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RAPID GELLING OF AIRCRAFT FUEL

By

A. R. Schleicher

February 1966

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FOR TECHNICAL STAFF AND
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FORT EUSTIS, VIRGINIA

CONTRACT DA 44-177-AMC-112(T)
THE WESTERN COMPANY OF NORTH AMERICA
RESEARCH DIVISION
DALLAS, TEXAS

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This report has been prepared by The Western Company, Research Division, under the terms of Contract DA 44-177-AMC-112(T). It consists of a study to determine the feasibility of rapidly gelling large quantities of aircraft fuels.

The results of this study have shown that large quantities of fuel (up to 50 gallons) can be rapidly gelled with relatively small quantities of chemical additives in less than one second.

Although the feasibility of rapidly gelling 50-gallon quantities of fuel has been demonstrated as described in this report, subsequent investigations have indicated that the practical application of a solidification system to an aircraft is questionable. These investigations revealed the need for mechanical and hydraulic forces for injection of the gelling agents that are not compatible with current and foreseen aircraft fuel systems.

Rapid solidification of fuel remains a promising crash-fire preventive measure. However, recent advancements in fuel emulsions or viscous gels appear to offer a greater potential as a solution to the broad spectrum of aircraft crash-fire problems; therefore, action is being deferred on rapid solidification, pending engineering resolution of those problems associated with injection of gelling agents in aircraft fuel systems.

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February 1966

RAPID GELLING OF AIRCRAFT FUEL

Final Report

by

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Prepared by:

**The Western Company of North America
Research Division
Dallas, Texas**

For

**U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA**

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SUMMARY

Experimental evidence has shown that the severity of accidental hydrocarbon fuel fires can be reduced by chemically solidifying the liquid fuel. The purpose of the subject work was to determine the feasibility of utilizing this principle to reduce the dangers of postcrash aircraft fires.

The feasibility of rapidly gelling large quantities of aircraft fuel has been investigated and established. The types and quantities of chemical gelling agents required were investigated. The times required for the gelling of 50-gallon quantities of fuel have been determined.

Mechanisms and power sources for mixing gelling agents with fuel have been evaluated. The hazards and penalties associated with these systems have been established.

Impact tests were made to determine the reduction of fire hazard with gelled fuel under dynamic conditions. These tests showed radical differences in performance between gels which behave similarly under static tests.

Soap type and amine-isocyanate gels have about equal effectiveness in reducing fire hazards in small scale experiments. The performance of the soap system was decidedly superior in terms of achieving rapid gelling of large quantities of fuel.

A visual presentation of this final report has been made in the form of a narrated color motion picture. This film presents a summary of results of the subject contract and a state-of-the-art report on fuel gelling.

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CONCLUSIONS

It has been proven that large quantities of fuel (50 gallons or more) can be rapidly gelled with relatively small quantities of chemical additives. The solidification of the fuel can be accomplished in less than one second from actuation of the system. As little as 2% (by volume or weight) of the fuel quantity is required in chemicals. This or higher concentrations can greatly reduce the severity of an impact fire with JP-4 jet engine fuel.

Gelling of fuel reduces the fire hazard by three means: reducing rate of fuel evaporation, increasing the burning time compared with liquid fuel, and controlling spread or dispersion of fuel under impact and shear. All of these factors are interrelated. It has been concluded that, under dynamic conditions, the limiting of dispersion of fuel is the factor of greatest benefit.

The testing program under this contract has repeatedly shown that static testing of gels yields little information on hazard reduction and does not adequately differentiate between different types of gels and their relative merits. Dynamic methods are required for meaningful results.

It has been concluded that the sodium soap gelling agents are superior to the amine-isocyanate agents for use in jet fuels (JP-1, JP-4). This judgement is based on: (1) reliability and level of performance, and (2) hazards associated with gelling agents. Certain of the amine-isocyanate agents can be used interchangeably with soap materials in a system designed for the latter. The effectiveness of the best of the amine-isocyanate gels in reducing fire hazards is comparable with that of the soap gels.

The use of propellants such as gunpowder and solid rocket fuels is judged to be the most reliable way to power the fuel solidification system with the least weight penalty. Based on the results of this program, fuel solidification is sufficiently established to progress to the state of actual use testing of an on-board system for a helicopter or light aircraft.

RECOMMENDATIONS

On the basis of information gained in this project, rapid fuel solidification seems feasible and useful at least with quantities of fuel as carried by helicopters and other relatively small aircraft. The approach appears promising enough to justify development and testing of a prototype system on an aircraft. The system should be pretested on laboratory mock-ups and finally tested for function and effectiveness under actual crash conditions. It is recommended that the tests be conducted with a soap type gelling system and that the system be electrically actuated and powered by a solid propellant material.

The gelling agents investigated in this program probably do not represent the ultimate in performance. We recommend further study to develop agents to give stronger gels with less additives. A program to establish firm foundations for predicting, measuring and comparing the properties of fuel gels would assist in applying gel research more effectively to the problem of crash safety.

DISCUSSION

INTRODUCTION

The Government has long been aware of the need for means of controlling postcrash aircraft fuel fires. Fuel fires have been a major cause of casualties in all types of aircraft crashes. Helicopters have a particularly high loss rate, especially on a passenger-mile basis. During the period 1 July 1957 to 30 June 1960, the U. S. Army experienced 42 helicopter accidents which resulted in fires. These crash and fire accidents resulted in 65 fatalities and a loss of \$6,150,000 in aircraft. Statistics for this period also show that probability of mortality was 22 times greater in fire crashes than in nonfire crashes.*

The Army's use of helicopters is steadily increasing. Simultaneously, the problem of postcrash fires becomes more acute. Government agencies have, for a number of years, been exploring various means of reducing fatalities due to such fires, but achievements have been limited.

The U. S. Army Aviation Materiel Laboratories have sponsored research on fuel solidification as a means of postcrash fire prevention. Preliminary experiments indicated that upon impact the solidified fuel would present much less of a fire hazard. The formation of a mist of fuel droplets and vapor would be prevented, reducing the possibility of a flash fire or vapor fireball. The solidified fuel vaporizes less rapidly than liquid fuel. Thus, even if a fire occurred, it would be much less extensive and less intense with the solidified fuel. Utilization of this method requires that chemical agents be injected rapidly into aircraft fuel cells when a crash is imminent. The chemical agents must produce very fast solidification of the craft's fuel supply.

The purpose of the subject program was fourfold: (1) to determine the feasibility of rapidly gelling up to 50-gallon quantities of JP-4 fuel, (2) to determine suitable chemical agents for the purpose, (3) to develop the mechanical means of adding and mixing the chemical agents into the fuel, and (4) to measure the relative hazards of liquid and gelled fuels and the penalties associated with a fuel gelling system. The following discussion is divided into sections covering each of the goals.

* Data taken from Report HF2-60, U. S. Army Board for Aviation Accident Research, Fort Rucker, Alabama, 1960.

FEASIBILITY OF GELLING LARGE QUANTITIES OF FUEL

To determine the feasibility of rapidly gelling a 50-gallon quantity of JP-4 jet fuel, a test bed was constructed. This test bed consists of a fuel tank, capable of holding in excess of 50 gallons, and two chemical injection cylinders. The fuel chamber is fitted with a transparent top. The horizontal cylindrical tank is 40 inches in length by 24 inches in diameter. The removable Plexiglas inspection and observation top is 26 inches long and 24 inches wide. The chemicals are injected from one end below the surface level of the JP-4. On the opposite end of the cylinder, below the fluid level, a four-inch observation window is installed. This window is also used for a light source or a camera location. The tank is vented for safety and has a cleanout opening. The tank is constructed from firebox steel (A285C). The design of the injection system consists of two cylinders, identical in design even though different volumes of chemicals may be used for a single test. The cylinders are constructed of Al06B steel with a design working pressure of 6000 psi and a bursting pressure of 15,000 psi. Free-moving pistons separate the chemicals from the power source. The pistons have multiple o-ring seals. The volume of the cylinders is such that a maximum of 6% total volume of chemicals may be injected into 50 gallons of fuel. The inside diameter of the chemical cylinders is 7 inches. The power source enters one end of the cylinder through a 1/2-inch pipe opening. On the opposite end, a 1-inch pipe plug is fitted with appropriate orifices and shear discs. The liquid chambers have red-line pressure gauges and attachments. Calculations showed that 3500 psi would be sufficient to permit injection of the chemical into the test-bed tank in less than 4 seconds. The orifice sizes can be varied in size from 1/8-inch to 3/4-inch by 1/8-inch increments. It is also possible to use a number of sizes of multiple-holed orifices, if required, as well as distribution tubes with multiple injection points. In actual practice, injection times well under one second were easily attained. A report of injection and gelling times is given in a later section covering mixing of the fuel. Figures 1 and 2 show the test-bed apparatus.

TESTING OF GELLING AGENTS

Laboratory experiments prior to the subject program had shown that it was possible to chemically solidify or gel JP-4 fuel in small quantities. Several chemical systems had been found capable of gelling the fuel. The Western Company had developed systems which had been used in petroleum technology. One of these systems was capable of gelling fuel very rapidly; others gel fuel more slowly. Most of The Western Company (or Westco) gelling agents are based on soap-type compounds. A system of caustic soda with fatty acids was known to rapidly gel fuel by an in-situ reaction. Under the sponsorship of U. S. Army Transportation Research Command* a program was conducted by Southwest

* Now U. S. Army Aviation Materiel Laboratories

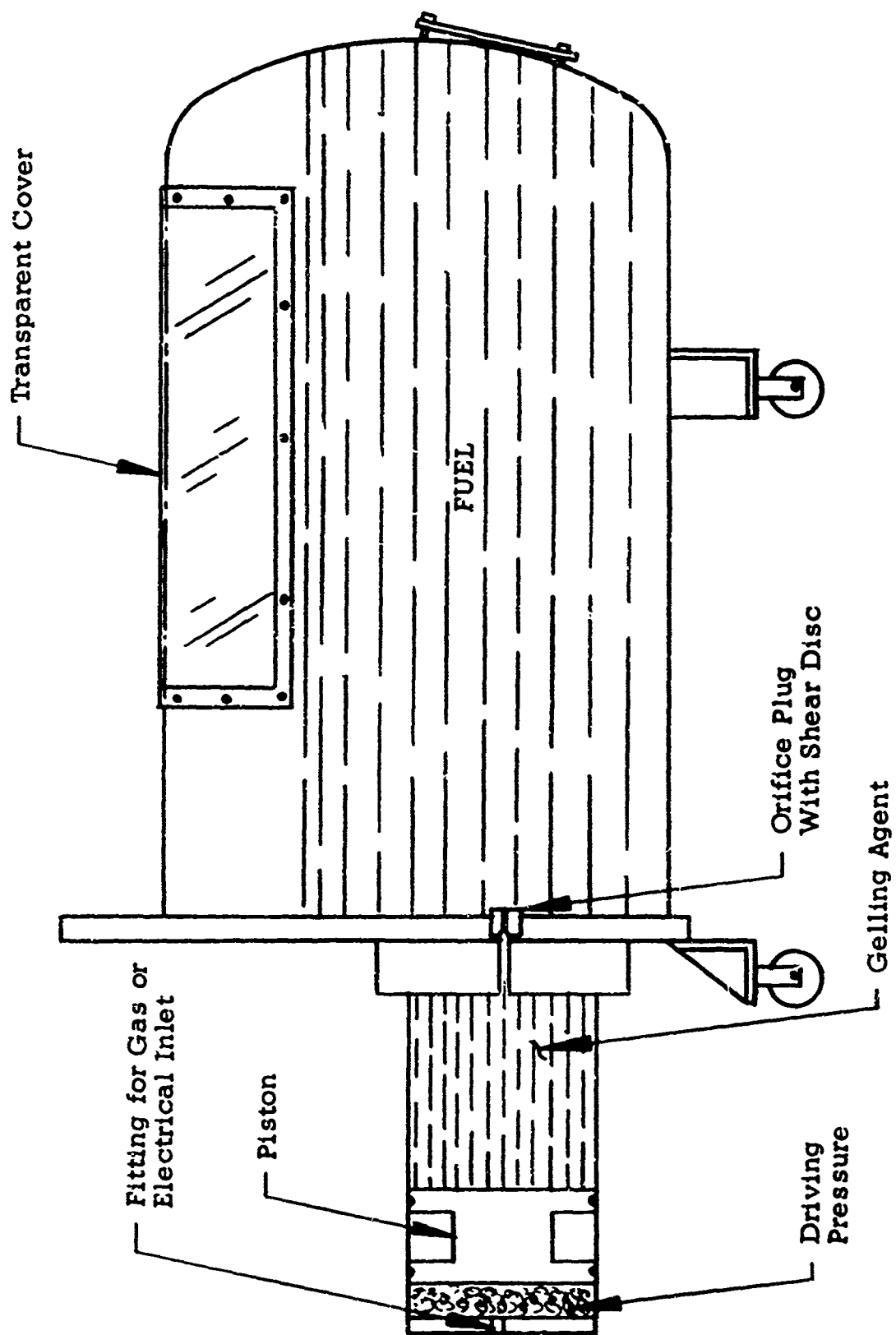


Figure 1. Test Bed for Fuel Gelling

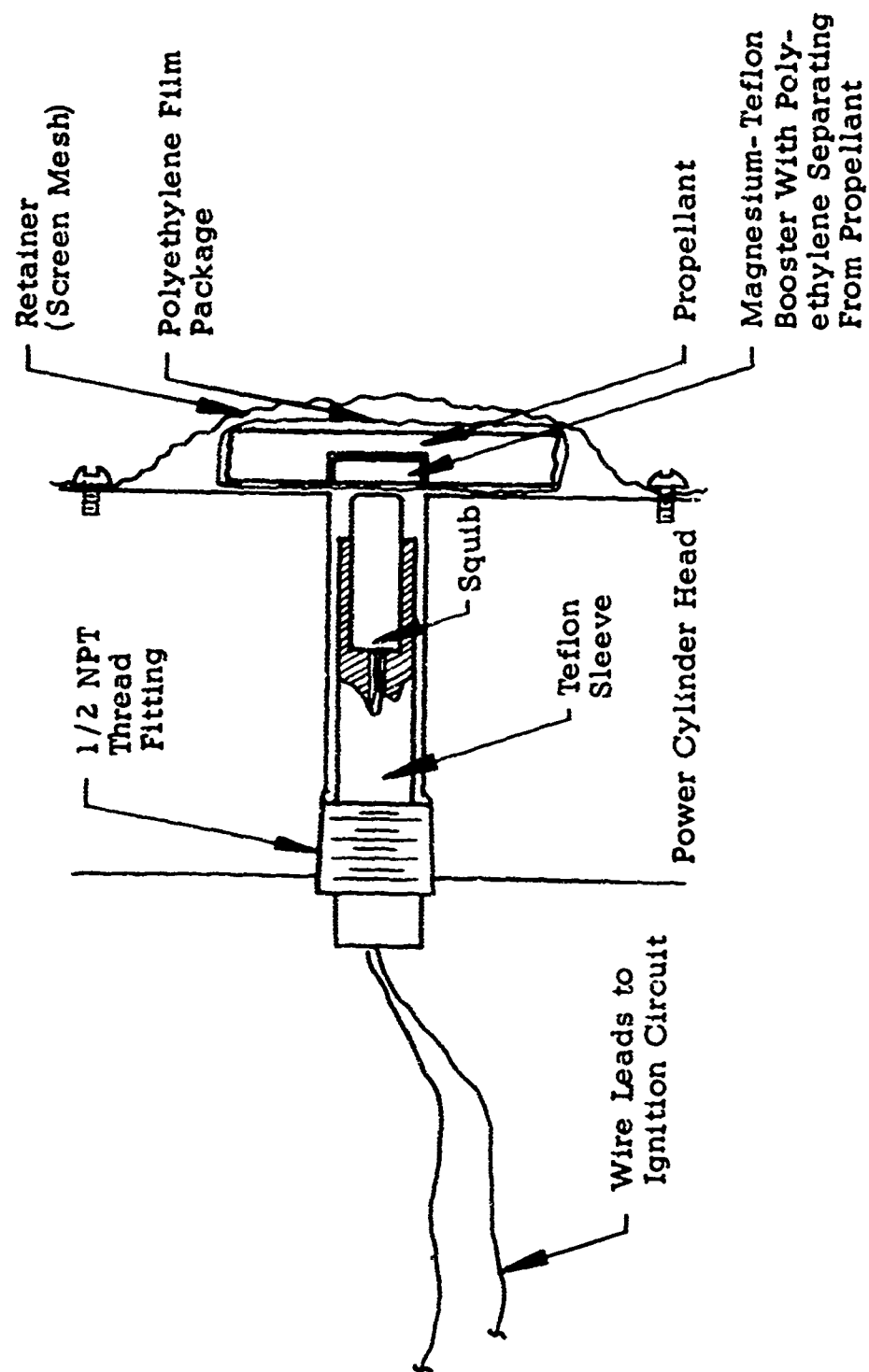


Figure 2. Detail of Propellant Power Arrangement
(Arrangement identical when powder is used with
packet of powder substituted for propellant and booster).

Research Institute investigating fuel gelling by in-situ reaction of amine and isocyanate compounds. A number of amine-isocyanate compounds were found capable of gelling JP-4. In Report USATRECOM 63-50, this work was reported and formulations recommended as being good candidates for a gelling system. The two recommended formulations consisted of toluene diisocyanate (du Pont Hylene TM-65) reacted with either lauryl amine or coco amine.

A comparison of the proprietary Westco gelling agents with amine-isocyanate gelling materials has been made. A number of different amine-isocyanate combinations were tested. Those tested were selected as being commercially available amines as recommended in USATRECOM Report 63-50. In addition, amine-isocyanate formulations developed by Westco were tested. In all cases the isocyanate used was du Pont Hylene TM-65, a blend of the 2,4 and 2,6 isomers of toluene diisocyanate. The recommended isocyanate gels appeared firm when made in beaker quantities of a few hundred cc or less. Examination revealed that these gels were wet with fuel on any exposed surfaces. When placed on paper, these gels wet the paper extensively. The 6% Westco gel is dry to the touch and does not wet other material on contact. The recommended isocyanate gels are brittle; under impact or other stress the structure breaks quite easily, exuding fuel freely. The gels appear to be rigid, fragile microstructures physically retaining the fuel. The fuel appears to be much more tightly held in the Westco gels.

The amine-isocyanate materials recommended were Armeen 12 (Armour Chemical Company) and Alamine 21D (General Mills) with toluene diisocyanate. Different proportions and total concentrations were tried in making these gels. This was done in an attempt to get better strength from these gels. Total concentrations of 10% to 15% were required to give gels approaching the strength of the Westco sodium soap gels at 4% to 6%.

Our experience has shown that gels which appear similar under static conditions may behave quite differently under mechanical stress. This is well known (though not well understood theoretically) in the field of polymer chemistry. There is no well established set of definitions for gel properties, such as hardness, Young's modulus, etc. Many physical properties of gels are time (rate) dependent. For this reason it is difficult to compare results from different experimenters. The time required for a gel to set is an example. Set time is usually based on visual observation for fast systems. Southwest Research Institute in their work apparently measure set time from the time of mixing the reactants. For purposes of the work reported here, we felt that the significant time measure is the complete time required from a start signal (i.e., closure of a switch) through the time required for mixing

until the fuel is too solid to splash or run. All of our time measurements were made on this basis for this program.

Laboratory gels of JP-4 were made with Hylene TM-65 and lauryl and coco amines. In order to obtain a gel it was found necessary to premix one gelling agent with the fuel. If both agents were added simultaneously, the stirring required for mixing destroyed the gel as it formed. Excessive stirring resulted in a slush of fuel and gel. Armeen 12 (laurylamine) is a waxy solid at room temperature. To dissolve laurylamine in JP-4, it was necessary to melt the amine and add it to warm fuel (about 100°F.). If the melted amine is mixed with cold fuel (room temperature or less), the amine tends to precipitate. A good gel was not obtained unless both the fuel and lauryl amine were warmed before mixing. If the solution is cooled to 65°F., a fine precipitate begins to form. Thus, there are drawbacks against the use of laurylamine. The performance in the 50-gallon tests did not show any special benefits to counter these drawbacks.

Considerable effort was devoted to finding an amine-isocyanate formulation with better performance than those previously mentioned. In USATRECOM Report 63-50, it was reported that analine gave no gel, but gave a precipitated product with toluene diisocyanate. Amine 803[®] gave a weak visco-elastic gel. Gelling is a chemical problem involving carefully controlled solubility. We have found that by tailoring solubilities, a virtually infinite number of chemical gelling systems are possible. An amine-isocyanate gel was made by balancing the excessive solubility of the Amine 803 product with the insolubility of the analine product. A gel was obtained with a mixture of these amines, using fatty acids as rate controls. The proportions of agents were varied till the best gel was obtained. The gels thus obtained rivalled the Westco gel in strength and dryness. Static burning rates were only slightly higher than the Westco gel. Data on compositions and comparisons of burning rates are shown in Tables I and II.

Unfortunately, Amine 803 is no longer manufactured and sufficient quantity for large scale tests was not obtainable. Since the development of new gel formulations was actually beyond the contract scope, work on these formulations was discontinued. The experimentation with the new formulations was carried on only because the recommended amine-isocyanate formulations did not appear promising.

Our initial goal in the 50-gallon tests was to obtain gelling times of less than five seconds. After only a few tests with the Westco agents

[®] Experimental product of Union Carbide and Chemical Company, (2 ethylhexyl, 3 aminopropyl ether).

TABLE I
BURNING TIMES, WESTCO GELS OF JP-4

% Volume Gelling Agents	Gel Character	Burning Times
0	Liquid JP-4	8 min. 40 sec.
1	Very viscous liquid	8 min. 9 sec.
2	Weak gel but retains form; light spread when burning	9 min. 40 sec.
4	Firm gel; no spread on burning	19 min. 50 sec.
6	Firm, dry gel; no spread on burning	25 min. 30 sec.
10	Hard, dry gel; crumbles dry; no spread on burning	27 min. 30 sec.

TABLE II
BURNING TIMES, AMINE GELS, 4%

Formulation	Gel Character	Burning Times
1	Firm, dry gel; no spread on burning	17 min. 13 sec.
2	Similar to No. 1; not quite as strong; no spread on burning	16 min. 37 sec.
3	Weak gel, but retains form; no spread on burning	16 min. 50 sec.
4	Somewhat weaker than No. 2; no spread on burning	16 min. 42 sec.
JP-4	Liquid	8 min. 40 sec.

Formulation	Composition by Parts Volume
1	1 analine 1 Hylene TM-65 1 Amine 803 [Ⓢ] 1 Westco Sol'n G ^{ⓈⓈ}
2	Same as No. 1 except Neofat 140 used instead of Sol'n G
3	1 analine 1 Alamine 21-D 1 1/4 Hylene TM-65 1 Amine 803 3/4 Sol'n G
4	1 Alamine 21-D 1 Hylene TM-65 1 analine 1 Neofat 140 ^{ⓈⓈⓈ}

- Ⓢ Experimental product of Union Carbide and Chemical Co. (2 ethyl-hexyl, 3 aminopropyl ether).
 ⓈⓈ Westco's proprietary organic acid formulation.
 ⓈⓈⓈ Product of Armour Chemical Company.

it was evident that a gelling time of one second was not an unreasonable goal. The gelling times are given in the next section of this report.

All of the large volume test successes were achieved with Westco caustic-fatty acid system. No really satisfactory gelling of 50-gallon fuel batches was achieved with the isocyanate-amine systems. The recommended compositions using Alamine 21D and Armeen 12 with toluene diisocyanate were tested in attempts to gel 50-gallon quantities of JP-4. In all cases the gel formed was a slurry which flowed readily from the system when the drain valve was opened, as shown in Figure 3. Concentrations of 4, 6, and 8% of gelling agents were tried. It appears that these gels are so weak that they are broken up by the mixing action as they form in the large system. Due to the poor performance of these systems, no useful hazard evaluation was obtained. It is our opinion that the Amine 803-analine system would perform well in large tests but may require additional testing and development. Table III gives a comparison of typical results in the 50-gallon tests. Further details of comparing the different chemical systems are given under the report section on hazard comparisons.

INJECTION AND MIXING OF GELLING AGENT

Experience has shown that the strength and homogeneity of fuel gels formed by in-situ reactions improves with faster and more thorough dispersion of the gelling agents. The gelling speed likewise increases. Experimental efforts were therefore directed toward developing simple reliable methods of rapidly injecting the chemical agents into the test-bed fuel chamber. Three power sources for propelling the chemicals into the JP-4 have been tested.

1. The compressed-gas injection system, which was powered by compressed nitrogen gas at up to 3500 psi.
2. The low-detonation-rate explosive injection system, consisting of a slow-burning gunpowder.
3. A gas-generating propellant injection system capable of producing the controlled amount of force required.

Times required for complete operation of the system, from initiation till the fuel is solidified, vary with size and configuration of injectors, driving pressures, and power source used. With single-hole 1/4-inch orifice plugs and compressed nitrogen as a power source, the total times ranged from 3 to 1.6 seconds over a range of 250 to 1500 psi working pressure. With 3/4-inch orifice plugs and nitrogen, the times ranged from 1.2 to 0.2 seconds with pressures of 250 and 2000 psi, respectively. Both gelling agents were injected simultaneously.



Figure 3. Amine-isocyanate Gel
Draining From Test Bed

TABLE III
50-GALLON GELLING TESTS (TYPICAL)

Gelling Agents	Volume Concentration (relative to fuel)	Propellant Wt (gms)	Results
Lauryl Amine [Ⓢ] and Hylene TM-65	Total 2%	Approx. 17 (ea. cyl.)	Rapid reaction, in- jection in less than 0.1 sec. Thickened fuel, no gel.
Lauryl Amine [Ⓢ] and Hylene TM-65	Total 4%	Approx. 17 (ea. cyl.)	Rapid reaction, in- jection in less than 0.1 sec. White slurry no gel.
Lauryl Amine [Ⓢ] and Hylene TM-65	Total 6%	Approx. 17 (ea. cyl.)	Same as above.
Westco-Caustic and Fatty Acids	Total 2%	Approx. 17 (ea. cyl.)	Injection in less than 0.1 sec. Medium strength gel in 0.5 sec.
Westco-Caustic and Fatty Acids	Total 4%	Approx. 17 (ea. cyl.)	Injection in less than 0.1 sec. Firm gel in 0.5 sec.
Westco-Caustic and Fatty Acids	Total 6%	Approx. 17 (ea. cyl.)	Injection in less than 0.1 sec. Very firm, dry gel in less than 0.5 sec.

[Ⓢ] Lauryl Amine was maintained at 90°F till injection in above tests.

Tests were also made with one of the gelling agents premixed in JP-4, injecting the other active agent. These tests tend to indicate that even if the premixing of one agent were permissible, the gelling action is not as rapid and consistent as when both agents are injected simultaneously. With Solution G premixed in JP-4, injection of G-5 caused virtually instant gelling right in the injection nozzle. This resulted in large chunks of gel near the orifice, interfering with injection and mixing action. The gelling times resulting were in the range of 5 to 15 seconds. The reverse procedure, premixing G-5 with JP-4, gave even poorer results with gelling times being many seconds.

It was found that separate gas pressure bottles and valves were required for each injection cylinder. When both cylinders were connected to a common bottle, one cylinder would "rob" the other, being completely emptied of chemical before injection from the other cylinder began. Although the compressed gas system was developed till it operated reliably, the weight penalties due to heavy gas reservoirs and valves make this system seem less desirable for an aircraft system than the other two power sources tested.

Very satisfactory results were obtained utilizing a gas-generating solid rocket propellant directly in the power chamber. This propellant is capable of producing gelling in a total time of 1/4 second at pressures of 1500 psi. Times as low as 0.1 second were achieved. Typical repeatable times were around 0.5 second for 50 gallons of fuel. The superior performance of the propellant versus the compressed gas seems to be due to the fact that the propellant generates pressure right where it is needed without having to flow gas through pipes and restrictions into the power cylinder.

About 30 grams of propellant will produce a pressure of 1000 psi in the test-bed power cylinders. The propellant used is Thiokol Company's Type TP-E-8034. The propellant is ignited by a 2-gram pellet of magnesium-Teflon booster. The booster is initiated by a du Pont S-95 electric squib. This combination proved to be very reliable, with no failures in over 100 firings. Comparable results were obtained using the electric squibs to fire Hercules "Red-Dot" smokeless powder. A charge of 8 grams of powder gave results comparable to those obtained with 30 grams of propellant. Both of these materials appear satisfactory for use in a practical system, meeting the criteria of speed, reliability, and low weight. With either material, the weight of the power material would be a negligible part of the total system weight.

Experimental results were obtained on the effects of distributive injection of gelling chemicals in a fuel tank. These tests have shown that it is possible to produce rapid fuel gelling independent of tank geometry. However, the tests also show that more efficient mixing and stronger gels can be obtained by considering tank geometry and

tailoring injectors to take advantage of circulation patterns in the tank.

A vertical test unit was used in a number of gelling tests for comparison with horizontal unit results. The vertical mixer injected the gelling agents down into the fuel. It was found that the vertical unit gave considerably different results from the horizontal. These differences were mainly due to the different tank geometries, but gravity effects were also present. In the vertical unit the fastest injection-gelling time obtained has been about 0.7 second, slightly longer than the best time for the horizontal test bed. It has been shown that either vertical or horizontal injections are usable even though the mixing process is a little different.

Tests in both large test units gave results on the effects of multiple injection points. It is possible to obtain reasonably good gelling with a number of small orifices, but better agitation of the fuel volume is obtained by a few relatively large injection orifices. In general, the more agitation, the firmer and more homogeneous the gel.

A sampling apparatus was constructed and tested. The device permits the taking of an undisturbed sample of the gelled fuel from the test-bed tank. The sample normally consists of a core of gel 3 1/4 inches in diameter and 18 inches long. Through the use of the sampler, laboratory tests may be performed on the undisturbed gel from any depth in the test bed. The sampler consists of a 3 1/4-inch ID cylinder of Plexiglas of 20 inches in length. A plunger, fitted with an o-ring, is used as an aid in lifting the gel from the gelled mass.

The conclusions of the mixing tests using Hylene TM-65 and lauryl or coco amines are summarized as follows:

1. Although the reactions seem fast enough, no success was achieved in the 50-gallon experiments. The gel is not strong enough to withstand the energy required for rapid mixing.
2. The gel produced in the 50-gallon unit was at best a slush.
3. Due to poor gelling, the data on injection and injectors are of no significance.

The conclusions of the mixing tests with Westco agents are summarized as follows:

1. Fifty gallons of JP-4 can be gelled very quickly in the test bed.

2. The gel produced is acceptably uniform throughout the test volume. It was found that gelling had occurred even in restrictions, fittings and pipes leading out of the test bed.
3. The injection rate and gelling time can be controlled by the driving pressures and orifice design.

FUEL GEL HAZARD TESTS

Experiments were conducted to determine the reduction in fuel fire hazards by gelling the fuel. Material hazards and other factors introduced by the gelling system were evaluated. The gelling reduces crash fire hazards in three ways: (1) limiting dispersion of the fuel into a finely divided state and area covered by fuel, (2) reducing the vaporization rate of fuel and, (3) reducing the intensity of burning (giving longer burning times).

Tests comparing vaporization rates of gelled and ungelled fuel confirmed that gelled fuel vaporizes much slower than liquid fuel, especially under impact splash conditions. An apparatus for obtaining consistent gelled fuel vaporization measurements was constructed. The apparatus is based on a modification of the Reid Vapor Pressure Test. The standard Reid test does not give accurate results due to variable surface effects when trying to compare liquid and gelled fuel. In the standard Reid test, the gel cannot be broken up reproducibly. To overcome this difficulty, the Reid apparatus was modified by placing a piston in the fuel cup so that the gel can be extruded through a perforated disc into the vapor chamber. The piston is then retracted and the vapor pressure versus time is read with the apparatus controlled at 100° Fahrenheit. Results thus attained are greatly different from static measurements on the undisturbed liquid or gel. This is shown on two graphs. Figure 4 shows pressure versus time curves for undisturbed JP-4 and JP-4 gelled with several concentrations of the G-5 + Solution G system and an amine-isocyanate system. Of greater importance are the curves in Figure 5. These curves compare liquid fuel and gelled fuel after being forced violently through small-diameter holes. This method more closely simulates a crash condition where fuel would be sheared and forced violently from a ruptured fuel tank. Of particular interest is the time range, about 0 to 5 minutes. Note the much slower vapor release by the gelled fuels.

A comparison of Figures 4 and 5 shows that the static test method may be misleading. Also, it is seen that agitation or splattering does not cause as sharp an increase in vaporization rates of the gels as it does with the liquid JP-4. The curves shown in Figures 4 and 5 also indicate that increasing the gelling agent concentration does not produce a corresponding reduction in vaporization rate. Burning rate tests were

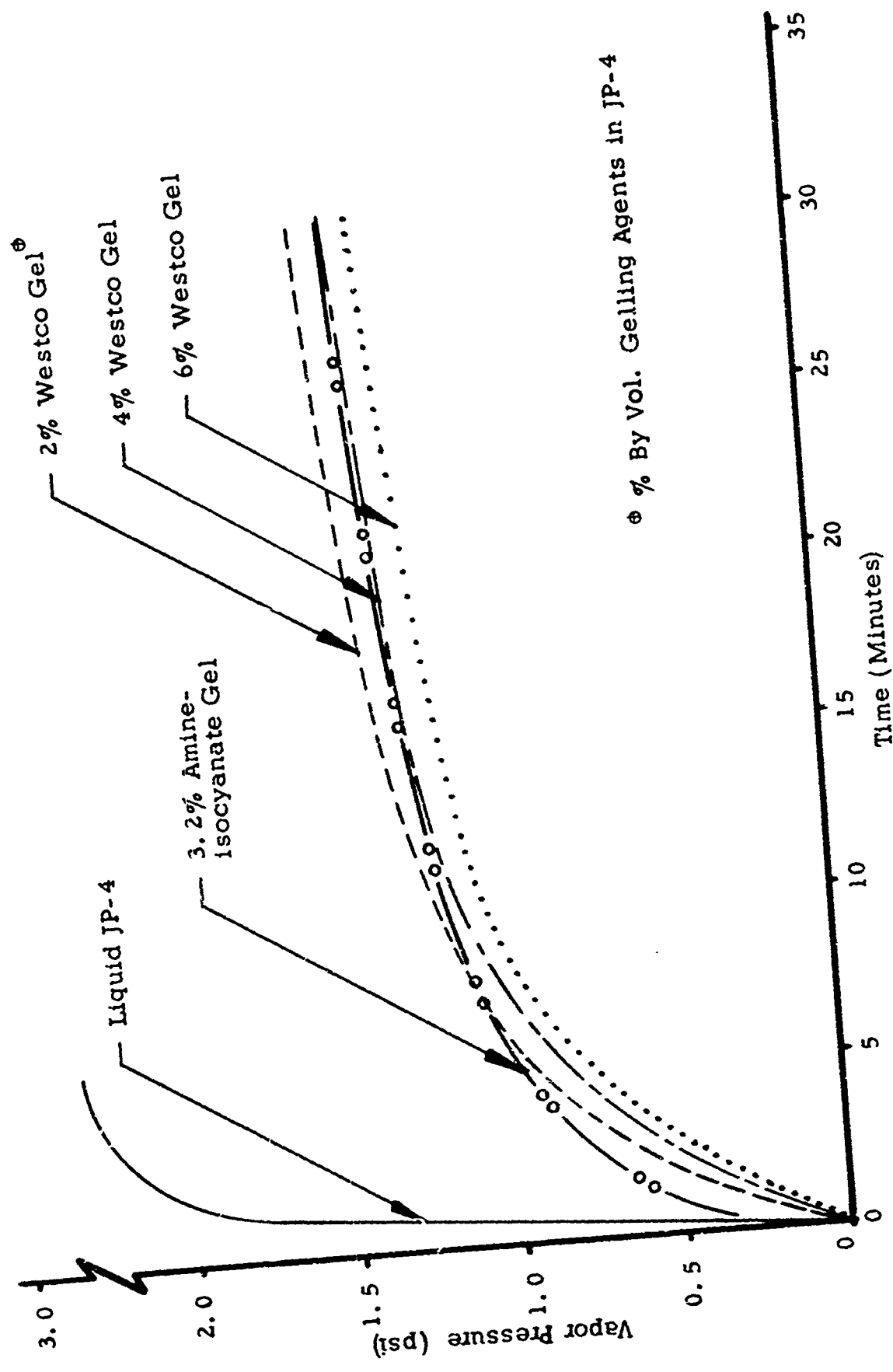


Figure 4. Gel Vapor Pressure (Extruded)

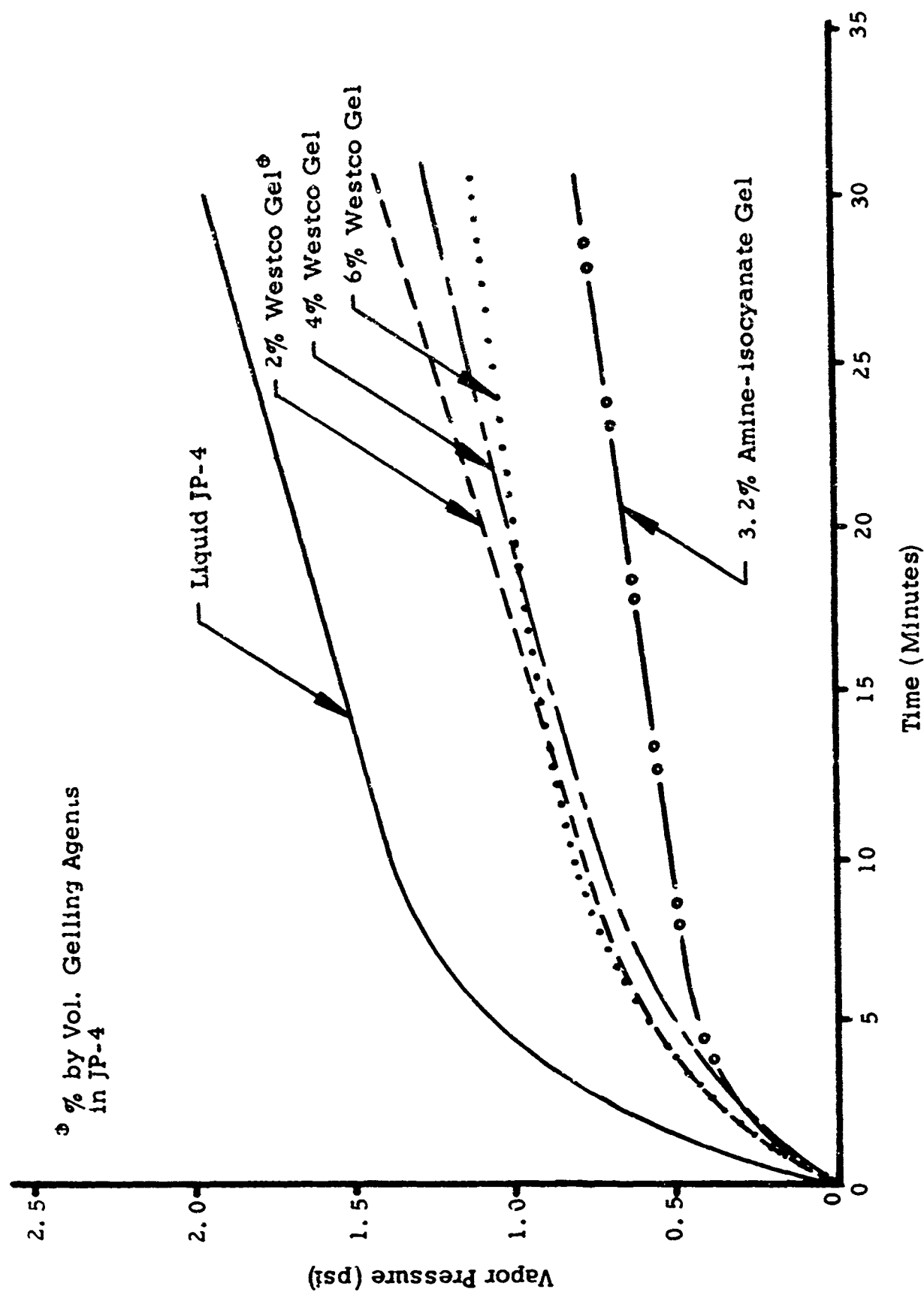


Figure 5. Gel Vapor Pressure (Static)

made to obtain comparisons of liquid and gelled JP-4. The accompanying graph shows the variation of burning times of 160-cc samples of fuel with different concentrations of Westco gelling agents. These samples were cylinders 2 1/2 inches in diameter by 2 inches long. The tests were conducted in a container made of glass foam insulating material. The dimensions of this container are such that a liquid sample has approximately the same exposed area as the initial area of the gelled samples.

The graph in Figure 6 and the accompanying Table I of burning times show a slight decrease in burning time for the 1% gel, compared to the liquid fuel. This variation is within experimental error, but may also indicate an effect due to increased area from a rough crust that forms on the gel as it burns. Note that this gel is actually a viscous liquid at 1% concentration, while the higher concentrations give more or less rigid gels.

Table II gives burning rates for 4 gels made with amine-isocyanate formulations. These gels have a gelling agent concentration of 4%. Note that the burning times do not differ greatly among different formulations. Also, it should be noted that the times are slightly less than for the 4% Westco gels.

Differences were noted in the burning process for the amine and the Westco gels. The Westco gels became covered with a coherent crust which persisted during the burning. The amine-isocyanate gels also showed crust formation, but the crust was disrupted by constant "sputtering" of small eruptions through the crust. This sputtering showered bits of the crust and specks of burning gel as much as 1 foot from the burning sample. It is not known whether this effect would be of any significance in a large-scale fire.

Previous experience and information gained in performance of the subject contract give strong indication that the greatest value of fuel gelling lies in control of the dispersion of fuel in a crash situation rather than in changing the burning characteristics of the fuel. Gelling fuel can reduce the vaporization rate and burning rate by factors of 2 to 6. This is a significant improvement, but a more critical factor is prevention of the intense first flash of fire after a crash.

Equipment was built to permit study of gelled fuel under impact conditions. The experimental setup consists of an air gun which fires containers of fuel against a target of steel grating with 1-inch openings. The container ruptures on the grating, allowing the fuel to disperse. Burners behind the grating provide sources for ignition of fuel vapors. The experiments are recorded on both high-speed and regular motion-picture cameras. This apparatus permits a study of the behavior of

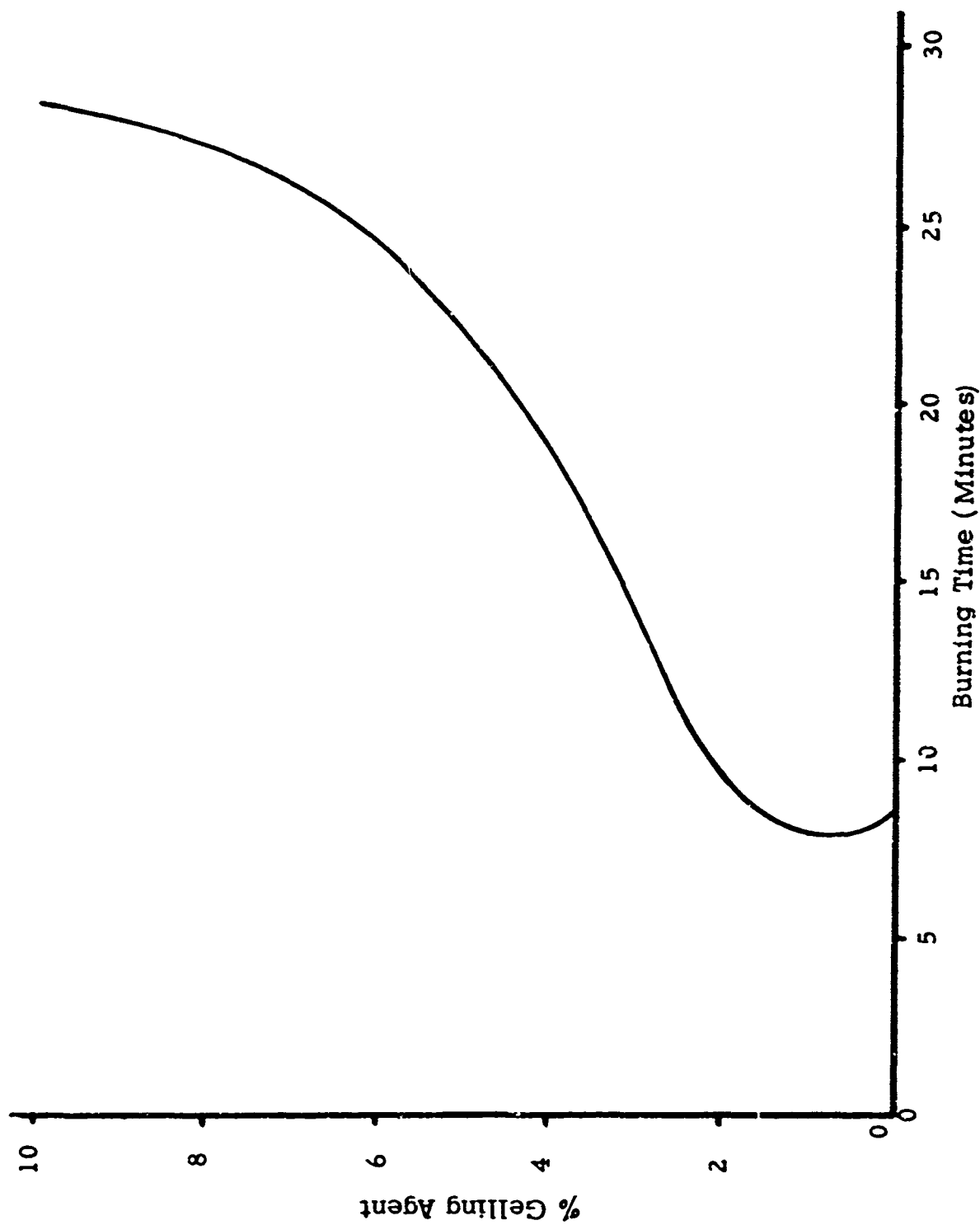


Figure 6. Gel Burning Time vs Westco Gel Formulation

gelled fuel on impact, showing clearly both the pattern of fuel dispersal and the propagation of flames when ignition occurs. In this manner the effectiveness of various gels may be compared under dynamic conditions. The dynamic testing of gels has provided the most dramatic demonstration of hazard reduction. The tests have clearly shown the reduction of the fire flash when fuel containers are impacted. In addition, it has been observed that the gelled fuel actually provides additional rupture resistance for its container. Figure 7 shows typical container damages.

The dynamic tests made utilized the air gun to project 50-cc (about 2 ounces) containers of fuel at velocities up to 500 feet per second from a distance of 40 feet. The target was a steel grating with a burner as an ignition source. Numerous tests were observed by high-speed photography, utilizing impact velocities of approximately 150 and 300 mph. At the lower speed, samples were projected in polyethylene bags. At the higher velocity, thin metal canisters were used. With a 6% gel it was difficult to rupture the metal containers even with velocities in excess of 400 feet per second. By contrast, the containers of ungelled fuel were literally shredded. With 4 to 6% gels, a considerable amount of fuel remained in the container after impact.

Photographs taken at 2000 frames per second show that the gelled fuel escaping from a ruptured container has a "splash-pattern" which is an over-all resemblance of a liquid. However, the gelled fuel is dispersed in strings and pieces which are relatively large compared with the rapidly evaporating mist of droplets formed by the liquid fuel. Photographs reveal that the larger part of 4 to 6% gels will pass through a flame without igniting. Gels of a lower percentage give more fire, but with 2% or more the fireball, which occurs with liquid JP-4, is practically nonexistent. Liquid JP-4 gives a flame 100 to 1000 times larger than a 2% gel of JP-4 under similar impacts. Results were essentially identical with Westco gels and the best amine-isocyanate gels (such as formulation 1 in Table I). The film which supplements this report shows examples of reduction of the fireball.

It should be noted that the properties of the fuel vapors are the same, whether the fuel is gelled or not. This means that the vapor pressure of a fuel gel will eventually reach the vapor pressure of the fuel liquid; however, the time required for vaporization is much greater with the gel. The chemical properties of the vapors from a gel are the same (with non-volatile gelling agents) as those from the liquid fuel. As a result, the flash points, flammable limits, ignition temperatures, ignition threshold energies, etc., are the same for vapors from gelled or liquid fuel. Any variation in the behavior of the two states of the fuel as regards burning is purely a rate factor due to retardation of vaporization by the gel. Liquid and solid fuels do not burn. All fuels must be vaporized or gasified before combustion can occur.

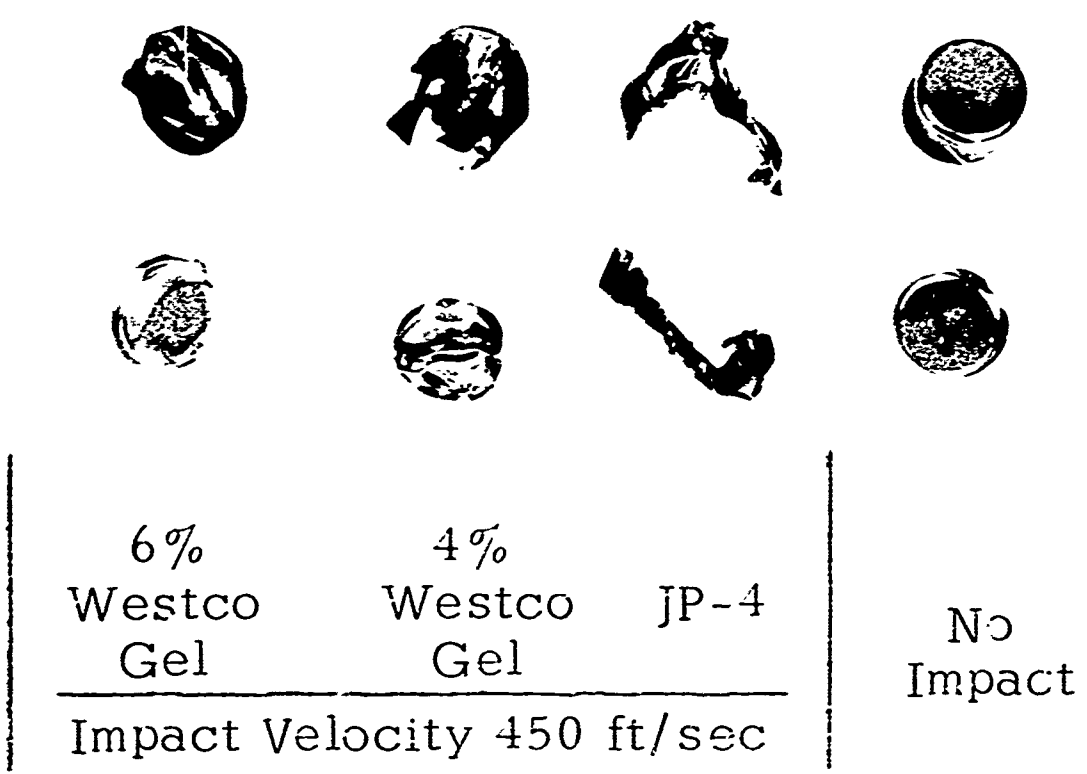


Figure 7. Effects of Gels on Container Impact Damage

Both the soap and amine gelling systems utilize chemicals which could be hazardous to personnel by direct contact. The caustic used in the soap system is very corrosive to all body tissues. The hazard is one of immediate burns by direct contact rather than due to poisoning of body chemistry. There is no vapor hazard from the caustic. Treatment after contact with caustic consists of immediate washing with a copious supply of water. The fatty acids used are of the type used as vehicles in paints and varnishes. These materials are not hazardous on contact except in unusual cases of allergic individuals. It is unlikely that enough of these fatty acids could be swallowed accidentally to cause serious or fatal consequences.

Data available on the amines and isocyanate are limited. The fatty amines, such as lauryl and coco, cause slow chemical burns to body tissues. Long term physiological damage may also occur. Thus, they may be fatal if ingested. External contact results in slow healing burns but the amines may be removed by quickly scrubbing with soap and water. Immediate removal generally prevents injury. Other amines vary greatly in their toxicity and no generalizations can be made. Toluene diisocyanate has a rather high toxicity by either ingestion or contact. It absorbs rapidly through the skin. The vapors are also toxic. Immediate washing with soap and water can generally prevent serious effects due to skin contact. Long term effects of repeated exposure to small amounts are unknown.

The physiological hazards of the gelling materials tested are shown in Table IV. In general, the gelling materials should not represent a serious problem to Army personnel concerned with actual systems. Proper prepackaging of the materials can eliminate handling hazards under ordinary conditions. Precautionary measures would be required in case of spillage due to accidents.

A preliminary hazard analysis has been made to predict the hazards due to the addition of a gelling system on an aircraft's fuel system. These hazards are based on a UH-1A helicopter as an example. It appears that the system should be manually initiated at the discretion of the pilot. The chance for human error exists, of course, but this is unchanged by the presence or absence of a fuel gelling system. Sequence interlocks may be employed to prevent accidental activation of the gelling system through human or mechanical failure. With proper safety interlocks, the gelling system with its power source (propellant or similar material) should represent no more on-board hazard than conventional armament materials. An extra margin of safety may be provided through the addition of a small fuel reservoir (1 or 2 gallons) between the main fuel cells and the power plant. A chamber this small could be made rupture-proof under any survivable impact conditions and would not be subjected to the gelling process. In case of accidental

TABLE IV
HAZARD TABLE, PHYSIOLOGICAL[Ⓢ]

Material	External Contact	Ingestion	Vapors	Comments
Caustic soda	Causes severe burns	Corrosive	None	Highly corrosive to all body tissue, but does not cause prolonged physiological effects other than burns
Fatty Acids	Very slight; should be washed off skin	Low toxicity; may cause temporary nausea or diarrhea	Slight at ordinary temperatures	Relatively harmless
Toluene Diisocyanate	Toxic; absorbs through skin; should be removed immediately	Toxic	Toxic; vapors very dangerous when heated to decomposition	Liquid and vapors hazardous; long-term effects unknown; may cause allergic sensitization
Amines	Varies from harmless to very corrosive	Variable from low to very high toxicity	Variable; generally high for volatile amines	The amines vary greatly in toxicity; little information available; may cause allergic reactions and long-term physiological effects.

[Ⓢ] Sources - Dangerous Properties of Industrial Materials, by N. I. Sax, Reinhold Pub. Corp., New York (1957), manufacturers of individual chemicals.

activation of the gelling system through human or mechanical failure, a sufficient quantity of usable fuel would remain to accomplish a crash landing. This would give the pilot more latitude in his decision on whether gelling of the fuel was justified in a hazardous situation. Mechanical reliability and hazards cannot be accurately evaluated till an actual prototype system has been built and tested.

The reduction in fire hazard has been measured on the basis of the vaporization curves shown in Figure 5. The ratio of the time in minutes required to reach 1 psi partial pressure for the gels, compared to liquid JP-4, is taken as a hazard reduction Factor A.

$$A = \frac{\text{time of gel}}{\text{time of liquid}} \quad \text{to reach 1 psi.}$$

This pressure was taken as being near the center of the flammability range for the fuel-air mixture. Factor B is based on estimates of new hazards associated with the power source of the gelling system based on B=1 for no additional hazard. The very small variations in B indicate that there is very little estimated difference in the power source hazards. Factor C is a measure of the relative estimated weight with penalty associated with the different power sources compared to C=1 for the weight of the system without power source. (For example, if the power source weighed as much as the rest of the system including material chemicals, the total weight would be doubled and C=2.) A figure of merit has been assigned as

$$M = \frac{A}{B + C}$$

These factors are given in Table V. It should be realized that these factors contain subjective elements and are only guides, based on a combination of experiment and experimental judgements. However, the M factors can serve as rough indicators of the path to be taken for future work. No tabulation can be made for the amine-isocyanate agents, since their performance precluded evaluation of a system. The larger values of M are more desirable.

TABLE V
SYSTEM HAZARD INDEX, WESTCO GEL

System	Factor A ^φ	Factor B ^φ	Factor C ^φ	$M = \frac{A}{B+C}$
None, liquid JP-4 fuel	1	1	1	1
Compressed gas power with				
2% gel	9.4	1.006	1.8	3.45
4% gel	10.8	1.006	1.8	3.85
6% gel	11.7	1.006	1.8	4.18
Propellant power with				
2% gel	9.4	1.003	1.01	4.17
4% gel	10.8	1.003	1.01	5.36
6% gel	11.7	1.003	1.01	5.81
Smokeless powder power with				
2% gel	9.4	1.002	1.005	4.68
4% gel	10.8	1.002	1.005	5.38
6% gel	11.7	1.002	1.005	5.83

^φ See text for explanation of factors.

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13. ABSTRACT The feasibility of rapidly gelling large quantities of aircraft fuel has been investigated and the types and quantities of chemical gelling agents required were evaluated. Mechanisms and power sources for mixing gelling agents with fuel have been evaluated and the hazards and penalties associated with these systems have been assessed. Impact tests were made to determine the reduction of fire hazard with gelled fuel under dynamic conditions. These tests showed radical differences in performance between gels which behave similarly under static tests.		

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Fuel Gelling Fuel Fire Hazards Crash Safety						

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