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Emulsified Fuel for Military Aircraft¹

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An analysis of statistics of aircraft crashes shows that approximately 70 percent of the fatalities are due to fire. The fire hazards in a crash situation are largely associated with liquid fuel. These problems may be either minimized or eliminated by thickening the fuel. This paper summarizes work carried out under an Army contract (DA 44-177-AMC-387(T)) aimed at the formulation of JP-4 fuel emulsions which reduce the fire hazards associated with liquid JP-4. Two JP-4 emulsions (designated WSX-7063 and WSX-7165) which appear to meet the study contractual requirements possess 99 percent of the fuel value associated with JP-4; they reduce the rate at which combustible vapors are released; they have yield stresses which will retard flow through a tank puncture; they are stable over the temperature range of —20 F to 130 F (WSX-7165 is stable over the range of —65 F to 160 F); and they are compatible with aircraft materials of construction. WSX-7165 is being made in 1000-gal batches and it is under evaluation by various engine manufacturers. The fuel has also been tested in several simulated crash situations and the results were quite favorable.

¹The views presented herein represent those of the authors and do not necessarily reflect the official Department of the Army position.

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Emulsified Fuel for Military Aircraft

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This paper is a report on work done under an Army-funded contract (DA 44-177-AMC-387(T)) on fuel emulsions. The work involved formulation of a fuel emulsion for use in aircraft to minimize the fire hazards associated with liquid JP-4 fuel. The properties of two fuel emulsions formulated under this contract will be discussed along with their handling characteristics and safety performance.

Background

In aircraft crashes approximately 70 percent of the fatalities are due to fire and not the crash itself. The fire hazards in a crash situation are largely due to liquid fuel. Fire hazards arise with existing fuels whenever fuel lines and/or tanks are ruptured by the force of impact in a crash situation. An analysis shows that, on impact, the fuel forms a mist and comes in contact with ignition sources. The fuel is then ignited and the flames spread very rapidly. These problems can be either minimized or eliminated by thickening the fuel. Thickening the fuel can be accomplished in two ways, either by gellation or emulsification. From a technical and practical standpoint, emulsification looks like the best approach to the safety problem (1).² Emulsions have several major advantages over gels: (1) emulsions are temperature insensitive, i.e., there is essentially no change in flow properties over a wide temperature range, (2) emulsions can be removed from tanks of low surface energy because they do not wet such surfaces, (3) emulsions appear to be stable in low shear pumps and when pumped they break at the nozzle where it is desirable, and (4) emulsions are fairly easy to reconstitute if broken.

Even though the emulsified fuel exhibits about the same vapor pressure as the original fuel, it is rendered safer in three distinct ways. First, the rate of vaporization per unit area is reduced under both dynamic and static conditions. Second, the tendency of the fuel to atomize on impact is very much less than with the unthickened fuel. Third, since the fuel is broken up into discrete mounds as opposed to a rather continuous

pool when a tank ruptures, rapid flame spread is minimized. Individual mounds may burn fiercely, but a large safety advantage is still gained because the fuel does not cover a large surface area; thus, flames are localized and will not spread rapidly.

Prior to our work, the Army investigated several emulsified fuels in their safety fuel program; however, all fuel emulsions investigated had one or more deficiencies (2,3,4). Some of these are listed below:

- Poor shelf-life
- Poor high- and low-temperature stability
- Incompatibility with practical materials of construction
- Lower combustion efficiency in comparison to the unmodified fuel

Thus, the purpose of this work was to formulate and evaluate fuel emulsions which have more satisfactory physical properties. These fuel emulsions were to be burned directly in aircraft engines. It is also envisioned that emulsification will reduce the hazards encountered in the logistical hauling of fuel. These fuels must meet almost all the requirements of liquid fuels. The principal characteristics that a fuel emulsion must possess for use in Army aircraft are summarized herewith.

Composition. Contain at least 97 percent of the fuel or its equivalent.

Stability. (1) Stable at room temperature for at least 30 days, (2) stable at -20 F and up to 130 F (desired; stable at -65 F and up to 160 F), (3) stable under a gravitational force of 500 g, (4) stable with respect to vibration (0.2 g force for 24 hr), (5) resistant to bacterial and fungal growth.

Corrosion. Must be compatible with general materials of construction.

Flow Properties. A yield stress > 1000 dynes/sq cm.

Safety Properties. Must substantially reduce rate of flame spread, rate of evaporation, and rate of burning.

Emulsion Theory

An emulsion is a heterogeneous system consisting of at least two immiscible liquids, one of

² Numbers in parentheses designate References at the end of the paper.

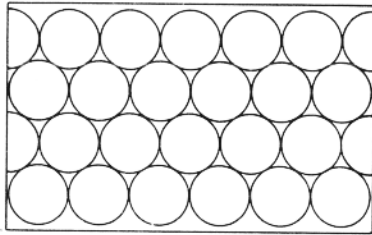


Fig.1 Diagrammatic representation of an emulsion containing 74 vol percent of disperse phase

which is dispersed in the other in the form of droplets. Thus, an emulsion consists of three major components:

- A disperse phase (internal or discontinuous phase)
- A continuous phase (external phase)
- An emulsifier (which may be either cationic, anionic, or nonionic)

The phase which is in the form of droplets is the disperse or internal phase and, the phase in which the droplets are dispersed is the continuous or external phase. In our fuel emulsions, JP-4 was to be the internal or disperse phase; the continuous phase material was to be defined.

In order to stabilize the emulsion against coalescence of the dispersed droplets, a third component is required: an emulsifier. The emulsifier which formed JP-4 fuel emulsions having the required resistance to flow (yield stress) and stability also had to be defined. In our approach to the problem, we mainly screened nonionic emulsifiers in order to minimize problems such as corrosion and combustion deposits which are frequently observed with members of the other classes of emulsifiers. Thus, the program resolved itself into defining the continuous phase material (s) and emulsifier (s) which form stable, viscous emulsions with JP-4 as the disperse phase and incorporated the critical requirements previously outlined.

At low concentrations (<74 vol percent) of disperse phase, the droplets are essentially spherical in shape. If the droplets were homogeneous spheres, the emulsion could contain only 74 vol percent of the JP-4 and the droplets would be packed so that they would just touch one another (see diagram in Fig.1). This close packing is responsible for the yield stress observed with these emulsions. Yield stress is defined as the minimum pressure required to initiate flow under standard conditions.

The dispersed droplets in our fuel emulsions, which contain 97.6 vol percent disperse phase, are not spherical. Rather, they are distorted poly-

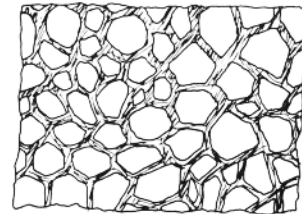


Fig.2 Diagrammatic representation of an emulsion containing 97.6 vol percent of disperse phase

hedra; this is shown diagrammatically in Fig.2. This shows the difficulty encountered in the stabilization of such a system. The significance of this is that the interfacial film about the droplets (formed by the emulsifier) is under considerable strain. Thus, for stabilization, an emulsifier which forms a very strong interfacial film is required. Therefore, emulsifiers capable of forming strong hydrogen bonds are preferred.

It is also obvious from Fig.2 that the more disperse phase present for any given emulsifier system, the more unstable the emulsion. For high-internal-phase emulsions at a fixed internal phase level (97 percent), optimizing the emulsion system resolves itself into minimizing the amount of emulsifier and maximizing the amount of continuous phase. This was, therefore, the strategy followed in this program.

APPROACH TO THE PROBLEM

Our approach involved the screening of continuous phase materials using the following criteria:

- Must be immiscible with JP-4.
- Must be a liquid; if not a liquid, must be soluble in a solvent which is immiscible with JP-4.
- Must have a solubility parameter ≥ 12 and be capable of hydrogen bonding.

The first two criteria are the basic general requirements for emulsification. The last item is based on a literature reference (5) which indicates that, if the solubility parameter of the continuous phase is less than 12, it is very difficult to form an emulsion with a hydrocarbon as the disperse phase. This is due either to the great tendency of such solvents to extract the emulsifier from the interface and/or the ease of solubilizing the disperse phase in the presence of such solvents and an emulsifier.

Continuous phase materials were selected for screening on the above basis. Organic solvents mixed with water were initially investigated as continuous phases; compositions initially corre-

Table 1 Solubility of Span 80 and Tween 80 Emulsifier in the Continuous Phase Materials Shown

	Weight Percent								
Organic Material A	100	65.0	48.5	--	--	--	--	--	--
Organic Material B	--	--	--	--	--	--	54	70	100
Organic Material C	--	--	--	41.0	57.0	100	--	--	--
Water	--	35.0	51.5	59.0	43.0	--	46	30	--
Appearance of Solution with 10% emulsifier	Hazy	Hazy	Hazy	Hazy	Hazy	Clear	Hazy	Hazy	Hazy
Acetone required to clear haze (ml)	--	1.0	2.0	4.0	2.5	--	2.0	25	25

sponded to freezing points of -20 F and -65 F. The pure solvents were not investigated initially as continuous phases because the literature suggested that, for nonaqueous systems, the hydrophile/lipophile balance (HLB) is not applicable (6). An emulsifier consists of an oil-loving part (lipophile) and a water-loving part (hydrophile); HLB is simply the percent of hydrophile in the emulsifier divided by 5. The HLB system was developed for water-based emulsions and is related to the solubility of emulsifiers in water (7). Therefore, for nonaqueous solvents mixed with water, the HLB parameter will apply. For such systems, the advantage to this is that only emulsifiers having the HLB in the required range will form stable emulsions; therefore, it was necessary to try only a limited range of emulsifiers. To minimize the number of experiments in search of effective emulsifier-continuous phase combinations, it was highly desirable to have the HLB system apply.

Determination of Required Emulsifier HLB

Using mixtures of water and nonaqueous solvents as the continuous phase, the required emulsifier HLB for emulsification of JP-4 was determined. To do this, we used the standard Atlas HLB Kit in which the emulsifier HLB varied from 2 to 18. The required emulsifier HLB was determined by adding 1 cc of the emulsifier from the HLB Kit to 1 cc of the continuous phase material. To this mixture was added 50 cc of JP-4 with vigorous shaking, after which the mixtures were allowed to stand. The emulsifier blend forming the most stable emulsions represented the required emulsifier HLB for the system. In this way the HLB requirement was determined with ± 1 HLB unit. This was done using each emulsifier blend in the HLB Kit for several

continuous phase systems in order to establish experimentally that an HLB in excess of 11 was required to emulsify JP-4 no matter what the continuous phase.

Screening Emulsifiers

After having determined the optimum emulsifier HLB, we next selected emulsifiers for screening on this basis. This narrowed down the number of emulsifiers considerably but still left a large number for screening. In order for an emulsifier to form a stable emulsion having JP-4 as the disperse phase, the emulsifiers must be most soluble in the continuous phase over the entire workable temperature range of the emulsion (-20 F to 130 F). Thus, the emulsifier must not only have the required HLB but must be most soluble in the continuous phase rather than the JP-4 from -20 F to 130 F. Therefore, emulsifier solubility in the continuous phase was used as another means of screening emulsifiers. Since hydrogen-bonding represents an excellent means of increasing solubility, continuous phase materials which have high hydrogen-bonding capabilities were given priority in our screening program.

Screening of emulsifiers with respect to solubility in the continuous phase involved simply mixing one part emulsifier with nine parts of the continuous phase material and observing whether a clear solution resulted. If the solution was hazy, a portion of the mixture was titrated with water in an effort to clear it. If it was not possible to clear it, the second portion was titrated with acetone in an attempt to clear it. In this manner, the degree of emulsifier solubility could be estimated and it was possible to assess whether the emulsifier was soluble enough to make it worthwhile for further screening. This approach

Table 2 Apparent Effect of Solubility Parameter of Continuous Phase on Emulsion Stability

	Weight Percent								
Organic Material(A)	100	65.0	48.5	--	--	--	--	--	--
Organic Material(B)	--	--	--	--	--	--	54	70	100
Organic Material (C)	--	--	--	41.0	57.0	100	--	--	--
Water	--	35.0	51.5	59.0	43.0	--	46	30	--
Solubility Parameter	14.2	16.6	18.6	21.4	20.5	18.0	18.3	16.7	13.4
<u>Stability (Vol.% Separation)</u>									
• 30 days @ room temp.	**	--	0.0	0.0	0.0	0.0	--	(90.0)*	**
• Six freeze-thaw cycles	--	65.0	10-15	10.0	5.0	1.5	65.0	--	--
* Broke after 24 hours									
** No emulsion possible									
<u>Composition of the Emulsions</u>									
1.5% Emulsifier									
1.5% Continuous Phase									
97.0% JP-4									

also allowed us to determine if the solvent plus water (in any combination) would be worth investigating with the given emulsifier system. If the emulsifier-continuous phase mixture was clear or required very little acetone or water to clear it, preparation of an emulsion was attempted with that emulsifier-continuous phase combination (Table 1).

The data presented in Table 2 basically show the apparent effect of solubility parameter (8) of the continuous phase on emulsion stability. The data show that for a given emulsifier system, the solubility parameter of the emulsifier must be close to that for the continuous phase. With the emulsifier combination Span 80 and Tween 80, optimum stability occurs with a continuous phase material having a solubility parameter of roughly 18.0. Because of this trend, we tried completely non-aqueous organic materials A, B, and C as continuous phases. The data in Table 2 show that only material C produced an emulsion, and this emulsion had greatly improved stability over this same material mixed with water. Organic material C apparently works with the emulsifier combination used because there is a reasonable match in solubility parameters and because of strong hydrogen-bonding between this continuous phase material and the

emulsifier. The latter makes the emulsifiers more soluble in this particular continuous phase than in the other solvents tested. This is further substantiated by the results of our solubility data for the aforementioned continuous phase materials with the same emulsifier combination (Table 1). Only in the case of continuous phase material C is a clear solution formed with this emulsifier combination. Thus, it is necessary to match solubility parameter, HLB, hydrogen-bonding, and polarity of the emulsifier and continuous phase for optimum solubility of the emulsifier in the continuous phase and for the production of an emulsion of maximum stability.

Laboratory Preparation of the Emulsions

The following procedure was proved most effective in the preparation of the fuel emulsions discussed in this paper. The emulsifiers were added to the total volume of JP-4 to be emulsified. The continuous phase material was added to a bottle fitted with a screw cap. The JP-4-emulsifier blend was then added to the continuous phase in small increments with intermittent shaking. This was continued until about one-fifth of the JP-4 was emulsified. The "seed" emulsion was then

Table 3 Compositions of WSX-7063 and WSX-7165 Fuel Emulsions

	Weight Percent	
	WSX-7063	WSX-7165
Continuous Phase	1.50	2.00
Emulsifier	1.50	1.0
JP-4 (MIL-T-5624G)*	97.0	97.0
*Contains both anti-icer and corrosion inhibitor		

Table 4 Some Typical Properties of WSX-7063 and WSX-7165 Fuel Emulsions

Property	WSX-7063	WSX-7165	JP-4
Yield Stress, dynes/cm ²	2000	2700	0.0
<u>Stability (Vol % Separation)</u>			
• 30 Days at Room Temperature	0.0	0.0	-
• Six 6-Hr Cycles at 130°F	2.0	trace-0.50	-
• After Centrifugation for 1 Hr at 500 g (RCF)	0.0	0.0	-
• Six 16-Hr Cycles at -65°F	75.0	0.0	-
Vibration Stability After 8 Hrs at 6 Cycles/Sec and 2 g	No Change	No Change	-
Net Heat of Combustion, BTU/lb	18,938	18,952	19,166
Four-Ball Wear (mm)	0.55	0.75	0.45
Ash Content, Wt%	<0.005	<0.005	<0.005
Sulfur Content	<200 ppm	<200 ppm	<200 ppm
Reid Vapor Pressure	1.9	2.0	2.3
<u>Compatibility - Corrosion (One Week at 130°F) of:</u>			
Aluminum	0.0 mg/in ²	+0.2 mg/in ²	0.0
Magnesium	<0.5 mg/in ²	-	0.1
Bronze	8.5 mg/in ²	5.0 mg/in ²	0.3
Copper	10.0 mg/in ²	~5.0 mg/in ²	0.2
304 Stainless	0.0 mg/in ²	0.1 mg/in ²	+0.4
Titanium Alloy	0.0 mg/in ²	0.2 mg/in ²	+0.4
Mild Steel	0.1 mg/in ²	0.5 mg/in ²	0.3
<u>Swelling Of (% Increase)</u>			
Neoprene	19	37	26
Butyl Rubber	148	146	143
Buna N (MS-902)	22	18.5	11
Buna N (MS-29513)	43	42	34
Silicone	87	85	86
Viton	5.0	3.4	3.0
<u>Resistance To Organism</u>			
Aerobacter Aerogenes at 86°F	>30 days	>30 days	>30 days
Pseudomonas Aeruginosa at 86°F	>30 days	>30 days	>30 days
Cladosporium Resinae at 77°F	>30 days	>30 days	>30 days
Flame Propagation Rate Relative to JP-4	2.0%	1.0%	100%
Burning Rate/Unit Volume Relative to JP-4	~20%	<10%	100%

Table 5 Other Engineering Properties of WSX-7063 and WSX-7165 Fuel Emulsions

Property	WSX-7063	WSX-7165*	JP-4
Specific Gravity at 60°F	0.782*	0.782*	0.756
Evaporation Rate (Relative to JP-4)			
After 1% Loss at -20°F	11%	0%	--
After 10% Loss at 25°F	7%	2%	--
After 20% Loss at 130°F	8%	4%	--
After 20% Loss at 160°F	8%	4%	--
Specific Heat (BTU/lb °F) *			
At 0°F	0.44*	0.44*	--
At 50°F	0.47*	0.47*	0.43
At 100°F	0.40*	0.40*	0.39
Thermal Conductivity* (BTU/sq Ft-Hr-°F)			
At 0°F	< 0.0815	< 0.0815	0.0815
At 50°F	< 0.0802	< 0.0802	0.0802
At 100°F	< 0.0790	< 0.0790	0.0790
Electrical Conductivity Specific, Mhos/cm at 77°F	3.5×10^{-6}	2.8×10^{-6}	1.0×10^{-13}
Damage To The Following at 77°F			
Methacrylate Plastic	Surface Damage in 8 hrs	Surface Damage in 8 hrs	Surface Damage in 8 hrs
Teflon	No Damage in 8 hrs	No Damage in 8 hrs	No Damage in 8 hrs
Polyethylene	No Damage in 8 hrs	No Damage in 8 hrs	No Damage in 8 hrs
Paints (alkyd.)	Damage in 8 hrs	Damage in 8 hrs	Damage in 8 hrs
*Calculated Values			

transferred to a Hobart mixer, which was mixed on the number 2 speed range until all the JP-4 was emulsified. The remainder of the JP-4-emulsifier blend was then added at such a rate so as to prevent the accumulation of free fuel.

In the laboratory process, a bottle is used initially to start the emulsion because the volume of continuous phase used is so small that it would not be mixed well by the Hobart.

DISCUSSION OF THE EMULSIONS FORMULATED AND CHARACTERIZED

Using the above approach, two fuel emulsions were formulated and completely characterized. These two emulsions were designated WSX-7063 and WSX-7165. The compositions of these emulsions are shown in Table 3.

Table 4 shows the typical properties of both WSX-7063 and WSX-7165 in comparison with those of JP-4. (Other engineering properties for these

emulsions are shown in Table 5.) Because the continuous phases of these emulsions are nonaqueous, the net heat of combustion per pound of these emulsions is about 99 percent that of JP-4. (Due to the high density of the emulsifier and continuous phase, there is essentially no difference in Btu/gal.) These emulsions are compatible with essentially the same elastomers and materials of construction as JP-4. Slight corrosion of bronze and copper was observed with these emulsions; however, this can be eliminated by use of small quantities of commercially available copper deactivators (if necessary) (Table 6). However, the level of corrosion of copper and bronze with these emulsions probably does not warrant this. At room temperature for a period of 30 days, the corrosion of copper and bronze with both WSX-7063 and WSX-7165 is almost insignificant as shown by the data in Table 7. The data further indicate that WSX-7165 is slightly more compatible with copper and bronze than WSX-7063.

Table 6 Effect of Commercial Inhibitors on Compatibility of WSX-7063 With Copper

Material	Copper Strip Corrosion Test (ASTM D 130)
JP-4	1B
WSX-7063 without inhibitor	4A
WSX-7063 with Amoco 150 (0.25%)	1B
WSX-7063 with UOP Cu Deactivator (0.25%)	1A
WSX-7063 with NaSul EDS (0.25%)	1A
WSX-7063 Vanlube 601 (0.25%)	1A
WSX-7063 with Mercaptobenzoethiazole (0.25%)	1A

Table 7 Compatibility of WSX-7063 and WSX-7165 With Materials of Construction at Room Temperature After 30 Days

Metals	Appearance		Wt Loss (Mg/in ²)	
	WSX-7063	WSX-7165	WSX-7063	WSX-7165
Copper	slight discoloration	slight discoloration	2.1	1.3
Bronze	very slight discoloration	very slight discoloration	2.1	0.73
316 Stainless Steel	no change	no change	0.0	0.0
Mild Steel	one very small rust spot	no change	0.0	0.0
Aluminum	no change	no change	0.0	0.0

Evaluation of Emulsions With Respect to Release of Combustible Vapors

Both emulsions, WSX-7063 and WSX-7165, were investigated with respect to evaporation rate over the temperature range of -20 F to 160 F under both dynamic and static conditions. These tests were run to ascertain the extent to which emulsification of JP-4 inhibits the generation of combustible vapors by the fuel (Figs.3-8). These data show that both WSX-7063 and WSX-7165 reduce the evaporation rate of the fuel by a significant extent even at 160 F. The release of combustible vapors was inhibited by a significant amount under all conditions with both emulsions. At -20 F, the rate of evaporation was reduced about 95 percent with WSX-7063 and about 99+ percent with WSX-7165 (Fig.3); at 77 F, the reduction was about 97 percent with WSX-7165 and some 90 percent for WSX-7063 (Fig.4); at 160 F, the reduction was about 86 percent with WSX-7063 and about 95 percent with WSX-7165 (Fig. 6). Fig.8 shows the evaporation rate data plotted for WSX-7063 and WSX-7165 on the same graph at

different temperatures. These data show that the evaporation rate of WSX-7165 at 160 F is about 29 percent less than that observed with WSX-7063 at 130 F. Thus, WSX-7165 has a significantly higher degree of thermal stability in comparison to WSX-7063.

The flame spread rates of WSX-7063 and WSX-7165 are some 98 to 99 percent less than the flame spread rate for liquid JP-4 (Table 4). The burning rates of these emulsified fuels on a laboratory-scale are some 80 to 90 percent less than that for liquid JP-4 (Table 4). In actual practice it can be expected that the burning rate reduction will be even greater since the burning rate depends on the surface area of fuel. The surface area of the emulsion in a crash situation would be many orders of magnitude less than the surface area of liquid JP-4 in the same crash situation. Thus, these data show that emulsification does indeed substantially reduce the rate of flame spread, rate of burning, and rate of evaporation of JP-4.

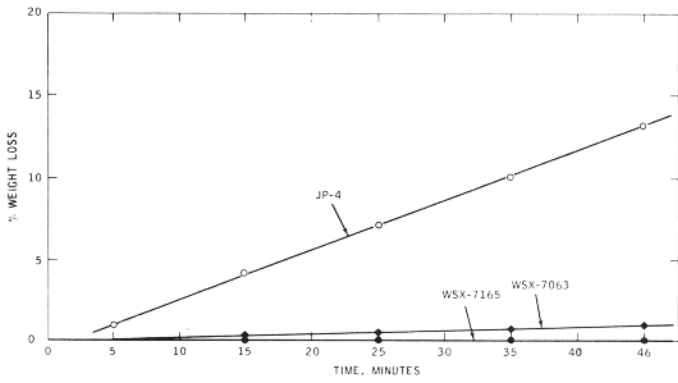


Fig. 3 Evaporation rates for JP-4 and fuel emulsions at -20 F

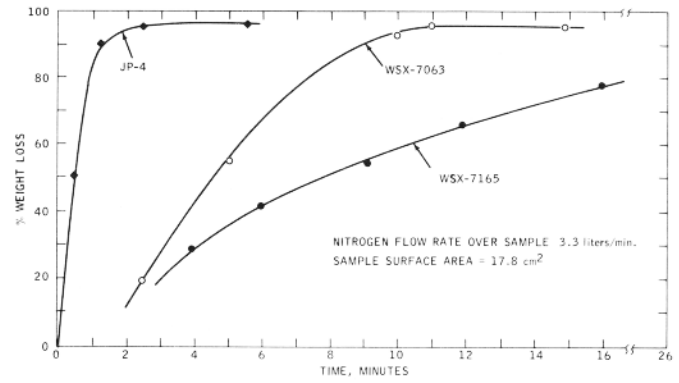


Fig. 6 Evaporation rates of JP-4 and fuel emulsions at 160 F

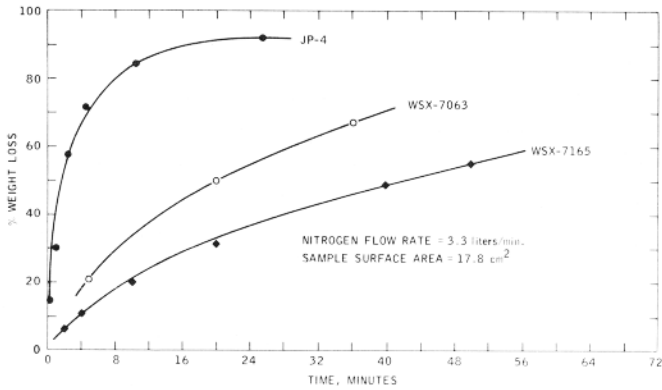


Fig. 4 Evaporation rates for JP-4 and fuel emulsions at 77 F

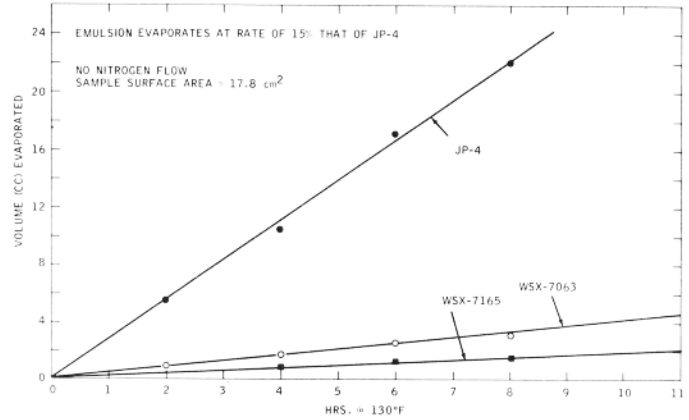


Fig. 7 Static evaporation rates for JP-4 and fuel emulsions at 130 F

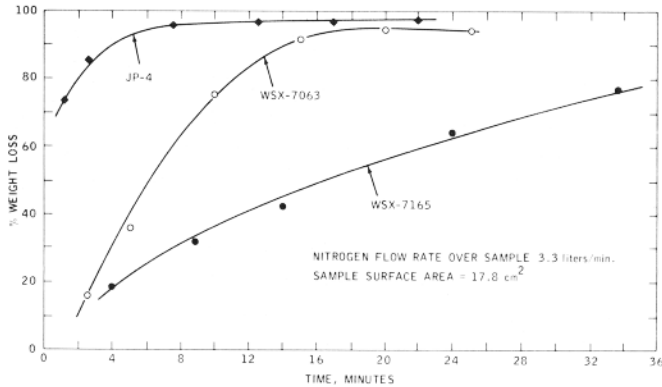


Fig. 5 Evaporation rates for JP-4 and fuel emulsions at 130 F

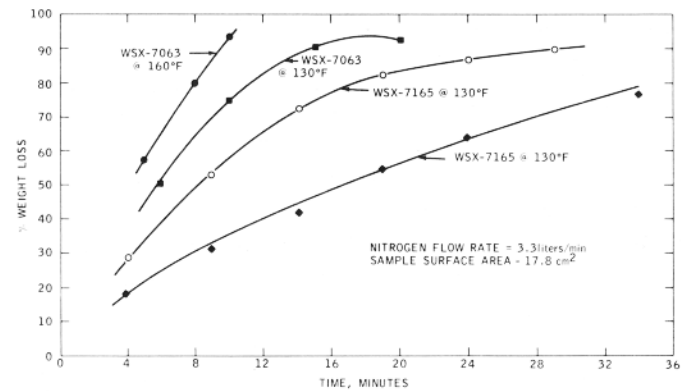


Fig. 8 Evaporation rates of WSX-7165 and WSX-7063 at 130 F and 160 F

Flow Properties of WSX-7063 and WSX-7165

WSX-7063 and WSX-7165 fuel emulsions have yield stresses of 2000 dynes/sq cm and 2700 dynes/sq cm, respectively. The flow curves which demonstrate the non-Newtonian behavior for these emulsions are shown in Fig. 9 along with similar data for JP-4. The viscosities of these emulsions are

100,000 to 150,000 times greater than that of JP-4 at low shear rates. The high apparent viscosity and high yield stress of these emulsions means that they will retard flow from a hole caused by a 0.50-caliber bullet. It has been estimated that when a bullet of this size enters a tank sideways,

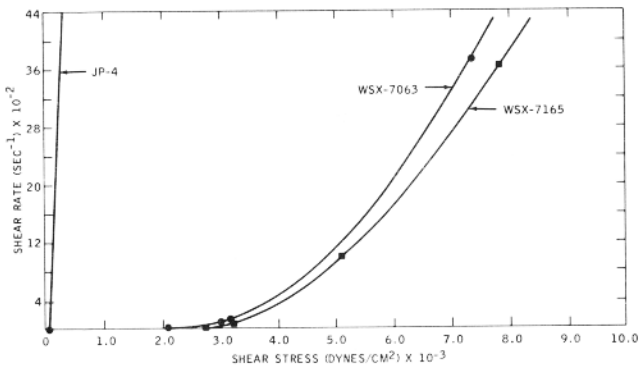


Fig. 9 Flow properties of WSX-7063 and WSX-7165 at 77 F

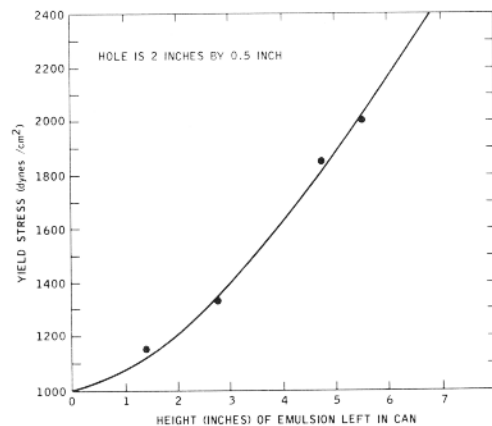


Fig. 10 Effect of emulsion yield stress on flow from a can with a hole

it will create a hole with dimensions of 2 in. by 1/2 in. The effect of yield stress on the tendency of fuel emulsions to flow through such a hole was investigated. These studies were carried out in a cylindrical can 5 1/2 in. high and 3 7/8 in. in dia with one end removed. The results are summarized in Table 8. The data in Table 8 show that for an emulsion with a yield stress of 2000 dynes/sq cm or greater, there will be essentially no flow of the fuel through a hole with dimensions of 2 in. by 1/2 in. under a static head of 5.50 in. The data further show, Fig. 10, that an emulsion having a yield stress of about 1000 dynes/sq cm would flow freely through a 2-in. by 1/2-in. hole. It appears that a yield stress of about 1500 dynes/sq cm is the lower limit for minimizing the flow of emulsions through a 0.50-caliber bullet hole. However, it should be realized that under sufficient static head, any emulsion will flow through such a hole.

Stability of WSX-7063 and WSX-7165

Both fuel emulsions, WSX-7063 and WSX-7165, also meet all the requirements set for stability (Table 4). These emulsions have a shelf life of

better than 30 days without any separation of JP-4; they are stable with respect to centrifugation at a relative centrifugal field of 500 g's; they are stable with respect to vibration over a frequency range of 0 to 32 cps at a frequency amplitude of 0.4 g for 24 hr. These emulsions were also stable when they were dropped in a partially filled steel bomb from a height of 200 ft onto a concrete surface. There was no appreciable breakdown of the emulsion (~ 0.5 percent). This test simulates a helicopter crash and indicates that no appreciable misting of the emulsion will occur under such an impact. The emulsions are stable to freeze-thaw conditions from -20 F to 130 F for WSX-7063 and from -65 F to 130 F and higher for WSX-7165 (Table 4). No separation was observed with these emulsions at 130 F for one week in a closed container. There was no separation of WSX-7165 at -65 F and 160 F after 30 days. When prepared properly, both of these emulsions are also stable with respect to the forces encountered in air, ship, and train shipment.

Table 8 Effect of Yield Stress on Amount of Emulsion Which Flows Through a 2-in. by 1/2-in. Hole

Yield Stress (dynes/cm ²)	Height (inches) of Emulsion After 5 Minutes*
1150	1.375
1325	2.75
1850	4.75
2000 (WSX-7063)	5.50
2300	5.50
2700 (WSX-7165)	5.50

* For all practical purposes emulsions stopped flowing

Table 9 Effect of Chemicals on the De-Emulsification of WSX-7063 and WSX-7165

Emulsion Sample	% JP-4 Separated			
	Emulsifier*		Isopropyl Alcohol	
	1.0%	2.0%	2.0%	5.0%
WSX-7063	97.0	97.0	97.0	97.0
WSX-7165	85.0	97.0	76.0	97.0

* Alkylaryl polyether alcohol

Pumpability

WSX-7063 and WSX-7165 were pumped using two different pumps at ambient temperature, 130 F, and -30 F, without any appreciable breakdown of the emulsion. These pumps are of the vane type, and they rotated at 480 rpm and 1200 rpm. The first unit (480-rpm pump) pumped the emulsions at 100 gal per min without any breakdown, whereas the low output (2 gal per min) high-speed vane pump caused about a 3 percent breakdown of the emulsion. Breakdown of the emulsion also occurred when we

tried to pump these emulsions with a 7000-rpm centrifugal boost pump from a helicopter tank. It would appear that emulsions can easily be pumped with a low-speed positive displacement pump, provided that they are not working against a back pressure valve, but that higher speed pumps will tend to cause some separation.

De-emulsification

Both WSX-7063 and WSX-7165 can be de-emulsified chemically or by means of shear. The effect

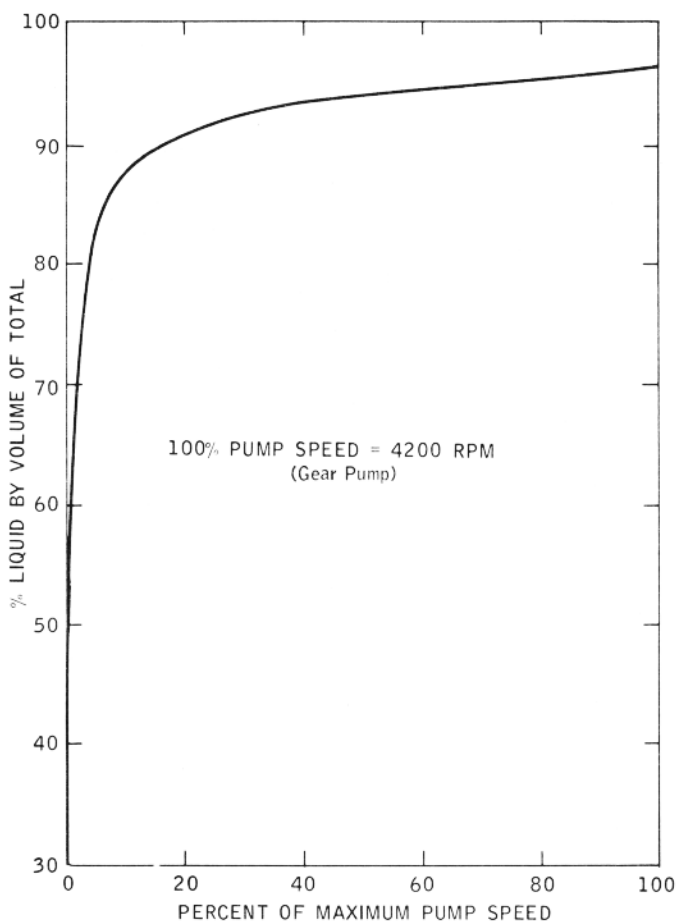


Fig.11 Effect of pump speed on de-emulsification of WSX-7063

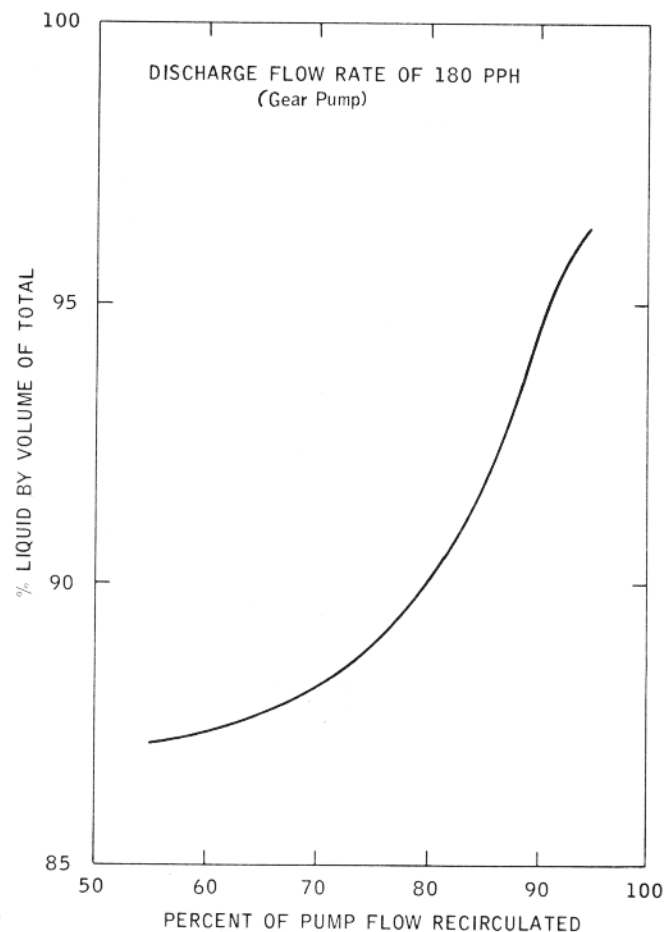


Fig.12 Effect of recirculation back to the pump on de-emulsification of WSX-7063

Table 10 Properties of MIL-T-5624G JP-4 and JP-4 Recovered From the De-Emulsification of WSX-7063 and WSX-7165

Distillation	Typical JP-4*	JP-4 Recovered from:	
		WSX-7063	WSX-7165
Initial boiling point, °F		250	210
10% Fuel evaporated	Report	266	240
20% Fuel evaporated	20% min at 290°F	273	252
End point, °F	485	490	495
Residue, vol. percent	1.5	1.5	1.5
Existent gum, mg/100 ml.	1.0	2.0	2.0
Total potential residue, 16 hour aging, mg/100 ml.	7.4	8.0	7.0
Sulfur, total, percent weight max.	< 200 P.P.M.	< 200 P.P.M.	<200 P.P.M.
Reid vapor pressure, 100°F psi	2.4	1.9	2.0
Heating value heat of combustion (BTU/lb. min)	20,345	19,991	19,995
Copper strip corrosion, ASTM classification	1	1	1
Water separometer index	85 min	15	15
4-Ball wear (7.5 kg, 130°F, 1800 R.P.M., 1 hr.)	0.450	0.436	0.449
<u>Corrosion Data* (mg/in²)</u>			
Aluminum	0.0	0.0	0.0
304 Stainless Steel	+0.3	+0.3	+0.1
Titanium alloy	+0.4	0.0	0.0
Bronze	0.2	0.3	0.1
Mild Steel	0.2	0.2	0.0

* A JP-4 that meets MIL-T-5624G
 ** One week at 130°F

of chemicals on the de-emulsification of these fuels is shown in Table 9. Both fuel emulsions are completely de-emulsified by such chemicals as alkylaryl polyether alcohol, isopropyl alcohol, butyl carbitol, and acetone. WSX-7165 and WSX-7063 fuel emulsions can also be de-emulsified by means of shear in a food blender or a pumping system. Figs.11 and 12 show the effect of shear on the de-emulsification of WSX-7063 in a high-speed gear

pump. The emulsion was de-emulsified completely by pumping in the gear pump at a discharge rate of 180 lb per hr; the pump ran at 4200 rpm and a back pressure of 115 to 400 psig (Fig.11). Fig.12 shows the effect of recirculating the emulsion in the gear pump at moderate pump speeds. The emulsion is completely broken down by increasing the percent of the emulsion recirculated in the pump. Similar results were also obtained with WSX-7165.

JP-4 Recovered from De-Emulsification

The JP-4 recovered from the de-emulsification of WSX-7063 and WSX-7165 by shear was completely evaluated and compared with the JP-4 prior to emulsification. These results are summarized in Table 10. The data in Table 10 show that the de-emulsified fuel from both WSX-7063 and WSX-7165 meet all the specifications of JP-4 (MIL-T-5624G) with the exception of water separometer index (WSI). The WSI for the de-emulsified fuel is 15 (the WSI for JP-4 is 85). This low WSI is due to the very small amount of residual emulsifier remaining in the de-emulsified JP-4, and is of little concern since the recovered fuel would presumably be used promptly. (WSI control is needed only when the fuel is to be stored where it might become wet.)

Summary of Preliminary Full-Scale Evaluations of WSX-7165

Fuel System Evaluation. Fuel emulsions WSX-7063 and WSX-7165 were both evaluated in a T-55 helicopter fuel control system. There was no rust, bacterial or fungal growth, or sticking of valves, linkages and other moving parts in this test. In the runs made in the T-55 system, the fuel system response to the two fuel emulsions was essentially the same as it was with the reference fuel. Some difficulty, however, was encountered in pumping WSX-7165 to the fuel control system because of its relatively high viscosity.

Full-Scale Crash Tests. The Aviation Safety Engineering and Research Division of Flight Safety Foundation, Phoenix, Arizona (AvSER) conducted two full-scale flight crash tests using WSX-7165. This work was performed under contract DAA J02-67-C-0004 from the U.S. Army Aviation Material Laboratories, (USAAVLABS) Fort Eustis, Virginia.

A helicopter crash test was carried out by AvSER in which the fuel tanks of the helicopter were filled with WSX-7165. In this test no fire was observed. A fire was observed in a similar test carried out using liquid JP-4.

Recently a C-45 transport crash test was carried out by AvSER with WSX-7165. The wing and fuselage tanks of the C-45 transport were filled with WSX-7165 fuel emulsion. The plane was powered by liquid fuel in an auxiliary tank located external to the aircraft. On impact the tanks ruptured and a fire occurred only on one side of the plane (the side containing the ruptured auxiliary tank that held the unthickened fuel). There was no fire on the other side of the plane. Due to the nature of the fire it was probably due to the unthickened fuel and/or a ruptured oil line. The fire caused some of the emulsion to ignite but the fire was controllable and there was no fireball.

Preliminary Engine Test. An 11-hr engine

test was carried out on WSX-7165 in a GE 7 LM100 turbine engine by the General Electric Co., Cincinnati, Ohio. This program was carried out under the joint sponsorship of the U.S. Army and the U.S. Navy under Contract DAA-702-67-C--38. The results show that engine starts and operation were about the same with the emulsified fuel as with plain JP-4; running time was limited on the emulsified fuel because of the fuel nozzle clogging (9). Clogging was caused by a higher than normal level of dirt contained in the fuel. Thus, burning of the emulsified fuel does not appear to present any problems at this time provided the fuel is clean.

Scale-Up of the Fuel Emulsions

About 16,000 gal of WSX-7063 and WSX-7165 have been prepared. Because the stability of WSX-7165 is much greater than that of WSX-7063, only WSX-7165 is currently being prepared in the plant. Our experience has involved the preparation of 1000-gal batches of these materials. Initially, some difficulties were experienced in the manufacture of these fuel emulsions, however, these difficulties have been sufficiently minimized so that emulsion of acceptable quality is now being prepared in 1000-gal batch-sizes. The scale-up of these emulsions, however, is still in the development stages. There are still several unresolved questions relative to level and extent of mixing which have to be answered before the large-scale production of these fuels can be considered routine.

Problems Encountered with the Fuel Emulsion

The main problems encountered with the fuel emulsions have been emulsion stability and emulsion cleanliness. The former has been significantly improved by processing conditions, and through the formulation of WSX-7165. Emulsion cleanliness control, on the other hand, is a problem which we have not as yet solved at a plant level. Work in this area, however, is continuing and considerable progress has been made. Emulsions have the disadvantage that the contaminants will not settle out as they will in the liquid fuel. It is therefore mandatory to have an effective way of removing contaminants from the fuel emulsions prior to feeding the fuel to the engine. Work will be carried out to assess the most effective way of achieving this.

CONCLUSIONS

Two fuel emulsions, WSX-7063 and WSX-7165, have been developed which when properly prepared have satisfactory shelf-life and thermal stability, and which appear to be compatible with practical materials of aircraft construction. These fuel

emulsions meet all the tentative requirements of a safety fuel. The data (actual crash tests) from other investigators indicate that there is a considerable safety advantage for emulsified fuel over unthickened fuel. Preliminary engine evaluations show that the performance of the emulsified fuels can be expected to be essentially the same as that with the unthickened fuel provided the fuel is clean. Emulsion cleanliness control is still a problem especially at the plant level and efforts are being made to overcome this problem. The two fuel emulsions that were formulated have been scaled-up and 1000-gal batches of both materials have been prepared. The process, however, is still not routine. Work is continuing to optimize WSX-7165 and WSX-7063 with respect to atomization characteristics and combustion performance.

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