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EXPERIMENTAL DETERMINATION OF THE IGNITION LIMITS OF JP-4 FUEL WHEN EXPOSED TO CALIBER .30 INCENDIARY PROJECTILES

By

Charles M. Pedriani

July 1971

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

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SUMMARY

This report describes the experimental efforts to define the ignition limits of JP-4 vapors subject to caliber .30 incendiary projectiles. A test fixture was fabricated which allowed a functioning incendiary projectile to pass through a known, uniform fuel/air vapor mixture. The resultant reaction was observed using high-speed photography. Ignitions occurred between fuel/air ratios of 0.5 and 3.0% JP-4 volume.

Additional tests were conducted to observe the flame suppression properties of reticulated polyurethane foam (RPF) and to document the fact that the impact flash from inert projectiles can ignite combustible fuel/air vapors.

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INTRODUCTION

STATEMENT OF PROBLEM

One of the hazards to an aircraft operating in a combat environment is fire caused by the impact of an incendiary projectile. Any study to reduce the vulnerability of an aircraft to incendiary projectiles is complicated by the large number of possible hits that could eventually result in an in-flight fire. However, the impact most likely to cause a catastrophic fire is an incendiary hit in the fuel cell. The ignition of fuel/air vapors in the void space (ullage) above the fuel in the tank could rupture the tank, spilling burning fuel throughout the aircraft and causing total destruction. A hit below the fuel level could cause a fire outside the fuel cell, fed by fuel leaking from the wound. The experimental work contained herein is directly concerned with incendiary and tracer-type projectiles passing through only the ullage of an aircraft fuel tank. The independent effects of projectile velocity, tank size, and projectile time in the tanks on the ignition limits of JP-4 vapors are studied. Some additional work was done on flame-arresting reticulated polyurethane foam (RPF) and ignition by impact flash. Extensive high-speed photography was used to study the ignition phenomenon in detail.

PROGRAM BACKGROUND

These ignition studies are only one part of the second phase of a three-phase program to reduce the vulnerability of aircraft fuel cells to incendiary/tracer ammunition.

Ullage Studies

In the first phase of the program, the ullage characteristics of aircraft fuel cells were studied. This effort was motivated by the fact that although the composition of the ullage of fuel containers could be determined under static conditions, there was no literature available which described the ullage under dynamic conditions.

It was hypothesized that the in-flight agitation of the fuel and the inflow/outflow of air due to fuel withdrawal and altitude changes would combine to significantly alter the fuel/air composition of the ullage. A preliminary test was run which confirmed the existence of a fuel/air vapor gradient in the ullage, so a more comprehensive effort was launched. The work was done both in-house and contractually. The effects of temperature, pressure, vibration, fuel withdrawal rate, tank geometry, and fuel type on the formation of combustible mixtures within simulated aircraft tanks were studied. Typical results obtained are shown in Figure 1. A fuel/air vapor gradient was found in the ullage which rendered some portions of the ullage hazardous (1.3 to 8.1%) for almost all flight conditions using JP-4 fuel. It was found that the vapor pressure of the fuel--which is determined by temperature and pressure--was the primary variable in determining the overall vapor content of the ullage. The details of these efforts are given in References 2 and 4.

Ignition Studies

The second phase of the overall effort is aimed at determining the ignitability of these fuel/air vapors when subject to incendiary projectiles. Ignition data[5] are published on the basis of spark ignition experiments. As an ignition source, a functioning incendiary projectile differs from a simple electrical spark, so it was hypothesized that the ignition limits of JP-4 using incendiary ammunition could be quite different from those obtained using an electrical spark. Consequently, the effort described herein was conducted to determine the incendiary ignition limits and characteristics of JP-4 vapors.

System Synthesis

In the third phase of the program, the knowledge gained in the first two phases will be combined so that a system or method can be designed and evaluated to eliminate the possibility of a catastrophic explosion due to an incendiary impact in the fuel cell.

OBJECTIVES

The phenomenon studied in these tests is the ignition of a known, uniform fuel/air vapor mixture by a functioning caliber .30 incendiary projectile. The ultimate goal is to gain knowledge of the ignition characteristics of JP-4 fuel vapor in the ullage of aircraft fuel tanks and to establish the ignition limits for JP-4 for various tube lengths and projectile velocities. Also, it was planned to determine whether the length of the tube or the projectile velocity had a controlling effect on the ignition limits. In addition, brief tests were conducted to evaluate the explosion suppression properties of RPF and to document the phenomenon of impact flash ignition. Extensive high-speed photography was used to document the results.

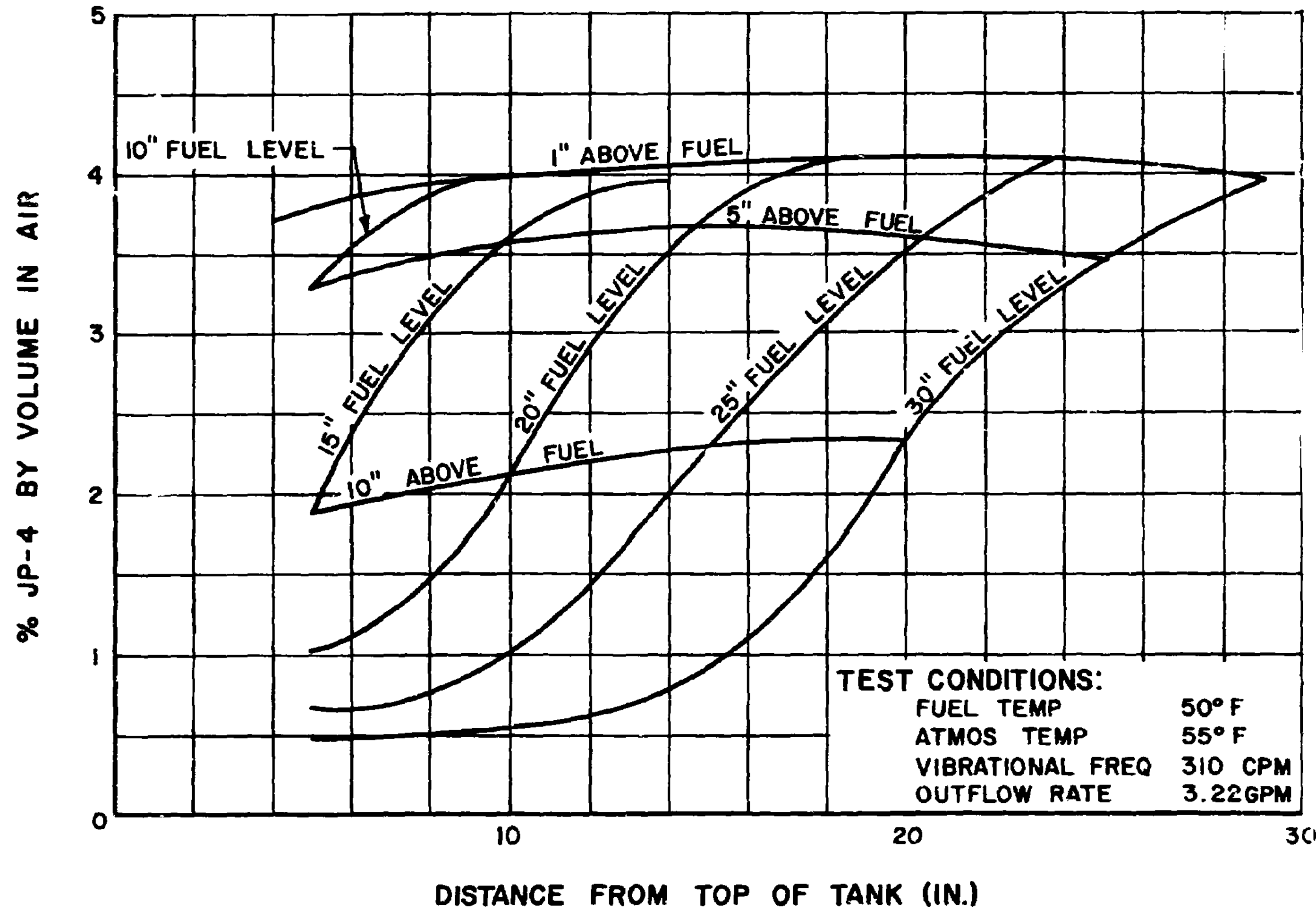


Figure 1. Typical Results of Fuel/Air Vapor Tests.

APPROACH

TEST FIXTURE DESIGN

A test fixture which would permit an incendiary projectile to pass through a fuel vapor mixture and ignite the vapor with no damage to the fixture was designed and built, as shown in Figure 2. The generating tank contains several inches of JP-4 fuel. The vapors above this fuel can be circulated through the target tube by means of a blower located as shown. The fuel/air ratio in the tube can be varied by changing the fuel temperature, blower speed, or height at which the transfer tubes attach to the generating tank. Access holes are located in the target tube so that the fuel/air ratio can be monitored using an MSA infrared analyzer. The ends of the target are covered with plastic to retain the vapors, yet blow out in the event of an explosion. Trap doors and flame-arresting RPF are located where the transfer tubes meet the target tube to eliminate the possibility of an explosion propagating to the generating tank. The 12-inch-diameter (1/4-inch wall) aluminum target tube is segmented so that its length can be varied from 18 to 54 inches, in increments of 6 inches. Heaters are installed in the base of the generating tank to raise the fuel temperature above ambient, and an immersion cooling unit is available to decrease the fuel temperature when required.

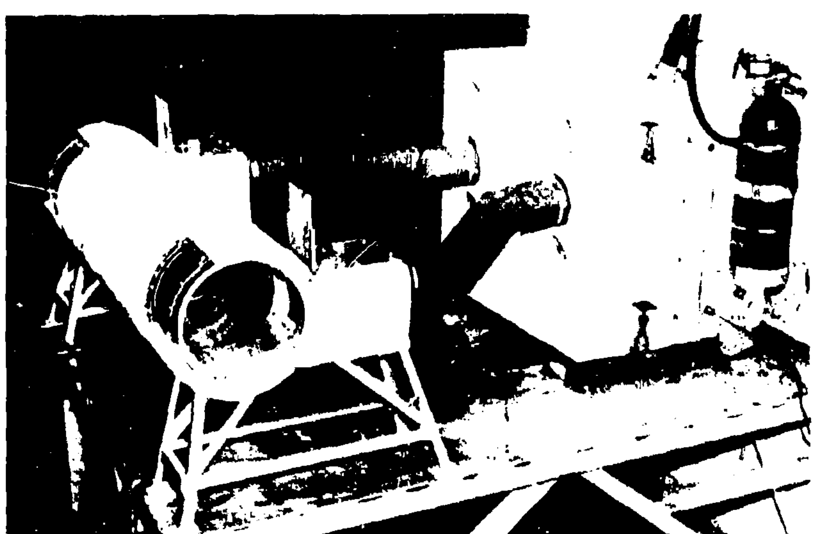


Figure 2. Incendiary Ammunition Test Fixture.

INITIAL TESTS

Before any useful data could be obtained from the test fixture, many questions had to be answered. First, could the fuel/air ratio in the target tube be controlled satisfactorily and would it be essentially uniform throughout the tube? Second, could the target tube sustain repeated explosions?

Controlling Test Parameters

A series of trials was run in which the fuel/air ratios in the target tube were monitored as the blower speed, fuel temperature, and transfer tube location were varied. It was found that the fuel/air ratio tended to reach an equilibrium in the system and was primarily a function of fuel temperature. Some latitude of control could be gained by "bleeding" the system, i.e., letting some of the vapors escape. The "age" of the fuel also played some role in establishing the equilibrium ratio. That is, "fresh" fuel produced ratios higher than fuel which was allowed to remain in the fixture for several days. To some degree, the amount of fuel in the generating tank also affected the fuel/air ratio. This effect was probably caused by the corresponding decrease in ullage volume. The blower speed or transfer tube location did not affect the equilibrium fuel/air ratio. Satisfactory control over the fuel/air ratio in the target tube was obtained through a combination of regulating the fuel temperature and bleeding the system.

Fixture Modification

The first series of actual ignition tests revealed much information about the fixture. Most importantly, it was evident that the target tube could withstand the explosion of vapors. Consequently, a clear-cast acrylic tube (12-inch overall diameter, 1/2-inch wall thickness) was ordered for use in place of the aluminum to facilitate high-speed photographic coverage. A total of 8 feet of tubing was obtained so that several lengths could be cut to change the overall length of the tube and to provide replacement in case of damage.

The acrylic tube did withstand repeated explosions with only minor scratches from high-speed particles. However, periodic cleaning was required. It was also found that the material used to cover the ends was important in the operation of the fixture. The thin plastic material used in the initial tests was not satisfactory. The projectile would tear a hole at both the entrance and the exit. Then the accompanying shock wave would cause air to be drawn in the entrance of the tube and fuel vapors to be drawn out the back of the tube. The vapors would then burn outside the back of the tube, and no ignition took place within the tube. Since this did not simulate the actual tank, urethane rubber material was substituted for the end pieces. The urethane permitted the projectile to pass through, but because of its partial sealing capability, it did not allow transfer of vapors or air into or out of the target tube. The end pieces were taped in place so that an explosion would not tear the rubber but would allow it to blow off in one piece.

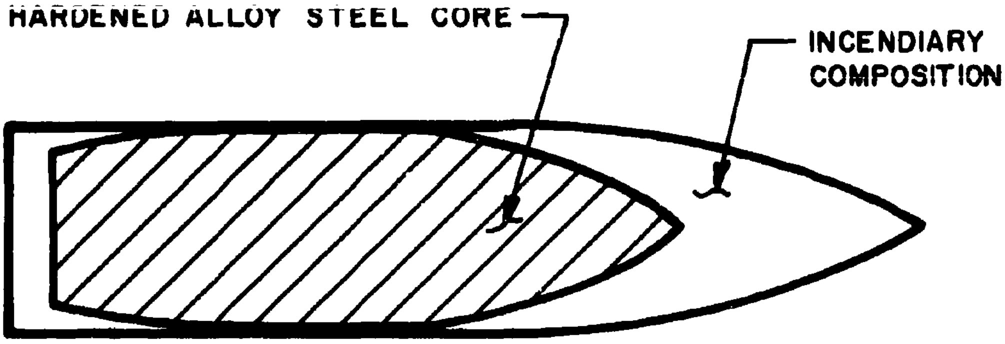
Incendiary and Armor-Piercing Incendiary Projectile Characteristics

Much information about the functioning characteristics of the incendiary (INC) and armor-piercing incendiary (API) projectiles was obtained. The projectiles are shown in a cutaway view in Figure 3. Note that the INC projectile has much more incendiary composition than the API. The incendiary composition burns when sufficient energy is applied. The composition is not oxygen balanced, so the final products are luminescent particles of magnesium and aluminum oxides. As would be expected, both the INC and API functioned with a bright flash; but the INC, because of its amount of incendiary composition, continued to burn for at least 20 feet.

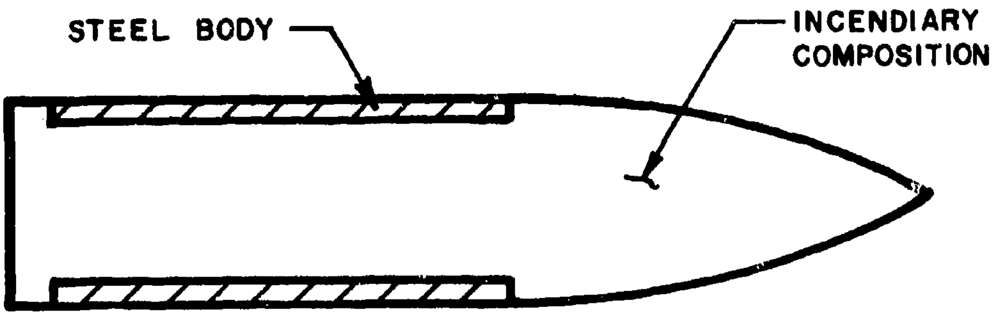
For these tests, a 1/8-inch-thick 2024T-3 aluminum plate was used to function the projectile. This function plate was placed 24 inches from the entrance of the tube so that only the burning projectile was exposed to the fuel vapors. It was found that if the initial function took place inside the tube, ignition of the vapors took place regardless of the fuel/air ratio. In addition, in the event of an impact on a helicopter, the round would probably function on the skin and only the burning incendiary would pass into the tank. It is possible that the thin aircraft skin would not function the round. Also, if the initial function took place inside the tank, an explosion would almost surely occur regardless of the fuel/air ratio in the tank.

Projectile velocities lower than 1300 fps could not be tested since the function plate almost stopped the projectile.

The ignition limits were obtained for two tube lengths--48 and 24 inches--and two projectile velocity regimes--about 1500 and 3000 fps.



a. ARMOR — PIERCING INCENDIARY



b. INCENDIARY

Figure 3. Cutaway View of Armor-Piercing Incendiary and Incendiary Projectiles.

RESULTS

DATA COLLECTION

The minimum information to be obtained from each test was whether or not ignition had occurred. This determination was best made using high-speed photographic coverage. In addition, photographic coverage made it possible to observe the mechanism or characteristic of the ignition. It was found that 2000 frames/second was optimum for studying the ignition. Frame rates faster than this prolonged screen time without supplying any additional information on the ignition. Additional overall coverage at 400 frames/second and 50 frames/second was provided. It was also necessary to use color film to be certain that the ignition was visible.

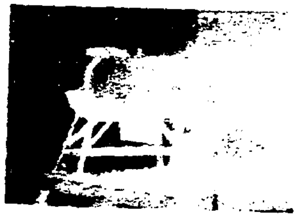
TEST VALIDITY

The high-speed film coverage was necessary to determine if, in fact, a given test was valid. For example, the only type of test considered to be valid was one in which the projectile functioned at the function plate and the burning projectile (or pieces of projectile) passed through the tube without extensive damage to the end pieces or transfer of vapor or air into or out of the tube.

These restrictions were made to reduce the scope of the problem to a workable number of variables while still simulating an incendiary projectile passing through the ullage. There were several phenomena that occurred on many tests that violated these restrictions. The end pieces had to be taped by hand onto the target tube, so there was some variation in the tightness of the pieces. Occasionally, one would be applied too loosely, so that the round, or its shock wave, would loosen the end, permitting air to enter the tube and locally alter the fuel/air ratio, and possibly encouraging ignition which otherwise would not have occurred.

Sometimes a rather jagged projectile would inject air as it passed into the tube, reducing the fuel/air ratio and thus causing a local ignition in an otherwise overrich tube. In some cases, this local ignition would loosen the end piece, letting in more air and thus further reinforcing the flame (Figure 4).

Functioning of the round was not always as expected. Occasionally, especially at lower velocities, the round would not function until it entered the tube, in which case an explosion took place regardless of the fuel/air ratio (Figure 5).



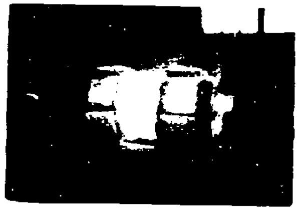
Frame 1. The round has functioned and is between the function plate and the target tube.

Frame 5. The projectile has passed through the tube, and glowing incendiary particles are in evidence around the target tube.

Frame 31. (t = 15 msec) Some limited ignition in the tube has caused the end pieces to bulge.

Frame 291. (t = 146 msec) The pressure rise has caused the end pieces to come loose, allowing gas to escape and burn outside the tube.

Figure 4. Selected Stills Reproduced From High-Speed Photography at 2000 Frames/Second, Showing a Limited Ignition and the "Bunsen Burner" Effect Created, With a Fuel/Air Ratio of 2.15%.



Frame 1. The initial function of the projectile occurred inside the target tube.

Frame 5. The vapors have ignited in spite of the high fuel/air ratio of 3.6%.

Frame 19. (t = 9.5 msec) The resultant pressure rise has blown the ends off.

Figure 5. Selected Stills Reproduced From High-Speed Photography at 2000 Frames/Second, Showing a Projectile Functioning Inside the Target Tube.

To summarize, if any of the above phenomena were observed in any test, the test was not used as a data point in determining the ignition limits.

DISCUSSION OF RESULTS

The ignition limits obtained are summarized in Figures 6 and 7. The black points indicate an ignition; the white points indicate no ignition. Some of the data points are shown as half black and half white, indicating a marginal or partial ignition. For these shots, a partial burning of the fuel was observed. This erratic burning is probably caused near the ignition limits by projectile disturbance of the fuel creating a nonuniform fuel/air ratio so that some of the tube is in the flammable limits.

Many controlled studies have been conducted to characterize the ignition and flammability properties of fuels.[5,6] It is very difficult, however, to apply these findings directly to the vulnerability of fuel tanks. Therefore, no attempt will be made to explain the results obtained herein in terms of well-established data. The results of this study stand apart and apply only to the condition studied, i.e., an incendiary round passing through a known, uniform fuel/air vapor mixture. The limits thus established, then, in no way refute or confirm classical data. However, the ignition limits found are below those obtained with the spark ignition apparatus. This might have been expected, since the burning incendiary composition which is oxygen deficient would use oxygen in the target tube, thus artificially enriching the mixture.

The most severe explosions took place when the mixture was in the 0.8 to 1.7% range (Figures 8 and 9). The severity of the explosion could be somewhat characterized by the velocity of the flame-front propagation through the tube (Figure 10). The very sharp explosion was characterized by flame-front velocities from about 160 to 200 ft/sec, while the richer ignitable mixtures, about 2.3%, were characterized by velocities about 40 ft/sec. It should be pointed out that a discrete flame front was not always present. Since the ignition source moves relative to the mixture, ignition can, and did, take place anywhere and everywhere along the flight path.

If ignition occurred, the projectile almost always left burning vapors in its wake. That is, only on a very few tests was there a measurable time delay between passage of the projectile and ignition (Figure 11). It is possible that in these tests, the ignition was there all the time, but it was not visible (to the film in the cameras).

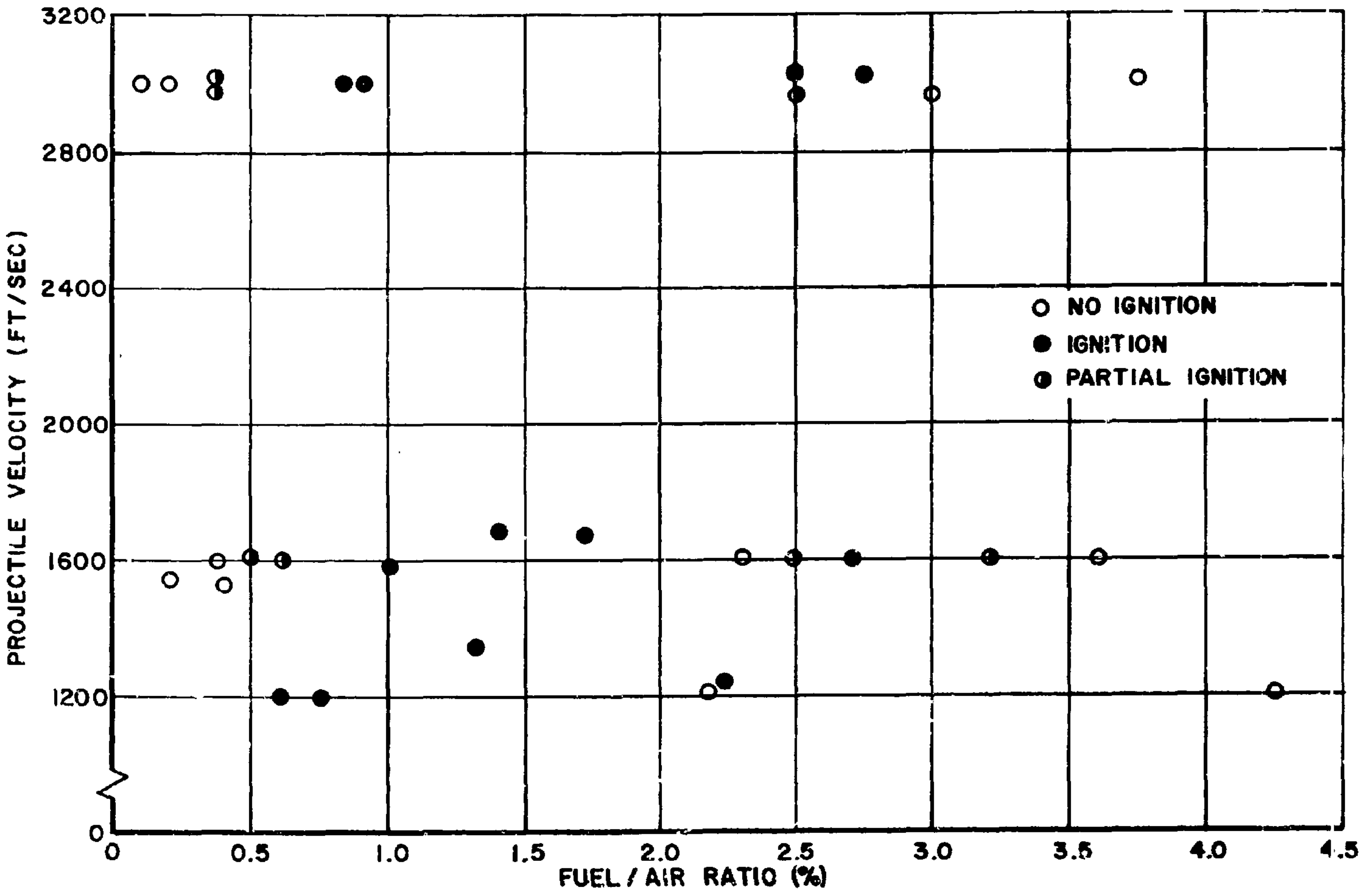


Figure 6. Summary of Tests With 48-Inch Tube.

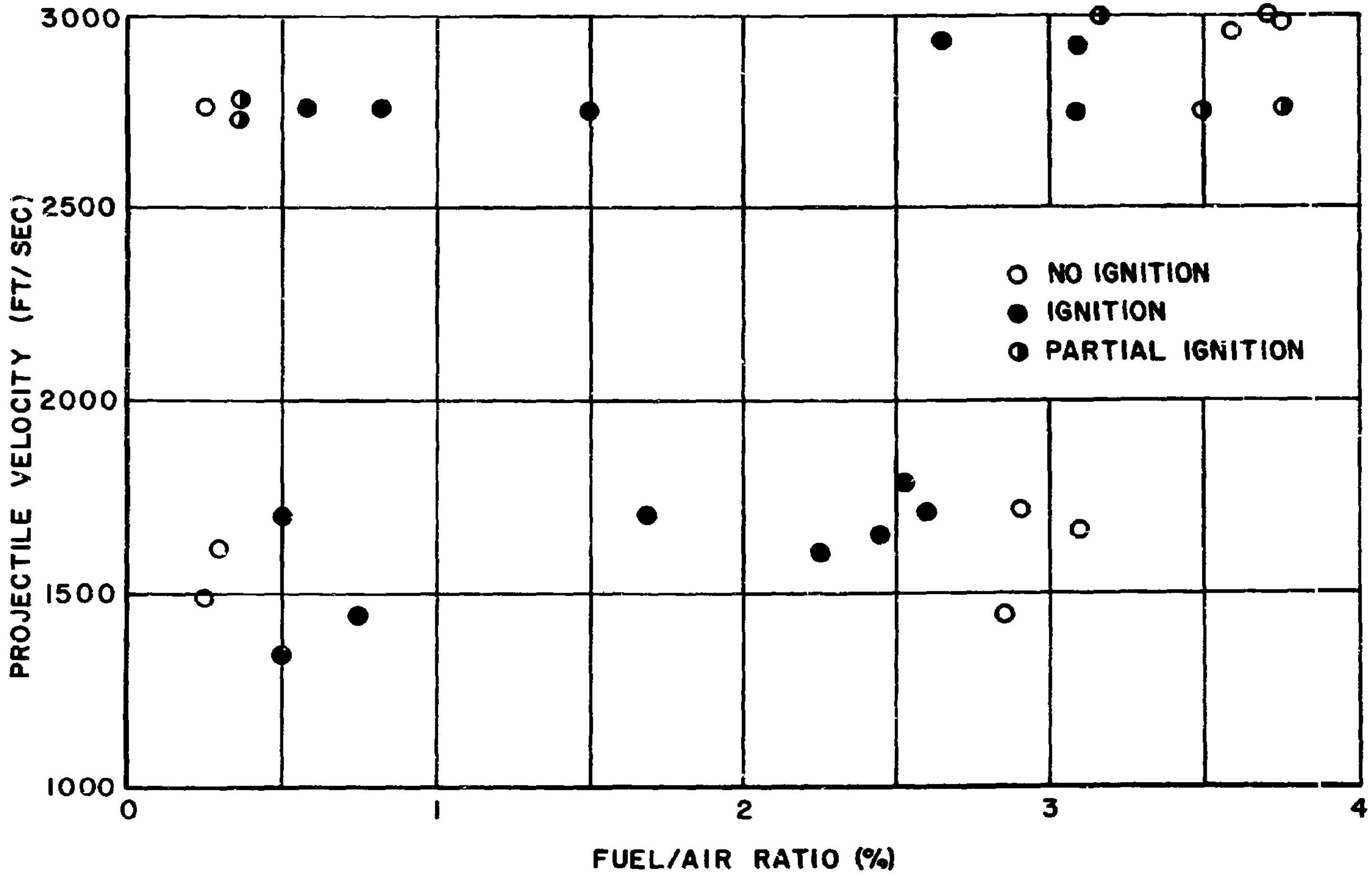
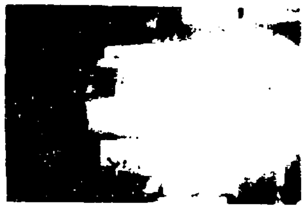


Figure 7. Summary of Tests With 24-Inch Tube.



Frame 1. The projectile has functioned and can be seen just entering the tube.

Frame 16. (t = 8 msec) The explosion has started and the ends have come loose.

Frame 26. (t = 13 msec)

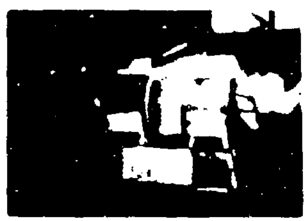
Frame 67. (t = 33 msec)

Figure 8. Selected Stills Reproduced From High-Speed Photography at 2000 Frames/Second, Showing a Typical Ignition, With a Fuel/Air Ratio of 0.65%.

Frame 1. The projectile has functioned and is between the function plate and the target tube.

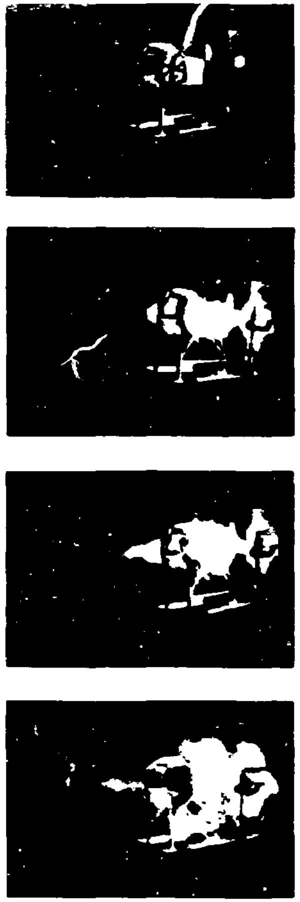
Frame 4. (t = 2 msec) The projectile has passed through the tube and is visible about 1.5 feet behind it.

Frame 11. (t = 5.5 msec) The vapors in the tube have ignited, and the pressure rise is beginning to flow off the end pieces.



Frame 26. (t = 13 msec)

Figure 9. Selected Stills Reproduced From High-Speed Photography at 2000 Frames/Second, Showing a Typical Ignition, With a Fuel/Air Ratio of 0.35%.



Frame 1. (t = 0 msec) The round has impacted the function plate at the right of the frame.

Frame 16. (t = 8 msec) The incendiary projectile has passed out of the picture to the left. Ignition has started at the entrance of the tube.

Frame 31. (t = 16 msec) The flame front is about two-thirds through the tube.

Frame 70. (t = 35 msec) The flame front has propagated through the tube.

Figure 10. Selected Stills Reproduced From High-Speed Photography at 2000 Frames/Second, Showing the Propagation of a Flame Front Through the Target Tube, With a Fuel/Air Ratio of 0.60%.

Frame 1. Functioning incendiary passing through the target tube.

Frame 12. The projectile has passed through the target tube. Some glowing incendiary is visible outside the entrance of the tube.

Frame 33. Same as Frame 12.

Frame 197. Ignition has started in the target tube 98.5 msec after the projectile has left the tube.

Figure 11. Selected Stills Reproduced From High-Speed Photography at 2000 Frames/Second, Showing a Time Delay Between Function of Projectile and Ultimate Ignition of the Vapors, With a Fuel/Air Ratio of 2.6%.

ADDITIONAL TESTS

Evaluation of Reticulated Polyurethane Foam

The test apparatus seemed ideal for examining the fire suppression properties of RPF. It was theorized that the suppression properties of foam would be demonstrated if the foam successfully prevented an explosion of vapors which had been flammable in previous tests. In addition, the feasibility of partially filling the tube with foam would be tested. The 48-inch target tube was then filled with 20 pores/inch RPF under about 2 to 4% compression. Using a fuel/air ratio of 1.1% in the tube, no ignition was obtained in either of two tests (Figure 12).

The target tube was then partially filled with foam as shown in Figure 13. In one test, the explosion was confined to the first compartment formed by the foam, but on the remaining two tests, the fire did propagate through the tube. A fuel/air ratio of 1.1% was used in all three tests.

In every test, there was some damage to the foam (Figure 14). In those tests in which no explosion occurred, the projectile made a hole in the foam and charred a 3-inch-diameter area around the hole. The foam previously occupying this space was reduced to small filaments which could clog the fuel system if not filtered. In the tests in which ignition occurred, the fire decomposed the foam to a gummy substance, which would require considerable maintenance, if not complete tank replacement. This is not much of a drawback, however, if an aircraft is saved in the process.

Impact Flash Ignition

During the ballistic testing of UH-1B flight control components, it was noted that the ballistic impact was characterized by considerable flash. This phenomenon was noted using caliber .30 APM2 ammunition when impacting a connecting link and a quadrant. It was theorized that this flash would be sufficient to ignite a fuel vapor mixture. Therefore, the components were installed in the target tube and impacted with caliber .30 APM2 projectiles at service velocity. Ignitions took place in three tests.

These tests were preliminary and very limited in scope; therefore, no firm conclusions have been drawn. The phenomenon of impact flash ignition is documented, so it is possible for an inert projectile to cause a fire in flight if it contacts the aircraft in the presence of flammable hydrocarbons.

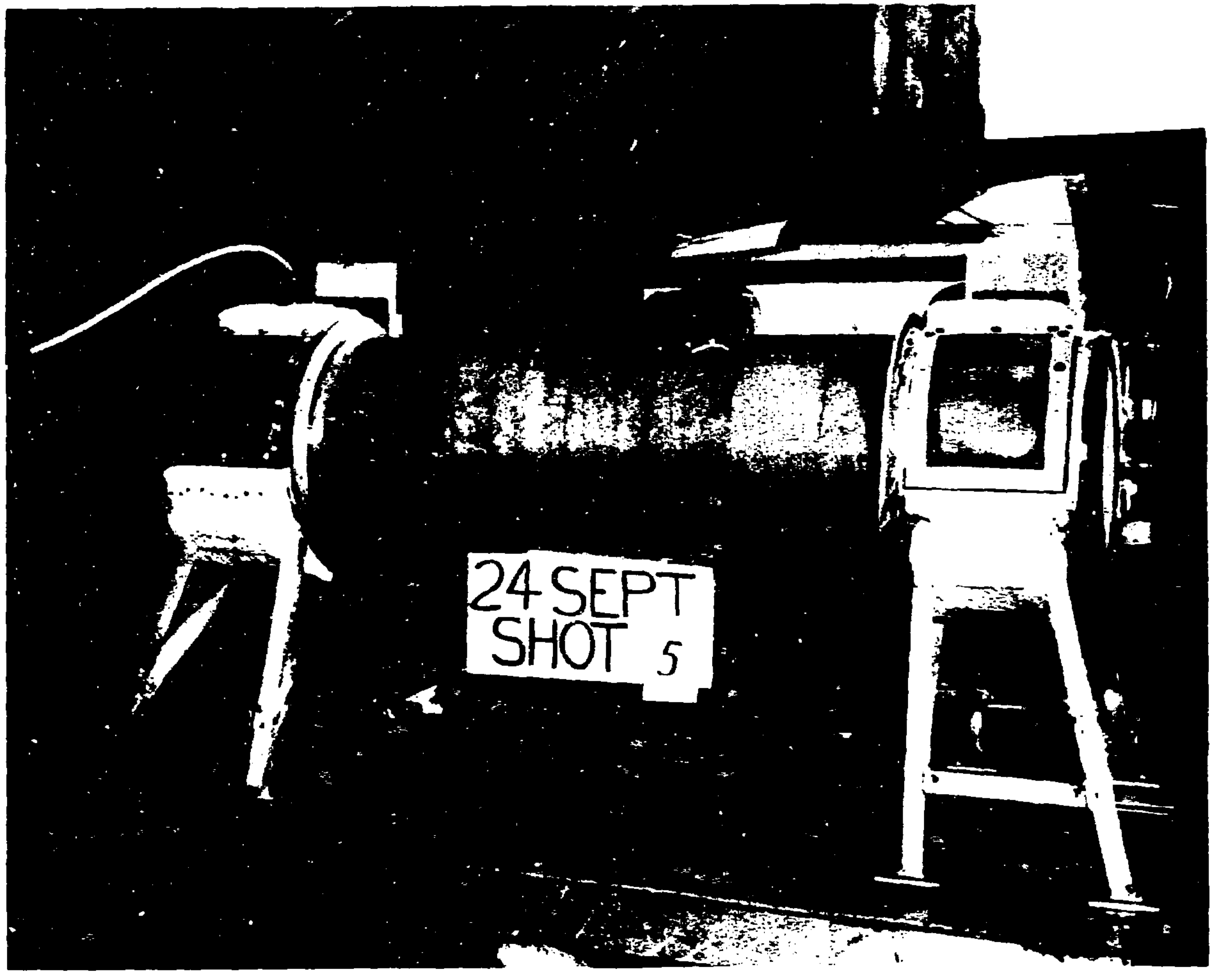


Figure 12. Target Tube Filled With 20 ppi Reticulated Foam.

Figure 13. Target Tube Partially Filled With 20 ppi Reticulated Foam.

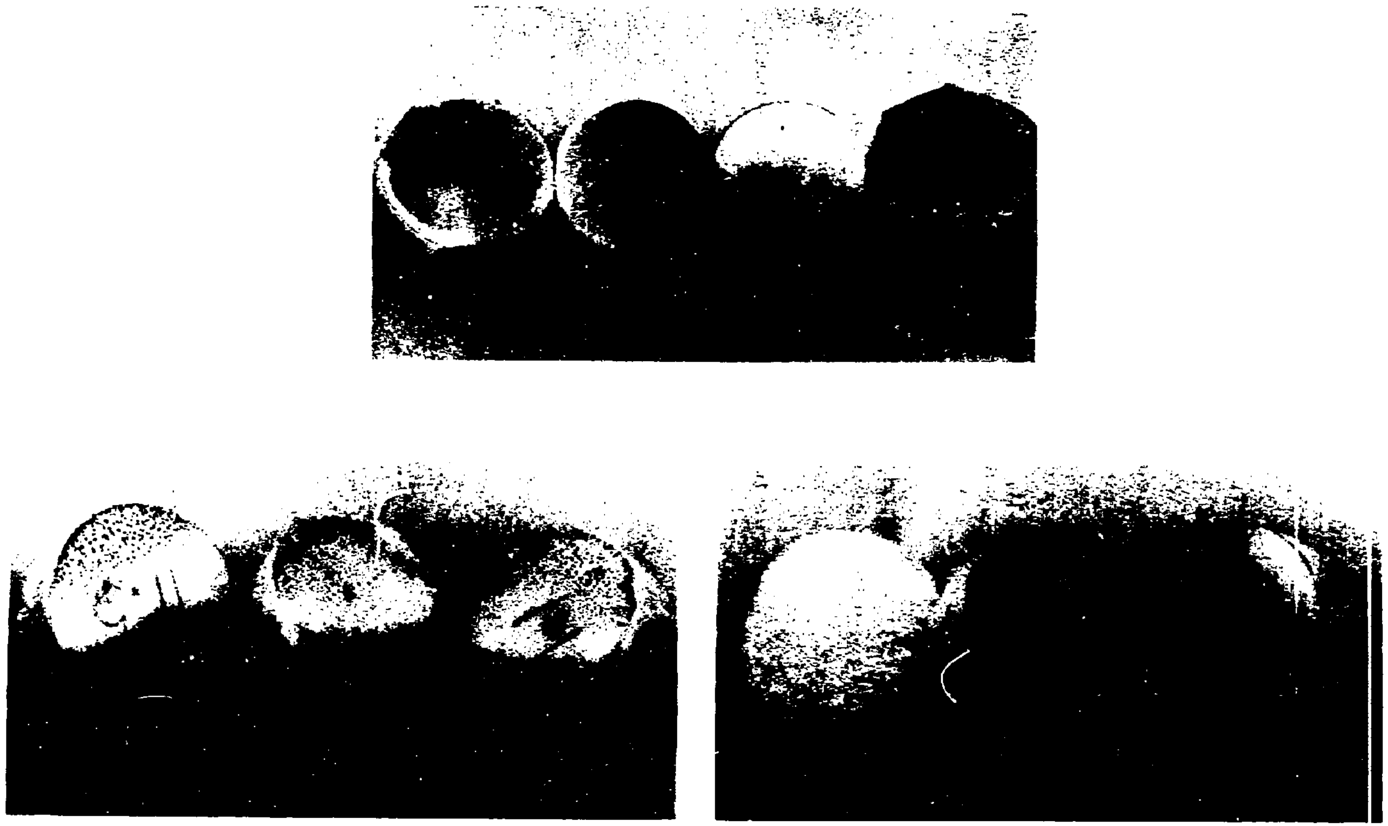


Figure 14. Foam Damaged by Burning Vapors.

CONCLUSIONS

For the test fixture used in this effort, the ignition limits were about 0.5 to 3.0% JP-4 by volume in air, using a functioning incendiary projectile as the ignition source. Every effort was made to make the test fixture similar to an aircraft tank so that it could be said with some confidence that the limits found in this fixture also apply to an actual fuel tank.

The upper limit found in these tests is considerably lower than that obtained using spark ignition tests. If, in fact, ignition of the ullage will not occur if the fuel/air ratio is above 3.0%, the problem of "inerting" the tank is greatly reduced.

Reticulated foam is an effective method of suppressing explosions of flammable mixtures which would be extremely hazardous in an unprotected tank.

It is possible for flammable mixtures to be ignited by the impact flash caused by an otherwise inert projectile.

RECOMMENDATIONS

It is recommended that:

1. The limits obtained by firing at an actual fuel tank be investigated. A brief test program consisting of a few shots at fuel/air ratios at or near the expected ignition limits would demonstrate the applicability of the test fixture data on an actual tank.

2. If the flammability predictions are verified for an actual tank, a system be designed to render the ullage fuel/air ratio above 3.0% for all flight conditions using JP-4 fuel. Such a system should be designed and evaluated and ultimately adopted for use in Army aircraft.

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