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PRELIMINARY INVESTIGATION OF BLAST HAZARDS OF RP-1/LOX AND LH_2/LOX PROPELLANT COMBINATIONS

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ABSTRACT

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This report discusses the current status of information regarding the blast hazards of liquid propellants and presents results obtained from one part of a comprehensive analytical and experimental investigation of this problem. The data generally were consistent with siting criteria now used for RP-1/LOX. However, explosive yields determined for LH_2/LOX were markedly lower than values reported by previous investigators and suggest that current siting criteria for this propellant combination may be overly conservative.

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RESEARCH AND DEVELOPMENT OPERATIONS

PROPULSION AND VEHICLE ENGINEERING LABORATORY

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SUMMARY

The development of large launch vehicles has created major problems in the siting of test stands and launch pads. Thus, RP-1/LOX vehicles are sited by using a TNT equivalent of 20 percent for quantities up to 500,000 pounds and an equivalent of 10 percent for any excess over that amount; LH_2/LOX vehicles are sited using a TNT equivalent of 60 percent.

This investigation was carried out as the in-house part of a comprehensive program now in progress to examine the validity of these equivalents and, if necessary, to establish new equivalents. Tests using 200 pounds of RP-1/LOX and LH_2/LOX were made with spill test and simulated tankage configurations. The results are considered preliminary and are not intended to prejudice the results of the more comprehensive program still in progress. However, they indicate that the spill test method of investigation on which the current TNT equivalent for LH_2/LOX vehicles is based probably gives excessive yields and, therefore, may not be valid for this propellant combination. This indicates that future investigations of liquid propellant blast hazards must simulate vehicle configurations and failure modes and suggests that the current LH_2/LOX TNT equivalent used for siting should be re-examined in the light of these findings.

INTRODUCTION

The development of large launch vehicles, particularly those utilizing new high-energy propellants, has created major problems in the siting of test stands and launch pads. Current vehicles such as the Saturn I have total propellant weights approaching one million pounds; for the Saturn V vehicle, which is now in an advanced stage of development, the weight of propellants is about six times larger.

Vehicles using RP-1/LOX presently are sited on the assumption that the maximum explosion involving these propellants would be equivalent to the detonation of a mass of TNT equal to 20 percent of the propellant weight, up to 500,000 pounds, plus 10 percent of any excess over that amount (ref. 1). These values are based largely on the results of small-scale tests involving a number of different test configurations (ref. 2) and are consistent with estimates of yields of up to 10 percent and higher from incidents involving flight-weight vehicles carrying up to 250,000 pounds of propellant.

The TNT equivalence of LH_2/LOX vehicles currently used for siting purposes is 60 percent (ref. 1) and is based on results of small-scale tests using spill-test configurations exclusively (ref. 3). This value is in marked contrast with the one percent yield estimated for the single major incident with these propellants for which a detailed investigation was possible (ref. 4).

Some small-scale tests with RP-1/LOX have suggested that the more closely vehicle configurations and failure modes are simulated the lower are the explosive yields (ref. 2). Such an effect might be expected to be even more pronounced with LH_2/LOX because of the wide flammability limits of mixtures of these propellants and their extreme ease of ignition. Even poorly mixed quantities are easily ignited. Thus, it appears questionable as to whether the results of small-scale spill tests which provide good mixing usually without spontaneous ignition can provide a valid basis for assigning the LH_2/LOX TNT equivalents to be used for siting purposes.

The information presented in this report is the result of one part of a comprehensive program (ref. 5) to determine the blast hazards of liquid propellants. The objectives of this portion of the program were threefold: (1) to develop a capability of making small-scale tests for study of blast effects, which necessitated the development of an instrumentation system and data-processing methods; (2) to use this experimental capability in obtaining information about the explosive hazard of LH_2/LOX for use in siting problems at MSFC and contractor facilities; (3) to insure an adequate capability for monitoring the contract research studies which constitute the bulk of the program. Therefore, the results of this study are considered preliminary and are not intended to prejudice the results of the more comprehensive programs still in progress.

This program was made possible by the cooperation of many groups and individuals at this Center. Tape recorders were obtained on loan from the Computation Laboratory during the early portion of the program; later, the Computation Laboratory assisted with the programming and computer operations which were necessary for data reduction and evaluation. Test Laboratory supplied propellants and worked on the design of the transfer systems. The Non-Metallic Materials and the Engineering Physics Branches of the Materials Division, Propulsion & Vehicle Engineering Laboratory assisted in the design, fabrication, and insulation of the

test articles. The Army Missile Support Command provided assistance in the handling of explosives and furnished the test site for the program under Government Order H-61510.

EXPERIMENTAL

The experimental portion of this investigation included the design, construction, and verification of an instrumentation system; the design and construction of the test articles and propellant transfer systems; and the actual conduct of the tests.

Instrumentation

Test data included the pressure-time history and time of arrival of the shock wave, the rate of growth and duration of the fireball, and atmospheric conditions. Both electronic instrumentation and photographic instrumentation were used.

Previous investigations involving similar tests had shown that multiple explosions were characteristic of events employing actual or simulated tankage (ref. 6). Therefore, high speed photography and a magnetic-tape system were used for recording much of the data and providing continuous records for periods of time up to approximately 5 minutes with resolution of events occurring less than 10 microseconds apart.

Electronic Instrumentation. - The side-on pressure histories and the arrival times of the shock waves were obtained with piezoelectric pressure transducers mounted on blast resistant stands (ref. 7) which were located from 25 to 250 feet from ground zero (FIG 1). Each transducer was connected by coaxial cable to a separate amplifier which was located in the instrument igloo. After amplification to a suitable level, the signals were recorded by a 14-channel wideband (20 KC) FM magnetic-tape recorder.

Playback of the recorded signals at reduced speed into an oscillograph gave permanent records from which numerical data were obtained. Comparison of the transducer signals with voltage calibration and timing signals, which also were recorded, permitted measurements of the overpressure, positive-phase impulse, and arrival time for each shock wave. A block diagram of the instrumentation system* is given in FIG 2.

* A more detailed discussion of the electronic instrumentation system and data analysis procedures will be given in a separate report.

The pressure measurement system was calibr. d by impressing on each transducer a pressure pulse of known magnitude. These pulses were generated by a portable shock tube in the earlier half of the investigation and by a pneumatic pressure step generator in the latter half. The latter afforded a wider range of pressure steps and greater ease of operation. The calibration signals were recorded and processed in the same manner as the signals from the various high explosive and propellant tests.

Photographic Instrumentation. - Four cameras with color film were used to obtain additional test information. Two of the cameras, which had speeds of 24 and 48 fps, were used for documentation; the other two cameras, operated at 400 fps, provided information about the geometric center of explosion and the rate of growth, maximum size, and duration of the fireball. Figure 1 shows the camera locations.

High Explosive Tests

Tests using high explosives of known characteristics were made to verify the accuracy of the instrumentation system. Composition C-4 was used instead of flake TNT or cast Pentolite because it could easily be molded by hand into a hemispherical shape. Charge weights ranged from 2.5 to 100 pounds and covered the expected range of yields for the propellant tests. All charges were detonated at ground level.

Evaluation of data for both the high explosive and propellant tests was based on a comparison of results with data for TNT. Reference curves used for this purpose are described in the Appendix. For purposes of comparison, composition C-4 was assumed to have a yield of 115 percent of that of TNT for both overpressure and impulse measurements (ref. 8).

Overpressure. - The peak side-on overpressure is the parameter most commonly used to compare explosions. Figure 3 is a plot of side-on overpressure versus normalized distance for all of the high explosive tests. The solid lines represent various percentage yields referenced to TNT and show approximately the limits of variations in the data. The dashed line is a third degree polynomial in logarithms which was fitted to the data by the method of least squares. This curve agrees well with the assumed curve for composition C-4 (115 percent TNT) although the individual data points scatter widely. This scatter appeared to be due primarily to two effects: the difficulty in interpreting non-ideal transducer signals and the variations in the energy expended in the cratering process.

Signals from the closest transducers often were distorted badly from the "ideal" shape. This occurred consistently with the larger charges (>25 lb) and frequently for the smaller ones. The distortion usually consisted of severe ringing, leading edge spikes, hash, and/or secondary shocks. Occasionally, the distortion was observed even for transducers located 65 feet away from the charge. In some cases, the secondary shocks and hash were caused by impact of pieces of ejected dirt and stone on the transducers and mounts. The ringing was due to transducer and mount ringing. The spikes were found to occur mostly in older transducers.

Regardless of the signal shape, every effort was made to deduce the nature of interfering signals and to compensate for them during the data reduction and interpretation process.

Crater sizes for a given charge weight varied widely and could not be predicted accurately. The soil where the tests were run was red clay. The soil conditions ranged from very hard to quite soft, thereby causing a large variation in the extent of cratering.

A secondary source of variation arose from a detectable and fairly consistent decrease in the sensitivity of some of the transducers during the program, which lasted approximately one year. For computational purposes, estimates of the sensitivity of these transducers were made for various test dates throughout the program.

Impulse. - The side-on positive phase impulse of the shock wave is important in target damage studies and was measured for all tests. The results are shown in FIG 4. As with the overpressure data, the solid lines show various equivalent yields, and the dashed line represents a fifth degree polynomial similar to that shown for the overpressure data. Agreement of the fitted curve with the 115 percent yield curve is fair. Data scatter is slightly less than for the overpressure data since the effects of noise and small irregularities are smoothed by the integration process. However, the deviations between the assumed C-4 curve and the fitted curve are somewhat greater than those for the overpressure data. It should be noted that the TNT reference curves for overpressure and impulse were derived from different sets of data. (See Appendix.)

Time-of-Arrival

No provision was made for recording an absolute zero time signal because the signal would have little utility for propellant tests in which multiple explosions occurred. However, the times required for the shock front to travel from one transducer station to the next were recorded. These values represented the differences in the times-of-arrival of the shock front at the different stations and were used with the speed of sound and station distances to calculate the overpressure in the shock front by means of the integrated form of the Rankine-Hugoniot equation. The lack of an absolute zero time signal precluded calculation of the overpressure corresponding to the closest station. The overpressures calculated in this manner were compared with those measured directly in FIG 5. Since the velocity of a shock wave is determined by the peak overpressure in the shock front, regardless of the origin of the wave, the expected relation between these over-pressures is a straight line of unit slope. The data are in excellent agreement with this expectation, thus confirming the validity of both sets of measurements. It should be noted that the time-of-arrival data are not subject to uncertainties due to irregularities of the pressure-time traces, drifts in transducer sensitivities, and errors in calibration. However, the overpressures determined from the time-of-arrival data are subject to uncertainties in determining the exact time of arrival at any station, the exact distance between transducer stations, and the speed of sound. The latter factor particularly is important for the relatively low overpressures determined in this study for which the velocity of the shock wave exceeds that of the speed of sound by only a small amount.

PROPELLANT TEST CONFIGURATIONS AND FAILURE MODES

Each of the propellant tests used a total of 200 pounds of propellant in ratios of 1 part RP-1 to 2.25 parts LOX by weight or 1 part liquid hydrogen to 5 parts LOX by weight. Since there was no provision for direct weighing, propellant weights were estimated volumetrically. The cryogenic propellants were overfilled slightly to allow for boiloff between filling and initiation of the test. Variations caused by this factor are estimated to be less than 5 percent of the total propellant weight at the time of ignition.

Spill Tests

The spill tests were made to obtain information on the potential yield when the propellants were mixed rapidly as partly impinging streams. Since this method of testing had been used previously for both RP-1/LOX and LH_2/LOX (ref. 3), these tests also permitted a comparison of results with those of other investigators.

The same general configuration was used for each test; i.e., the propellants were spilled simultaneously into a small (approximately 6-inch deep) depression in the ground. The resulting mixture was ignited either with a black powder squib (as a flame type ignition source) or with a #8 blasting cap plus a small explosive charge consisting of 4 ounces of C-4 (as a shock-type ignition source).

In the first few tests, galvanized steel garbage cans were used to hold the propellants; however, aluminum cans were used in later tests. The liquid hydrogen cans were insulated with four to six inches of a low-density polyurethane foam. After the temperature of the can had stabilized, liquid hydrogen could be held for about one hour before replenishment was necessary. The LOX containers were not insulated.

A diagram of the RP-1/LOX test setup is shown in FIG 6A. The liquids were spilled or poured together by using Primacord to cut the cables holding the containers upright. The cutting of the restraining cables was taken as zero time for determination of the time delay before ignition. The time interval between initiation of the tests and firing of the squib or explosive charge varied from 0.5 to 40 seconds and included the time required for the containers to drop, which was approximately 0.5 second. Seven tests were run; six were ignited with high-explosive (#8 blasting cap plus 4 ounces of C-4) and the other with a black-powder squib.

Shown in FIG 6B is a diagram of the LH_2/LOX test setup. The liquids were spilled by the same method used for the RP-1/LOX tests. However, a delay time of 0.5 second was used between the cutting of the cable restraining the LH_2 containers and that restraining the LOX container to allow for the longer falling time of the larger container. Zero time was considered to coincide with the cutting of the LH_2 container cable, and all delay times were measured from this reference. Scheduled delay times before ignition ranged from 1 to 10 seconds. However, delay times greater than 2.5 seconds were not realized because of premature ignition of the propellant mixture during the two tests with the longest delay times. All tests were ignited with 4 ounces of C-4 plus a #8 blasting cap except those that ignited spontaneously. A total of six tests was run in this series.

Tank Tests

The tandem-tank tests were made to provide information about the explosive yields occurring under conditions more closely simulating various types of vehicle failures. The general configuration and setup were the same for each test; i.e., the LOX was in the bottom tank and the RP-1 or LH_2 in the top tank. The LH_2 tanks were insulated with six inches of polyurethane foam on the sides and top, and two to six inches of foam was used on the bottom. depending upon the type of failure under study. Details of the various configurations are shown in FIG 7A through FIG 7I, and these same numbers are used to identify the corresponding configuration for convenience in discussion.

Five tank configurations, 7A through 7E, were used for the RP-1/LOX tests. Configuration 7A used a flexible linear shaped charge (FLSC)* placed vertically against both tanks as the failure mode. In Configuration 7B, two 12-inch lengths of FLSC were placed between the tanks; one was taped to the bottom of the RP-1 tank and the other to the top of the LOX tank. The space separating the two lengths of FLSC did not exceed one inch. Configuration 7C used a coil of FLSC placed against the top of the LOX tank. Configurations 7D and 7E were similar in that the bottom of the RP-1 tank was replaced by an aluminum foil diaphragm. However, in 7D, the diaphragm was cut with a mechanical cutter; whereas, in 7E, it was burst by pressurizing the RP-1 tank with gaseous nitrogen to simulate vehicle failure due to overpressurization of the fuel tank.

In Configurations 7D and 7E, the resulting mixtures of propellants were ignited by 4-ounce C-4 charges which were located near the propellant interface. In the other three RP-1/LOX configurations, the FLSC served as the ignition source. Delay times between breaking of the diaphragms and detonation of the C-4 charges for 7D and 7E ranged from 1 to 15 seconds. A total of seven tank tests was run with RP-1/LOX.

The LH_2/LOX tank configurations are illustrated in FIG 7F through FIG 7I. Configuration 7F used a vertical length of FLSC which was taped to the sides of the tanks and was held in place by the foamed insulation. Configuration 7G used a coil of FLSC taped to the top of the LOX tank. The foam thickness on the bottom of the LH_2 tank was two inches. For Configuration 7H, 200 gr/ft Primacord was placed in an aluminum tube which was fastened to the inside of the LH_2 and LOX tanks. Configuration 7I used an aluminum-foil diaphragm bonded to the bottom of the LH_2 tank. This diaphragm was broken by closing the vent valve which allowed the LH_2 tank to self-pressurize. The LH_2 tank bottom had only two inches of foam. A charge of 4 ounces of C-4 was provided for ignition of the mixture; however, this proved unnecessary because all LH_2/LOX tank tests either were initiated by the FLSC or ignited spontaneously. Because of the spontaneous ignition, no measurable delay was experienced in the diaphragm-rupture tests. A total of seven tests was run.

* One-hundred gr/ft flexible linear shaped charge was used throughout the tests.

PROPELLANT TEST RESULTS

Inspection of the propellant test results suggested that they could be discussed most conveniently after grouping by propellant type (RP-1/LOX or LH_2/LOX) and test configuration (spill or tank test).

Figure 8 presents the 43 overpressures determined for the seven RP-1/LOX spill tests plotted as a function of normalized distance. The number of usable data points for each test varied from 3 to 13, depending on the number of transducers available for a given test. Overpressures ranged from 0.43 to 27 psi. Yields based on individual overpressures ranged from 12 to 51 percent, and average yields for individual tests ranged from 17 to 37 percent. The lowest average yield corresponded to an ignition delay of 40 seconds and the highest to a delay of 1.7 seconds. The average yield for the single test using a black powder squib for ignition (37 percent) did not differ appreciably from the corresponding value for a similar test using a high explosive igniter (35 percent). The normalized impulse data for these same tests are given in FIG 9. In general, the results are in excellent agreement with those based on overpressure data. Thus, the yields based on individual values ranged from 11 to 35 percent, and average yields ranged from 13 to 33 percent. The tests exhibiting the lowest and highest average yields were the same for both overpressure and impulse measurements.

The 75 overpressures determined for the seven RP-1/LOX tank tests are plotted as a function of normalized distance in FIG 10. The number of usable data points for each test varied from 4 to 12. Overpressures ranged from 0.05 to 19 psi. Yields based on individual overpressures ranged from 0.02 to 30 percent, and average yields for individual tests ranged from 0.04 to 23 percent.

Further inspection of the results indicated a marked separation of the data with respect to failure mode and ignition delay. For the three tests in which some form of destruct action was simulated, ignition was effected by the destruct system, and no appreciable delay occurred between the release of propellants and the time of ignition. For these tests, the average yields ranged from 0.04 to 0.2 percent. For the four tests in which the failure mode consisted of rupturing the bulkhead, ignition was effected by a high explosive charge located outside the tanks but adjacent to the propellant interface. The average yields for these tests were 0.2, 1.0, 5.0, and 23 percent. The two lower values were obtained by using a cutter to remove the diaphragm; this method subsequently was found to give only a small rupture, and the remaining tests were conducted by overpressurizing the RP-1 tank.

Figure 11 presents the normalized impulse data for the same tests. Again, the results are in good agreement with those based on overpressure data. Thus, the average yields for simulated destruct tests ranged from 0.08 to 0.4 percent, and those for the tests using a bulkhead failure mode ranged from 0.1 to 19 percent.

In FIG 12, the measured overpressures are plotted against the corresponding values calculated from the time-of-arrival data for all RP-1/LOX tests. The data points are coded with respect to test configuration, i.e., spill test, tank test with simulated destruct action, and tank test with simulated bulkhead failure. Most of the results are distributed uniformly about a straight line of unit slope. However, overpressures which were calculated from the time-of-arrival data tended to be somewhat lower than the determined values for the tank tests employing destruct systems. For these tests, the yields were extremely small (less than 0.2 percent), which suggested that the pressures may have resulted from simple deflagrations and resulting thermal disturbances rather than detonation type reactions. The near coincidence of the overpressures determined directly and those calculated from time-of-arrival data again confirms the overall validity of the test results.

In FIG 13, the yields based on individual overpressure measurements are plotted against the corresponding values based on impulse measurements. The data points are coded according to test configuration, i.e., spill test, tank test with simulated destruct action, and tank test with simulated bulkhead failure. The results appear to be distributed uniformly about a straight line of unit slope, indicating coincidence of yields determined by impulse and overpressure measurements except for scatter of the data. This overall trend differs from that indicated by inspection of individual spill test results. For this propellant combination, yields based on overpressure for any given test tended to increase with the distance from ground zero to a particular transducer station; however, no similar trend was noted for yields based on impulse (FIG 14). The separation of yields for the three test configurations indicated by coding of the points is shown clearly in FIG 13 in that spill test and destruct test results account for most of the highest and lowest values, respectively, with the bulkhead failure results generally falling intermediate between these values.

The 31 overpressures determined for the six LH_2/LOX spill tests are plotted as a function of normalized distance in FIG 15. The number of usable data points for each test varied from 3 to 12. Overpressure ranged from 0.4 to 36 psi. Yields based on individual overpressures ranged from 5.3 to 178 percent, and average yields for individual tests ranged from 6.3 to 144 percent. The lowest average yield corresponded to an ignition delay of one second and the highest to a delay of approximately 2.5 seconds. The latter test was programmed for a delay of 3.5 seconds; however, premature ignition occurred, possibly due to static electricity, and the high explosive igniter was recovered substantially undamaged after the test. The apparent yield for this test may have exceeded the true yield because of the location of the point of initiation. Inspection of the shockwave data and photographic records of the test indicated that the center of the blast was several feet closer to the transducer stations than expected.

In another spill test, for which no data are given, premature ignition of the LH_2 occurred during the spilling process, just before the propellants came into contact. Inspection of color films of the test indicated that ignition took place as the hydrogen began to spill from the container, and burning LH_2 was spilled subsequently onto the LOX. No significant pressures (or yields) were recorded which suggest that most of the LH_2 was consumed by an LH_2/air reaction before contacting the LOX.

Figure 16 presents the normalized impulse data for these same tests. In general, the results are in good agreement with those based on overpressure data. Thus, the yields based on individual values ranged from 5.5 to 135 percent, and the average yields ranged from 6.2 to 97 percent.

The 82 overpressures determined for the seven LH_2/LOX tank tests are plotted as a function of normalized distance in FIG 17. The number of usable data points for each test varied from 10 to 13. Overpressures ranged from 0.07 to 4.1 psi. Yields based on individual overpressures ranged from 0.1 to 4.0 percent, and average yields for individual tests ranged from 0.3 to 1.3 percent.

In sharp contrast to the results for RP-1/LOX tests, the yields for the bulkhead rupture tests (average values of 0.3 to 1.1 percent) and those employing some form of destruct action (average values of 0.3 to 1.3 percent) did not differ markedly. This was probably due to the fact that for each LH_2/LOX bulkhead rupture test ignition took place spontaneously immediately on overpressurization and rupture of the bulkhead. Thus, no time was available for mixing of the propellants before ignition.

The normalized impulse data (FIG 18) are in good agreement with overpressure data. Thus, the average yields for simulated destruct tests ranged from 0.6 to 1.6 percent, and those for the tests using a bulkhead failure mode ranged from 0.4 to 1.4 percent.

In FIG 19, the measured overpressures are plotted against overpressures computed from the time-of-arrival data. All LH_2/LOX tests are included in this plot. As with the high explosive and RP-1/LOX data, the results are distributed almost uniformly about a straight line of unit slope.

In FIG 20, the yields based on individual overpressure measurements are plotted against the corresponding values based on impulse measurements. The data points are coded with respect to test configuration, i.e., spill tests, tank tests with simulated destruct action, and tank tests with simulated bulkhead failure. As with the RP-1/LOX data, the results are uniformly distributed about a straight line of unit slope, indicating coincidence of yields based on overpressure and impulse measurements. Inspection of results of individual tests failed to reveal any significant departures from this trend.

In contrast with the findings for RP-1/LOX, inspection of FIG 20 fails to reveal any marked separation of the results for tank tests employing simulated destruct action and those employing bulkhead failure modes, particularly rupture of the diaphragm by overpressurization of the fuel tank. Thus, the individual data points for these types of tests overlap extensively, and the average yields for the two types do not differ markedly. However, the separation of results for tank tests and for spill tests, in general, was sufficiently marked so that no overlapping occurred and the average yields differed widely.

In reviewing the data for the propellant tests (both RP-1/LOX and LH_2/LOX), it was noted that multiple explosions occurred frequently. However, in all instances, the first explosion was equal to or greater than those occurring subsequently. Therefore, only data for the initial explosions have been included.

The diameter and duration of the fireball for each propellant and high explosive test were measured by inspection of individual frames of high speed color films. Results for several of the tests have been reported previously. (See reference 4.) A more detailed analysis and discussion of the results will be presented in a future report.

CONCLUSIONS

Because of the preliminary nature of this investigation and the anticipated results of more comprehensive studies which are in progress, quantitative conclusions regarding the TNT equivalents of RP-1/LOX and LH_2/LOX are not warranted at this time. However, the results presented herein indicate the validity of various test methods and should be considered in any future assessment of the hazards associated with these and other liquid propellants.

Specifically, the maximum average value for RP-1/LOX spill tests (37 percent based on overpressure) exceeds the maximum reported value of up to 10 percent or higher for flight weight vehicles by approximately a factor of three. For RP-1/LOX tank tests, a similar factor of two appears reasonable. In view of the uncertainties associated with the estimates of yields for incidents involving full-scale vehicles and the marked dependence of small-scale test results on test configurations and failure modes, the results obtained by either method of testing appear to be in reasonable agreement with actual experience and with the values currently used for siting vehicles with this propellant combination.

For LH_2/LOX, the average values for tandem tank tests are in excellent agreement with the estimate of yield for the single full-scale incident for which data are available. Also, the average value for the spill tests is consistent with the value currently used for siting vehicles with this propellant combination. However, the results based on tank tests and actual experience are less than the spill test results and current siting value by almost two orders of magnitude. This difference arises because the current siting value is based exclusively on spill test data. For such tests, spontaneous ignition may not occur or it may be delayed until a substantial amount of mixing occurs, which results in relatively high explosive yields. For the tank tests and also for the single full-scale incident, ignition took place immediately upon release of the propellants, thus precluding any substantial amount of mixing and resulting in negligible explosive yields.

These findings emphasize the extreme dependence of the explosive hazard of any liquid propellant combination on the nature of the propellants. It has been proposed that the hypergolic nature of such propellant combinations as Aerozine 50/N_2O_4 and monomethyl hydrazine/ N_2O_4 has the effect of insuring near instantaneous ignition, thus precluding substantial mixing and resulting in low explosive yields. However, it has not been recognized generally that the potential ignition sources associated with almost any mode of release of LH_2 from vehicle type hardware may be sufficient to insure a similarly low explosive yield for LH_2/LOX vehicles.

Although the results of this investigation are preliminary, they show that future investigations of liquid propellant blast hazards must simulate vehicle tankage and failure modes to insure valid results. The results also suggest that the current LH_2/LOX siting criteria based on spill test results probably are unnecessarily conservative and should be reexamined in the light of these findings.

APPENDIX

Calculations of yields for overpressure and impulse measurements were made by comparing the experimental values with expected values for TNT by using a Burroughs 5000 Computer. For computational purposes, a numerical equation relating the expected values for TNT to the normalized distance was needed. Although much work relating the blast parameters for TNT to normalized distance had been published, some difficulty was encountered because numerical equations either were inadequate or obsolete and much of the previous data had been presented graphically. Accordingly, numerical reference equations were developed in the manner described below specifically for use in this investigation and may not be suitable for other applications.

A compilation of side-on peak overpressures ranging from approximately 0.08 to 9.0 psi (based on the recent Canadian series of TNT tests) has been recommended by the Armed Services Explosives Safety Board (ASESB) (ref. 9). Because an equation was needed which would be applicable to overpressures above this range of values, the ASESB-recommended data were combined with data for overpressures ranging from 15 to 1,000 psi which were read from a previous curve fit of Ballistic Research Laboratory (BRL) data for overpressure versus normalized distance by personnel at Patrick Air Force Base. The faired data points read from the previous curve fit were spaced approximately equally over the range of values and were equal in number to the recommended ASESB data points. This combined population of data was then fitted to polynomials of the form:

$$\log_{10}P_s = A_0 + A_1\log_{10}Z + A_2(\log_{10}Z)^2 + \ldots\ldots$$

by least squares technique using a General Electric 225 Computer. Polynomials of degree one through eight were tried; the best fitting equation was as follows:

$$\begin{aligned}\log_{10}P_s = {} & 3.03690565 - 1.68766220t - 0.170270827t^2 - \\ & 1.76879129t^3 + 2.37334419t^4 - 0.597589031t^5 - \\ & 0.407020568t^6 + 0.241854130t^7 - 0.0352841785t^8\end{aligned}$$

where:

$$t = \log_{10}Z$$

$$Z = ft/lb^{1/3}$$

Because of the use of faired data, the usual estimates of the reliability of this equation are invalid. However, the agreement of the plotted equation with the data points (both faired and experimental) from which it was derived was considered excellent. Also, the agreement between this curve and a curve of similar form recently released by the BRL (ref. 11) is excellent. It should be noted that no physical significance is attributed to the particular form of empirical equation used. Rather, it was selected from the several forms immediately available because of the excellent fit of the data.

The impulse reference curve was obtained similarly except that all the data for curve fitting were faired data points read from a graph by Kingery (ref. 10). This report had not been released officially at the time of this investigation, but a preliminary copy was made available through the courtesy of Mr. A. J. Hoffman of BRL. The resulting best fit equation was as follows:

$$\begin{aligned}\log_{10} (I/W^{1/3}) = {} & 1.37703351 + 1.34774352t - 6.2165434t^2 + \\ & 9.3974174t^3 - 7.7852913t^4 + 3.4779270t^5 - \\ & 0.78420437t^6 + 0.069720053t^7\end{aligned}$$

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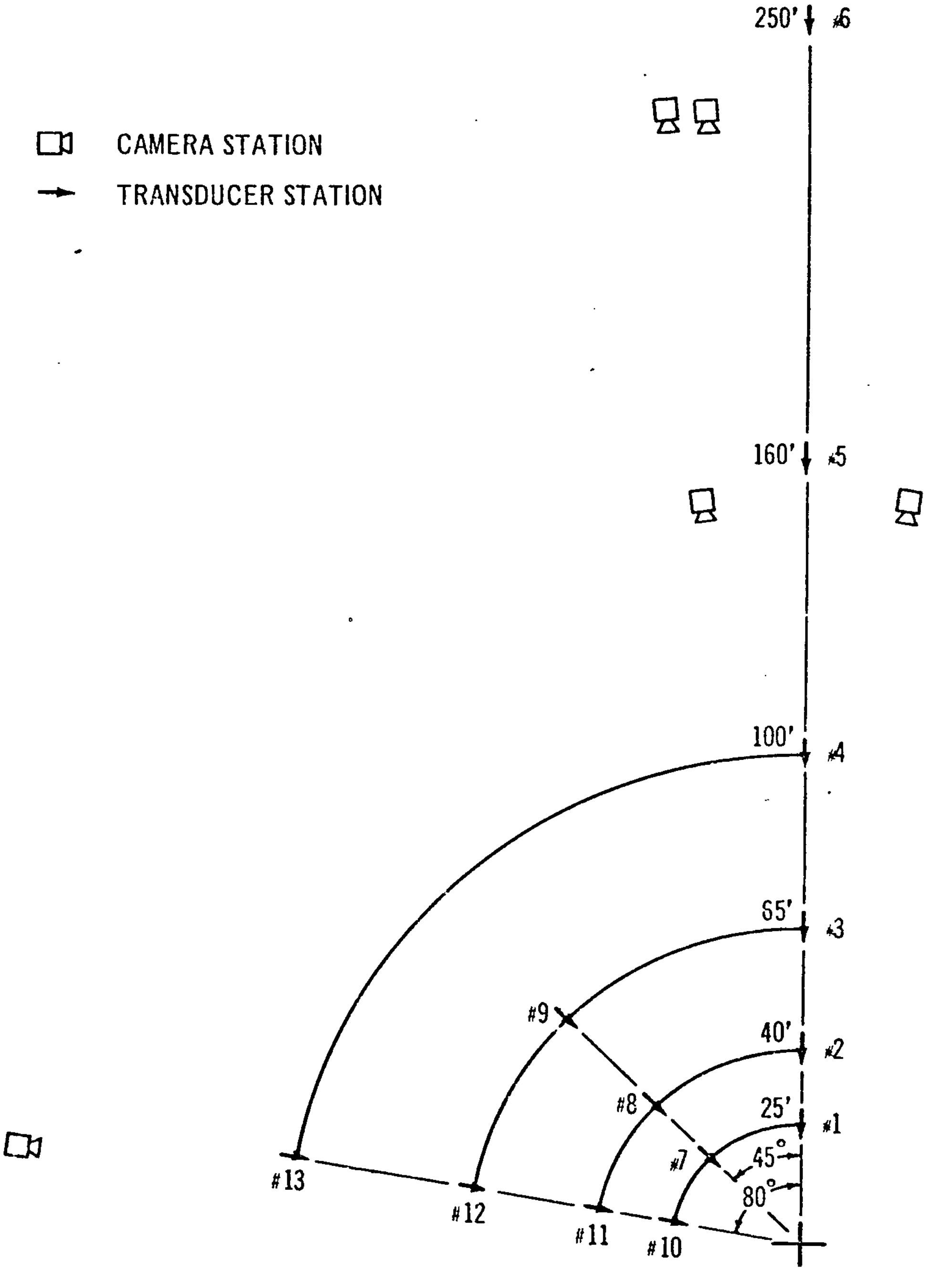

FIGURE 1.- FIELD INSTRUMENTATION LAYOUT

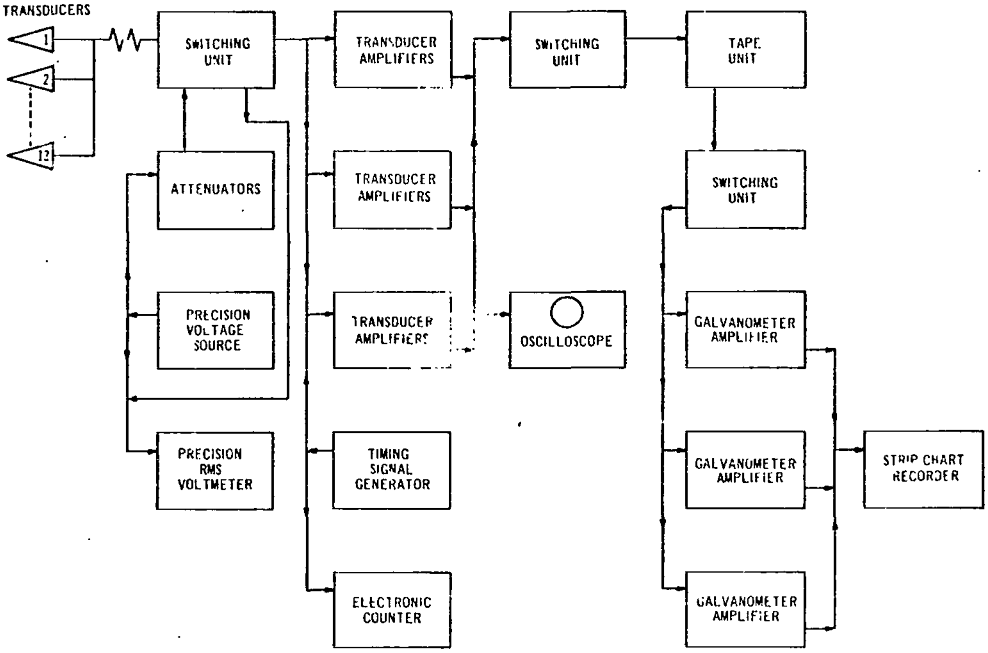

FIGURE 2.- BLOCK DIAGRAM OF BLAST RECORDING AND PLAYBACK INSTRUMENTATION

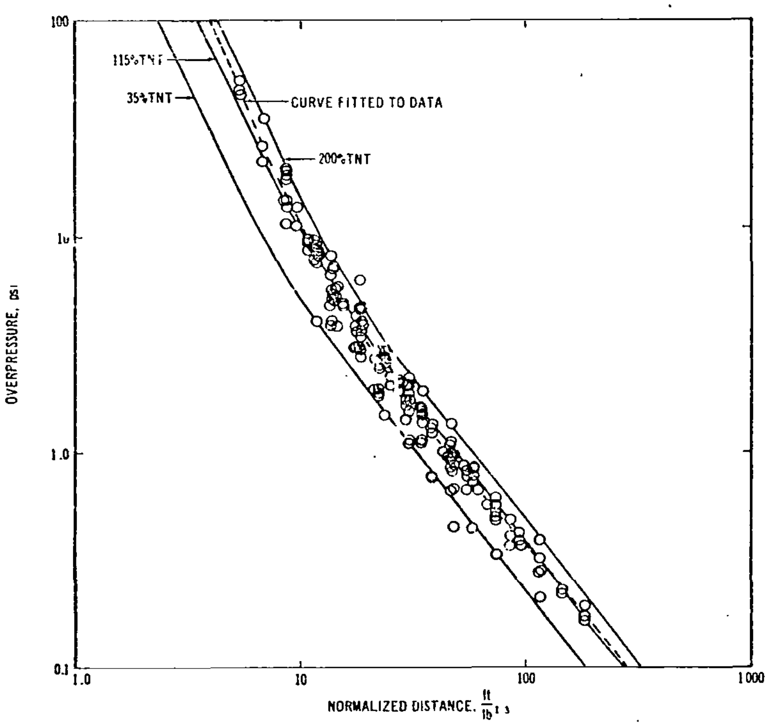

FIGURE 3.- PEAK OVERPRESSURE VS NORMALIZED DISTANCE FOR HIGH EXPLOSIVE CALIBRATION TESTS

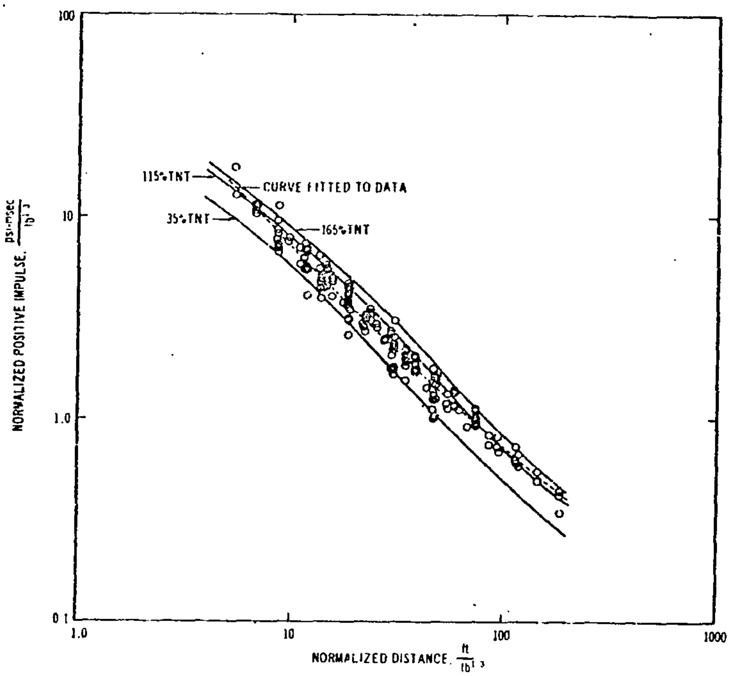

FIGURE 4.– NORMALIZED POSITIVE IMPULSE VS NORMALIZED DISTANCE FOR HIGH EXPLOSIVE CALIBRATION TESTS

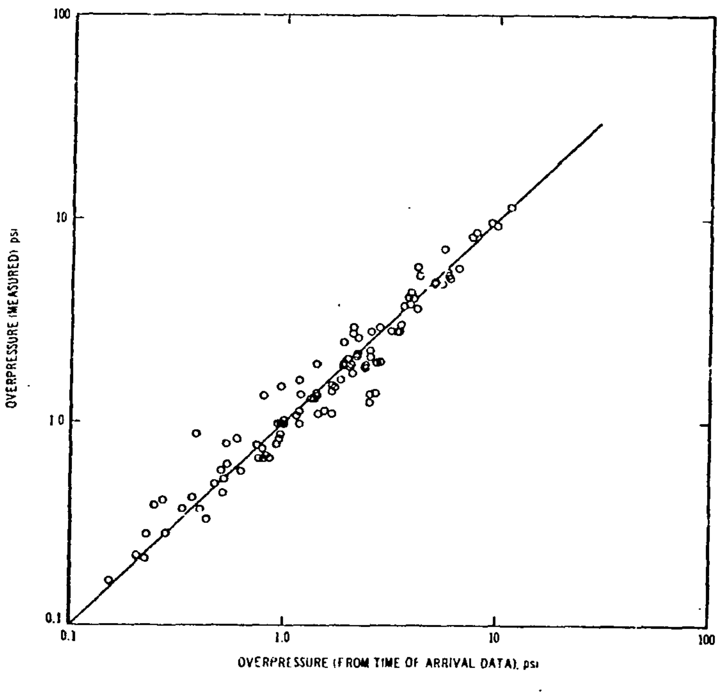

FIGURE 5.– MEASURED PEAK OVERPRESSURE VS PEAK OVERPRESSURE DERIVED FROM TIME-OF-ARRIVAL DATA FOR HIGH EXPLOSIVE TESTS

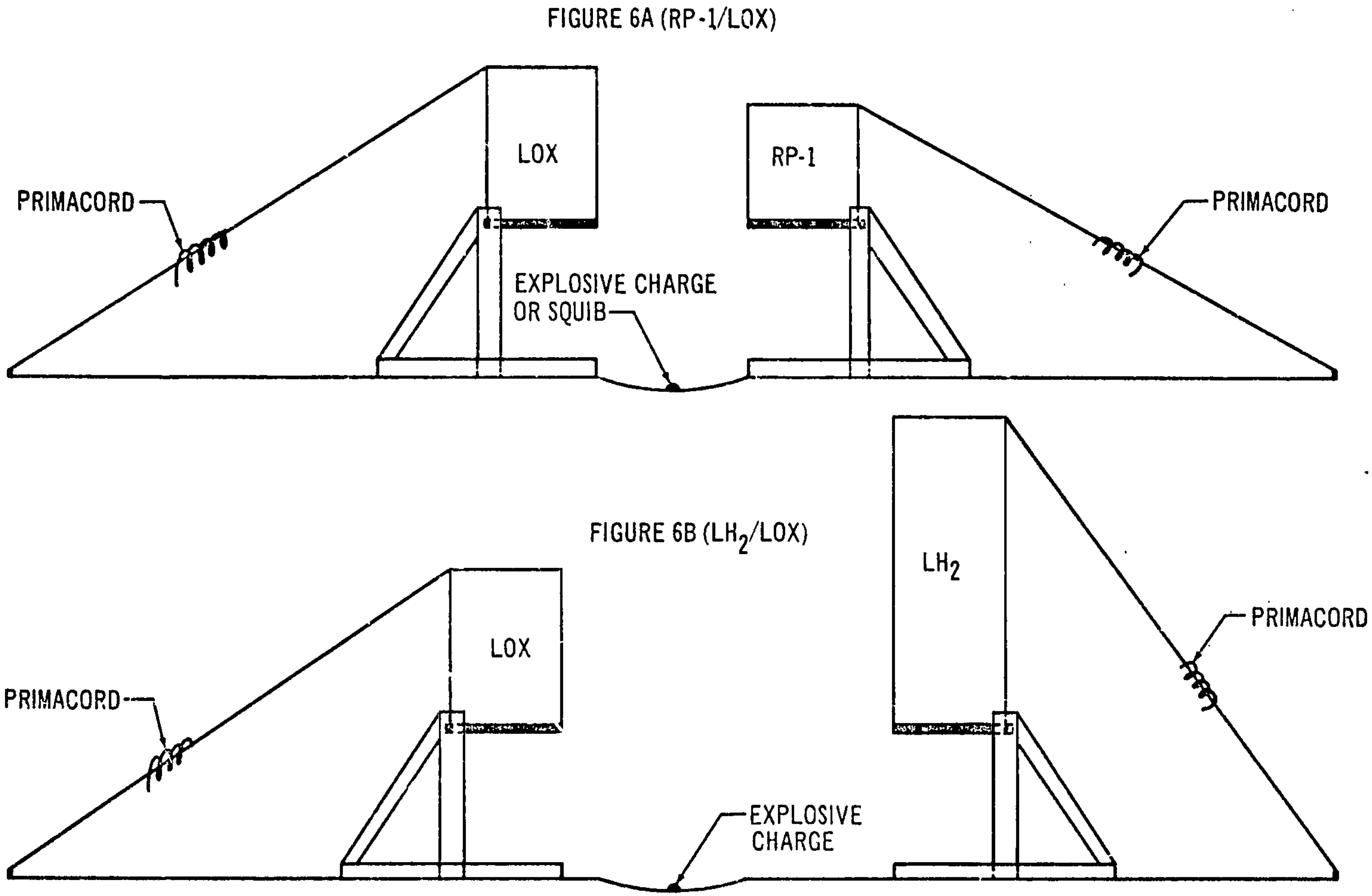

FIGURE 6.– SPILL TEST ARRANGEMENT

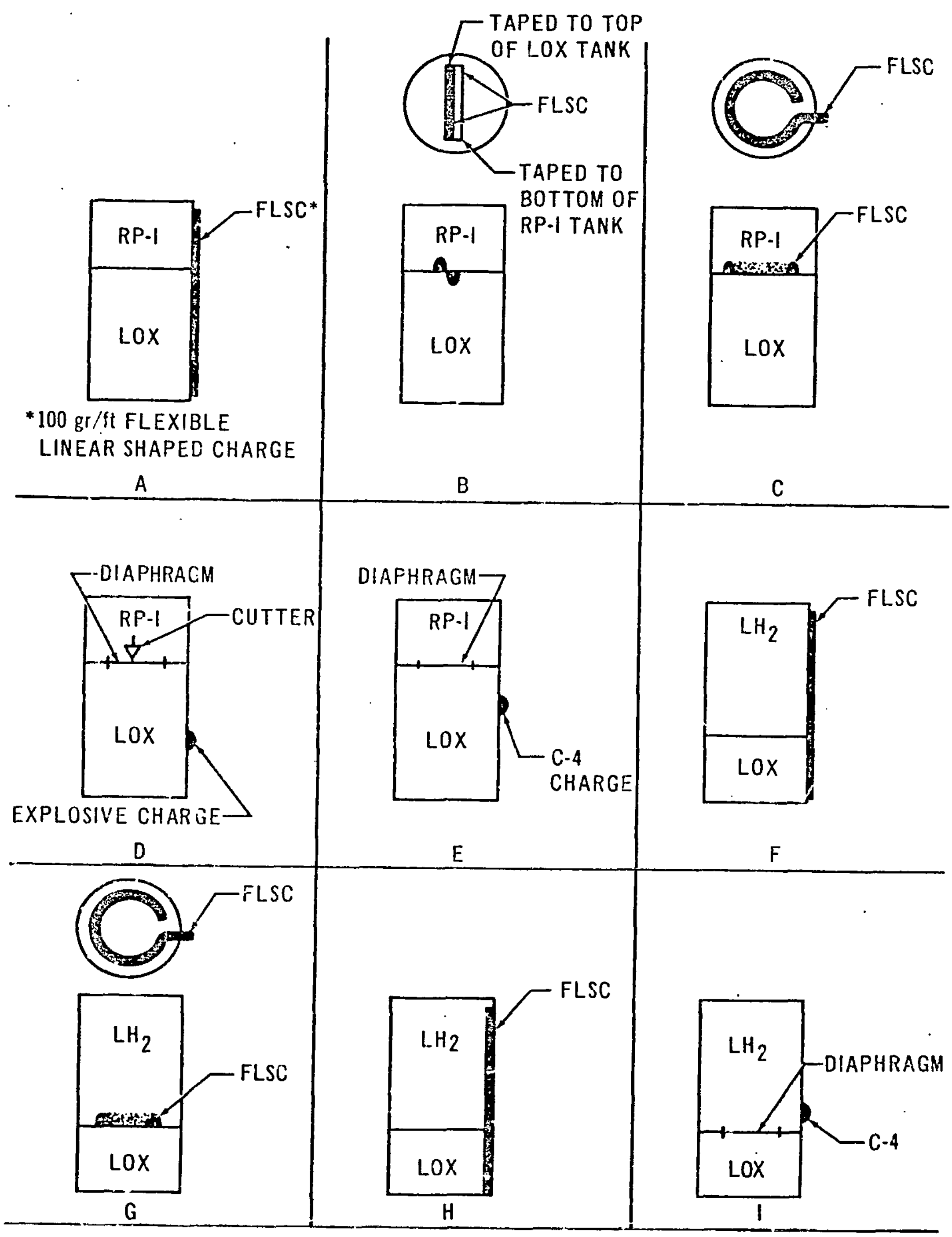

FIGURE 7.- TANK TEST FAILURE CONFIGURATIONS

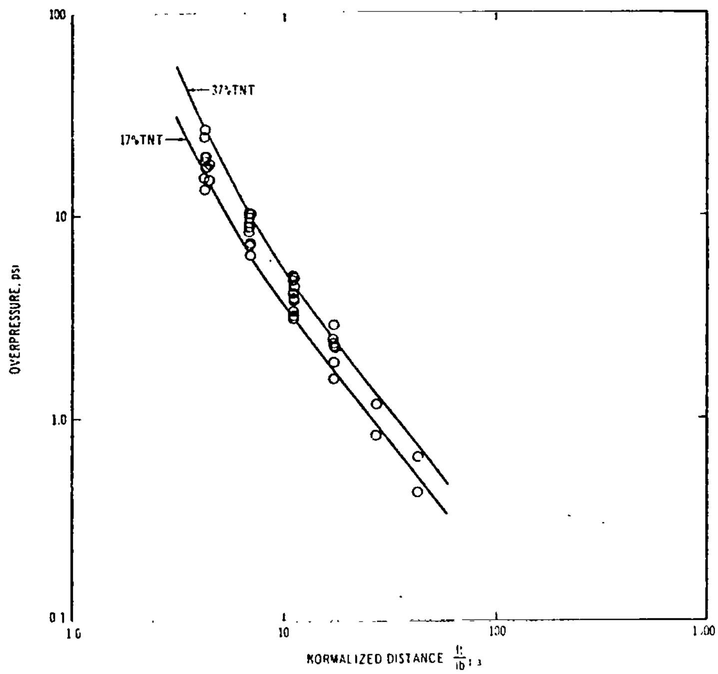

FIGURE 8 – PEAK OVERPRESSURE VS NORMALIZED DISTANCE FOR RP-1 LOX SPILL TESTS

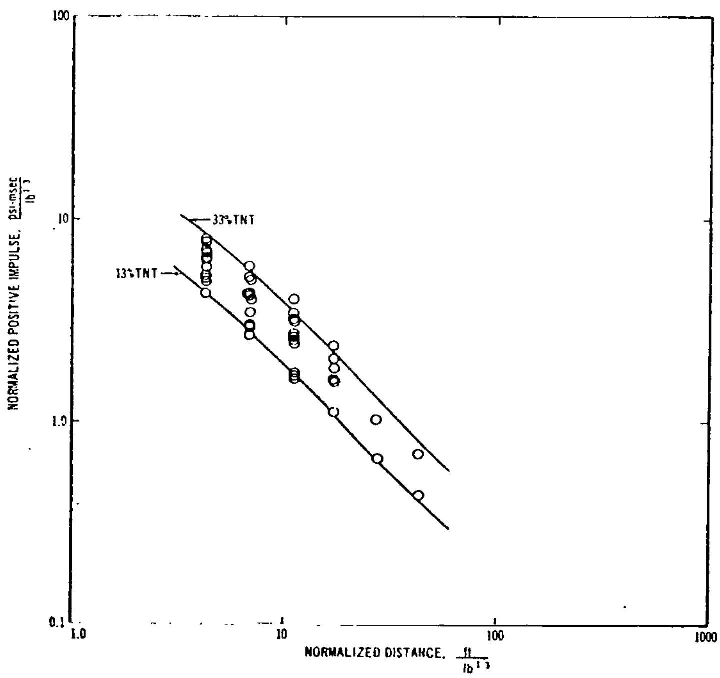

FIGURE 9.– NORMALIZED POSITIVE IMPULSE VS NORMALIZED DISTANCE FOR RP-1 LOX SPILL TESTS

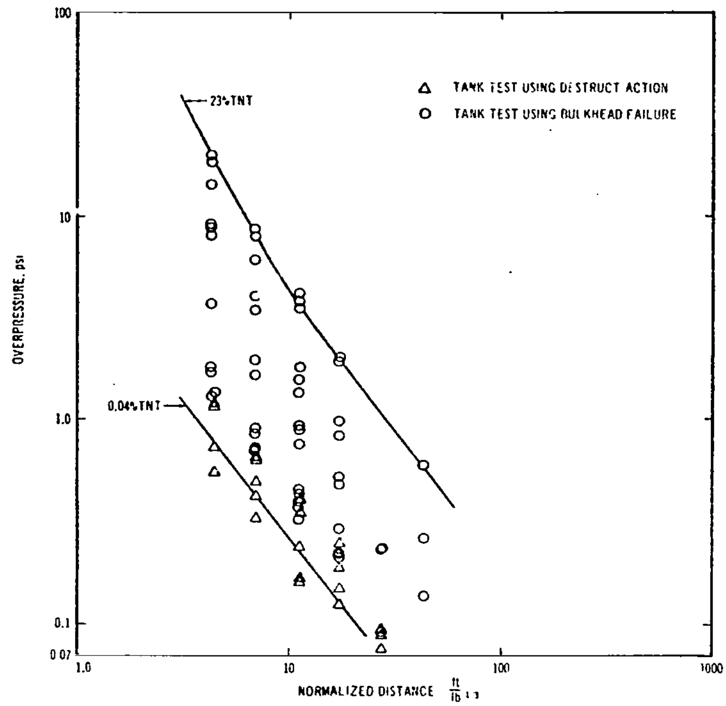

FIGURE 10.- PEAK OVERPRESSURE VS NORMALIZED DISTANCE FOR RP-1 LOX TANK TESTS

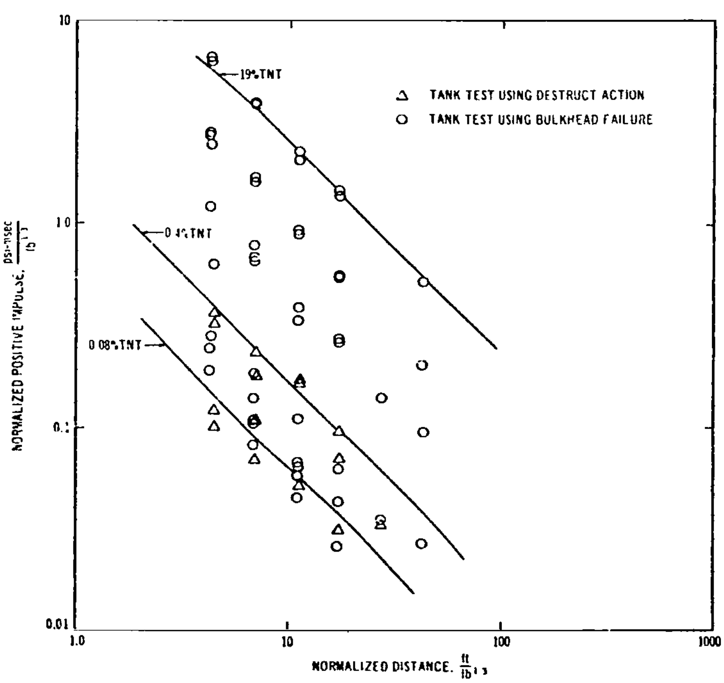

FIGURE 11.- NORMALIZED POSITIVE IMPULSE VS NORMALIZED DISTANCE FOR RP-1 LOX TANK TEST

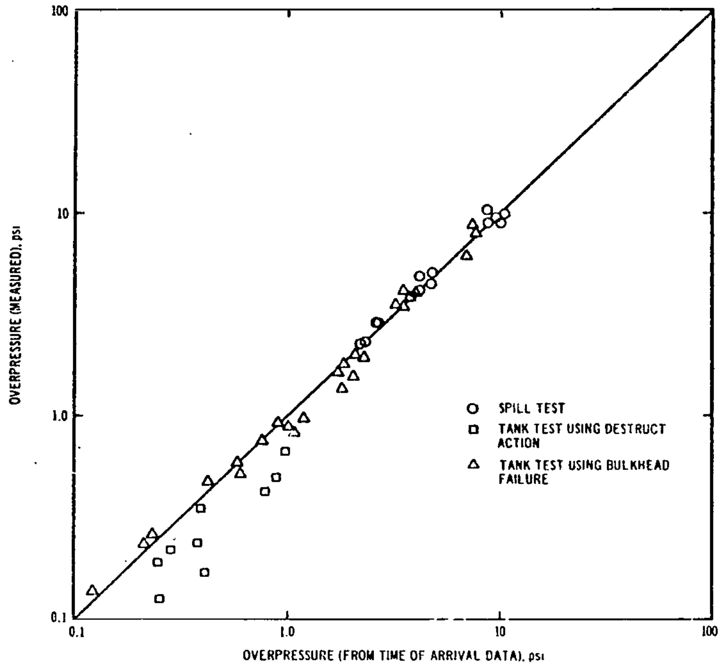

FIGURE 12.– MEASURED PEAK OVERPRESSURE VS OVERPRESSURE DERIVED FROM TIME-OF-ARRIVAL DATA FOR RP-1 LOX TESTS

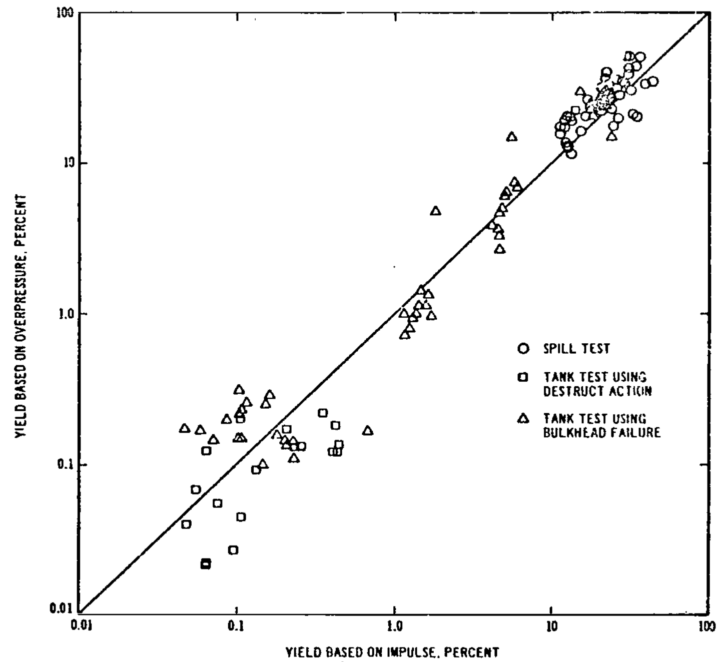

FIGURE 13.– YIELD BASED ON PEAK OVERPRESSURE VS YIELD BASED ON POSITIVE IMPULSE FOR RP-1/LOX TESTS

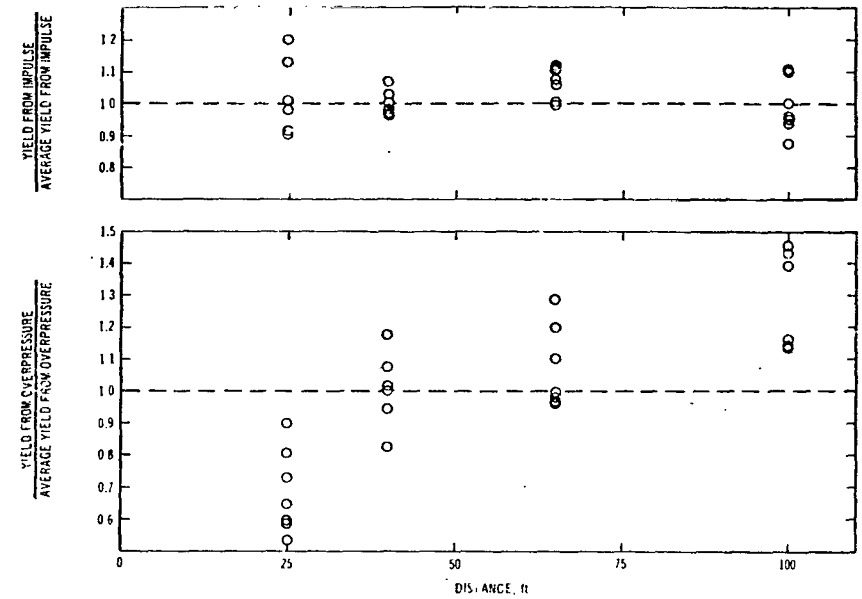

FIGURE 14 - EFFECT OF DISTANCE ON RELATIVE YIELD DETERMINED FOR INDIVIDUAL TRANSDUCER STATIONS FOR RP-1 LOX SPILL TESTS

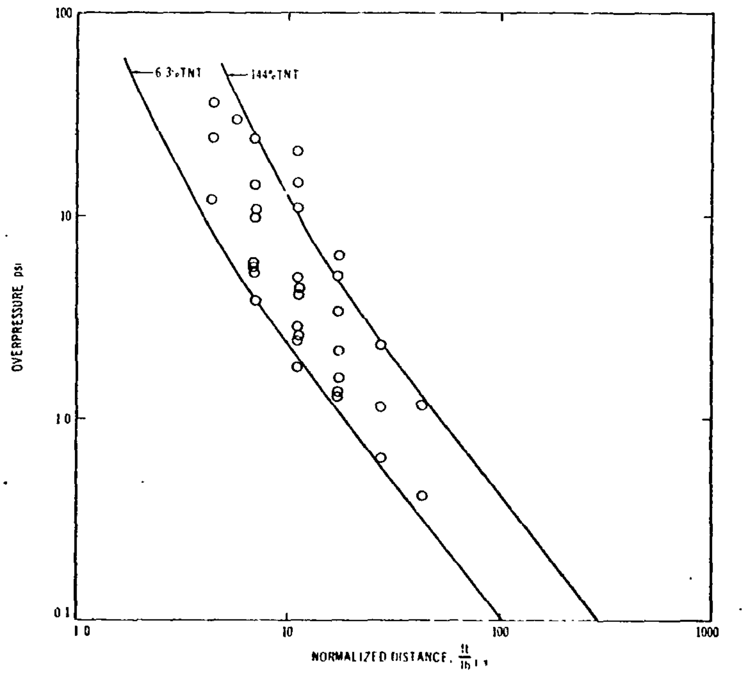

FIGURE 15 - PEAK OVERPRESSURE VS NORMALIZED DISTANCE FOR LH_2 LOX SPILL TESTS

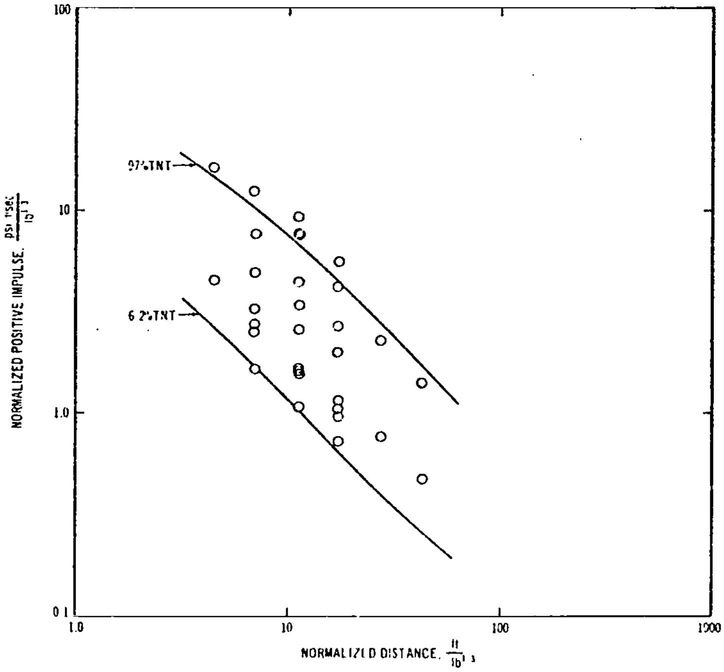

FIGURE 16.– NORMALIZED POSITIVE IMPULSE VS NORMALIZED DISTANCE FOR LH_2 LOX SPILL TESTS

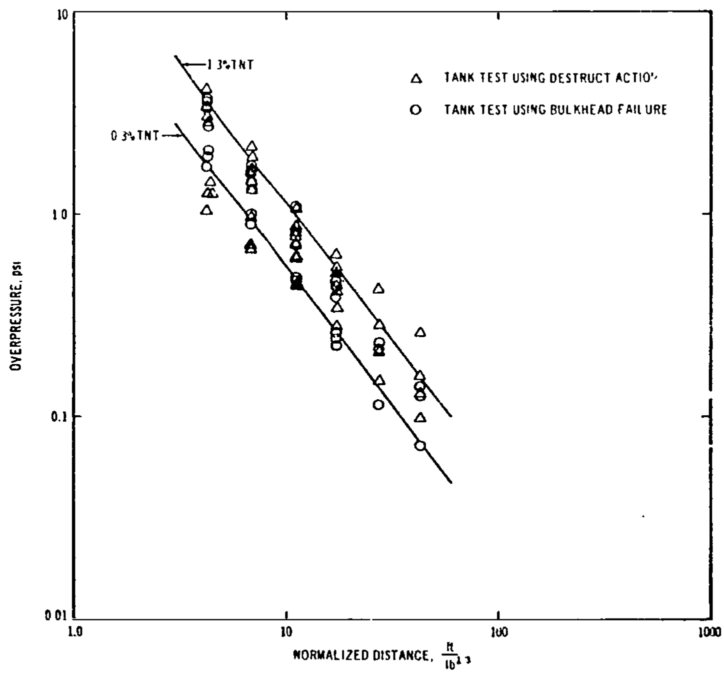

FIGURE 17.– PEAK OVERPRESSURE VS NORMALIZED DISTANCE FOR LH_2 LOX TANK TESTS.

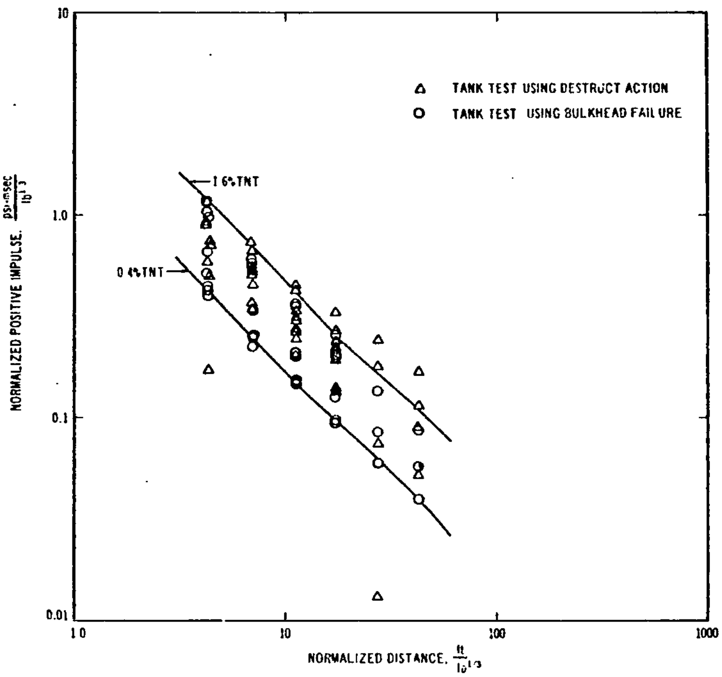

FIGURE 18.– NORMALIZED POSITIVE IMPULSE VS NORMALIZED DISTANCE FOR LH_2 LOX TANK TESTS

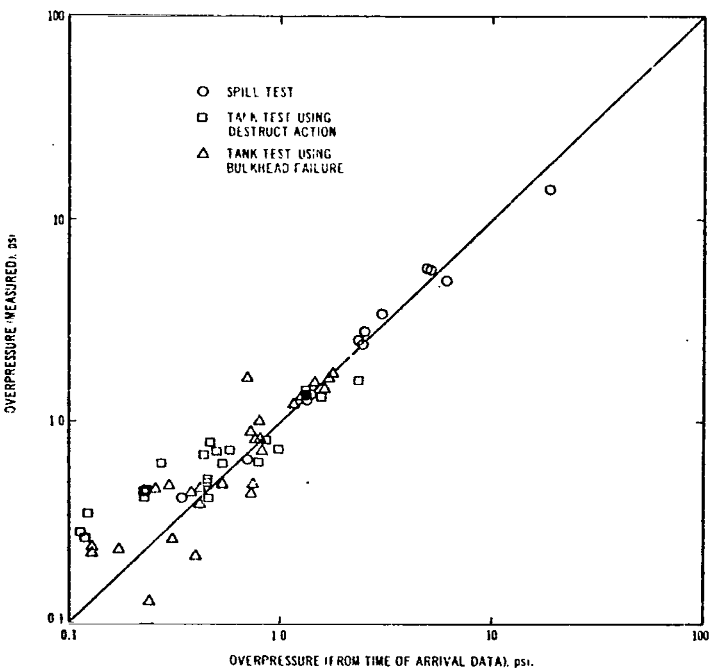

FIGURE 19.– MEASURED PEAK OVERPRESSURE VS OVERPRESSURE DERIVED FROM TIME-OF-ARRIVAL DATA FOR LH_2 LOX TESTS

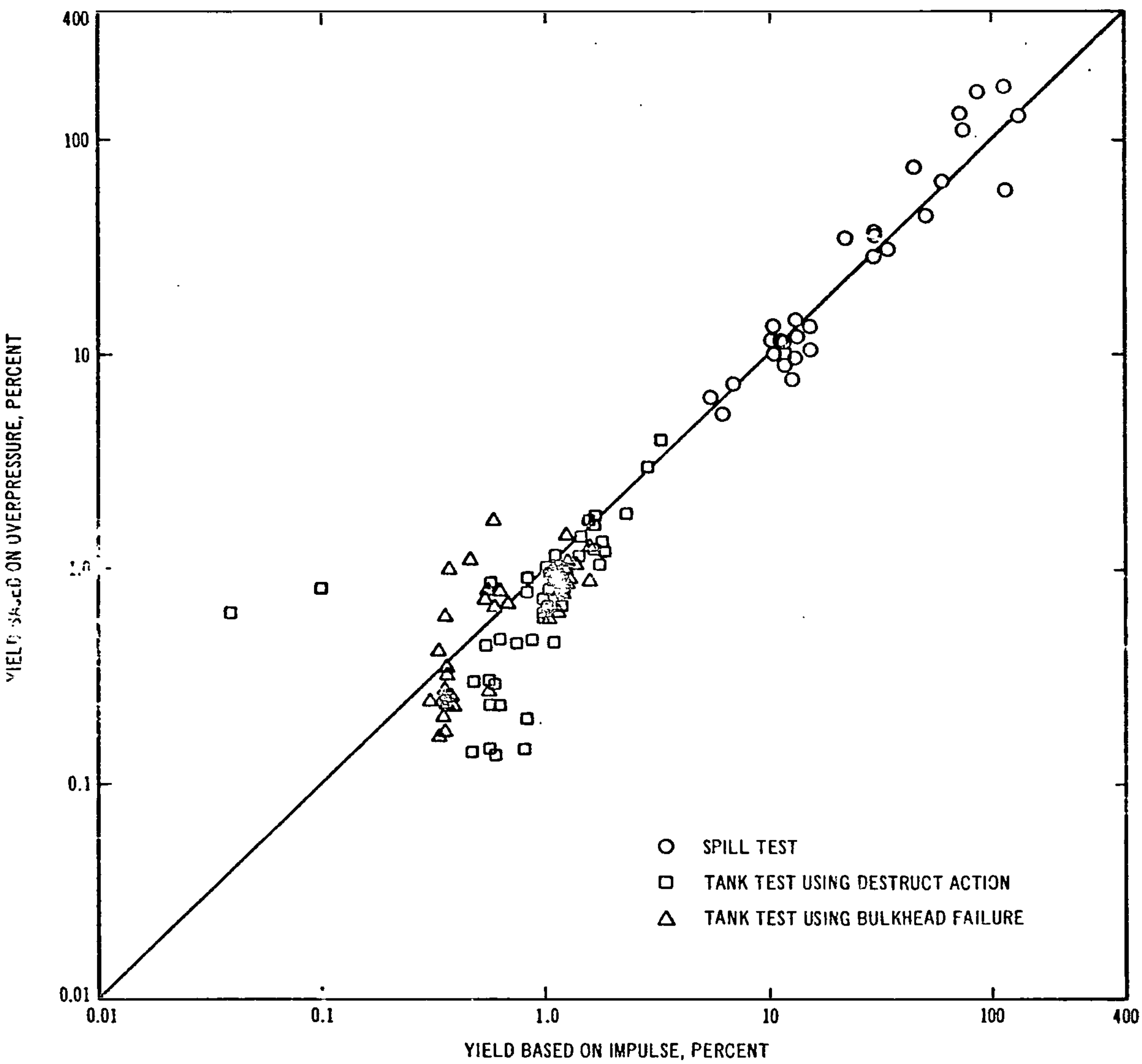

FIGURE 20.– YIELD BASED ON PEAK OVERPRESSURE VS YIELD BASED ON POSITIVE IMPULSE FOR LH_2/LOX TESTS

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PRELIMINARY INVESTIGATION OF BLAST HAZARDS OF RP-1/LOX AND LH_2/LOX PROPELLANT COMBINATIONS

By John B. Gayle, Charles H. Blakewood, James W. Bransford, William H. Swindell, and Richard W. High

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This document has also been reviewed and approved for technical accuracy.

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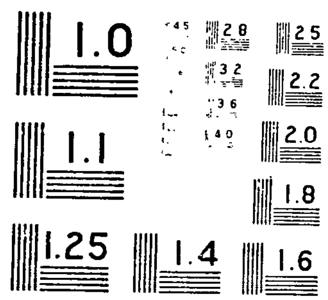

MICROCOPY RESOLUTION TEST CHART
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