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EVALUATION OF THE EFFECTIVENESS OF ANTI-MIST FUEL ADDITIVES IN PREVENTION OF AIRCRAFT FUEL TANK ULLAGE FIRES AND EXPLOSIONS

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Wright-Patterson Air Force Base, Ohio

January 1974

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AIR FORCE/56780/18 June 1974 — 450

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UNCLASSIFIED

Security Classification

AD-781378

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) AF Aero Propulsion Laboratory Wright-Patterson Air Force Base, OH 45433	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE

Evaluation of the Effectiveness of Anti-Mist Fuel Additives in the Prevention of Vapor Phase Fire and Explosions

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

December 1972 through March 1973

5. AUTHOR(S) (First name, middle initial, last name)

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6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
January 1974	22	None

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO. 3048	AFAPL-TR-73-111
c. Task No. 304807	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d. Work Unit 30480752	

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Air Force Aero Propulsion Laboratory Wright-Patterson Air Force Base, OH 45433

13. ABSTRACT

A series of vertical gunfire tests was conducted at Wright-Patterson AFB in order to assess the effectiveness of fuel additives in reduction of the fire and explosion hazards that can be associated with kerosine (JP8) fuel under gunfire conditions. This program considered commercial additives which have been developed for the fire-safe fuel efforts of the FAA, the Army, and the British Government. The additives were intended to prevent fuel mist or spray during a crash situation. This effort considered the effectiveness of these additives at a concentration of approximately 0.3% wt. in the prevention of explosions of fuel mist or spray as a 50 calibre armor piercing incendiary (API) ordnance round passes through the liquid-vapor interface. Results indicated that additives could be effective. Two of the four materials evaluated, CONOCO AM-1 and Imperial Chemical Industries, Ltd. FM-4 reduced average pulse pressure rise to less than 10 psi as compared to 40 psi rise with neat JP-8. Additives were not effective when evaluated in JP-4 fuel.

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UNCLASSIFIED

Security Classification

Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Gunfire Aviation Fuel, JP-4, JP-8 Flammability Limits Fuel System Vulnerability Aviation Safety						

ia

Security Classification

☆U.S.Government Printing Office: 1974 — 758-435/642

EVALUATION OF THE EFFECTIVENESS OF ANTI-MIST FUEL ADDITIVES IN PREVENTION OF AIRCRAFT FUEL TANK ULLAGE FIRES AND EXPLOSIONS

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FOREWORD

This report describes the results of one of the Air Force Aero Propulsion Laboratory programs directed towards the prevention of fire and explosions within aircraft fuel systems. This specific in-house program was accomplished under project 3048, task 304807, work unit 30480752 entitled, "Investigation of Low Penalty Technology for Reduction of JP-8 Hazards." The program was conducted during the period of 1 Dec 1972 through 15 Feb 1973 on the outdoor gun range operated by AFFDL.

Sincere appreciation is extended to representatives of Continental Oil Company, ESSO Research and Engineering Company and the British Defense Ministry for providing the additives and assisting in the blending of the fuel/additive mixtures.

This report has been reviewed and is approved for publication.

B. P. Botteri

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Chief, Fire Protection Branch
Fuels and Lubrication Division

TABLE OF CONTENTS

PURPOSE:

A series of vertical gunfire tests was conducted to evaluate the effectiveness of anti-mist fuel additives in reducing fire and explosions in the ullage of the fuel tanks containing kerosine type (JP-8) fuel. The ability of the anti-mist fuel additives either to eliminate any combustion reaction, measured by fuel tank pressure rise, or to control the level of reaction below a pressure rise of 10 psi could help point the direction of future Air Force efforts in the modified fuels area.

BACKGROUND:

The vulnerability aspects of military fuels have been the subject of much discussion over the past eight years. The high percentage of aircraft losses in South East Asia (SEA) attributed to "fire and explosions" stimulated interest in the determination of the vulnerability of the fuel and the means whereby the fuel could be made safer. Two separate approaches were considered: (1) the modification of the properties of the fuels and (2) the use of a less vulnerable fuel. These approaches were in addition to the various fuel tank protection techniques (flame arrestors, inerting, etc.) which are available for the vulnerability reduction of fuel tanks.

The standard Air Force fuel is a wide cut hydrocarbon fuel, designation JP-4, conforming to specification MIL-T-5624. The normal flammability limits, -20 to 80°F, as well as the nonequilibrium conditions in fuel tanks, lead to a potentially high probability of a fuel fire and explosion at any point in a mission. Gunfire testing by the Air Force has verified the extreme hazards with JP-4 when subjected to impact by 50 calibre armor piercing incendiary (API) projectiles.

Attempts to modify the JP-4 by use of gelling or emulsifying met with little success in the 1960's. Although the flow properties were altered to reduce the fuel leakage and the vaporization rates were reduced by the additives, gunfire testing revealed the same level of vulnerability as the neat fuel. Based on these results, the Air Force suspended work on the modified fuels in 1969 and concentrated efforts on the low volatility fuels approach. This led to the development of JP-8 fuel conforming to requirements of MIL-T-83133. This kerosine, quite similar to commercial jet fuel, has been determined to be less susceptible to fire and explosion induced by gunfire with structural damage that was less than with JP-4. Many other factors, however, must be considered in the determination of the overall desirability of JP-8. A report on this subject is planned for the near future.

Although the Air Force had no specific interest in the modified fuels, efforts by other agencies such as the FAA and the Army have continued to look at modified fuels as a technique to reduce the potential fire hazard in a crash situation. Here the emphasis is on containment of the fuel in the tanks, thus preventing mixing of the fuel with ignition sources. In the past few years efforts in this area have switched from the high viscosity fluids to thin gels or emulsions. This change was made, in part, to overcome some of the fuel handling problems, such as flow of the fuel from the tanks to the engines.

The most recent approach to fuel modification consists of the anti-mist additive. These additives, at a concentration of about one half percent by weight in the fuel, do not appreciably alter the fuel properties. However, under conditions encountered when a fuel tank ruptures on impact, the fuel released exits as droplets in lieu of a fine mist or spray. By reducing the atomization process, the probability of a fire is reduced. Efforts in this area have identified several promising anti-mist additives which, based on either laboratory or full-scale crash tests, significantly reduce the fire hazard in a crash situation. Several commercial materials have been identified. The British Government, through contractual activities with Imperial Chemical Industries (ICI) have developed a material designated FM-4. The U.S. Army, through its laboratory efforts has identified a Conoco Chemical product designated AM-1 and the FAA has sponsored studies which considered AM-1 and other additives. Testing by these agencies, including full-scale aircraft crashes, has been encouraging but not completely successful in eliminating fires. Further, there is no relationship of these results to fires induced by gunfire.

PROGRAM:

An Air Force Aero Propulsion Laboratory in-house gunfire test program was established in order to evaluate the merits of these additives for Air Force usage. Three producers and one sponsor, the British Government, submitted samples of the anti-mist agents for consideration. These samples were supplied at no cost to the government. In return the supplier was provided test results and a copy of the photo coverage of the testing.

SAMPLE PREPARATION:

The additives were supplied in a hydrocarbon solvent, having a flash point in excess of 120°F. This concentrate, consisting of two to five percent of active ingredients, was blended into a neat JP-8 fuel with a flash point of 114°F. This specific batch of fuel had been utilized in previous gunfire tests; therefore, a known baseline existed. Except for FM-4, the actual blending was carried out under the direct supervision of the manufacturer. Both the fuel and additive were stored indoors at a temperature of 60 to 70°F. This precluded the potential problems associated with the additives at the lower temperatures. The ambient temperatures were in the range of 20 to 40°F. In general, the mixing procedure consisted of weighing out a given quantity of JP-8 fuel into an open head 55 gallon drum mounted on a scale. Within the drum was an air driven paddle-type mixer. The speed of the paddle was controlled so that a gentle mixing action was achieved. The concentrate was slowly added to the JP-8 until the desired total weight was achieved. Once the desired percentage of additive, on a weight basis, was obtained, the mixing operation continued until a uniform blend was achieved. The point at which the additive was considered in solution was the disappearance of the shear lines and "globs" of the additive. The mixing time was about 30 to 40 minutes. After blending, the fuel was transferred to clean five-gallon containers. These containers were maintained indoors until just prior to the testing. However, severe ambient conditions less than 30°F, required external heat sources on the gun range to maintain the desired temperatures. Hot air heat sources were applied and, in some instances, bulk fuel temperatures approached 90°F. Fuel was allowed to cool down to 60-70°F range prior to testing.

With the above procedures, three of the four materials were blended with no problems. However, the additive submitted by ESSO Research and Engineering appeared to present some problems. This material, an experimental additive made on a pilot run, when added to JP-8 formed a slightly cloudy mixture. Additional mixing time and modification of the blending procedure did not change the solution. Further, a few very small "globs" were noted. These results raised a serious question as to whether the additive was in solution. However, due to time restrictions, it was not possible to obtain another sample or to further investigate the solubility problem. Therefore, the blend was tested in this condition with a note on solubility.

TEST SETUP:

The testing was conducted at WPAFB on the horizontal gun range, operated by AFFDL. Since this outdoor range is normally used only for horizontal tests, it was necessary to design and construct a special rig which permitted testing in a vertical mode. This rig, as shown in Figure 1, consisted of a test platform attached to a hydraulic scissors type of lift. In order to maintain flexibility, the entire setup was made portable so that it could be towed to the range and installed or removed in a one-day period. The test article, along with power, instrumentation, photo coverage and the fire control system was mounted on the test platform. This setup was remotely controlled from the test console located in the instrument trailer. The trailer was located just behind a revetment adjacent to the range. To assist in evaluation of the data, as well as fire control, a closed-circuit TV system was included in the test setup.

Once the vertical lift rig was in place, the test platform was raised to the desired height. A 50 calibre weapon with bolt action was located just below and slightly in front of the rig. Provisions were for a 60° pitch-up between the weapon and the ground, thus giving a 30° obliquity for the bottom surface of the test article. For fire control, three CO_2 nozzles were positioned in the catch-basin area, just below the entrance and at the exit area of the projectile. In order to minimize damage by the projectile exiting to the tank, a backstop, consisting of 4 x 4 oak timber, backed by a one and one-half inch aluminum plate, was an integrated part of the test setup. Added safety measures included the standby of the Base Fire Department to extinguish the fire if the normal system was insufficient.

The test article consisted of a one hundred gallon rectangular tank 18-inches high, 36 inches x 36 inches. Primary structure was one-inch steel plates with provisions for entrance and exit plates. The entrance area located on the bottom consisted of an 8-inch diameter flange with a steel retainer ring. Exit area on the top was 28 inches in diameter, which also, utilized a steel retainer ring. These areas contained the normal aircraft type of aluminum (2024-T3) with the thickness of 0.090 inch at the entrance and 0.180 inch at the exit. O-ring grooves in the flanges assured complete sealing of the test article during the testing. The instrumentation within the test article consisted of a pressure transducer and two thermocouples, one measuring fuel temperatures and the other measuring ullage temperatures. Figure 2 shows the test setup.

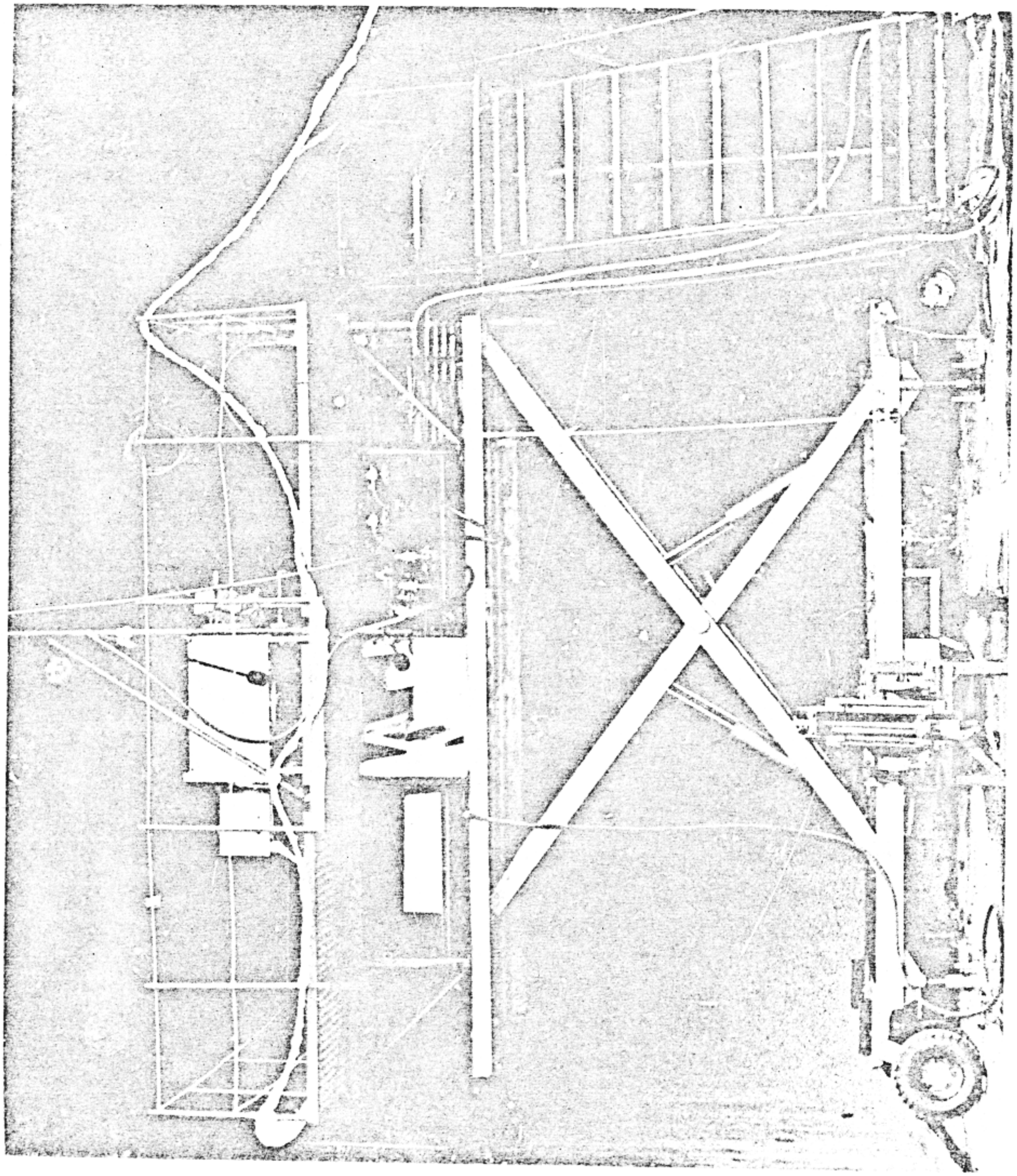

Figure 1. Modified Test Rig at WPAFB

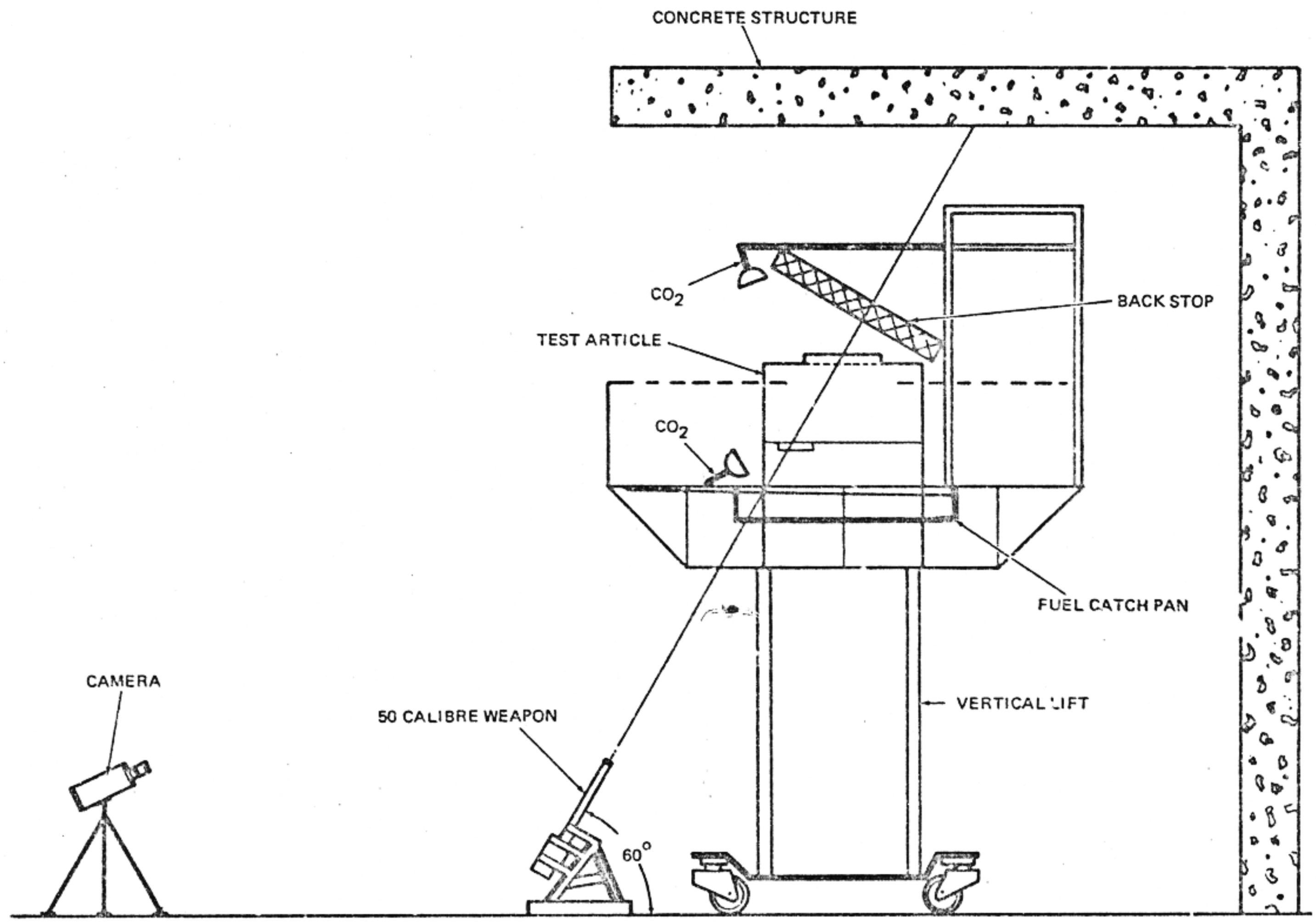

Figure 2. Profile View of Test Setup

The standard test sequence consisted of placing approximately six gallons of test fluid in the test article which corresponded to a liquid level of three inches. Since high shear rates, associated with pumping action could possibly alter the anti-mist additives, the fuel was poured through the exit area and then the tank was sealed. As soon as the range was cleared, the test was conducted. The threat for these tests consisted of a 50 calibre Armor Piercing Incendiary (API), type M-8, fired at a velocity of approximately 2400 ft/sec. This velocity in conjunction with the 0.090 inch 2024-T3 entrance plate and 30° obliquity assured maximum incendiary burning within the ullage of the test article. The total travel of the projectile through the liquid was four inches. This test setup resulted in approximately 95% ignition of the various fuels during the test program.

RESULTS:

The testing was designed to provide for at least fifteen tests at any one set of conditions. A high number of tests was chosen so that statistical analysis could be conducted on the results. Past gunfire tests have demonstrated that there is a certain amount of uncertainty associated with projectile/tank interactions, hence it is not possible to rely on a few tests.

The baseline was established with the neat JP-8 fuel. A total of fifteen tests was conducted and there were reactions in thirteen tests; the average pulse pressure rise, created by the explosion of the fuel vapors, was 38.0 psi. This data was in agreement with past gunfire tests with JP-8. In contrast the average pressure rise encountered with JP-4 was 54.8 psi.

The objective of the anti-mist additives was to defeat the normal fine spray of fuel associated with projectile penetration in a liquid to vapor mode. Based on the results from the four different additives, this appears to be a feasible method for protection of the ullage of JP-8 fuel systems. The data from these gunfire tests are shown in Table I. Two materials, Conoco AM-1 and ICI FM-4, each at a concentration of 0.3% by weight, were effective in controlling the internal reactions. Although the percentage of ignition was about the same as that of the neat JP-8, the average pressure rise was less than 10 psi. Out of the thirty-two tests, with these two additives, there were only five tests where the pressure rise was greater than 10 psi. The belief of AFAPL is that if the reaction severity can be limited to a pulse pressure rise less than 10 psi, then the damage to most fuel tanks would not be catastrophic.

The data pertaining to the XD 8132 also indicates a reduction in the quantity of fuel reacting with the incendiary, but the reduction is not as significant as that obtained with either AM-1 or FM-4. A greater number of tests resulted in pressure rises greater than 10 psi and the average was in excess of the desired level of 10 psi. The performance of the ESSO A in JP-8 was not appreciably different than the neat JP-8. Since there was a question pertaining to the solubility of the additive in the fuel, it is difficult to determine whether the performance is truly indicative of that anticipated with this material.

Table I

SUMMARY OF ANTI-MIST FUEL ADDITIVE EVALUATION

Fuel/Additive*	Total Shots	No. of Reactions	Avg. Pressure Rise (psi)	Highest Pressure (psi)	No. of Reactions Over 10 psi
Base Line Neat JP-4	16	14	54.8	72.0	14
Neat JP-8 (Flash Point 114°)	15	13	38.0	55.0	13
JP-4 + FM-4	15	12	67.5	79.0	12
JP-8 + ESSO A	16	16	31.7	62.0	14
JP-8 + FM-4	16	14	8.6	40.0	2
JP-8 + AM-1	15	12	9.8	33.0	3
JP-8 + XD 8132	15	15	13.1	30.0	6

*All fuel additives at a concentration of 0.3% by weight with exception of XD 8132. Concentration was 0.7%.

For comparison purposes, a series of tests was conducted with JP-4 which resulted in average overpressures in the order of 55 psi. Sufficient FM-4 concentrate was available to permit blending of an anti-mist fuel with a JP-4 base. Since at the test temperatures the vapor phase of JP-4 would be in the flammable zone, we did not expect the presence of the anti-mist additive to alter the probability of a fire. In fact, it appeared that the overpressures with the additive were greater. Average pressure rise was 67.5 psi vs 54.8 psi for the neat fuel. Since all the tests were conducted at fuel temperatures of 50 to 70°F, neat JP-4 could be driven towards an over-rich condition while the additive/JP-4 was maintained in the flammable zone.

STATISTICAL ANALYSIS:

Statistical methods were used in the comparison of the various fuel types to assess the question, "If a difference between the response variables (overpressure) for two fuels is noted, is the difference small enough that it could have occurred by chance, or is it so large that it most probably is a true measure of the difference between the two fuels?" The following statistical expressions were used in this analysis (the reader may refer to the many textbooks on the subject for details).

The sample mean

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i$$

where $x_1, x_2 \ldots x_n$ denotes the responses of the random variable x, and n is the size of the sample, provides an unbiased and minimum variance estimate on the population mean μ, which is unknown.

The sample variance

$$S^2 = \left[\sum_{i=1}^{n} (x_i - \bar{x})^2 \right] \Big/ (n-1)$$

provides an unbiased estimate of the population variance σ^2. Moreover, if S_1^2 and S_2^2 are two independent estimates of the same unknown σ^2, based on n_1 and n_2 samples, respectively, then

$$F = S_1^2 / S_2^2 \quad \text{or} \quad S_2^2 / S_1^2$$

(the ratio selected in such a way that the larger S^2 is in the numerator). This yields an F with $n_1 - 1$ and $n_2 - 1$ degrees of freedom for the numerator and denominator, respectively, assuming $S_1^2 > S_2^2$, which could be compared with F distribution values for homogeneity of variance.

The T test which was used to test for the significant difference of means was based on the assumption that there was "homogeneity of variance." Thus, the F ratio was used as a measure to check the validity of this underlying assumption. Values of the F ratio near one are desired. Once such an assumption is established as valid, then any difference in the data is solely due to the difference in means. In a large number of cases in Table II, the F ratio was not significant, which ensured homogeneity of variances. Hence, we made a general assumption of "homogeneity of variance," which enabled us to use the T test for the difference in means.

The criterion for comparing the means was the Student T test.

$$T = \frac{|\bar{x}_1 - \bar{x}_2|}{\left(\frac{(n_1 - 1)\,\sigma_1^2 + (n_2 - 1)\,\sigma_2^2}{n_1 + n_2 - 2}\right)^{1/2}} \left(\frac{n_1\, n_2}{n_1 + n_2}\right)^{1/2}$$

A T_c value was chosen to test the results. If the calculated T is less than T_c, there is probably no significant difference between the means. If the calculated T is larger than T_c, the two means are not necessarily different, but it provides a strong argument in favor of a difference.

A T_c value associated with the 95 percentile point was used in the comparison. This is equivalent to a 10% error for the "two-tail" problem of interest; that is, if 100 sets of response variables are to be compared, at least 90 sets would verify the conclusion and no more than 10 sets would not. Values of T_c are given in most statistical reference books as a function of degree of freedom ($DF = n_1 + n_2 - 2$) where, for example, n_1 is the number of tests with JP-4, and n_2 the number with JP-8.

The results of the statistical analysis for the various fuel combinations are given in Table II. It should be noted that the mean overpressures of Table II were based on all tests whereas the average overpressure of Table I was based on only those tests involving a fuel reaction. The reason being that the probability of ignition could be a function of fuel type and since the incendiary projectile functioned for all tests, it was desirable from a reduction in aircraft vulnerability standpoint to include all the test results in the statistical analysis.

The results show that all fuel types (JP-8, JP-8/ESSO-A, JP-8/FM-4, JP-8/AM-1, JP-8/XD-8132) had statistically significant lower overpressures than did JP-4, at least to the 90% confidence level. Using the "best" additive (FM-4) in JP-4 did not show a significant difference when compared to neat JP-4. With the exception of ESSO-A, all additives in JP-8 resulted in significant lower overpressures than did neat JP-8. Finally, FM-4 and AM-1 were the "best" additives in JP-8 and no statistical difference between these two additives was proven in the test program.

Table II

STATISTICAL OVERPRESSURE (psi) RESULTS

No.	TEST DESCRIPTION	OBS. - n	SIGMA - σ	MEAN - $\bar{x}^{(1)}$	F RATIO	T VALUE	$T_c^{(3)}$
1	JP-4 vs JP-8	16 15	20.27 15.31	47.937 32.933	1.75	$2.31^{(2)}$	1.699
2	JP-4 vs JP-4 w/FM-4 (0.3%)	16 15	20.27 28.88	47.937 54.0	2.03	0.68	1.699
3	JP-4 vs JP-8 w/ESSO-A (0.3%)	16 16	20.27 15.78	47.937 31.687	1.65	$2.53^{(2)}$	1.697
4	JP-4 vs JP-8 w/FM-4 (0.3%)	16 16	20.27 9.44	47.937 7.50	4.61	$7.23^{(2)}$	1.697
5	JP-4 vs JP-8 w/AM-1 (0.3%)	16 15	20.27 10.05	47.937 7.833	4.06	$6.90^{(2)}$	1.699
6	JP-4 vs JP-8 w/XD 8132 (0.7%)	16 15	20.27 8.33	47.937 13.067	5.92	$6.19^{(2)}$	1.699

Table II (continued)

No.	TEST DESCRIPTION	OBS. - η	SIGMA - σ	MEAN - $\bar{x}^{(1)}$	F RATIO	T VALUE	$T_c^{(3)}$
7	JP-8 vs JP-4 w/FM-4 (0.3%)	15 15	15.31 28.88	32.933 54.0	3.56	$2.50^{(2)}$	1.701
8	JP-8 vs JP-8 w/ESSO-A (0.3%)	15 16	15.31 15.78	32.933 31.687	1.06	0.22	1.699
9	JP-8 vs JP-8 w/FM-4 (0.3%)	15 16	15.31 9.44	32.933 7.50	2.63	$5.61^{(2)}$	1.699
10	JP-8 vs JP-8 w/AM-1 (0.3%)	15 15	15.31 10.05	32.933 7.833	2.32	$5.31^{(2)}$	1.701
11	JP-8 vs JP-8 w/XD 8132 (0.7%)	15 15	15.31 8.33	32.933 13.067	3.38	$4.42^{(2)}$	1.701
12	JP-8 w/ESSO-A (0.3%) vs JP-8 w/FM-4 (0.3%)	16 16	15.78 9.44	31.687 7.50	2.79	$5.26^{(2)}$	1.697

Table II (continued)

No.	TEST DESCRIPTION	OBS. - η	SIGMA - σ	MEAN - $\bar{x}^{(1)}$	F RATIO	T VALUE	$T_c^{(3)}$
13	JP-8 w/ESSO-A (0.3%) vs JP-8 w/AM-1 (0.3%)	16 15	15.78 10.05	31.687 7.833	2.46	4.98 (2)	1.699
14	JP-8 w/ESSO-A (0.3%) vs JP-8 w/XD 8132 (0.7%)	16 15	15.78 8.33	31.687 13.067	3.59	4.07 (2)	1.699
15	JP-8 w/FM-4 (0.3%) vs JP-8 w/AM-1 (0.3%)	16 15	9.44 10.05	7.50 7.833	1.13	0.10	1.699
16	JP-8 w/FM-4 (0.3%) vs JP-8 w/XD 8132 (0.7%)	16 15	9.44 8.33	7.50 13.067	1.29	1.74 (2)	1.699
17	JP-8 w/AM-1 (0.3%) vs JP-8 w/XD 8132 (0.7%)	15 15	10.05 8.33	7.833 13.067	1.46	1.55	1.701

(1) Mean overpressure (psi) based on all tests.

(2) Significant statistical difference.

(3) T_c = T value at 95% (10% error - two tail).

ADDITIONAL TESTS:

Samples of the additive/fuel blend were subjected to complete specification (MIL-T-83133) analysis, and results of pertinent properties are shown in Table III. The areas which resulted in "out of spec" values can be attributed to the composition of the additives. Since the materials may be classified as high molecular weight polymers, the existent gum test, consisting of evaporation of the fuel, would be expected to result in a high value. In fact, the Army Fuels Laboratory has considered this test as a means of measurement of additive concentration. In other test results, the thermal stability, pressure drop and the smoke point tests indicate the tendency for these materials to clog fine filters. This is a more serious problem area for it points out potential problems associated with ground handling where filtration is a factor.

Table III

COMPARISON OF FUEL SPECIFICATION TEST

Test	JP-8	AM-1	ESSO-A	XD 8132	FM-4
Gravity °API	43.7	43.5	43.5	42.6	44.3
Freezing Point °F	Below -51	-62	-65	-24	Below -51
Existent Gum mg/100ml	0.4	201.4	163.0	254.4	155.6
Smoke Point	24.0	Crust Forms on Wick, Won't Burn			
Flash Point, °F	112	114	112	114	115

In addition to the specification tests, the viscosity of the materials was determined at three temperatures: 77°, 0°, and -30°F. High viscosity values were obtained and several materials appeared to be thixotropic at -30°F. The results of these tests are shown in Table IV.

CONCLUSIONS:

1. The test program indicated that the anti-mist additives at a concentration of 0.3% by weight in JP-8 fuel can be effective in the control of fuel tank explosions resulting from 50 calibre incendiary gunfire.

2. When used in JP-4 fuel, the anti-mist additive was not effective in reducing the explosion hazard.

Table IV

VISCOSITY OF ANTI-MIST FUELS AT VARIOUS TEMPERATURES

Kinematic Viscosity, CS

SAMPLE	TEMPERATURE			
	77°F	0°F	-30°F	
JP-8	1.74	4.53	8.07[b]	
FM-4	1.78	4.59	8.17[a]	
XD 8132	6.66	24.19[a]	a,c	
ESSO-A	13.21	34.5[a]	56.1[a]	
AM-1	7.83	20.58[a]	37.4 40.4	a, d
Repeat of AM-1 (Sample 2)			44.8 55.5 58.2	a, d
Repeat of AM-1 (Sample 3)			42.2 46.5	a, d

[a]Precipitation observed

[b]Slight haze; ice crystals

[c]Could not measure; thixotropic

[d]Sample AM-1 appeared to be thixotropic at -30°F

3. The characteristics of the anti-mist additives, that is, the high molecular weight composition, create several potential compatibility problems associated with fine filters or orifice passages to be encountered in A/C fuel systems.

4. Low temperature operation of the fuel/additives could be a problem within the aircraft due to the apparent increase in viscosity.

RECOMMENDATIONS:

The Air Force interest in further development of the anti-mist fuel additives is dependent upon the decision for conversion from JP-4 to JP-8 fuel. In view of the energy crisis and the general reduced availability of hydrocarbon fuels, the conversion from JP-4 to JP-8 for Air Force operations is not considered feasible, at least not for the near-term future. If the change is undertaken, then it is recommended that additional studies be directed towards the identification of the class or species of additives which offers the most potential in terms of vulnerability reduction and minimum impact on system performance. Future studies should concentrate on the latter area and determine if, by minor variation of the structure of the additives, the potential problem areas of low temperature operation, filter clogging and shear stability can be eliminated.