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Development of Crash-Safe Turbine Fuels

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The Federal Aviation Administration is engaged in programs to reduce the probability and/or severity of fire in commercial jet transport aircraft that are involved in ground crash situations. One of the approaches being taken is the development of a modified aviation turbine fuel that will provide a significant reduction in the crash-fire hazard. The modified fuels program, initiated in 1964, brought to light that under small-scale simulated crash conditions the fire reduction benefits of fuel thickeners result from their ability to physically bind the fuel and thus reduce the rate of vaporization and the exposed surface area available to support a fire. Dozens of thickened fuel candidates have undergone cursory screening, and a small percentage of those that looked promising have been subjected to a crash fire rating system designed to provide relative values of candidate fuels. Chemical and physical studies, completed in 1971, on two of the leading fuel candidates greatly improved their fluidic property with no adverse affect on their fire retardative properties, while in mist form. The agency's plans, to demonstrate the safe operation of aircraft using a modified fuel and to demonstrate the improvement in crash fire safety by conducting full-scale crash tests, are proceeding to take shape due primarily to the continued progress being made by the developers of the gelled fuels.

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INTRODUCTION

The Federal Aviation Administration's (FAA) crash-safe fuels program is a segment of a primary mission to improve the overall crashworthiness of aircraft. The objectives of this program are to reduce the probability and severity of fire during aircraft ground-crash situations. The approach being taken by the agency is a direct attack on the source of the aircraft fire problem by fostering the development of turbine engine fuels that will provide a significant reduction in the ground-crash-fire hazard when fuel is inadvertently released from an aircraft's fuel system.

DISCUSSION

The FAA launched its first effort in May 1964 to determine the feasibility of whether a thickened turbine fuel could provide reduced fire hazards under aircraft ground-crash conditions and yet, in its thickened state, be compatible with existing jet transport fuel systems and burn efficiently in a turbine engine. The initial project was conducted under contract by The Western Co., Richardson, Texas (1).[1] Several additives for gelling turbine fuel were studied and tested to predict their ability to maintain turbine engine quality fuel as well as their ability to reduce or prevent fire under simulated crash conditions in the presence of an open flame. The effort produced a thickening agent, known as N-coco-γ-hydroxybutyramide (CHBA) (formulation FAA 1069-1), which gave a strong solid gel when mixed in the ratio of 1.5 percent to the weight of the fuel. The FAA 1069-1 reduced the amount of flame generated under small-scale impact tests by 85 percent and the flame propagation rate in trough tests by 97 percent as compared to ungelled fuel.

The project brought forth the facts that under small-scale simulated crash conditions, the fire-reduction benefits of fuel thickeners re-

[1] Numbers in parentheses designate References at end of paper.

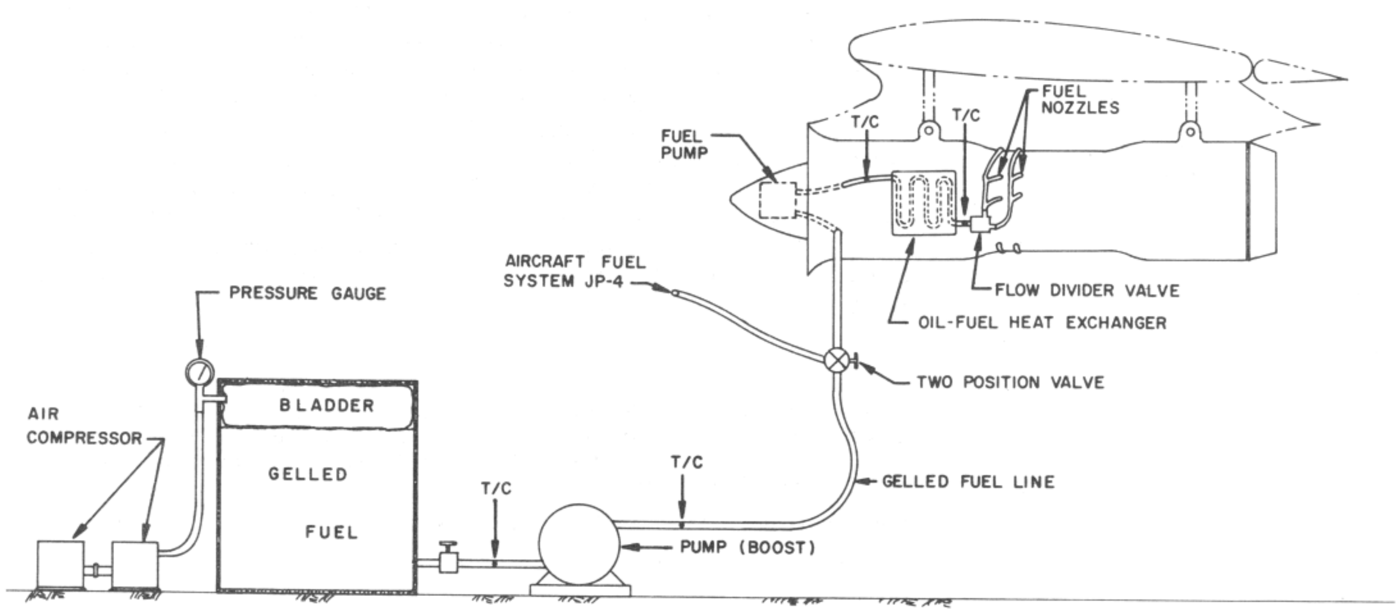


Fig. 1 J47 test equipment schematic for FAA1069-1 gelled fuel

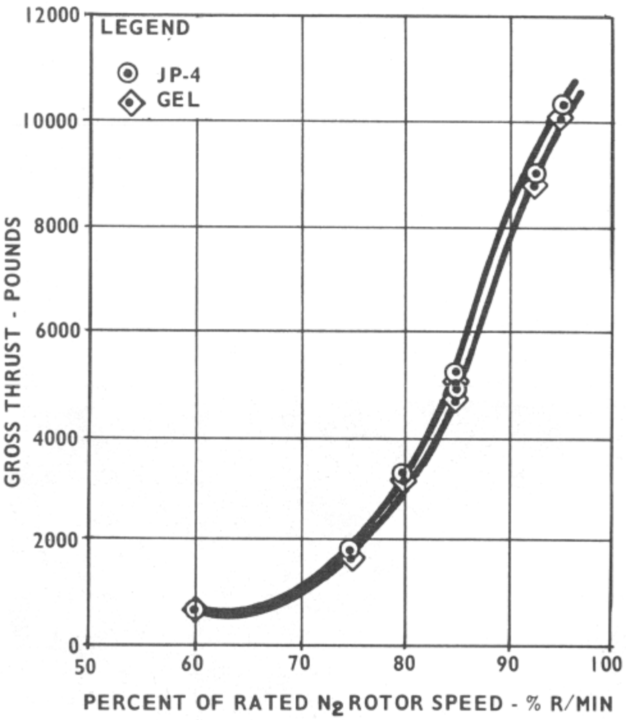


Fig. 2 J57 sea level static thrust versus percent N_2 rpm when using JP-4 and gelled fuels

sult from their ability to physically bind the fuel and thus reduce the rate of vaporization and the exposed surface area available to support a fire.

As they became more aware of the thickened fuel potential as a crash safety item, interest was shown by petroleum and chemical companies in furnishing candidates for evaluation. A project was started at the agency's National Facilities Experimental Center (NAFEC), Atlantic City, New Jersey, to develop a series of small-scale tests for determining burning characteristics of fuels in the mist and liquid forms. Special emphasis was placed on fuel misting since it had long been known to be extremely hazardous in aircraft ground-crash situations (2-5).

The degree to which a fuel will become an aerosol after being air-sheared and the flammability characteristic of that aerosol-fuel in the presence of an open flame, electric arc, or hot surface was evaluated by propelling a 1-gal quantity of fuel at 90 mph horizontally over any one of the aforementioned ignition sources (6, Air Gun Test Method). Fuel dispersion and subsequent flammable characteristics of fuel after impact were evaluated by propelling a 120-gal-capacity fuel tank into an inclined steel plane at 80 mph in the presence of open flames (6, Catapult Test Method). Later tests of this nature

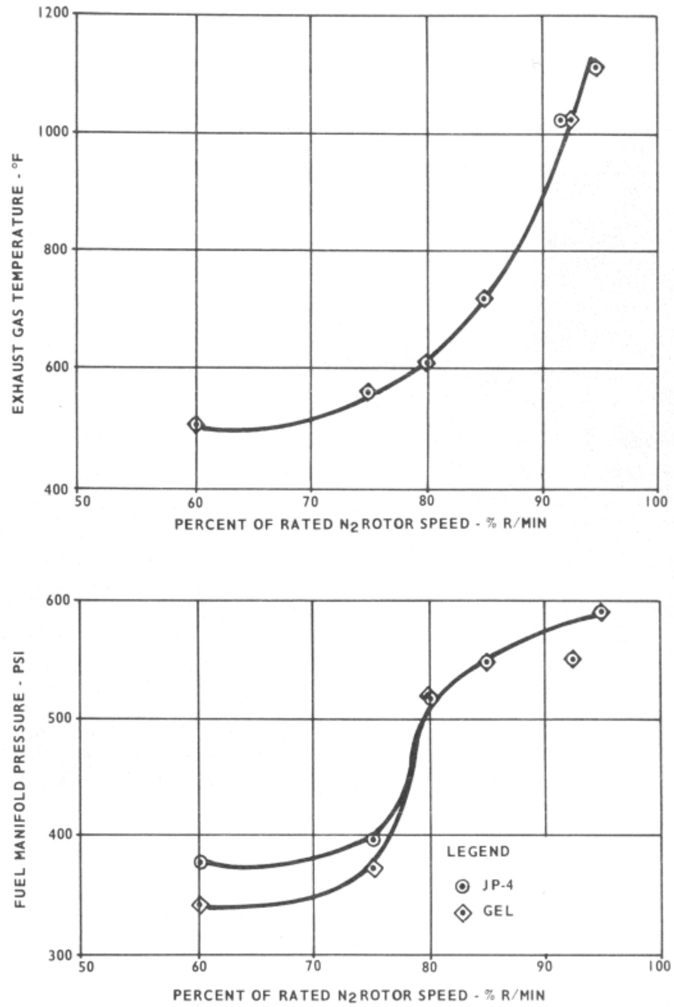


Fig. 3 J57 sea level static performance parameters when using JP-4 and gelled fuels

have been to skid the tank on concrete for a distance of 40 ft into a 10-in.-high transverse steel obstruction in the presence of open flames. Fuel spill patterns resulting form vertical impact were investigated by dropping 120-gal-capacity tanks onto a flat surface from 35 ft (6, Vertical Drop Test Method). The fourth means of evaluating fuel behavior in a simulated crash environment was to drag a 120-gal-capacity tank on concrete and observe the dispersion and flammable characteristic of the dispersed fuel as the bottom of the tank ruptured due to abrasion, from the runway surface and tearing from spikes embedded in the runway. The ignition source in this case was an electric arc on the underside of the tank (6, Drag Test Method).

A second contract was awarded to The Western Company for the purpose of identifying the best fuel-modifier system that would provide us with a controlled flammability fuel (7). Concurrently with this effort, the Bureau of Mines, Pittsburgh,

Fig. 4 One gallon of Jet A fuel converted to fuel mist and exposed to open flames

Pennsylvania, was awarded a contract (8) to develop a laboratory method of rating the potential crash-fire hazards of hydrocarbon-type aircraft fuels, both regular and modified. The crash-fire hazard rating system was essential to The Western Company during the screening of fuel modifiers in its effort to find a reliable crash-safe turbine fuel. The Al-2-ethylhexanoate (aluminum octoate) gel was selected as the best of 55 modified fuels tested.

Concurrent with the studies described in the foregoing, a series of tests were conducted to determine the compatibility of gel fuels with typical turbine engines.

The initial engine tests were made with the very thick FAA 1069-1 gelled fuel. This particular gel had many obvious faults insofar as its adaptability to aircraft use, but at the time, it was the best fuel available. In order to deliver the gel to the engine, it had to be squeezed from the tank by inflating a bladder. Fig. 1 is a schematic of the J47 test arrangement. The bladder delivered the fuel to a boost pump which sheared the gel to a slurry consistency and delivered it to the engine. The engine in this test was a J47-GE-25 turbojet. The results of these tests (9) indicated that the gel would operate successfully in an engine. A comparison of the performance of the engine, when operating with neat JP-4 and gel, indicated that the exhaust gas temperature and engine rpm remained essentially the same for both fuels over a range of power settings from idle to

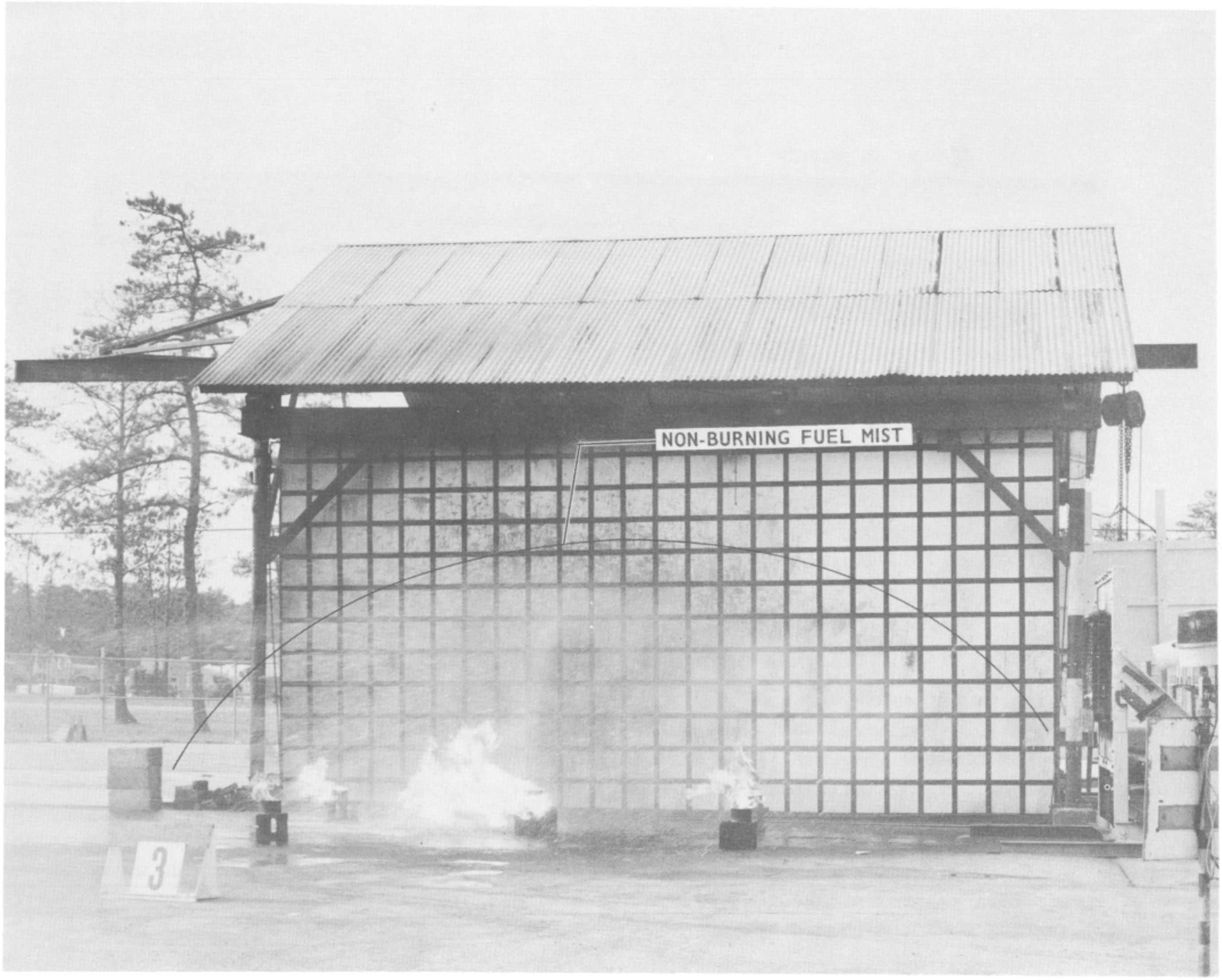


Fig. 5 One gallon of gelled Jet A fuel converted to fuel mist and exposed to open flames

100 percent rpm. The engine was successfully started using the gel; however, before engine shutdown, JP-4 was used to purge the lines and fuel control since the gel had a tendency to solidify in the lines and the flow-divider valve when left overnight in the system.

In 1967, The Dow Chemical Company submitted a gelled fuel composition which received good ratings in the air gun test. The Dow fuel, the FAA 1069-1 gelled fuel, and an emulsified fuel were tested in a gas turbine engine system (10) by the Naval Air Propulsion Test Center (NAPTC), Naval Base, Philadelphia, Pennsylvania. This work was conducted by the Navy for the FAA. One or more problems associated with all three thickened fuels were encountered. The problems ranged from excessive pressure drop across fuel filters, clogging of the filters, significant changes in combustion performance, presence of sodium in the additive, and, in the case of the emulsion, severe separation of the additive from the fuel in the filter causing zero fuel flow.

The Dow Chemical Company continued to make improvements to its gelled fuel and, early in 1968, had developed a gel with an apparent viscosity of 13,000 to 20,000 centipoises. By this time, 21 different types of regular and modified fuels had been tested by the air gun method. Many of the fuel types were furnished in varying formulations totaling over 200 individual tests. Gels of the thixotropic, pseudoplastic, plastic, dilatant, and rheopectic types were tested. In

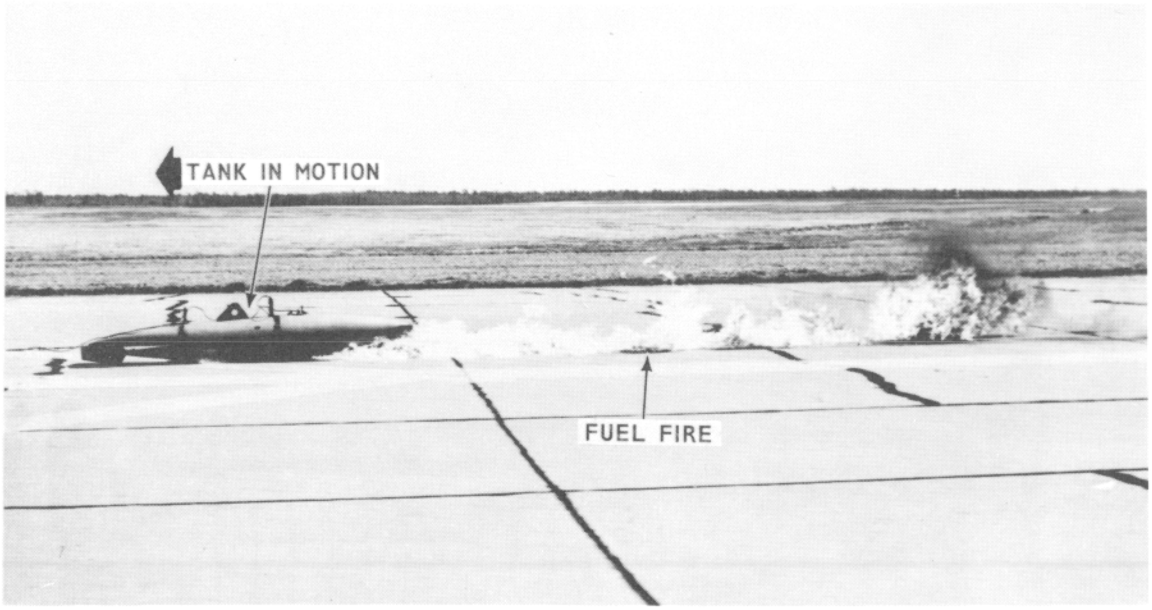


Fig. 6 Tank containing 120 gal of Jet A fuel
being dragged in presence of electrical spark

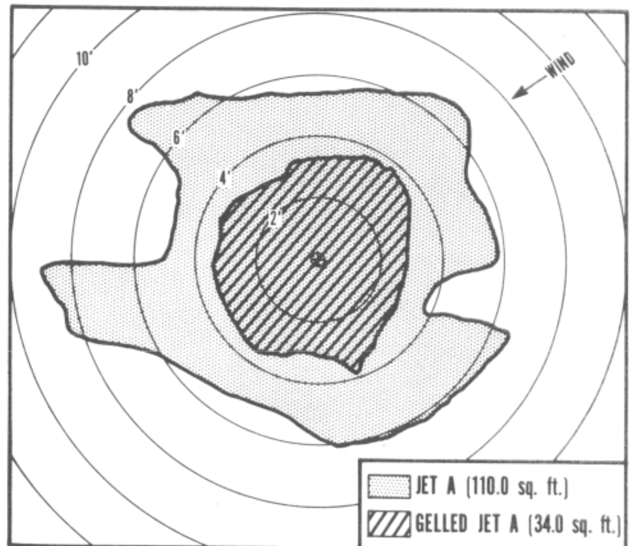
addition, a variety of emulsions — fluorinated fuels, and one naphthalene compound — were also evaluated. Several organizations have cooperated with the FAA thus far in the program (Appendix 1). Fluidity of the formulations was not a major consideration in the early stages of the program, since suppliers were primarily concerned with producing a turbine fuel that would be less vulnerable to ignition in a simulated crash environment (primarily the aerosol state) and still possess the heating valve required for operation in an engine. The majority of the fuels were rather viscous, i.e., emulsions with yield stresses $\geqq$800 dynes/sq cm and gels with apparent viscosities$\geqq$8000 centipoises (< 100 dynes/sq cm). The compatibility that these thickened fuels would have with a jet transport aircraft fuel system was very dubious. It became imperative that the fluidic requirements of the modified fuels be determined, because it was typical of the emulsions and gels then under evaluation to lose their ability to provide acceptable controlled flammability characteristics as their respective yield stress and viscosities were reduced.

In March 1968, the Douglas Aircraft Company instituted a study under FAA contract to determine the compatibility of gelled and emulsified fuels with a four-engine jet transport fuel system and to provide insight into the problems that might be associated with the everyday use of these fuels. A leading candidate emulsified fuel having a yield stress of 700 dynes/sq cm and a gelled fuel whose apparent viscosity was 17,000 centipoises were selected for the anlaysis. For this study, the DC-8 aircraft Model 62 configuration was chosen as the vehicle. Problem areas associated with the use of the gelled and emulsified fuels in the fuel subsystems of the DC-8-62 aircraft were identified. By extrapolation from small-scale tests and analysis of results obtained from tests performed on several of the system components, a general picture of the compatibility problem was developed.

The study (11) concluded that the gelled and emulsified fuels examined were not compatible with an unmodified four-engine commercial jet transport aircraft fuel system and that many modifications would be required to current aircraft to approach conventional fuel system performance levels. The primary cause of incompatibility was, of course, the highly viscous characteristic of the fuels tested. The major fuel system changes, as brought out in the Douglas report, concerned the: Fill System, Fuel Transfer System, Engine Feed System, Jettison System, Fuel Quantity Measurement System, and the Vent System.

Following the compatibility study, Douglas Aircraft Company was contracted to study (12) the economics of jet fleet conversion to the use of a gelled fuel. Again, the DC-8-62 aircraft was used as the vehicle for which a modification program

Fig. 7 Tank containing 120 gal of gelled Jet A fuel being dragged in presence of electrical spark



DATA:

EVENT	TIME (min.) JET A FUEL	GELLED JET A FUEL (250 cps)
1. CAP REMOVAL TO MAX SPREAD	3	2
2. IGNITION TO COMPLETE FLAME COVERAGE	3*	1
3. DURATION OF BURN	8	4

* Approx. 40% of Wetted Surface Burned Off.

NOTES:

OUTSIDE AIR TEMPERATURE .... 73°F
FUEL TEMPERATURE .... 68°F
FUEL QUANTITY .... 3 gal.
WIND VELOCITY .... 5 mph
FUEL WAS SPILLED FROM A HEIGHT OF 3 FT. THROUGH A 1⅝" HOLE

Fig. 8 Spilled fuel patterns on concrete

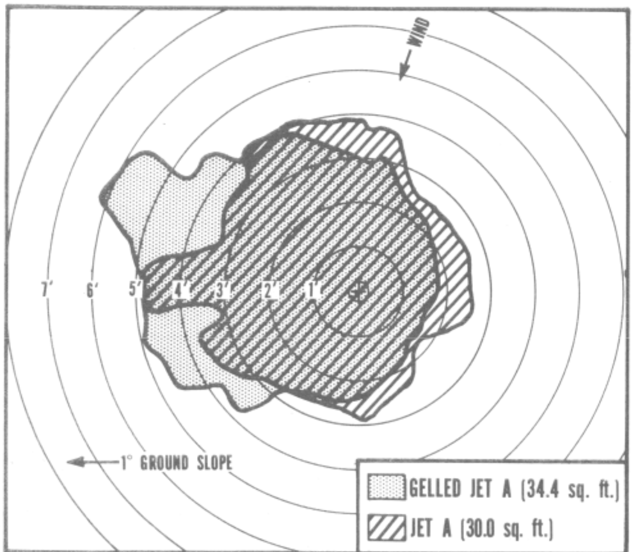
was outlined and the cost was estimated. Based on the DC-8-62 analysis, it was concluded that conversion and operation for the 10 years, 1972-1981, of all United States air carrier jet passenger aircraft would increase the total operating costs by approximately 4.5 percent.

The largest component of the increase was estimated to be the gelling agent which at a 2-percent concentration was expected to add approximately 25 percent to the cost of jet fuel. An economic study at this point in time on a gelled fuel that had been found to be incompatible with an aircraft fuel system, topped by the many unkowns still to be resolved that could change a study of this nature several fold, might be criticized. It was deemed important to obtain some answers on the subject even though they might be considered broad approximations, and, if nothing else, the real message emanating from the study was that the amount of additive used for any thickened fuel formulation should be kept to a minimum.

Meanwhile, a second series of engine tests (13) were conducted at NAFEC with three types of gel: (a) a styrene polymer-based gel, 2.0 percent concentration; (b) a new sodium-free styrene polymer Dow gel, 2.0 percent concentration; and (c) an aluminum octoate gel, 0.2 to 1.0 percent concentration. The first two polymer gels had viscosities of approximately 13,000 centipoises, and the third gel had viscosities ranging from 2800 to 13,000 centipoises. The two polymer gels operated successfully on the J47 engine from idle to 100 percent power but were unable to start the engine. The engine had to be started using regular fuel, and when the speed was brought up to idle rpm, a two-way valve was actuated to switch over to the gel. The J47 engine could not be started using the gel because the fuel manifold pressure at light-off was insufficient to effectively vaporize the thickened fuel.

The third gel, aluminum octoate, was incapable of successfully sustaining combustion in the J47 engine. Even at fuel manifold pressures as high as 250 psi, combustion could not be sustained, and when switching back to regular fuel to avoid engine flame-out, a successful switch-over could not be effected. The aluminum octoate was thereby withdrawn as a candidate.

The second engine used in these tests (13) was a Pratt & Whitney J57 turbojet. The results of these tests are shown in Figs. 2 and 3 wherein the relative performance of the sodium-free polymer gel is compared to neat JP-4 fuel. It is apparent that only slight performance changes result from the use of the gel in this engine. In addition, the J57 engine could be started with the gel since the fuel manifold pressure at engine light-off was approximately 300 psi, far in excess of that re-



DATA:

EVENT	TIME (min.) JET A FUEL	GELLED JET A FUEL (250 cps)
1. CAP REMOVAL TO MAX. SPREAD	1	5
2. IGNITION TO COMPLETE FLAME COVERAGE	4	2.5
3. DURATION OF BURN	9	6

NOTES:
OUTSIDE AIR TEMPERATURE .... 73°F
FUEL TEMPERATURE .... 68°F
FUEL QUANTITY .... 3 gal.
WIND VELOCITY .... 5 mph
FUEL WAS SPILLED FROM A HEIGHT OF 3 FT. THROUGH A 1⅝" HOLE

Fig. 9 Spilled fuel patterns on gravel

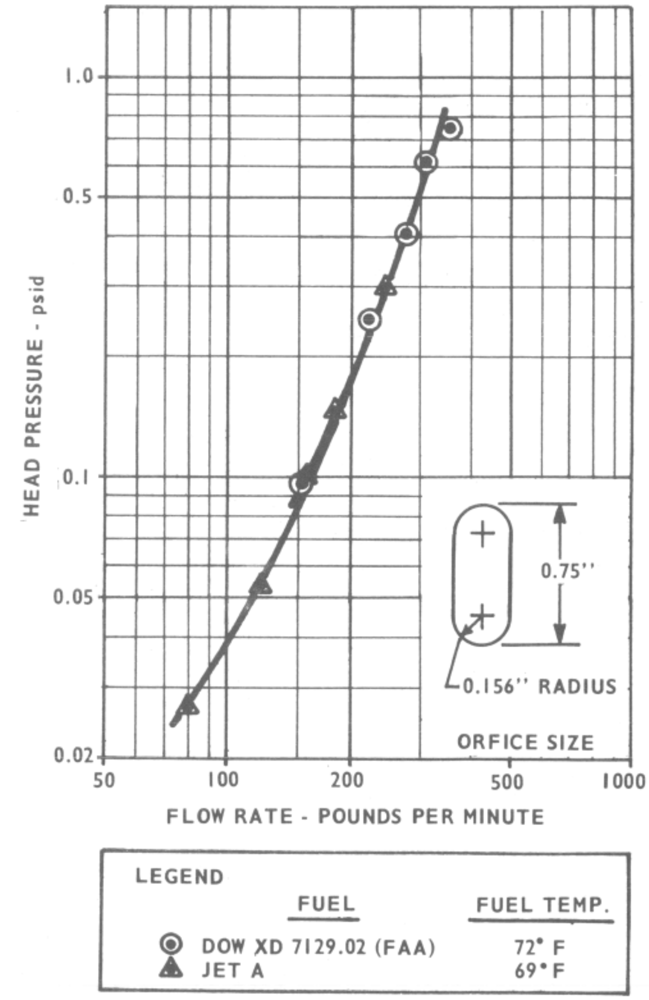


Fig. 10 Flow rate versus head pressure of XD7129.02 gelled and neat Jet A fuels through an oval orifice

quired for gelled fuel vaporization.

These engine tests definitely indicated a problem area for gelled fuels. The gels must resist atomization in order to be effective in reducing the misting characteristics when in a crash, but, at the same time, the gel must be atomized in the combustion chamber in order to burn efficiently.

At the start of 1970, it was evident that both the gelled and emulsified fuels were incompatible with an unmodified commercial jet aircraft fuel system, although the gelled fuels had consistently performed well in the small-scale simulated crash test (air gun test) and performed reasonably well in engine tests.

The Dow Chemical Company and Anheuser-Busch, Inc. made timely submissions of candidate gels in the 5000-centipoises range at this time. The subsequent good performance of these gels in the air gun test justified exploration of the possibility of developing lower viscosity thickened fuels which could retain their crash-safe characteristics and also possess acceptable fluidic properties. Contracts were concurrently awarded to the two aforementioned companies to perform chemical and physical studies on their own formulations which, until the time of contract awards, had been in-house efforts on the part of both contractors. The contractual work was to be devoted to improving the gelled fuel(s) to the highest level possible for crash-fire safety with flow characteristics compatible with fuel systems of today's aircraft. Both contractors made substantial improvements to their thickened fuels and also gained a better understanding of the rheological phenomena related to thickened hydrocarbons.

The optimum fuel developed from the Dow Chemical study (14), designated XD-7129.02 (FAA), has a low-shear apparent viscosity range of 250 to 500 centipoises at 75 F. This newest formulation is pseudoplastic with dilatant tendencies through a small range of low-shear rates and also possesses a thixotropic property. The optimum Anheuser-Busch gelled fuel (15), designated FAA-CL-12, has characteristics resembling the Dow gel. The gelling agent is synthesized from carbohydrate materials, and the modified fuel exhibits plastic, thixotropic, and viscoelastic properties.

The results of small-scale simulated crash tests, shown in Figs. 4 through 7, indicate the degree of success thus far obtained with the two aforementioned gelled Jet A fuels.

A series of tests was then undertaken to determine the gelled fuel's speading characteristics on concrete and gravel surfaces as compared to the performance of unmodified fuel. This was done by releasing 3 gal of fuel from a height of 3 ft through a 1 5/8-in.-dia hole. The data recorded were: (a) the time from fuel release to maximum spread, (b) the time from ignition application to complete flame coverage, (c) duration of burn, and (d) size of spill area. Figs. 8 and 9 show comparative spreads of the gelled XD-7129.02 (FAA) and neat Jet A fuels on concrete and gravel surfaces.

The data showed that the gelled fuel produced the same size spread area on both surfaces. The neat fuel's spread was 260 percent greater on the concrete than on the gravel surface, and surprisingly the gelled fuel's spread was 14 percent greater than the neat fuel's spread on the gravel surface. The low spread area of the neat fuel resulted from its ability to percolate into the soil (gravel). This same percolating characteristic of neat fuel explains the reduction in time to maximum spread and also explains the 60 percent increase in the time for the flame to cover the wetted gravel surface. The duration of the fire was greater for the neat fuel, however, since the wetted gravel acted as a wick. Despite the fact that the neat fuel produced a wetted area on concrete 220 percent larger than the gelled fuel, it could not support combustion on 60 percent of that area.

Flow tests were performed on the gelled and neat Jet A fuels in order to grossly compare their performance in aircraft fuel tanks. The series of tests was suggested by the McDonnell-Douglas Corp. with no intention of assigning a rating scale, pass/fail criterion, or definite correlation with previous results of other programs. The tests were intended to be performed with neat fuel in order to provide a baseline performance with which each gelled fuel could be compared.

The results of the fuel's flow performance through openings chosen to represent orifices and different pipe sizes are shown in Figs. 10 through 13.

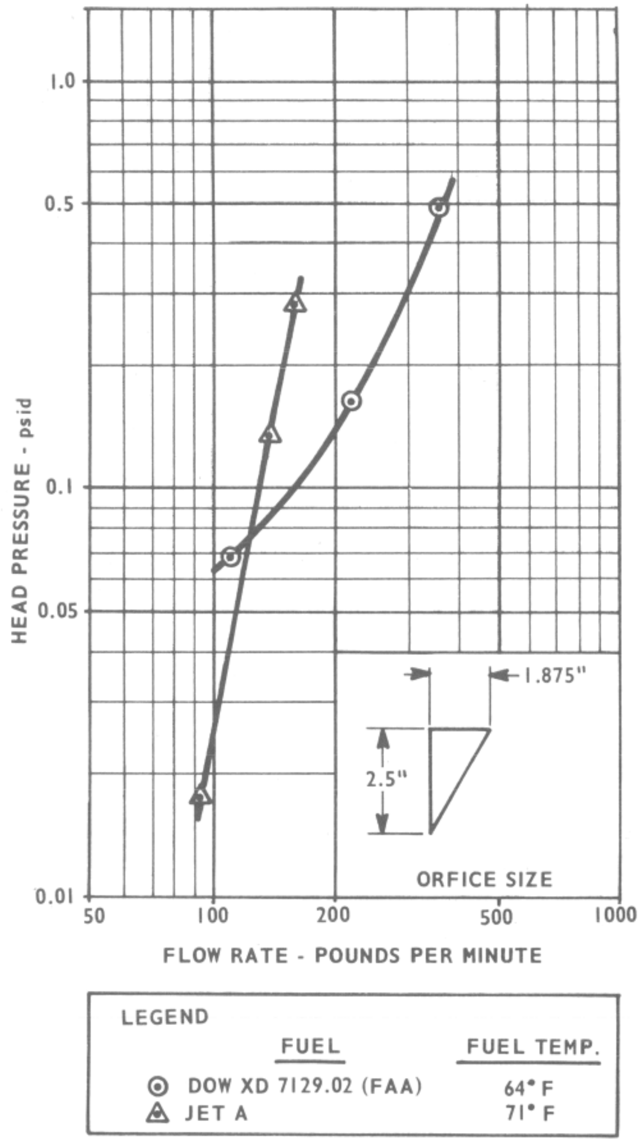


Fig. 11 Flow rate versus head pressure of XD7129.02 gelled and neat Jet A fuels through a triangular orifice

The development of the low viscosity gels warranted a closer study of the atomization characteristics of the gels when forced through fuel nozzles. These studies indicate that some problems are still present insofar as starting turbine engines with gels. Some of the modern engines have very low fuel manifold pressures at light-off, and the spray pattern pictures obtained in the study indicate poor atomization at pressures which correspond to idle rpm. The engines which have been preliminarily investigated are the CJ805 and the TF-33 in addition to the J47 and the J57. Typical J47 fuel spray patterns resulting from a range of nozzle pressures are shown in Fig. 14. The comparison of the atomization of

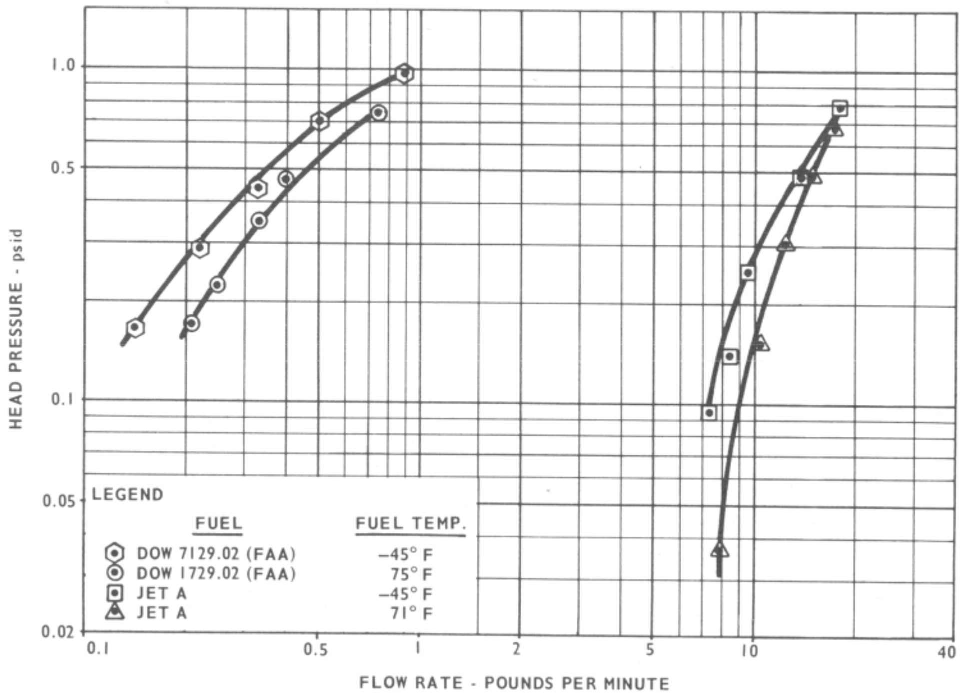


Fig. 12 Flow rate versus head pressure of XD7129.02 gelled and neat Jet A fuels through a .028 x 1/2- x 48 in. tube

neat Jet A with the XD7129.02 gel (1.7 percent concentration and 250 centipoises) is made in these photographs. It is apparent that due to poor atomization at nozzle pressures below 60 psi, very poor combustion efficiencies would prevail and erratic engine operation would take place. A short engine run using the J47 engine verified this when it was found that the engine could not be switched over from JP-4 fuel to gel at rpm's below 60 percent which corresponds with about 66-psi fuel manifold pressure. At this level and above, the engine performed as well with gel as with JP-4. No attempt to start the engine with the gel was made, since it was obvious from the spray tests and the engine light-off characteristics that a successfull light-off would be impossible without modification to the engine fuel system.

Additional atomization tests were made using a J79 nozzle. In these tests, the performance of the XD7129.02 gel was compared with neat Jet A fuel over a range of relatively low pressures. It is apparent from Fig. 15 that the gel does not atomize satisfactorily until the nozzle pressure exceeds 100 psi. The J79 nozzle is less effective than the J47 nozzle in atomizing the gel in the low-pressure range as shown in the photos. The effect of working the gel was also investigated. In these tests, the fuel was forced through a nozzle at 200 psi. It was then recirculated and forced through the J79 nozzle at low pressures (50→ 100 psi) and photographed. The effect of this work on the atomizing characteristics of the fuel is shown in Fig. 16. At pressures as low as 50 psi, the droplet size of the worked gel appears to be such that it would sustain combustion. This would indicate that preworking of the fuel prior to delivery to the nozzles aids in improved gel atomization during the starting cycle. Further work in this area is planned.

AREAS OF INVESTIGATION

The future plans in the project include four distinct areas of investigation. They are:

Engine Compatibility with Gelled Fuel

Sea level static tests of a modern turbine engine wherein a CJ-805 turbojet will be run through the prescribed cycle of starts, acceleration, decelerations, and power settings which make up an engine qualifying test: The fuel control, nozzles, filters, combustion chamber, and turbine will undergo pre- and post-test inspections to determine any changes or potentially harmful buildups on the components. In addition, components of the engine will be tested under simulated altitude conditions to evaluate the engine component performance under conditions it would experience in actual flight.

Aircraft Fuel System Compatibility with Gelled Fuel

Full-scale aircraft fuel system tests will be conducted wherein the fuel system performance will be evaluated while using gelled fuel. The performance of the jettison system, the fuel transfer pumps and filters, and the amount of unusable fuel remaining in a tank will be determined. A portion of the fuel system will then be tested under simulated altitude conditions to evaluate the system performance when using the gel under pressure and temperature conditions it would experience in flight. The test article for these tests will be a Convair 880 fuel system.

Flight Test of the Gel in a Typical Commercial Jet Aircraft

Assuming success in the engine and fuel system tests, a limited flight test program is planned using the FAA's 880 aircraft as the test vehicle. One of the four engines of the aircraft will be operated using gel fuel while flying the aircraft over a range of conditions representing the aircraft's flight envelope. The gel fuel will be isolated from the fuel system used by the other three engines during the tests.

Full-Scale Crash Tests

Full-scale crash tests of RB-66B aircraft are planned with the gelled fuel in the tanks and the engines operating at the time of the crash. This work will include at least three crashes, one with regular Jet A fuel and Two with gelled fuel, wherein the tanks will be ruptured during the crash. Positive ignition sources will be present in the vicinity of the crash for the Jet A and for one of the gelled fuel tests. The third test using the gelled fuel will not have positive ignition sources.

The planned tests will indicate the degree of compatibility of the gel with present-day aircraft. Problem areas, which could require minor modifications to the aircraft fuel system or engine start procedure, will be investigated and installed in the test aircraft if it is deemed advisable to continue into the flight test program. The word, "minor," in referring to modifications may be somewhat vague, but it is recognized that some changes of location of pumps or additional pumps may be necessary to make the fuel system perform satisfactorily. If this is the extent of the required change, it would be minor.

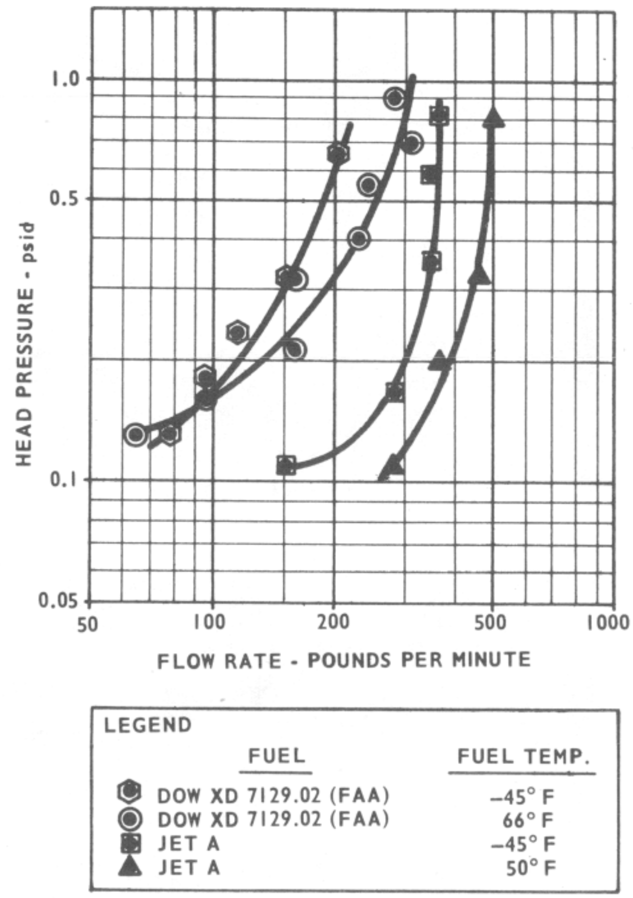


Fig. 13 Flow rate versus head pressure of XD7129.02 gelled and neat Jet A fuels through a 0.062- x 2½- x 72-in. tube

CONCLUSION

The gelled fuel technology has advanced to the point where the controlled flammability fuel characteristics are no longer solely dependent on viscosity. The phrase, thickened fuel, may soon be an obsolete concept. The progress thus far has been substantial in reducing the ignitibility of an aerosol fuel and the horizontal flame spread rate over liquid fuel, which were the initial goals when the program started. One early objective, which has not been attained, is the achievement of a substantial reduction of the area of fuel spills on the ground. This has become an impossibility when one of the major criteria for an acceptable safe fuel is maximum compatibility with present-day aircraft. However, the fact that a relatively low-viscosity gel can greatly reduce the ignitibility of a fuel mist can thus, in turn, reduce the hazard of a fuel spill.

The FAA's crash-safe fuel program will

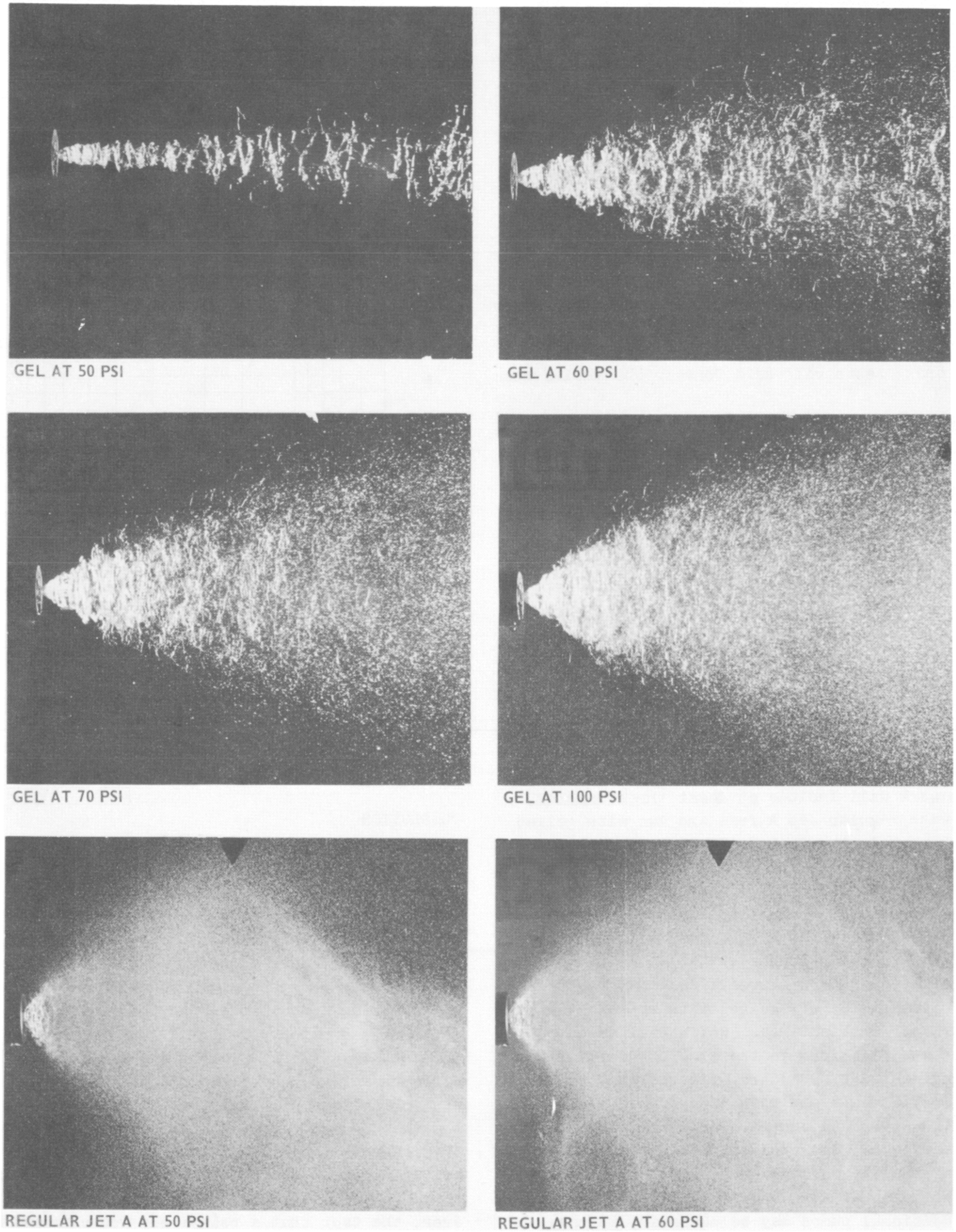


Fig. 14 Performance of J47 fuel nozzle using XD7129.02 gelled fuel and neat Jet A fuel at various pressures

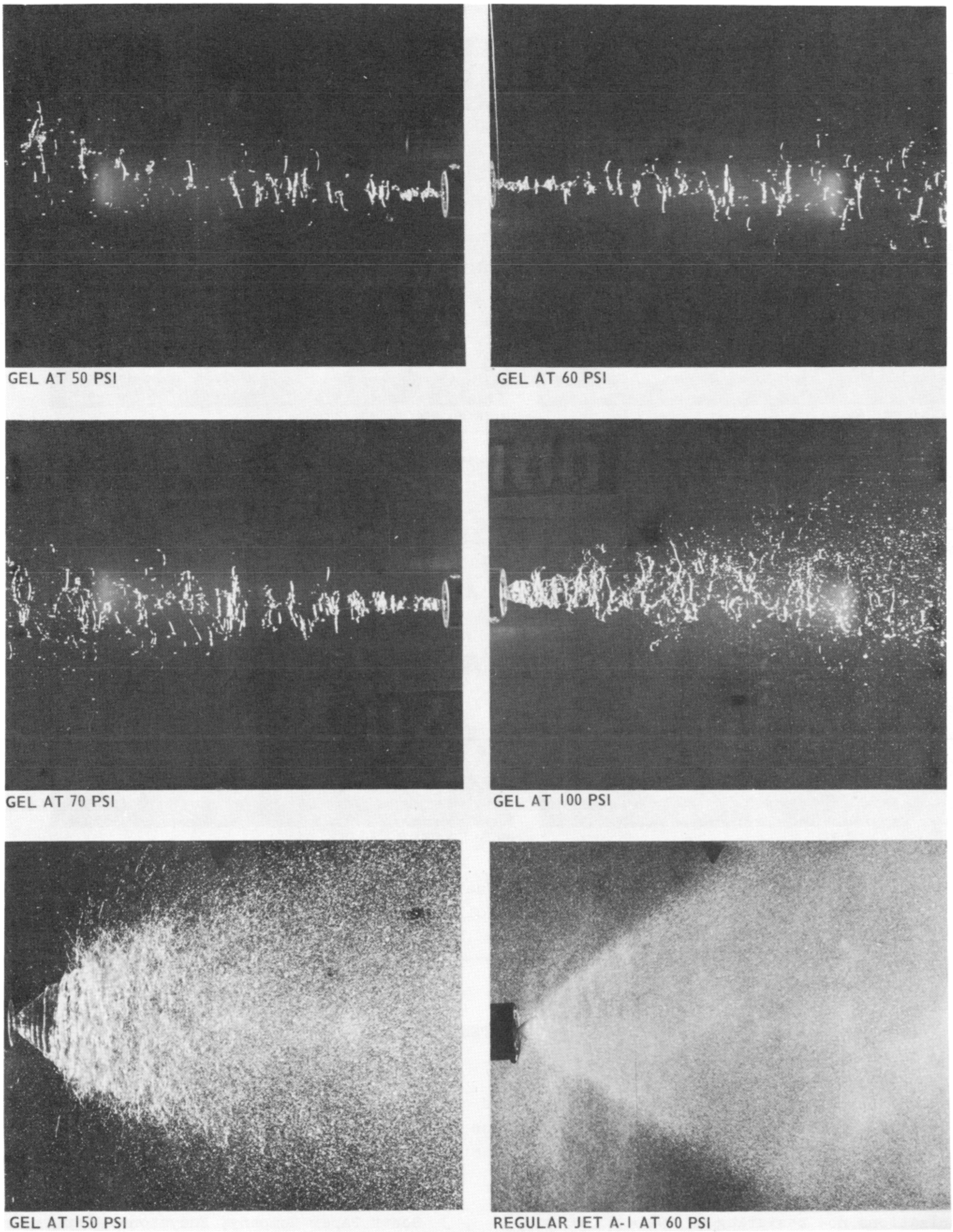


Fig. 15 Performance of J79 fuel nozzle using XD7129.02 gelled fuel and neat Jet A fuel at various pressures

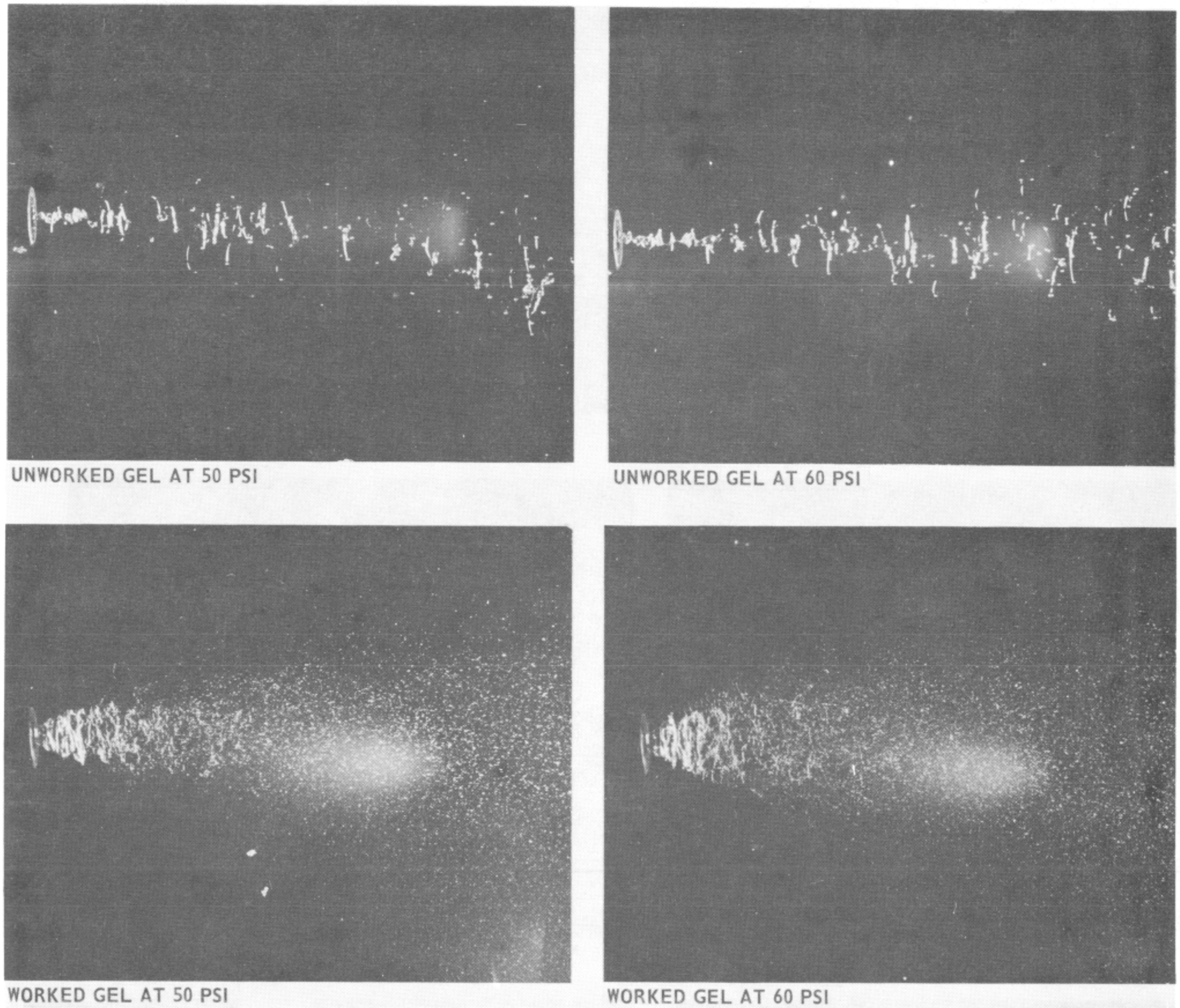


Fig. 16 Performance of J79 fuel nozzle using unworked and worked XD7129.02 gelled fuel at various pressures

hopefully answer such questions as:

1 Is it compatible with the aircraft fuel system?
2 Does it really have the potential to reduce and/or eliminate ground crash fires?
3 What will be its economic impact on the aircraft industry?

It is hoped that with the cooperation from the many organizations now assisting us, we will be able to report the successful completion of this endeavor in the near future.

APPENDIX 1

Organizations that have contributed materials and/or engineering services to the Federal Aviation Administration's crash-safe turbine fuel program:

1 The Western Company, Richardson, Texas
2 Texaco, Incorporated, Beacon, New York
3 Scott Paper Company, Eddystone, Pennsylvania
4 The Boeing Company, Seattle, Washington
5 U. S. Naval Air Propulsion Test Center, Philadelphia, Pennsylvania

6 Air Logistics Corporation, Pasedena, California
7 B. F. Goodrich Company, Akron, Ohio
8 Southwest Research Institute, San Antonio, Texas
9 U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia
10 Petrolite Corporation, St. Louis, Missouri
11 Esso Research and Engineering Company, Linden, New Jersey
12 Bureau of Mines, Pittsburgh, Pennsylvania
13 The Dow Chemical Company, Midland, Michigan
14 Coating and Chemical Laboratories, Aberdeen Proving Ground, Maryland
15 Anheuser-Busch, Incorporated, St. Louis, Missouri
16 Coordinating Research Council, New York, New York
17 Monsanto Research Corporation, Dayton, Ohio
18 Douglas Aircraft Company, Long Beach, California
19 Chevron Research Company, San Francisco, California
20 Imperial Chemical Industries, Slough, Bucks, England.

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