal acting (1) as an ingredient at the solid surface and in the gas phase and (2) in the gas phase only. In the absence of aluminum the combustor was unstable, exhibiting an oscillation frequency of 3800 cps with a peak-to-peak amplitude of 55 percent. The addition of fine aluminum powder to the propellant in the main chamber was sufficient to damp out the high-frequency instability. Addition of aluminum to the gas generator propellant only was also effective in eliminating instability provided that an equivalent concentration of metal particles was added. It was concluded that the addition of aluminum powder to solid propellants suppresses instability by acting as an attenuator of sound in the gas phase rather than altering the driving or response of the propellants. Viscous damping is inferred to be the principal damping mechanism. Addition of the aluminum produced a nonacoustic disturbance which appeared to be eliminated at higher operating pressures.

Author

Introduction

The ability of fine metal powders to suppress combustion instability has been well demonstrated in practical solid propellant motors. It was generally believed that the metal powders were effective at the burning surface of propellants rather than in the gas phase.(1),(2),(3) At a 1960 panel it was concluded that "a considerable body of experimental observations exist to indicate that the site of the action of suppressants, such as aluminum and aluminum oxide, is in the active layer at the burning surface in contrast to the possibility they might function as alternators of sound in the gas phase." However, base on recent experimental work it was concluded that the incorporation of aluminum in solid propellants does not significantly affect the response function of the propellant combustion zone;(4) that is, the driving is unaffected by aluminum. Since the driving was unaffected by aluminum it was concluded in reference 4 that the change in growth rate brought about by the addition of aluminum to the propellant must be due to increased damping caused by suspended metallic particles in the combustion gases. This conclusion is contradictory to the earlier observations(1),(2),(3) and presented a source of puzzlement to the authors of reference 4. The limitations and sources of uncertainty in the treatment of their data were discussed in reference 4. The uncertainty was based on the assumptions that (1) the burner damping is the same before and after burnout and (2) that the frequency during the growth and decay of the oscillations is the same. The qualified conclusion was that "the response functions of the propellants are approximately the same, and the greatest effect of the additives is in producing damping, which one infers as being due to viscous damping caused by particles in the gas."(4) Examination of the discrepancy that currently exists regarding the manner of suppression forms the basis for this paper. The principal objective of this study was to determine whether aluminum powder is effective as a surface ingredient or in the gas phase or exhibits a combined effectiveness. The results of a new experimental technique utilizing a solid propellant vortex combustor are presented. This burner exhibits a transverse mode of instability and incorporates the effect of a velocity field in contrast to the center-vented combustor (T-burner) with end burning grains used in reference 4. Use of end burning grains leads to zero velocity at the propellant surface. Comparison of the results obtained in the present study with the conclusion arrived at with the center vented should serve as a check on the validity of gas phase effectiveness.

Apparatus and Procedure

Motor Assembly

The experimental combustor was composed of a main chamber having a shallow center perforated propellant grain, a hot gas generator and an instability jet. The mode of operation is illustrated in figure 1(a). The gas generator feeds combustion gases tangentially into the main chamber igniting the main propellant and causing transverse mode combustion instability. A cross section of the assembled motor is shown in figure 1(b). The main chamber and the assembly was held together with two clamping rings having 48 1/4 inch bolts. Pressurization of the space between the two windows with nitrogen at 250 psia prevented the windows from bowing during the firing. Two throat diameters were used: 1/2 and 3/4 inch. The motor with the 1/2 inch throat gave a maximum design pressure of 45 psia with radial burning, that is, in the absence of tangential flow to the propellant surface. Use of the 3/4 inch throat yielded an unchoked condition with radial burning. Further details regarding the motor behavior and design are given in references 5, 6 and 7.

Propellant

The propellant in the main chamber, 5 inches in inside diameter, 7 inches in outside diameter by 1/2 inch thick, was cast into place above an expendable plexiglass ring. Subsequent to an 18 hour cure the top surface was machined flat leaving it 1/8 inch higher than the motor surface. Compression of the propellant grain between the plexiglass surfaces prevented combustion from occurring on the top surface of the propellant. Burning was restricted to the inside diameter of the grain only.

The propellants used in this study were composed of ammonium perchlorate and polybutadiene acrylic acid, 81 and 19 percent by weight, respectively. The oxidizer was a blend of ground (11μ) and unground (88μ) crystals. Both the propellant in the main chamber and the gas generator had 30 percent ground oxidizer. Fine aluminum powder (5μ mean weight diameter) was added to the propellant replacing a portion of the oxidizer. The particle size distributions are given in reference 8. The percentage of the metal used was 0, 1/2 and 1 percent by weight in the gas generator and 0 and 1/2 percent in the main chamber. The aluminum was added either to the main propellant or to the gas generator charge. In the former case the aluminum could function both as an ingredient at the solid surface and in the gas phase whereas in the second case the aluminum was introduced into the swirling gas flow above the solid surface and for all practical purposes could only be effective in the gaseous zone.

Instrumentation

A high-frequency, helium bled, water-cooled quartz-crystal transducer was used to record chamber pressure at a point close to the initial inside diameter of the propellant grain, see figure 1(d). The output from the high frequency transducer, the main chamber pressure measured at several positions and the gas generator pressure were recorded directly on magnetic tape. The location of the transducers is shown in figure 1(d). The mounting of the high-frequency transducer is shown in figure 2.

Measurement of the amplitude of the pressure oscillations with aluminum in the main chamber indicated the effectiveness of the metal acting both as a solid surface ingredient and in the gas phase. Measurement of the oscillation amplitude with aluminum in the gas generator only indicated the amount of gas phase damping. The behavior of the combustor in the absence of any aluminum has been investigated[5],[6] and serves as a reference case. Figure 3 represents the three basic ways in which the experimental tests were conducted. A total of 65 firings were made; 15 with no aluminum, 22 with aluminum in the motor propellant and 28 with aluminum in the generator.

Results and Discussions

General Pressure-Time Behavior

The increase of burning area within the gas generator yielded a gradually increasing pressure (fig. 4). The corresponding change in the main chamber pressure, P_c, follows the generator output quite closely. The flow field within the motor was primarily tangential relative to the burning propellant surface and gradually increased in magnitude for about 6 seconds after which the generator ceased burning. Following generator burnout, the unconsumed propellant continued to burn in the low-pressure environment. The flow during this remaining portion of the test quickly changed to the radial direction toward the nozzle entrance. The maximum pressure developed in the motor with the 1/2 inch throat was approximately 285 psia. In the absence of tangential flow, the maximum operating pressure was experimentally observed to be 35 psia. For the motor with the 3/4 inch throat, which would operate unchoked without tangential flow, the maximum pressure was 105 psia. These large increases in motor chamber pressure were caused by (1) addition of mass from the gas generator, (2) erosive burning due to the high tangential velocities in the main chamber, and (3) reduction of the effective nozzle throat area due to vortexing flow in the vicinity of the nozzle. The latter has been shown[6] to be primarily responsible for the large chamber pressure.

Reference Condition - No Aluminum

An oscilligraph record of the pressure-time behavior for the motor with the 3/4 inch throat (corresponding to fig. 4) and containing nonaluminized propellant is shown in figure 5. The maximum amplitude of the pressure oscillation was approximately 55 percent and the oscillation frequency was about 3500 cps. This frequency corresponded to the first traveling transverse mode and varied with a change in the inside diameter of propellant grain.[6] Figure 6 shows the resolution of the pressure oscillation as recorded by the high frequency transducer. (The disturbance labelled "signal interference" in fig. 5 was caused by the closing of a relay at ignition power cutoff which altered the amplitude of timing signal. It can also be seen on the other runs).

Aluminized Propellant

The addition of a 1/2 percent by weight of 5μ aluminum powder to the propellant in the main chamber was sufficient to damp out the high-frequency instability. See figure 7. However, a low frequency "oscillation" was introduced by the aluminum, whose general behavior was characterized by periods of 80-200 cps oscillations followed by random noise as shown in figure 8. The amplitude varied throughout the run, measuring less than 15 percent. This low frequency oscillation did not correspond to any of the acoustic modes of the chamber, but rather was associated with the burning behavior of the metal particles[9],[10] and is discussed in the next section.

Addition of aluminum to the generator charge only was also effective in eliminating high-frequency instability provided that an equivalent concentration of metal particles was added. Figure 9 shows the pressure-time trace when 1/2 percent of aluminum was incorporated in the gas generator. Resolution of the wave shape (fig. 10) revealed the existence of a low amplitude high frequency oscillation as well as the nonacoustic disturbance noted above. Increasing the aluminum content to 1 percent completely eliminated the low amplitude high-frequency component, see figures 11 and 12. The amount of aluminum required in the gas generator in order to obtain an equivalent concentration of particles (relative to using aluminized propellant in the main chamber) was determined from the ratio of the burning areas and linear regression rates of the main chamber and gas generator. It was determined that at the beginning of the run the required weight of aluminum in the generator should be approximately twice that in the main chamber whereas towards the end of the run the required weight is approximately 1.5 times greater. Use of the propellant with 1 percent aluminum in the generator described above would therefore yield a concentration of aluminum particles in the main chamber equivalent to or greater than that obtained with a 1/2 percent of aluminum added to the main chamber.

The conclusion to be drawn is that aluminum powder damps high-frequency combustion instability in composite propellants by producing gas phase damping rather a surface effect.

Nonacoustic Behavior

The low-frequency distrubance introduced by the addition of aluminum did not correspond to any of the acoustic modes of the chamber. It is believed to be associated with the burning behavior of the aluminum and further believed to be pressure dependent. Although details of the pulsating mechanism are under intensive study, the present understanding is speculative.[11] In order to verify the pressure dependancy of the phenomenon, tests were conducted with the motor having a 1/2 inch diameter throat. Aluminized propellant (1/2 percent by weight) was used in the gas generator. As shown in figures 13 and 14 the low-frequency nonacoustic oscillations were eliminated by operating at these higher chamber pressures. The low-amplitude, high-frequency oscillation evident in figures 13 and 14 were due to the insufficient quantity of aluminum added to the gas generator. (See also previous section where the addition of 1 percent eliminated the high-frequency oscillation).

Experimental Limitations

Several factors should be considered in interpreting the experimental results presented herein. When aluminum is introduced into the main chamber via the gas generator some of the aluminum particles may travel to the propellant surface and conceivably produce some surface effect. If this did occur to any extent the hot aluminum particles held against the surface by centrifugal force would produce an augmentation in the burning rate of the propellant. However, the mean pressure-time behavior of the motor did not significantly differ from the nonaluminized case, indicating that the propellant burning rate was not influenced by the presence of hot metal particles in the chamber. Hence it is concluded, that to first order, metal particles were not retained on the propellant surface. Photographic observations offer difficulties due to problems of smoke emission, resolution and field of view. Other factors to be considered are that size distribution and degree of reactivity of the metal particles may not be the same in both cases where aluminum was used. With the exception of a small number of agglomerated particles it is believed that the nature of the particles produced by the gas generator are similar to those produced by the main chamber propellant.

The addition of the aluminum to the propellant did not significantly alter the burning rate as measured in a strand burner. The generator operated at a choked condition both with and without aluminum in the propellant. Hence the exit velocity of the jet entering the main chamber was unaltered by the addition of aluminum. It is expected therefore that the tangential velocity in the chamber was not appreciably different with or without aluminum.

A practical limit exists on the amount of aluminum that can be added to the gas generator propellant due to plugging of the instability jet. In figure 11, it is evident that the maximum generator pressure with 1 percent aluminum is significantly larger than in the other runs. Several runs made with 2 percent aluminum in the generator revealed rather erratic pressure-time traces due to plugging and unplugging of the instability jet. Post-firing inspection revealed the presence of a substantial amount of aluminum in the jet passage.

Damping Mechanism

The experimental results yielded strong evidence that the damping effectiveness of aluminum occurs in the gas zone rather than at the burning surface. Modes of damping other than particulate damping are possible. A recent study[12] has considered the possibility of damping due to droplet deformation, surface vibration of a droplet, droplet shattering and aluminum blockage of the burning surface from acoustic disturbances. It was concluded in reference 12 that particulate damping is the dominant dissipative mechanism in the high frequency range. However, an order of magnitude analysis indicated that agglomerates of aluminum on the burning surface blocking interaction with the acoustic field could be as important as particulate damping. The results of the present study suggest that such is not the case at low levels of aluminum loading. It has been further postulated[13] that the aluminum promotes a catalytic effect on the gas phase reactions. The present study does not refute this possibility. However, any proof of this mechanism requires detailed analysis of the gas phase reactions in the flame zone. Spatial resolution of the combustion reactions are a necessity in order to asses the catalytic effect. The technique presented in reference 14 offers a possibility of obtaining the necessary measurements.

Comparison of the theoretical amount of particulate damping with the observed damping was not possible due to the difficulty in determining a growth constant for the pressure oscillations.

If particulate damping is the principal dissipative mechanism then knowledge of the aluminum size and number of particles in the gas become the important parameters in achieving combustion stability. As determined by Epstein and Carhart,[15] the particulate (viscous) damping constant depends on the particle radius R and concentration n according to the relation:

$$\alpha = \frac{6\pi R}{c}\, \nu n(1 + Z)\left[\frac{16Z^4}{16Z^4 + 72\delta Z^3 + 81\delta^2(1 + 2Z + 2Z^2)}\right]$$

where

$$Z = \left(\frac{\omega}{2\nu}\right)^{1/2} R$$

ω is the angular frequency, c is sound speed, ν is kinematic viscosity and δ is density ratio.

Alumina Particle Size

Measurement of the size distribution of the alumina particles in the combustor remains as a critical item in determining stability behavior. Qualitative information of metal behavior was obtained in references 16 and 17. Limits were obtained on particle sizes and the effects of aluminum size, concentration and combustion pressure were obtained. High-speed photographs indicated particle motion on the surface leading to the formation of agglomerates. The effect of oxidizer particle size was subsequently investigated(8) and shown to be significant in influencing metal agglomeration. The previous information was used to formulate a conceptual model of the agglomeration process dependent on two factors: (1) particle movement and collision on the surface and (2) proximity of aluminum particles. This model was generally substantiated for PBAA-AP propellants by a later study conducted over a pressure range up to 500 psia, using strands of propellants both with (port simulation) and without (head end simulation) a superposed velocity field.(18) The significant feature of these studies is that the aluminum oxide particle size could be independent of the original aluminum size added to the propellant, this change being brought about by agglomeration. Further attempts to measure size distributions near the burning propellant surface have not yielded useful information due to restrictions on both photographic resolution and field of view.(19) Further work on the mechanism of agglomeration with a variety of propellant combinations has led to considering only the proximity of metal particles(20) in the propellant. With few exceptions(20),(21) very little new information has been obtained on the mechanism of agglomeration in recent years; a phenomenon which by its very nature appears to defy an exact description. Understanding the factors that govern agglomeration such as given in references(16),(18) has lead to the use of propellant compositions which yield oxide particle sizes of 1 to 2 microns. This size is believed to be the optimum required for damping instability in typical solid rocket operation.(22),(23)

Conclusions

The experimental results obtained with the vortex burner showed that aluminum added in the gas phase was as effective in damping out transverse mode instability as the aluminum added as an original ingredient of the propellant. It was concluded that the aluminum was effective in the gas phase in producing dissipative forces and further surmized that the mechanism of damping was due to viscous and thermal effects (particulate damping).

These results indicate that aluminum should be effective in damping out combustion instability in liquid rocket engines depending on the amount of driving present in the system. Further, the method of injection could be similar to that used in the present study.

References

1. Price, E. W., "Combustion instability in solid propellant rocket motors," Astronaut. Acta 5,63-72 (1959).

2. McClure, F. T. et al, "A general review of our state of knowledge, first report of the working group on solid propellant combustion instability," Applied Physics Lab., Johns Hopkins University, TG 371-1 (July 1960).

3. McClure, F. T. et al, "Panel discussion of solid propellant instability," Eighth Symposium (International) on Combustion (Williams and Wilkins Co., Baltimore, 1962), p. 908.

4. Horton, M. D. and McGie, M. R., "Particulate damping of oscillatory combustion," AIAA J. 1, 1319-1326 (1963).

5. Povinelli, L. A. and Heidmann, M. F., "Study of transverse mode solid propellant combustion instability," Applied Physics Lab., Johns Hopkins University CPIA Publication No. 68 Volume 1 (January 1965), p. 409.

6. Povinelli, L. A., Heidmann, M. F., and Feiler, C. E., "An experimental investigation of transverse mode solid propellant combustion instability in a vortex burner," NASA TN D-3708 (November 1966).

7. Povinelli, L. A., "NASA-Lewis solid propellant combustion research," Compilation of Abstracts of Paper for the Sixth AFOSR Contractors' Meeting on Solid Propellant Combustion Research, Stanford Research Institute, AFOSR-5331 (January 17, 1964).

8. Povinelli, L. A., "Effect of oxidizer particle size on additive agglomeration," NASA TN D-1438 (November 1962).

9. Povinelli, L. A., "Behavior of large aluminum particles in composite propellants," Applied Physics Lab., Johns Hopkins University, CPIA Publication No. 68, Volume 1 (January 1965), p. 373.

10. Price, E. W., Rice, D. W., and Crump, J. E., "Low-frequency combustion instability of solid rocket propellants," Naval Ordnance Test Station TP 3524 (July 1964).

11. Price, E. W., "Experimental solid rocket combustion instability," Ninth Symposium (International) on Combustion (The Combustion Institute, Pittsburg, Pa., 1965), p. 1067.

12. Oberg, C. L. and Huebner, A. L., "Effects of Aluminum on solid-propellant combustion instability," Rocketdyne Div., North American Aviation, Inc. R-6654, AFOSR-66-1847 (July 1966).

13. Brzustowski, T. A., "On the burning of metal additives in solid-propellant rocket motors," Can. Aeron. Space J. 9, 141-149 (1963).

14. Povinelli, L. A., "A study of composite solid-propellant flame structure using a spectral radiation showgraph technique," AIAA J. 3, 1593-1598 (1965).

15. Epstein, P. A. and Carhart, R. R., "The absorption of sound in suspensions and emulsions. I: Water fog in air," J. Acoust. Soc. Am. 25, 553-565 (1953).

16. Watermeier, L. A., Aungst, W. P., and Pfaff, S. P., "An experimental study of the aluminum additive role in unstable combustion of solid rocket propellants," Ninth Symposium (International) on Combustion, W. G. Berl, ed. (Academic Press, New York, 1963), p. 316.

17. McCarty, K. P., "Techniques for studying the combustion of aluminum in solid propellants," Pyrodynamics 1, 71-87 (1964).

18. Povinelli, L. A. and Rosenstein, R. A., "Alumina size distributions from high-pressure composite solid-propellant combustion," AIAA J. 2, 1754-1760 (1964).

19. Crump, J. E., "Photographic survey of aluminum combustion in solid propellants," Applied Physics Lab., Johns Hopkins University CPIA Publication No. 68, Volume 1 (January 1965), p. 367.

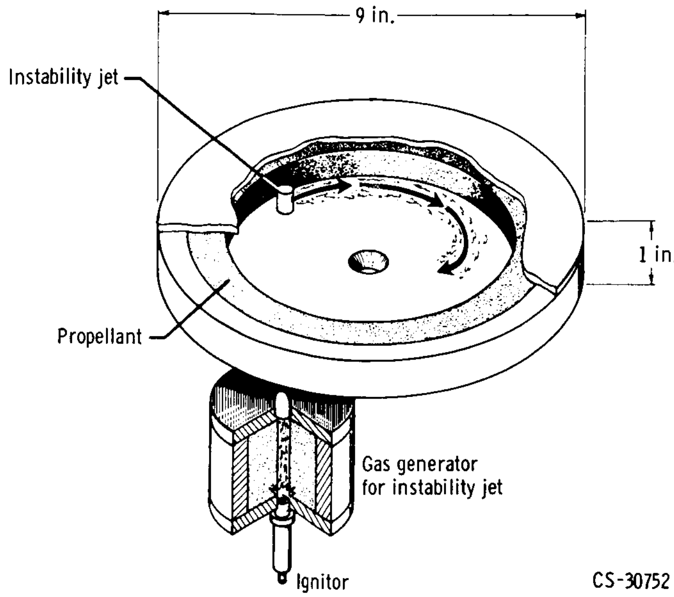
20. Crump, J. E., "Aluminum combustion in composite propellant," Applied Physics Lab., Johns Hopkins University CPIA Publication No. 105, Volume 1 (May 1966), p. 321.

21. Miller, R., "Effect of ammonium perchlorate on the combustion of aluminum in CMDB propellants," Applied Physics Lab., Johns Hopkins University CPIA Publication No. 59.

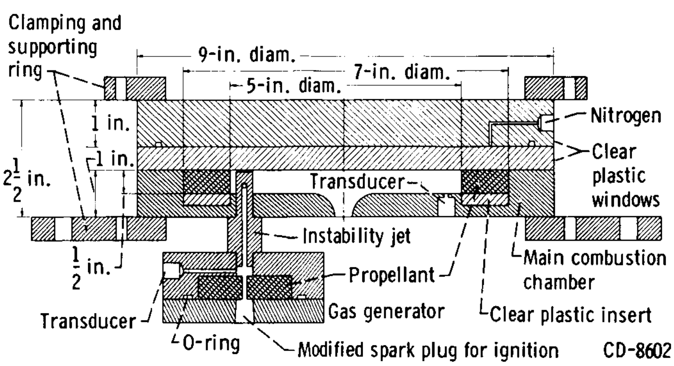
22. Blair, D. W., "Particle damping of a plane acoustic wave in solid propellant combustion gases," AIAA J. 1, 2625-2626 (1963).

23. Dobbins, R. A. and Temkin, S., "Sound propagation in a gas-particle mixture and combustion instability," Applied Physics Lab., Johns Hopkins University CPIA Publication No. 118 (September 1966), p. 113.

E-3726



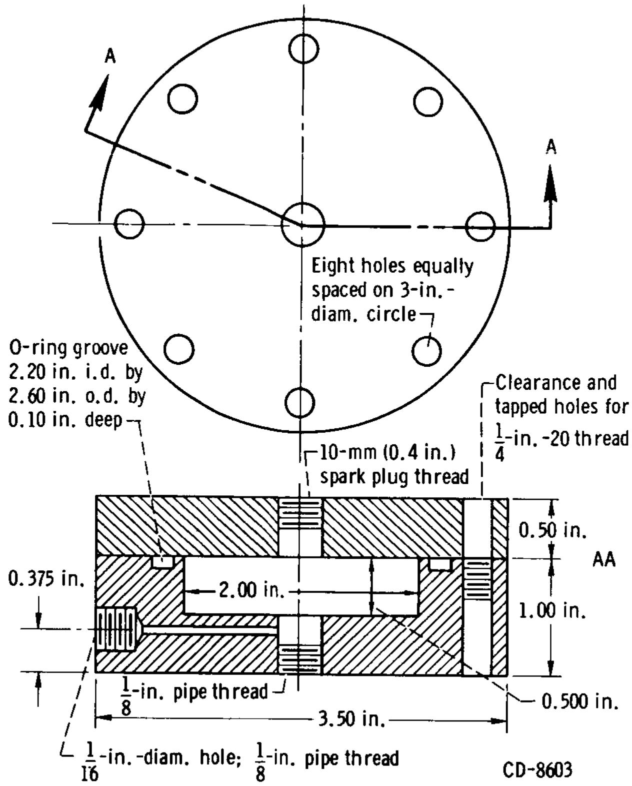
(a) Experimental geometry and mode of operation.



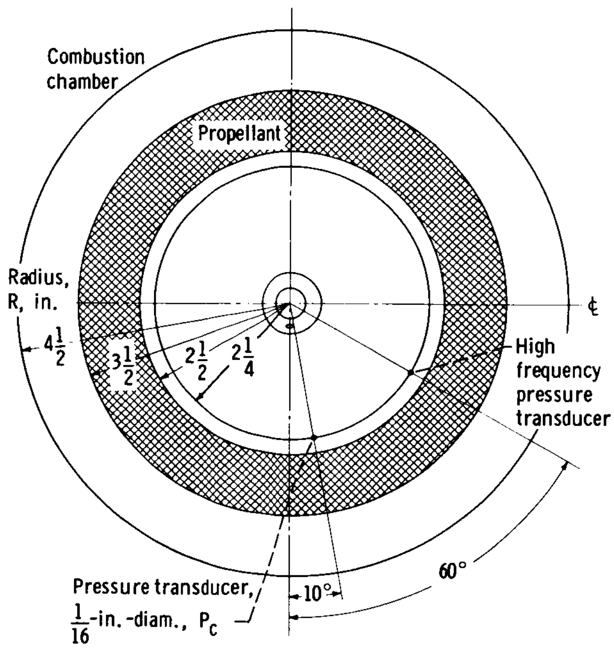
(b) Motor, gas generator, and instability jet assembly.

Figure 1. - Experimental combustor.

E-3726



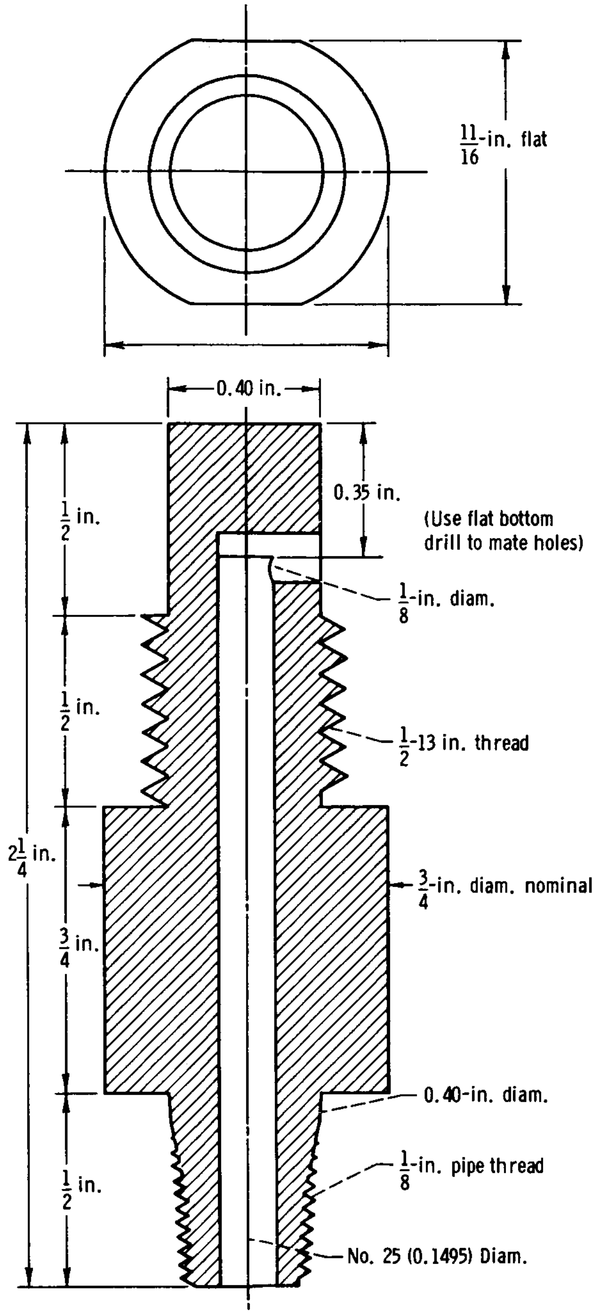
(c) Gas generator details; material, brass.



(d) Typical pressure transducer locations.

Figure 1. - Continued.

E-3726



(e) Instability jet design; material, copper.

Figure 1. - Concluded.

E-3726

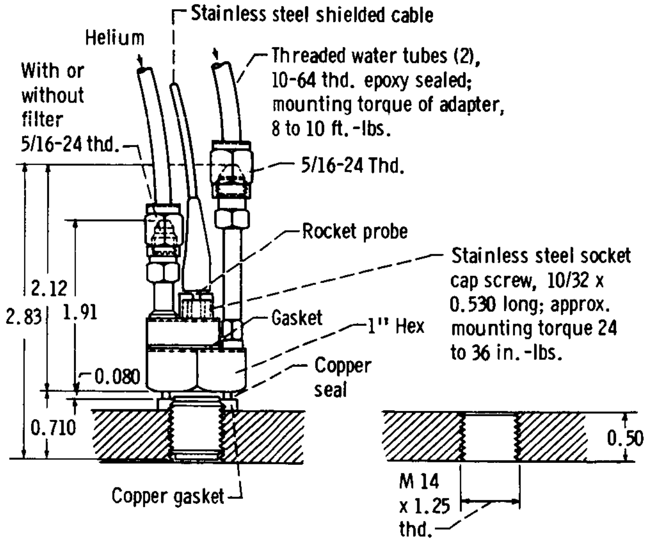
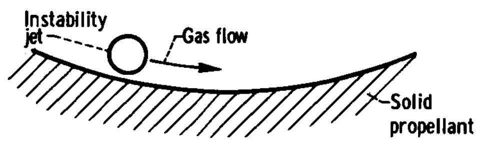
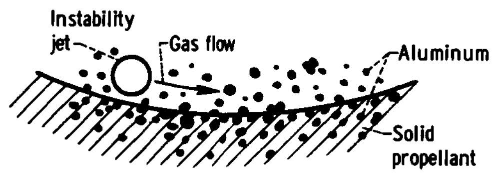


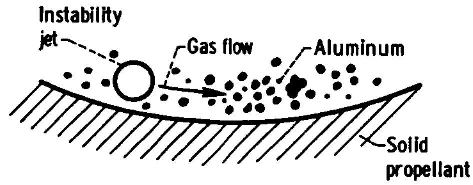
Figure 2. - High-frequency pressure transducer mounting details.



(a) No aluminum.



(b) Aluminum in main chamber propellant.



(c) Aluminum in generator propellant.

Figure 3. - Location of aluminum in propellant.

E-3726

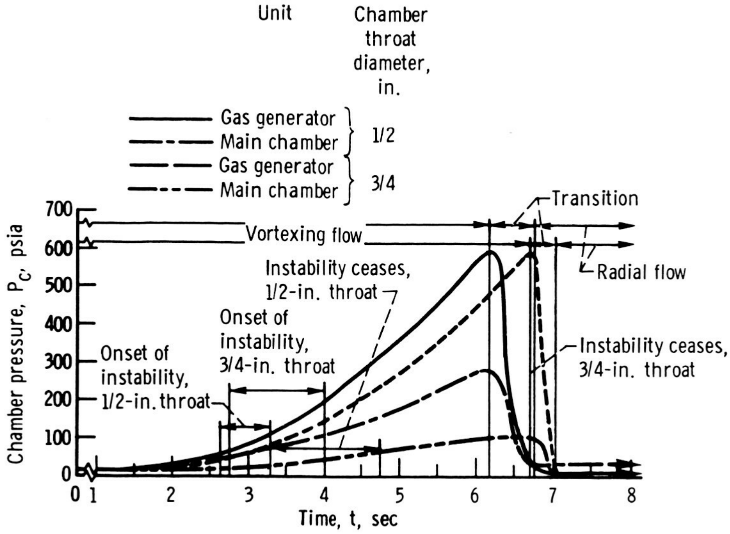


Figure 4. - Pressure-time behavior of gas generator and main chamber.

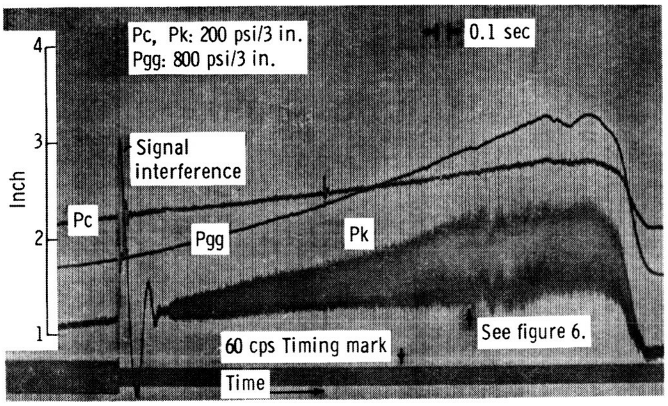


Figure 5. - Pressure - time trace without aluminum. Pk, high frequency; Pgg, gas generator; Pc, chamber pressure.

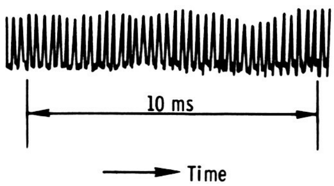


Figure 6. - High frequency channel. Chamber pressure wave shape. Oscillation frequency 3840 cps.

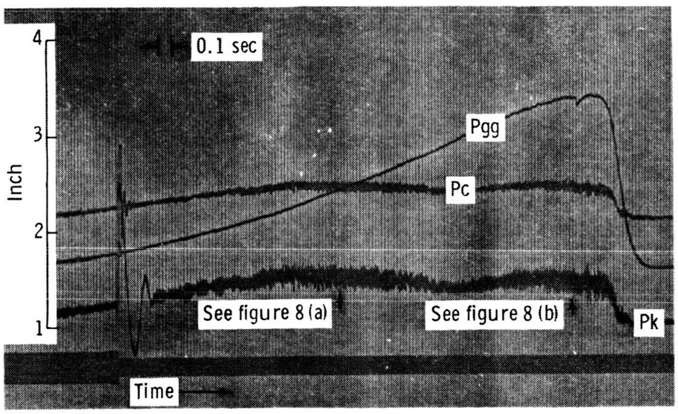
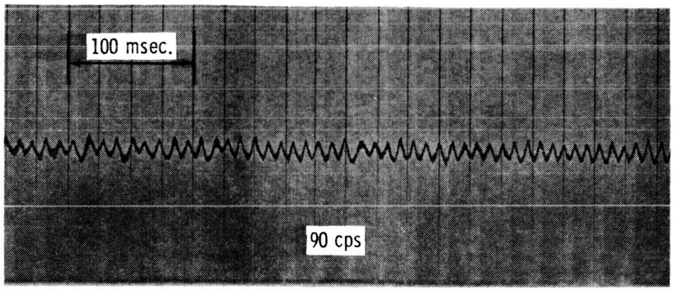
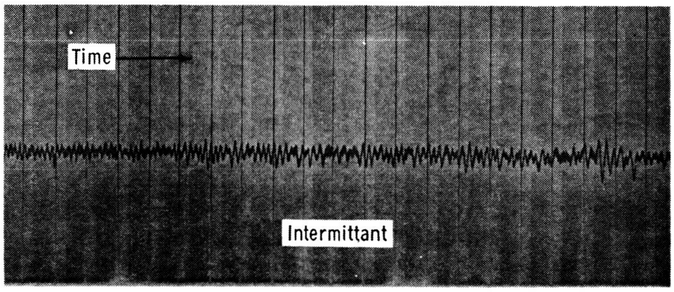


Figure 7. - Pressure - time trace with 1/2 percent aluminum in motor.

E-3726



(a) Wave resolution at time indicated in figure 7.



(b) Wave resolution at time indicated in figure 7.

Figure 8. - High-frequency channel. Chamber pressure wave shape with 1/2 percent aluminum in motor.

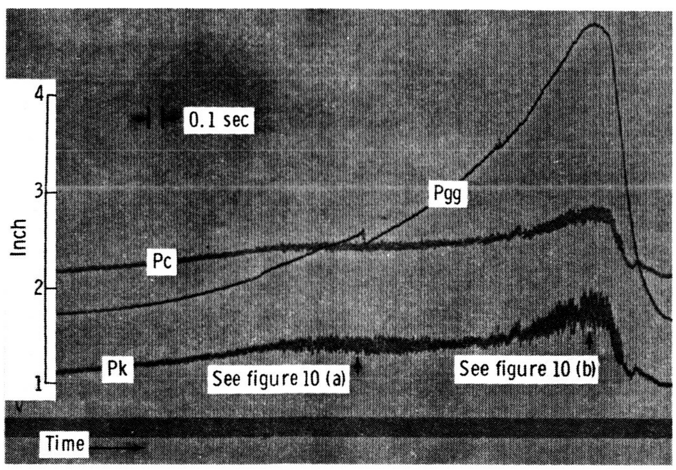
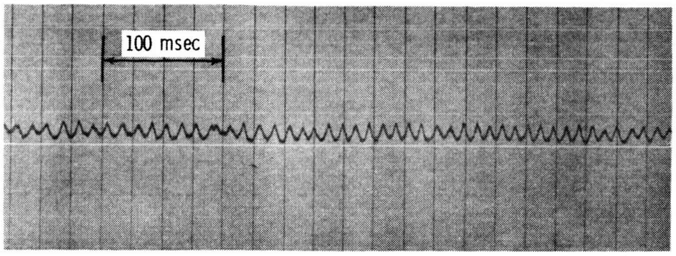
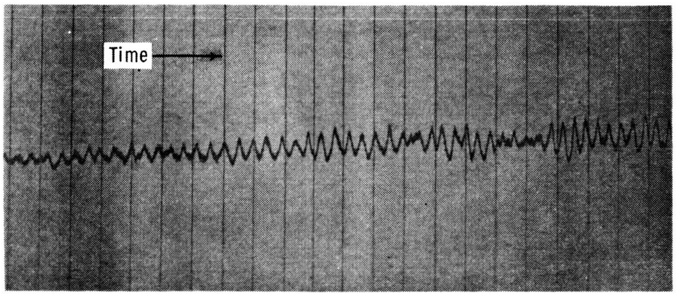


Figure 9. - Pressure - time trace with 1/2 percent aluminum in gas generator.



(a) Wave shape resolution at time indicated in figure 9.



(b) Wave shape resolution at time indicated in figure 9.

Figure 10. - High-frequency channel. Chamber pressure wave shape with 1/2 percent aluminum in gas generator.

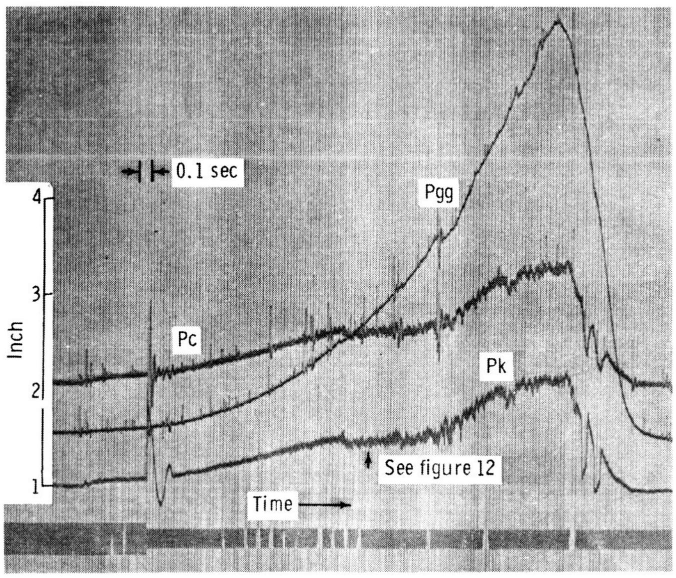


Figure 11. - Pressure - time trace with 1 percent aluminum in gas generator.

E-3726

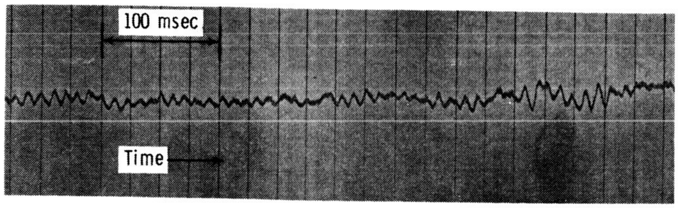


Figure 12. - High-frequency channel. Chamber pressure wave shape with 1 percent aluminum in gas generator.

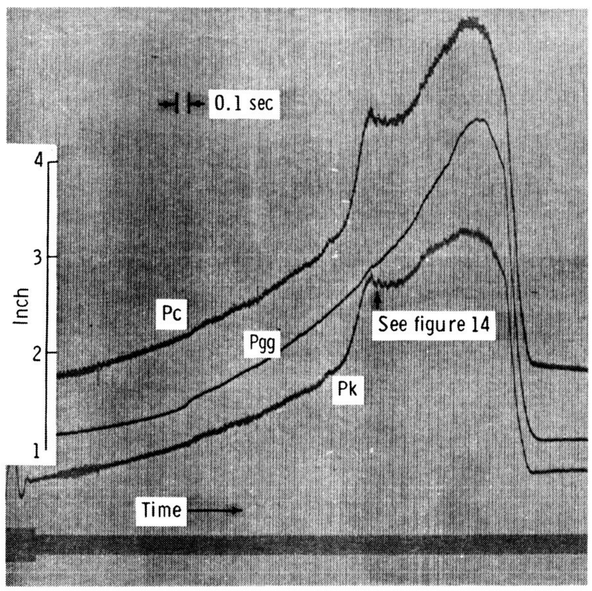


Figure 13. - Pressure - time trace with 1/2 percent aluminum in gas generator. Throat diameter, 1/2 inch.

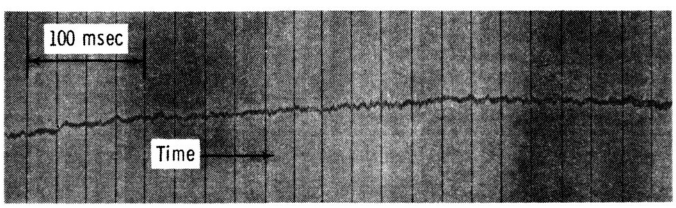


Figure 14. - High-frequency channel. Chamber pressure wave shape with 1/2 percent aluminum in gas generator. Throat diameter, 1/2 inch.

NASA-CLEVELAND, OHIO E-3726