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PRELIMINARY INVESTIGATION OF FUEL TANK ULLAGE REACTIONS DURING HORIZONTAL GUNFIRE

R. G. CLODFELTER
E. E. OTT, CAPTAIN, USAF

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13. ABSTRACT

This report deals with the effect horizontal gunfire has on the flammability of hydrocarbon turbine fuel in aircraft fuel tanks. Two fuels, JP-4 and JP-8 were used in the testing. The fuels were placed in an explosion proof test vessel and subjected to CAL .50 (Armor-Piercing Incindiary) gunfire. A wide range of conditions were investigated and the results are presented. The test program was designed to briefly explore the many facets of the fuel tank fire and explosion problem with the intent of investigating in more detail during future testing those areas which appear to be of major significance.

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I-C

FOREWORD

This report was prepared by R. G. Clodfelter and Capt E. E. Ott of the Fire Protection Branch, Fuels and Lubrication Division, Air Force Aero Propulsion Laboratory (AFAPL/SFH). The work reported herein was accomplished under Project 3048, "Fuels, Lubrication and Fire Protection," Task 304807, "Aerospace Vehicle Fire Protection."

This report covers research accomplished from December 1970 through June 1972.

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This report was submitted by the authors June 1972.

This technical report has been reviewed and is approved.

Charles R. Hudson
CHARLES R. HUDSON
Chief, Fuels and Lubrication Division

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SECTION I

INTRODUCTION

A one month test effort was conducted to explore the fire and explosion response of the ullage space of a fuel tank when subjected to CAL .50 Armor-Piercing Incindiary (API) horizontal gunfire. A short test period was established due to the limited availability of the gun range at Wright-Patterson Air Force Base. The test plan was designed to be broad in scope since it was based on the general opinion that the response of a vapor reaction was somewhat predictable and any unique facets of the fuel tank ullage fire and explosion problem could be investigated in detail more effectively at a later time if a broad base existed.

For the foregoing reasons the following six test types were selected for exploration:

1. Standard Test
2. Externally Connected Tank Test
3. Compartmented Tank Test
4. Fuel Level Test
5. Entrance Plate Test
6. Exit Dry Bay Test

The Standard Test was so termed because each of the other five "types" can be considered a modification of the Standard Test. The influence of these modifications were then determined by comparison with the results of the Standard Test.

The Standard Test consisted of firing into the ullage of an uncompartmented tank containing only a nominal amount of liquid fuel (4.4% by volume). For the Externally Connected Tank Test a second fuel tank was connected to the standard tank by a flexible hose to simulate an aircraft fuel system with interconnected tanks. The Compartmented Tank Test was performed by adding an extension to the standard tank and separating the two by a perforated wall. In the Fuel Level Test the bullet trajectory was held fixed while the amount of fuel within the standard tank was increased so that the liquid vapor interface approached the projectile trajectory. The entrance plate on the standard tank was changed in diameter and thickness to meet the requirements of the Entrance Plate Test. Both the Fuel Level and Entrance Plate Tests were included to assess the influence these items would have on the transfer of energy from the projectile to the liquid and the possible generation of fuel spray in the ullage. The Exit Dry Bay Test was designed to determine if a projectile traveling through the ullage of a fuel tank could generate an external fire on the exit side of a fuel tank. In these tests, a closed dry bay was attached to the exit side of the standard tank.

For each of these six test types numerous shots were made at various temperatures, pressures, and fuel types. In addition to the basic six test types, a short series of "Combination & Special" shots was made to explore nonequibrium conditions and other unique facts.

Some of the results of this test program were predictable and other results were not as expected. The general conclusion of the program was that additional investigation is required to explain some of the results, particularly for interconnected tanks.

SECTION II

APPARATUS USED IN HORIZONTAL TESTS

A cylindrical stainless steel tank which could be modified as shown in Figure 1 was used in this test program. The tank, called a "J" Tank, included pressure and temperature measuring equipment which was added during a previous program dealing with vertical gunfire testing. This equipment consisted of three thermocouples for monitoring the preignition temperatures of the tank ullage, tank interior wall, and fuel. Two pressure transducers were used to measure reaction overpressures. Whenever a tank extension was used one transducer was located in the main tank body and the other in the extension. When no extension was used both transducers were mounted in the main tank body. All tests used an exit plate 19 1/4 inches in diameter.

Film coverage was made of all shots. The exterior of the tank was photographed normally at 64 frames per second and the interior at approximately 6400 frames per second. During most tests the interior camera viewed the main tank body. However, in the Externally Connected Tank Test and the Compartmented Tank Test the interior camera saw only the extended portion. The "J" tank was used in all tests. It was mounted such that the planes of the entrance and exit plates were vertical. The CAL .50 API projectile was fired horizontally from a gun mounted about 25 feet away from the tank. All tests were conducted with a projectile velocity of approximately 2850 Ft/second. The bullet was aimed such that it passed through the center of the tank. A closed circuit fuel spray and circulation system was installed within the tank so that equilibrium vapor concentration could be obtained. Aluminum 2024T4 entrance and exit plates were used in all tests.

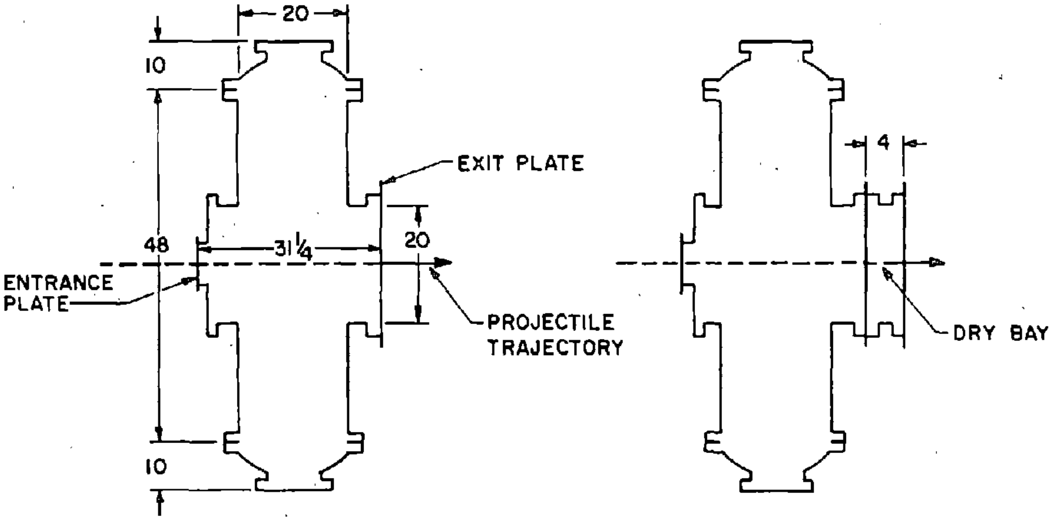
Specific apparatus and configuration used in each of the six test types was as follows:

1. Standard Test

The first series of horizontal shots were the Standard Test.

a. STANDARD TEST

b. EXIT DRY BAY TEST



c. EXTERNALLY CONNECTED TANKS TEST

d. COMPARTMENTED TANK TEST

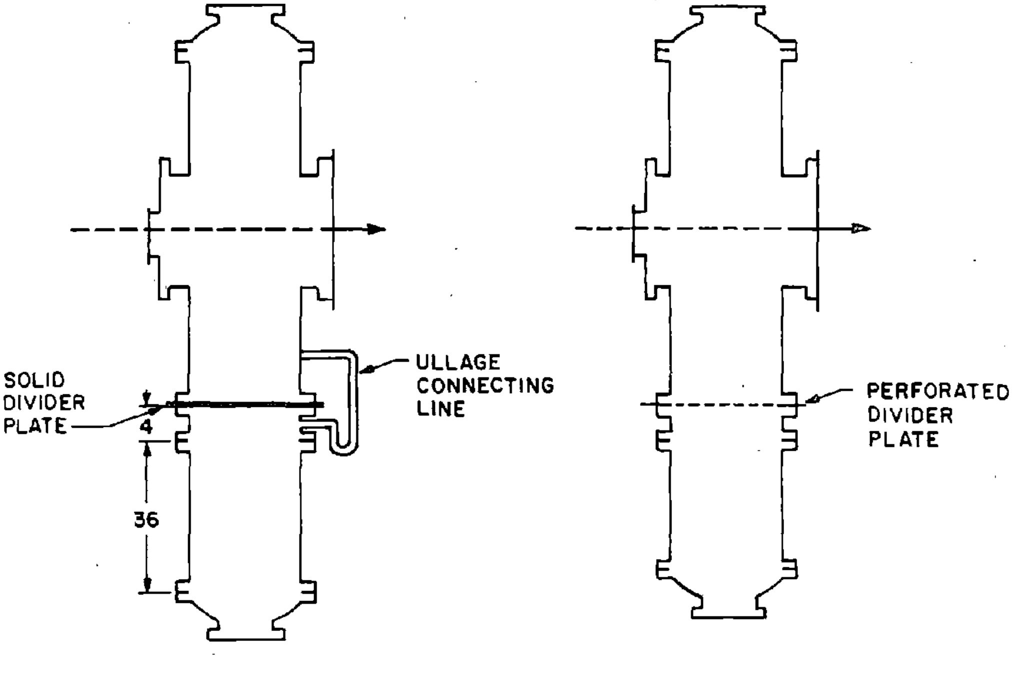


Figure 1. Tank Configuration (Plan View)

The test conditions consisted of the following parameter values:

a. The "J" tank in its unextended configuration had a volume of 90 gallons. (See Figures 1a and 2),

b. An 8 inch diameter, 0.125 inch thick entrance plate (See Figure 3a),

c. A 19 1/4 inch diameter exit plate; the thickness was varied to withstand the expected overpressure (See Figure 4),

d. An 8 inch bullet trajectory height above the liquid surface; this corresponded to 1 1/2 inch maximum fuel depth and 4 gallons (See Figure 5).

2. Externally Connected Tank Test

These tests were conducted using the "J" Tank with an extension added to one end as shown in Figure 1c. The extension was separated from the main tank body by a 1/4 inch thick aluminum plate. The ullages of the tanks were connected by a 1 inch diameter hose. The length of the connecting path was approximately 2 feet. A fuel spray/circulation nozzle was installed within the extension tank in order that equilibrium vapor conditions would be formed in both tanks. In this configuration the main tank volume was approximately 80 gallons with the extension tank volume of approximately 55 gallons.

3. Compartmented Tank Test

The compartmented tank was formed by adding an extension to the "J" Tank as illustrated in Figure 1d. The 1/4 inch aluminum plate which divided the extension from the main body was perforated by four one inch diameter holes located near the top (See Figure 6). Several small holes at the bottom of the plate allowed the fuel level to equalize between the two compartments. The volume of these compartments was the same as the externally connected tanks previously discussed. A fuel spray/circulation nozzle was also included in the extended portion to insure equilibrium fuel vapor conditions.

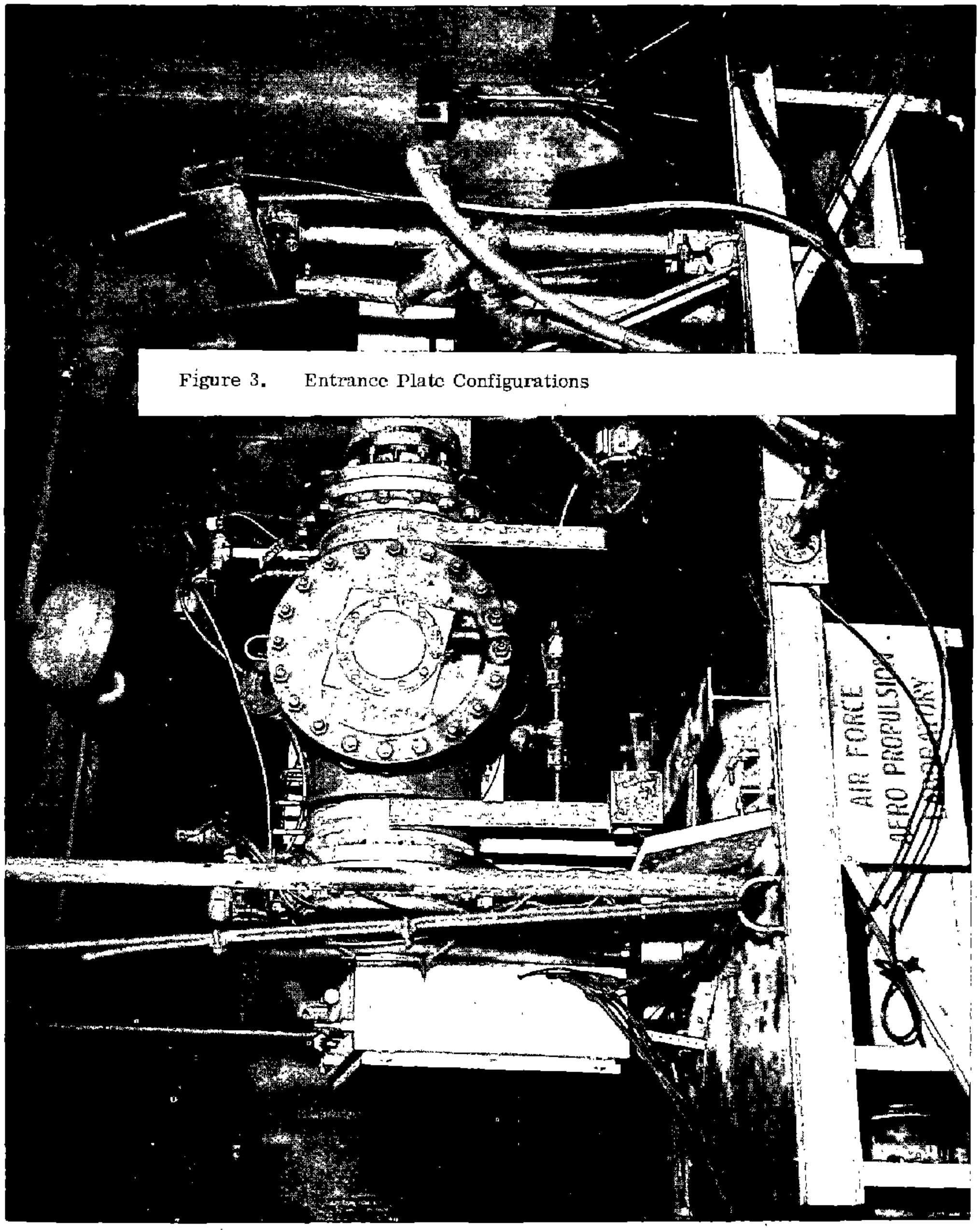
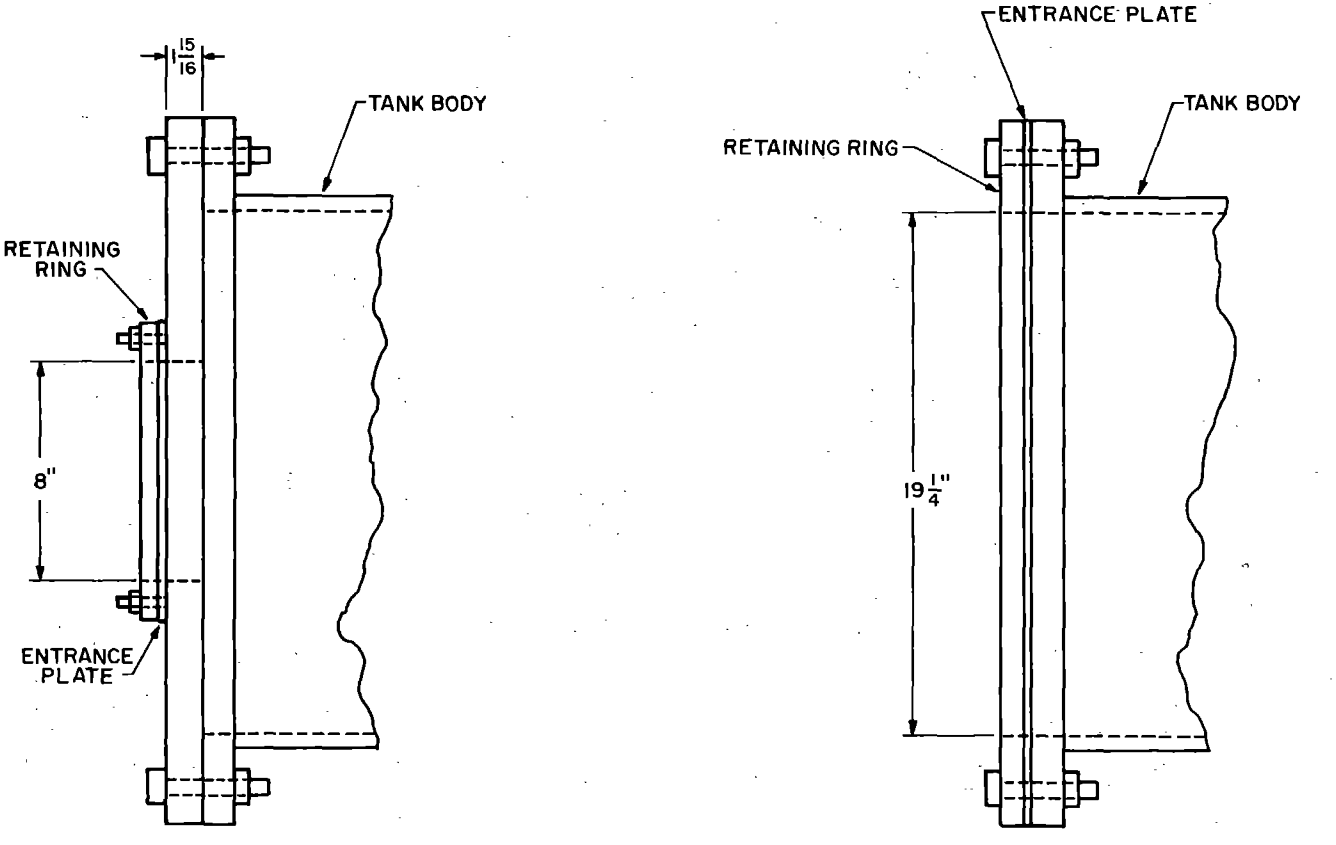


Figure 3. Entrance Plate Configurations

Figure 2. "J" Tank in Standard Test Configuration



a. 8" ENTRANCE PLATE

b. $19\frac{1}{4}$" ENTRANCE PLATE

Figure 3. Entrance Plate Configurations

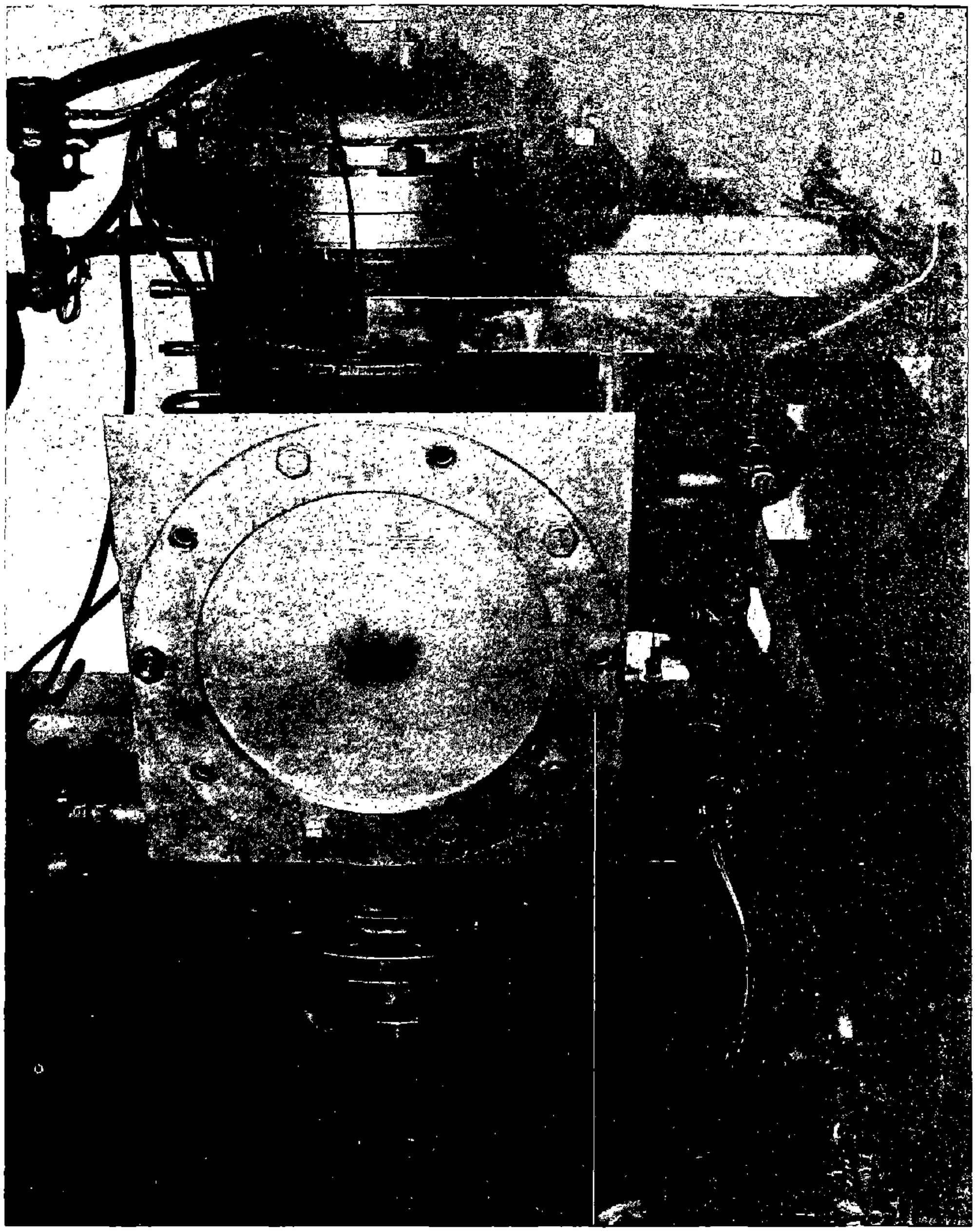


Figure 4. Exit Plate of Standard Test

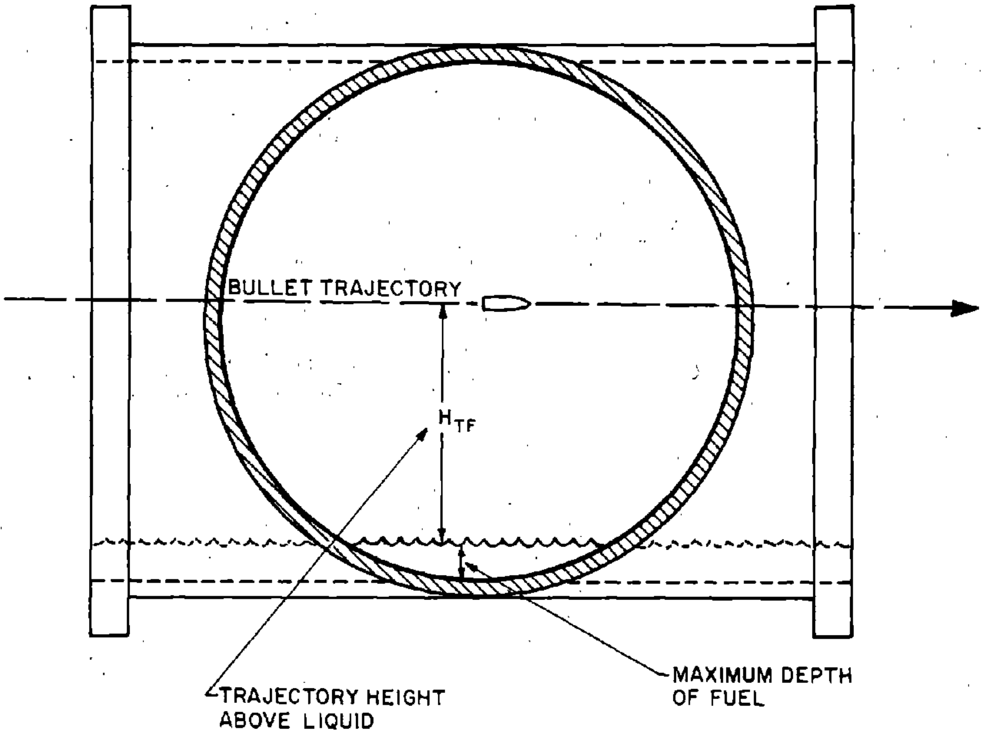


Figure 5. Bullet Trajectory Through Test Tank

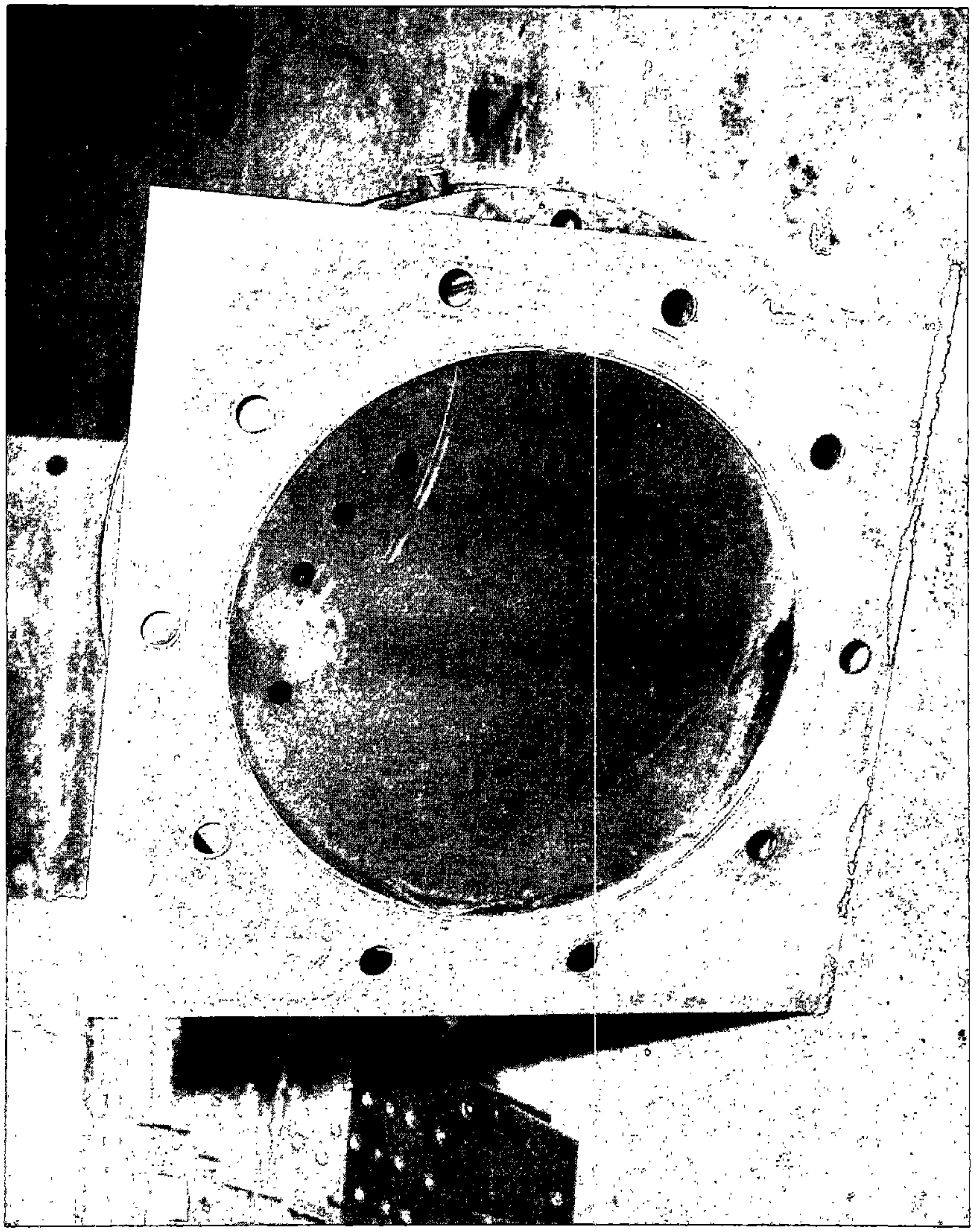


Figure 6. Perforated Plate of Compartmented Tank Test

4. Fuel Level Test

To investigate the effect of the projectile passage over the liquid-vapor interface and the possible generation of fuel spray, the test tank was returned to the standard configuration and the amount of fuel within the tank was varied. It was believed that the massive flange to which the 8 inch entrance plate was fastened would absorb the energy transmitted to the entrance plate during penetration. Thus, any difference in the results of these tests would be due to the influence of the projectile's passage over the liquid and not its energy lost during penetration.

5. Entrance Plate Test

The objective of these tests was to impart different amounts of energy from the projectile to the fuel during penetration. This was done by replacing the 8 inch entrance plate with a 19 1/4 inch diameter plate as shown in Figure 3b. The thickness of the new plate was also varied at three levels, 0.060, 0.125 and 0.250 inch. The amount of fuel in contact with the entrance plate was changed by adding different amounts of fuel to the tank.

6. Exit Dry Bay Test

A dry bay was added to the standard "J" Tank by sandwiching a small extension between two exit plates as shown in Figure 1b. The extension was 19 1/4 inches in diameter and 4 inches in length (See Figure 7). Its volume was 4.8 gallons. The exit plates used were 0.090 inch in thickness.

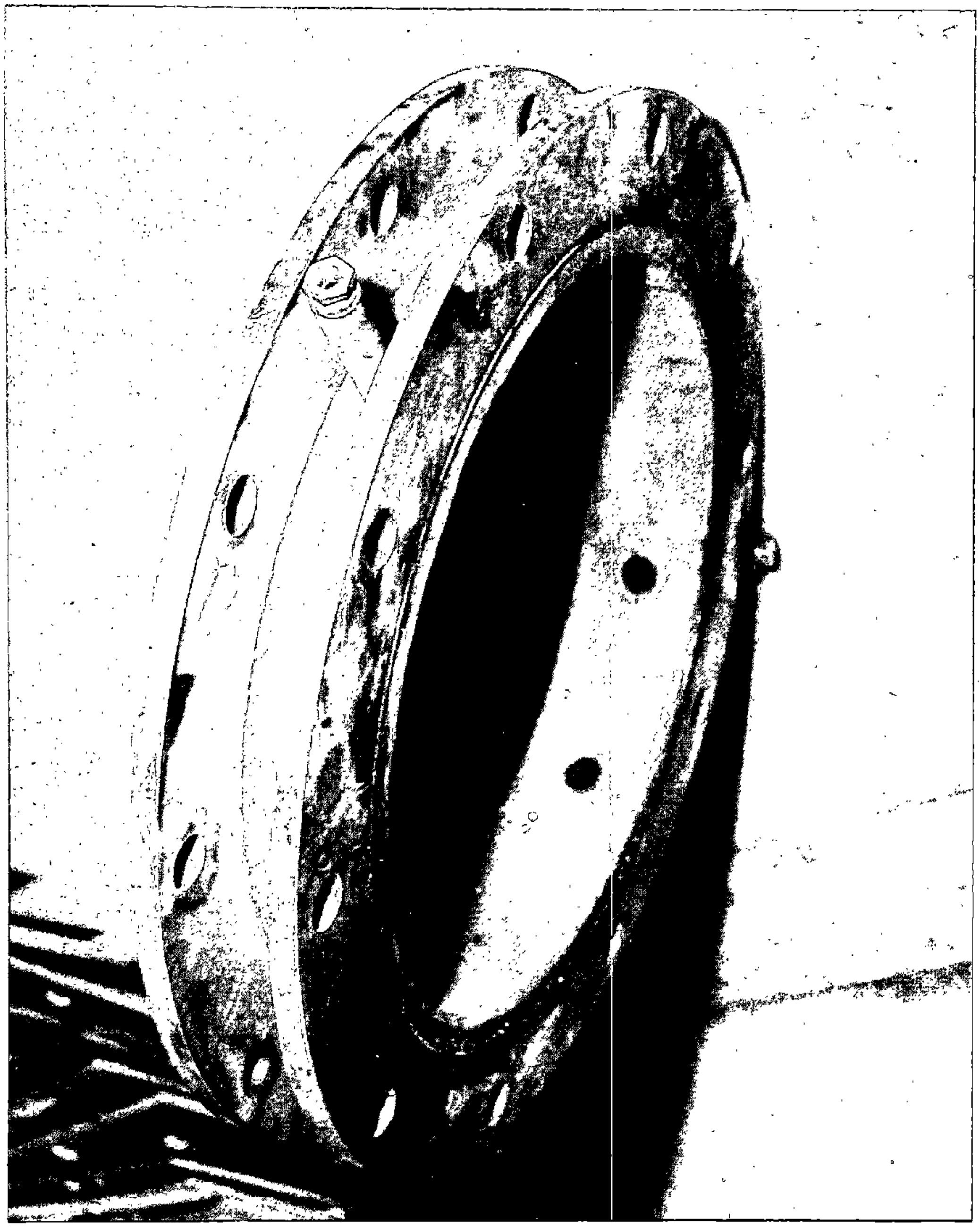


Figure 7. Exit Dry Bay Extension

SECTION III

PROCEDURES USED IN HORIZONTAL TESTS

The desired fuel/ullage temperatures were produced by heating the fuel before placing it in the tank and heating the tank by blowing hot air around it.

Equilibrium fuel vapor concentrations were obtained by the following procedure: After the entrance and exit plates were installed the tank was evacuated to less than 5 psia. The vacuum lines were closed and the fuel pumped into the tank. The fuel was circulated through the spray system for at least 5 minutes at the below atmospheric pressure. The ullage pressure was then increased to the desired test value and the fuel spray-circulation continued for another 5 minutes. The shot was fired approximately 2 minutes after the spray was stopped.

In all tests the temperatures of the ullage and fuel were nearly equal. Also, in all but four special tests which are appropriately identified in the test results section, equilibrium fuel vapor concentrations were achieved.

SECTION IV

TEST RESULTS FOR HORIZONTAL SHOTS

A total of 130 tests were conducted. The individual test conditions and results of these tests are given in Appendix I. The following abbreviations are used in the tables gathered in this appendix.

T_L - Temperature of fuel, °F

T_U - Temperature of ullage, °F

T_W - Temperature of tank wall, °F

D_E - Diameter of entrance plate, inch

X_E - Thickness of entrance plate, inch

D_F - Maximum fuel depth, inch

H_{TF} - Height of bullet trajectory above liquid, inch

P_I - Initial ullage pressure, PSIA

F/A - Fuel to air mass ratio (Based on British Petroleum Institute method of vapor pressure and mass estimation using distillation data)

ΔP_M - Peak overpressure in main tank body, PSI

ΔT_M - Time that ΔP_M was measured, seconds

ΔP_C - Peak overpressure in extended tank section, PSI

ΔT_C - Approximate time that ΔP_C was measured, seconds

δP_C - Overpressure in extended tank section at time ignition occurred in that section, PSI

Figure 8 will help the reader understand the definitions more easily.

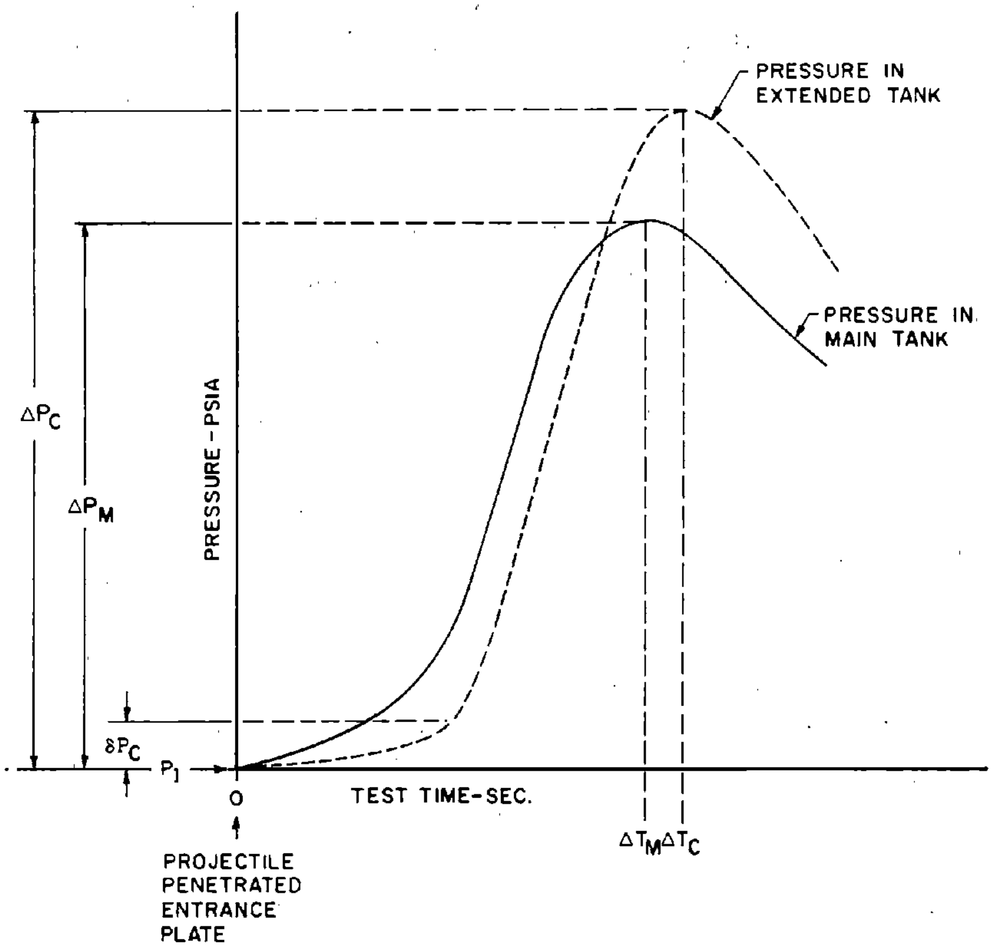


Figure 8. Measured Parameters

SECTION V

DISCUSSION OF TEST RESULTS

1. Standard Test (Figure 1a and Table I)

In Figures 9 and 10 the reaction overpressures are plotted as a function of initial temperature for JP-4 and JP-8 at atmospheric initial pressure and JP-4 at 30 psia. Two important characteristics of the data are immediately apparent. First, there is a fuel rich flammability temperature limit for the JP-4. At atmospheric pressure this limit is in the 51°F to 59°F region and at 30 psia it is between 89°F and 101°F. The standard lean and rich flammability limits as determined by laboratory experimentation are shown on these figures for comparison. The other important observation which applies to JP-8 is that the ullage is ignitable at temperatures well below the flash point (105°F) and the resulting overpressure decreases with decreasing temperature.

To understand these observations one must consider the ullage composition environment. First, the ullage contains an equilibrium fuel vapor concentration. The magnitude of this concentration is dependent upon the volatility of the fuel. Fuel volatility is, in turn, dependent upon its chemical composition and its temperature. Increasing the fuel temperature will increase the equilibrium vapor concentration. Second, the ullage is in contact with the liquid fuel surface. In gunfire tests, additional fuel in the form of vapor or spray may enter the ullage from the liquid surface. The additional fuel could be generated by impact of the projectile and/or evaporation due to incendiary burning or initial fuel combustion. It is this additional fuel that causes the complicated results seen during gunfire.

In shooting fuel tank ullages which contain rich equilibrium vapor concentrations the only effect of additional fuel is to make the ullage more fuel rich. Thus, it was expected that rich limits would be found for gunfire tests. The only exception to this would be when the fuel tank is ruptured, due to the projectile, in such a way that air is ingested causing the fuel/air ratio to decrease.

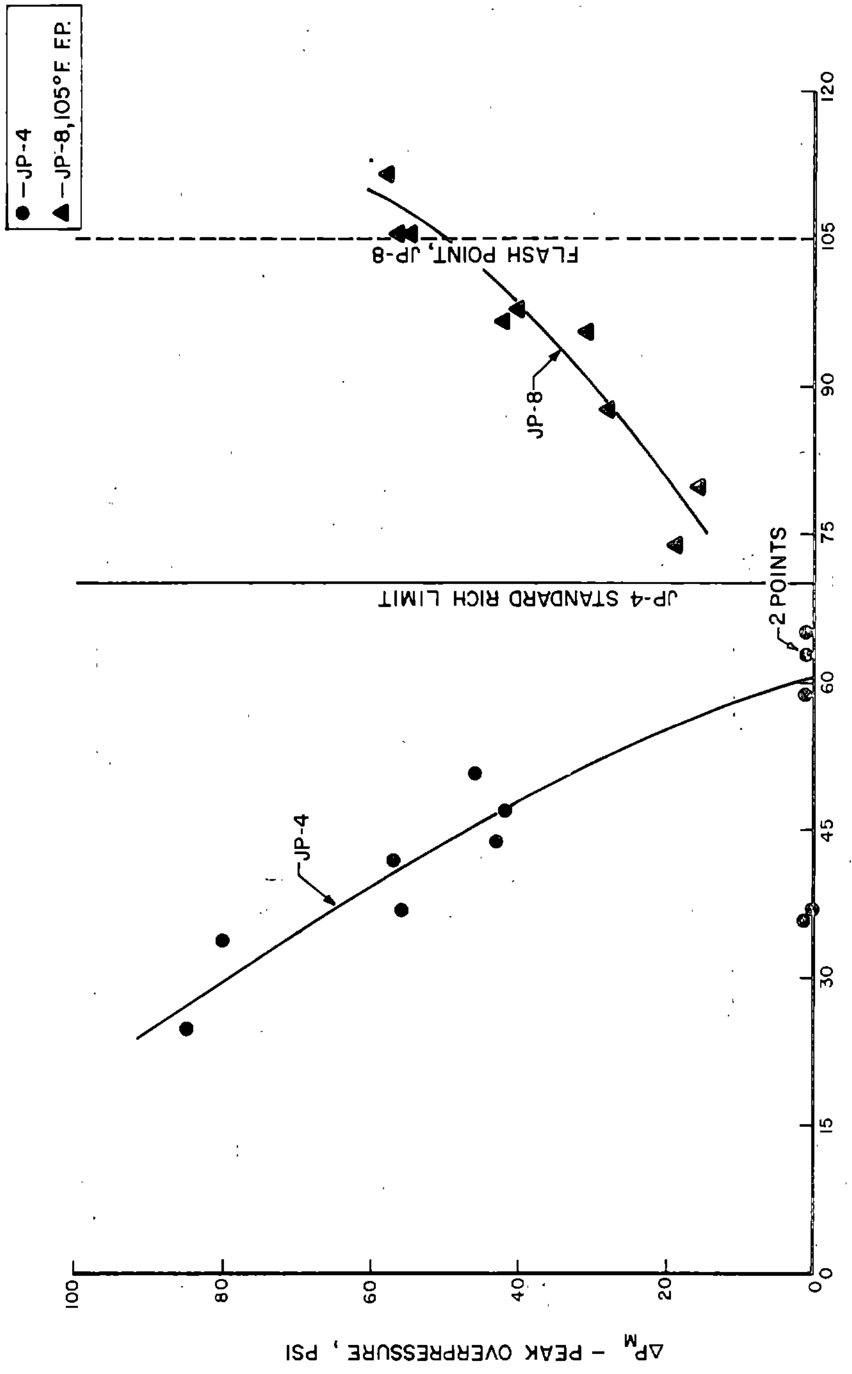


Figure 9. Overpressure for Standard Test with Atmospheric Initial Ullage Pressure

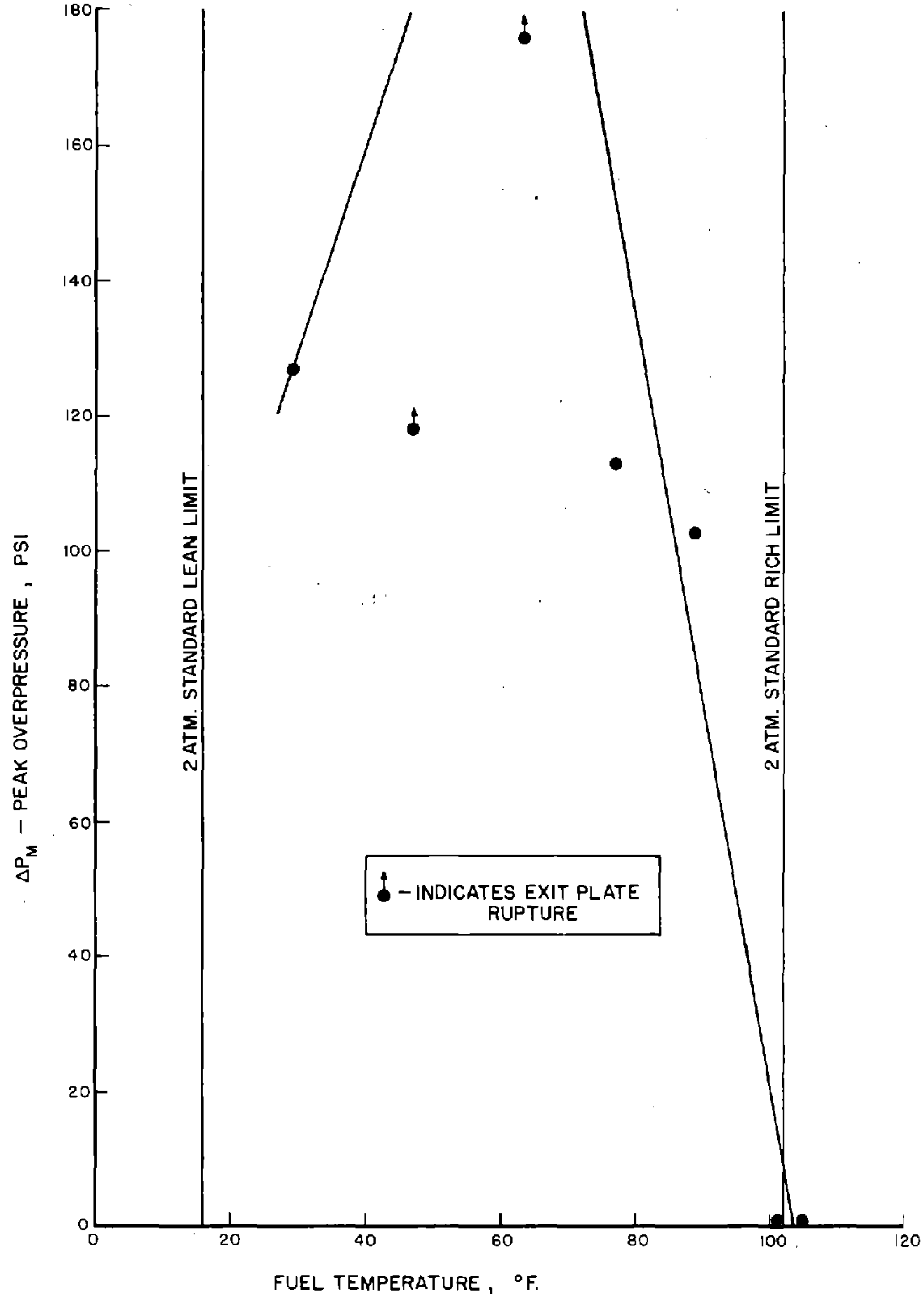


Figure 10. Overpressure for Standard Test with JP-4 at 30PSI Initial Ullage Pressure

The hazards of initially lean fuel vapor ullages are much more complex and uncertain. Depending upon the amount and nature of the fuel added, an ullage can remain nonflammable, become flammable, or be shifted past the rich limit into a nonflammable condition.

Apparently in the shots using JP-8, 105°F flash point, a small amount of fuel was added to the ullage which shifted it into a flammable condition. The overpressures are remarkably similar to overpressures measured during flammability tests of the ullages in sloshing fuel tanks previously conducted by the Air Force Aero Propulsion Laboratory (AFAPL) and reported in technical report AFAPL-TR-70-65[1].

Figure 11 shows the times from projectile impact to peak overpressure for the standard tests at atmospheric pressure. For the JP-4 data we see that the times increased rapidly near the rich limit of 51°F to 59°F as previously described. The times to peak overpressure for the JP-8 show an apparent peak at a temperature slightly less than the flash point of the fuel. A similar time peak phenomena was observed in AFAPL-TR-70-65 (See Figure 12). Due to the limited amount of data available the exact shape of this curve cannot be determined, however, the time peak phenomena was probably due to a transition from one type of combustion process to another. It should be noted that the times to the left of the peak were associated with much lower overpressures than the times to the right of the peak. One might expect the time required to reach a lower overpressure to be shorter and as the temperature continues to decrease to the point of no reaction that the time to maximum overpressure would again increase.

Regression Equations for the Standard Test Results

Since the Standard Tests were conducted with several variables including fuel type, initial temperature, and initial pressure it was desirable to be able

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(1) AFAPL-TR-70-65 "Effects of Fuel Slosh and Vibration on the Flammability Hazards of Hydrocarbon Turbine Fuels within Aircraft Fuel Tanks", E.E. Ott, November 1970

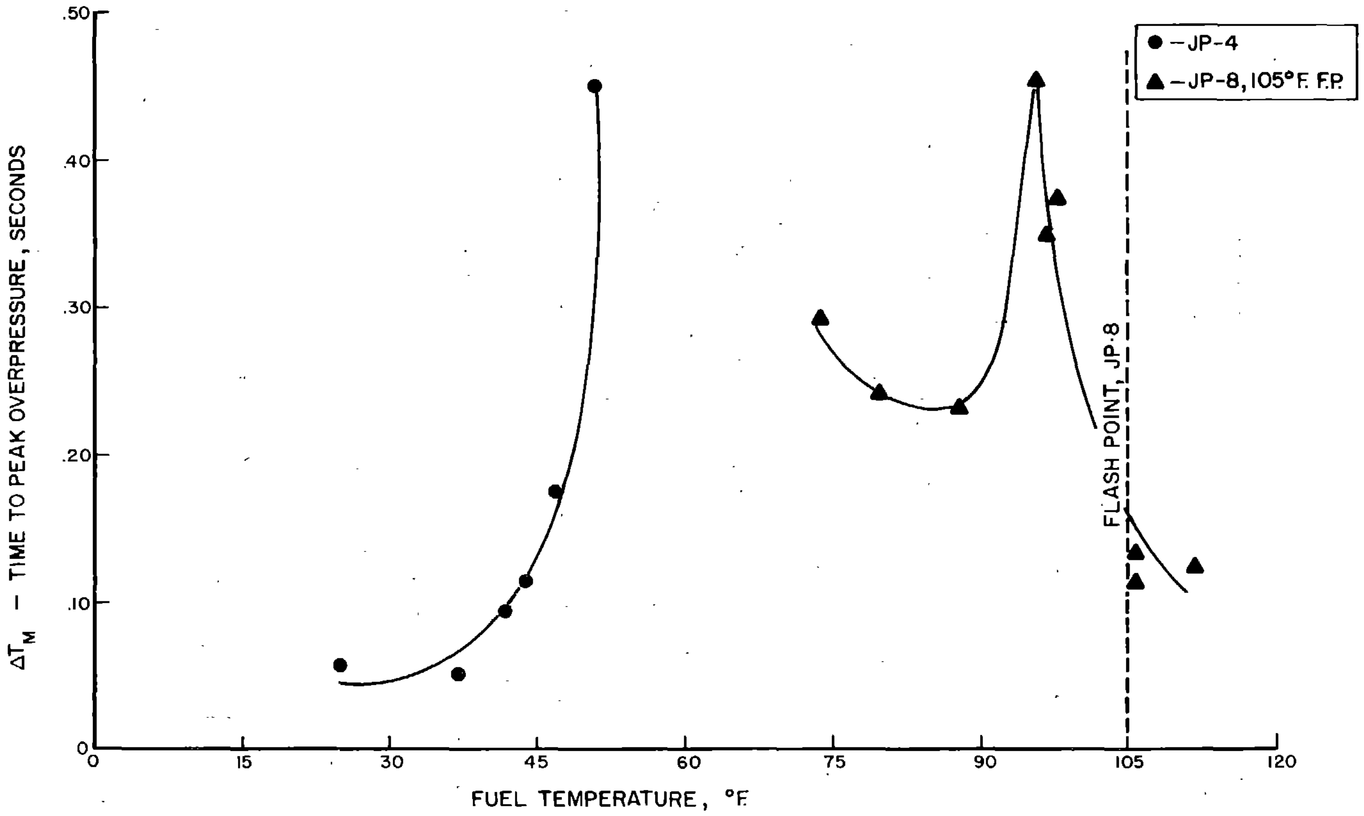

Figure 11. Times-to-Peak Overpressure for Standard Test with Atmospheric Initial Ullage Pressure

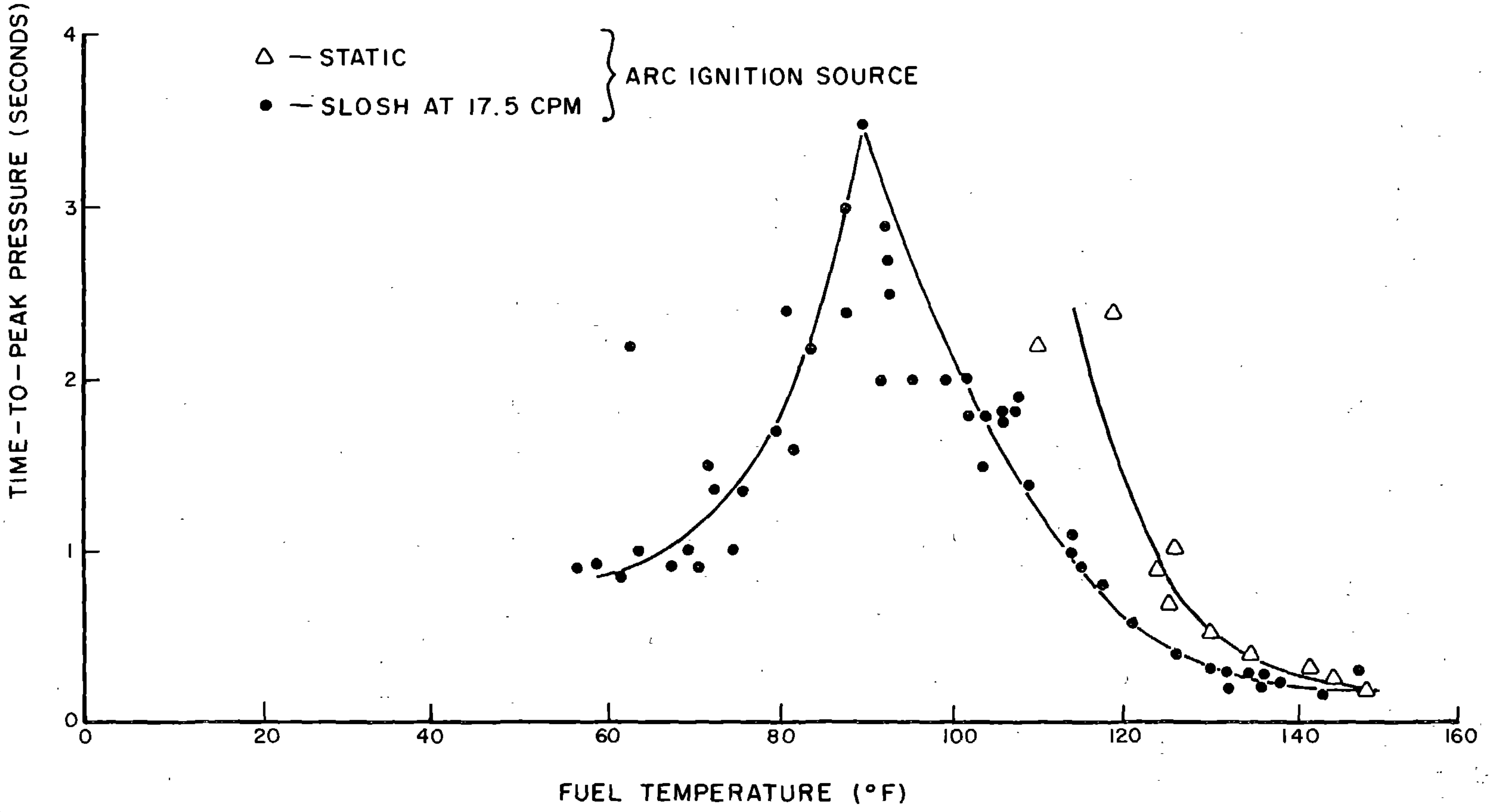

Figure 12. Times-to-Peak Reaction Pressure for JP-8 Fuel at One Atmosphere Initial Ullage Pressure (From AFAPL-TR-70-65)

to express the test results in an efficient form for later comparison. Appendix II gives the basis for the development of Figure 13. On this Figure all the Standard Test results are plotted for both fuels. By plotting the overpressure ratio $\frac{\Delta P_M}{P_I}$ versus the fuel/air mass ratio the effect of initial pressure and fuel type no longer must be considered independently.

A regression equation

$$\frac{\Delta P_M}{P_I} = \frac{6052.6\ (F/A)^4 - 1104.1\ (F/A)^2 + 185.8\ (F/A) - 1.4}{(F/A + 1)^2}$$

with a multiple correlation coefficient (R_c) of 0.9875 was developed for the data.

A second regression equation

$$\frac{\Delta P_M}{P_I} = \frac{2,913,100\ (F/A)^4 - 535,383\ (F/A)^2 + 89,752\ (F/A) - 511}{T\ (F/A + 1)^2}$$

with a multiple correlation coefficient of $R_c = 0.9864$ was also developed including the effect of initial temperature (T_I) as suggested in Appendix II. A regression analysis discussion is given in Appendix III. Both equations express the data very well for the lean mixtures ($\phi < 1$) with the latter offering an improvement near stoichiometric ($\phi = 1$). For the rich mixtures ($\phi > 1$), both equations were less accurate due to the limited test data in this region and the large variance associated with the ignition process.

The equation

$$\frac{\Delta P_M}{P_I} = \frac{2,913,100\ (F/A)^4 - 535,383\ (F/A)^2 + 89,752\ (F/A) - 511}{T\ (F/A + 1)^2}$$

was used in later sections of the report to establish comparison data.

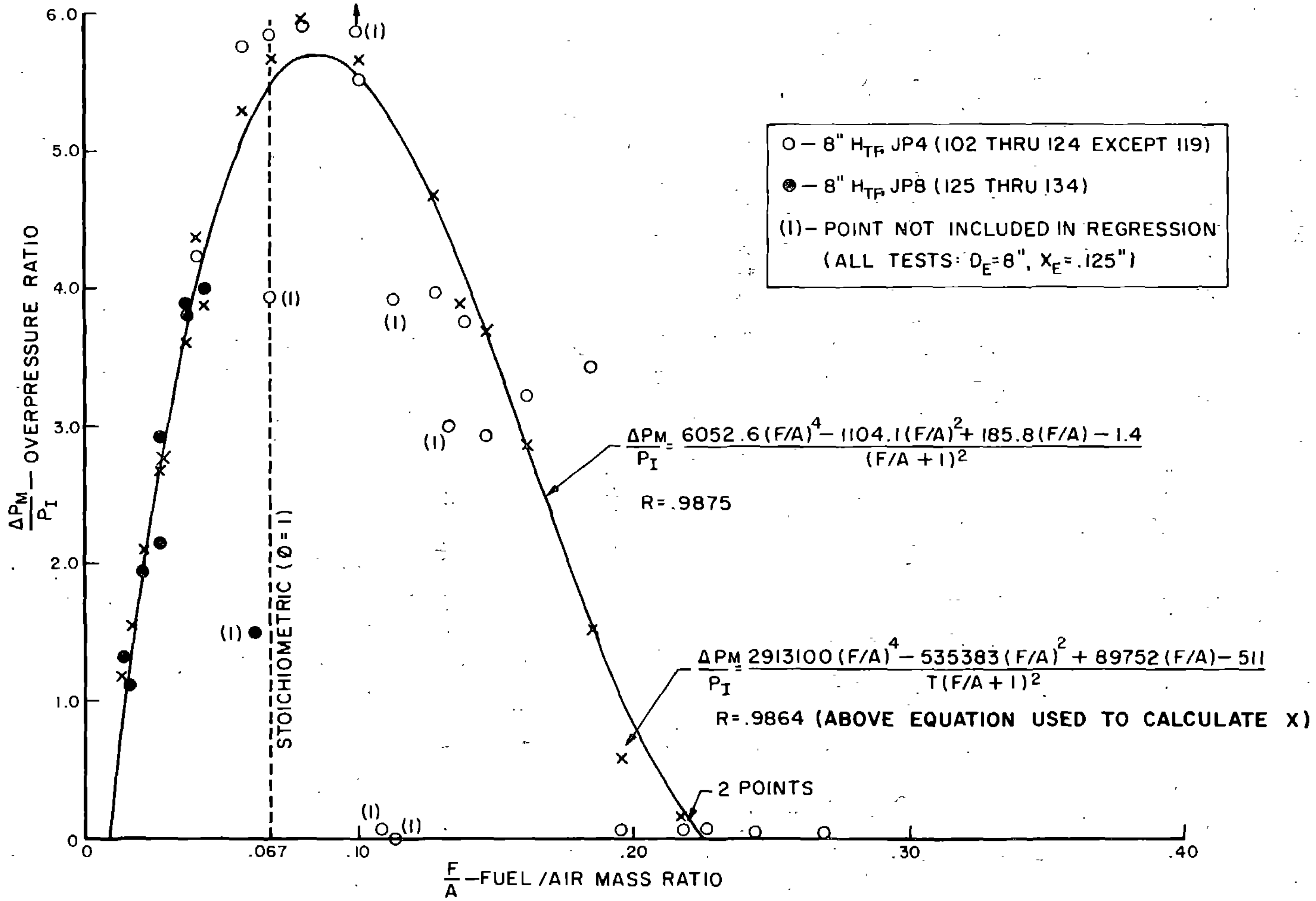

Figure 13. Regression Equations for the Standard Test Results

2. Externally Connected Tank (Figure 1 and Table II)

Six shots were performed with the externally connected tank and JP-4 fuel. No flame propagation from the impacted tank to the connected tank was observed in any test. The testing in this test type was very limited in scope and only the following general observations can be stated.

Upon comparing these test results with the previous baseline Standard Test results (Figure 14), it may be observed that the overpressures for the 1 ATM. tests were not affected by the external interconnect. The 1 inch diameter hose, 2 feet long, apparently was not of sufficient size to relieve the pulse pressure reaction in the main tank associated with the 1 ATM initial pressure condition. For the 2 ATM. tests there was some apparent affect of the interconnection on the peak overpressure. The times to reach peak overpressure were much longer for the 2 ATM. tests than for the 1 ATM. tests. The reason being that for the 1 ATM. tests the fuel/air mass ratio was near stoichiometric, which has short reaction times, and the 2 ATM. tests were near the lean limit, which has longer reaction times. With longer reaction times associated with the 2 ATM. tests the interconnect vented sufficient gases to affect the peak overpressure. To have this large of an affect it was felt that the vented gases were reactants rather than combustion products.

3. Compartmented Tank Test (Figure 1d and Tables III, IV, and V)

The Compartmented Tank Tests were begun with the primary intent of observing the frequency of combustion transfer between one tank compartment to an adjacent compartment. Such flame transfer is of great interest to aircraft safety because some integral wing tanks are compartmentized by the internal structure.

It was first reasoned that JP-4, having a vapor pressure large enough to produce flammable vapor concentrations, would support flame propagation between compartments, while JP-8 would produce little or no flame transfer. From the data to be presented, it will be shown that such a distinct difference between the two fuels did not occur. Even though the JP-8 had almost no vapor

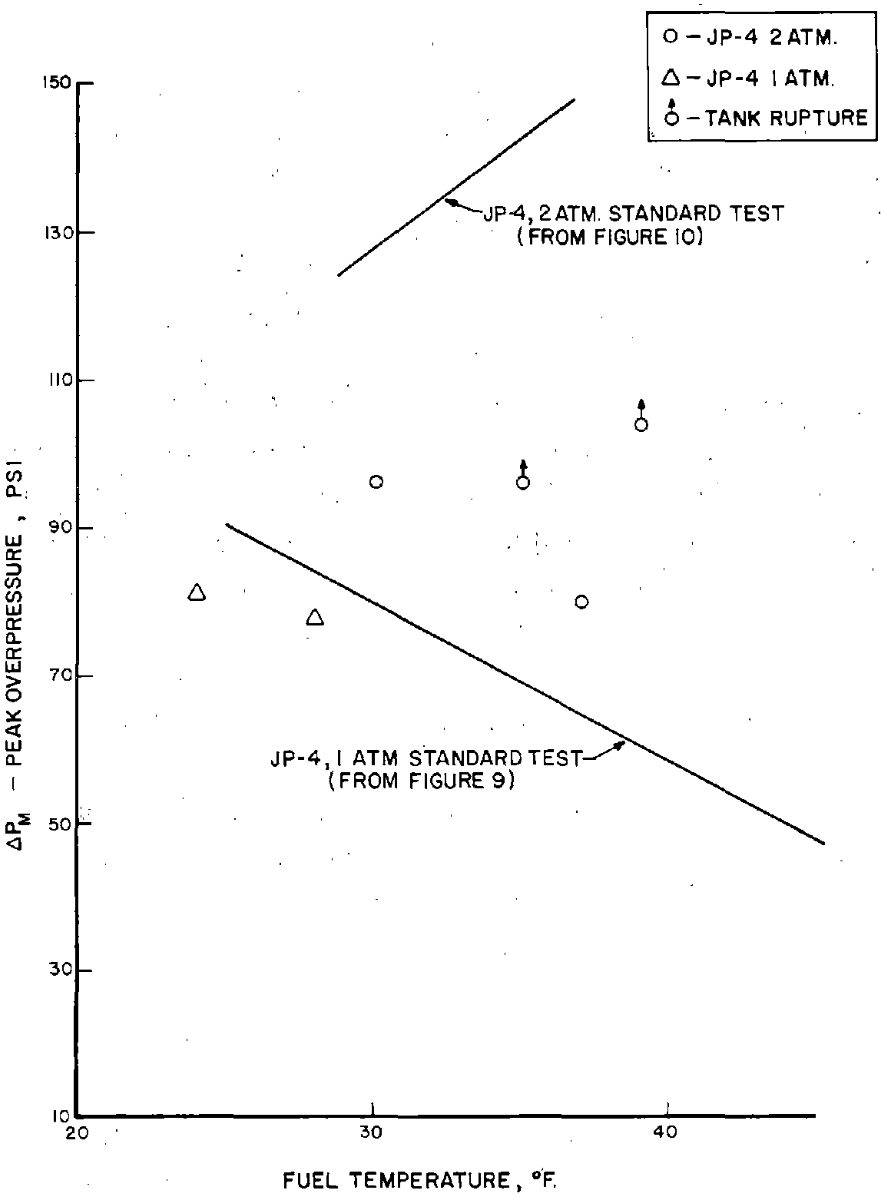

Figure 14. Overpressure Comparison for Standard Test and Externally Connected Tank Test

present in the tanks before the hit, combustion still took place and in several instances was propagated to the unpenetrated compartment.

An unanticipated result of tank compartmentation became overt early in the testing. The overpressure developed in the unpenetrated compartment sometimes was much larger than that in the hit compartment. Upon consideration of this result, it was felt that unburned gases were being forced into the unpenetrated compartment during the initial part of the combustion process in the hit compartment. This additional gas increased the pressure in the unpenetrated compartment so that when combustion was initiated in this compartment a higher than expected overpressure resulted. This transfer of gases should, as a consequence, decrease the expected overpressure in the hit compartment.

In order to determine if the high unpenetrated compartment overpressures were being caused by a gas transfer process as outlined above, the test series was increased to allow shots with propane. Propane, being all vapor at the test conditions, eliminated the possibility that fuel spray was being generated in the unpenetrated compartment thus causing the unusual overpressures. The same phenomena was observed with the propane as it had been with JP-4 and JP-8.

Figure 15, 16, and 17 give the overpressure ratios for both the main tank and connected tank as a function of fuel/air mass ratio for each of the three fuels, JP-4, JP-8, and propane. The calculated overpressure ratios resulting from the regression equation developed previously for the Standard Test series are presented in these three Figures for comparison.

Upon review of the results of the JP-4 tests as shown on Figure 15 it was observed that the main tank and connected tank overpressures are in general lower than the calculated value based on the Standard Test series. This result was as expected since it was thought that the only effect of adding the connected tank would be to provide an additional means for overpressure relief of the main tank. The combustion process in the main tank should, at least in the initial stages, be independent of the connected tank. Another result was that with F/A > 0.102 no combustion occurred in the connected tank during six tests. Below the fuel/air mass ratio of 0.102, eight of fifteen tests resulted in combustion transfer to the connected tank. The fact that combustion transfer

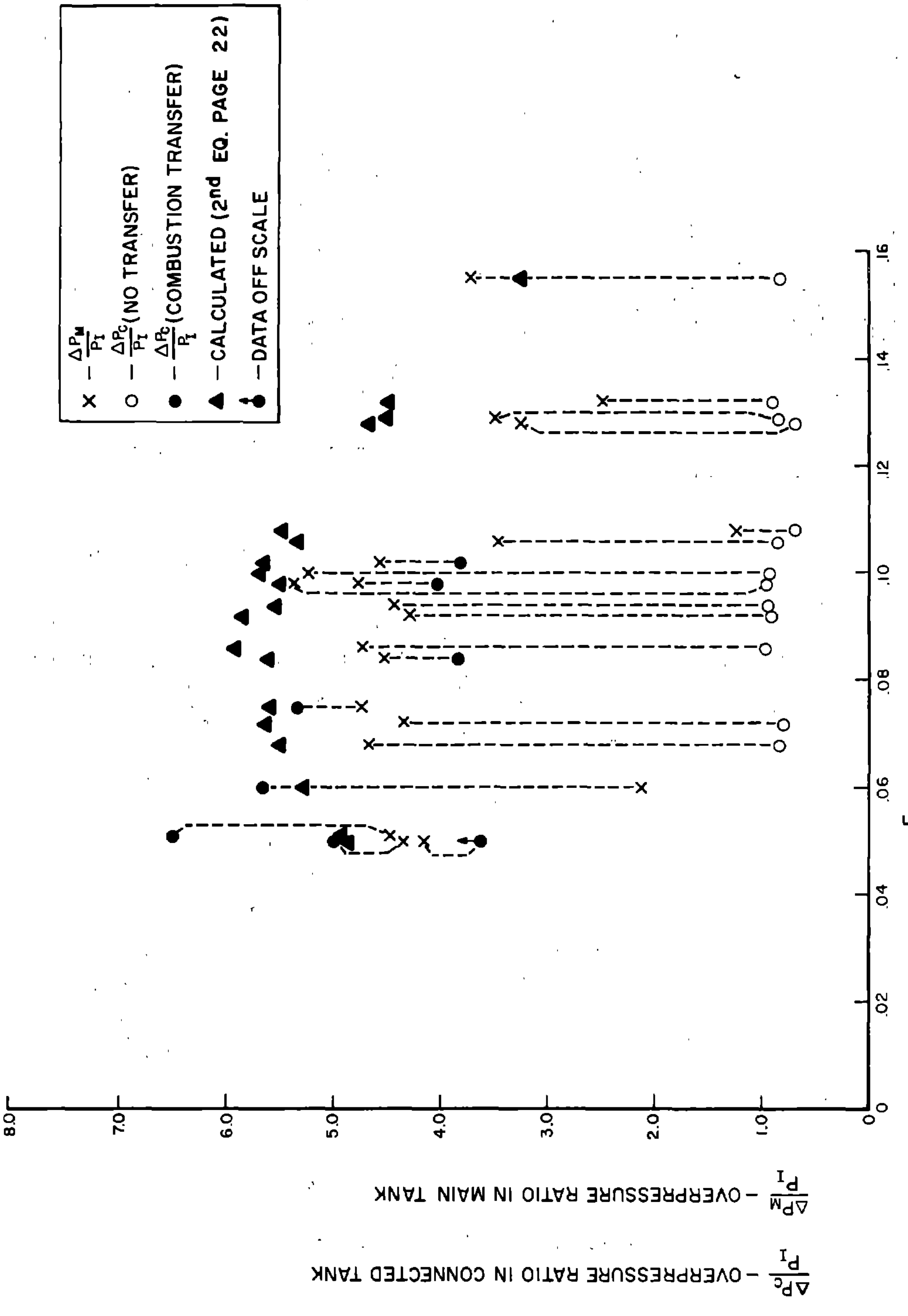

Figure 15. Overpressure Ratios Using JP-4 (Compartmented Tank Test)

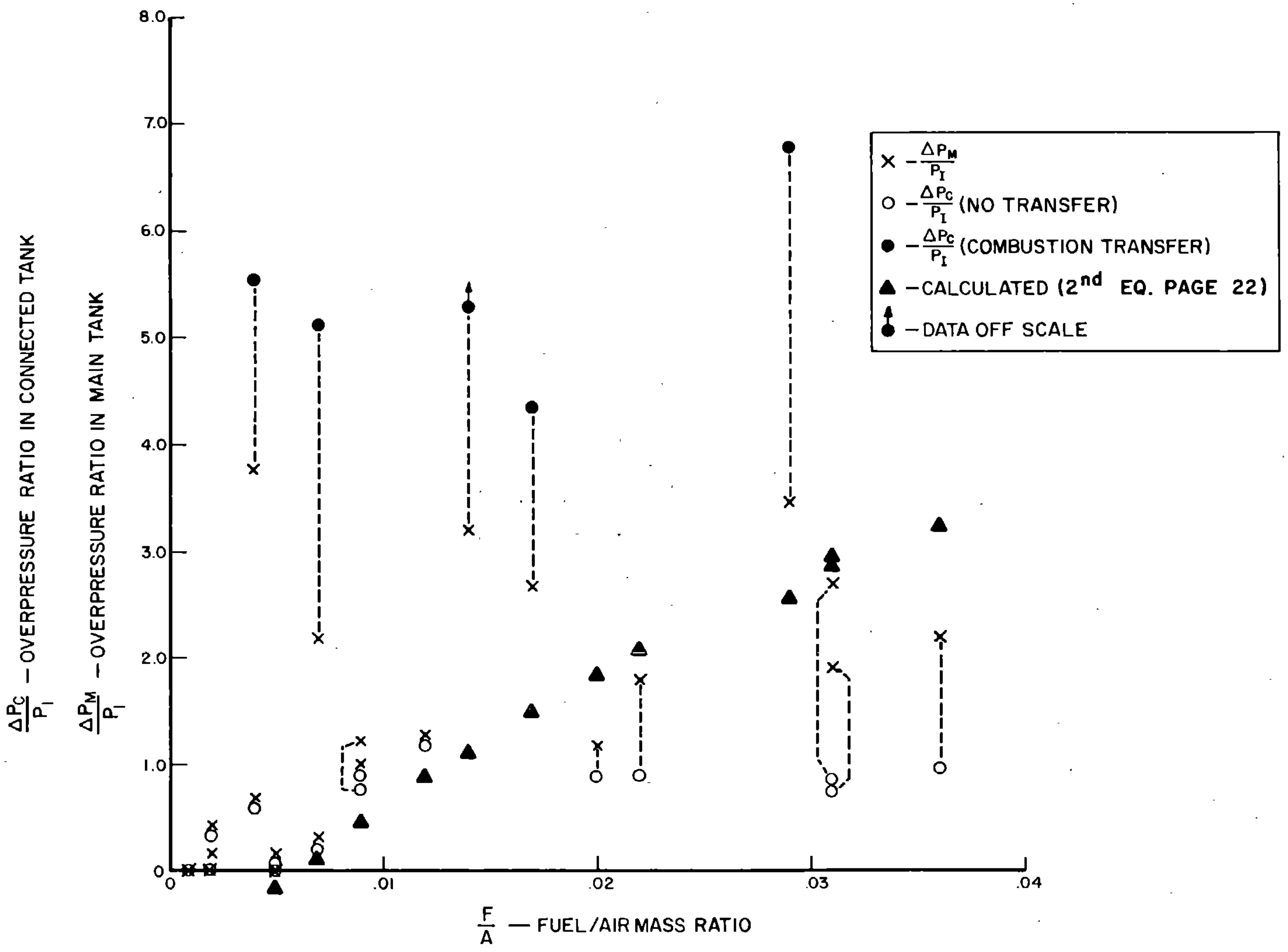

Figure 16. Overpressure Ratios Using JP-8 (Compartmented Tank Test)

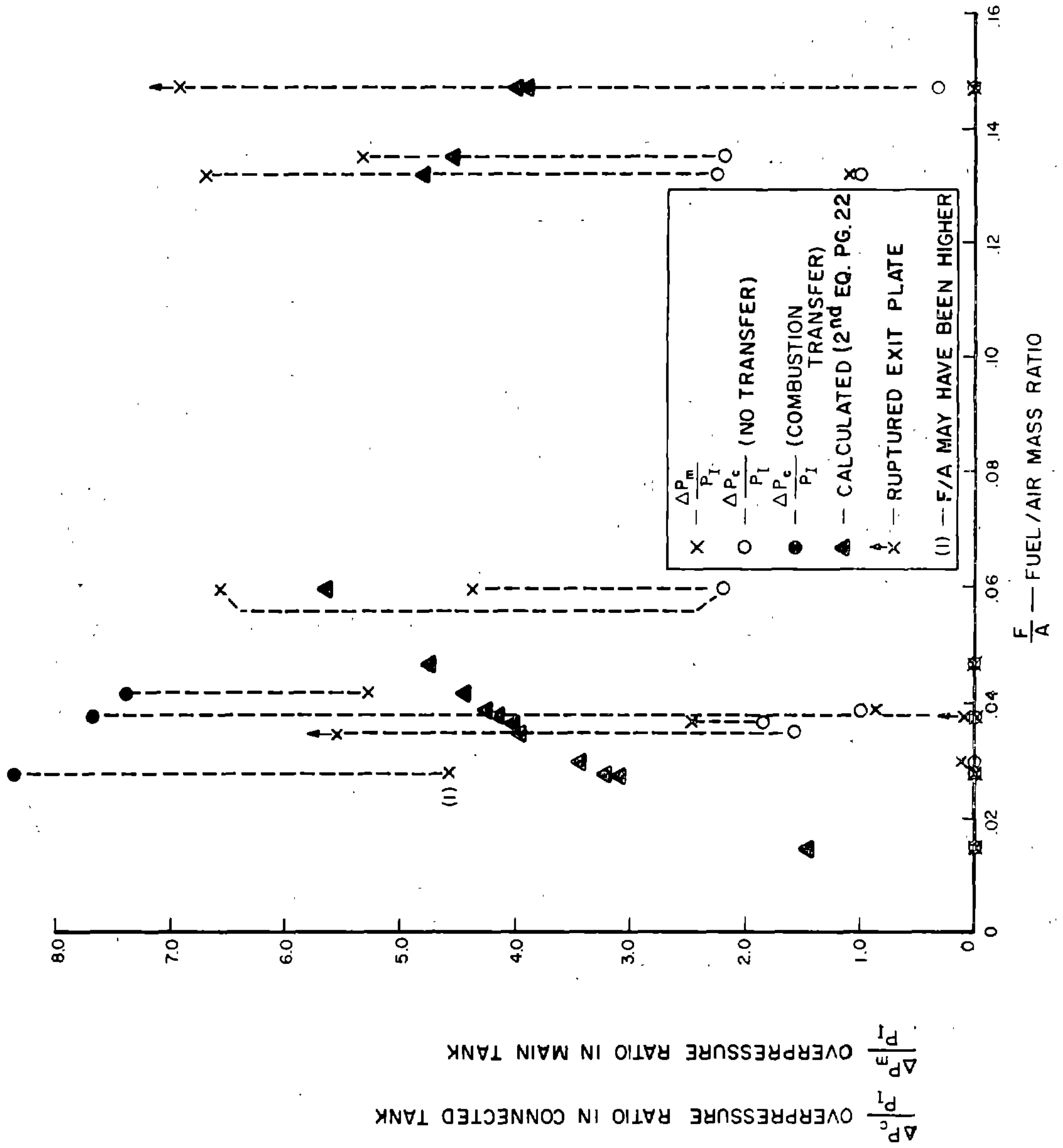

Figure 17. Overpressure Ratios Using Propane (Compartmented Tank Test)

did not occur during the six tests with F/A > 0.102 (all six tests were within the Standard Flammability Limits for Hydrocarbon of $0.03 \leq F/A \leq 0.28$) was highly unusual with the reason for the lack of occurrence unknown. It also should be noted that when combustion transfer did not occur the connected tank overpressure ratio, $\frac{\Delta P_C}{P_I}$, fell in the narrow range of 0.7 to 1.0. When combustion transfer occurred, about half the tests resulted in a higher overpressure in the connected tank than in the main tank.

The JP-8 tests as shown on Figure 16 also gave some interesting and unexpected results. When combustion transfer did not occur, the resulting overpressures agreed quite well with the calculated values.

For the five of the twenty one tests which resulted in combustion transfer into the connected tank, both the main tank and connected tank gave overpressures higher than expected. In addition, the overpressure in the connected tank was higher than in the main tank. Apparently there was an interaction between the two tanks which may have generated additional fuel spray and/or evaporation and therefore higher than expected overpressures. The transfer of unburned gases from the main tank to the connected tank cannot account for both tank pressures being higher than anticipated. In order to further investigate these unexpected results, eighteen tests were conducted with gaseous propane. The results are given on Figure 17. Again the results show combustion transfer occurring only at the lower F/A ratios and the connected tank pressure higher than the main tank when there was combustion transfer. Unfortunately, since no propane tests were conducted during the Standard Test series it cannot be proved that liquid spray was the reason for both tank pressures being higher than expected in the earlier JP-8 tests. Comparing the propane results with the calculated values based on the JP-4 and JP-8 Standard Test series there were some higher than expected pressures which leaves the possibility that some other phenomenon may be involved in addition to fuel spray.

The propane results clearly show that when no liquid fuel was involved and equilibrium existed, the lower flammability limit, F/A ≈ 0.03, as determined from Standard Laboratory Methods, was maintained.

Figure 18 gives the connected tank to main tank overpressure ratio for all the tests in the Compartmented Tank Test series. The following items may be observed.

a. At a F/A < 0.08 combustion transfer occurred in 13 out of 33 tests and the pressure ratio, $\frac{\Delta P_C}{\Delta P_M}$, was always greater than one, when combustion transfer occurred.

b. With $0.08 < F/A < 0.11$ combustion transfer occurred during 3 of 10 tests and $\frac{\Delta P_C}{\Delta P_M}$ was slightly less than one.

c. With $F/A > 0.11$ combustion transfer did not occur during eight tests.

d. Fuel lean reactions dominate the combustion transfer phenomena.

At least part of the reason for $\frac{\Delta P_C}{\Delta P_M} > 1$ at small F/A may be that lean reactions tend to have slower initial pressure rise rates and these slower rates, presumably, allow more gas to bleed into the connected compartment.

The combustion transfer phenomena between tanks is an important item for further investigation. It is believed that the phenomenon is highly dependent on tank configuration and results of this program are not directly applicable to an aircraft environment.

In this test series the method used for connecting the two tanks was typical of integral wing tanks, whereas the threat (vapor impact) and the configuration of the tank were typical for a fuselage tank. The results therefore should serve only as a departure point for additional analysis.

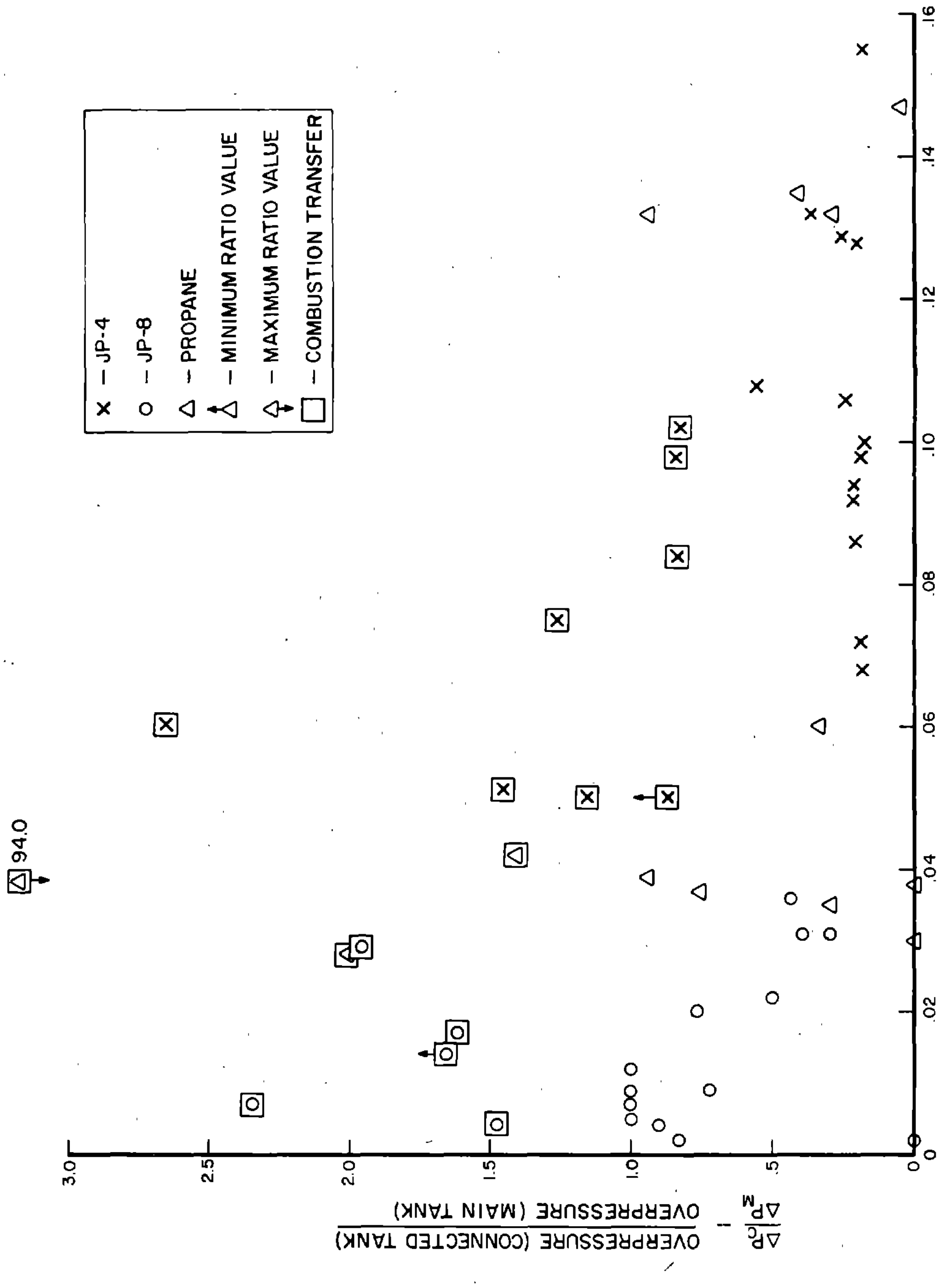

Figure 18. Connected Tank to Main Tank Overpressure Ratio

4. Fuel Level Test (Figure 1a & Table VI)

In this test series the fuel level was varied in order to investigate the possible influence that the distance between projectile trajectory and liquid-vapor interface (H_{TF}) could have on the reaction overpressure. It was expected that as the liquid surface approached the projectile trajectory greater amounts of fuel spray and/or vapor due to incendiary burning would be produced. It was felt that vapor generation due to incendiary burning was a second order effect and not the primary mechanism for adding fuel to the ullage. The same size entrance plate (D_E = 8 inches and X_E = 0.125") that was used in the Standard Tests was also used in this series. Since the energy absorbed by the tank during entrance plate penetration and the resulting fuel spray may also be a function of the fuel level it was impossible to ascertain whether the dominant fuel spray was produced by impact or by aerodynamic forces caused by the bullet while passing over the liquid surface.

Figure 19 presents the results of this series (H_{TF} = 4.5 inches and 1 inch) and the Standard Test (H_{TF} = 8 inches) for comparison.

In order to assess the influence of H_{TF} on overpressure the regression equation

$$\frac{\Delta P_M}{P_I} = 52.3\ F/A - 245.2\ (F/A)^2 + 8.94\ (F/A\ H_{TF}) - 5.88$$

$$(F/A\ H_{TF})^2 - 0.14\ H_{TF} + 0.874 \text{ with } R_c = 0.9711$$

was developed for tests with $F/A < 0.105$. From the plots of this equation on Figure 19 it may be observed that for very lean fuel/air mass ratios ($F/A < 0.016$) a decrease in H_{TF} results in an increase in the overpressure ratio. The normal lean flammability limit is approximately $F/A = 0.03$, therefore, any reaction must be as a result of conditions generated by the projectile. Since for $F/A < 0.016$ $\frac{\Delta P_M}{P_I}$ was greater for H_{TF} of 1 inch and 4.5 inches compared to H_{TF} of 8 inches it was concluded that more interaction between the projectile and the liquid fuel occurred at the smaller values of H_{TF}. It should be noted that the regression equation served only as

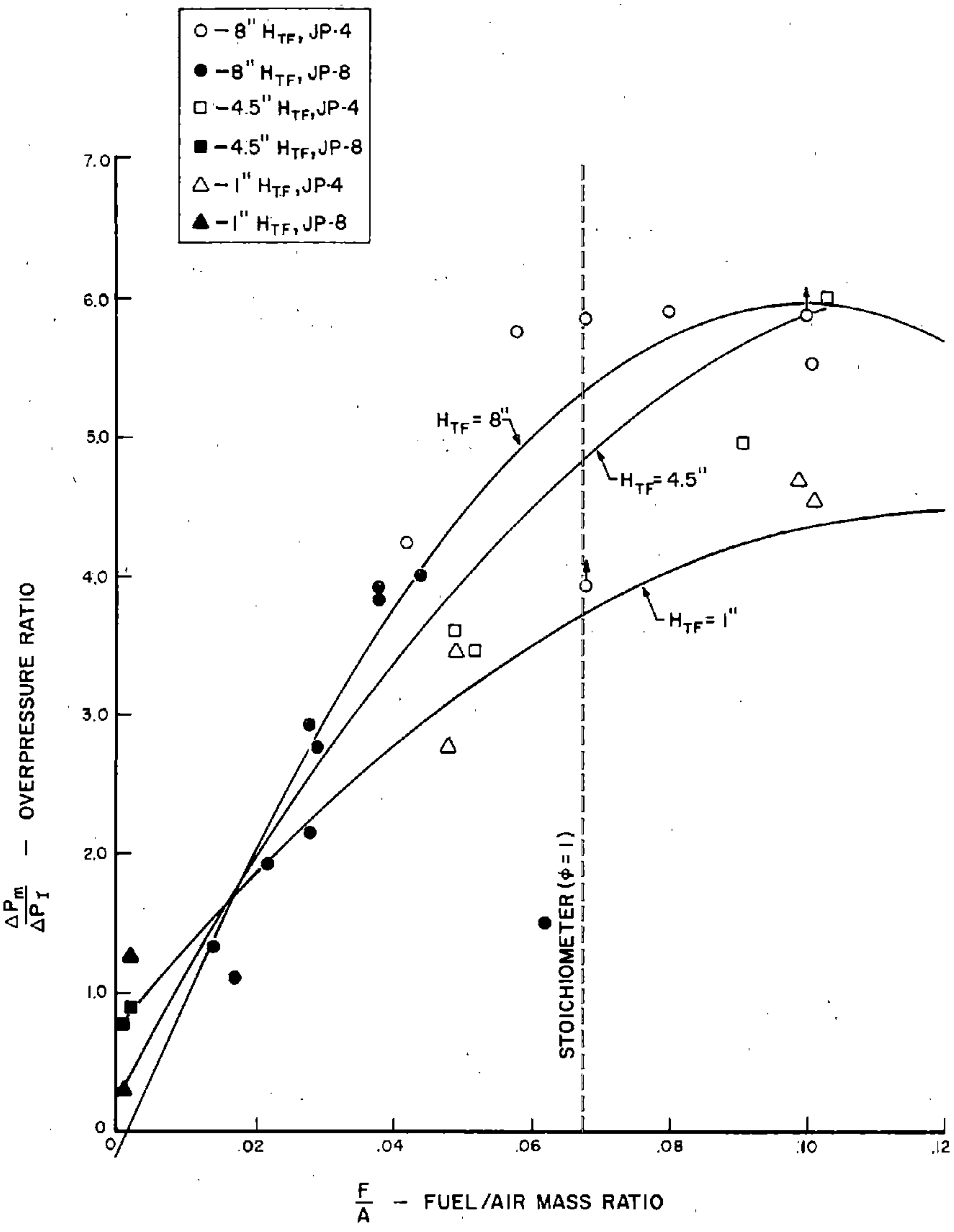

Figure 19. Overpressure Ratio for Various Fuel Levels

a tool for plotting the three curves of Figure 19 and was not based on a theoretical insight into the interaction between F/A and H_{TF}.

In the normal flammability region (F/A > 0.03) it may be observed that $\frac{\Delta P_M}{P_I}$ decreased as H_{TF} decreased. The reason for this is not completely known. However, part of the answer may be that the fuel spray and/or incendiary generated vapor together with the initial fuel vapor created a local fuel rich region which was either slow burning or nonflammable causing a lower than normal overpressure. In order to evaluate this Figure 20 was developed which gives the time to ΔP_M as a function of F/A. No clear trend was evident although minimum times occurred near stoichiometric as would be expected. Another factor to be considered was the release of dissolved oxygen from the fuel due to agitation caused by the projectile. It is questionable whether this additional oxygen can be released in sufficient time to affect the reaction. The foregoing factors could not be completely explained due to the limited amount of test data.

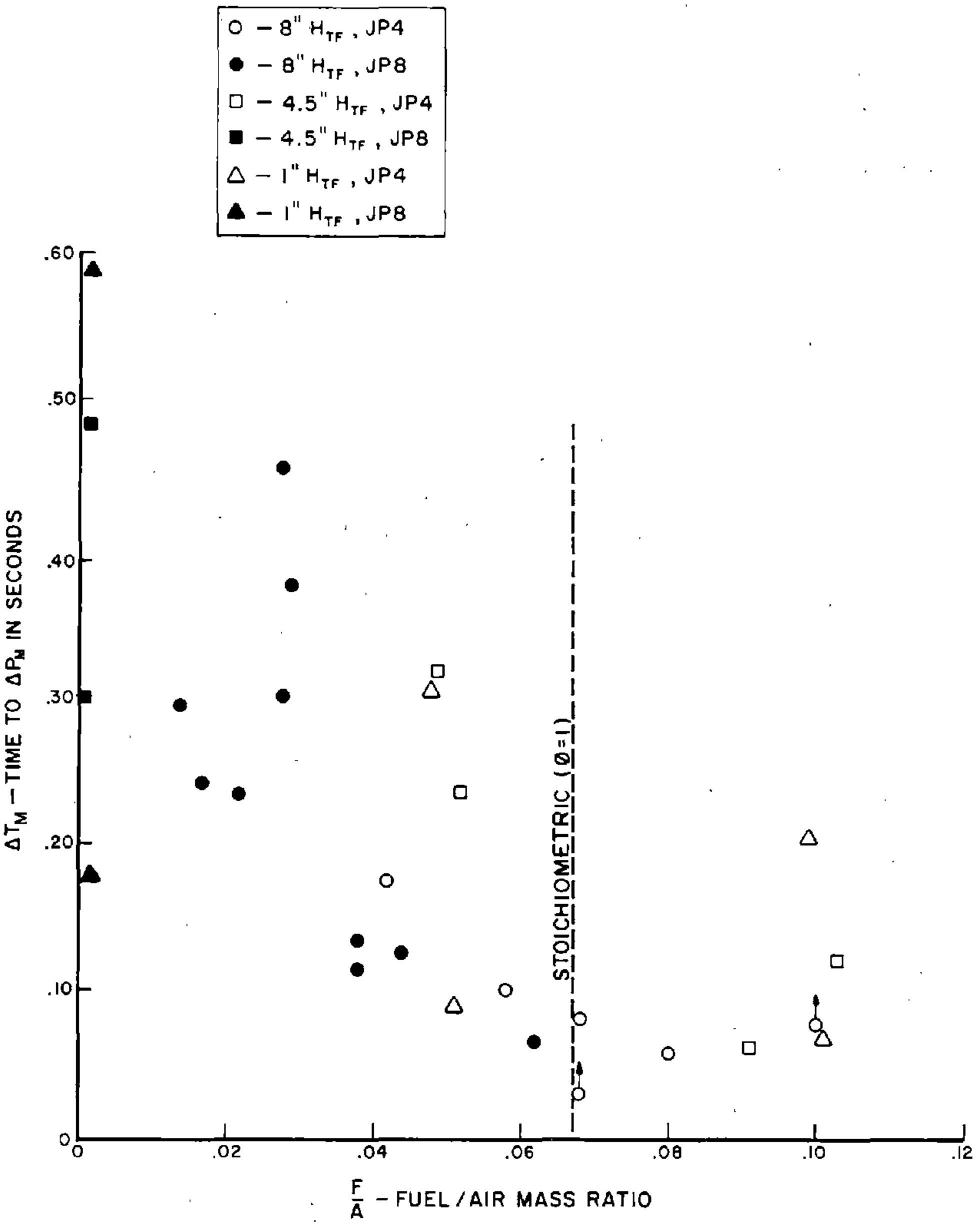

Figure 20. Time to ΔP_M for Various Fuel Levels (Lean Reactions)

5. Entrance Plate Test (Figure 1a & Table VII)

This test series considered the possibility that various entrance plate factors might affect the amount of fuel spray produced upon projectile impact. Only tests where extremely lean initial conditions existed were investigated ($F/A \leq 0.002$) so that increased reaction overpressure would indicate an increase in fuel spray. Increasing the diameter of the entrance plate should allow more deflection upon impact and more energy transfer to the liquid for a given fuel level. This assumes liquid contact with the entrance plate or $D_E > 2H_{TF}$. Increasing the thickness of the entrance plate would have two possible effects. First, more energy would be absorbed by the plate during penetration of the projectile. Second, it is a known fact that plate thickness affects incendiary functioning and therefore the ignition source. From film data of the shots it was seen that the 0.125 inch plate causes the incendiary to burn primarily in the region of the exit plate. The 0.250 inch plate caused burning near the entrance plate. The 0.060 inch plates failed to ignite the incendiary within the tank. Besides affecting the region of burning, the entrance plate thickness could possibly govern the amount of incendiary that is burned within the tank. These effects were considered to have little effect on reaction overpressures for the 0.125 inch and 0.250 inch plates used in this series.

The trajectory path to fuel level distance, H_{TF}, was also varied in the test series. Changes in H_{TF} could have two possible effects. First, the amount of fuel in contact with the entrance plate would change. Second, the aerodynamics of the projectile in the ullage may interact with the liquid/vapor interface producing more fuel spray as H_{TF} is reduced.

Six shots were conducted during the Entrance Plate Test series. Two shots (221 and 226) provided no useful information since the entrance plate thickness (0.060 inch) was insufficient to activate the projectile incendiary. The remaining tests (222 through 225) and tests 217 through 220 of the Fuel Level test series are compared on Figure 21. As noted previously only $F/A \leq 0.002$ were considered and the major cause for an increase in reaction overpressure should be due to an increase in the amount of fuel spray produced by the projectile. It should be noted that to have any type of reaction with $F/A \leq 0.002$ requires some fuel spray. Before discussing the test results, it should be realized that

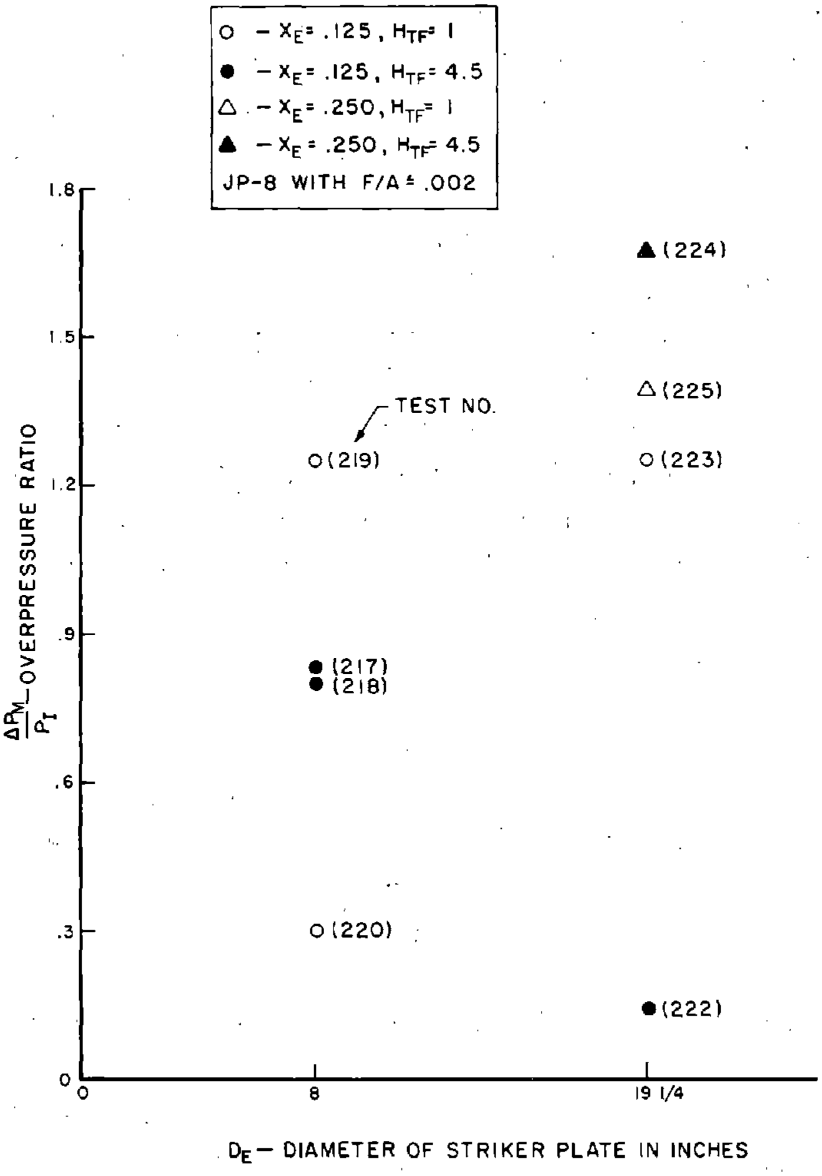

Figure 21. Entrance Plate Test Results

no positive statements are possible considering the limited amount of data available for the several parameters which were investigated. No overwhelming gross effects were observed, however, the following items should be considered in the design of a more detailed experiment.

a. For tests 217 and 218, fuel was not in contact with the entrance plate, yet overpressures were observed. Possible cause being spray generation from aerodynamics of projectile or energy transfer from exit plate to fuel.

b. Upon comparing tests 219 and 220 with 217 and 218 the effect of H_{TF} is unknown.

c. Comparing test 222 with 223 and 224 with 225 the effect of H_{TF} is again questionable.

d. Upon comparing tests 224 and 225 with a 0.250 inch entrance plate with the remaining tests which utilized a 0.125 inch plate, the former resulted in higher overpressures. Possible cause being more fuel spray resulting from the thicker plate.

The major result of this test series was that ullage reactions occurred even at very low initial fuel/air ratios when subjected to horizontal gunfire.

6. Exit Dry Bay Test (Figure 1b and Table VIII)

Six shots which were entirely exploratory in nature were conducted with a 19 1/4 inches diameter times 4 inches long dry bay attached to the exit side of the standard tank. The results are given on Figure 22. The overpressure ratios for both the main tank and exit dry bay are shown as a function of fuel/air mass ratio on this Figure. For comparison shots 207 through 210 of the Fuel Level Test series with the standard tank configuration are given. All shots were conducted at comparable initial conditions with the exception of Tests 215 and 216. Test 215 had 4.5 inches of fuel and Test 216 had 8 inches of fuel. Due to equipment malfunction no dry bay pressures were recorded during these two tests. All other points had only 1 inch of fuel.

It is obvious from the test results that significant overpressures may be generated in an exit dry bay with vapor phase projectile hits. Fuel spray is apparently carried into the dry bay by the wake of the projectile and the ignition is either by the incendiary of the API projectile or hot gases from the reaction in the main tank. Upon comparing the main tank overpressures from the Fuel Level Test series which utilized the standard tank configuration and no dry bay with the standard tank and dry bay results, a possible trend may be observed. The main tank overpressures with an exit dry bay were higher than without the dry bay. This was particularly true at the lower fuel/air mass ratios. The reason for this is not known, however, at least part of the reason may involve the restriction on pressure relief due to the reaction in the dry bay.

7. Combination and Special Test (Table IX)

Table IX gives the results of eight special shots that were conducted in addition to the six basic test types. The first two tests listed, 101 and 119, are Standard Tests (Figure 1a) except that the procedure for achieving equilibrium vapor concentration was not used. This would tend to render the JP-4 Fuel/air ratio leaner than otherwise expected based on equilibrium conditions. Tests 153 and 154 were also nonequilibrium tests to assess the effect of fuel tank venting. For these tests the regular procedure for Compartmented Tank Tests (Figure 1d) was used with the initial ullage pressure at 30 psia. Immediately before firing (approximately 15 seconds) the ullage was vented to atmosphere

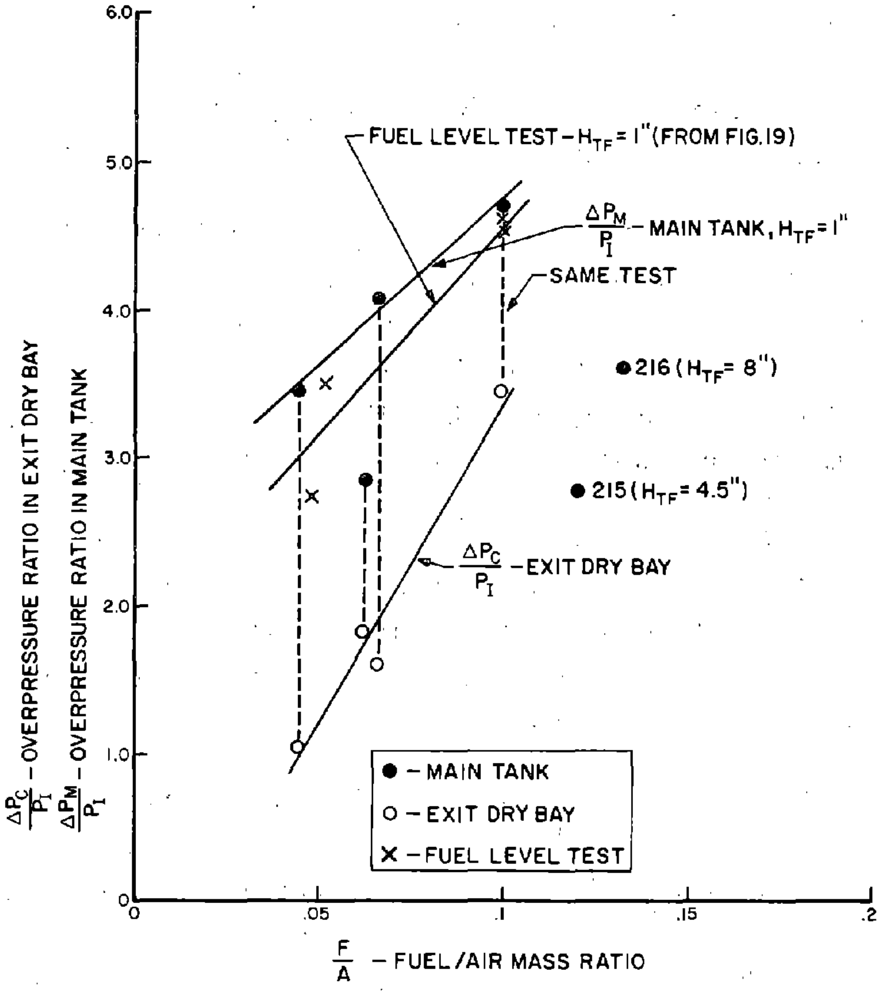

Figure 22. Overpressure Ratio for Exit Dry Bay Test with JP-4

so that the pressure at time of impact was atmospheric. It was felt that this venting procedure would tend to render the JP-4 fuel/air mixture leaner than that calculated for equilibrium conditions at one atmosphere. Test 230 was conducted with the 19 1/4 inches dia. X 0.125 inch thick entrance plate and tank configuration as shown on Figure 1a. The uniqueness of this test with JP-8 was that the fuel spray system was left running during the shot. The fuel spray should tend to drive the fuel/air ratio rich.

Comparing the results of the foregoing tests with equilibrium tests the following observations are offered:

a. Test 101 - With a JP-4 fuel temperature of 43°F and equilibrium conditions an overpressure of 54 PSI would be expected based on the Standard Test results as shown in Figure 9. An actual overpressure of 84 PSI was recorded during test 101 which corresponds to a leaner fuel-air ratio or an equivalent equilibrium fuel temperature of about 28°F. This is a 15°F depression in temperature (fuel/air mass ratio) due to nonequilibrium conditions.

b. Test 119 - This nonequilibrium test with JP-4 at a fuel temperature of 85°F resulted in no reaction. Assuming a 15°F temperature depression due to nonequilibrium gives an apparent fuel temperature of 70°F. Comparing this temperature with the JP-4 rich limit of about 60°F as given in Figure 9 a reaction would not be expected, therefore the results of tests 101 and 119 agree.

c. Tests 153 and 154 - These nonequilibrium tests with JP-4 were compared with the equilibrium test results for the compartmented tank as given in Figure 15. No difference between the two sets of results were observed.

Test 230 - This nonequilibrium test with JP-8 at a fuel temperature of 30°F can not be compared directly to any other equilibrium test. An overall assessment of the JP-8 equilibrium tests indicates an expected overpressure of less than 20 PSI at 30°F. Due to the fact that the fuel spray system was active during this test, an overpressure of 33 PSI was recorded.

Tests 227, 228, 229 were a combination of the Entrance Plate Test and Exit Dry Bay Test with JP-8 fuel at equilibrium. In other words, the configuration shown on Figure 1b was used with the regular entrance plate (8 inches dia. X 0.125 inch thick) replaced with a 19 1/4 inches dia. X 0.090 inch thick entrance plate for test 227 and a 19 1/4 inches dia. X 0.125 inch thick plate for tests 228 and 229. The fuel depth was also varied. These tests were entirely exploratory with no unique results observed.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were established from the test program.

1. The standard rich limit was maintained for JP-4 fuel under equilibrium conditions.

2. The standard lean limit was extended for JP-8 fuel and the resulting overpressure decreased with decreasing temperature.

3. A 1 inch diameter hose, 2 feet long, prevented combustion transfer between two tanks with JP-4 fuel. This hose did not affect the reaction overpressure in the main tank at 1 ATM initial pressure but did lower the overpressure for the 2 ATM initial pressure tests.

4. For compartmented fuel tanks (wall interconnect) combustion is more likely to be transferred from one compartment to another with fuel vapor lean ullages than with rich ullages.

5. A very lean fuel vapor ullage with liquid present does not prevent combustion transfer between compartmented fuel tanks (wall interconnect).

6. Due to unburned gas transfer from the hit compartment to the wall interconnected compartment, a higher than expected overpressure may result if combustion transfer occurs. During some tests higher than expected overpressure occurred in both compartments.

7. The distance between the projectile trajectory and liquid-vapor interface (H_{TF}) has an effect on the reaction overpressure. At very low fuel/air ratios the overpressure increased as H_{TF} decreased. With $F/A > 0.016$ the overpressure decreased as H_{TF} decreased.

8. Significant overpressures may be generated in an exit dry bay with a vapor phase projectile hit.

9. Nonequilibrium conditions will alter the expected results based on equilibrium conditions.

When applying the above conclusions to the safety evaluation of JP-4 and JP-8, one must bear in mind that volatility is the primary difference between the two fuels. JP-4 has a vapor pressure approximately 50 times larger than JP-8. This means that under identical conditions a fuel tank containing JP-4 will probably have 30 times as much fuel vapor mass in the ullage as a tank containing JP-8. In addition, the bulk of the testing was conducted at equilibrium initial conditions. If equilibrium conditions could be relied upon in an aircraft fuel tank the comparison of the two fuels is simply a question of knowledge of fuel tank temperature probability. Since an aircraft fuel tank is in a high nonequilibrium state, additional assessment is required. Projectile dynamics and aircraft slosh and vibration tend to make the ullage rich. Venting tends to render the ullage lean. The combined effect of these opposing factors has never been investigated in a single test program. It is believed, however, that venting is dominant. If this is true, JP-8 would be the preferred fuel for the type of threat investigated in this program. It is therefore recommended that further investigation be initiated to study these combined effects in detail as well as those factors which were not completely explainable as discussed in the report.

APPENDIX I

TABLES

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TABLE I

STANDARD TEST

TEST NR.	FUEL	T_L °F	T_U °F	T_W °F	D_E INCH	X_E INCH	D_F INCH	H_{TF} INCH	P_I PSIA	F/A	ΔP_M PSI	ΔT_M SECOND	REMARKS
102	JP-4	51	48	49	8	0.125	1 1/2	8	14.3	.162	46	.45	
103	"	63	56	56	"	"	"	"	14.3	.218	1	NA	
104	"	65	59	59	"	"	"	"	14.3	.227	1	NA	
105	"	59	55	55	"	"	"	"	14.3	.196	1	NA	
106	"	36	32	30	"	"	"	"	14.3	.108	1	NA	
107	"	37	37	35	"	"	"	"	14.3	.113	0	NA	
108	"	37	35	35	"	"	"	"	14.3	.113	56	.052	
109	"	44	41	41	"	"	"	"	14.3	.133	43	.117	
110	"	47	45	44	"	"	"	"	14.3	.147	42	.175	
111	"	42	41	42	"	"	"	"	14.3	.128	57	.094	
113	"	63	63	63	"	"	"	"	14.3	.218	1	NA	
120	"	25	22	22	"	"	"	"	14.4	.080	85	.058	
124	"	34	33	33	"	"	"	"	14.5	.101	80	UKN	
112	"	47	45	45	"	"	"	"	30	.068	118	.030	RUPTURED EXIT PLATE
114	"	63	60	61	"	"	"	"	30	.100	176	.077	RUPTURED EXIT PLATE
115	"	77	73	72	"	"	"	"	30	.139	113	.110	
116	"	89	87	90	"	"	"	"	30	.185	103	.375	
117	"	105	100	108	"	"	"	"	30	.269	1	NA	
118	"	101	98	100	"	"	"	"	30	.244	1	NA	
121	"	29	28	28	"	"	"	"	30	.042	127	.175	

TABLE I (CONCLUDED)

TEST NR.	FUEL	T_L °F	T_U °F	T_W °F	D_E INCH	X_E INCH	D_F INCH	H_{TF} INCH	P_I PSIA	F/A	ΔP_M PSI	ΔT_M SECOND	REMARKS
122	JP-4	32	31	31	8	0.125	1 1/2	8	20	.068	117	.081	
123	"	34	32	32	"	"	"	"	25	.058	144	.103	
125	JP-8 105° F. P.	112	112	112	"	"	"	"	14.5	.044	58	.125	
127	"	106	112	112	"	"	"	"	14.4	.038	55	.114	
128	"	98	99	100	"	"	"	"	"	.029	40	.375	
129	"	97	95	96	"	"	"	"	"	.028	42	.300	
130	"	106	97	100	"	"	"	"	"	.038	56	.133	
131	"	96	90	100	"	"	"	"	"	.028	31	.454	
132	"	88	84	85	"	"	"	"	"	.022	28	.233	
133	"	80	77	77	"	"	"	"	"	.017	16	.242	
134	"	74	72	71	"	"	"	"	"	.014	19	.293	
126	"	111	114	114	"	"	"	"	10	.062	15	.066	

TABLE II

EXTERNALLY CONNECTED TANK TEST

TEST NR.	FUEL	T_L °F	T_U °F	T_W °F	D_E INCH	X_E INCH	D_F INCH	H_{TF} INCH	P_I PSIA	F/A	P_M PSI	T_M SECOND	ΔP_C PSI	ΔT_C SECOND	δP_C PSI	REMARKS
135	JP-4	24	24	24	8	0.125	1 1/2	8	14.5	.076	81	.062	5	.600	5	
136	"	28	28	28	"	"	"	"	14.5	.085	78	.044	8	.780	8	
137	"	30	30	30	"	"	"	"	30	.043	96	.273	15	.932	15	
138	"	35	35	35	"	"	"	"	30	.049	96	.118	3	.140	3	RUPTURED EXIT PLATE
139	"	37	36	34	"	"	"	"	30	.052	80	.682	19	1.57	19	
140	"	39	39	31	8	.125	"	"	30	.045	104	.14	4	.174	4	RUPTURED EXIT PLATE

TABLE III

COMPARTMENTED TANK TEST USING JP-4

TEST NR.	FUEL	T_L °F	T_U °F	T_W °F	D_F INCH	H_{TF} INCH	P_I PSIA	F/A	ΔP_M PSI	ΔT_M SECOND	ΔP_C PSI	ΔT_C SECOND	δP_C PSI	REMARKS
141	JP-4	28	26	24	1.5	8	14.4	.086	68	.050	14	.120	14	
142	"	30	29	29	1.5	8	14.4	.092	62	.040	13	.116	13	
145	"	49	47	47	1.5	8	14.2	.155	53	.065	12	.320	12	
194	"	34	32	32	1.5	8	14.4	.102	66	.061	55	.074	5	COMBUSTION TRANSFER
195	"	36	35	35	1.5	8	14.4	.108	18	1.32	10	.536	10	
199	"	44	44	43	1.5	8	14.4	.132	36	.362	13	1.29	13	
200	"	43	43	42	1.5	8	14.4	.128	47	.067	10	.876	10	
143	"	32	29	30	1.5	8	27	.050	112	.179	98+*	.172	12	*READOUT OFF SCALE COMB. TRANS.
144	"	35	32	32	1.5	8	29	.050	126	.086	145	.106	5	COMB. TRANS.
146	"	51	50	50	1.5	8	30	.075	142	.071	160	.096	7	
147	"	55	54	53	1.5	8	23.5	.106	82	.035	20	.366	20	
148	"	56	54	54	1.5	8	20	.129	70	.041	17	.316	17	
149	"	56	54	54	1.5	8	26	.098	124	.099	105	.161	10	COMB. TRANS.
150	"	56	53	54	1.5	8	26	.098	140	.056	25	.280	25	
151	"	57	56	56	1.5	8	27.5	.094	122	.069	26	.360	26	
152	"	56	56	56	1.5	8	30	.084	136	.050	115	.055	10	COMB. TRANS.
196	"	36	34	35	1.5	8	30	.051	134	.220	195	.228	14	COMB. TRANS.
197	"	43	41	41	1.5	8	25	.072	108	.044	20	.160	20	
198	"	37	41	41	1.5	8	16	.100	84	.051	15	.092	15	
201	"	43	43	43	1.5	8	30	.060	64	.110	170	.082	5	COMB. TRANS.
202	"	47	47	47	1.5	8	30	.068	140	.056	25	.280	25	

TABLE IV

COMPARTMENTED TANK TEST USING JP-8, 118°F FLASH POINT

TEST NR.	FUEL	T_L °F	T_U °F	T_W °F	D_F INCH	H_{TF} INCH	P_I PSIA	F/A	ΔP_M PSI	ΔT_M SECOND	ΔP_C PSI	ΔT_C SECOND	δP_C PSI	REMARKS
155	JP-8	124	124	124	1.5	8	14.5	.036	32	.263	14	.448	14	
156	"	104	104	104	"	"	14.5	.020	17	.190	13	.440	13	
157	"	98	94	94	"	"	14.5	.017	39	.259	63	.204	12	COMBUSTION TRANSFER
159	"	88	84	84	"	"	14.5	.012	18	1.070	18	1.160	18	
161	"	80	80	79	"	"	14.5	.009	14	.860	14	.946	14	
163	"	119	116	114	"	"	14.5	.031	28	.055	11	.300	11	
184	"	56	63	65	"	"	14.6	.004	55	.357	81	.440	6	COMB. TRANS.
185	"	74	80	80	"	"	14.6	.007	32	.437	75	514	10	COMB. TRANS.
186	"	80	87	86	"	"	14.6	.009	18	.265	13	1.170	13	
188	"	60	63	62	"	"	14.5	.005	2	–	2	–	2	
189	"	55	55	54	"	"	14.5	.004	10	.480	9	.440	9	
190	"	33	30	30	"	"	14.4	.002	6	.444	5	.444	5	
193	"	32	30	30	"	"	14.4	.002	2.5	.274	0	0	0	
158	"	95	92	94	"	"	30	.007	8	.340	8	.456	8	
160	"	94	88	88	"	"	10	.022	18	.154	9	.380	9	
162	"	143	142	141	"	"	30	.029	104	.404	204	.422	12	COMB. TRANS.
164	"	106	103	103	"	"	10	.031	27	.064	8	.124	8	
165	"	104	96	96	"	"	20	.014	64	.420	106+*	.364	12	*READING OFF SCALE COMB. TRANS.
187	"	71	74	72	"	"	20	.005	0	0	0	0		
191	"	33	30	30	"	"	12	.002	0	0	0	0	0	
192	"	33	30	30	1.5	"	18.5	.001	0	0	0	0	0	

TABLE V

COMPARTMENTED TANK TEST USING PROPANE

TEST NR.	FUEL	VOL. %	T_U °F	P_I PSIA	F/A	ΔP_M PSI	ΔT_M SECOND	ΔP_C PSI	ΔT_C SECOND	δP_C PSI	REMARKS
166	C_3H_8	2.23	8	14.6	.035	81	.045	23	.188	23	
167	"	1.83*	8	14.6	.028	67	.779	131	.826	10	COMB. TRANS. *LIQUID C_3H_8 MAY HAVE LEAKED INTO TANK
168	"	1.00	13	14.6	.015	0	0	0	0	0	
169	"	1.93	10	14.6	.030	2	—	0	0	0	
170	"	2.38	11	14.6	.037	36	.085	27	.240	27	
171	"	<3.80	12	14.6	<.060	64	.055	32	.220	32	
172	"	3.80	14	14.6	.060	96	.036	32	.196	32	
173	"	8.15	22	14.6	.135	78	.063	32	.208	32	
178	"	8.8	10	14.6	.147	0	0	0	0	0	
179	"	8.0	10	14.6	.132	16	.430	15	.512	15	
174	"	1.82	23	30	.028	0	0	0	0	0	
175	"	2.41	20	24.5	.038	> 2	> .500	188	.640	3	COMB. TRANS. RUPTURED EXIT
176	"	2.41	22	25	.038	1	—	0	0	0	
177	"	8.8	20	22.5	.147	156	.029	7.5	.050	7.5	RUPTURED EXIT
180	"	8.0	13	20	.132	134	.039	45	.212	45	
181	"	2.5	21	18	.039	16	.570	15	.584	15	
182	"	2.67	21	25	.042	132	.140	185	.478	5	COMB. TRANS.
183	"	3.00	28	25	.047	0	0	0	0	0	

TABLE VI

FUEL LEVEL TEST

TEST NR.	FUEL	T_L °F	T_U °F	T_W °F	D_E INCH	X_E INCH	D_F INCH	H_{TF} INCH	P_I PSIA	F/A	ΔP_M PSI	ΔT_M SECOND	REMARKS
203	JP-4	30	28	28	8	0.125	5	4.5	14.5	.091	72	.061	
204	"	33	28	28	"	"	5	4.5	27	.052	94	.235	
205	"	35	34	34	"	"	5	4.5	30	.049	108	.317	
206	"	35	36	36	"	"	5	4.5	14.5	.103	87	.120	
207	"	33	32	32	"	"	8.5	1	14.5	.099	68	.208	
208	"	34	32	32	"	"	8.5	1	30	.048	83	.313	
209	"	36	36	36	"	"	8.5	1	30	.051	105	.088	
210	"	34	36	36	"	"	8.5	1	14.5	.101	66	.073	
217	JP-8 (118°F.P.)	41	41	41	"	"	5	4.5	14.4	.002	12	.483	
218	"	46	44	44	"	"	5	4.5	30	.001	24	.298	
219	"	42	42	42	"	"	8.5	1	14.4	.002	18	.586	
220	"	40	40	40	"	"	8.5	1	30	.001	9	.176	

TABLE VII

ENTRANCE PLATE TEST

TEST NR.	FUEL	T_L °F	T_U °F	T_W °F	D_E INCH	X_E INCH	D_F INCH	H_{TF} INCH	P_I PSIA	F/A	ΔP_M PSI	ΔT_M SECOND	REMARKS
221	JP-8 (118° F. P.)	40	40	40	19 1/4	0.060	5	4.5	14.4	.002	0	0	NO INCENDIARY FUNCTION
222	"	38	38	38	19 1/4	0.125	5	4.5	"	.002	2	-	
223	"	40	40	39	19 1/4	0.125	8.5	1	"	.002	18	.235	
224	"	40	40	40	19 1/4	0.250	5	4.5	"	.002	24	.244	
225	"	28	28	28	19 1/4	0.250	8.5	1	"	.001	20	.256	
226	"	28	28	28	19 1/4	0.060	8.5	1	14.5	.001	0	0	NO INCENDIARY FUNCTION

TABLE VIII

EXIT DRY BAY TEST

TEST NR.	FUEL	T_L °F	T_U °F	T_W °F	D_E INCH	X_E INCH	D_F INCH	H_{TF} INCH	P_I PSIA	F/A	ΔP_M PSI	ΔT_M SECOND	ΔP_C PSI	ΔT_C SECOND	δP_C PSI	REMARKS
211	JP-4	33	33	34	8	0.125	8.5	1	14.5	.099	68	.066	50	.056	8	
212	"	30	30	30	"	"	8.5	1	20	.066	82	.078	32	.188	0	
213	"	31	30	30	"	"	8.5	1	30	.044	104	.228	31	.428	10	
214	"	32	32	32	"	"	8.5	1	22	.062	63	.145	40	.265	4	
215	"	40	40	40	"	"	5	4.5	14.4	.120	40	.142	UNK	UNK	UNK	EQUIPMENT MALFUNCTION
216	"	44	41	41	"	"	1.5	8	14.4	.132	52	.123	UNK	UNK	UNK	DRY BAY, NO MEASUREMENTS

TABLE IX

COMBINATION AND SPECIAL TESTS

TEST NR.	FUEL	T_L °F	T_U °F	T_W °F	D_E INCH	X_E INCH	D_F INCH	H_{TF} INCH	P_I PSIA	F/A	ΔP_M PSI	ΔT_M SECOND	ΔP_C PSI	ΔT_C SECOND	δP_C PSI	REMARKS
101	JP-4	43	41	42	8	0.125	1.5	8	14.3	≤.131	84	.040	NA	NA	NA	NON EQUILIBRIUM VAPOR
119	"	85	83	83	"	"	"	"	14.2	≤.386	0	0	NA	NA	NA	"
153	"	56	55	55	"	"	"	"	14.2*	(1)	54	.047	11	.280	11	*REDUCED FROM 30 JUST BEFORE FIRING
154	"	54	52	52	"	"	"	"	14.2*	(2)	65	.038	11	.382	11	"
227	JP-8 118°F.P.	28	28	28	19 1/4	0.090	8.5	1	14.5	.001	0	0	0	0	0	ENTRANCE PLATE AND DRY BAY
228	"	28	28	28	"	0.125	5	4.5	14.5	.001	19	.344	9	.132	9	"
229	"	30	30	30	"	"	1.5	8	14.5	.001	11	.438	2	.252	2	"
230	JP-8 118°F.P.	30	30	30	19 1/4	0.125	1.5	8	14.5	≥.001	33	UNK	NA	NA	NA	ENTRANCE PLATE WITH FUEL SPRAY

(1) F/A = .085 AT 30PSIA & .185 AT 14.2 PSIA

(2) F/A = .082 AT 30PSIA & .176 AT 14.2 PSIA

APPENDIX II

DETERMINATION OF INFLUENCE OF INITIAL ULLAGE CONDITIONS UPON PEAK REACTION PRESSURE

System: Gases in the ullage of a rigid fuel tank.

Assumptions:

1. Gases obey perfect gas law, $PV = nRT$
2. Heat of reaction added to gases, no heat loss to tank
3. Specific heats of reactants and products are constant and equal
4. System is homogeneous and at equilibrium
5. Increase in gas moles after combustion can be ignored

Using the perfect gas law as applied to a constant volume process we have:

$$P_I / T_I = P_F / T_F = (P_I + \Delta P) \; / \; (T_I + \Delta T) \qquad (1)$$

Where:

P_I = initial system pressure

T_I = initial system temperature

P_F = final system pressure

T_F = final system temperature

ΔP = reaction pressure rise $(P_F - P_I)$

ΔT = reaction temperature rise $(T_F - T_I)$

Solving Equation 1 for Δ T yields

$$\Delta T = \frac{\Delta P T_I}{P_I} \tag{2}$$

With the equation

$$Q = M C \Delta T \tag{3}$$

Where:

Q = heat released
M = system mass
C = system specific heat

For fuel lean reaction ($\phi < 1$) it may be stated that the heat released (Q) will be proportional to the amount of fuel in the ullage. Since the amount of fuel is proportional to the fuel vapor density, we have $Q \;\alpha\; P_V/T_I$. With the sys-mass (M) proportional to P_I/T_I and the system specific heat constant,

Equation (3) becomes:

$$\frac{P_V}{T_I} \;\alpha\; \frac{P_I}{T_I} \Delta T \quad \text{or} \quad \Delta T \;\alpha\; \frac{P_V}{P_I} \tag{4}$$

Substituting Equation (4) into Equation (2) yields

$$\frac{\Delta P}{P_I} \;\alpha\; \frac{P_V}{P_I T_I}$$

Since the fuel/air mass ratio (F/A) is

$$F/A \approx \frac{P_V}{P_I} \text{ for } P_V << P_I$$

and assuming equal molecular weight for both the fuel and air

We find that

$$\frac{\Delta P}{P_I} \;\alpha\; \frac{1}{T_I}\left(\frac{F}{A}\right) \text{ for } \phi < 1$$

For fuel rich reaction ($\phi > 1$), the heat released (Q) will be proportional to the oxygen available and since the oxygen available is proportional to

to $\frac{P_I - P_V}{T_I}$ we see that $Q \;\alpha\; \frac{P_I - P_V}{T_I}$.

The system mass (M) will be proportional to $\left(\frac{P_I}{T_I}\right)$ and with the system specific heat constant, Equation (3) becomes:

$$\frac{P_I - P_V}{T_I} \alpha \frac{P_I \Delta T}{T_I} \tag{5}$$

$$\text{or } \Delta T \alpha \frac{P_I - P_V}{P_I}$$

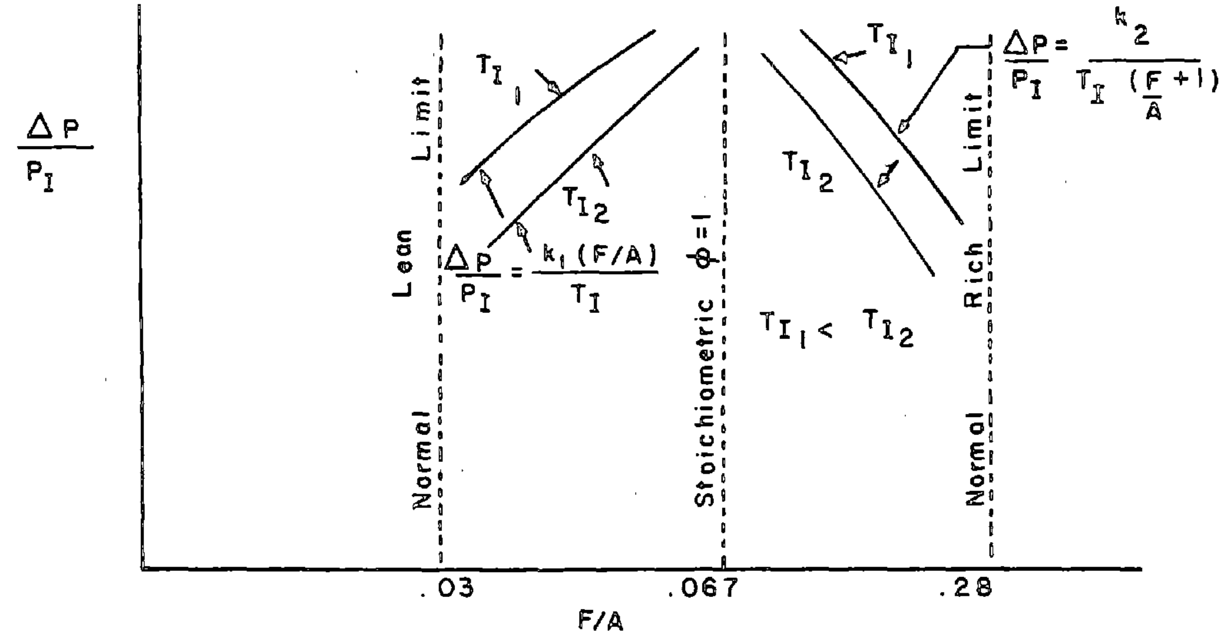
Substituting Equation (5) into Equation (2) yields

$$\frac{\Delta P}{P_I} \alpha \frac{P_I - P_V}{T_I P_I} \tag{6}$$

Since $\frac{P_I}{P_I - P_V} = \frac{F + A}{A} = \frac{F}{A} + 1$ assuming equal molecular weight for both the fuel and air we obtain

$$\frac{\Delta P}{P_I} \alpha \frac{1}{T_I \left(\frac{F}{A} + 1\right)}$$

In summary, for the hydrocarbons of interest, we would expect correlation of the various parameters as shown below:



APPENDIX III

REGRESSION ANALYSIS

A stepwise multiple regression analysis program was used to determine prediction equations and these equations have been noted in the report. These equations were developed for the data based on the approach of least squares. Certain basic assumptions were required before the program could be used. It must be assumed that the model can be properly expressed by using linear coefficients in the regression equations. All variables must also be assumed to be multivariate normally distributed.

Several models were used in the regression analysis and were based on the parameters developed in Appendix II which were;

$$\frac{\Delta P_M}{P_I}, \frac{1}{T}, \text{ F/A and } \frac{1}{F/A+1} .$$

The first model was developed to predict the overpressure ratio $\frac{\Delta P_M}{P_I}$

for the standard test results as given on Figure 13. The data points included all the points for both JP-4 and JP-8 except as noted on Figure 13. The following equations were the best generated for this data set.

$$\frac{\Delta P_M}{P_I} = \frac{6052.6\ (F/A)^4 - 1104.1\ (F/A)^2 + 185.8\ (F/A) - 1.4}{(F/A + 1)^2} \qquad (1)$$

with $R_c = 0.9875$

$$\frac{\Delta P_M}{P_I} = \frac{2,913,100\ (F/A)^4 - 535,383\ (F/A)^2 + 89,752\ (F/A) - 511}{T\ (F/A + 1)^2} \qquad (2)$$

with $R_c = 0.9864$

The multiple correlation coefficient (R_c) is a measure of the significance or the worth of the equation for prediction. As may be seen there was little difference between the two equations. This was expected since the range of temperatures used in the test program was small. Equation (2) was selected as superior based on the results of Appendix II. This was an item which should be verified by additional testing over a wide temperature range.

The next model developed was for the data points given on Figure 19. The best resulting equation was;

$$\frac{\Delta P_M}{P_I} = 52.3 \frac{F}{A} - 245.2 \, (F/A)^2 + 8.94 \, (F/A \; H_{TF}) - 5.88 \, (F/A \; H_{TF})^2 - 0.14 \, H_{TF} + 0.874 \tag{3}$$

with $R_c = 0.9711$

Temperature was not included in the development of this model. The requirement for normal distribution was not satisfied. Therefore, the value of this equation as a model was questionable.

A third model was developed to investigate the combined effect that fuel/air ratio (F/A), striker plate thickness (X_E), striker plate diameter (D_E), and projectile trajectory to fuel distance (H_{TF}) may have on the overpressure ratio. The data used in this analysis was the JP-8 tests with $F/A < 0.05$. This included tests 125 through 134 except 126 of the Standard Test series, 222 through 225 of the Entrance Plate Test series and 217 through 220 of the Fuel Level Test series. The best resulting equation was;

$$\frac{\Delta P_M}{P_I} = 217.2 \, (F/A \; H_{TF})^2 + 48.71 \, (F/A \; H_{TF}) + 7.32 \, X_E - 0.77 \tag{4}$$

with $R_c = 0.9719$

During the development of this equation it was consistently noted that the striker plate thickness (X_E) was much more important in the correlation than the striker plate diameter D_E.

The foregoing discussion was presented to clarify the regression equations used in this report and to serve as a departure point for future investigators.