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EXPLOSIVE OXIDATIONS INITIATED BY SIMULATED METEOROID PENETRATION INTO SPACECRAFT ATMOSPHERES

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ABSTRACT: Hypervelocity impact tests were conducted in an evacuated range on target samples which simulated a NASA S-IVB wall configuration since this stage is planned as the primary structure in the NASA Orbiting Workshop program. The samples formed part of the wall of a large tank which contained an oxygen-rich atmosphere. The explosive oxidations which occurred inside the tank as a result of perforation were observed and the results were analyzed. The bare thermal insulation on the inside of the wall further enhanced the otherwise severe reaction which occurs with a metallic wall in the presence of enriched oxygen.

KEY WORDS: hypervelocity impact, meteoroid penetration, spacecraft, combustion front, oxygen atmosphere, oxidative detonation, oxidative flash, blast overpressure

INTRODUCTION

The perforation of the wall of a vessel by a hypervelocity projectile will produce an explosive-like reaction inside the tank if the tank contains an oxygen-rich atmosphere. Studies (1-10)[1] have shown that the extremely hot fragments of projectile and wall materials rapidly undergo a chemical reaction with the oxygen in the immediate vicinity of the perforation, producing a combustion front which penetrates into the tank. This violent reaction is accompanied by a brilliant flash of light.

The process just described is similar to the situation which could exist if the wall of a manned space vehicle were to be perforated by a meteoroid. There is ample reason for concern regarding the effect of such an encounter on the human occupants of

[1]The numbers in parentheses refer to the list of references appended to this paper.

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the space vehicle. Among the phenomena which could present a serious pathological hazard to human occupants are the blast overpressure, the intense light flash, and the high temperatures associated with the combustion front. The possibility that a spacecraft fire would be initiated by the combustion front and accompanying hot particles is a secondary, but perhaps equally serious, potential hazard. Ways to alleviate these problems are discussed in Refs. 9 and 11.

Roth (8) has presented a literature review and survey of this flash oxidation hazard from the biomedical point of view. Much of his discussion is focused on the work of Gell and his colleagues at Ling-Temco-Vought (1-3). These workers exposed white rats to this oxidative detonation inside a vessel which was perforated by a high-velocity projectile. These animals suffered various degrees of injury and incapacitation, and under some test conditions mortality occurred. It was impossible to determine whether death occurred primarily as a result of the blast effects or as a result of burns received by the animal.

Several recent studies (4-7) have produced additional information regarding the mechanism of this oxidative reaction and its potential hazards to spacecraft structures, systems, and personnel. However, all questions have not been answered, and any additional experimental information which becomes available should be welcomed by those concerned with spacecraft design.

In a recent test program (9) at AEDC, hypervelocity impact tests were conducted on target samples which simulated a wall configuration of the Saturn S-IVB stage. The S-IVB stage is planned as the primary structure in the NASA Orbiting Workshop program. On many of these tests, the target sample was attached to a large tank which permitted the rear of the wall sample to be exposed to an oxygen-rich atmosphere during perforation. The main purpose of these tests was to evaluate methods of preventing or minimizing combustion of the polyurethane foam which covered the inside of the wall sample. As a result of these tests, the decision was made to install a 3-mil aluminum foil fire-retardant liner to cover the insulation and to install a micrometeoroid bumper on the vehicle (11). At the same time, however, these tests provided an opportunity to observe the blast effects inside the test tank at the time of perforation. ~~The combustion~~ front was recorded photographically on a large number of these tests. In addition, on a limited number of these tests, transducers were placed inside the test tank to allow further observation of the phenomena associated with the combustion front. The purpose of this paper is to describe these observations and to relate them to previously available information on the subject. The present results, although limited in extent, provide information which applies specifically to an uncovered polyurethane insulation and unbumpered wall configuration.

TEST CONFIGURATION

LAUNCHER AND RANGE

These tests were conducted in the Hypervelocity Impact Range S-2 at AEDC. The range includes: (1) a two-stage launcher; (2) a blast tank into which muzzle gases expand and in which the projectile (1/8 in. diam., type 2017 aluminum spheres in these tests) is separated from the sabot; (3) a connecting tube along which velocity measuring shadowgraphs are located; and (4) a target tank where the test specimen is impacted by the projectile. The large size (6 ft. diam. by 21 ft. long) of this target tank permits the impact testing of unusually large configurations in a vacuum environment. In the present test, it permitted the use of a relatively large (3 ft. diam. by 5 ft long) test tank whose volume was greater than that of any vessel used in previous explosive oxidation impact studies (1-7).

TARGET CONFIGURATION

The wall specimen used on this test was designed to simulate the Saturn S-IVB basic wall structure. It consisted of a 0.125 in. thick, type 2014-T6 aluminum sheet to which a 1 in. thick layer of closed-cell polyurethane foam was bonded. The foam was sealed with a layer of glass fabric and a coat of polyurethane resin. A photograph of the rear of a wall specimen is shown in Fig. 1. This polyurethane insulation provides thermal insulation on the inside of the tank to prevent liquid hydrogen boil-off for the propulsive stage.

The target specimen was attached to the upstream end of the test tank, with the foam insulation on the inside. The test tank was mounted inside the range target tank with its axis on the range centerline. Provisions were made for evacuating the test tank prior to charging it with the desired gas mixture.

INSTRUMENTATION

The combustion front inside the test tank was recorded photographically on a large number of those tests reported in Ref. 9. The tank was equipped with a side port (approximately 10 in. diam.) immediately behind the upstream tank flange, providing a view normal to the tank centerline. The uprange edge of this field of view was about 4 in. behind the rear of the wall specimen. In addition, another port was located in the rear end of the test tank, providing an unobstructed centerline view of the rear of the wall specimen. The side port was used most often for this high-speed camera coverage, because the rear port was usually occupied by other instrumentation systems. A 16-mm camera was used, and the framing rate during the event was usually about 3200 frames/sec.

For the shots which are of particular interest in this report, additional instrumentation devices were placed inside the test tank to record the passage of the combustion front. This additional instrumentation consisted of four quartz pressure transducers and four lead-zirconate piezoelectric "time-of-arrival" gages. These devices were mounted in four pairs at 12 in. intervals longitudinally in the tank. Each pair consisted of one of each type of gage. The devices were attached to a bracket which was cantilevered from the rear end of the test tank. The bracket was shock-mounted at its point of attachment to the tank. A sketch of this arrangement is presented in Fig. 2. The outputs of these devices were amplified and recorded on magnetic tape.

Three tests were also conducted with iron-constantan thermocouples located inside the test tank. The thermocouple junctions were resistance welded using 0.002 in. wires. These thermocouples were fabricated using a standard thermocouple connector and ceramic insulator as shown in Fig. 3, and the devices were mounted on the bracket inside the test tank with the exposed junction facing forward. The thermocouples were located at 8 in. intervals as shown in Fig. 2. The reference junctions were immersed in ice baths, and the thermocouple outputs were displayed and recorded on oscilloscopes.

The instant of projectile impact on the wall specimen was monitored by means of a radiometer which observed the initial impact flash. The radiometer output was recorded on the magnetic tape to provide a time reference for the pressure gages and time-of-arrival gages inside the test tank. The radiometer output was also used to trigger the oscilloscopes which were used to display the thermocouple outputs.

TEST RESULTS

TEST CONDITIONS

For the tests of interest in the present report, the test tank was charged with the desired gas mixture to a pressure of 5 psia. The test gases were nitrogen and oxygen, and individual tests were conducted with specific volumetric mixtures of 21 percent oxygen (air), 45 percent oxygen, 59 percent oxygen, 70 percent oxygen, as well as 100 percent oxygen or nitrogen. All tests of interest were conducted using 1/8 in. diam. aluminum spherical projectiles at velocities in the 20,000-26,000 ft/sec regime.

The target configuration previously discussed was used on all tests of interest in this report. Impact usually occurred within the target area covered on the rear by the polyurethane foam. However, on a few shots, including two of the shots made with the additional instrumentation devices inside the tank, target perforation occurred outside of the area covered by the foam. These shots provided a fortunate opportunity for comparing the test results for an insulated wall with the corresponding behavior for a simple aluminum wall.

PHOTOGRAPHIC OBSERVATIONS OF OXIDATIVE FLASH

Typical film sequences of the oxidative flash occurring inside the test tank at impact are presented in Figure 4. Film exposure resulted from luminosity inside the tank produced by the rapid oxidation of projectile and wall materials. The film clip at the left depicts perforation of the 1/8 in. thick aluminum wall without foam insulation. The duration of the event recorded on the film is about 6 msec. The second, third, and fourth film clips depict perforation of a typical wall specimen for the case of

45, 70, and 100 percent oxygen mixtures, respectively. The complete duration of the events on these tests, of which only the initial portions are shown in the figure, were 34, 44, and 53 msec for the 45, 70, and 100 percent oxygen mixtures, respectively. The exposure of the pictures indicates qualitatively that the intensity of the combustion front increases with increasing oxygen concentration. On other tests with 5 psia of air in the test tank, film exposure was too weak for printing. On tests using 100 percent nitrogen, no film exposure occurred.

The fifth film clip in Fig. 4 was obtained through the rear port of the test tank instead of the side port. The camera was focused on the rear of the test specimen, the outline of which is visible in the first frame. The sharpness of focus is reduced as the flame front propagates into the tank. Duration of the recorded event was about the same as for the adjacent film clip (100 percent oxygen). This view, unrestricted by port size, indicates that the flame front penetrates throughout the test tank.

These film clips demonstrate clearly the effect of the polyurethane foam on the oxidative flash. In the absence of the foam, the metallic wall and projectile provided the only particles available for oxidation. Furthermore, production of these particles is complete within a relatively short time interval after impact. However, with the addition of polyurethane foam to the wall, a large volume of low-density, highly combustible material is ejected into the oxidizing atmosphere inside the tank at impact. Also, the foam continues to be ejected for a long period of time compared with the single metallic wall condition. The overall effect of the presence of the foam is to significantly increase (by an order of magnitude) the duration of the oxidative flash inside the tank.

VELOCITY OF COMBUSTION FRONT

The "time-of-arrival" gages inside the test tank responded to the phenomena inside the tank. Typical oscillograph playback traces of the recorded data are presented in Fig. 5. The results shown in Fig. 5a are typical for those tests for which impact occurred within the area covered by the foam. The results for one of the two shots which missed the foam are shown in Fig. 5b. In the latter case, the type of response obtained from these gages indicates that the leading edge of the disturbance is well defined as it passes through the tank. In the case of impact within the foam-covered area, however, the leading edge is somewhat "smeared out" by the interaction between the foam and the high-speed metallic particles.

The time interval from projectile impact to arrival of the disturbance at each gage location inside the tank was read from the oscillograph traces as indicated in Fig. 5. In the case of impacts through the foam, an attempt was made to define the instant of arrival of the strong part of the front instead of its weak leading edge. A degree of judgement was required in the definition of this instant because of the smearing of the front. These results are presented in Fig. 6. Although there is some scatter in these results, the data clearly indicate slopes on the distance-time plots corresponding to a propagation velocity of about 8000 ft/sec for impacts which perforated the foam and about 22,000 ft/sec for impacts which missed the foam. These results appear to be independent of the oxygen concentration in the test tank.

It is evident that the experimental distance-time measurements shown in Fig. 6 do not extrapolate back to the origin of the plot. This is largely because the bracket which held the instrumentation devices was mounted approximately 8 in. below the tank centerline. Since the disturbance front which propagated through the tank was non-planar and was, to a first approximation, hemispherical in shape, its arrival at a gage position could occur significantly later than its arrival at the corresponding centerline position. The general shifting in time of the results from shot to shot probably resulted from the random dispersion of the projectile impact location with respect to the tank centerline. It is believed that the large upward shift in the results for shot 300 (Fig. 6e) was the result of a premature impact flash signal from a small particle preceeding the projectile rather than the effect of a change in gas composition.

The velocity of the disturbance which produced the time-of-arrival gage response does not correspond with the velocity of cloud motions as observed on the 16-mm film (Fig. 4). In the later case, for impacts which perforated the bare foam, the leading edge of the luminous cloud which initially passes across the camera field of view has a velocity of about 800 ft/sec, a full order of magnitude less than that indicated by the gage response. Therefore, there is reason to conclude that the billowing luminous clouds which are visible in the 16-mm camera pictures represent a stage of the impact process which is fundamentally different from the initial disturbance stage. These differences are worthy of further study.

PRESSURE MEASUREMENTS

When a thin wall is perforated by a hypervelocity projectile, the expanding debris cloud immediately behind the point of impact will contain fragmented, melted, and vaporized materials. It is convenient to visualize that a "pressure" exists within this expanding cloud. More precisely, the cloud contains momentum which produces an impulse acting on any surface the cloud strikes. If the cloud is completely vaporized, thereby consisting of a very large number of very small particles, the usual concept of pressure may be valid for time scales and space scales of interest. However, appreciable vaporization cannot be produced in most materials, including those of the present test, at velocities attainable with light-gas guns. Therefore, the debris cloud in these tests consisted of discrete solid and molten fragments instead of a "continuous" expanding vapor. Nonetheless, a piezoelectric pressure transducer located within a few projectile diameters of the impact location in the present tests would likely observe an apparent stagnation pressure on the order of a few kilobars (12,13).

The stagnation pressure in the debris cloud decreases as the cloud expands away from the target sheet. Furthermore, the radial pressure profile in the cloud falls off very rapidly with increasing distance from the axial centerline. The instrumentation bracket inside the tank (Fig. 2) on the present test was located below the tank centerline not only to prevent transducer damage from fragments within the debris cloud but also to minimize any contribution to the measured pressure which could result from the debris cloud rather than from the combustion front. It was hoped that any pressure observed by the transducers would result entirely from the explosive oxidation of the wall and projectile materials, the effects of which were expected to propagate throughout the tank.

None of the pressure transducers inside the tank on these tests recorded an overpressure exceeding the noise level generated by mechanical shock at impact. This mechanical noise level never exceeded the equivalent of 5 psi and was less than 3 psi for most tests. Therefore, these results imply that any overpressure which may have existed at the transducer locations never exceeded 5 psi.

This result is somewhat surprising in view of reported maximum overpressures of 38 psi (3), 100 psi (4), 75 psi (5), and 150 psi (6) obtained in previous investigations. It should be noted, however, that all of the investigations of this type have involved widely differing test configurations (projectile, target, tank volume, transducer location, etc.). Furthermore, the use of a piezoelectric transducer in a mechanical shock environment is no easy task since the crystal responds to acceleration as well as pressure. Finally, it is possible that some investigations may have indicated abnormally high overpressures because of the interaction of the expanding debris cloud with the blast overpressure. Nonetheless, it is not possible to explain with certainty the large difference in blast overpressure between the present measurements and those of other investigators. Nor is it possible to identify which particular sets of measurements, if any, are in error. The large differences between observations illustrate the need for additional testing to resolve the present uncertainty.

TEMPERATURE MEASUREMENTS

Temperature measurements were obtained on two tests using a 70 percent oxygen atmosphere and one test using air. An oscilloscope trace of the output of one thermocouple on a test with 70 percent oxygen is shown in Fig. 7. A rapid temperature increase is observed to begin about 5 msec after projectile impact. The signal then reaches a plateau corresponding to about 1600 F within 15 msec. The indicated temperature remains near this level for about 35 msec and then decreases steadily toward ambient conditions. This type of response was typical for all thermocouples used on these tests.

The maximum indicated temperatures recorded on these three tests are summarized in Table 1. The second thermocouple consistently recorded the higher temperature, indicating a spatial variation in maximum temperature inside the tank. It is impossible to determine whether the impact velocity difference or the spatial variation in temperature was primarily responsible for the lower maximum temperature which occurred on the second test with 70% oxygen. It is clear that the indicated temperature is strongly dependent upon the oxygen concentration inside the test tank. The implication is that most (if not all) of the heating which occurs after impact is a direct result of the rapid combustion of impact debris. The contribution of the individual components (insulation and aluminum plate) to the heating effect was not determined.

DISCUSSION

The phenomena which occurred when the test specimen was perforated on these tests can be separated into two categories. The first category includes those phenomena which are associated with the impact and perforation events only, i.e., those which would occur even in the absence of an oxidizing atmosphere. The second category includes the additional phenomena which occur because of the presence of oxygen inside the test tank.

The first category includes the formation of the debris cloud of fragmented, melted, and vaporized projectile and wall materials which expand into the test vessel. The leading edge of this debris cloud is thought to have produced the initial response of the time-of-arrival gages on these tests. The presence of oxygen in the test tank apparently had little effect on the initial character of the debris cloud since the propagation velocity of the disturbance was the same with or without oxygen. On the other hand, the character of the debris cloud was obviously influenced by the presence of the polyurethane foam insulation which was bonded to the inside of the aluminum wall.

Although the oxygen concentration did not affect the initial character of the debris cloud, the quantity and state of the materials contained within the debris cloud strongly influenced the duration and severity of the oxidation process. In particular, the large quantity of finely divided, low-density, combustible material ejected from the insulated wall resulted in an order of magnitude increase in the duration of the oxidative flash compared with the single metallic wall condition. The billowing luminous clouds visible in the 16-mm film records are probably the gaseous products of combustion of the foam with oxygen. The effects of these burning products on other spececraft materials is not included in this paper. A limited study of secondary combustion is reported in Ref. 9.

The results presented herein have demonstrated the possibility that an exposed and unprotected internal thermal insulation could aggravate the reaction which would occur upon meteoroid perforation of an unbumpered spacecraft hull without a fire retardant liner. The phenomena treated in the present paper would occur only in the event of meteoroid perforation of the basic workshop wall. No attempt has been made in this investigation to assess the probability of such an occurrence or to evaluate methods of reducing this probability. The probability of this event can clearly be eliminated for all practical purposes by the use of meteoroid shielding techniques. As a result of tests reported (9), NASA elected to install an external micrometeoroid bumper and an internal fire retardant liner on the Saturn Workshop to alleviate these problems (11).

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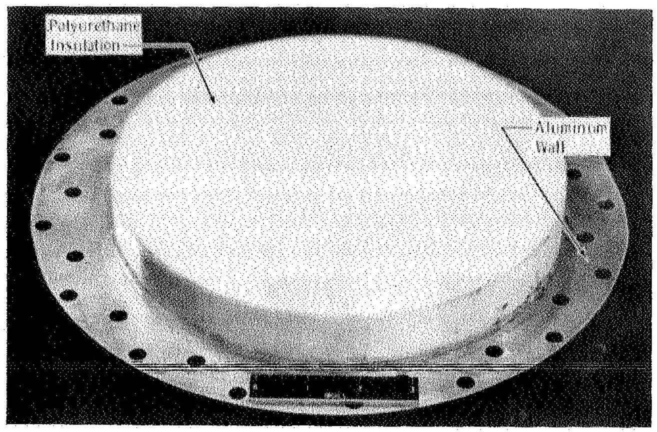


Fig. 1--Wall Specimen (Inside View)

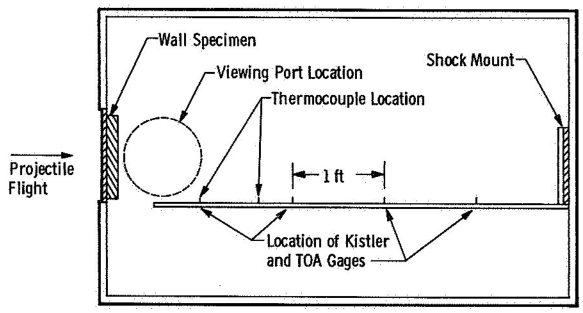


Fig. 2--Schematic of Test Tank

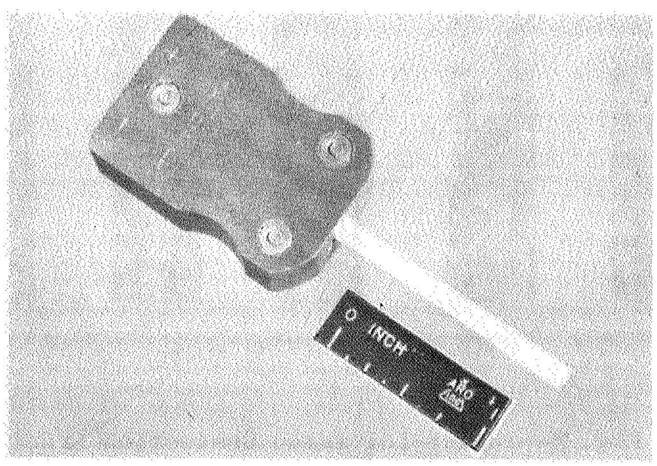


Fig. 3--Thermocouple

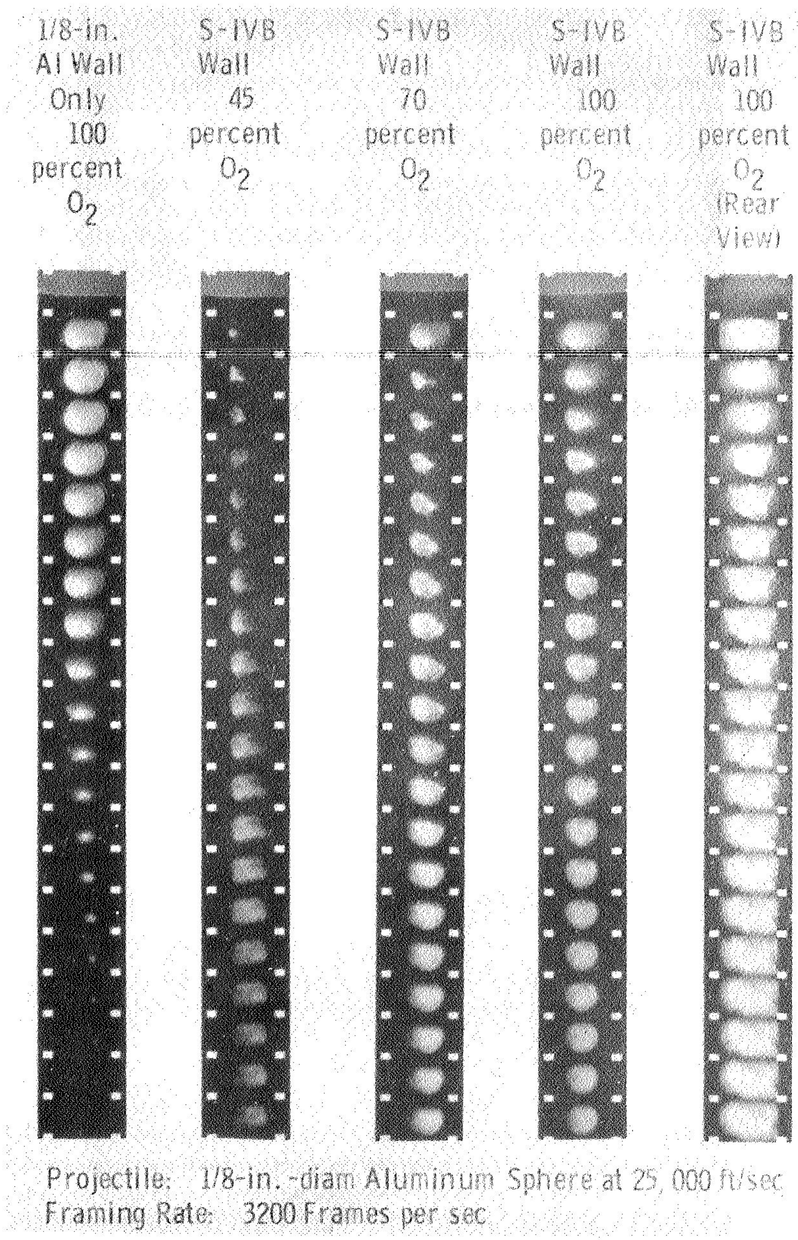
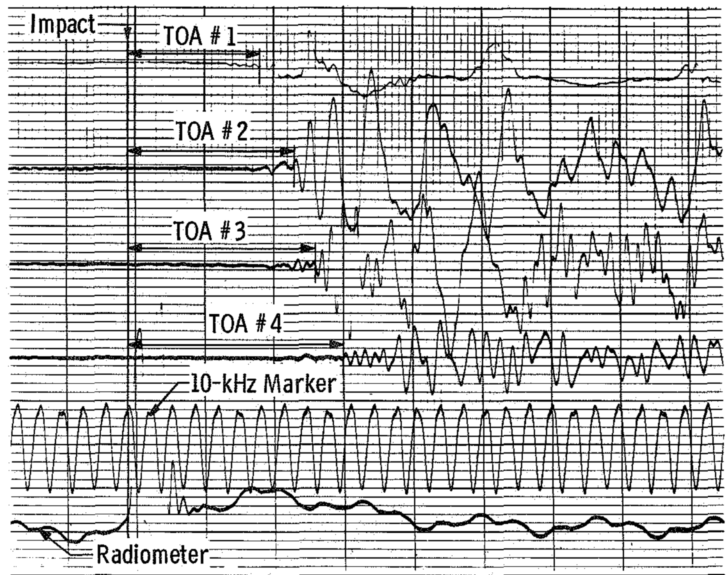
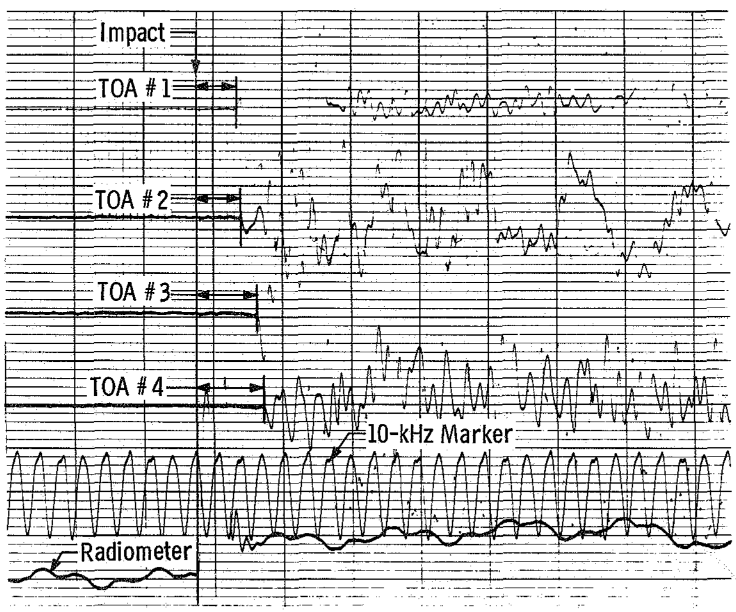


Fig. 4--Impact-Initiated Combustion Front



a. Impact through Foam



b. Impact through Aluminum Wall Only

Fig. 5--Oscillograph Traces

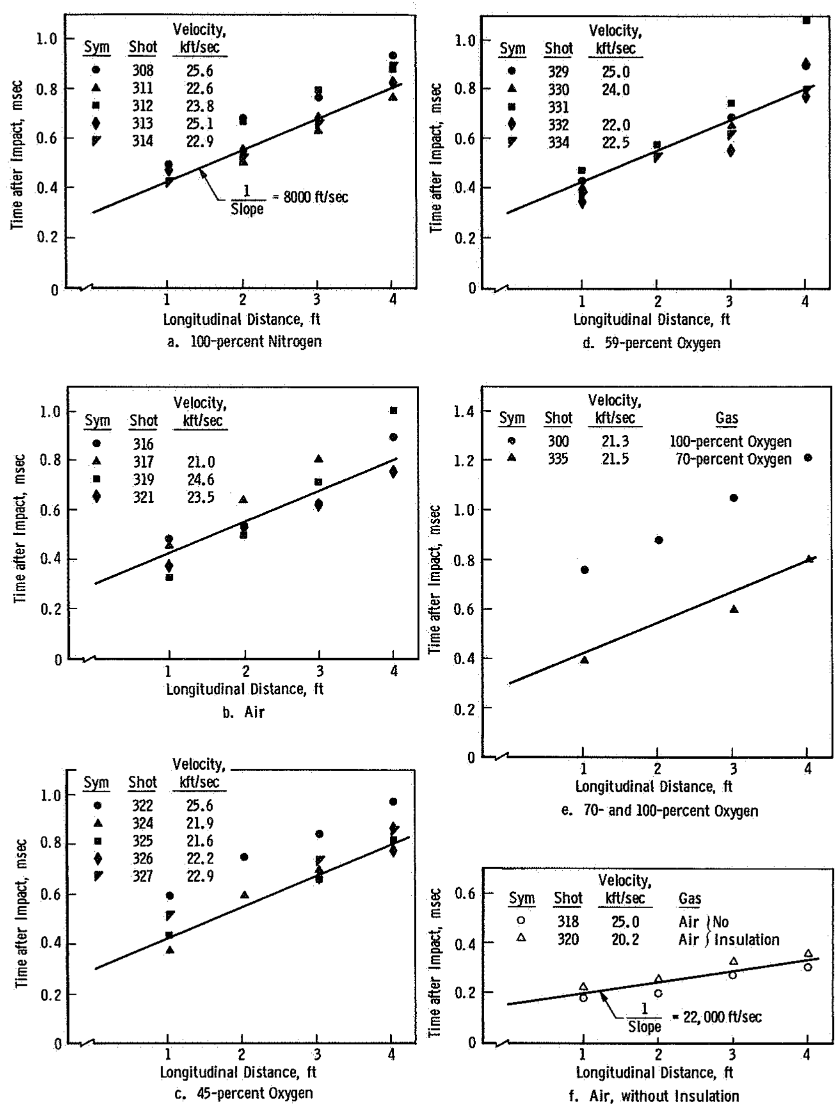


Fig. 6--Time-of-Arrival Results

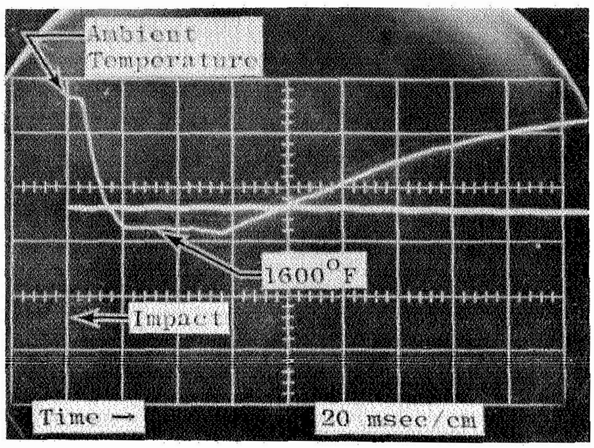


Fig. 7--Thermocouple Output

TABLE 1--Temperature Measurements

Shot	Velocity (ft/sec)	Gas Composition	Thermocouple No. 1 (F)	Thermocouple No. 2 (F)
1	26,300	70% O_2, 30% N_2	1075	1600
2	24,300	70% O_2, 30% N_2	825	1325
3	25,500	Air	200	300

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