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DS-70-1

FINAL REPORT

Contract No. FA68NF-273

Project No. 520-005-05X

A STUDY OF THE COMPATIBILITY OF A FOUR ENGINE COMMERCIAL JET TRANSPORT AIRCRAFT FUEL SYSTEM WITH GELLED AND EMULSIFIED FUELS

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Aircraft Development Service

By

DOUGLAS AIRCRAFT COMPANY

McDonnell Douglas Corporation

Long Beach, California

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DOUGLAS AIRCRAFT COMPANY
McDONNELL-DOUGLAS CORPORATION
Long Beach, California

FOREWARD

This report was prepared by Douglas Aircraft Company for the Federal Aviation Administration. The work effort was part of a program of the Engineering and Safety Division, Aircraft Development Service Washington, D.C. The work was administered under the direction of Mr. Ralph A. Russell who served as project engineer for the Propulsion Section, Aircraft Branch, Test and Evaluation Division, National Aviation Facilities Experimental Center, Atlantic City, New Jersey.

ABSTRACT

The rheological and physical properties of four gelled and three emulsified turbine fuels were evaluated. One gelled and one emulsified fuel were selected for further test and analysis in a compatibility study with a four engine commercial jet transport aircraft fuel system. Full scale testing of system components was performed. Penalties and problem areas associated with using the fuels were identified by an analysis of the fuel system. A full-scale ground test program to evaluate an aircraft fuel system's performance on thickened fuels was outlined. Results show significant decreases in available fuel and large increases in system weights are associated with the use of the thickened fuels described. Substantial fuel development is indicated before application to commercial aircraft.

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INTRODUCTION

Fuels thickened by gellation or emulsification have been proposed as a means of improving crash safety by reducing the hazards of fuel fires. Work is underway to evaluate the safety gain of thickened fuel usage from the standpoint of ignition and burning characteristics. A program to determine the compatibility of a four engine jet transport fuel system with gelled and emulsified turbine fuels was conducted under contract from the Federal Aviation Administration to provide insight into the problems associated with the everyday use of these fuels.

Section A describes a comparative screening of the rheological and physical properties of modified fuels along with other characteristics. This resulted in a selection of the most promising candidates for further study. Section B is devoted to analyzing the effect of the selected fuels in a commercial jet aircraft. For this study, the DC-8, Model 62 configuration, was chosen as the vehicle. Included in this section is a discussion of the test program, specifically designed to allow systems analysis using the selected fuels. A component pressure drop test in combination with a DC-8 boost pump performance test supplied sufficient data to evaluate the aircraft piping systems. A pump-down test in conjunction with an orifice flow test provided data with which fuel residuals were determined. Problems identified in all areas are discussed and solutions outlined. Section C outlines a full scale aircraft fuel system ground test program. Application of this data to a flight test program will be the responsibility of follow-on investigations.

SECTION A

FUELS SELECTION AND SUPPLEMENTAL TESTING

A program of laboratory testing was undertaken to provide data on the fuels available at the start of the contract study. The fuels included a total of four gels herein identified as Fuel A, Fuel E, Fuel F, Fuel G and three emulsified JP-4 fuel formulations herein identified as Fuel B, Fuel C and Fuel D. This testing produced rheological data and allowed a screening of fuel characteristics.

A summary of their properties and other available information was made to assist in selecting one gel and one emulsion with which to complete the subsequent phases of the contract. The data gathered at that time is listed in Table I, and interpreted in the text below. Data for the gels, Fuel F and G, was relatively unavailable and thus does not appear on the tabular listing. What data is available is included in the following commentary.

FUEL CHARACTERISTICS

Rheology. Rheological properties of gelled and emulsified fuels were measured to aid in studies of flow of the thickened fuels in actual aircraft systems. A cone penetrometer was used for yield value determinations, and capillary and rotational viscometers were used for shear rate - shear stress measurements. The test methods were ASTM D217-65T (modified) for the cone penetrometer and D1092 for the capillary viscometer. The cone penetration test appears to be a practical method for measuring the yield value or consistency of a thickened fuel. Unpreventable surface roughness and trapped air bubbles in the thickened fuels interfered with the test results in some instances but these were overcome by repeated tests. Smooth gelled fuel surfaces were obtained by filling the penetrometer cup and then allowing the fuel to rest.

Slippage due to non-wetting or fuel separation and differential wetting of the walls of the capillary viscometer can be a major source of error in tests on thickened fuels. Slippage was exhibited with the Standard Oil Development Pressure Viscometer by sudden drops in pressure at constant hydraulic oil flow rates.

Slippage also occurs with rotational viscometers. Two indications of slippage were low dial readings and lack of thickened fuel adherence to the spindle upon withdrawal. The spindle was checked after each test to assure that fuel had adhered to the entire fuel contact area.

The emulsions have actual yield stresses, whereas the gels do not. Since the test measurement for yield stress takes but five seconds, a yield stress is indicated for some gels. If the time were extended to hours or days, the gels would have no yield stress.

Fuel A. The yield value for gel Fuel A, measured by the ASTM 217-65T Cone Penetration Test, should perhaps be called a pseudo-yield value. The lack of a true yield stress was indicated by the free spreading of the fuel upon a flat, smooth surface and by the complete release of air bubbles when the fuel came to rest.

TABLE I

GEL AND EMULSIFIED FUEL SUMMARY

PROPERTY		FUEL A	FUEL B	FUEL C	FUEL D	FUEL E
Yield Stress, dynes/cm^2	130°F	152	400	1190	775	---
	74°F	355	530,690,660	1140,1570,2700	788	385 (worked)
	0°F	470	940	1240	1700 @ -3°F	---
	-65°F	---	1430	1780	---	---
Gravity, °API		---	52.2[a]	53.7[a]	---	43.0
Specific Gravity		---	---	0.782	0.731	0.8109
Heat of Combustion, Btu/lb						
	Gross	---	---	19,184	---	19,518
	Net	---	18,445	18,288	---	---
Vapor Pressure, lb. (thickened fuel)		---	2.2	0.3	---	---
Vapor Pressure, lb (recovered fuel)		---	2.4	1.1, 2.0	---	---
Cloud point, °F		---	---	---	---	+115
Freezing point, °F		NO DATA AVAILABLE				
Electrical conductivity, mhos/cm		---	---	2.8×10^{-6} @77°F	---	---
Dielectric constant		NO DATA AVAILABLE				
Specific heat, Btu/lb.°F		---	---	0.40 @ 100°F	---	---
Flash point, °F		---	33,25	71,65	---	133 (closed cup)

TABLE 1 (Continued)

Existent gum, mg/100 ml	---	44.0[a]	119.8[a]	---	---
Total potential residue, mg/100 ml	---	85.7[a]	130.9[a]	---	---
Sulphur % wt.	---	---	0.02	---	None
Mercaptan sulfur, % wt.	NO DATA AVAILABLE				
Aromatics, % vol.	---	12.8[a]	10.9[a]	---	---
Olefins, % vol.	---	0.7[a]	2.8[a]	---	---
Total acidity, mg KOH per gram	NO DATA AVAILABLE				
pH	---	6.7	6.7	4.7	---
Icing inhibitor, % vol.	---	0.13	0.015	---	---
Ash, % wt.	---	---	0.005	---	---
Water, % vol.	---	1.24	0.69	---	---
WSIM	---	---	14	---	---
Storage stability					
Vol. % separation 30 days C.R.T.	---	---	0.0	3% separation of JP-4, 1 wk	---
Yield stress, dynes/cm^2	---	600 rec'd No change, 8 mos.	2700 1500 1 wk. 1450 1 mo.	1100 750 @ 1 mo. & stabilized	---
Temperature stability	-65°F to 160°F	-40°F to 130°F	80°F to 200°F	-65°F to 210°F	130°F liquid
Vibration stability	---	---	No change	---	---
Evaporation rate	NO DATA AVAILABLE				
Corrosion					
Mild steel	None	Moderate	Severe[b]	No effect	None
Aluminum	None	None	None	Slight	---

TABLE 1 (Continued)

Copper	None	Slight	Moderate	Moderate	None
Other metals	---	Magnesium affected	Magnesium affected	4340 steel	---
Elastomer compatibility	No effect	---	Slightly worse on Buna N than JP-4	---	---
Four ball wear, mm. (JP-4 is .45)	---	---	0.75	---	---
Mircobial resistance	No effect	Readily attacked	Compares with JP-4	---	Not attacked
Adhesion	Low	High	High	---	---
Combustion efficiency	Poor	Acceptable	Acceptable	Acceptable	Acceptable
Atomization in engine	Acceptable	Acceptable	Acceptable	Most difficult	Acceptable
Pumpability	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable
Lubricity in pumps	Short term OK	OK in 150 hrs	Short term OK	OK in 150 hrs	Short term OK
Development	Not optimized	Not optimized	Being optimized	Being optimized	Not optimized
Availability for test program	Available	Available	Available	Not available	Available
Company activity/funding	Active/Indep	Active/Indep	Active/Fund	Active/Fund	Inactive

(a) Recovered fuel

(b) Corrosion inhibitor being added.

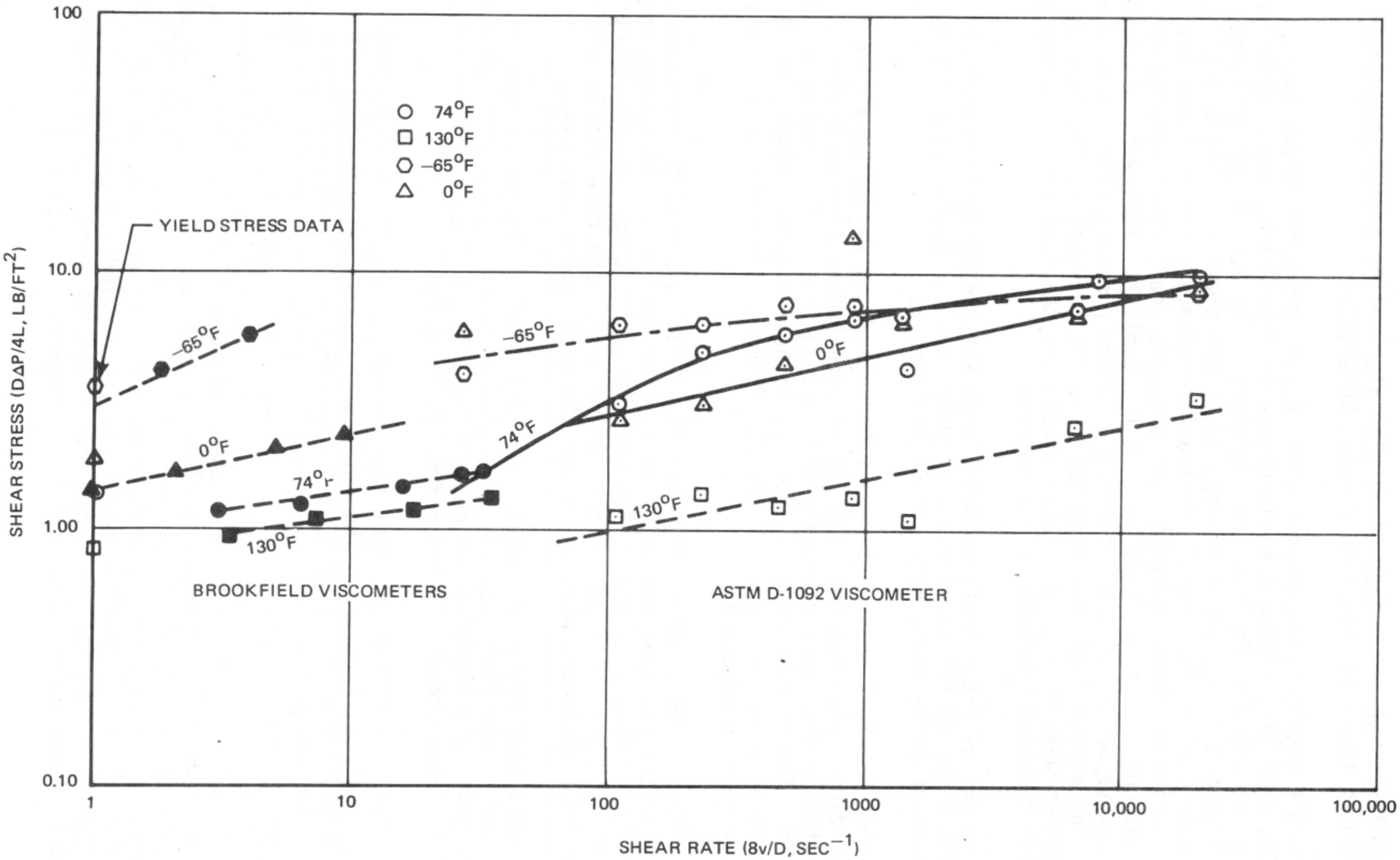


FIGURE 2
FLOW DIAGRAM FOR EMULSIFIED FUEL B

-65°F capillary viscometer test along with fluctuating system pressures. In some instances there was about 50 percent separation.

During the 0°F capillary viscometer test, severe pressure surges took place. The capillary effluent would change in appearance from a globular shape to a rod shape as it left the capillary. The rod shaped effluent appeared frequently with rapidly dropping system pressure. There was little separation of fuel in this test. Instead of averaging the high and low pressures, which differed markedly, the pressure peaks were averaged and used for calculations. This was done because the capillary effluent flow rate appeared equivalent to that of other tests where pressure differences were minimal. The actual fuel flow rate could not be measured as the time of peak pressures were brief. At steady conditions the fuel flow rate was the same as the constant hydraulic oil flow rate.

The data curves of the Brookfield Rotational Viscometer tests cannot be joined with those of the capillary viscometer tests. Again, this may be due to inherent differences between the instruments.

Fuel C. Fuel C did not appear to degrade by releasing liquid fuel during standing. Penetrations measured at room temperature on different dates were essentially the same, averaging 308 units giving a yield value of 1160 dynes/sq.cm. Temperature changes appeared to have a comparatively small effect, ranging from 1780 dynes/sq.cm. at -65°F to 1190 dynes/sq.cm. at 130°F. This can be seen in Figure 3.

Severe pressure surges, and a large amount of fuel separation, occurred when the two smallest diameter capillaries were used in the 74°F room temperature capillary viscometer test. The peak pressures were used for shear stress calculations in each instance. The pressures were much more stable and little or no free fuel separated when the other six capillaries were used.

Pressures were comparatively stable and little emulsified fuel breakdown occurred in the 130°F capillary viscometer test. In the 0°F capillary viscometer test, the pressure surged continuously and the emulsified fuel separated in large amounts, ranging from 25 to 50 percent.

The -65°F capillary viscometer test gave anomalous results as indicated on the flow diagram, Figure 3. The data curve is below the 130°F curve rather than above the 0°F curve as would be expected. Pressures varied within a narrow range for each capillary, but there was substantial separation of fuel. A repeat test using three capillaries confirmed the location of the -65°F curve. In the repeat test, the fuel appeared to be completely broken as it left the capillary when observed through the cold box window. Upon removal from the cold box, the effluent fuel appeared to be a transparent, syrupy liquid instead of the translucent emulsion. As the effluent fuel warmed to room temperature an emulsion phase reformed to produce two separate phases, of which about fifty percent was emulsion, the remainder free liquid fuel. This peculiarity of the fuel may have been responsible for the anomalous displacement of the shear curve, which is otherwise unexplainable.

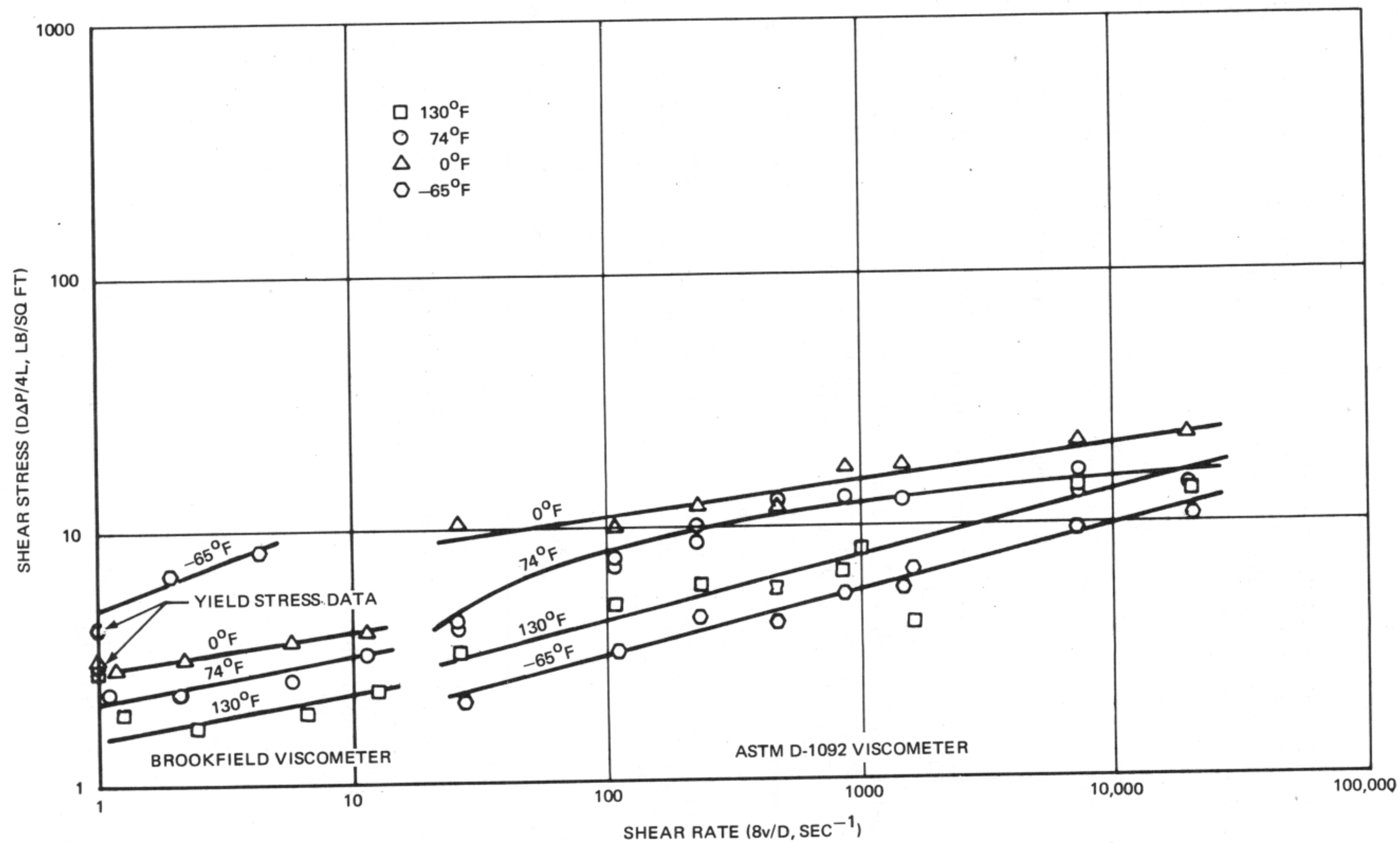


FIGURE 3
FLOW DIAGRAM FOR EMULSIFIED FUEL C

The Brookfield Viscometer curves are similar to those of Fuel A and Fuel B in that not all temperature curves can be linked with the corresponding curve of the capillary viscometer. There was no major displacement of the -65°F curve representing data obtained with the rotational viscometer.

Fuel C has the highest yield value as measured by several laboratories. This ranges from a high of 2700 dynes/sq.cm. immediately after manufacture to 1140 dynes/sq.cm. some days or months later when received for test by another laboratory. These are room temperature measurements.

Fuel D. Emulsion Fuel D formulation was apparently not affected by increasing temperature to 130°F, but decreasing temperature raised the yield from 788 dynes/sq.cm. to 1700 dynes/sq.cm. A newer Fuel D formulation is supposedly not nearly so affected by low temperature, however, this emulsion was not available for testing.

Fuel E. Although yield values are generally lower for the gels than for the emulsions, gel Fuel E at 1-1/2% is quite solid after preparation. In this state it has a yield value well above 10,000 dynes/sq. cm. and is obviously unusable. After working, it takes on an applesauce consistency which it keeps. It will not regain structure as do the other gels Fuel A, Fuel F and Fuel G. In the sauce form it has a yield value of 385 dynes/sq.cm.

Fuel F. The gel Fuel F has a yield value of 860 dynes/sq. cm. when unworked and a yield value of 390 dynes/sq. cm. when worked. This gel does not reform immediately after working but reformation takes place within 24 hours.

Fuel G. Fuel G is a later formulation of Fuel A and does not give a yield value with the ASTM D217 30 gram cone because the cone never comes to rest.

Figure 4 indicates the effect of temperature on the yield stress for the emulsions and gels available for test at the start of this program. Converted to units applicable to the flow diagrams Figures 1 thru 3, this data appears on the left hand edge of the graph. The value of the shear rate function in this case is not applicable since pentrometer yield stress measurements are static (zero shear rate).

Stability. Generally the emulsions relax during the first month of storage to an equilibrium yield value which apparently is maintained if a corrosion condition does not exist. When stored in mild steel containers, as opposed to glass, breakdown and loss of yield value can occur. The equilibrium yield values obtained were: Fuel C: 1140 to 1500; Fuel B: 600; and Fuel D: 750 dynes/sq.cm. There is no long term yield data for the gels but by observation there is no apparent physical change in Fuel A. Free fuel appears on Fuel E after long storage. Producer tests of Fuel C indicated no JP-4 separation over several months. Apparently these tests were carried out in glass or in a non-reactive container. Fuel C does break partially when stored over a long period in steel drums. Fuel B also breaks partially in steel drums.

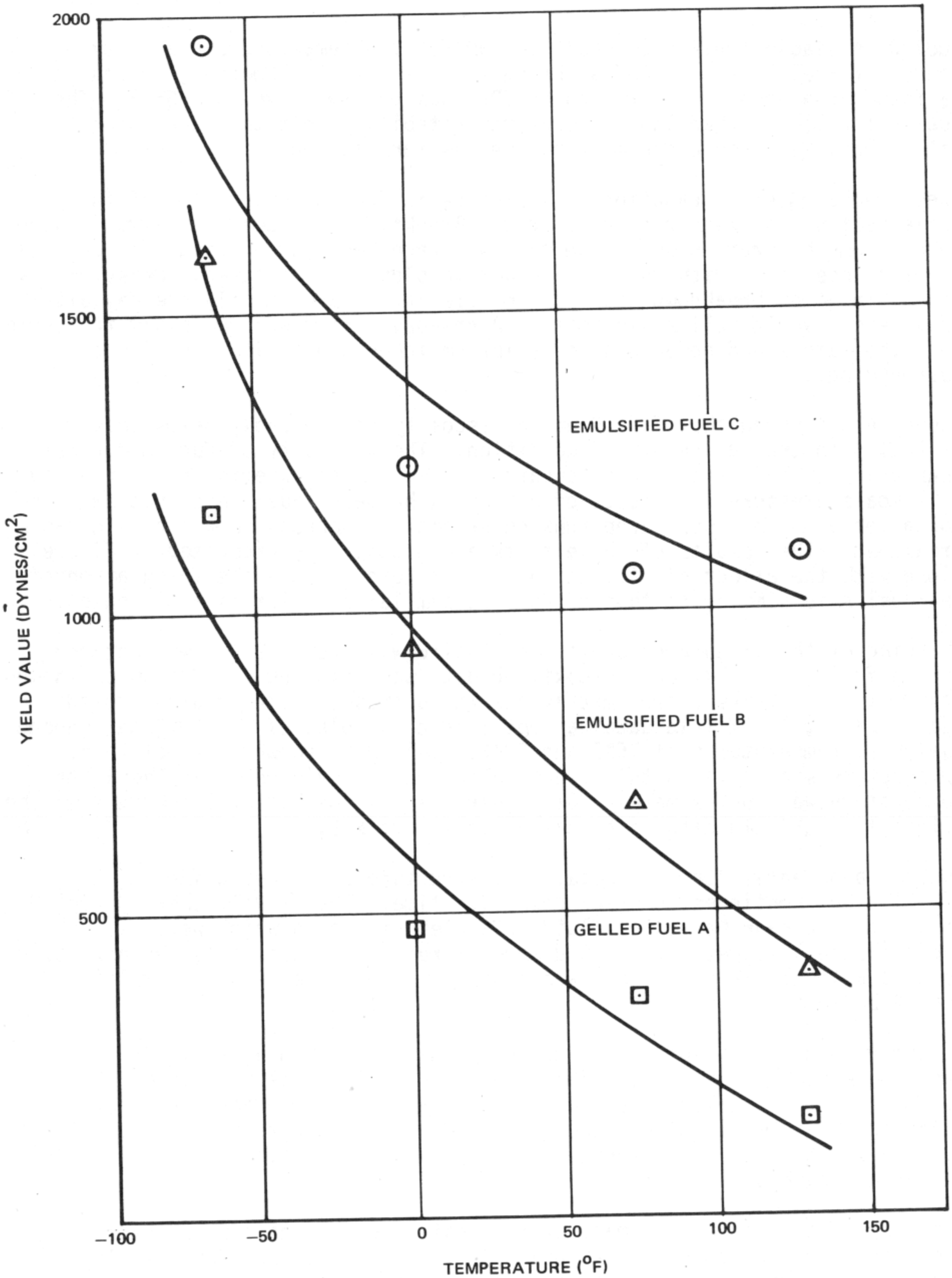


FIGURE 4
EFFECT OF TEMPERATURE UPON YIELD VALUES

Fuel C is stable from below -80°F to 200°F. The temperature stability range for Fuel B is reported as being -40°F to 130°F. However, in contractor tests no breakdown or separation of JP-4 was observed even at -65°F. The old Fuel D formulation had low temperature instability, but this according the literature, has been overcome with the new formulation.

Fuel breakdown or degradation of structure in Fuel G as a result of full scale testing was measured by using the Brookfield Viscometer. Samples were taken from the drum in which the fuel was received and constituted a control or reference value with which all other samples were compared. Measurements of gel in which breakdown was noticed were made approximately one day after they were used in full scale tests. A one-day period was necessary to assure that the sample had come to an equilibrium temperature with the laboratory surroundings.

These tests showed that Fuel G had a viscosity considerably below that of Fuel A in the "as received" condition. The viscosity of Fuel G did not change appreciably after being sheared to the extent experienced in running full scale pressure drop tests of a heat exchanger. Fuel which had been used for a series of pressure drop runs on several components showed considerable breakdown. The results of these tests are graphically presented in Figure 5 along with the effect of storage and temperature. Since the formulation of gel Fuel A is similar to that of Fuel G, similar behavior is anticipated.

Thinning of the mixture of barrels of Fuel G with temperature was noticed during full scale testing. Brookfield data was obtained at 78°F which showed apparent viscosities approximately one-third those of the original "used" fuel. Later, Brookfield data was obtained on samples of the original unused Fuel G at temperatures of 75°F and 92°F. This data showed the gel to be temperature-sensitive in this range. The apparent viscosity at the lower temperature was approximately 70% higher than at the higher temperature. The original Brookfield data is contained in Appendix I.

The gel apparently does not regain its structure after being sheared heavily, but continues to break down with time. The heavily sheared Fuel G returned to a near Newtonian fluid. Samples of Fuel A which were used in the pressure viscometer tests and were stored in a glass container also broke down to a liquid in time. No data history was obtained on the samples of Fuel A because breakdown was not immediately apparent.

In order to conserve sufficient material for the pump down test, an additive was mixed with the broken Fuel G to restore its structure. The purpose was to stabilize the fuel to prevent continued breakdown after shearing. This additive was supplied and added by the representative of the fuel manufacturer. The effect was a temporary restoration, but not a stabilization after shear.

Two barrels of Fuel G were made at the test site from gelling agent and fuel meeting ASTM commercial kerosene fuel specification. The stabilizing additive was put in to prevent breakdown. This material was mixed with Fuel G which had been made at the manufacturers plant. Samples of this mixture from the supply tank upstream of a throttled centrifugal pump and from a

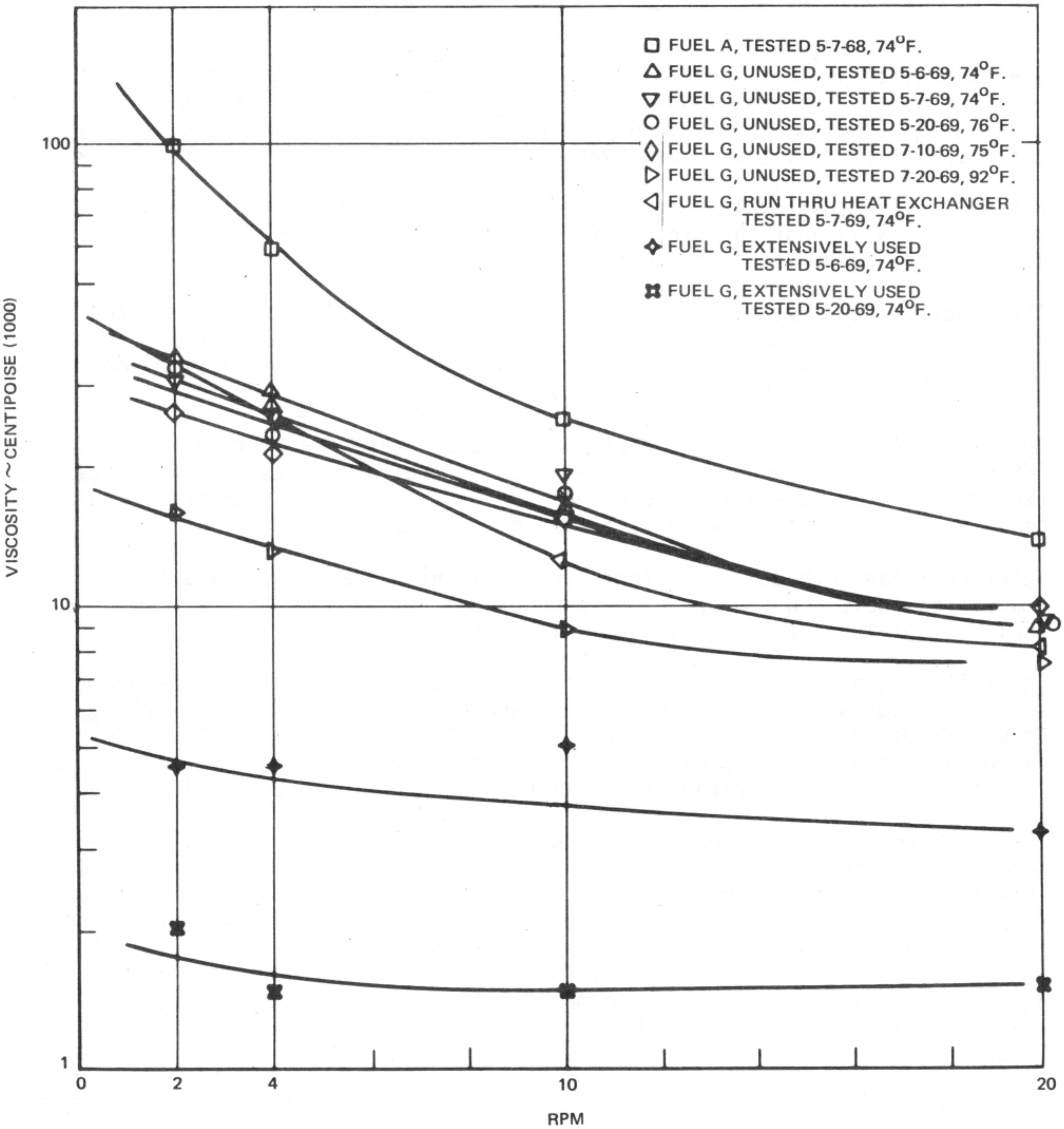


FIGURE 5
GELLED FUEL VISCOSITY DEGRADATION

receiver barrel downstream of the pump were compared after the test run. As shown in Appendix Figure 3.16 a decrease in viscosity was apparent. No measurements of this type were made on the emulsion because it is highly broken after similar pumping.

Chemical and Physical Properties. Most physical and chemical properties are controlled by the parent fuel, JP-4 or Jet A, from which the emulsions or gels are made. The additional phase constitutes 2% to 4% of the mix and would affect specific gravity only slightly, e.g., Fuel C specific gravity is about .78, whereas the JP-4 used was about .76 specific gravity.

Net heat of combustion is lowered in most instances due to the water content but is generally near the minimum for JP-4, 18,400 BTU's per pound, for the fuels tested according to the literature.

The vapor pressure measurements taken on the thickened fuels and reported in the literature apparently were not adjusted for vapor losses during the manufacture. If there were no vapor losses, an equilibrium pressure should be 2 to 3 pounds in the closed test cylinder.

The emulsifiers of the fuel emulsions affect the water separation index (WSIM) of fuel recovered from the emulsions. The values, as should be expected, are extremely low, being around 15. However, this property would be unimportant or of no value if emulsions were used.

Water addition much above the formulation amount appreciably thins the emulsified fuels. Water can be suspended in small amounts in the gelled fuel; but of large additions, most will settle.

The solid contaminant in many thickened fuel samples has been high since solids can not settle out. This is an inherent property of the material. Gross solids would have to be removed upon delivery to an aircraft. Fuel cleanliness can be significantly improved once thickened fuels are introduced to widespread use and appropriate housekeeping procedures are implemented.

Corrosion. Corrosion evaluations made by different laboratories were made using different procedures. However, tests made on fuels at SWRI[1] revealed that Fuel C is severely corrosive to mild steel whereas Fuel B and the Fuel D formulation tested were but mildly corrosive. Compared to JP-4, Fuel B and C also corrode magnesium. Cadmium plated 4130 steel is apparently unaffected. Each of the emulsions attacked copper. The Fuel D emulsion also attacks 4340 steel. Fuel C was being reformulated by addition of corrosion inhibitors. The corrosive effects of the others may possibly be overcome similarly. Producer tests for corrosion by Fuel A indicated that there is little effect.

Elastomer Compatibility. The emulsions soften EC-776 Buna N coatings more than JP-4 or a JP-4 water mixture. This is expected because of the presence of surfactants in these fuels that give superior wetting or penetration of EC-776 than water alone. EC-776 has long been known to soften in water and this feature along with poor microbial resistance caused its replacement in newer jet aircraft.

[1]Southwest Research Institute.

Fuel E was very severe upon EC-776. The other gels had or should have no effect different than that of the parent fuel.

Polyurethane fuel tank coatings, Vithane polyurethane fuel cell material, and PR-1422 Thiokol sealants were not affected by any of the thickened fuels in contractor tests.

Wear/Lubricity. Fuel C was reported as having a high wear on bearings in a 4-ball test. The 4-ball test is a common test to measure friction and lubricity. There was no data for other fuels in this test.

Various reports have been made of pump failures while using the various fuels so the aspect of lubricity was noted particularly wherever mentioned in the literature. No evidence could be found to indicate that any of the modified fuels affected systems using fuel as a lubricant. There were reports of pump failures while using various fuels but these failures were all accompanied by contamination of the fuel with foreign matter picked up in the systems or possibly in the manufacture. Actually, some reports indicated the lubricating qualities to be improved, however, this has not been thoroughly investigated for all fuels.

Microbial Resistance. Fuels B, E and F were tested for the support of microbial growth. Fuel B supported growth more readily than the others. This may be a characteristic of water base emulsions without growth inhibitors. The organisms live in the water and feed on the fuel. Fuel E had an effective growth inhibitor. Fuel F did not affect micro-organisms differently than did the control specimen.

Fuels A and C were subsequently found to support micro-organic growth. Fuels D and G were not tested.

Adhesion and Cohesion. There was little comparative data for these properties. The adhesion of Fuels A, B, and C were tested only qualitatively at this time in the contractor laboratory. The amount of fuel remaining on the sample coupons appeared to be a function of the speed of withdrawal. The emulsions adhered in an approximately equivalent manner. Less gel than emulsion was retained on the coupons.

Contractor slide-tray tests indicated that large quantities of Fuel B and Fuel C, emulsified fuels, but little of the Fuel A, gelled fuel, could be held up as unavailable in aircraft tankage because of their adhesiveness. Additional testing with FUEL B indicated that adhesion decreased with increased yield stress. The thickened fuels adhere less to EC-776 integral fuel tank top coating than to other fuel tank top coatings and to aluminum alloys. The adherence to 823-010 polyurethane top coating was about that to aluminum.

Outgassing. The emulsified fuels tested expanded in volume as much as 18 to 25 percent under the test conditions. Figure 6 shows the action of the fuels when subjected to a simulated climbout as recorded in the test. Not all gas bubbles are retained in the fluid mass. Some percolate from bubble sites up through the fuel along an erratic path to the surface. Before release of

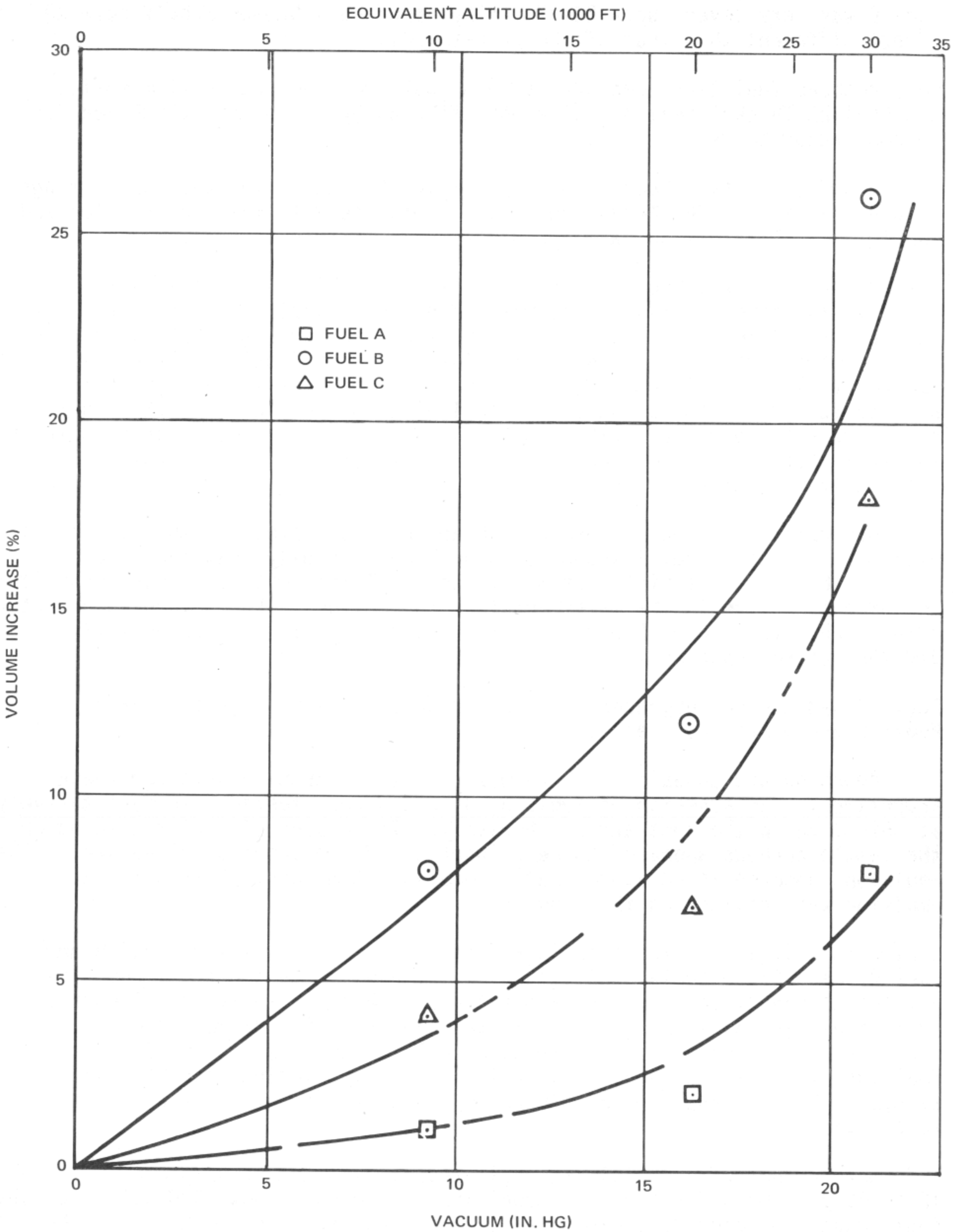


FIGURE 6.
VOLUMETRIC EXPANSION OF THICKENED FUEL WITH ALTITUDE

gas a bubble would swell and then collapse when the gas was released. The process would be repeated in a manner similar to breathing.

Fuel A had few gas bubbles initially compared to the emulsified fuel. The number and size of bubbles increased with altitude; but unlike those in the emulsified fuels, the bubbles rose to the fuel surface releasing the gas. This resulted in comparatively little volumetric expansion as seen in the graph. Bubble patterns are shown in the photographs included in Figures 7 and 8. Results are affected by the amount of air trapped in the fuels during manufacture and handling, the amount of air in solution and by the amount of low vapor pressure constituents in the base fuel.

Processing. A consideration in selecting a fuel for ultimate use in the field is the method of manufacture. Can the fuel be modified at the field location? Is the process a batch or a continuous process? Can the introduction of air into the fuel during this process be eliminated or controlled to a minimum? These questions, along with "what will the ultimate cost per gallon be for quantity usage?", can only be answered or estimated by the suppliers and received only minor consideration in this study.

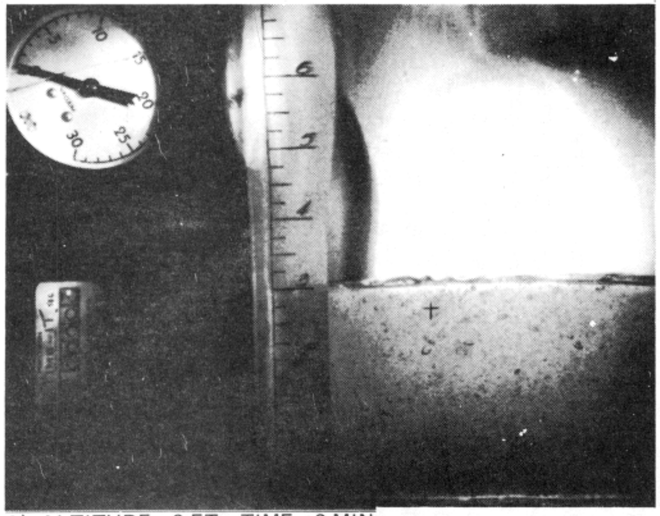
Availability. The question of availability of fuels for a test program was of first level importance in selecting the fuels to be used in subsequent phases. In some cases, this was a function of the producers activity in the area of controlling the flammability of fuels. In others, a state of development could have been the deciding factor.

Safety. The safety aspects of the various fuels are still quite subjective after the testing that has been performed. The Bureau of Mines work was not completed at this time, so the results of a systematic approach to the testing of all fuels under conditions which are agreed to be most representative were not available. The preliminary work of the Bureau of Mines and of Falcon Research and Development were the best to date and were considered in evaluating relative safety gain potential.

SELECTION CRITERION. After reviewing all the reported testing on the various modified fuels, it was quite apparent that very few direct comparisons could be made. The different investigators had unique methods and test setups, some of which were either inadequately described or not described at all. Therefore, it was impossible to put the fuels on the same basis for comparison and evaluation. What test information could be obtained on the various fuel gels and emulsions were screened and put with the experience gained in in-house testing. Various physical properties are listed in Table I along with some qualitative aspects of fuel usage, availability and development.

The conclusion as to which fuels to recommend was based on the answer to a few simple and basic questions:

Q. Which emulsified fuel will provide the best vehicle for obtaining the desired results of this program?



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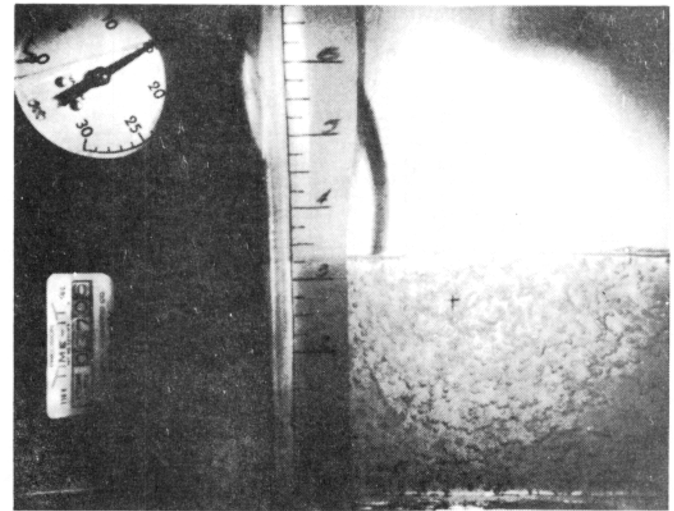

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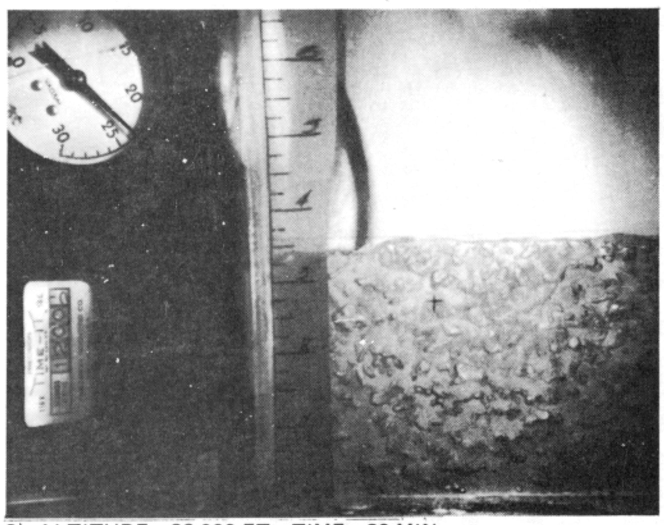

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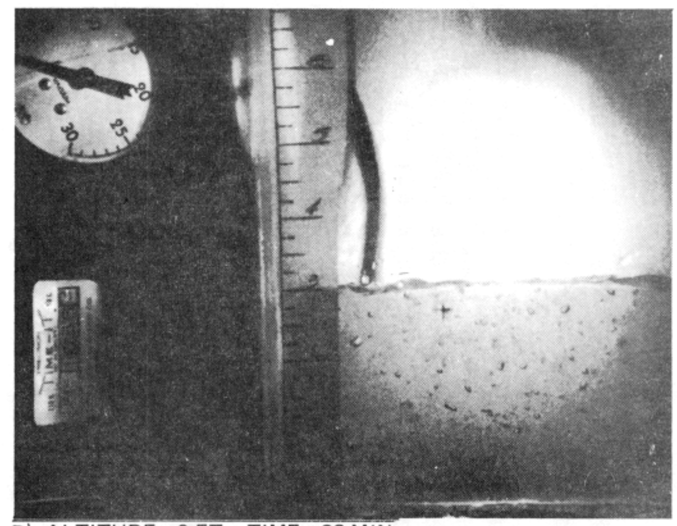

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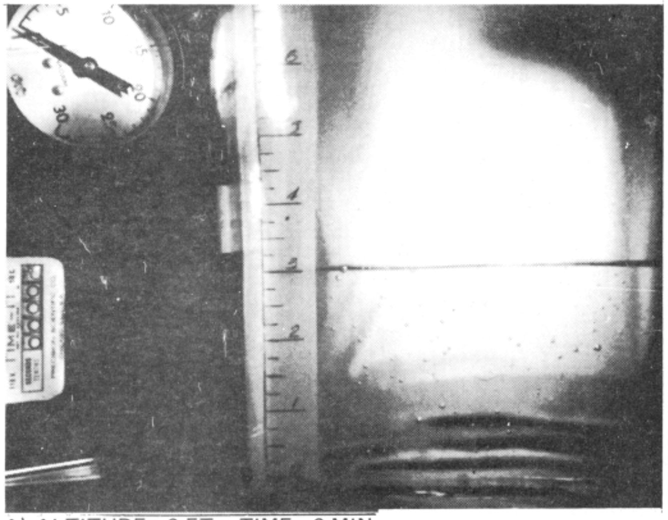
FIGURE 7
EFFECTS OF ALTITUDE - FUEL B



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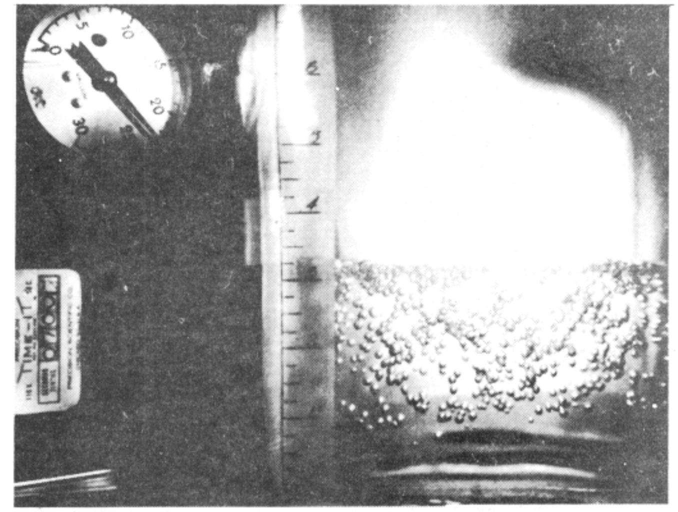

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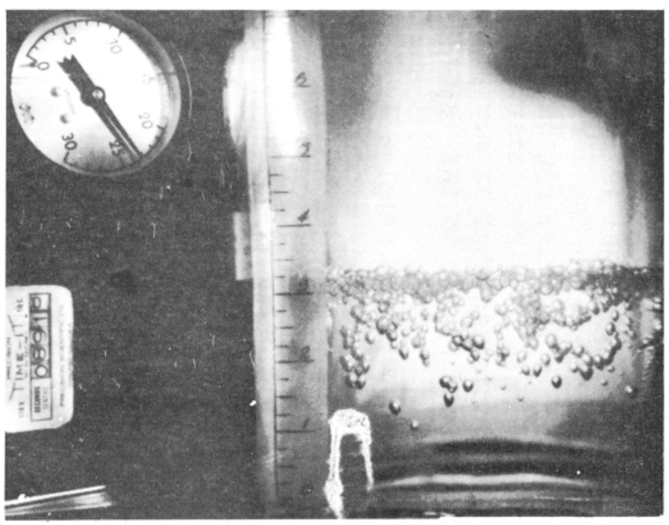
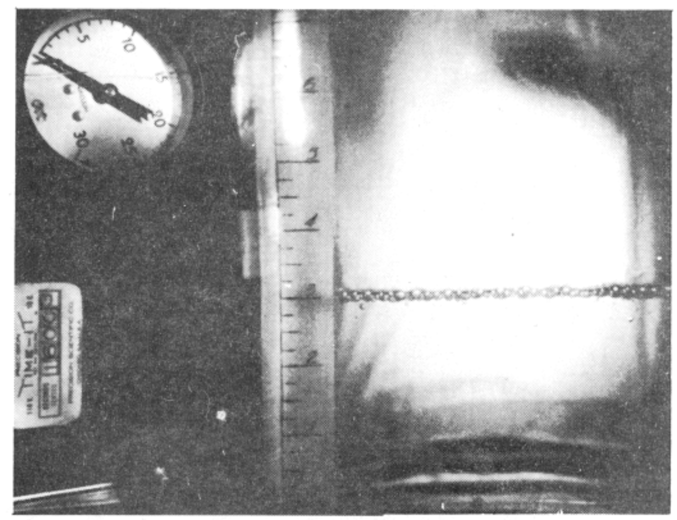


C) ALTITUDE: 36,000 FT TIME: 15 MIN



D) ALTITUDE: 0 FT TIME: 27 MIN

FIGURE 8
EFFECTS OF ALTITUDE - FUEL A

A. The fuel must be capable of test in the range of yield stress from approximately 500 to 2000 dynes/sq.cm. This range is selected to give the largest possible separation of parameters for testing to permit the most confidence in extrapolation of results. It is felt that lower yield values will be required of a fuel which is most compatible with existing fuel systems. Fuel C emulsion will relax to a yield stress of only 1200 dynes/sq.cm., whereas Fuel B will relax to 600 dynes/sq.cm. and Fuel D to 650 dynes/sq.cm. Although these values are approximate, it clearly indicates elimination of Fuel C from further consideration.

Q. Which emulsions were available for testing in the initial phase of this contract?

A. The Fuel D emulsion would probably have provided a satisfactory vehicle for this program, but it was decided not to consider this emulsion because a satisfactory formulation was not available.

The Fuel B emulsion was therefore recommended.

Q. Which gels have been tested enough to provide a good confidence level in their performance?

A. Much testing has been done on Fuel A and Fuel E. The Fuel F gel, besides having a slow reformation rate, has seen only limited testing and was therefore not considered further.

Q. Which gel will provide the best vehicle for the test program?

A. Testing of Fuel E gel has shown a lack of reproducibility of test data in the contractor's rheological testing although it had given good results in the area of engine usage. However, this gel will not reset after shear. It goes into a sauce consistency and has a very low yield stress in this form. The Fuel A gel is therefore recommended. Fuel A is the only currently developed gel which has a rapid recovery after being subjected to shear as indicated in the Navy Engine Laboratory combustor tests and has shown promise in the Bureau of Mines safety tests. In addition, the cohesive properties of Fuel A indicated that it may produce a minimum fuel hangup on the tank surface which would result in the least unusable fuel.

REVIEW. It was originally intended to use an emulsion whose yield stress could be varied over a desirable range in order to obtain full scale test data for various yield values. At the time of fuel selection, there was no experience to indicate problems with this approach. It turned out after full scale testing data were examined that "working" the fuel to the desired stress level would not yield consistent results. Contact was made with others performing similar testing and they too were experiencing anomalous results. The fuel vendor, in work for a government agency proceeding with emulsion development, had planned a similar approach to this material when contacted for discussions of the test results. All were merely exploring since no one else had done and reported similar work. No solution was evident for resolving the anomalous results. A test program to obtain such resolution was not within the scope of the present investigation. Therefore, it was agreed that current emulsion analysis would be based on data from relaxed Fuel B.

While Fuel A was being used in the laboratory test program for determining rheological properties, the gel producer came up with a new formulation which is identified as Fuel G. Fuel A contained metallic compounds which had shown to be undesirable in combustion engines. The amount of resin was reduced to about 2% in Fuel G. What other changes were made is unknown as the resin gellants are proprietary. Although the two gels Fuel A and Fuel G are somewhat similar in appearance, there are differences in their rheology. Fuel G can not be measured for yield value by the 30 gram cone penetrometer and the apparent viscosity of the material is much lower than Fuel A. The FAA directed the Contractor to use Fuel G in subsequent testing.

SECTION B

APPLICATION TO COMMERCIAL AIRCRAFT

TEST PROGRAM. A test program was initiated to provide more specific criteria with which to evaluate fuel selection and to determine the impact of these fuels on existing commercial aircraft design practices. The test program provided the basic data with which to perform system analysis of a DC-8, Model 62 aircraft. The areas of investigation included: component pressure drop, line pressure drop, orifice flow, fuel tank pump-down and pump performance testing. Where applicable to the analysis of system performance, this data is included in the following discussions. Interpretation and application of test results is contained in the analysis section of this report.

Component Pressure Drop Test. Pressure drop test results on eight components simulating those contained within the fuel system of a DC-8 aircraft are summarized in Figures 9 through 16. In addition frictional pressure drop was determined for two line sizes as shown in Figures 17 and 18. Combined frictional and form loss for a 1-1/2 inch line is indicated in Figure 19.

Analysis of the data presented reveals three important features: The first aspect of the component flow characteristics is the extremely high pressure required to initiate flow. The detrimental effect of this on a pump suction system is obvious. In addition, that portion of the fuel system operating by gravitational effects would be essentially inoperative. The second aspect applicable to the emulsion only is the yield stress build-up. As a generalization, it was assumed that high shear components would break down emulsions to a lower yield stress; the opposite effect was observed. As examples, the heat exchanger and filter, commonly labled as high shear devices, produced a yield stress increase of 25% to 40% respectively. This was with the emulsion entering the device in a relaxed condition. A complete record of yield stress buildup is presented in Appendix II. The last aspect which is to be observed from the component pressure drop data is the anomalous effect of initial yield stress. For the most part, component pressure drop using emulsion increased with increasing yield stress. This is to be expected when reviewing the orifice test data presented later in this report. In some cases, see Figure 9 and Figure 13, the opposite effect was recorded. More extensive testing of this phenomena is indicated in Figure 20.

It will be observed that no pattern exists whereby the initial yield stress can be correlated to the pressure drop relationship. Obviously other parameters influenced emulsion flow characteristics in addition to yield stress. The pressure flow rate relationship may be dependent on the amount of free fuel contained within the continuous phase. Unfortunately this is not directly measurable by yield stress. The need for additional rheological testing is indicated.

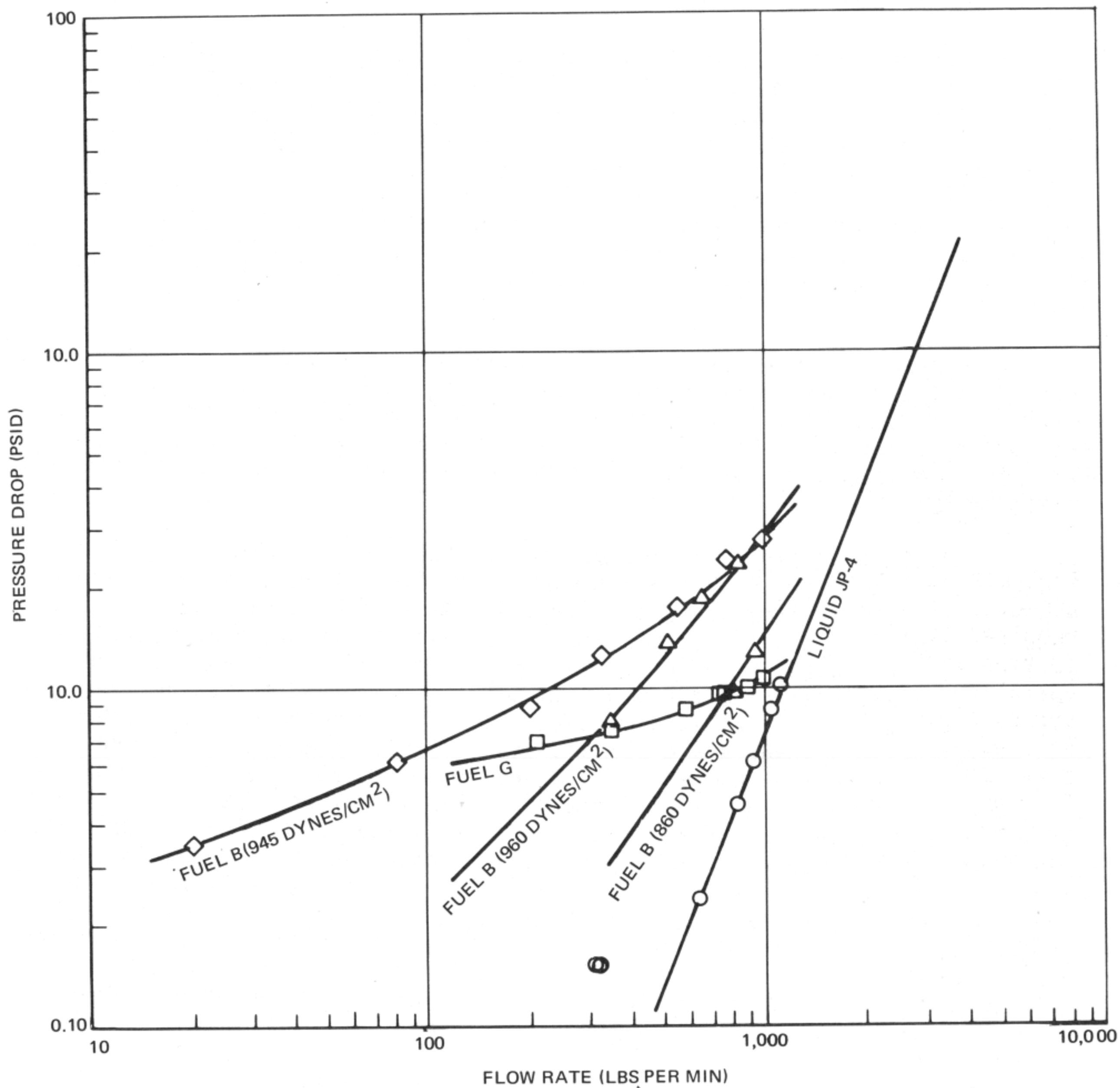


FIGURE 9
COMPONENT PRESSURE DROP – GLADDEN P/N 313880 CHECK VALVE

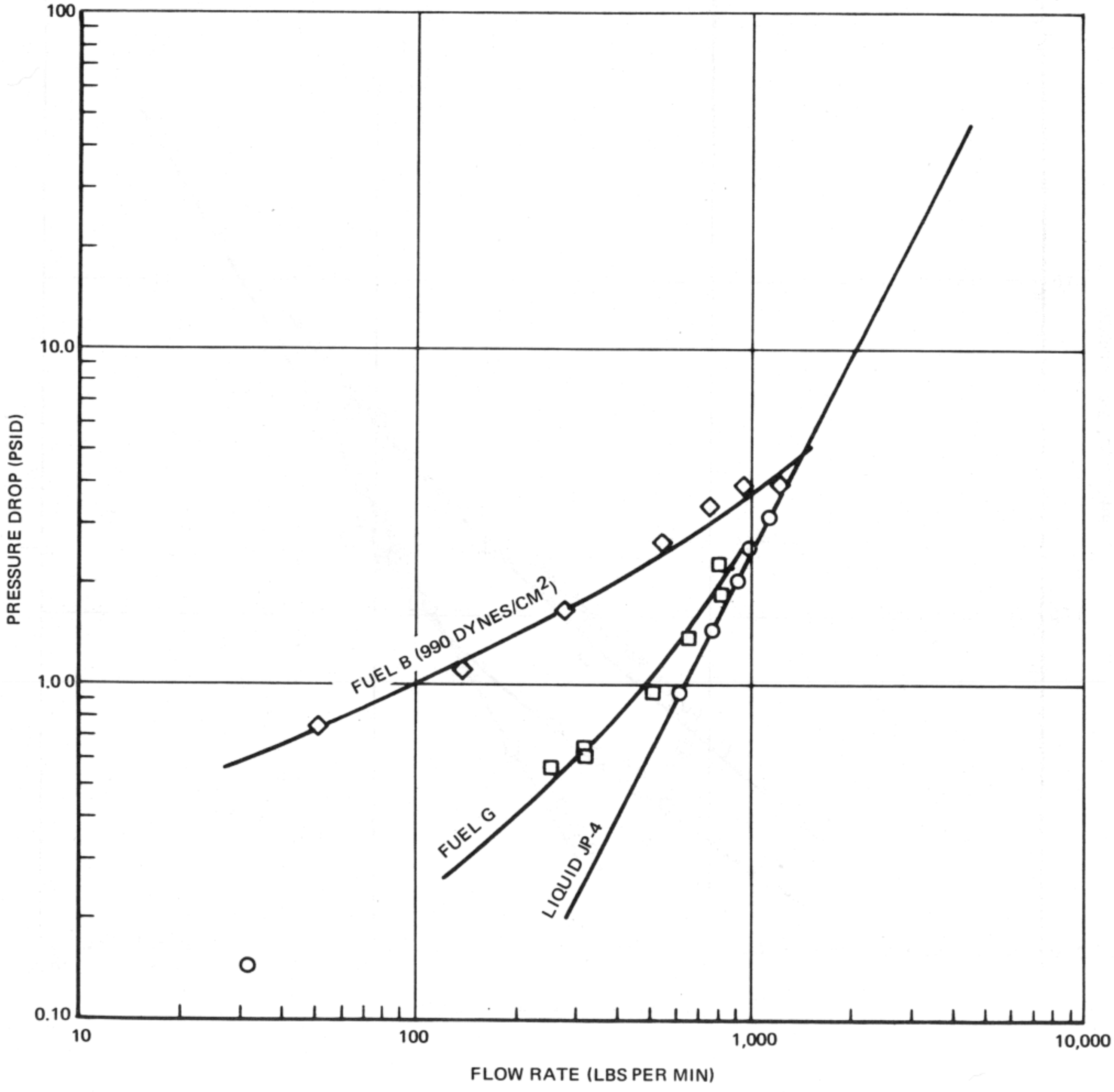


FIGURE 10
COMPONENT PRESSURE DROP – KOEHLER P/N 7-89615 FUEL LEVEL CONTROL SHUT-OFF VALVE

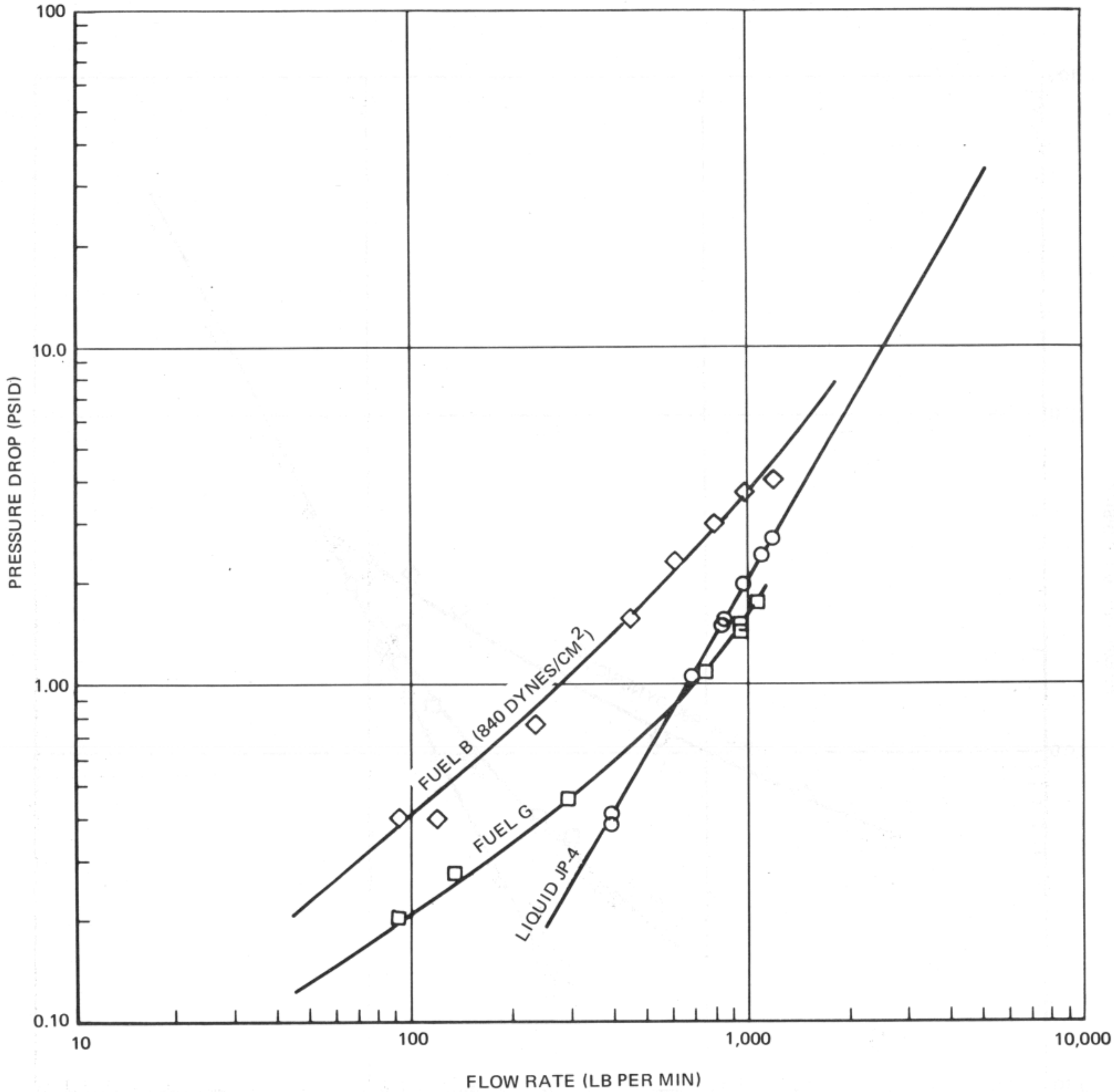


FIGURE 11
COMPONENT PRESSURE DROP – GLADDEN P/N 413800 SELECTOR VALVE

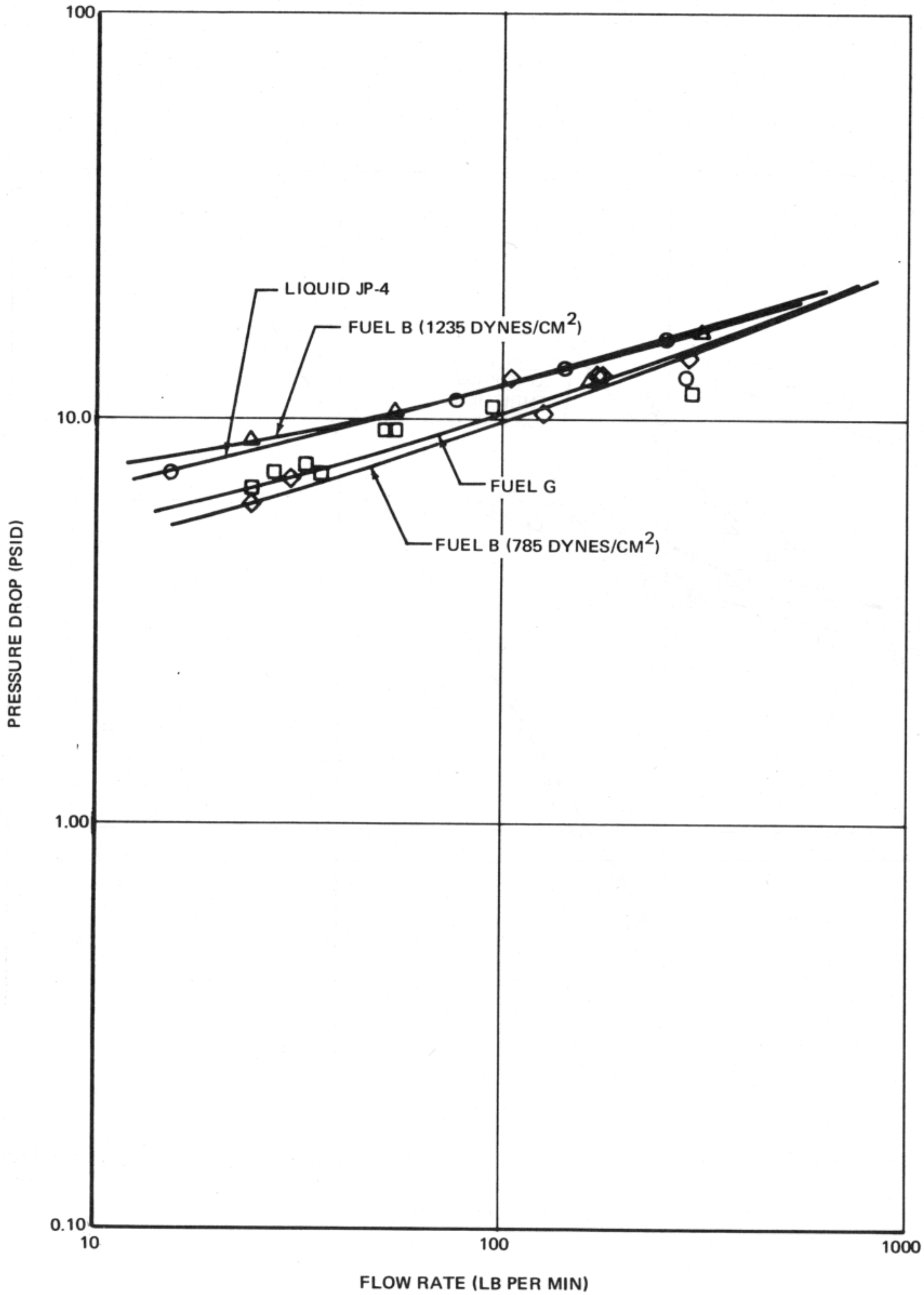


FIGURE 12
COMPONENT PRESSURE DROP – PARKER AIRCRAFT P/N 1112-578216
POPPET CHECK VALVE

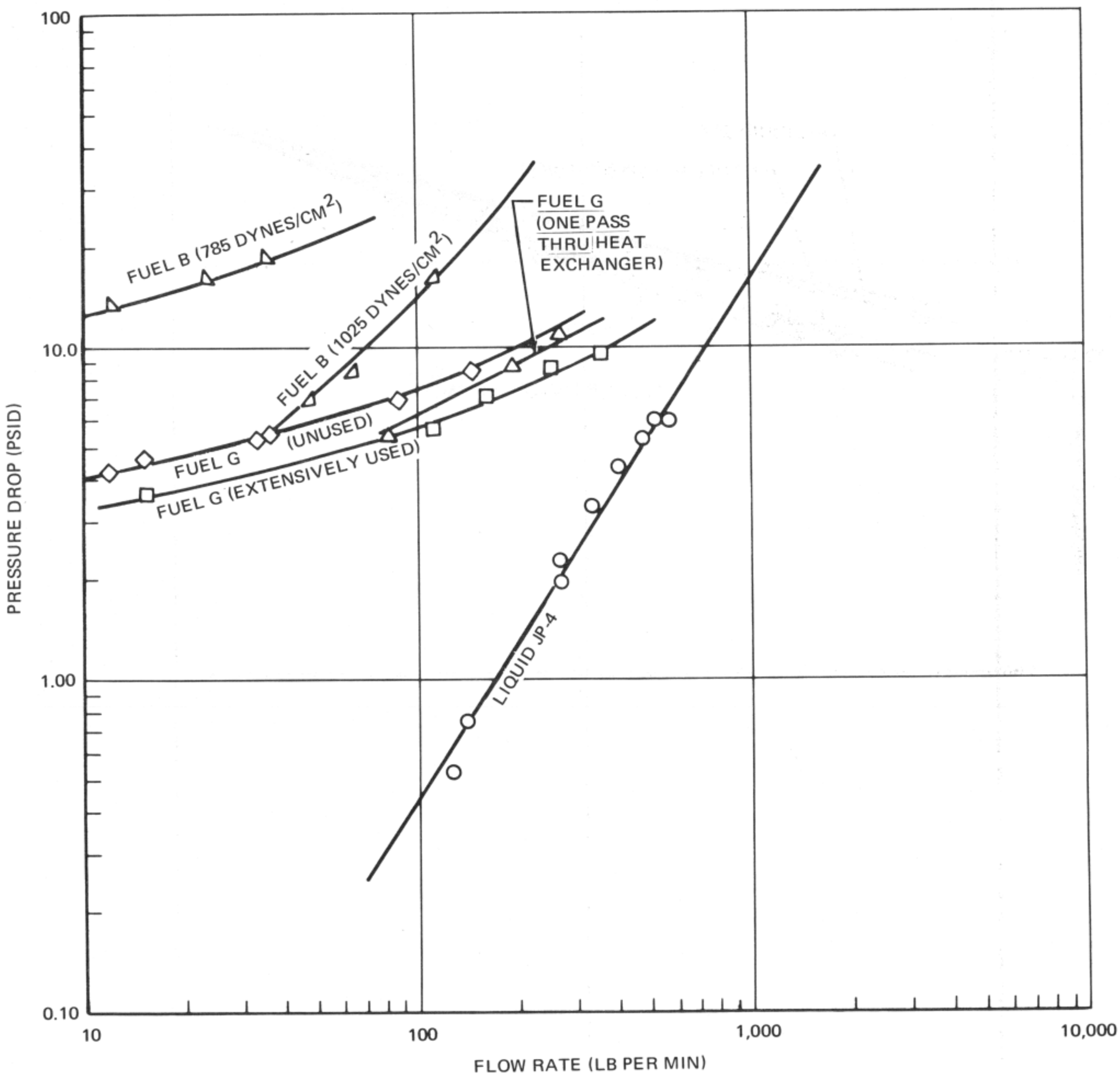


FIGURE 13
COMPONENT PRESSURE DROP – AIRESEARCH P/N SK21412 HEAT EXCHANGER

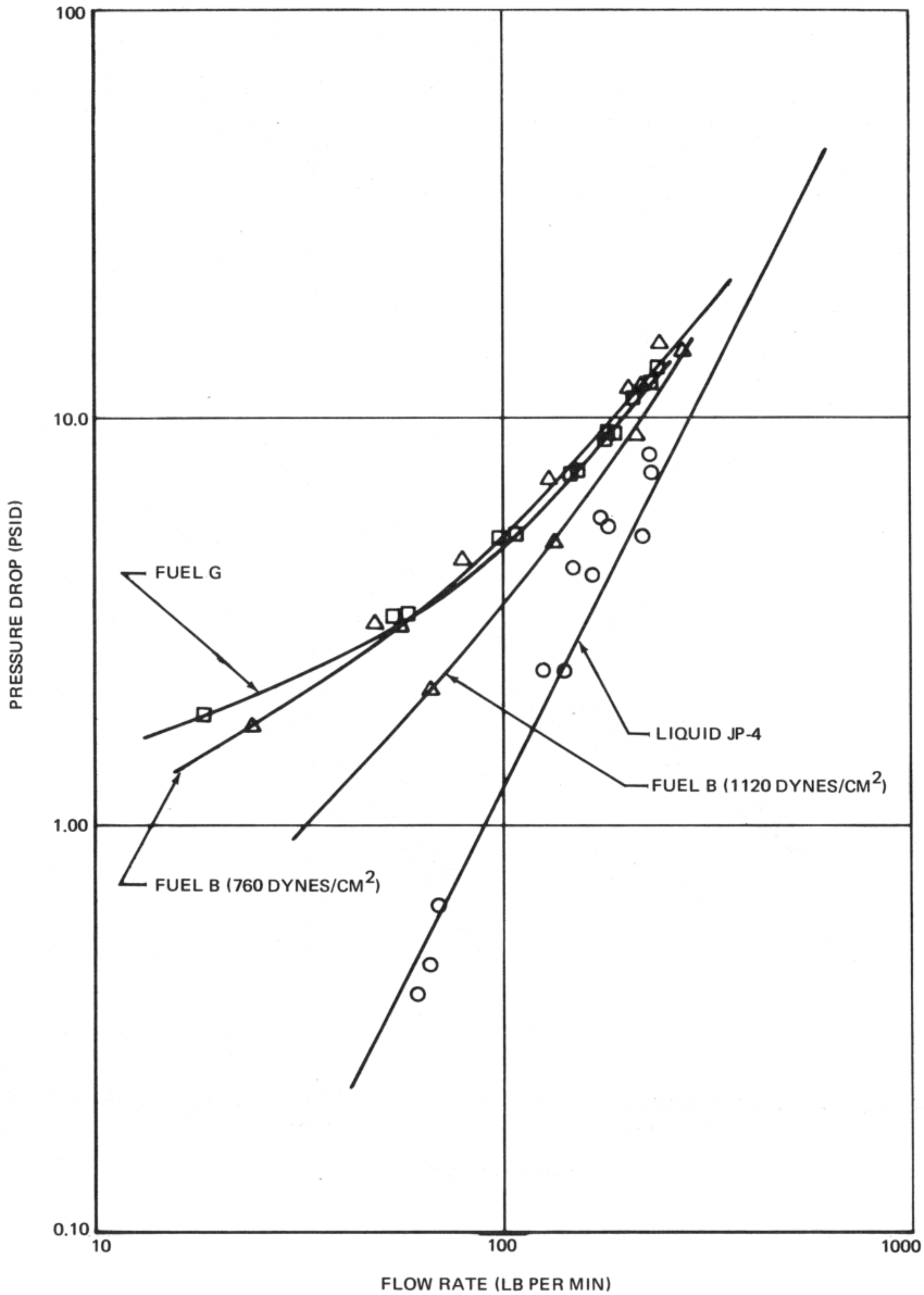


FIGURE 14
COMPONENT PRESSURE DROP – PALL CORP P/N MCS 1001G16 FILTER WITH 40 MICRON ELEMENT

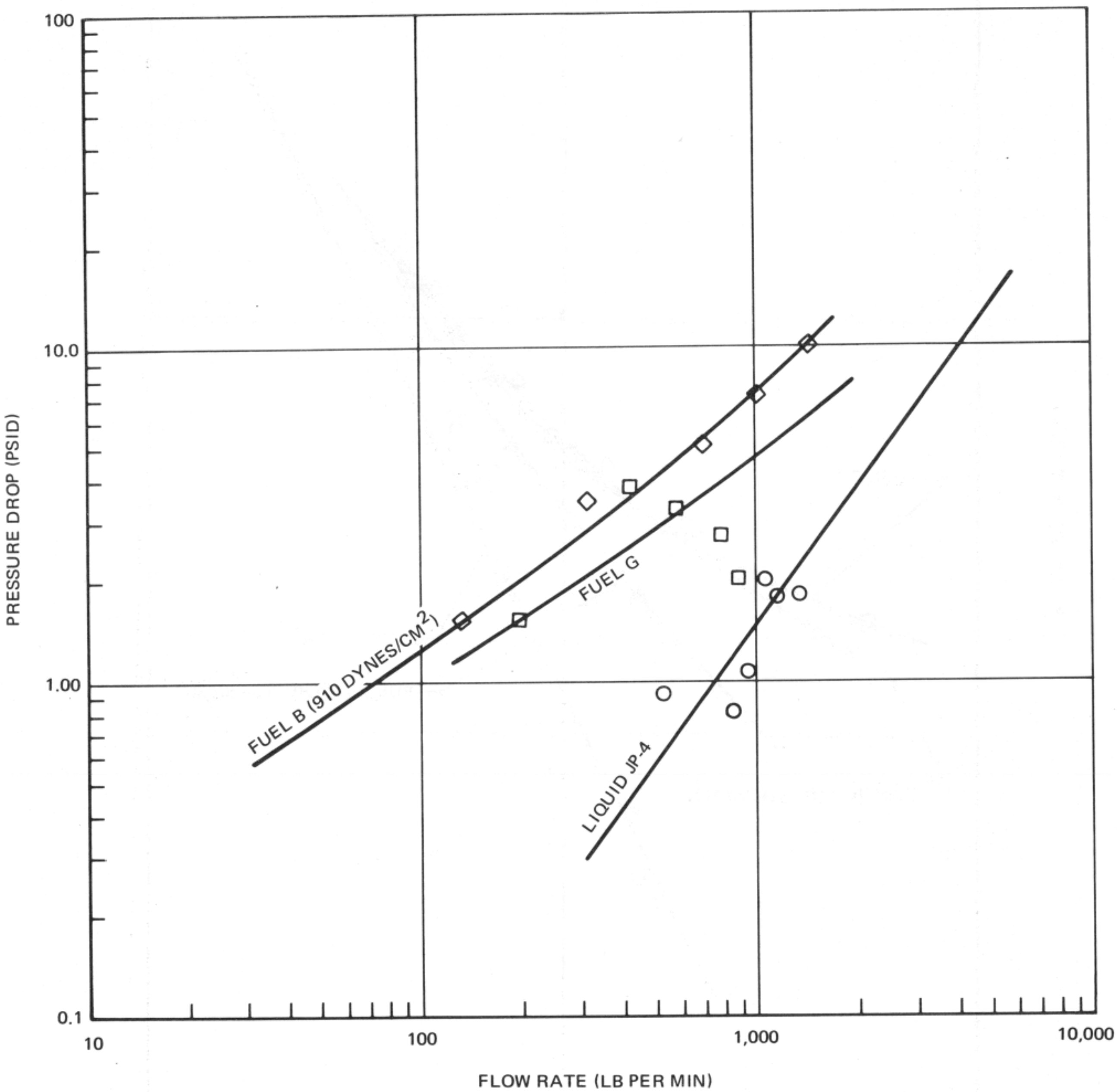


FIGURE 15
COMPONENT PRESSURE DROP – PARKER P/N 565520 BULKHEAD CHECK VALVE

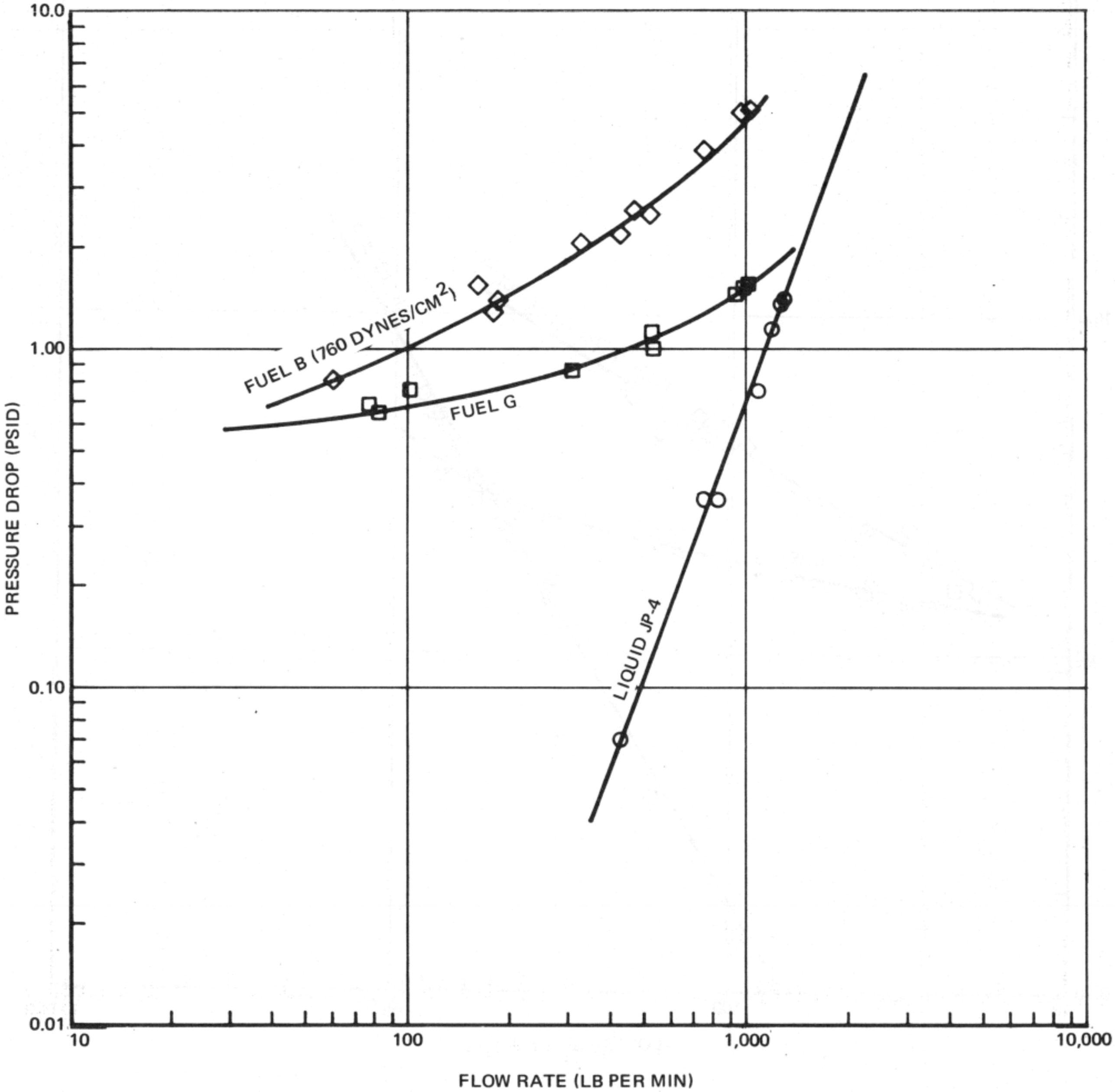


FIGURE 16
COMPONENT PRESSURE DROP – PARKER AIRCRAFT P/N F110 REFUELING NOZZLE AND P/N F406B ADAPTER

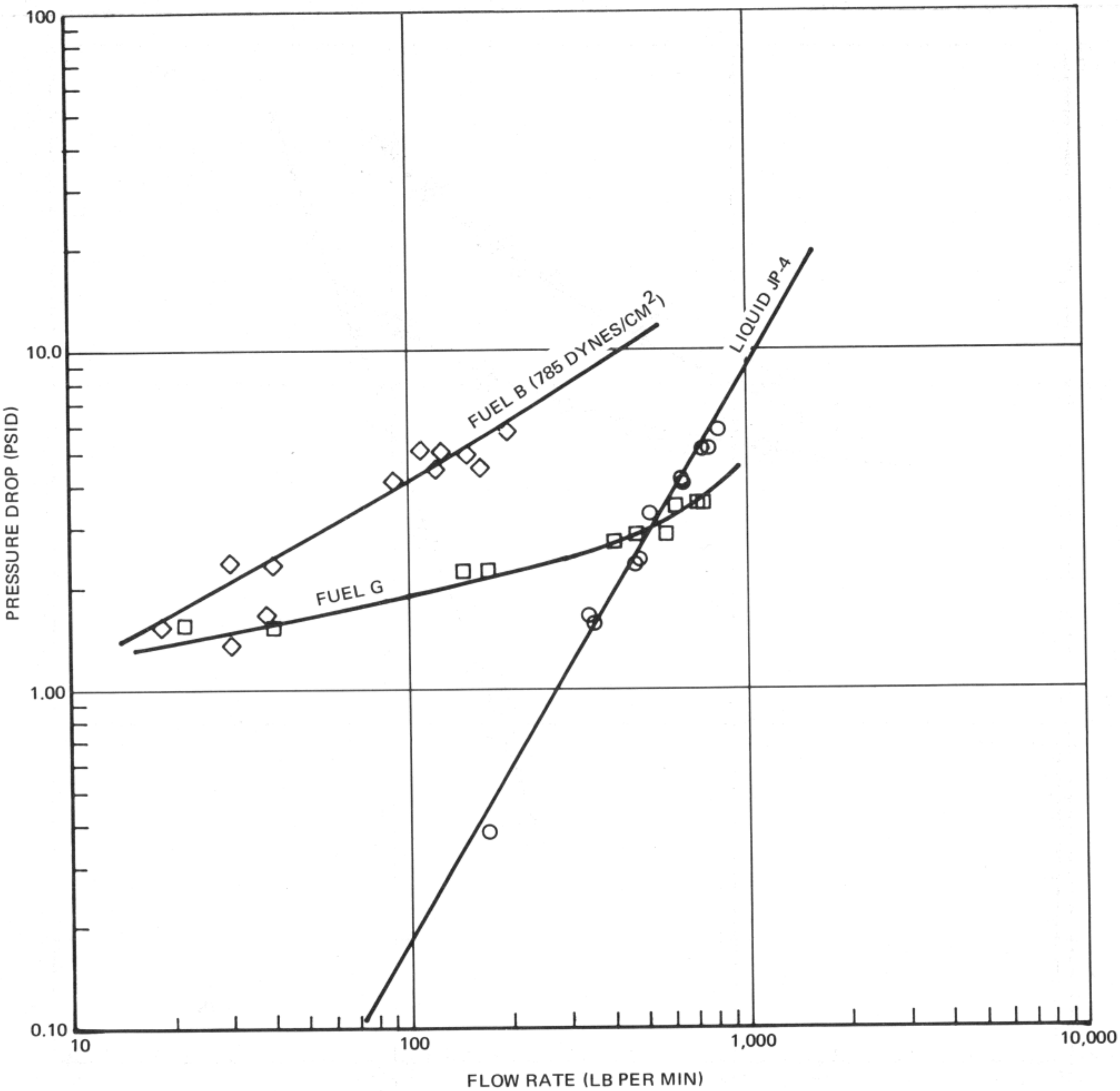


FIGURE 17
LINE PRESSURE DROP – 1-1/2 INCHES, 0.035 WALL; STRAIGHT AL TUBE, 10 FEET LONG

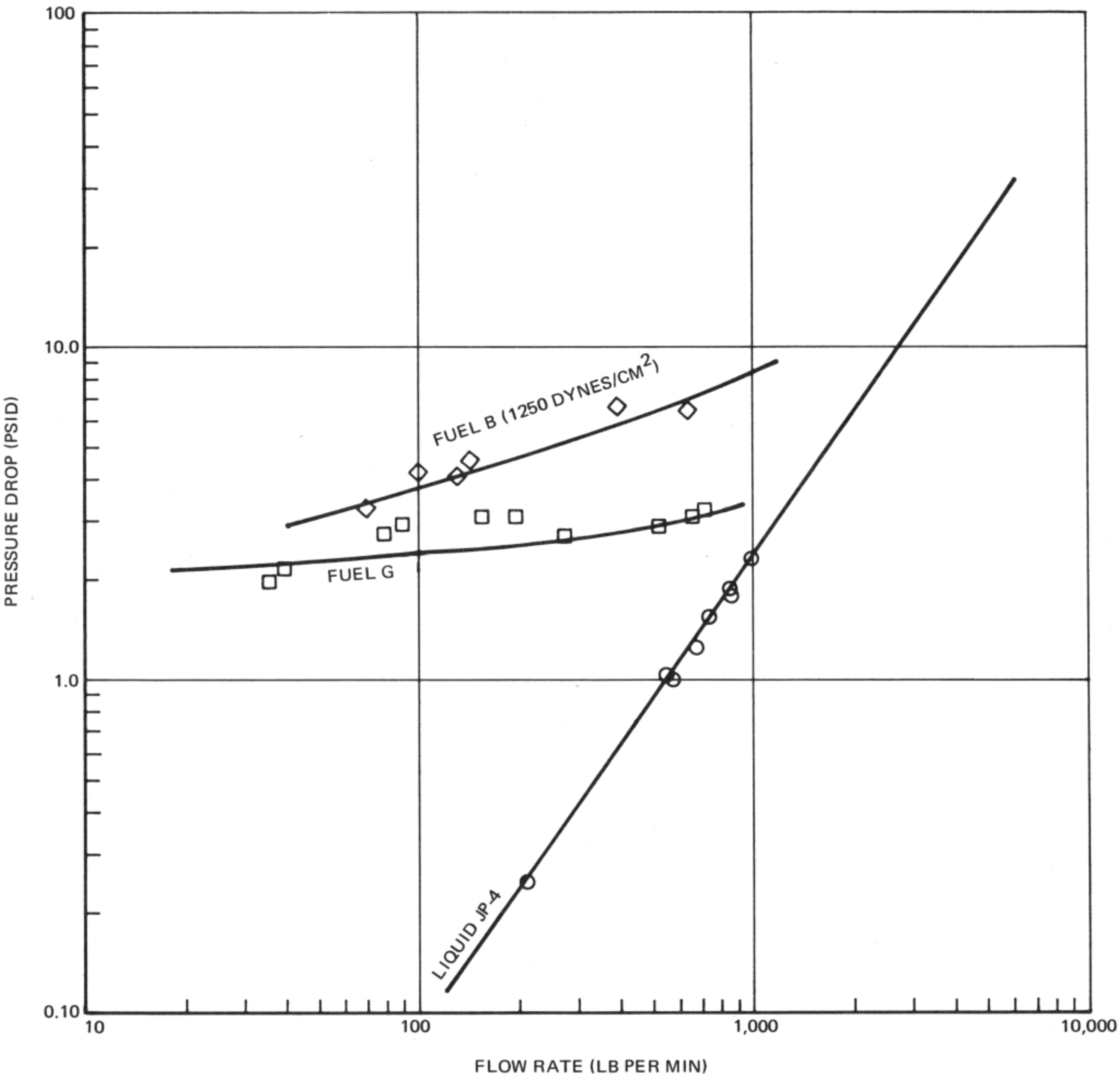


FIGURE 18
LINE PRESSURE DROP – 2 INCHES, 0.035 WALL STRAIGHT AL TUBE, 10 FEET LONG

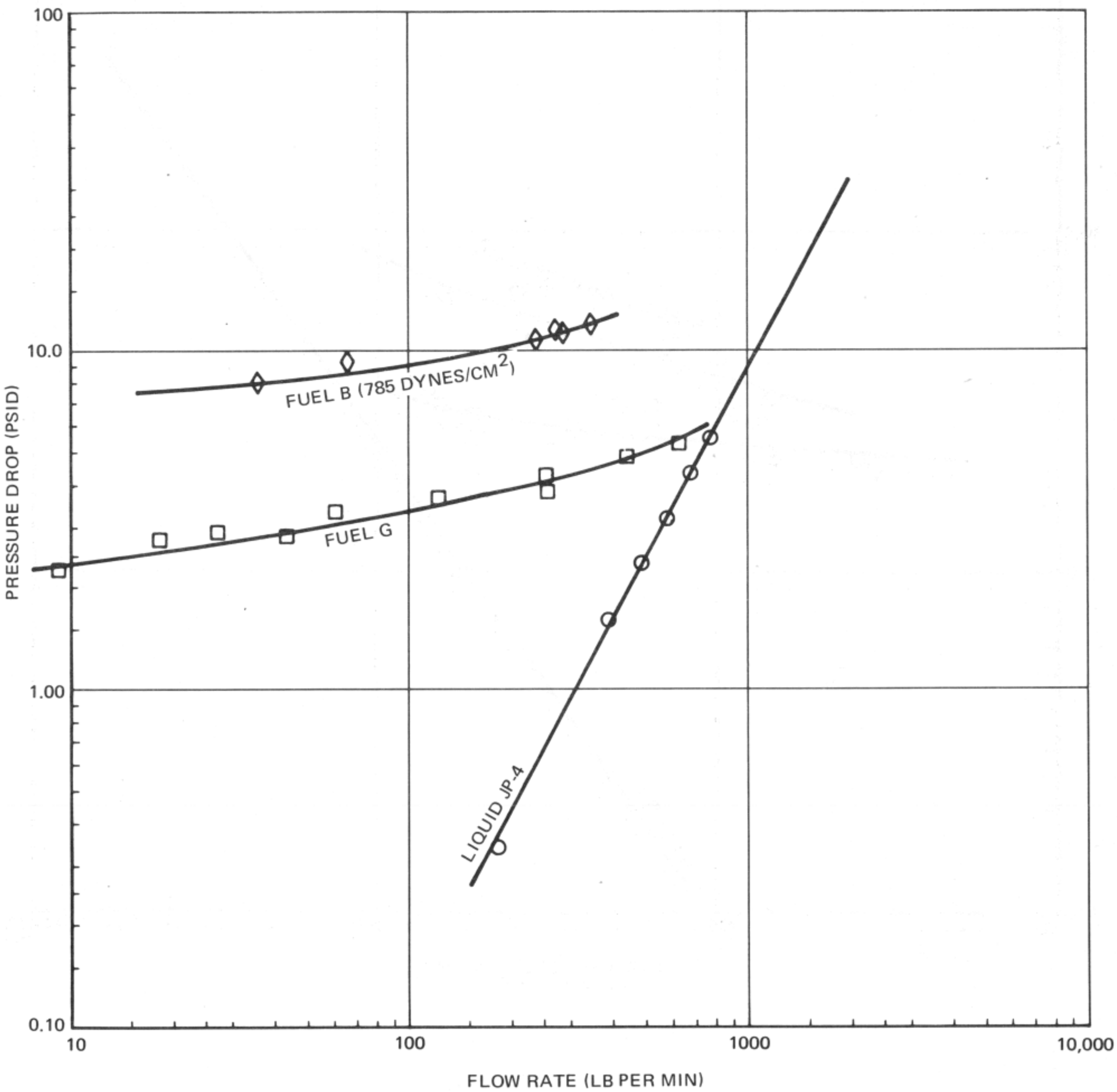


FIGURE 19
LINE PRESSURE DROP – 1-1/2 INCHES, 0.035 WALL AL TUBE, 10 FEET LONG WITH 90 DEGREE BEND

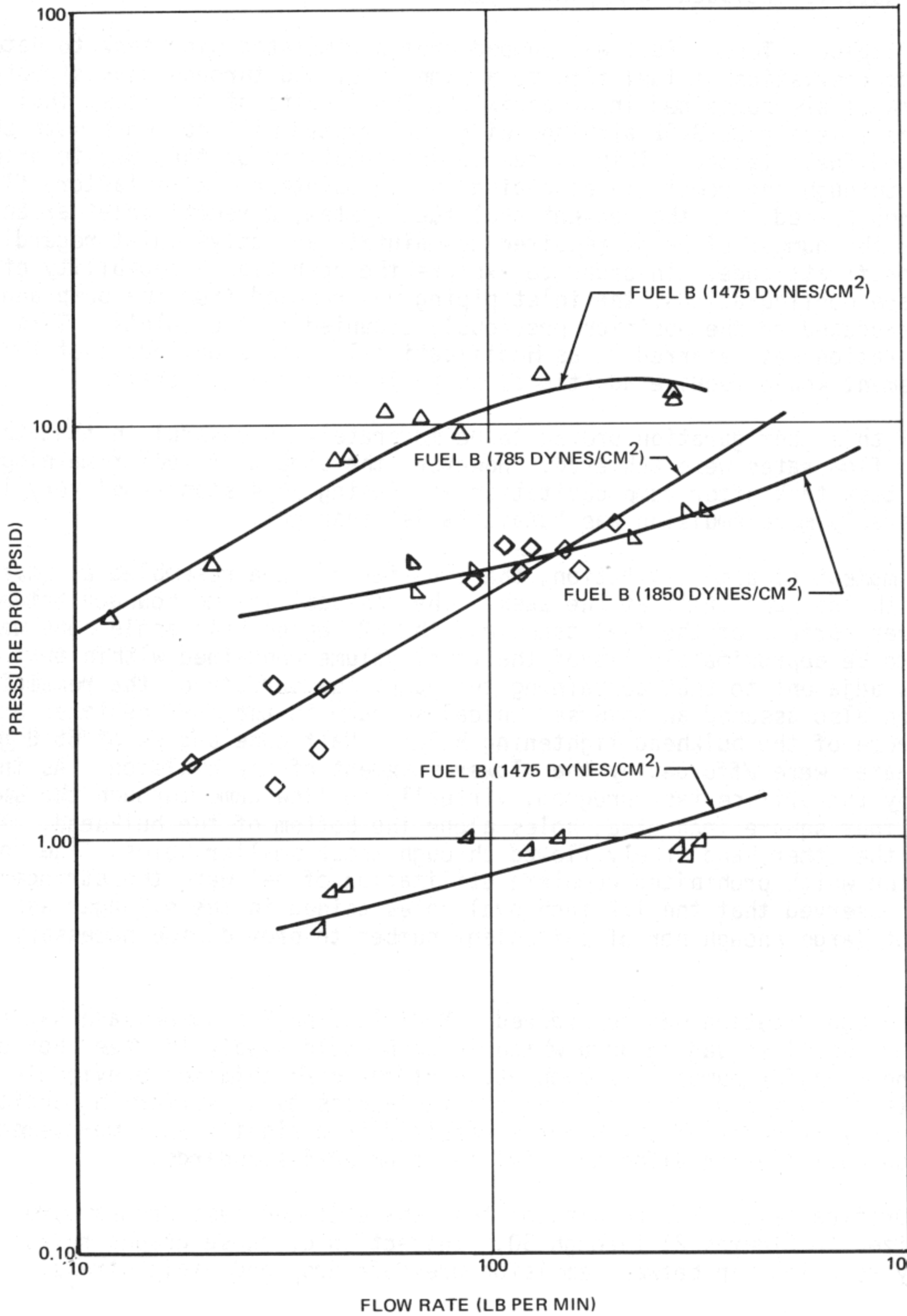


FIGURE 20
EFFECT OF VARIOUS YIELD STRESSES ON LINE PRESSURE DROP – 1-1/2 INCHES, 0.035 WALL, STRAIGHT AL TUBE, 10 FEET LONG

A full description of the component test facilities and procedure as well as raw data is included in Appendix II.

Pump-Down Test. Fuel was pumped from a simulated wing tank to determine the characteristics of fuel flow to a pump inlet and through tank structure. The details are contained in Appendix III. The results of this test indicated that the existing DC-8-62 airplane wing fuel system will not work with the thickened fuels tested. This is due to the inability of the pump to prime itself through the remote inlet piping and to maintain a satisfactory flow rate once primed. In the conventional fuel system, a remote inlet arrangement reduces the number of pumps required to maintain an active inlet regardless of aircraft attitude. In order to explore the operational capability of alternate configurations, the inlet piping was removed from the pump and the pump relocated to the position previously occupied by the inlets. This configuration was referred to as Modification 1. It is obvious that this arrangement would require additional pumps in an actual aircraft.

Test of this configuration proved to be moderately successful in that the desired flow rates were achieved. However, the amount of fuel remaining in the test tank after pump cavitation was (using JP-4 standards) very large. Considerably more emulsion was "unavailable" than gel.

At the moment of pump cavitation, the emulsion surface resembled an inverse cone with the pump inlet at the apex. The residual volume bounded between the lower surface of the fuel tanks and the 82 degree half angle cone was found to be approximately 17% of the total volume contained within that bay. In bays adjacent to that containing the pump, the surface of the remaining emulsion also assumed an inverse conical shape with the apex centered on the lower edge of the bulkhead lightening holes. Half cone angles of 65 degrees and greater were afforded by the slower movement of the emulsion. As indicated by the orifice test program, virtually no flow came through the small, one to four square inch area, holes along the bottom of the bulkhead. The gel on the other hand freely flowed through these smaller holes. The obstruction which prohibited complete utilization of gel were the stringers. It was observed that the 1/2 inch oval holes coined in the stringer web were not large enough nor of sufficient number to provide the necessary flow rate.

A second modification was considered. Modification 2 assumed each bay to contain a small scavaging pump which in turn would supply the feed box of the existing transfer pumps. Extrapolation of the data obtained previously allowed analysis of this configuration without the necessity of performing additional testing. This phase of the program resulted in a significant improvement in emulsion utilization although still far from JP-4 standards.

Orifice Test. The results of this phase of the test program are summarized in Figures 21 through 30. Inspection of these graphs reveal an orderly relationship between emulsion pressure drop and yield stress.

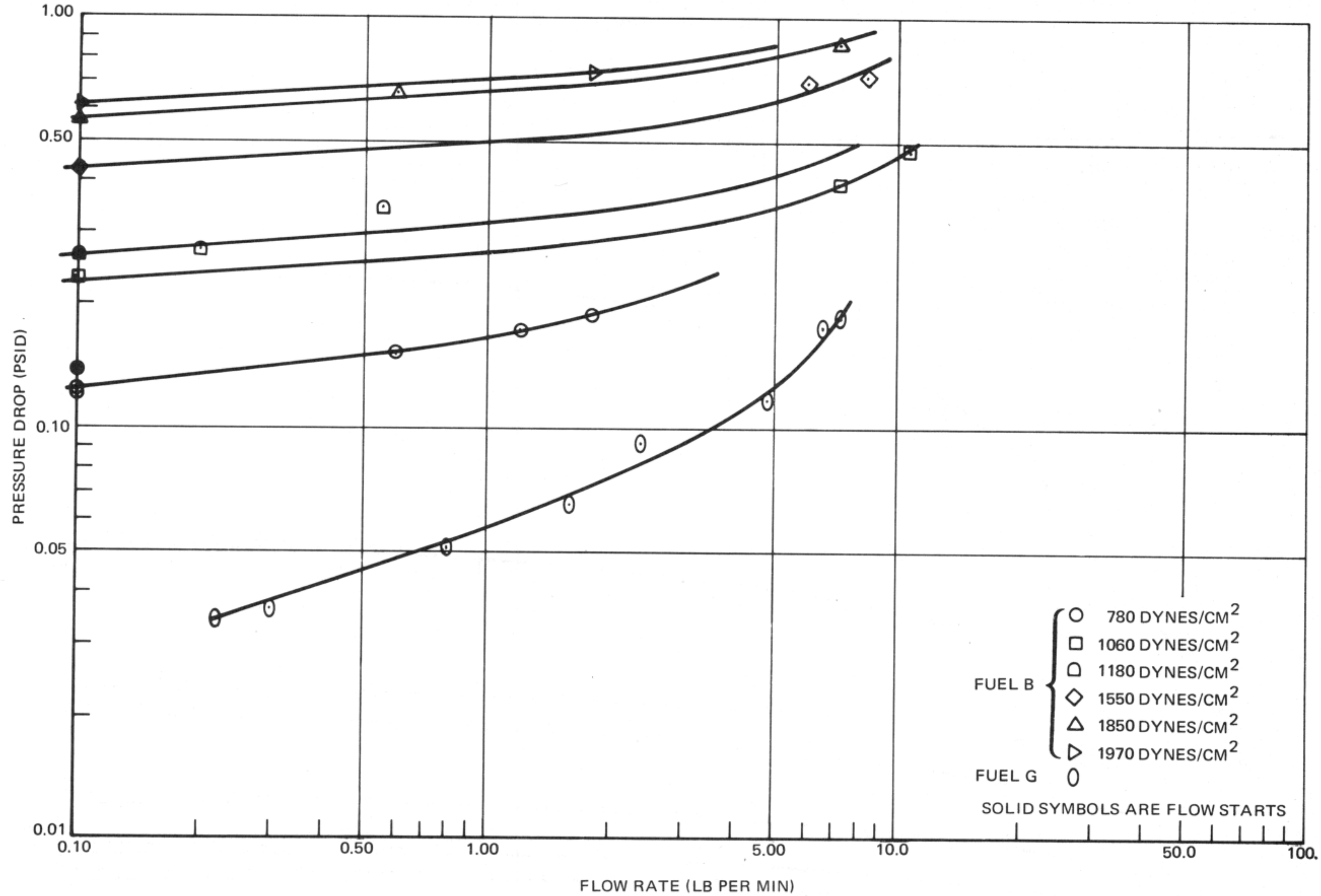


FIGURE 21
ORIFICE FLOW – 1/2-INCH-DIAMETER HOLE

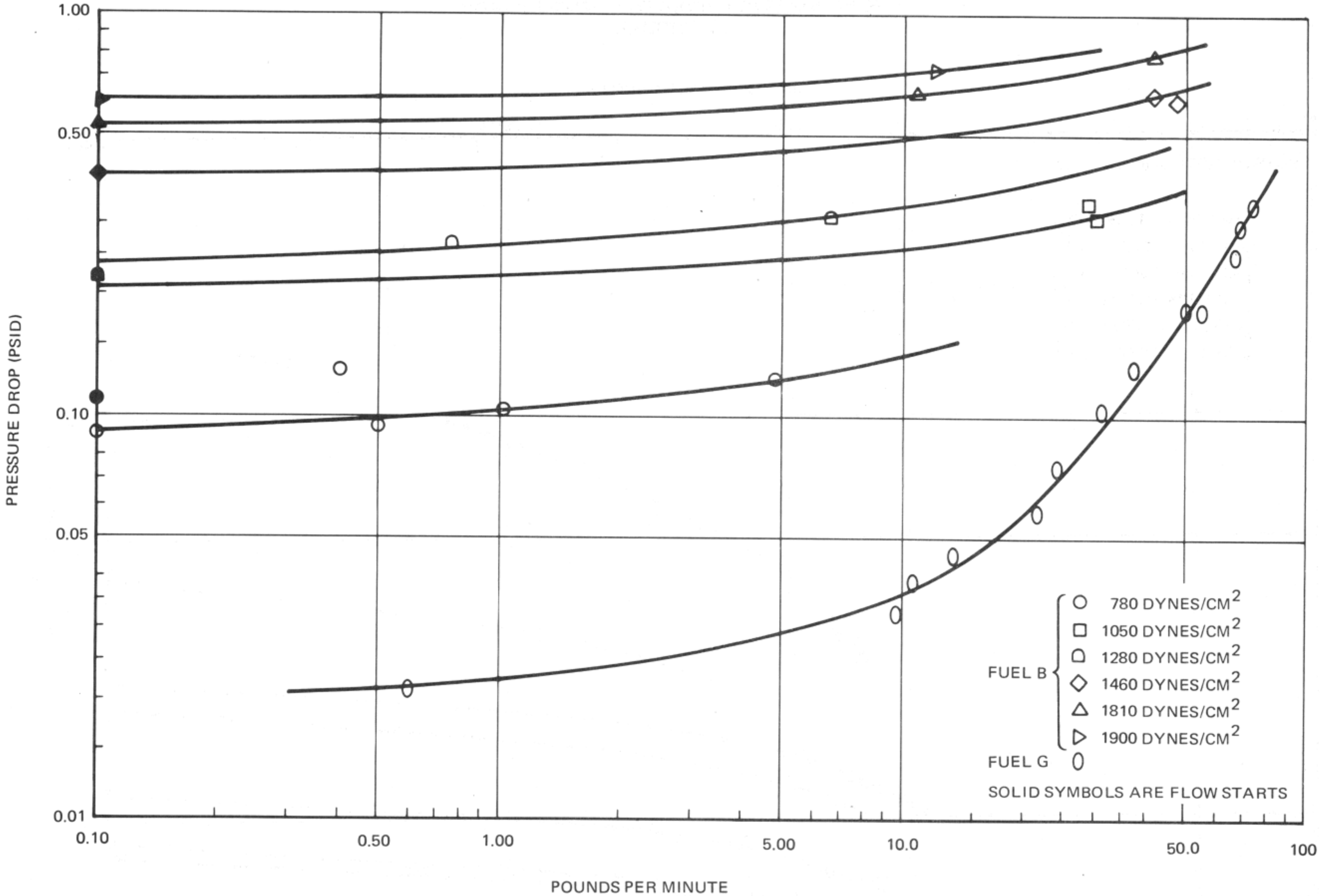


FIGURE 22
ORIFICE FLOW – 1-INCH-DIAMETER HOLE

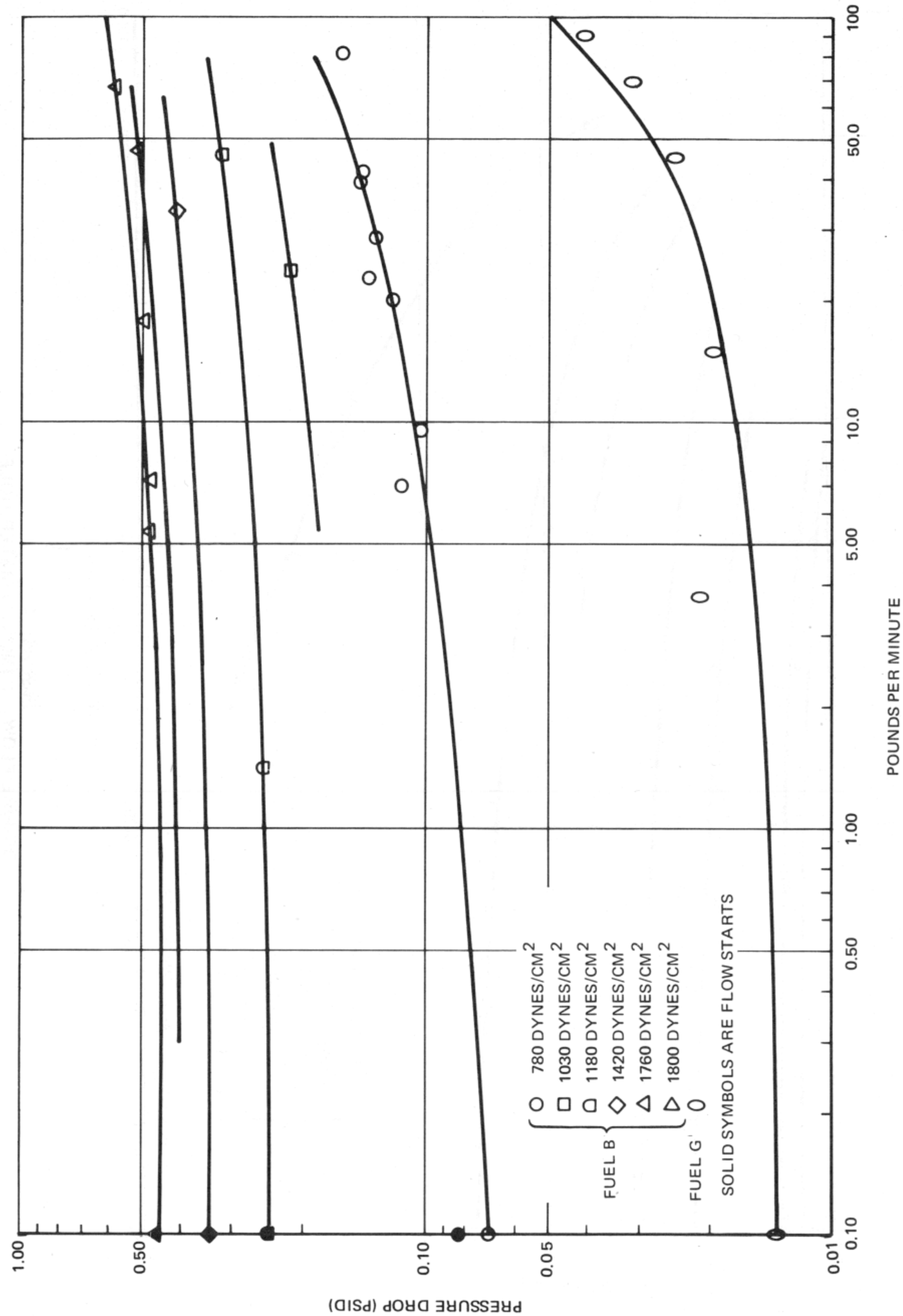


FIGURE 23
ORIFICE FLOW – 2-INCH-DIAMETER HOLE

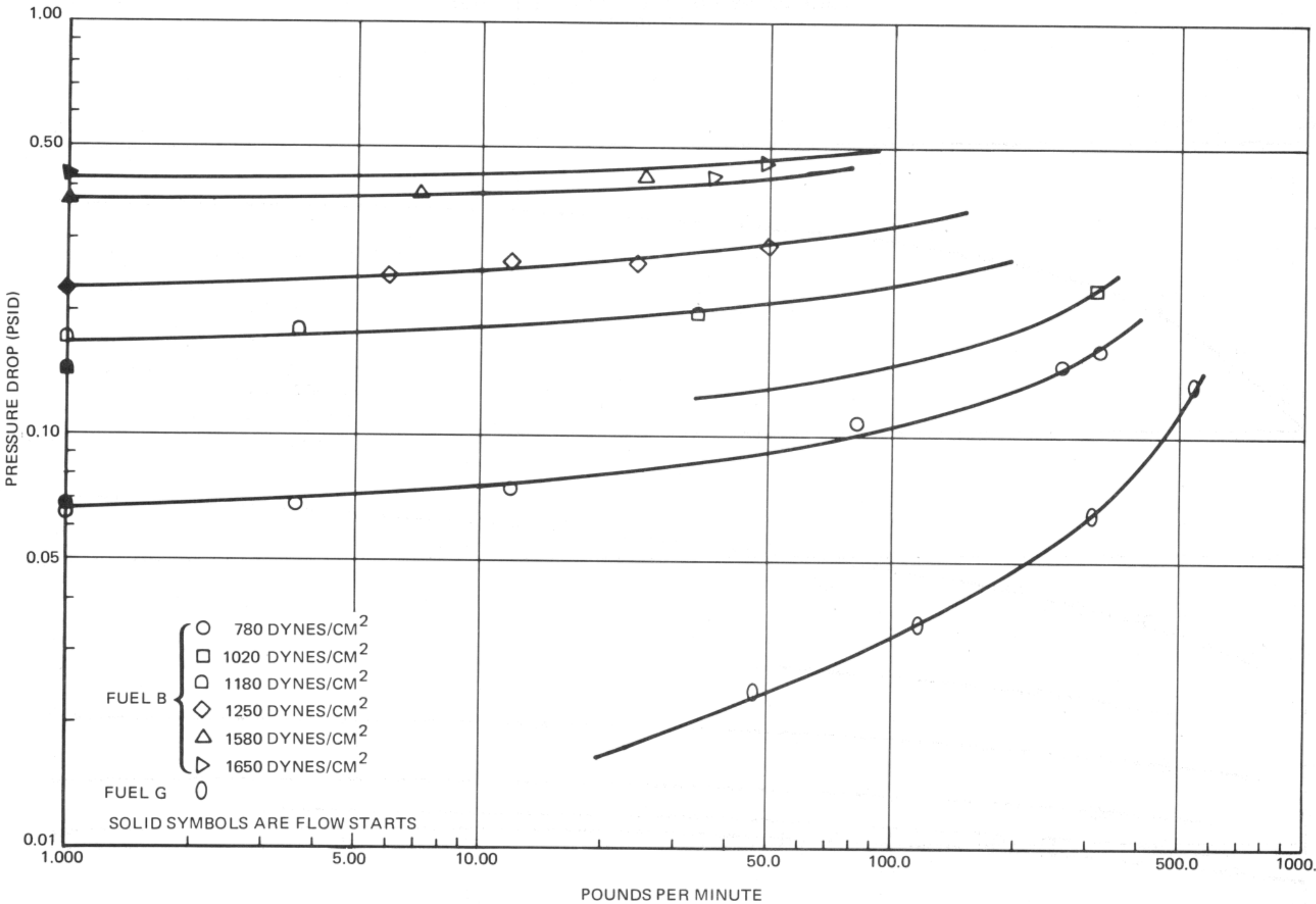


FIGURE 24
ORIFICE FLOW – 3-INCH-DIAMETER HOLE

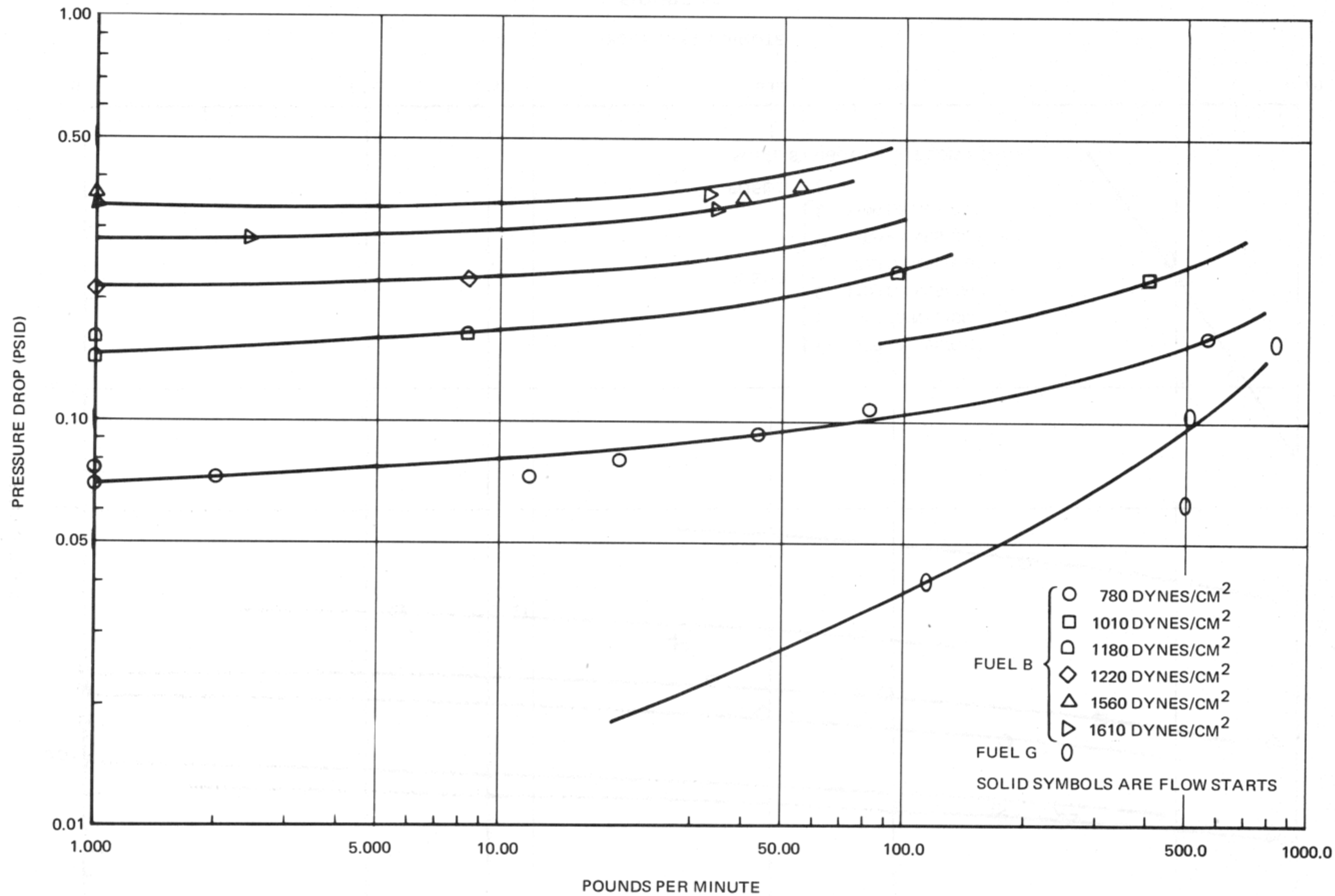


FIGURE 25
ORIFICE FLOW – 4-INCH-DIAMETER HOLE

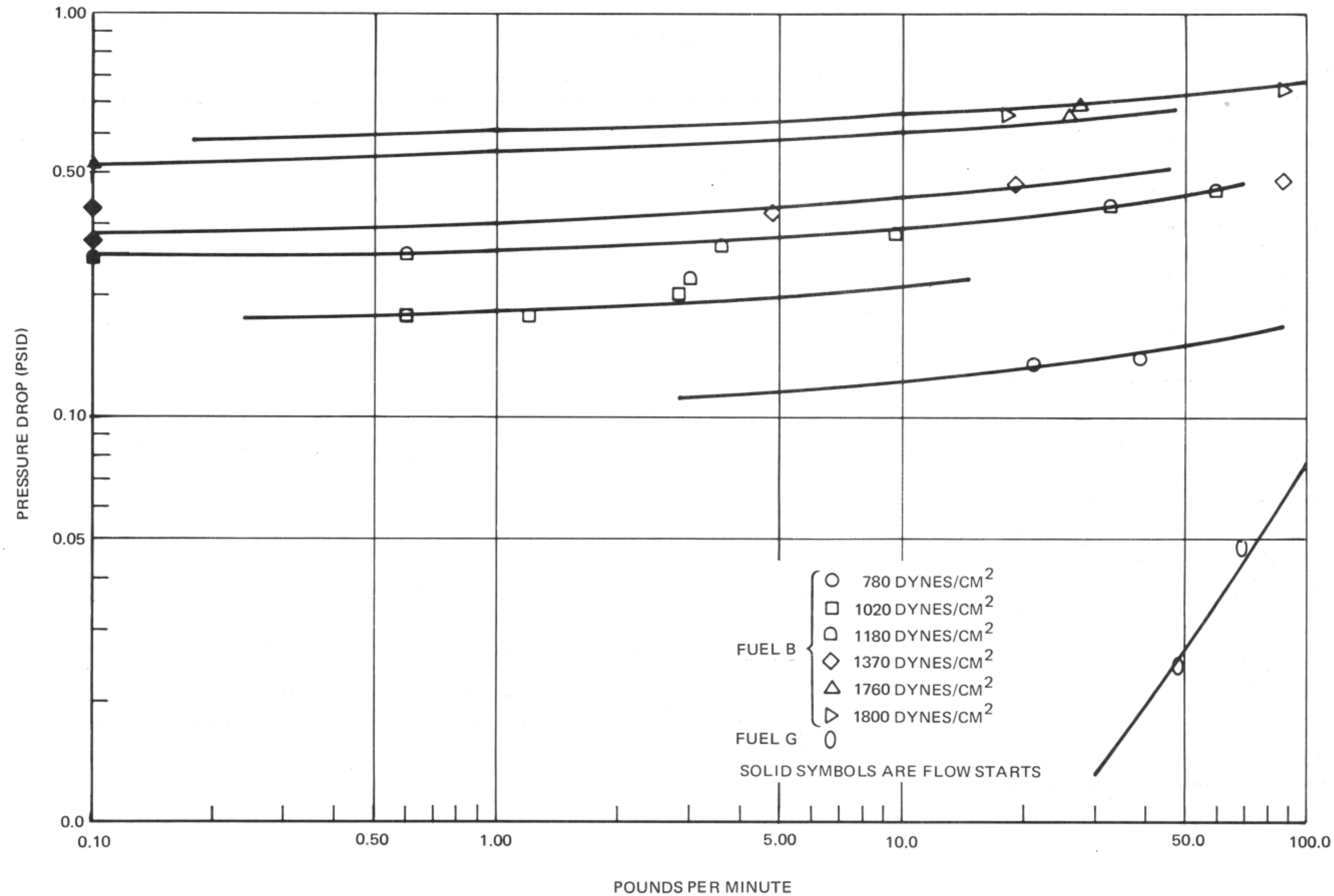


FIGURE 26
ORIFICE FLOW – 1/2 x 4-INCH SLOT

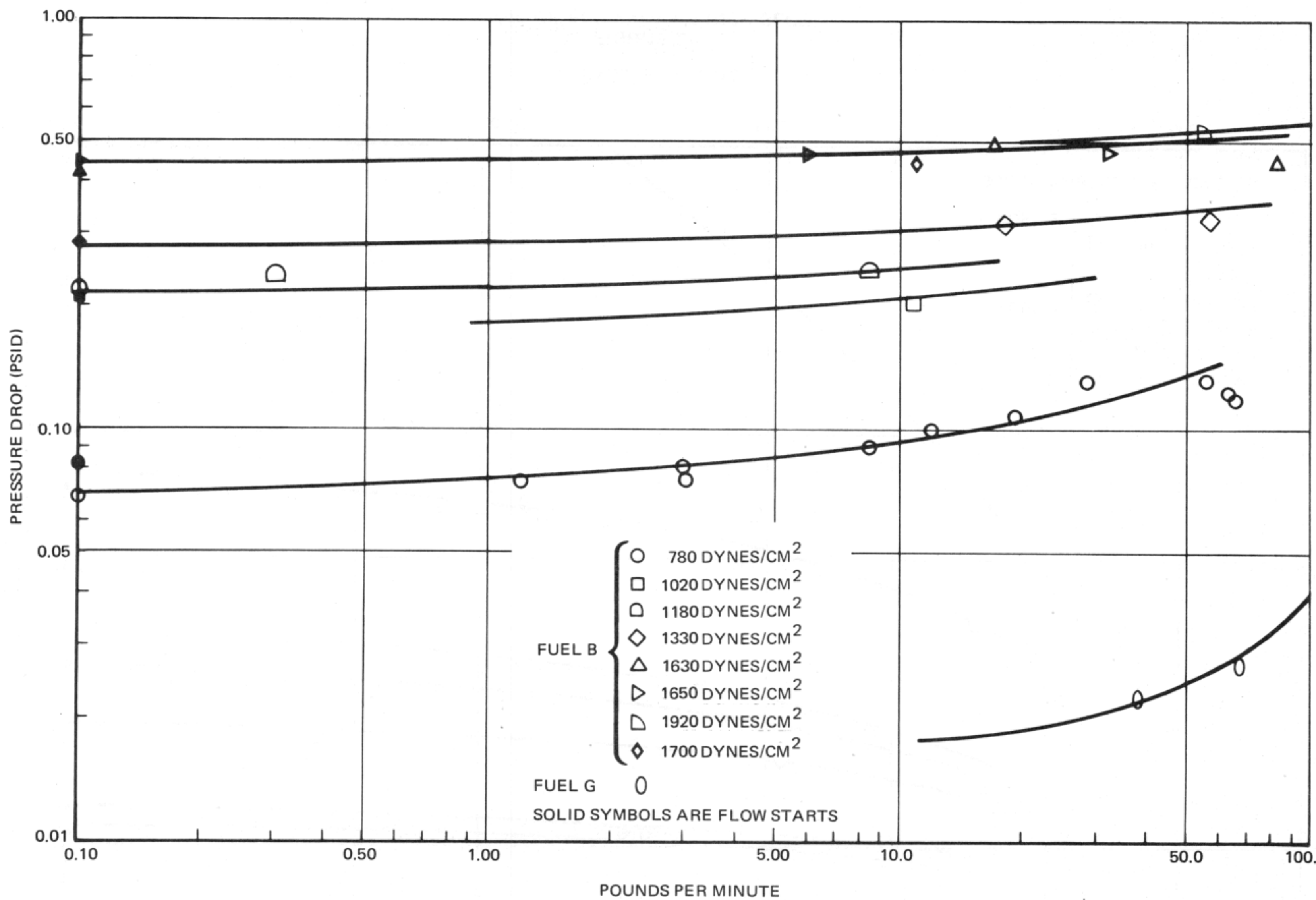


FIGURE 27
ORIFICE FLOW – 1 x 3-INCH SLOT

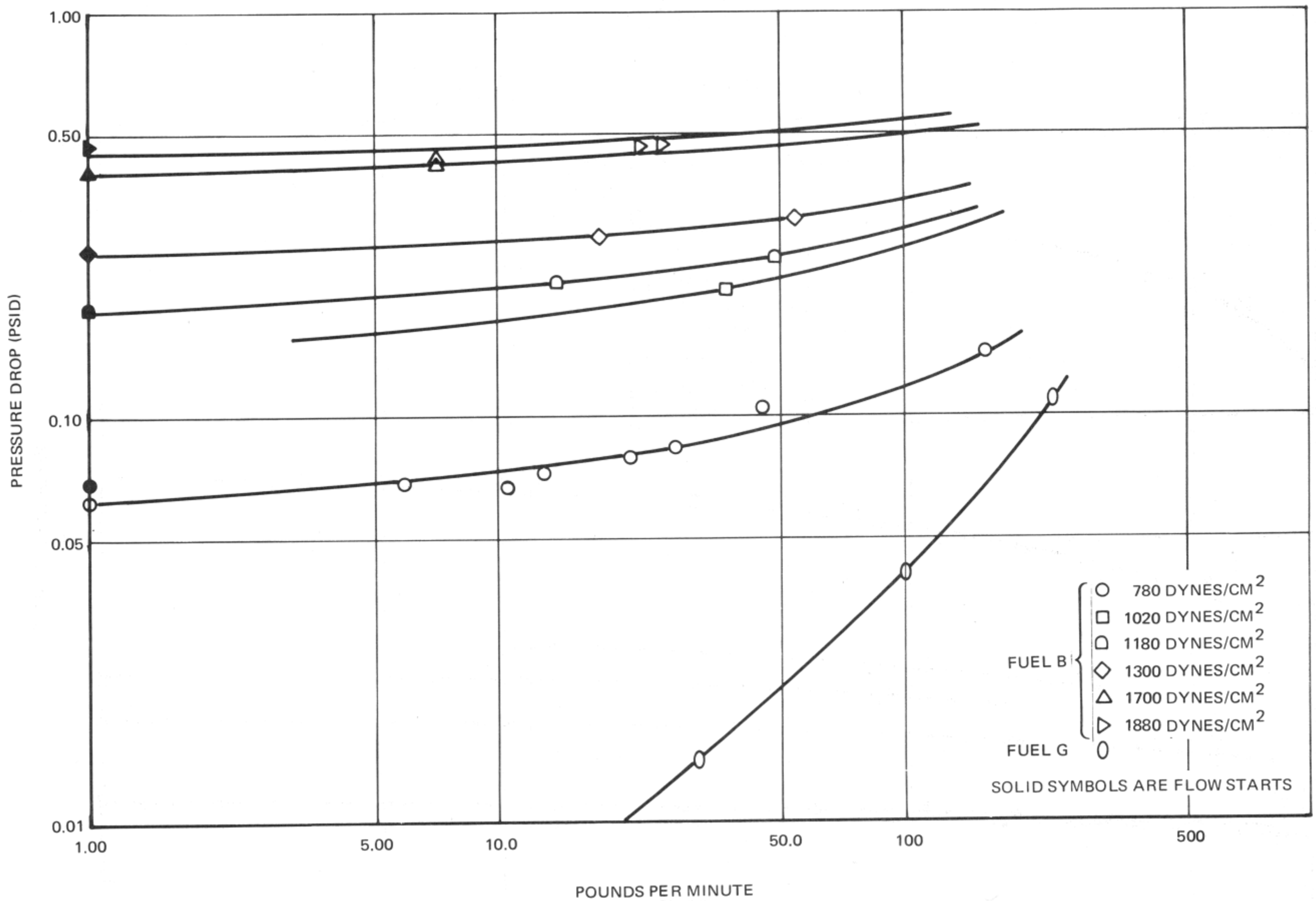


FIGURE 28
ORIFICE FLOW – 1 x 4-INCH SLOT

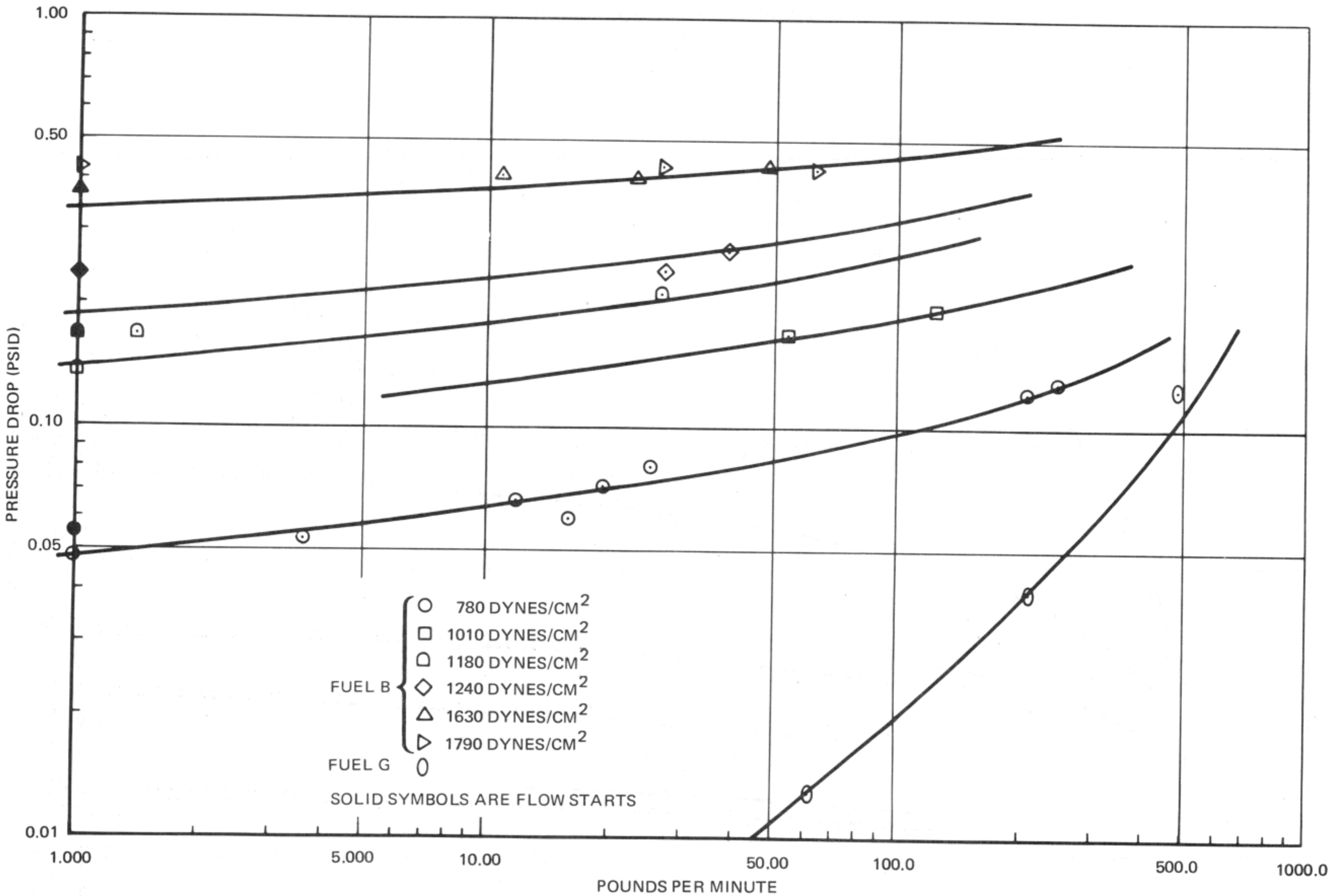


FIGURE 29
ORIFICE FLOW – 1 x 6-INCH SLOT

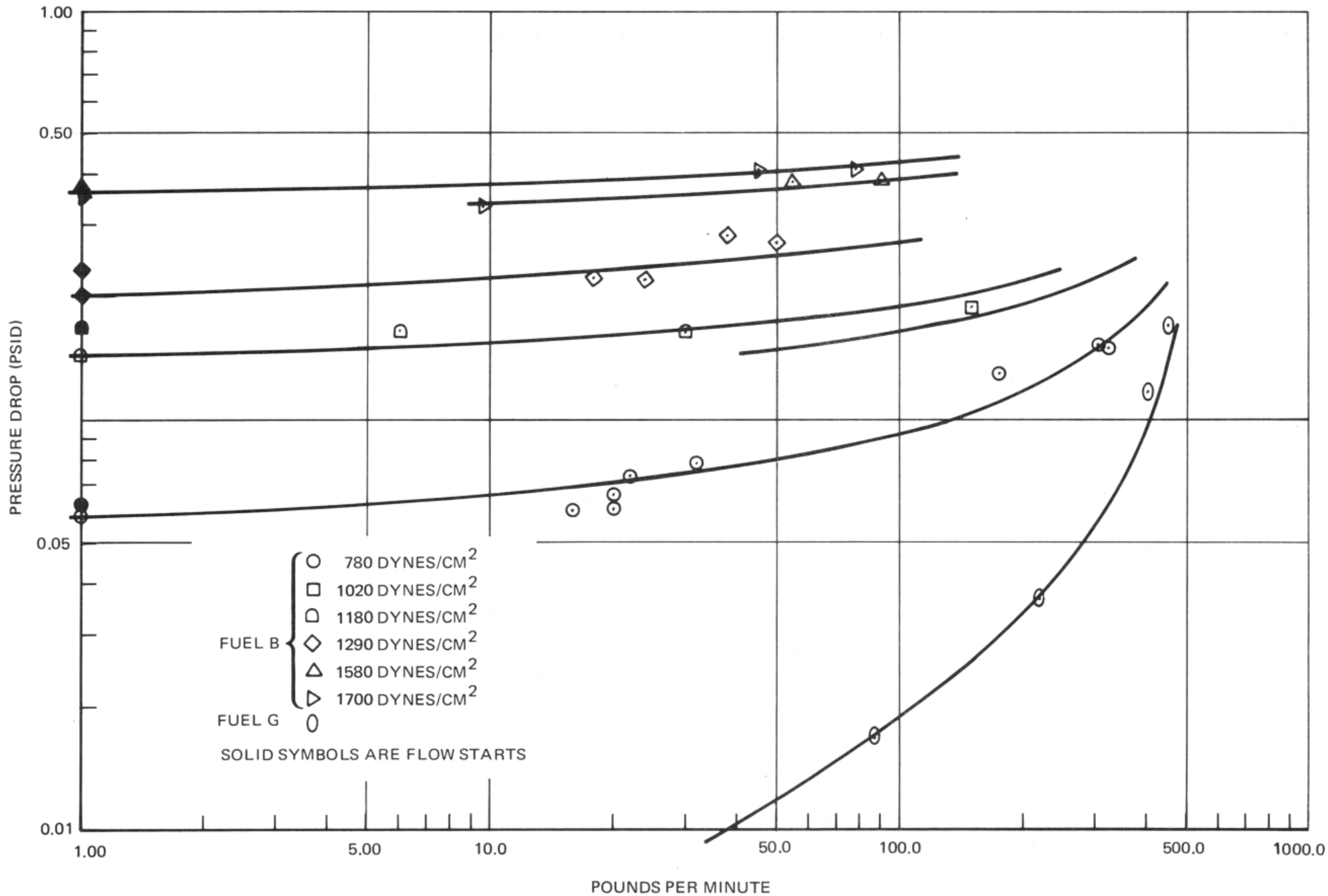


FIGURE 30
ORIFICE FLOW – 2 x 4-INCH SLOT

Although this contrasts with some of the component pressure drop tests, the data is valid where emulsion break-down does not occur. This aspect is loosely correlated to the appearance of the emulsion before and after the orifice test. For the most part the emulsion did not take on a glossy appearance after flow, where with the component pressure drop test, the expended emulsion appeared glossy. The glossy appearance is associated with emulsion break-down although no test was devised to quantitatively analyze this aspect.

For the smaller orifice sizes, the data indicates that the flow rate of emulsion is disproprotionately affected by the area of the orifice whereas the gel is not. Figures 27 and 29, also Figures 26 and 28 are representative of the flow rate-area relationships associated with the two fuels tested. Within the accuracy of the program, the two-to-one area ratio is directly reflected by the gel flow rate. Comparing relaxed yield stress levels, the flow of emulsion does not exhibit this characteristic. For the same two-to-one area increase, the emulsion flow rate increases from four to twenty times. Comparing equivalent areas by Figures 23 and 27, reveals the emulsion flow rate is also dependent on the shape of the orifice. In this case the flow rate for the 1 inch by 3 inch slot is roughly twice as great as for the 2 inch diameter hole. The gel flow rate for these two cases were practically identical.

A full description of the orifice test facilities and procedures as well as raw data is included in Appendix IV.

Pump Performance Test. The performance characteristics of a DC-8 fuel transfer pump using the selected fuels and JP-4 for comparison is summarized in Figure 31.

The fact that the flow rate for emulsion Fuel B is considerably lower than that for JP-4 is obvious. What is not evident is that both the emulsion and gel caused the pump output pressure to fluctuate. Temporary pressure decays up to 50% were observed. The cycle period and duration were variable and could not be correlated with any external influence. It was noticed however that the frequency of pressure fluctuations is increased with increased back-pressure.

Another aspect of pump performance which is not reflected in Figure 31 is cooling. Since the aircraft fuel transfer pumps are of the submersible type, cooling is achieved by fuel flow through a by-pass system. A portion of the outlet flow is routed through the pump housing in direct contact with the electric motor. In all the tests performed using emulsion and gel, cooling was sufficient. Unfortunately the existing pumps did not route the cooling flow directly back to the inlet. This results in a puddle of broken emulsion or hot, low viscosity gel collecting adjacent to the pump cooling discharge ports. Depending on the location of the brackets, supports, accessory piping, etc, large quantities of broken emulsion could become stratified within the unbroken emulsion before developing a passage to the pump inlet. In an operational configuration the cooling flow outlet could be made to terminate within the pump inlet duct in some installations.

A description of the pump facilities, procedure and raw data is presented in Appendix V.

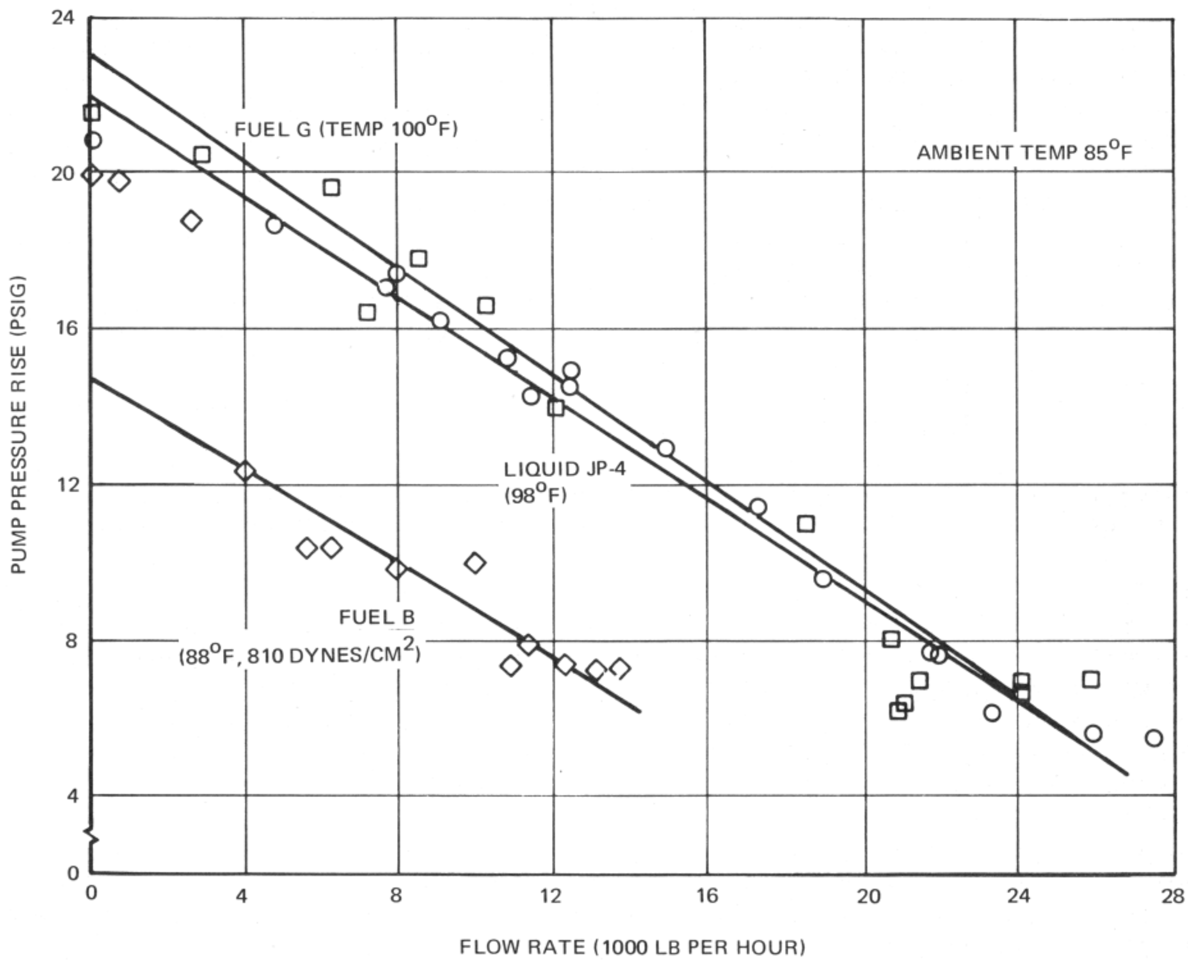


FIGURE 31
DC-8 FUEL PUMP PERFORMANCE

SYSTEMS ANALYSIS

All of the subsystems of a conventional turbine powered transport type aircraft, the Douglas DC-8 Model 62, were examined to estimate their performance when using the fuels used in full scale testing. These subsystems were broken into the major headings of fill, vent, jettison, transfer and crossfeed, engine feed, and tankage arrangement. The full scale test data was used in conjunction with the data generated from the laboratory testing to provide a base from which the tools of analysis were developed. Generally accepted procedures of fuel systems analysis were followed.

GENERAL. Pressure drops in a system are generally divided into three groups: form losses- those associated with bends, tees, expansions, etc.; friction losses- those attributed to wall friction in flow through tubing; and component losses- those attributed to friction and from losses within a valve, etc.

Form Losses. Form losses are generally calculated by use of a loss coefficient which is defined as the dimensionless ratio of pressure drop to the dynamic pressure at the inlet. Right angle bend loss coefficients are determined for a system at a particular flow rate and fluid conditions. Bend angles less than ninety degrees are evaluated by applying a correction factor to the right angle bend loss coefficient.

Loss coefficients for the ninety-degree bend were calculated to provide a basis for scaling losses to pipe sizes other than those tested. The liquid flow test data obtained during this program for a pipe with and without a ninety-degree bend is not used in this analysis because the variation is within the scatter band of the instrumentation accuracy and can not be confidently evaluated.

The 90° bend loss data was calculated for lines larger than 1.5" by calculating a loss coefficient for the thickened fuel at a specific flow rate. A loss coefficient was calculated for a liquid at the same flow rate for 1.5" and for larger lines. The loss coefficient for thick fuel was scaled to the larger size by the ratio of liquid fuel loss coefficients. The loss coefficient thus obtained was multiplied by the dynamic head in the larger line to obtain the 90° bend loss in the larger line.

Several factors affecting loss coefficients are not considered in this analysis because their effect is small compared to the effect of other fluid properties and the level of rigor desired at this time. If thickened fuels were to be considered in the design of new aircraft, a large amount of basic flow data would have to be run for the specific fuel under consideration to give a satisfactory confidence level in design analysis.

Bend loss coefficients are a function of Reynold's number which in turn is an inverse function of diameter at a constant flow rate. Diameter effects on loss coefficient have been accounted for by scaling the 1.5" line loss coefficient by the ratio of the corresponding liquid loss coefficients. Reynold's number is also an inverse function of viscosity. The effects of viscosity are included in the flow test data and have been carried through in scaling from one line size to another.

Friction losses. Friction losses are generalized into a pressure loss per unit of pipe length. Liquid flow calculations are generally made using some variation of the Darcy-Weisbach equation. Plots of straight pipe pressure loss from full scale testing with tare removed are directly convertible to a loss per unit length by dividing the pressure scale by the length of the test section.

The two-inch diameter pipe loss test curve, Figure 18, is not for the same yield value as the one and one-half inch diameter line shown in Figure 17. The general condition of the fuel used in both tests was also different in that relatively unused fuel was used in the 1.5" O.D. line where well-used material was used in the 2" O.D. line. Since the use of this data is very questionable, an estimate of a two-inch line friction loss curve at 785 dynes/sq cm. was made on the basis of the test data for the 1.5" line. The test curve for 2" O.D. line was scaled proportionately with the 1.5" line data in order to obtain an estimated curve for the 2" O.D. line at about 785 dynes/sq cm. This appears to be a conservative estimate based on the trends of the data obtained on the 1.5" O.D. line.

Figures 32 and 33 show frictional loss estimates made on the basis of the ASTM D-1092 pressure viscometer data. Comparative lines are shown for the full scale lines tested. The distribution of the lines for different diameters from the pressure viscometer predictions were used in scaling test data for prediction of frictional pressure drops at larger diameters than tested.

The data for the gel with a 1.5" O.D. line, Figure 17, shows a crossing of the liquid fuel line at about 500-600 lbs/min. This may be due to a prolongation of laminar flow with the thicker fluid. The slope of the curve is actually much flatter than a laminar line and appears to have the characteristics of starting from a high yield point and then moving into a laminar or turbulent flow characteristic. Tests at higher flow rates may show what is happening and when and if the curve will come back into a turbulent line. The curves labeled "full scale" in Figures 32 and 33 were used in the analysis.

Component Losses. Component losses are difficult to calculate analytically. Many components used in the DC-8 have been tested for pressure drop using the gel and the emulsion. Pressure loss data from testing is used in the analysis. In some cases, the pressure drops were too low to measure accurately and the losses of these components have been used with the tare included or a maximum value has been assigned. These losses are too low to seriously affect any analyses in this effort and could have been ignored.

Fill nozzle/adapter pressure drop for the Douglas modified fill adapter with thickened fuel was obtained by ratioing the equivalent orifices corresponding to liquid and thickened fuel pressure drops for the tested component (Figure 16) and factoring the liquid pressure drop of the stock component accordingly. The cracking pressure of the Douglas modified adapter was maintained.

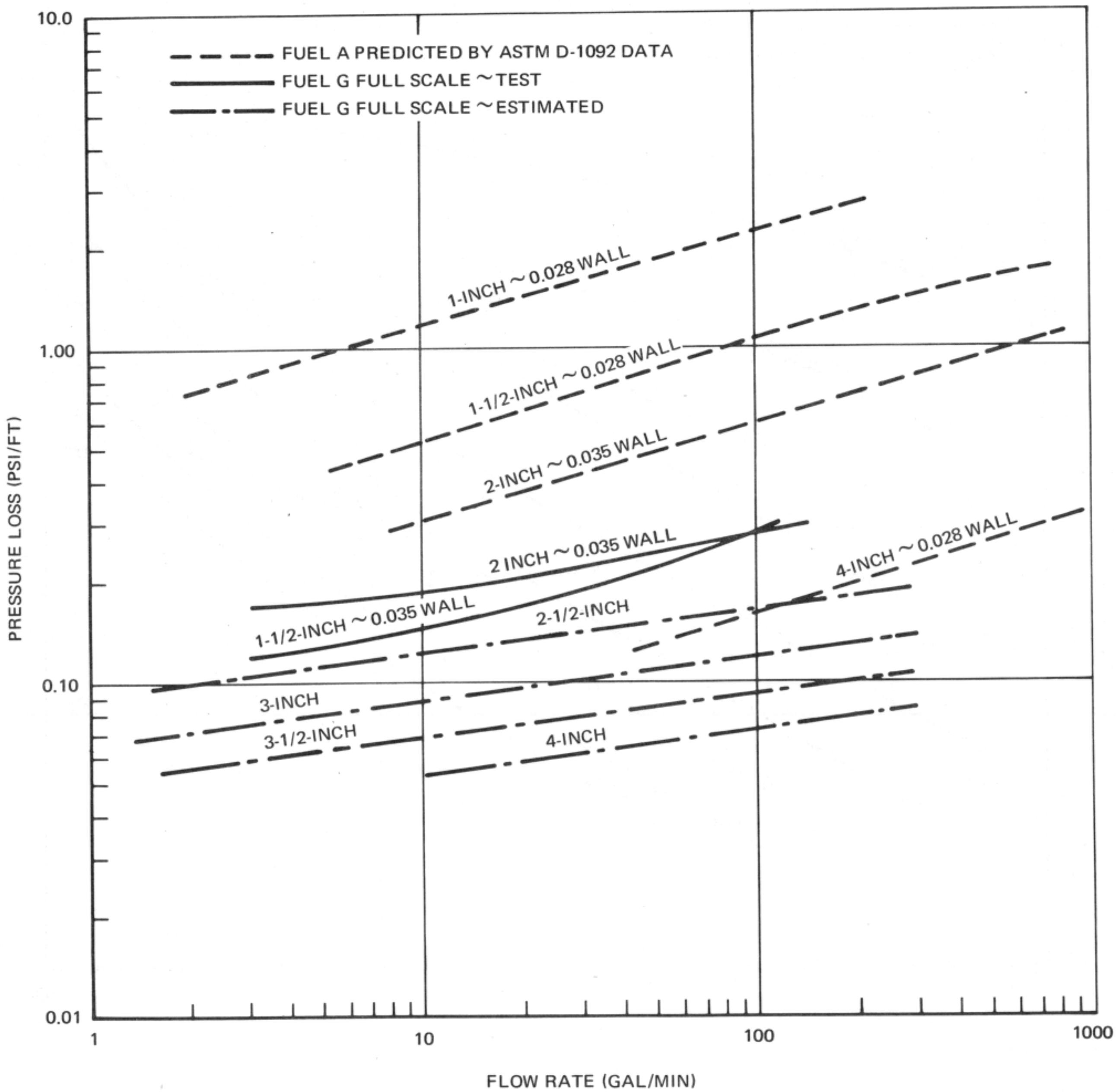


FIGURE 32
LINE FRICTION PRESSURE DROP FOR FUELS A AND G

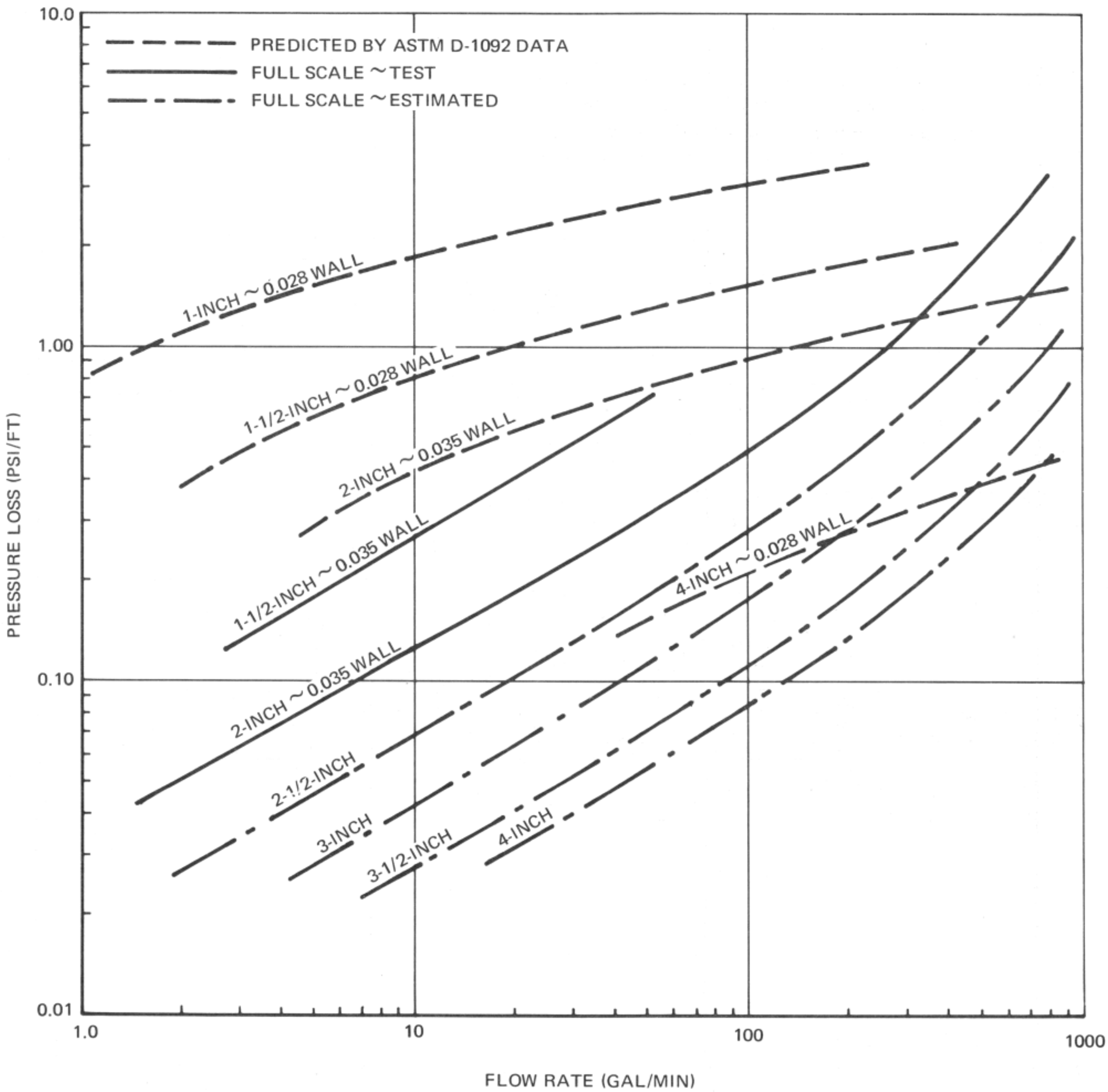


FIGURE 33
LINE FRICTION PRESSURE DROP FOR FUEL B

Minimum Pressure Drops. Minimum pressure drops, or that pressure required to initiate flow, are calculable from the yield value of the fuel by equating shear stress at the wall at zero flow to yield stress through the relationship, DP/4L = yield stress, where D is the pipe diameter, P is the pressure required to initiate flow, and L is the length of the pipe. Calculations of this sort are theoretically valid, but were not systematically checked in the full scale test rig. The indication of a constant pressure loss at low flows in the test data plots indicates some merit to this approach.

FILL SYSTEM. Fill analyses were conducted to estimate the initial fill rate and fill times when using the thickened fuels. Supply pressures of 50 psig were assumed. Higher supply pressures would give higher flow rates and lower fill times. Ground servicing equipment would probably be modified if the tested fuels were used by an operator. The results of such a program are not speculated upon at this time.

Comparative rates were calculated assuming all tanks were open to admit fuel and four supply nozzles were in use. See Figure 34 for fill system configuration. In actual practice only selected tanks would be on line for a specific length of time to give a required partial fuel loading. Such loadings would be a function of the route length and possibly special management procedures imposed by the use of a thickened fuel. Times are estimated for fueling the entire aircraft. Estimated fueling times and rates shown in Table II.

Aircraft now in development are designed for fueling from two nozzles on one side of the aircraft. The high flow rates possible with an advanced fueler provide shortened turn-around times and decrease the traffic around an aircraft being serviced. Two-nozzle filling would hardly seem practical with a thickened fuel and, therefore, four nozzles would be used.

VENT SYSTEM. Vent systems of current commercial aircraft are usually sized by the requirement of keeping tank pressures below structural limits in the case of failure of the tank fill shutoff system. Provisions are made to assure tank venting at all attitudes and rates of climb and descent. Some aircraft use float-operated valves to accomplish one or more of these tasks. See Figure 35 for configuration of DC-8, model 62 vent system.

Tank overpressure on fill shutoff failure will be a problem. Overfill pressures using either fuel are estimated at approximately 10 psi above the structural limit in the tank which is critical in a liquid system. All tanks will have to be checked in each aircraft to determine the modifications necessary.

As shown in Figure 6, some fuels have been shown to swell to over 125% of their volume in the laboratory tests. Adequate expansion space would have to be provided to accommodate this swelling to prevent fuel from filling the vent system. Current regulations require 2% expansion space in a liquid system.

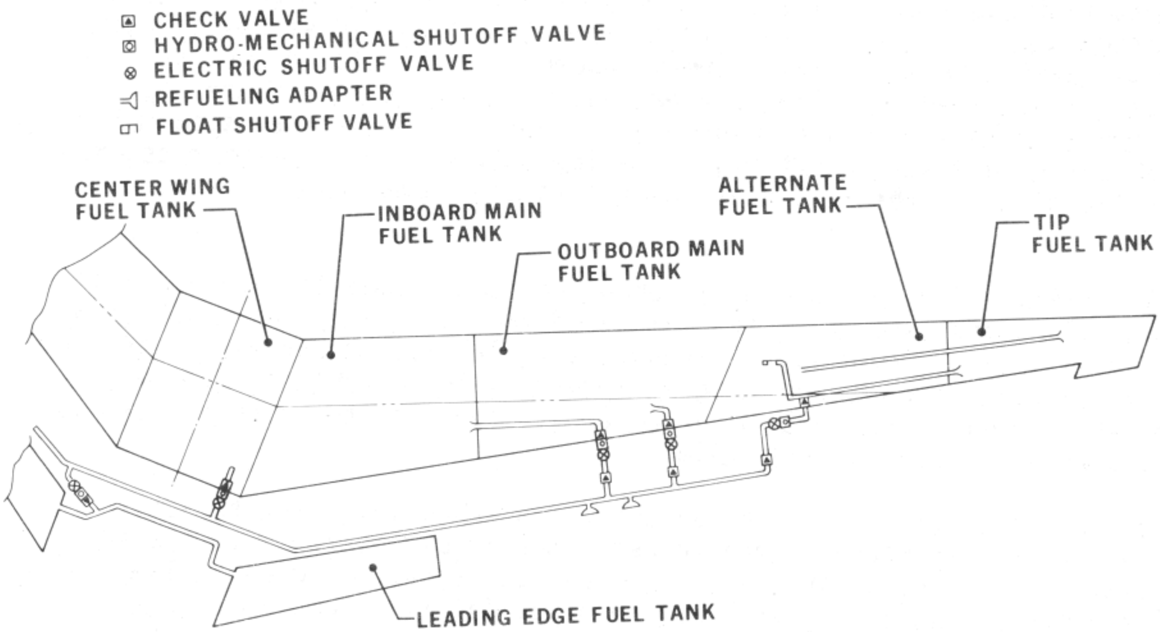


FIGURE 34
DC-8 FILL SYSTEM

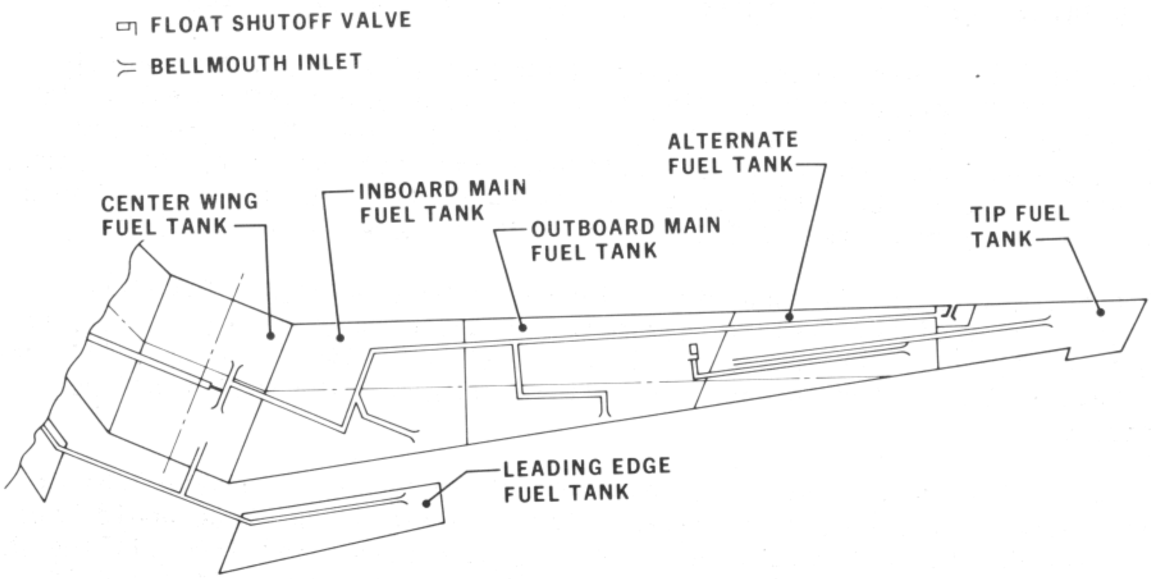


FIGURE 35
DC-8 VENT SYSTEM

TABLE II

FILL ANALYSIS SUMMARY

EMULSION FUEL B		
	INITIAL RATE	285 GPM
	EST. FILL TIME	110 MIN.
GEL FUEL G		
	INITIAL RATE	690 GPM
	EST. FILL TIME	46 MIN.
LIQUID JP-4		
	INITIAL RATE	1530 GPM
	EST. FILL TIME	20.5 MIN.

Climb vents are often controlled by float valves. These depend on the bouyancy of the fluid for actuation and on the weight of a float for relief to the down position. These devices are generally placed in crowded surroundings near the top of the tank. There have been occurrences where check valves were held open by thick fuel between the flapper and the cavity into which it is pushed. Such a condition could possibly occur with valve floats, prevent tank relief, and force fuel into the main vent. Liquid fuel can be drained from vent lines into the tank for use and to clear vent lines, but thick fuels could not.

JETTISON SYSTEM. The jettison system on the DC-8 is a gravity flow system. Calculations show the line losses in the jettison piping to be equivalent to approximately twenty feet of head at the initial dump rate. This head is not available. The average dump rate required is equal to about three times the takeoff fuel flow used in some calculations of unusable fuel. This rate would obviously leave much more undumpable fuel in the tanks than would be desirable. Figure 36 shows the configuration of the DC-8 dump system.

A pump pressurized dumping system could be employed and would require extensive analysis to determine the ideal system for the actual fuel to be utilized in the aircraft. Such an analysis would involve pump placements and pressure requirements, system plumbing, and overboard exit location. Pumps used in a jettison system whose only function was jettison could be of the centrifugal type since fuel breakdown would be desirable to aid in evaporation and since the fuel is leaving the aircraft.

FUEL TRANSFER SYSTEM. Fuel transfer occurs in several ways in the DC-8 fuel system. Fuel is transferred by gravity flow from the forward auxiliary tank to the center wing tank and from the outboard compartment of the outboard alternate tank to its inboard compartment. The minimum head required for these transfers may be estimated from a yield stress consideration. The head at which flow stops may also be estimated. Such calculations ignore the effects of vibration and aircraft motion on these transfers. The flow will stop when a structural member interferes with the head over the outlet. Surfaces which are near an outlet also serve to reduce flow. An example of such a tank outlet is in the outboard compartment where the tank drain line exits parallel with the tank floor. See Figure 37 for transfer system configuration on the DC-8, Model 62.

Flow from the forward auxiliary tank must equal four engine flow rate at early cruise, or about 35 gpm. Such a flow through a 1-1/2" line approximately 15 feet long would require a head of over 100 inches from frictional loss considerations alone, using the data from Figures 32 and 33. Similar calculations on the outboard compartment transfer line indicate that the minimum required flow can not be met even with the maximum head available and room temperature fuel.

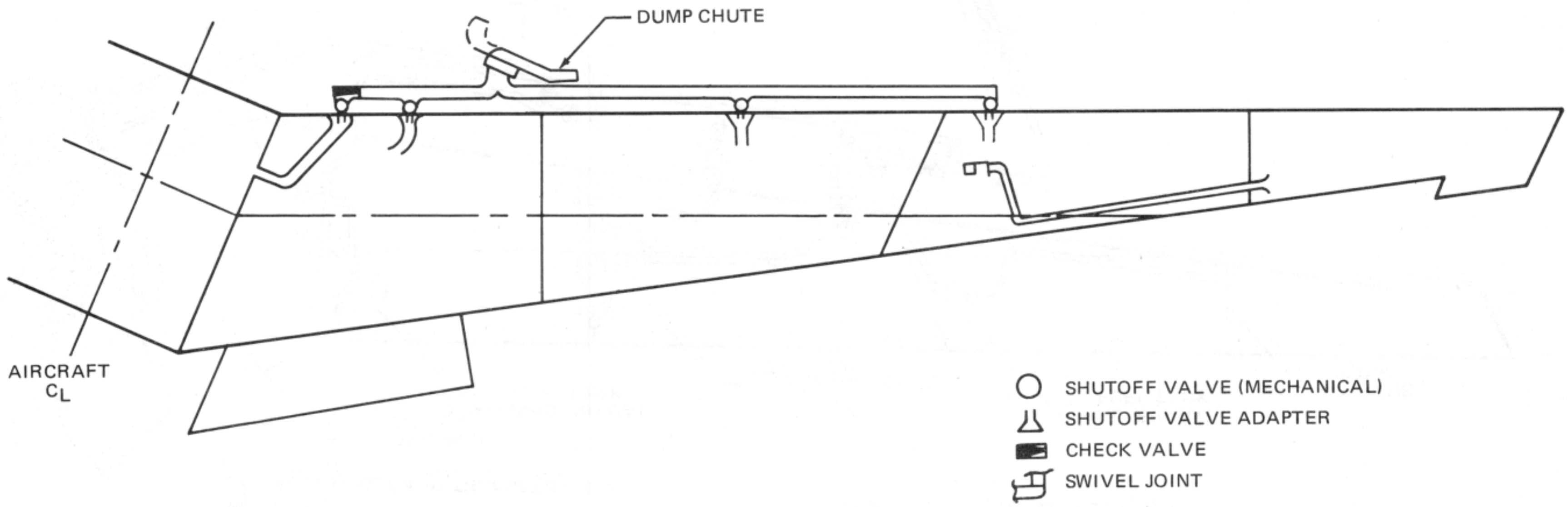


FIGURE 36
DC-8 FUEL DUMP SYSTEM

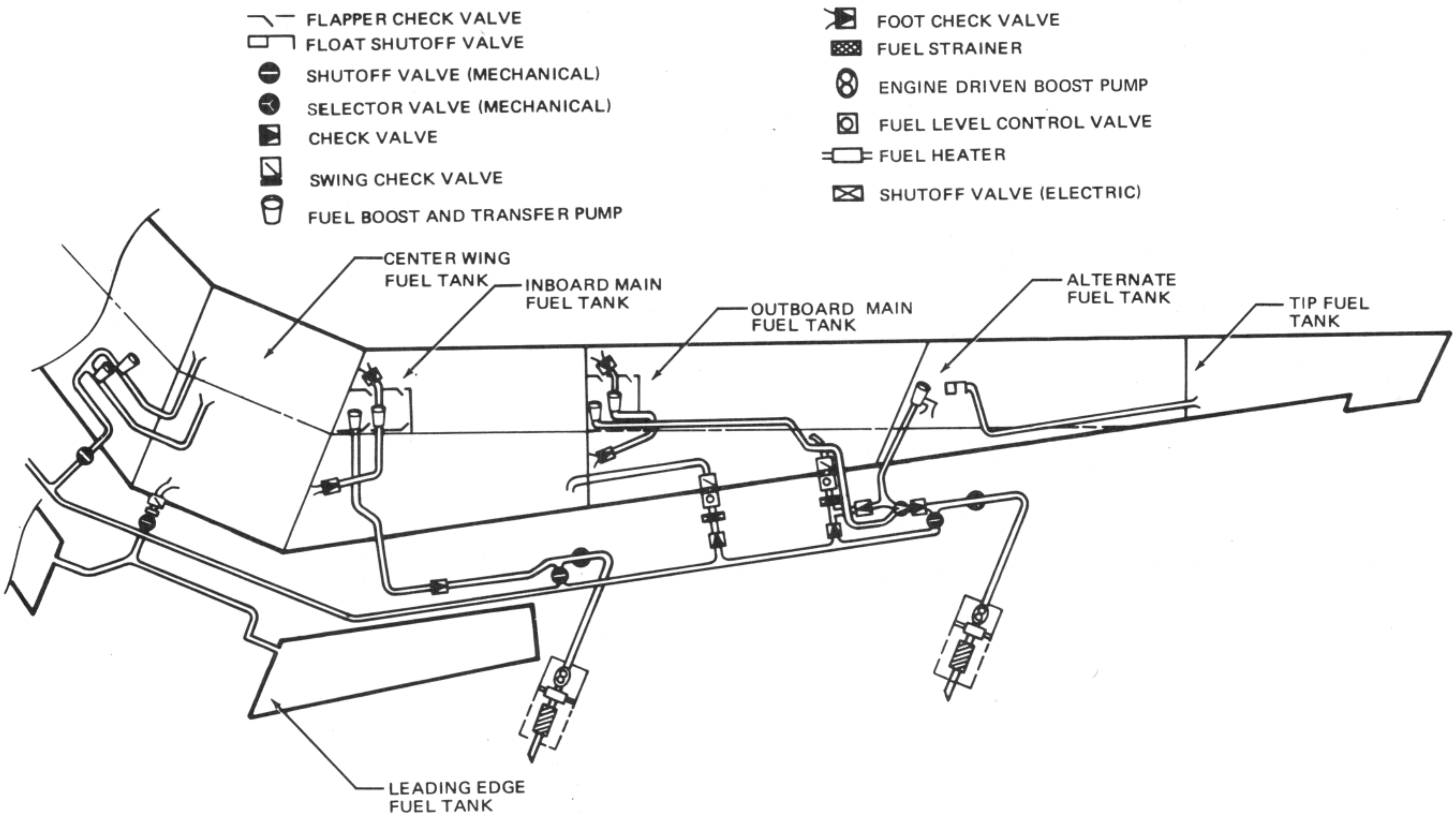


FIGURE 37
DC-8 FUEL FEED AND TRANSFER SYSTEM

Fuel normally scavenged from the center wing and crossfeed manifold will not be available. The scavenge pump does not have the lift capability to overcome the large inlet line pressure drop of either of these fuel recovery techniques.

The fuel normally transferred from the center wing to the mains would probably not be available in a stock airplane, even with a fuel as thin as the gel used in full scale system testing. The tests showed that adequate flow rate could not be attained with a long inlet line on the DC-8 pump.

Fuel transfer from the outboard alternate to the outboard main would only require a pump output of approximately 22 psi for gel at the cruise flow rate. This is lower than the pressure required to feed the engine directly from this tank, but capability of direct engine feed would probably be required of this pump.

Pumps used for transferring fuel from the remote areas of the main tank to the reservoir boxes are the same as fuel boost pumps. This system of remote pickups can not be used with the pumps installed in the stock airplane. All fuel pumps used in the airframe system are of the centrifugal type and would impose higher shear on any fluid. This will normally break emulsions and could cause gel breakdown.

ENGINE FEED SYSTEM. The engine feed system on the DC-8 is normally operated in suction feed. This capability is built into the system to give an added safety advantage in the event of a crash on landing or takeoff in which the fuel feed line is severed. In this condition the boost pumps would not be running and thereby pumping fuel overboard to feed an existing fire or to increase the probability of fire. With thickened fuels this safety advantage would be lost.

The stock engine feed system includes a centrifugal engine driven boost pump which would cause fuel breakdown. This pump was removed from the system for the analysis. The FAA has required that the thickened fuel be delivered to the engine in an unbroken condition. The fuel/oil heat exchanger upstream of the fuel filter has been retained since it is not known at this time what type fuel may be used and whether or not fuel heating may be required. Removing this device from the feed system would reduce the pump output pressure required. A heat exchanger in this area would probably be inefficient with the thickened fuel. Placing it downstream of the engine driven main fuel pump would be advisable, because the fuel may be partially broken and heat transfer would be enhanced.

Pump pressure requirements have been estimated for single engine fuel feed and two engine fuel feed. These are shown in Figure 38, along with the pressure requirement for cruise fuel flow transfer from the outboard alternate tank to the outboard main. The DC-8 uses only one boost pump per main tank

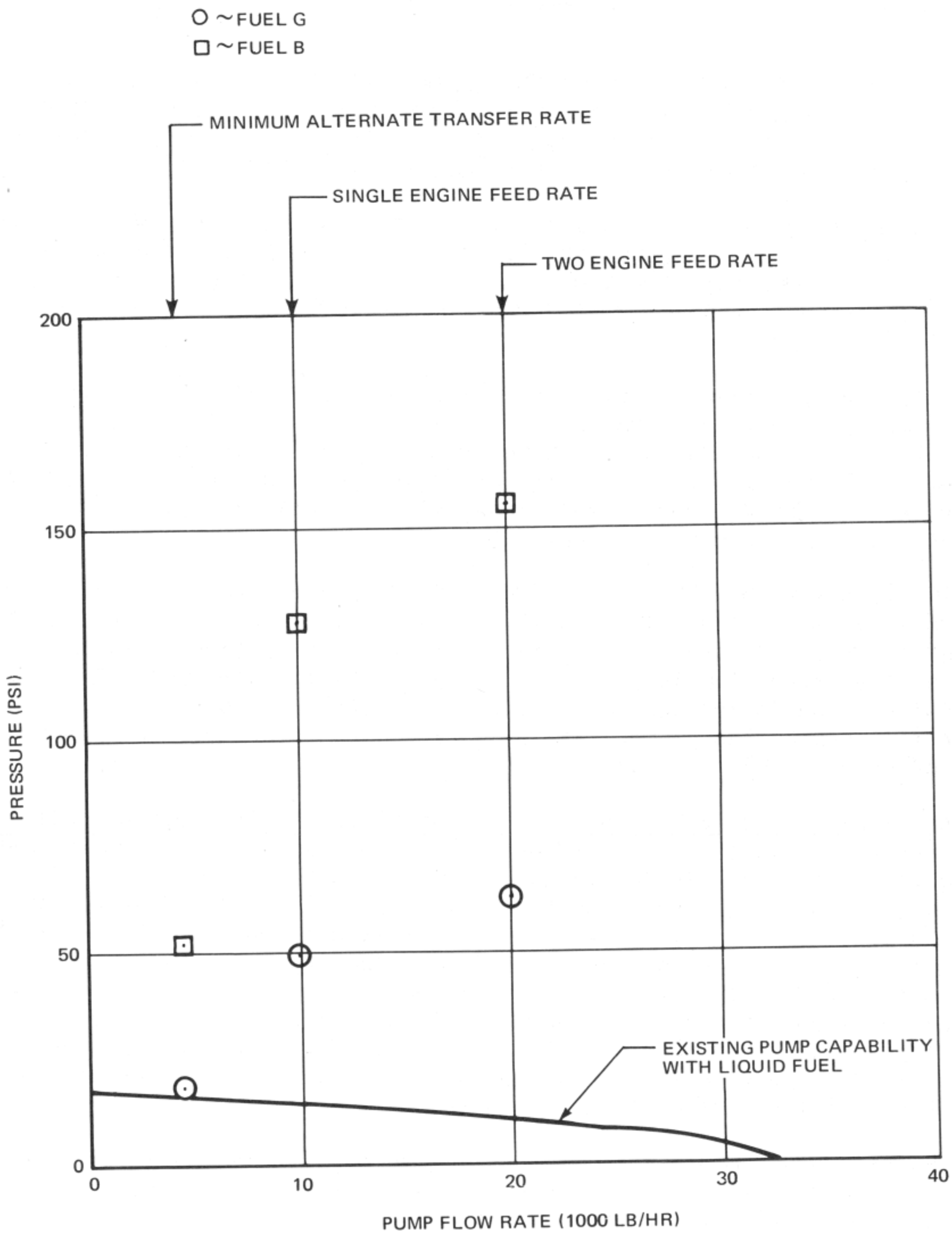


FIGURE 38
PUMP PRESSURE REQUIREMENTS FOR THICKENED FUELS

because of the suction feed capability. Each boost pump is designed to have the capability of feeding two engines, one on crossfeed, for the case where boost pumps are desired and one pump is inoperative. A fuel system modified to use thickened fuel may require more than one boost pump per tank in a parallel configuration. Therefore, two engine feed may not be required from one pump.

TANK FUEL QUANTITIES. Fuel quantities and tank volume are divided into tank trapped, drainable sump, unusable, undumpable, usable, and expansion space. Tank trapped is that amount of fuel which is not removable from the aircraft short of mopping operations. It is that quantity of fuel left after tank sumps are completely drained. Drainable sump fuel is that quantity of fuel above trapped fuel to the level where pump runout occurs in ground attitude. Unusable fuel is determined as that quantity of fuel above tank trapped which is left in the tank after runout in flight. Usable fuel is the quantity between the top of unusable and the full shutoff level. Expansion space is the volume between full shutoff level and the point where vent overflow begins in the normal ground refueling conditions. Undumpable fuel is a minimum usable fuel quantity which must remain in the tanks after jettison operations are complete. This quantity is that required to meet a particular set of conditions prescribed in the Federal Air Regulations. These levels are depicted in Figure 39. The total fuel quantities presented in Table III are determined during aircraft calibration and are reported to the FAA as part of the certification requirements.

Thickened fuel usage would possibly prompt a redefinition of some of these quantities. The normal ideas, procedures, and equipment used in liquid fuel systems may not be applicable, but this depends on the nature of the fuel which would eventually be selected for use.

Conventional fuel sump drains will not work with the fuels tested because they are too small, but sump drains may not be necessary. In a liquid fuel system the sumps provide a means of clearing the tanks of accumulated water. With thickened fuels of the nature of those currently under investigation, water will probably not be a problem. The emulsified fuels with an aqueous external phase will absorb a great deal of water into the external phase. The other fuels will carry water along with them, and will not allow droplets to settle out except on very long standing. Contaminants will also be held in suspension and will be carried with the fuel. Tank trapped fuel quantity on the DC-8-62 is approximately 21 gallons for the total airplane. This is approximately 0.1% of the total tankage volume.

An unusable fuel analysis was performed to estimate the amount of fuel which would be unrecoverable from the tanks. Results of the pumpdown tests were used to give an estimate of the fuel remaining in the bay where a pump inlet was located and to aid in estimating the amount of fuel which would be remaining in the bays remote from the pump inlet. Figure 40 illustrates the compartmentalization of the DC-8 fuel tanks and the total capacities of each section. Calculations were made on the basis of the orifice flow test

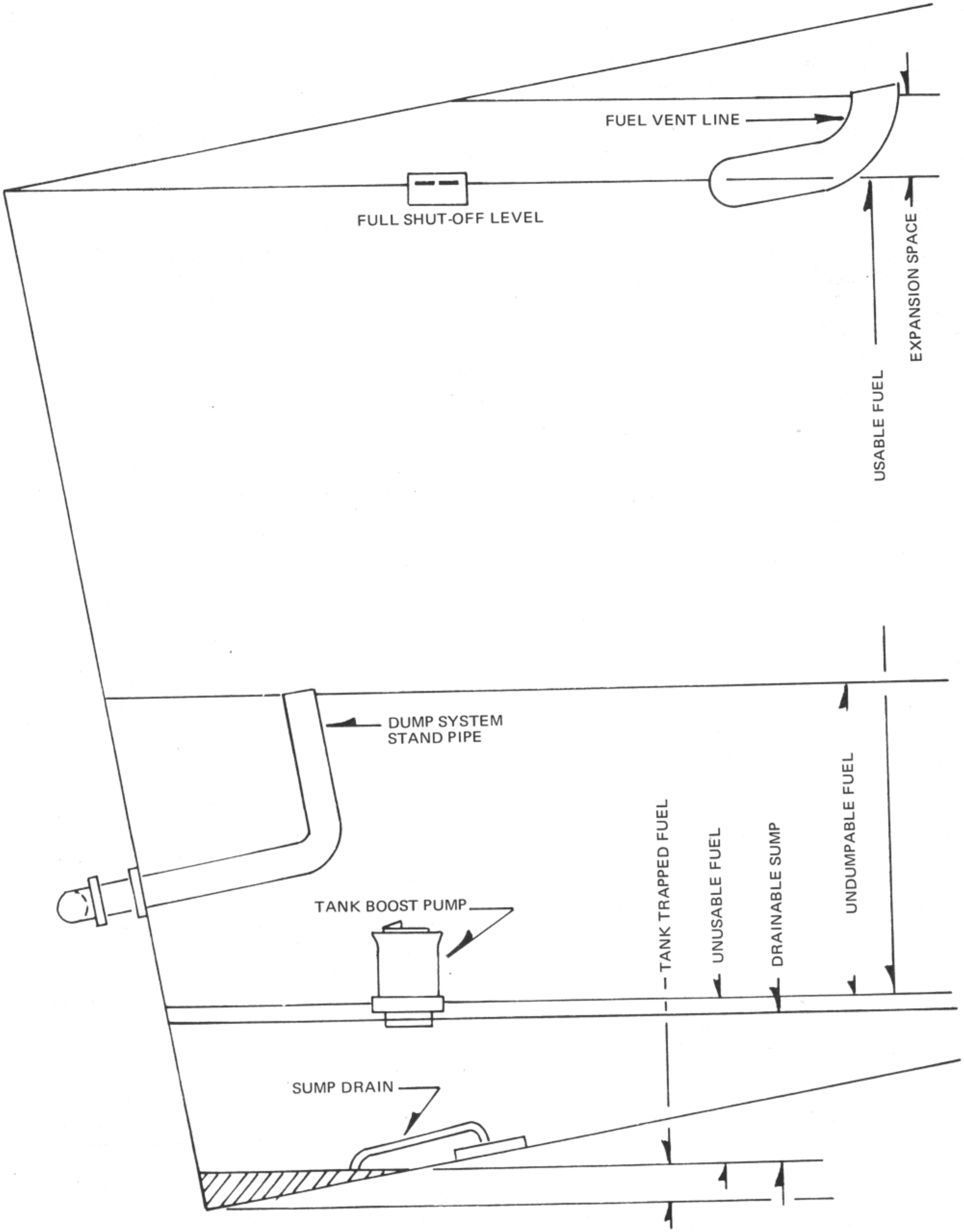


FIGURE 39
FUEL TANK CAPACITY NOMENCLATURE

TABLE III

TANK CAPACITIES DC-8-62
(Gallons)

TANK / QUANTITY	OUTBD. ALT.	OUTBD. MAIN	INBD. MAIN	SUB-TOTAL x 2	CENTER WING	FWD. AUX.	TOTAL
Trapped	2.6	2.0	4.2	17.6	2.7	0.5	20.8
Drainable Sump	4.5	9.2	6.9	41.2	5.2	4.4	50.8
Unusable	3.6	5.4	9.9	37.8	5.2	4.4	47.4
Usable	1640.9	2938.7	4454.0	18067.2	4184.3	2007.4	24258.9
Expansion Space	13.6	100.1	89.4	406.2	114.6	46.0	566.8
Undumpable	10.2	398.3	570.8	1958.6	1288.8	0	3247.4

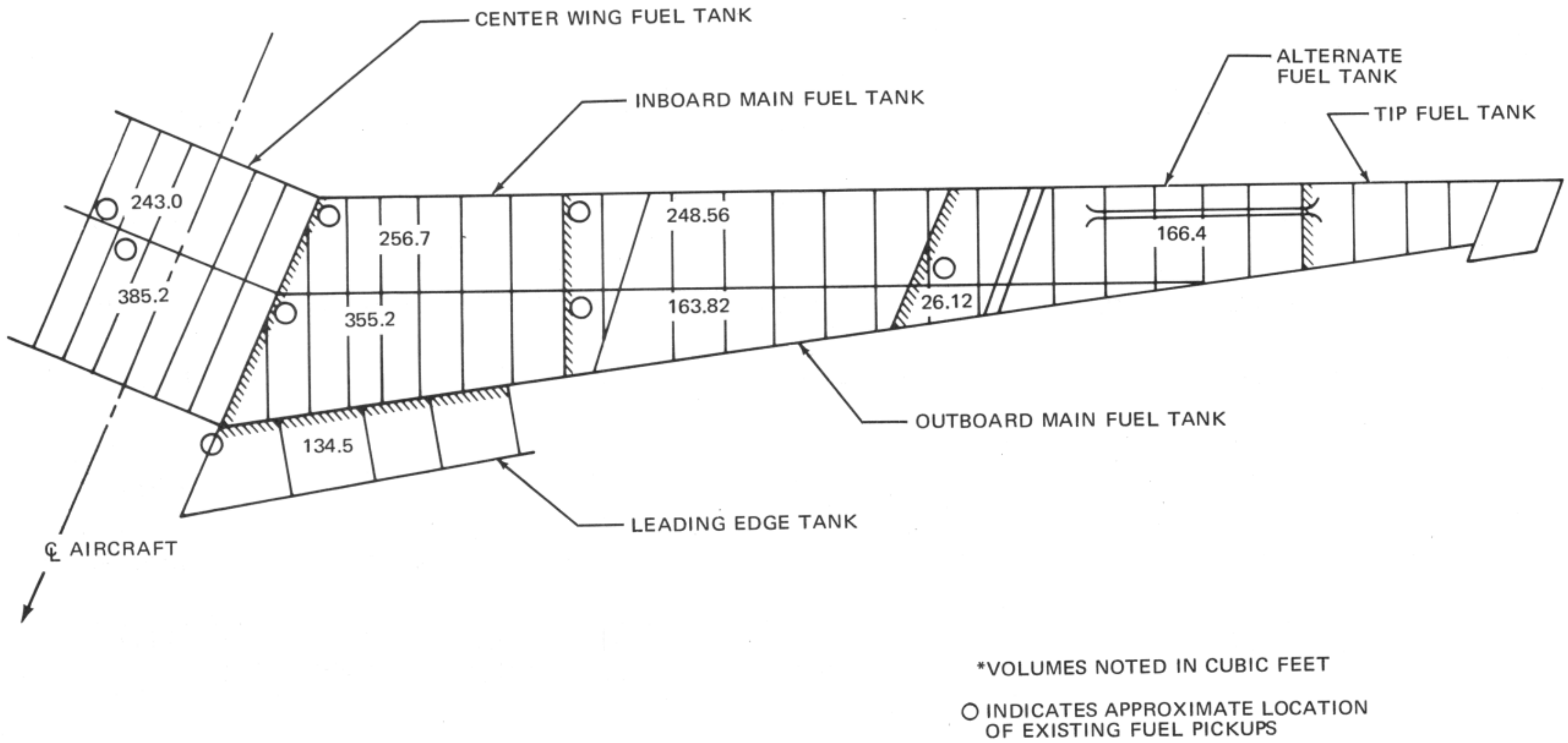


FIGURE 40
DC-8 FUEL TANKAGE

results to predict the amount of fuel which would be left in the remote bay during the test. These correlated well with the test results. The gel was the only fuel which gave significant flow through the drain holes, as would be expected.

The amount of emulsion remaining in the tanks was a geometrical problem. The fluid level gradient between bays was calculated on a modification to the level noted in the pumpdown test. The angle obtained in the test was reduced somewhat by an arbitrary consideration of the test conditions and the behavior of the emulsion surface in other testing.

The results show that a fuel as stiff as the Fuel B emulsion will not flow to the pump through the drain holes provided. The center spar provides an effective barrier to fuel transfer because it is a major structural member and does not have large flow paths through it. The ribs which separate open tank bays have lightening holes in them and have holes near the bottom of the tank to provide for drainage along the wing toward the pump inlets. Stringers have oblong holes which provide fore and aft drainage low in the tank.

Unusable fuel estimates have been made for Fuel G and Fuel B for three cases. The first case is a stock airplane in which the assumption has been made that the present pumps are used in their present locations. The engine feed line pressure drops are assumed to be within the capability of the boost pumps for emulsion because there is significant breakdown. For comparison, the gel is assumed to be handled in the same manner. This case is unrealistic but points out the basic situation upon which improvements are made by modifications to the airplane.

In this base case, the fuel in the forward auxiliary tank is not available if it must transfer by gravity to the centerwing tank as it does in the liquid system. The minimum pressure required for the flow rate required is not available from head alone. Fuel from the centerwing tank is not available because the inlet loss to the remotely located pumps is too great to permit the required flow. The same situation exists in the main tanks where a pump is used to scavenge fuel from remote tank areas to keep a reservoir around the feed pump full of fuel. A percentage of the fuel contained in the reservoir would be the only available fuel. The alternate tank transfer pump has no inlet line. Fuel would have to be fed directly to the engine from this pump. Results are shown in Table 4. Fuel G would be approximately 93% unusable and Fuel B would be approximately 98% unusable. Any number of minor modifications could be made to the aircraft to increase fuel availability. Structural modifications are considered major changes and are not considered. Minor modifications are limited to additions of pumps and small piping which would not require structural redesign. The spectrum of systems is as broad as from the basic system to one having a pump in every bay of the tanks. This would be a limiting case for non-structural modifications.

A basic modification was assumed to the system which would involve replacing the pumps now installed with pumps which would have the capability of feeding

TABLE IV

DC-8 FUEL UTILIZATION
(All Values in ft^3)

		EXISTING SYSTEM			
		FUEL G		FUEL B	
FUEL TANK	CAPACITY	10,000 #/HR	3000 #/HR	10,000 #/HR	3000 #/HR
Front Ctr Wing	385.2	0.0	0.0	0.0	0.0
Rear Ctr Wing	243.0	0.0	0.0	0.0	0.0
Front Inbd Main	701.4	0.0	0.0	0.0	0.0
Rear Inbd Main	513.4	15.0	16.0	10.0	10.0
Front Outbd Main	327.6	0.0	0.0	0.0	0.0
Rear Outbd Main	497.2	17.0	18.0	14.0	14.0
Front Alt	52.2	19.6	26.2	0.0	1.8
Rear Alt (Incl. Tip)	332.8	166.4	200.0	46.6	49.8
Leading Edge	269.0	0.0	0.0	0.0	0.0
TOTAL	3330.8	218.0	260.2	70.6	75.6
% Utilization	100.0	6.70	7.80	2.12	2.28

the engine with unbroken fuel and which would have the suction capability for using the remote inlets. Pump additions were assumed in the leading edge tank. This is identified as Modification #1. The amounts of fuel recovered for this arrangement are shown in Table V.

The weight penalty for going to a Modification #1 system is about 65 pounds. The added weight penalty is not large because only an incremental increase is considered on the existing pumps. Lines were considered to stay the same.

Further modifications may be made to the system where pumps are placed in strategic positions in the tanks. Reference to Figures 3.4 thru 3.12 in Appendix III show that a large step may be taken in reducing unusable fuel by placing pumps so that unclaimed or only partially claimed fuel volumes are made usable. Placement of these pumps is dependent on surrounding structural characteristics of any given position.

The limiting case would be where each bay was provided with a pump inlet. This might take the form of small pumps whose function was to transfer fuel out to a central pickup point. Such a scheme is considered as Modification #2 and the results are shown in Table VI, This reduces the unusable fuel for Fuel G to about 4% and for Fuel B to about 17%. These figures are to be compared with those for a liquid system where unusable fuel is slightly over 0.2%. Each percent of unusable fuel increases the dead weight of the aircraft by about 1650 pounds. Any scheme for recovering fuel must necessarily provide for draining the volume below the stringer line. Approximately 7.5% of the fuel is contained in this volume.

The weight penalty for Modification #2 is estimated to be 968 pounds. This weight is for either Fuel G or Fuel B, and includes the increment added for Modification #1.

The analysis of unusable fuel did not consider that the tanks would have had to have been filled to a level short of liquid fuel capacity in the first place. Expansion of fuel due to air expansion and air and vapor evolution could mean a reduction in fuel volume availability by as much as 20% with Fuel B. Fuel A losses due to increased expansion space were 7.4% to 30,000 feet. Cruise altitudes higher than this are common.

The total unavailable fuel volume for Fuel B considering expansion space loss and assuming a Modification #2 recovery would then be 17% + 20%, or 37% This is not directly calculable for Fuel G because altitude expansion tests were not conducted on that gel formulation.

Fuel can not be jettisoned from the basic airplane because of the gravity transfer requirements of this system. The undumpable fuel quantity for an aircraft using thickened fuels would be first determined as an increment of fuel above the then normal unusable level and based on increased gross weights, etc. The flow rate out of the tanks would be increased to at least three times the maximum flow rate assumed in the unusable fuel study with a corresponding fuel unavailability which would depend on the system selected for use.

TABLE V

DC-8 FUEL UTILIZATION
(All Values in ft^3)

		SYSTEM MODIFICATION #1			
		FUEL G		FUEL B	
FUEL TANK	CAPACITY	10,000 #/HR	3000 #/HR	10,000 #/HR	3000 #/HR
Front Ctr Wing	385.2	282.5	378.0	92.4	97.2
Rear Ctr Wing	243.0	152.0	216.0	58.3	61.4
Front Inbd Main	710.4	628.2	676.0	238.0	248.6
Rear Inbd Main	513.4	390.0	430.2	159.4	166.0
Front Main	327.6	262.8	296.0	63.6	65.0
Rear Main	497.2	392.4	422.0	104.4	108.6
Front Alt	52.2	19.6	26.2	0.0	1.8
Rear Alt (Incl. Tip)	332.8	166.4	200.0	46.6	49.8
Leading Edge	269.0	242.0	258.0	64.5	70.0
TOTAL	3330.8	2535.9	2902.4	827.2	868.4
% Utilization	100.0	76.1	87.1	24.8	26.1

TABLE VI

DC-8 FUEL UTILIZATION
(All Values in ft^3)

FUEL TANK	CAPACITY	SYSTEM MODIFICATION #2			
		FUEL G		FUEL B	
		10,000 #/HR	3000 #/HR	10,000 #/HR	3000 #/HR
Front Ctr Wing	385.2	351.0	383.0	320.0	320.0
Rear Ctr Wing	243.0	206.0	231.0	202.0	202.0
Front Inbd Main	710.4	676.0	693.0	624.0	624.0
Rear Inbd Main	513.4	446.0	475.4	412.0	412.0
Front Main	327.6	296.0	314.0	264.0	264.0
Rear Main	497.2	460.0	476.0	400.0	400.0
Front Alt	52.2	50.2	51.2	42.8	42.8
Rear Alt (Incl. Tip)	332.8	287.0	310.0	269.0	269.0
Leading Edge	269.0	260.0	263.7	228.5	228.5
TOTAL	3330.8	3032.2	3197.3	2762.3	2762.3
% Utilization	100.0	91.0	96.0	82.9	82.9

ENGINE SYSTEM. Testing on engines and engine systems has been occurring periodically over the last several years. The most recent extensive experience has been with the emulsions. This was reported by Pratt & Whitney Aircraft for the Army in USAAVLABS Technical Report 69-4. In this report, the fuel herein identified as Fuel B was concluded to have superior overall performance relative to the other emulsified fuels tested. Its performance in the areas tested was nearly identical to JP-4. These tests were extensive and involved long run times. A problem still exists in curing a filter plugging problem which others have found. This is experienced after the fuel has been highly sheared and broken. Plugging was not experienced in the Douglas full scale test program, possibly because of low shear conditions and low total volume flow.

The gels have not undergone extensive testing and only minor engine runs have been made with the gelled Fuel G. Combustor testing of Fuel A for the FAA has been reported by the Naval Air Propulsion Test Center in NAFEC Report NA-69-1 (DS-68-27). This work was limited to a single combustor and showed Fuel A[2] to perform substantially different than the baseline JET A liquid fuel depending on the conditions.

A curve of fuel flow rate versus nozzle pressure drop in the NAPTC report showed a characteristic line for Fuel A much the same as those found for Fuel G in the full scale testing reported here. Nozzle pressure drops were significantly below those for liquid flow at high flow rate and above those for liquid flow at low flow rate.

TEMPERATURE EFFECTS

Cold Fuel Effects. The effect of cold fuel on a piping system is a function of how much of the loss is due to frictional drop and how much is due to form losses. The analysis shows form losses to be the dominant loss in all piping systems. Therefore, cold fuel effects may not be significant. The feed system would experience an approximate 15% increase in pump pressure required. However, because there may be questions about the form loss data, the effects of cold fuel may be even greater.

The viscometer data show shear stress to be higher at extremely low temperatures than at room temperature. An estimate of the effects of temperature on fluid movement may be made by ratioing the shear stresses for high and low temperature at the same shear rate. Doing so shows the gel to be less affected by temperature at low shear rates than the emulsions. In general, a doubling of pressure loss may be expected at low shear rates with either fluid. This implies that tank drainage rates may be decreased by about 30% at low temperatures and the unusable fuel quantity will be more than doubled.

Hot Fuel Effects. Hot fuel effects on a fuel system are usually felt in pump performance, in low pressure feed systems, and in fuel/oil coolers. Essentially zero inlet length would be required if current centrifugal pumps are used in low pressure systems. Obviously, the minimum length will be a

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[2] Referred to as Fuel Y in Report NA-69-1

function of the characteristics of the fuel eventually selected for use. Fuel lines of current systems would have enough pressure drop that adding the required margin above vapor pressure to fuel pressure delivered by a pump will only add a few percent to the pump pressure output requirements.

Low pressure conditions; i.e., those whose absolute pressures are near the vapor pressure of the fuel, are not likely in systems with inherently high pressure drops and where remote suction inlets are not attractive.

Fuel/oil coolers rely on good heat transfer characteristics of the fuel in turbulent flow. Thickened fluids have shown low heat transfer coefficients even in low concentrations of thickener. Very little data is available to generalize thickened fuel heat transfer. The condition of the fuel at the heat exchanger will vary depending on the fuel type used and the system, but indications are that other oil cooling methods would have to be analyzed to provide the best method for a particular application

PROBLEM AREAS

Several problem areas have been made apparent as a result of the program undertaken. The ramifications of these problems and possible solutions are outlined and discussed below. Detail requirements of modifications suggested would have to be determined for a final configuration and would involve the total effects of other modifications used in combination.

Pumps. An obvious deficiency in the pressure output of the stock pumps has been pointed out by the analysis if the fuel ultimately used was one of the ones tested. New pumps would have to be fitted which were of higher capacity. This is not a particular problem but would result in increased electrical load and could raise the emergency electrical load significantly. If there was only a moderate increase in pressure such that current pumps could be used, the higher backpressure would eventually take its toll in shorter pump life. This is not a problem with replaced tank pumps, but could be important with engine pumps unless they, too, are replaced.

The current pumps will break the emulsion so a low shear pump would be required for keeping fuel in the engine feed line in an unbroken condition. Breakdown would also occur if high shear pumps were used for transfer. The pump used for routine transfer of fuel in the full scale testing performed by the contractor has a satisfactorily low shear rate and this type should be considered. The pump has an elastomeric impeller and excellent suction capability.

The long life electric motors used in boost pumps are constant speed motors. Turning a positive displacement pump of low shear will possibly require a bypass because of varying flow rate requirements in engine feed and in normal transfer. The problem of shear is then transferred to the bypass device. No clear solution is available for this problem. Bypass shear may be tolerable with a fast resetting gel.

Pump reprime is a problem with the fuels and the centrifugal pumps tested. Acceleration type surges did not present a problem. Initial prime with a dry inlet line and the stock tank pump was a problem with both fuels. The pump was equipped with a conventional liquid ring reprime element. Flow could not be started again after deadheading the pump for a few seconds with the gel. Flow from the reprime element was passed out of the pump. Positive displacement pumps did not give a reprime problem.

Conventional aircraft fuel transfer pumps run "wet"; i.e., they use liquid fuel for cooling and lubrication. The internal bypass cooling flow is highly sheared and is returned to the tank. This flow can free large amounts of fuel from the emulsified form. A decrease in heat transfer using thickened fuels could cause a cooling problem, especially with hot fuels. Circulation around pumps would be reduced, so exterior fin cooling is not expected to be as successful as dissipation through structure. No problems were encountered in the full scale testing and only pumps which may have marginal cooling flow should be a problem with the gel.

Fuel pumps used in the system identified as Modification #2 may worsen the fuel recovery with some emulsions if the continual working of the fuel during recirculation builds the yield stress to a high level.

Gauging. Testing indicates the gel and emulsion used do not flow out of the probes in a satisfactory manner. Teflon surface coating of the probes is not a solution for fluids of high yield value because irregular internal surfaces provide fuel traps. Very large plate separations or the use of nucleonic gauging could provide the answer along with an investigation of fuel dielectric characteristics. A decrease in accuracy over the conventional system used with liquids is to be expected.

Filters. Contaminants carried in thickened fuels are expected to be a problem until proper housekeeping is effected in all fuel supply systems and until tankage is thoroughly cleaned. Some fuels after being sheared have shown a tendency to agglomerate on filters and trap very fine contaminant. Therefore, larger filters may be required in the airframe system. A space problem may occur and these filters, which are normally carried on the engine, may have to be relocated to the leading edge or tankage areas. Proper housekeeping or new materials in storage and handling systems should cure this problem in time.

Ground Servicing Equipment. Current ground servicing equipment would have to be modified to handle fuel such that it is delivered to the aircraft in a desirable form. This can take the form of low shear positive displacement pumps. This and the higher pressures required for fill systems will require that failsafe pressure limiting provisions be provided.

Ground Servicing Procedures. Two nozzle fill systems on medium and large aircraft would not be practical so four nozzles could be used to decrease turnaround times. This results in more manpower and equipment costs and adds to congestion of servicing vehicles.

Low Fill Rates. Fill rates are very low even using four nozzles on the DC-8. Increasing supply pressure alone will adversely affect the vent system in the overfill case. A solution to the fill system problem would be to modify the fill system plumbing by moving it inside the tanks where room is available for larger lines. The present location on the DC-8 is space-limited. This concept was used on a proposed configuration and is considered feasible.

Overfill Pressures. Overfill pressures predicted with the stock system exceed structural limits when using the fuels tested. The solution is to enlarge the vent system piping or to employ pressure limiting valves as is currently being done in new aircraft. The valve configuration would have to be made compatible with the fuel selected for use and would be a new part. Structural limits may be increased significantly by minor structural modifications depending on the wing construction and where the limiting stress levels occur.

Fill Valves. The hydromechanical fill valves currently used on the DC-8 do not operate satisfactorily with the fuels tested. The electric valves can be used instead and the hydromechanical valve can be removed to save weight. However, if the normal fuel schedule is followed, the electric valve life would be shortened to an unacceptable level.

Float Switches. Float switches currently used to control fuel levels electrically will not work with the fuels tested because the holes which give access to and drainage from the floats are too small. These may be replaced by larger open floats at a weight penalty.

Line Pressure. Line wall gauges will have to be increased commensurate with higher operating, proof and burst pressure requirements. Higher pressure drops inherently give higher operating pressures. One solution is the use of thinner fluids.

Wing Tip Compartment Fuel Transfer. Gravity fuel transfer is a problem, particularly with the outboard or "reserve" fuel tank compartments. This fuel is held until late in every flight when it may be very cold. This fuel may be transferred by adding pumps to the system.

Jettison Flow Rates. Gravity transfer of fuel is too slow to provide adequate flow of fuel to a small number of jettison pumps. This results in low dump rates for existing pump jettison systems and may not permit enough fuel to be dumped. A solution may be found in application of the current rules for jettisoning rates of FAR 25.1001 or in limiting aircraft gross weight to the extent where jettisoning is not required under these rules. Each aircraft will have to be examined for its particular requirements. Aircraft gross weights on short routes may normally fall under the weight where jettisoning is required.

Parts Accessibility. Adding new parts to an aircraft in areas where the original design did not provide ready access presents a maintenance problem. Adding access panels is a weight penalty. Maintenance time and effort is increased considerably by the problem of residual tank fuel which is undrainable by a gravity system. A tradeoff will have to be made in each case of parts placement to evaluate probable economic gain or loss of alternate placement. This is a particular problem with pump additions for fuel recovery.

Dried Fuel Residue. Gels have been found to leave a sticky residue. A significant increase in cracking pressure of a check valve was found in one case, Figure 41. A check valve flapper was held open in another case. The solution is to test and evaluate proposed fuels for such characteristics.

Unusable Fuel. The analysis reveals high and varying quantities of unusable fuel. This adds a dead weight penalty in the form of unrecoverable fuel and in the addition of equipment for partial recovery of this fuel. The solution is a tradeoff of fuel recovered versus weight and complexity added for that purpose. Enlargement of structural drain holes is only a minor consideration because these holes would occur in areas of generally high stress levels in a system which was made as light as possible in original design.

Expansion Space. Expansion space requirements due to fuel swelling do not add weight, but detract from the quantity of fuel loaded. A solution would be the use of a fuel which gives a low percentage of expansion with altitude. Careful attention to the avoidance of trapping air during fuel treatment and handling can minimize the problem.

Fuel In Vent Systems. Fuel may find its way into vent systems during climbout, maneuvers, or gusting conditions. Thickened fuel may not drain from the vent by gravity and could build in quantity with time. This may cause temporary plugging of the vent lines with resultant abnormal pressure cycling amplitudes and increased fatigue stressing. A solution is to provide adequate vent space.

Fuel Management. Tank fuel levels are controlled in a liquid system to provide an optimum fuel weight distribution in the wings. This is done to provide relief for wing bending moments and for center of gravity control. Transfer of fuel is semi-automatic and requires little crew attention. The addition of more pumps or of smaller packaging of fuel supplies to increase fuel utilization will result in more complex management procedures and produce more chance for error. Sound system design to minimize problems is required.

Dispatch Inoperative (Minimum Equipment) List. The list of equipment which may be inoperative at takeoff and the compensating conditions applied may become a very serious complication in use of thickened fuels. Redundancy in system modifications to attain a satisfactory level of safety will be required and will add a weight penalty over that required to merely accomplish a basic task on the assumption of no system failures. Dispatch delays could be substantial without a required level of redundancy or system independence.

Reliability. The addition of parts to a system to make it compatible with a thicker fuel is a complication of the system and detracts from its basic reliability. Any solution so far discussed generally requires the addition of parts. Therefore, changes should be sought which are toward more simple systems.

Systems Analysis and Testing. The systems testing and analysis which was carried out on this contract point out that much work will need to be done in the area of performance on any particular fuel chosen for development. The scope of testing will have to be enlarged tremendously to provide design data for retrofit analyses and for new designs. The available design data will have to be increased to include, for example, other pipe sizes, surface conditions, temperature effects, surge pressure phenomena, shear rates, thixotropicity, rheopexy, form losses of various body shapes, losses for orifice types other than those tested, pressure measurement techniques, effects of contaminants. An improved confidence level will have to be developed in understanding the flow characteristics of a particular fuel selected in order to extrapolate test data into untested regions. Complete coverage of the required performance region with a testing program can provide the necessary information.

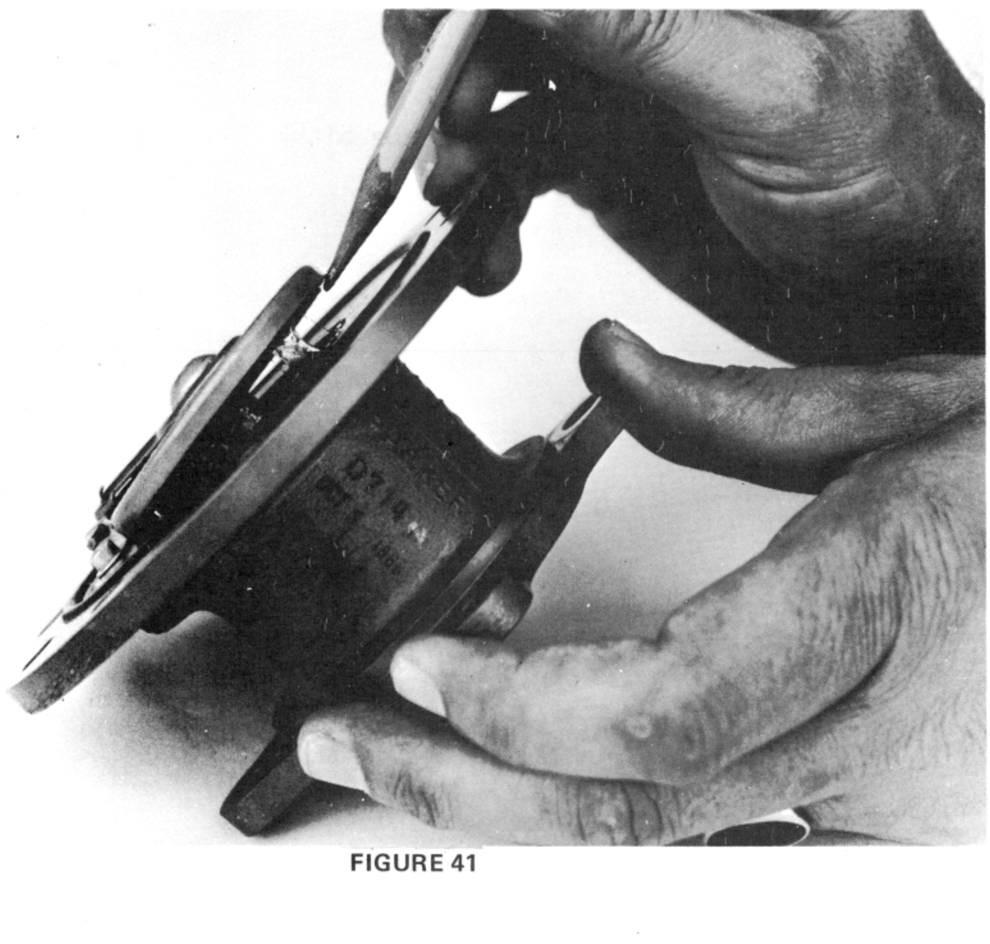

FIGURE 41

SECTION C

EXPERIMENTAL GROUND TEST OUTLINE

The following experimental ground test outline suggests a series of tests which may be conducted on any airplane to evaluate airframe and engine fuel systems performance when operating with a candidate gelled and/or emulsified fuel. The object of this program is not to certify an aircraft for use with a particular fuel, but to qualify the system by obtaining an adequate confidence level that the aircraft could be used with the fuel in a flight test program. It is assumed that the flight test program will start with the candidate fuel being used in only part of the system, e.g., one tank set/ engine combination, and that inflight environmental effects will be evaluated during a flight test program.

Additional tests are included which will examine the aircraft for compatibility with use of a candidate fuel. Some or parts of these tests may be made on mockup rigs. Tests for compatibility only are followed by an asterisk.

AIRFRAME TESTS

Fill System. Conduct filling operations on each tank selected for engine feed. This must be done on an individual basis to determine fuel quantity loaded.

Add weighed amount of fuel to tank to shutoff level recording amount added to determine where shutoff level is. Last increment may be added at full fill rate to determine overshoot.*

Record fill rates during increments.*

Inspect tank fuel for physical condition. Record measurements of yield stress of tank samples.

During test fill inspect operation of all functions such as pre-check of high level shutoff, intermediate level controls, etc., which may be provided.*

Record gauging system readings at each increment.

Compare "full" quantity with liquid system calibration values or intended fill quantity at automatic shutoff.*

Vent System. Tank pressures near the vent inlets should be monitored during fill to assure vent adequacy.

An over-fill should be done in increasing supply pressure increments to predict tank pressure at overfill with full supply pressure.*

Jettison System. Fill tanks completely. If an emulsion is being tested and an intra-tank transfer subsystem has been installed, operate the system for the time required to fly from maximum gross takeoff weight to the weight where jettison is no longer required. This will work the fuel in the tanks. Record amount of fuel loaded.*

Aircraft should be positioned to inflight jettison attitude.*

Operate jettison system for complete dump to undumpable fuel level.*

Catch effluent flow samples to check for jettisoned fuel quality.*

Determine fuel quantity jettisoned, average rate and rate changes with time.*

Examine tank to determine distribution of fuel quantity remaining for system improvements and fuel rapid drain characteristics.*

Transfer System. Fill tanks with weighed amount of fuel and transfer fuel in normal management schedule.

Determine transfer rate adequacy and operation of shutoff levels.

Note condition of fuel transferred from tank to tank both for quality and effects of working.

Note condition of fuel in tanks from which transfer is effected to evaluate cooling return flow condition as required.

Determine residual fuel in alternate or auxiliary tanks.

Engine Feed System. Fill tanks with known quantity of fuel. Pump fuel from tanks over a selected mission profile to obtain an unusable fuel estimate. This may be combined with engine test runs if runout can be made in a ground attitude. A fuselage at flight attitude may be desirable.

Record fuel quantity removed versus time.

Record quantity gauging system readings at intervals on the way down from full to empty.

Determine engine inlet pressure versus flow rate for the fuel feed system.

Sample fuel at engine inlet and record fuel quality and physical condition.

ENGINE TESTS

Preliminary. Examine fuel for content of known undesirable elements, eg. sodium, potassium.

Fuel used in the tests should be prefiltered through at least a 40 micron filter.

Perform cold flow tests on engine system to identify problems with spray nozzles, pumps, fuel control, etc. Detailed tests may vary with the particular engine under investigation.

Operational. The following series of tests will indicate possible engine operational problems and will give an adequate confidence level in engine operations on a thickened fuel. It is assumed the engine has been shown analytically to be capable of operation on the fuel. The test series will consist of eight cycles of six hours each. Each cycle is to be broken down as shown below. The total time in the series may be factored according to the level of existing experience with a particular fuel and the confidence level desired depending on the subsequent testing to be performed. Restarts after long duration shutdown are to examine problems with fuel hang up on injector nozzles. Minimum starter energy levels should be used to provide miminum atomization energy to the injectors.

Perform normal engine start at lowest starter energy level.

Run for one hour total consisting of 5 minutes at idle and 5 minutes at take off power.

Shutdown for 2 hours minimum and restart.

Run for one hour total consisting of 10 minutes at each of six intermediate thrust levels between idle and Maximum Continuous Thrust (MCT).

Shut down for 2 hours minimum and restart.

Run for one hour at MCT.

Shut down for 2 hours minimum and restart.

Run for one hour at MCT.

Shut down for 2 hours minimum and restart.

Run for one hour at MCT.

Shut down for 2 hours minimum and restart.

Run for one hour consisting of 6 periods of ten minutes each following the schedule:

3 minutes at idle

2 minutes at MCT

1 minute at idle

2 minutes at maximum reverse

2 minutes at idle

Shut down for 15 minutes minimum and restart.

Special engine runs may be made to point out problems other than those associated with long term hot operation. False starts should be made to examine the capability of the engine to void itself of fuel. The engine is brought up to start rpm, fuel controls are manipulated in the normal manner and the engine is shut down. Ignition is not used. Visual examination of internal areas may be required to indicate residual fuel.

A series of runs should be made to investigate changes in response characteristics of fuel controls, variable stator control systems, etc., due to the use of thickened fuel. One series will be acceleration/deceleration cycles in which the throttle is moved in snap movements from idle to takeoff position and returned. Power level position change is started slightly in advance of the rotor speed arrival at the target end point so that essentially no dwell time is experienced at the end point and maximum transiency is obtained. This test will show possible compressor stall problems and should be of approximately ten cycle duration.

The particular engine under study should be examined for system pecularities warranting test. Of specific interest would be any system using fuel as a hydraulic fluid or where fuel has extended residency especially under high temperature conditions. Heat exchangers using fuel as a cooling medium will be of particular interest in the testing. Auxiliary methods of temperature control may be necessary.

A complete tear down and inspection of all parts of the engine affected by the fuel should be made after the test run. This would include, but not be limited to, the fuel control, fuel pumps, actuation cylinders and fuel lubricated surfaces. Effects of thermal breakdown should receive special emphasis. All screens and filters should be examined during each extended shutdown.

Instrumentation will be required to record total run time, power level position, rotor speeds, fuel flow rate, oil temperature, fuel pressure and temperature at the engine inlet, exhaust gas temperature, turbine inlet temperature, ambient temperature and pressure, and filter pressure drop. Start characteristics will be recorded in terms of time to ignition, time to starter cut out, stabilized idle speed, gas temperatures and fuel manifold pressure.

SUMMARY OF RESULTS

Rheological data was determined for two emulsified fuels and one gelled fuel. Data on other fuels was compiled for comparison.

Pressure loss data for several aircraft fuel system components was determined to be higher with the gelled and emulsified fuels tested than with liquid fuels.

Analyses of the several fuel sub-systems of the DC-8-62 indicate that in a liquid system which is to operate with either the gelled or the emulsified fuel tested:

A) Increased fill times may be expected
B) Jettison system revisions may be necessary
C) More and larger pumps would be required
D) Available fuel is reduced
E) Revised fuel feed systems would be required.

Large increases are to be expected in the operating empty weight of an existing aircraft modified to operate on either the gelled or the emulsified fuel tested.

Areas of indicated modification or of possible difficulties are identified for consideration of gelled or emulsified fuel use.

Ground test programs are outlined which will evaluate airframe and engine fuel system performance when operating with candidate gelled or emulsified fuels. Additional tests are included which will examine an aircraft for compatibility with use of a candidate fuel.

CONCLUSIONS

1. The thickened fuels examined have shown compatibility with currently applied tank coating, but some may be incompatible with older coating still in service.

2. Emulsions have shown some cases of corrosion enhancement.

3. The thickened fuels examined do not degrade Vithane polyurethane fuel cell material.

4. Water tends to thin the emulsions tested. The gel tested will suspend small amounts of water.

5. There is a tendancy for light solids to stay suspended in thickened fuels.

6. ASTM D-1092 use is questionable for precise determination of shear stress/shear rate relationship with some fuels.

7. Published data on non-Newton fluids are insufficient to permit aircraft designers to adequately predict the performance of the fluids.

8. Fill systems of current aircraft are not compatible with realistic refuel times when using the fuels tested. Full fuel level shutoff methods may not work with these fuels.

9. Customary vent system practices are not compatible with the thickened fuels examined primarily because of insufficient expansion space.

10. Currently flying jettison systems are not compatible with the thickened fuels examined because of low fuel flow rate to the pickup points.

11. Current methods of fuel transfer are not compatible with the thickened fuels examined because of drainage requirements and pump suction requirements.

12. Centrifugal pumps used in current aircraft are not compatible with the fuels examined because of fuel breakdown and pressure rise requirements.

13. Current methods of fuel recovery from tankage are not compatible with the fuels examined without accepting the associated penalties.

14. Current methods of establishing aircraft empty weight are not compatible with fuels which may have a varying yield value or viscosity resulting in the inability to establish a zero fuel weight.

15. Fuel system cleanliness can present a problem with the thickened fuels examined because solid contaminant will not settle out.

16. Currently used fuel gauging equipment is not compatible with the fuels examined because of inhibited inflow and out flow from the probes.

17. Current filter sizes and bypass valve setting are not compatible with the thickened fuels.

18. Current ground servicing equipment is not compatible with the fuels examined because of low system capacity and fuel breakdown.

19. An aircraft modified to be compatible with thickened fuels will probably have a decreased overall system reliability.

20. Unmodified four-engine commercial jet transport aircraft fuel systems are not compatible with the gelled and emulsified fuels examined. Many modifications to current aircraft are required to approach liquid fuel system performance levels.

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APPENDIX I

This section is to provide a more detailed discussion of the rheological test program than that included in the main text. Some test data is included in the main text under Table I.

PURPOSE

The objectives of the laboratory phase of the program reported herein were to determine rheological properties of gelled or emulsified fuels. The rheological data was employed for pressure drop versus flow rate calculations and development of flow charts for piping systems.

MATERIALS

1. Fuel A, a resin gelled ASTM Type Jet A fuel with a resin concentration of 2.5% by weight.

2. Fuel B, an emulsified JP-4 fuel with a semiaqueous external phase.

3. Fuel C, an emulsified JP-4 fuel with a non-aqueous external phase.

EQUIPMENT

1. Penetrometer, conforming to specifications of ASTM method D217, -65T (modified) Precision Scientific Co., Chicago, Illinois.

2. Penetrometer plastic cone and aluminum plunger, 30 grams, Precision Scientific Co.

3. Penetrometer steel cup, 3 in. I.D. x 2-1/2 in. depth.

4. Glass bottles, 16 oz, 3-1/2 in. I.D. x 3-1/2 in. depth.

5. S.O.D. Pressure Viscometer, and a series of eight capillaries with 40 to 1 length/diameter ratios, conforming to specification of ASTM D1092, Precision Scientific Co.

6. Hydraulic oil, 320 SUS viscosity at 100°F, 30.1° API at 60°F.

7. Hydraulic oil, MIL-H-5606.

8. Sub-Zero Test Cabinet, American Instrument Co., modified to give access ports for connecting tubing to cylinders of pressure viscometer.

9. Brookfield Synchro-Lectric Viscometer, Models LVF, RVF, and HAF, Brookfield Engineering Laboratories, Stoughton, Mass.

PROCEDURE

Yield stress, the finite shear stress required to initiate flow of a material, is not readily measurable for non-Newtonian fluids such as the thickened fuels, but it can be closely approximated. One of the more practical methods that has been used with thickened fuels is a modification of the cone penetration test, ASTM D217. The cone penetrometer of the test is a common instrument available in most petroleum laboratories.

Flow properties, or shear stress-shear rate relationships, and apparent viscosities of liquids are determined with viscometers, the principal types being capillary and rotational. With the capillary viscometer, the test liquid is forced through a small diameter tube or capillary, and viscosity and other flow properties are determined from the volumetric flow rate, system pressure, and the tube or capillary dimensions. A standardized, controlled flow rate, capillary viscometer is specified by ASTM D1092. Some other capillary viscometers employ a controlled pressure, but the principles are the same. With rotational viscometers, the test fluid exposes a rotating spindle to a viscous resistance or drag directly related to the rotational speed of the spindle. Viscosity and the other fluid flow properties are determined from the speed and the measured force required to overcome the resistance. Low, controlled shear rates below those of the capillary viscometer can be obtained with rotational viscometers; consequently, Brookfield Synchro-Lectric viscometers were used to provide supplemental shear data.

Yield Value by Cone Penetrometer. The method used in this program, employing the cone penetrometer, was a modification of ASTM D217 by Beerbower. The principal parts of the penetrometer were a 30 gram cone and aluminum plunger rod, plunger rod clutch jaws, a release mechanism and a depth gauge. In the test the penetrometer was set to the zero position where the point of the cone just touched the smoothed surface of the fuel, the cone was released, and the penetration read on the depth gauge. The depth gauge indicated in one-tenth millimeters the travel distance or penetration of the cone in five seconds after release from the zero position. The yield value, calculated from the penetration by the Beerbower technique, is the result of the cone weight divided by the equilibrium wetted cone area adjusted for buoyancy. A relationship between yield value and penetration of the 30 gram cone is given in Figure 1.1. The yield value can also be used as a measure of the consistency of a thickened fuel.

Penetrations were made at 130°F, 0°F, -65°F, and room temperature. Yield stress values obtained by this method are presented in Table 1-I. The standard grease cup of ASTM D217 was used as the fuel container for the room temperature tests; wide mouth glass bottles, approximately the same size as the standard grease cup, were used for the tests at the other temperatures.

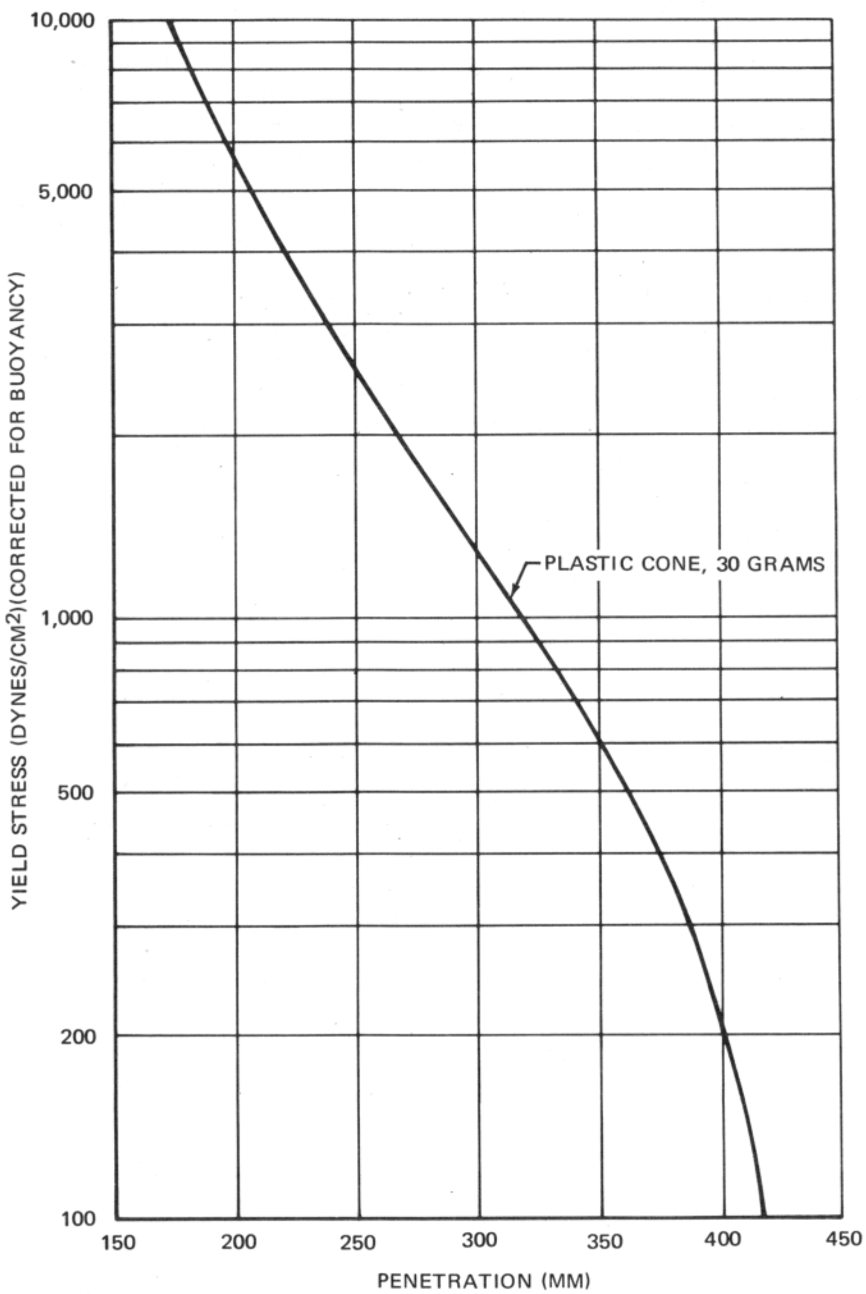


FIGURE 1.1
YIELD VALUE FROM PENETRATION CHART

TABLE 1-I
THICKENED FUEL YIELD VALUES

Temp °F	Fuel A		Fuel B		Fuel C	
	$\frac{dynes}{cm^2}$	$\frac{lb}{ft^2}$	$\frac{dynes}{cm^2}$	$\frac{lb}{ft^2}$	$\frac{dynes}{cm^2}$	$\frac{lb}{ft^2}$
130	152	0.317	400	0.835	1190	2.49
74	355	0.742	680	1.42	1160	2.42
0	470	0.980	940	1.96	1240	2.59
-65	1170	2.44	1600	3.34	1950	4.07

The 130°F temperature was obtained by using a water bath; the 0°F and -65°F temperatures were obtained using low temperature environmental chambers. A sample bottle was removed from its hot or cold environment several seconds before the penetration of the fuel was measured.

Shear Data by Capillary Viscometer. The S. O. D. Pressure Viscometer and the method of ASTM D1092 were used to provide shear stress-shear rate data and apparent viscosities. The S.O.D. Pressure Viscometer, a capillary viscometer, is shown schematically in Figure 1.2. The instrument data is in Table 2-I. In this test thickened fuel was forced from a steel cylinder through one of a series of eight capillaries by a floating piston pushed by hydraulic oil. The mean shear rate, shear stress, and the apparent viscosity were calculated from the predetermined equilibrium hydraulic oil flow rate, the equilibrium pressure developed, and the capillary dimensions using Poiseuille's flow equation. Log plots were made to show the shear stress-shear rate and the apparent viscosity-shear rate relationships with temperature for each fuel.

The capillary end cap was removed from the cylinder and the cylinder charged with thickened fuel, keeping air inclusion to a minimum. The cap was replaced and the cylinder above the piston was filled with hydraulic oil. A hydraulic oil having a viscosity of 320 SUS at 100°F was used for the tests at room temperature and 130°F; a MIL-H-5606 hydraulic oil was used for the 0°F and -65°F tests because its pour point was below -65°F. After being filled with oil, the cylinder was attached to the test apparatus hydraulic system. With a capillary in place and a drive gear connected, the positive displacement pump was started, and the system was operated with the oil reservoir return valve opened to displace all the air. The valve was closed and the pump continued to run until an equilibrium pressure was obtained. A mercury manometer was used for lower pressures, a bourdon tube pressure gage for higher pressures. Tests were made with each of the series of eight capillaries.

Copper tubing wrapped around one of the viscometer pressure cylinders was used to transmit heat from hot water to the fuel in the 130°F tests. The tubing, cylinder, and caps were insulated with polyurethane foam. The capillaries were insulated with a foamed rubber or an asbestos tape. A thermocouple, protruding into the fuel through the capillary end cap, and a temperature potentiometer were used for temperature measurement.

The 0°F and -65°F tests were made with bare pressure cylinders in a controlled tmperature cold box. The fuel-filled cylinders and capillaries were cold soaked overnight before placement into the test system. Stainless steel tubing joined the test cylinder to the hydraulic system through ports in the cold box. After a test and changing of capillaries or cylinders, the bulk fuel temperature was allowed to equilibrate before starting another test.

The capillaries were solvent cleaned before each use to remove residual wall contaminant. Hot Stoddard's solvent was used first and was followed successively by rinses with methyl ethyl ketone and isopropyl alcohol.

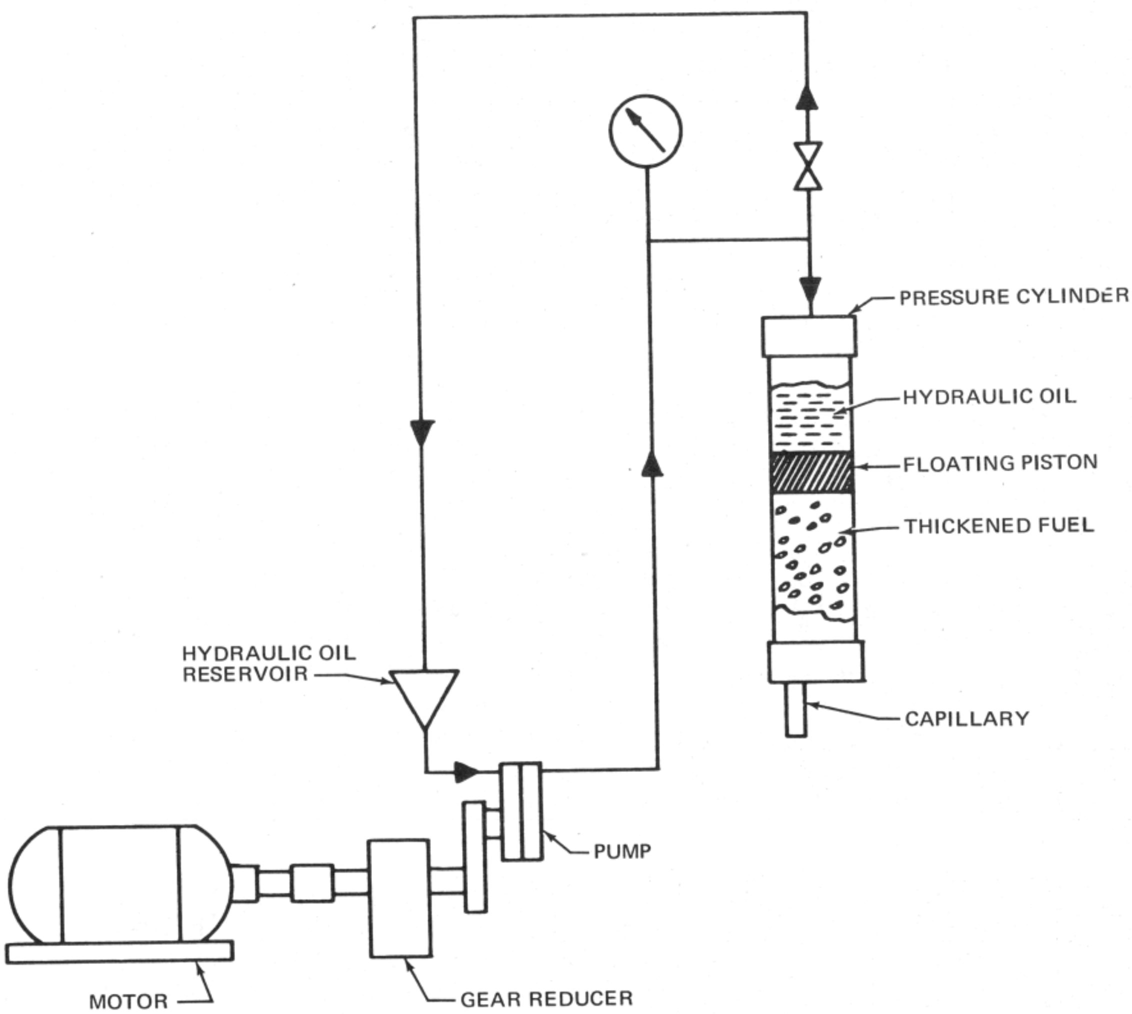


FIGURE 1.2
S.O.D. PRESSURE VISCOMETER

TABLE 2-I
S.O.D. PRESSURE VISCOMETER DATA

Hydraulic oil flow rates	
with 64 tooth drive gear	0.134 ml/sec
with 40 tooth drive gear	0.0828 ml/sec

Capillary dimensions and flow factors

No.	Diameter cm	Length cm	K 64 tooth gear	K 40 tooth gear
8	0.0404	1.81	0.0185	0.0300
7	0.0617	2.55	0.0719	0.116
6	0.0993	4.05	0.303	0.491
6B	0.102	4.09	0.329	0.532
5	0.116	4.87	0.462	0.748
5B	0.112	4.86	0.405	0.656
4	0.141	6.09	0.825	1.34
3	0.184	7.42	1.97	3.18
2	0.235	9.84	3.93	6.36
1	0.376	15.5	16.3	26.4

where

$$K = \frac{68,944 \pi R^4}{8L \; V/t}$$

Pressure corrections
Piston head
Weight: 402.5g; Area = 2.63 in.^{2}; Head: 0.339 psi
Liquid head, room temperature and 130°F
Hydraulic oil
Specific gravity @ 60°F: 0.877
Height: 17 in. (average); Head: 0.53 psi
Fuel (thickened JP-4)
Specific gravity @ 60°F: approx. 0.78
Height: 4 1/2 in. (average) Head: 0.13 psi
Total head, room temperature and 130°F tests
= 0.34 + 0.53 + 0.13 = 1.00 psi

Liquid head, cold temprature tests
Hydraulic oil
Specific gravity @ 60°F: 0.861
Height: 47 in. (avg.). Head: 1.45 psi
Fuel (thickened JP-4)
Height: 4 1/2 in. (avg.) Head: 0.13 psi
Total head, cold temperature tests
= 0.34 + 1.45 + 0.13 = 1.92 psi

The flow characteristics listed in Table **3-I**, **4-I** and **5-I** were calculated using the following equations of the ASTM test method:

Apparent viscosity, η

$$\eta = \frac{F}{S} = \frac{\left[\frac{p\pi R^2}{2\pi RL}\right]}{\left[\frac{4\,v/t}{\pi R^3}\right]} = \frac{p\pi R^4}{8L\,v/t} \qquad (1)$$

$$= \frac{68{,}944\,p\pi R^4}{8L\,v/t},\ \text{poise}$$

where F is shear stress in dynes/cm^2, S is shear rate in sec^{-1}, p is observed pressure in dynes/cm^2, P is the observed pressure in psi, R is the capillary radius in cm, L is the capillary length in cm, and v/t is the flow rate in cc/sec.

Mean shear rate, S

$$S = \frac{4\,v/t}{\pi R^3},\ \text{sec}^{-1} \qquad (12)$$

Shear Stress, F

$$F = \frac{p\pi R^4}{2\pi RL} = \frac{pR}{2L} = \eta \times S,\ \text{dynes/cm}^2$$

$$= \frac{\eta \times S}{478.8},\ \text{lb/ft}^2 \qquad (3)$$

The flow rate used in the calculations was that of the hydraulic oil obtained with either of the two pump drive gears of the viscometer. This flow rate and the fuel flow rate at equilibrium pressure are the same.

Corrections were necessary for treating pressure data from the capillary viscometer. First, the head above the capillary inlet developed by the hydraulic oil, the thickened fuel and the piston was added to the observed pressure. Second, pressure losses due to capillary entrance and kinetic energy effects were subtracted from the observed pressure when significant. Wilkinson stated that the correction for these lossed is approximately equal to $1.5\rho\, u_m^2/g$, where ρ is density, u_m is mean velocity, and g is the gravitational constant.

Mean shear rate and shear stress can also be expressed by the following equations (4) which were used in setting up shear diagrams and pipe flow charts:

TABLE 3-I
FUEL A CAPILLARY VISCOMETER TEST DATA

Gear: 40 tooth — Flow rate: 0.028 ml/sec.

Gear: 64 tooth — Flow rate: 0.134 ml/sec.

Capillary	Pressure psig.	Apparent Viscosity $\eta = P \times K$ poise	Shear Rate S, sec^{-1}	Shear Stress $dynes/cm^2$ $= \eta \times S$	Shear Stress $lb./ft^2$
	Temperature: 73°F.				
Gear: 40 tooth					
8	10.0	0.300	12,807	3,840	8.02
7	6.8	0.793	3,586	2,850	5.95
6	4.4	2.16	860.4	1,855	3.87
5	4.2	3.14	546.4	1,713	3.58
4	3.3	4.31	299.4	1,316	2.75
3	2.6	8.27	134.5	1,110	2.32
2	2.2	14.0	64.82	908	1.895
Gear: 64 tooth					
8	11.4	0.211	20,729	4,370	9.12
7	7.6	0.547	5,805	3,170	6.62
6	5.1	1.544	1,393	2,170	4.53
5	4.8	2.21	884.4	1,955	4.08
4	3.8	3.13	484.7	1,517	3.17
3	3.0	5.9	217.7	1,285	2.68
2	2.3	9.05	104.9	949	1.98
	Temperature: 130°F				
8	10.73	0.198	20,729	4,120	8.59
7	7.54	0.542	5,805	3,140	6.57
6	5.28	1.60	1,393	2,230	4.66
5	4.74	2.19	884.4	1,933	4.04
4	3.80	3.13	484.7	1,520	3.18
3	3.16	6.22	217.7	1,355	2.83
2	2.62	10.28	104.9	1,080	2.26
1	1.93	31.5	25.70	808	1.69
	Temperature: 0°F				
8	16.5	0.305	20,729	6,320	13.5
7	9.2	0.662	5,805	3,940	8.01
6	6.9	2.19	1,393	2,910	6.07
5	6.3	2.91	884.4	2,570	5.37
4	4.7	3.88	484.7	1,880	3.92
3	4.2	8.26	217.7	1,800	3.76
2	3.5	13.8	104.9	1,440	3.01
1	2.7	44.2	25.70	1,130	2.36
	Temperature: -65°F				
8	71.2	1.32	20,729	27,300	57.0
7	36.6	2.63	5,805	15,250	31.8
6	16.1	4.88	1,393	6,790	14.2
5	14.6	6.74	884.4	5,960	12.4
4	11.4	9.40	484.7	4,560	9.42
3	10.0	19.67	217.7	4,280	8.94
2			104.9		
1	4.08	66.7	25.70	1,714	3.57

TABLE 4-I
FUEL B CAPILLARY VISCOMETER TEST DATA

Gear: 64 tooth Flow rate: 0.134 ml/sec.

Capillary	Pressure psig.	Apparent Viscosity $\eta = P \times K$ poise	Shear Rate S, sec^{-1}	Shear Stress $dynes/cm^2$ $= \eta \times S$	Shear Stress $lb./ft^2$
Temperature: 74°F.					
8	11.85	0.219	20,729	4,530	9.48
7	10.45	0.752	5,805	4,360	9.12
6	4.49	1.36	1,393	1,895	3.96
5	7.34	3.37	884.4	2,980	6.23
4	6.32	5.22	484.7	2,530	5.28
3	4.69	9.22	217.7	2,010	4.21
2	3.31	13.0	104.9	1,363	2.85
1	2.03	33.1	25.70	850	1.78
Temperature: 130°F.					
8	4.4	0.0815	20,729	1,687	3.53
7	3.6	0.259	5,805	1,500	3.13
6	1.3	0.394	1,393	548	1.145
5	1.6	0.739	884.4	653	1.364
4	1.5	1.236	484.7	599	1.250
3	1.6	3.14	217.7	685	1.430
2	1.3	5.11	104.9	535	1.116
Temperature: 0°F.					
8	10.8	0.200	20,729	4,130	8.63
7	7.3	0.525	5,805	3,050	6.36
6	6.9	2.09	1,393	2,910	6.08
5	18.2	8.40	884.4	7,420	15.50
4	4.9	4.03	484.7	1,960	4.08
3	3.4	6.69	217.7	1,460	3.04
2	3.1	12.18	104.9	1,280	2.66
1	6.6	10.78	25.70	2,770	5.78
Temperature: -65°F					
8	10.5	0.194	20,729	4,020	8.40
7	7.9	0.568	5,805	3,290	6.87
6	7.0	2.12	1,393	2,970	6.17
5	8.0	3.70	884.4	3,270	6.82
4	8.2	6.76	484.7	3,280	6.84
3	6.2	12.2	217.7	2,660	5.55
2	6.5	25.5	104.9	2,680	5.58
1	4.7	76.7	25.70	1,970	4.12

TABLE 5-I
FUEL C CAPILLARY VISCOMETER TEST DATA

Gear: 64 tooth   Flow rate: 0.134 ml/sec

Capillary	Pressure psig.	Apparent Viscosity $\eta = P \times K$ poise	Shear Rate S, sec^{-1}	Shear Stress $dynes/cm^2$ $= \eta \times S$	Shear Stress $lb./ft^2$
Temperature: 74°F.					
8	18.5	0.332	20,729	7,080	14.77
7	18.0	1.293	5,805	7,500	15.65
7	16.0	1.150	5,805	6,660	13.90
6	14.0	4.24	1,393	5,900	12.33
5	15.5	7.15	884.4	6,320	13.18
4	14.6	12.04	484.7	5,840	12.18
3	9.56	18.80	217.7	4,090	8.53
2	8.47	33.3	104.9	3,450	7.28
1	4.93	80.6	25.70	2,070	4.32
3	10.97	21.6	217.7	4,690	9.79
2	8.12	31.9	104.9	3,340	6.98
1	4.74	77.3	25.70	1,988	4.14
Temperature: 130°F.					
8	18.3	0.339	20,729	7,020	14.65
7	16.5	1.185	5,805	6,880	14.37
6	4.69	1.42	1,393	1,980	4.14
5	8.12	3.75	884.4	3,220	6.73
5B	9.80	3.97	977.7	3,890	8.13
4	6.70	5.52	484.7	2,680	5.58
3	6.41	12.62	217.7	2,750	5.74
2	5.67	22.3	104.9	2,340	4.88
1	3.70	60.3	25.70	1,552	3.24
Temperature: 0°F					
8	27.9	0.517	20,729	10,700	22.3
7	23.6	1.695	5,805	9,840	20.5
6	19.7	5.97	1,393	8,320	17.3
5	20.6	9.52	884.4	8,410	17.5
4	14.6	12.0	484.7	5,840	12.2
3	14.0	27.5	217.7	5,990	12.5
2	11.9	46.7	104.9	4,900	10.2
1	11.8	192.5	25.70	4,950	10.3
Temperature: -65°F					
8	13.1	0.242	20,729	5,020	10.5
7	10.9	0.783	5,805	4,540	9.48
6B	6.0	1.98	1,301	2,580	5.38
6	7.3	2.21	1,393	3,080	6.43
5	6.2	2.86	884.4	2,530	5.28
4	4.9	4.03	484.7	1,960	4.08
3	4.8	9.43	217.7	2,060	4.29
2	3.6	14.1	104.9	1,480	3.10
1	2.2	35.9	25.70	922	1.92

Mean shear rate, S

$$S = \frac{8V}{D} = \frac{32q}{\pi D^3}, \text{ sec}^{-1} \tag{4}$$

where V is mean linear velocity in ft/sec of the fluid through a pipe or tube, D is the pipe or tube diameter in ft, and q is flow rate in cu ft/sec.

Shear stress, F

$$F = \frac{D\,\Delta P}{4L}, \text{ lb/ft}^2 \tag{5}$$

Shear Data by Rotational Viscometer. Supplemental shear data for shear rates below those attainable with the capillary viscometer were measured with Brookfield rotational viscometers. A typical Brookfield Synchro-Lectric Viscometer is shown in Figure 1.3. The viscometer rotates a cylindrical or disc spindle in a test fluid and indicates on a dial the percent of full-scale torque required to overcome viscous resistance by the fluid to the induced movement. A synchronous indicator motor drives the spindle through a spring. The degree that the spring is wound, indicated on the dial, is proportional to the viscosity of the fluid for any speed and spindle used. Viscometer specifications are presented in Table 6-I.

The instrument manual procedure was used. Only the cylindrical spindles, #4 for Model LVF and #7 for Models HAF and RVF were used for shear data generation. The unguarded spindle was immersed into a thickened fuel sample to the immersion groove and the instrument started. Readings were taken at each instrument speed setting. The viscometer model used depended upon the fuel viscosity. Test temperatures were obtained with either a hot water bath or a low temperature chamber. Samples were removed just before testing and tested quickly.

The flow characteristics listed in Tables 7-I, 8-I and 9-I were derived from the following equations adapted from Bowen, Mason and Kreiger:

Shear stress, F

$$F = \frac{2T}{\pi d^2 h} = CR, \text{ dynes/cm}^2 \text{ or lb/ft}^2 \tag{6}$$

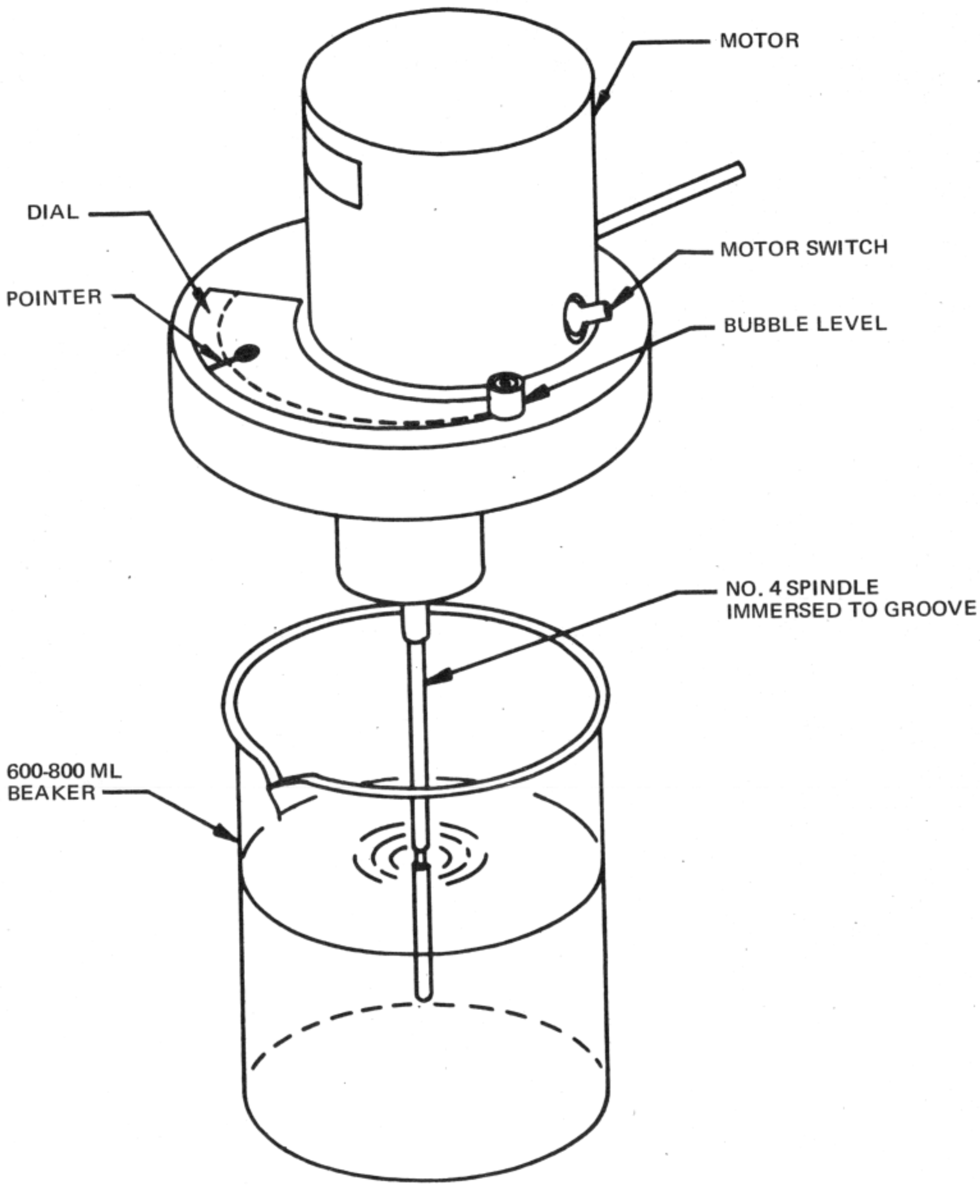


FIGURE 1.3
BROOKFIELD VISCOMETER

TABLE 6-I

BROOKFIELD SYNCHRO-LECTRIC ROTATIONAL VISCOMETER SPECIFICATION

Model LVF	
Full range torque, dyne-cm	673.7
#4 spindle diameter, in.	0.125
#4 spindle height, in.	1 1/4
Instrument speeds, rpm	6, 12, 30, 60
Instrument factor, C	
dynes/cm^2	13.5
lb/ft^2	0.0281
Model RVF	
Full range torque, dyne-cm	7,187
#7 spindle diameter, in.	0.125
#7 spindle height, in.	2
Instrument speeds, rpm	2, 4, 10, 20
Instrument factor, C	
dynes/cm^2	89.5
lb/ft^2	0.187
Model HAF	
Full range torque, dyne-cm	14,374
#7 spindle diameter, in.	0.125
#7 spindle height, in.	2
Instrument speeds, rpm	1, 2, 5, 10
Instrument factor, C	
dynes/cm^2	179
lb/ft^2	0.373

TABLE 7-I
FUEL A
BROOKFIELD VISCOMETER TEST DATA

Temp. °F	N	R	Shear Stress dynes/cm²	Shear Stress lb/ft²	n'' from graph	Shear Rate (mean) sec-1	Viscosity cps
Model LVF							
73	6	33.2	438	0.932	0.216	3.04	33,200
	12	42.5	574	1.194		6.08	21,300
	30	49.3	666	1.387	3n'' + 1	15.2	9,850
	60	54.0	729	1.516	= 1.648	30.4	5,400
-65	6	61.0	823	1.72	0.200	3.13	61,000
	12	63.0	864	1.77		6.26	31,500
	30	75.0	1012	2.11	3n'' + 1	15.7	15,000
	60	84.8	1145	2.38	= 1.600	31.3	8,480
0	6	39.2	528	1.10	0.208	3.09	39,200
	12	45.5	613	1.28		6.17	22,800
	30	56.5	762	1.59	3n'' + 1	15.4	11,300
	60	63.0	850	1.77	= 1.624	30.9	6,300
126	6	9.3	126	0.261	0.194	3.17	9,300
	12	22.5	304	0.632		6.33	11,200
	30	43.1	582	1.21	3n'' + 1	15.8	8,620
	60	51.0	688	1.43	= 1.582	31.6	5,100

TABLE 8-I
FUEL B
BROOKFIELD VISCOMETER TEST DATA

Temp. °F	N	R	Shear Stress dynes/cm²	Shear Stress lb/ft²	n'' from graph	Shear Rate (mean) sec⁻¹	Viscosity cps
Model LVF							
74	6	39.8	538	1.14	0.213	3.05	39,800
	12	45.0	608	1.26		6.11	22,500
	30	54.2	732	1.52	3n'' + 1	15.3	10,850
	60	65.1	879	1.83	= 1.639	30.5	6,500
128	6	34.4	464	0.967	0.192	3.18	34,400
	12	38.5	520	1.11		6.36	19,200
	30	45.8	619	1.29	3n'' + 1	15.9	9,180
	60	53.5	722	1.50	= 1.576	31.8	5,350
Model HAF							
-65	1	5.0	895	1.86	0.447	0.357	400,000
	2	7.0	1250	2.61		0.714	280,000
	5	10.5	1880	3.92	3n'' + 1	1.78	168,000
	10	14.0	2500	5.22	= 2.342	3.57	112,000
Model RVF							
5	2	7.5	672	1.40	0.239	0.972	150,000
	4	8.8	787	1.64		1.94	88,000
	10	11.0	984	2.06	3n'' + 1	4.86	44,000
	20	13.0	1160	2.43	= 1.717	9.72	26,000

TABLE 9-I
FUEL C
BROOKFIELD VISCOMETER TESTS

Temp. °F	N	R	Shear Stress dynes/cm^2	Shear Stress lb/ft^2	n'' from graph	Shear Rate (mean) sec^{-1}	Viscosity cps
Model RVF							
74	2	10.6	948	1.98	0.176	1.09	212,000
	4	11.2	1000	2.09		2.19	112,000
	10	12.9	1160	2.41	3n'' + 1	5.47	51,600
	20	15.9	1420	2.97	= 1.527	10.9	31,800
Model HAF							
-65	1	8.7	1560	3.25	0.422	0.369	696,000
	2	12.5	2240	4.66		0.737	500,000
	5	18.5	3490	6.91	3n'' + 1	1.84	296,000
	10	23.0	4120	8.58	= 2.265	3.69	184,000
Model RVF							
3	2	12.9	1160	2.41	0.168	1.11	258,000
	4	14.5	1300	2.71		2.22	145,000
	10	17.4	1560	3.25	3n'' + 1	5.55	69,700
	20	19.0	1700	3.55	= 1.504	11.1	38,000
129	2	9.2	823	1.72	0.133	1.19	184,000
	4	9.0	805	1.68	3n'' + 1	2.39	90,000
	10	10.6	948	1.98	= 1.40	5.97	42,400
	20	12.9	1150	2.41		11.9	25,800

where

T = torque

d = spindle diameter

h = immersed length of spindle

R = dial reading, or percent of full-scale instrument torque

C = instrument factor, or one percent of full scale instrument shear stress.

Shear stress can also be expressed as in Equation (5).

Shear rate at the wall of a cylinder is determined directly with the rotational viscometer. It is calculated from spindle speed N in rpm and n", the slope of the line on a logarithmic plot of R versus N. The equations used are below:

Shear rate at the wall, S_w

$$S_w = \frac{4\pi N}{60n''}, \ \sec^{-1} \tag{7}$$

$$n'' = \frac{d \log R}{d \log N} \tag{8}$$

Mean shear rate and wall shear rate are related as follows:

$$S = \frac{4n''}{3n''+1} S_w \tag{9}$$

$$S = \frac{8V}{D} = \frac{\left[\frac{4\pi N}{60n''}\right]}{\left[\frac{3n''+1}{4n''}\right]} = \frac{0.835\ N}{3n''+1}, \ \sec^{-1} \tag{10}$$

The calculated rotational viscometer data were plotted on the same shear diagrams as the capillary viscometer data.

Aircraft Piping Flow Charts. Aircraft piping flow charts, shown in for thickened fuels were developed using a technique by Bowen. Various values of shear stress and shear rate taken from the shear diagram were tabulated and converted to pressure loss per foot of pipe and fuel flow in gallons per minute.

Pressure loss per foot of pipe length is obtained as follows:

$$\frac{\Delta p}{L} = \frac{\text{SHEAR STRESS}}{\left[\frac{D}{12} \times \frac{144}{4}\right]} = \frac{\text{SHEAR STRESS}}{3.0\,D}, \quad \frac{\text{psi}}{\text{ft.}} \tag{11}$$

where L the length of pipe is one foot and D the internal pipe diameter is in inches. The constant K_a of the tables equals 3.0.D. The flow rate Q in gpm is obtained as follows:

$$Q = \frac{\text{SHEAR RATE}}{\left[\frac{32}{\pi \times 448 \times (D/12)^3}\right]} = \frac{\text{SHEAR RATE}}{\left[\frac{39.2}{D^3}\right]}, \quad \text{gpm} \tag{12}$$

where D is in inches. The constant K_b of the tables equals $39.2/D^3$. The constants are given in Table 10-I for each pipe size used. Flow rate and pressure drop calculation results using the constants are given in Table 11-I for shear stress-shear rate correlated data. These data and flow velocities are presented in the pipe flow charts for 74°F in Figures 1.4 and 1.5

Flow rates and pressure losses for a fuel and a test temperature can be obtained by using data from the specific shear diagram and Figures 1.4 and 1.5. The two figures can be used to convert shear rate and shear stress to flow rate and pressure loss for a pipe diameter. The conversion charts were prepared by employing the conversion equations used for the 74°F pipe flow charts.

Table 12-I contains the Brookfield data used to produce Figure 5 presented in the main text. From the data it should be obvious that any flow calculation is only as accurate as the estimate of the state of the material in an actual system.

TABLE 10-I
AIRCRAFT PIPE FLOW CONSTANTS

Nominal Pipe Size in.	Pipe Wall Thickness in.	Pipe I. D. in.	$(I.D.)^3$ $in.^3$	K_a	K_b
1	0.028	0.944	0.841	2.83	46.6
1 1/2	0.028	1.444	3.01	4.33	13.0
2	0.035	1.930	7.20	5.78	5.44
4	0.028	3.944	61	11.8	0.643

TABLE 11-I
FLOW, PRESSURE DROP CALCULATED FOR PIPE SIZES

Nominal pipe size, in.		1		1 1/2		2		4	
Internal diameter, in.		0.944		1.444		1.930		3.944	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
$\frac{D\Delta P}{4L}$	$\frac{32\,q}{\pi D^3}$	Δpsi/ft. (1)÷2.83	Q, gpm (2)÷46.6	Δ psi/ft (1)÷4.33	Q, gpm (2)÷13.02	Δ psi/ft. (1)÷5.78	Q, gpm (2)÷5.44	Δ psi/ft. (1)÷11.8	Q, gpm (2)÷0.643
	Fuel B at 74°F								
1.62	25	0.572	0.537	0.363	1.92	0.281	4.60	0.137	39
2.5	60	0.915	1.29	0.577	4.61	0.432	11.0	0.212	93
3.0	100	1.10	2.15	0.693	7.68	0.519	18.4	0.254	155
5.0	400	1.77	8.58	1.15	30.7	0.865	73.5	0.423	622
6.2	1,000	2.27	21.5	1.43	76.8	1.07	184	0.525	1,550
8.3	4,000	3.04	85.8	1.92	307	1.44	735	0.703	6,220
9.7	10,000	3.55	215	2.24	768	1.68	1840	0.822	15,500
	Fuel A at 74°F								
1.83	60	0.646	1.29	0.423	4.61	0.317	11.0	0.155	93
2.14	100	0.756	2.15	0.494	7.68	0.371	18.4	0.181	155
3.2	400	1.13	8.58	0.738	30.7	0.553	73.5	0.271	622
4.1	1,000	1.45	21.5	0.947	76.8	0.710	184	0.347	1,550
6.1	4,000	2.16	85.8	1.41	307	1.06	735	0.517	6,620
7.5	10,000	2.65	215	1.73	768	1.30	1840	0.636	15,500
	Fuel C at 74°F								
4.7	25	-	-	-	-	-	-	0.398	39
6.6	60	2.33	1.29	1.52	4.61	1.14	11.0	0.559	93
7.7	100	2.72	2.15	1.78	7.68	1.33	18.4	0.653	155
10.4	400	3.68	8.58	2.40	30.7	1.80	73.5	0.872	622
12.0	1,000	4.23	21.5	2.77	76.8	2.08	184	1.04	1,550
14.3	4,000	5.05	85.8	3.30	307	2.47	735	1.21	6,220
16.0	10,000	5.65	215	3.70	768	2.77	1840	1.36	15,500

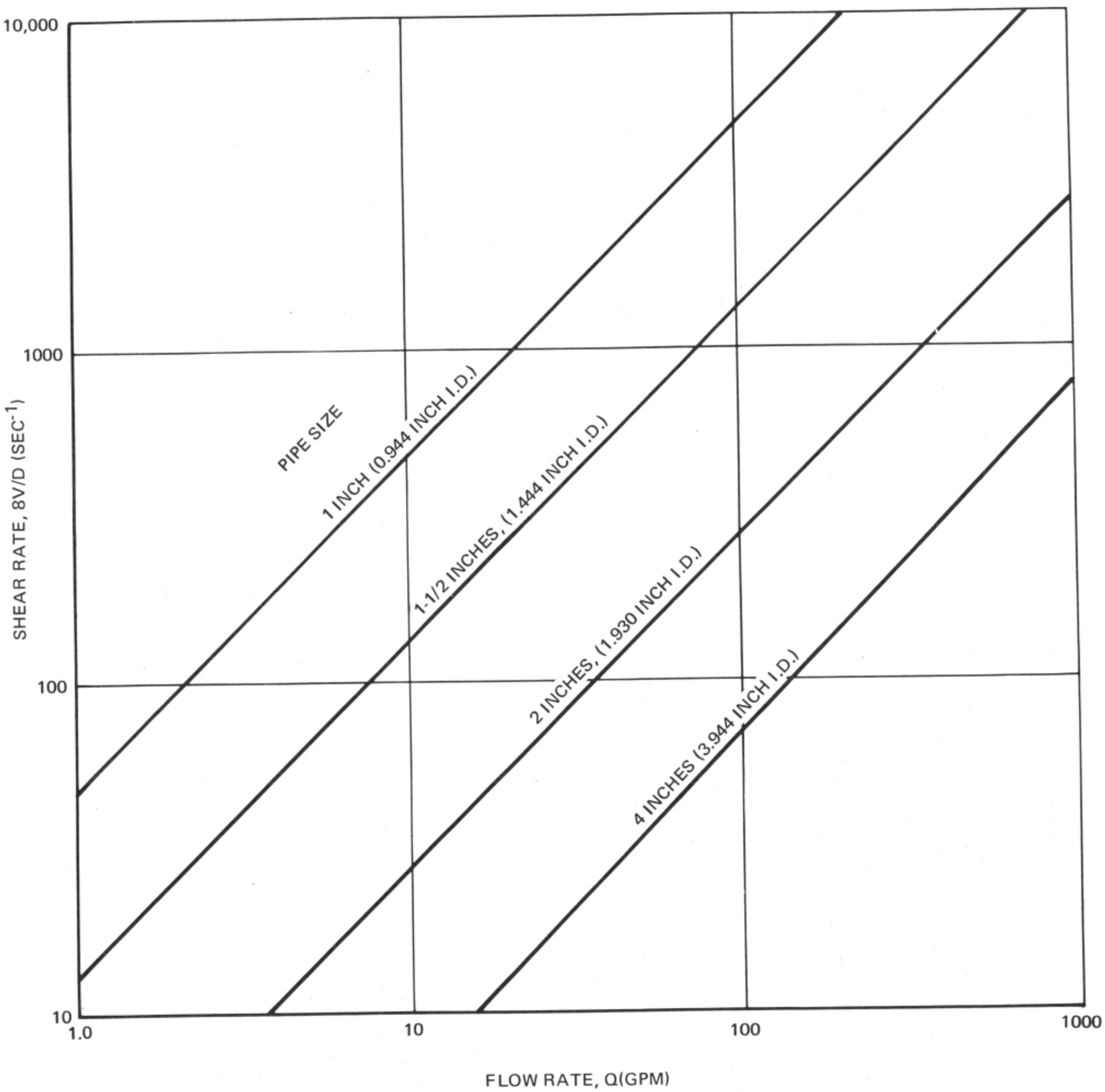


FIGURE 1.4

SHEAR RATE TO FLOW RATE CONVERSION CHART

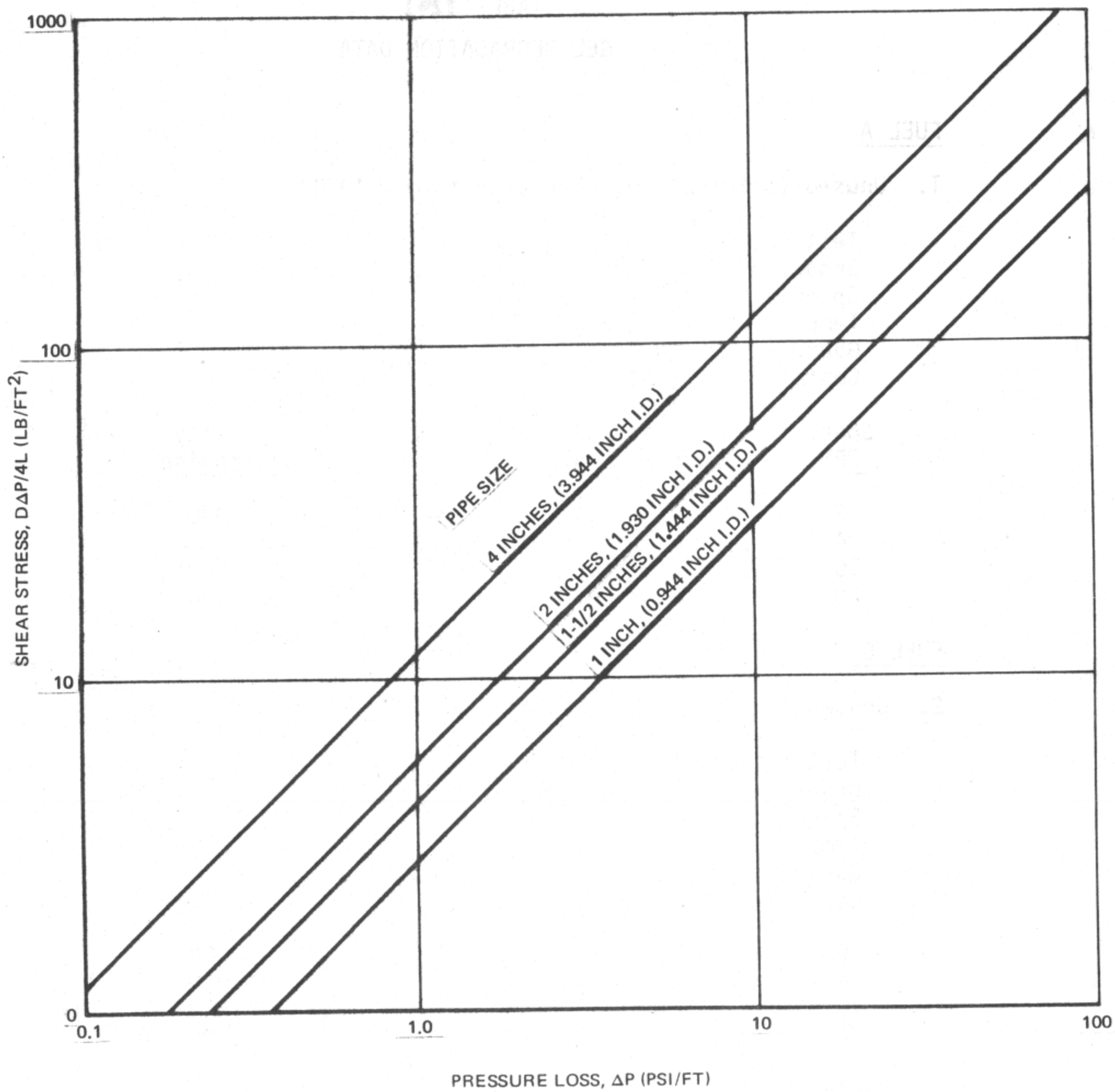


FIGURE 1.5
SHEAR STRESS TO PIPE PRESSURE LOSS CONVERSION CHART

TABLE 12-I

GEL DEGRADATION DATA

FUEL A

1. Unused (original to contractor summer 1968)

Test Date: May 7, 1969
Brookfield: RVF
Spindle: #6
Temp: 74°F
Guard: None
Container: 1 Quart Can

Speed RPM	Reading % Full Scale	Time Seconds	Viscosity Centipoise
2	20.0	120	100,000
4	23.3	240	58,200
10	25.5	360	25,500
20	28.0	480	14,000

FUEL G

2. Unused (orginal to contractor 5-6-69)

Test Date: May 6, 1969
Brookfield: RVF
Spindle: #6
Temp: 74°F
Guard: None
Container: 1 Quart Can

2	7.0	120	35,000
4	12.0	240	30,000
10	16.7	360	16,700
20	18.0	480	9,000

3. Unused (same sample as in 2)

Test Date: May 7, 1969
Conditions as in 2.

2	6.2	120	31,000
4	10.1	240	25,200
10	19.3	360	19,300
20	17.8	480	8,900
20	18.7	600	9,350

TABLE 12-I (Continued)

4. Unused (same sample as in 2)

Test Date: 5-20-69
Conditions as in 2 except
Temp: 76°F

Speed RPM	Reading % Full Scale	Time Second	Viscosity Centipoise
2	6.5	120	32,500
4	9.3	240	23,300
10	17.8	360	17,800
20	18.0	480	9,000
20	18.0	600	9,000

5. Unused (same sample as in 2)

Test Date: 7-10-69
Conditions as in 2 except
Temp: 75°F

2	5.3	120	26,500
4	8.5	240	21,200
10	15.8	360	15,800
20	15.8	480	9,900

6. Unused (same sample as in 2)

Test Date: 7-20-69
Conditions as in 2 except
Temp: 92°F

2	3.2	120	16,000
4	5.2	240	13,000
10	8.8	360	8,800
20	15.5	480	7,730

7. Used
Run through heat exchanger on May 6, 1969

Test Date: 5-7-69
Conditions as in 2.

2	6.7	120	33,500
4	10.8	240	27,000
10	12.5	360	12,500
20	16.2	480	8,100
20	15.3	615	7,650

TABLE 12-I (Continued)

8. Extensively used in pressure drop tests

Test Date: 5-6-69
Conditions as in 2.

Speed RPM	Reading % Full Scale	Time Second	Viscosity Centipoise
2	0.9	120	4,500
4	1.8	240	4,500
10	5.0	360	5,000
20	6.5	480	3,250

9. Extensively used in pressure drop tests

Test Date: 5-20-69
Conditions as in 2.

2	0.4	120	2,000
4	0.6	240	1,500
10	1.5	360	1,500
20	3.0	480	1,500
20	3.2	600	1,600

APPENDIX II

This section provides a more detailed discussion of the component test program than that included in the main text. The test data tabulated in this section is summarized in the main text, Figures 9 thru 20.

PURPOSE

This phase of the gelled and emulsified fuel evaluation provides component pressure drop data necessary for system performance evaluation using the fuels under consideration. In addition, this program indicates sources of modification required to achieve compatability with existing fuel system design philosophies and examines emulsion and gel breakdown characteristics which have never been extensively analyzed with flight hardware. The components chosen for evaluation were obtained by consideration of the major fuel subsystems within the aircraft. Performance evaluation of any subsystem required that the pressure drop of components within that subsystem be completely defined. The data evolved herein was used in the system analysis.

DISCUSSION

After considering the fuel flow rate required of the various components for aircraft operation, the test set-up shown on Figure 2.1 and 2.2 was created. By adjusting the pressure head on the tank, various flow rates could be achieved through the component. The flow rates were then correlated to the differential pressure recorded across the two transducers. Differential pressure transducers were employed in order to make the output signal independent of the system static pressure. By this method a transducer with reduced range can be employed, thereby improving accuracy. Strain gage bridge type transducers were employed since their flush diaphragm construction permits direct exposure to the pressure media. By installing the transducer diaphragm flush with the inside edge of the component interconnect piping, sense lines are eliminated. Through previous testing experience with non-Newtonian fluids, it was found that instrumentation requiring displacement within small line tubing could not measure pressure with acceptable accuracy. Figure 2.3 indicates the installation details of the flush diaphragm transducer. Inlet and outlet piping connected to the component was made equivalent to the nominal size of the component and of sufficient length to minimize internally induced turbulence.

The flow rate was determined by weight change over a predetermined time increment. The system capacity and the amount of sample available did not allow extensive flow time at each particular flow rate. Test data scattering was due to the magnified effect of flow start transients in combination with short run time. Conversely, short flow runs did not require flow rate compensation due to the decreasing fuel head. Generally, a constant pneumatic transfer pressure was sufficient to achieve near constant flow rates. Pneumatic transfer pressure was held constant through each flow run by installation of a large regulator feeding from the plant air system into an ullage of the order of thirty times the volume displaced during any one run. Initial testing utilized an ullage pressure transducer, the recording of

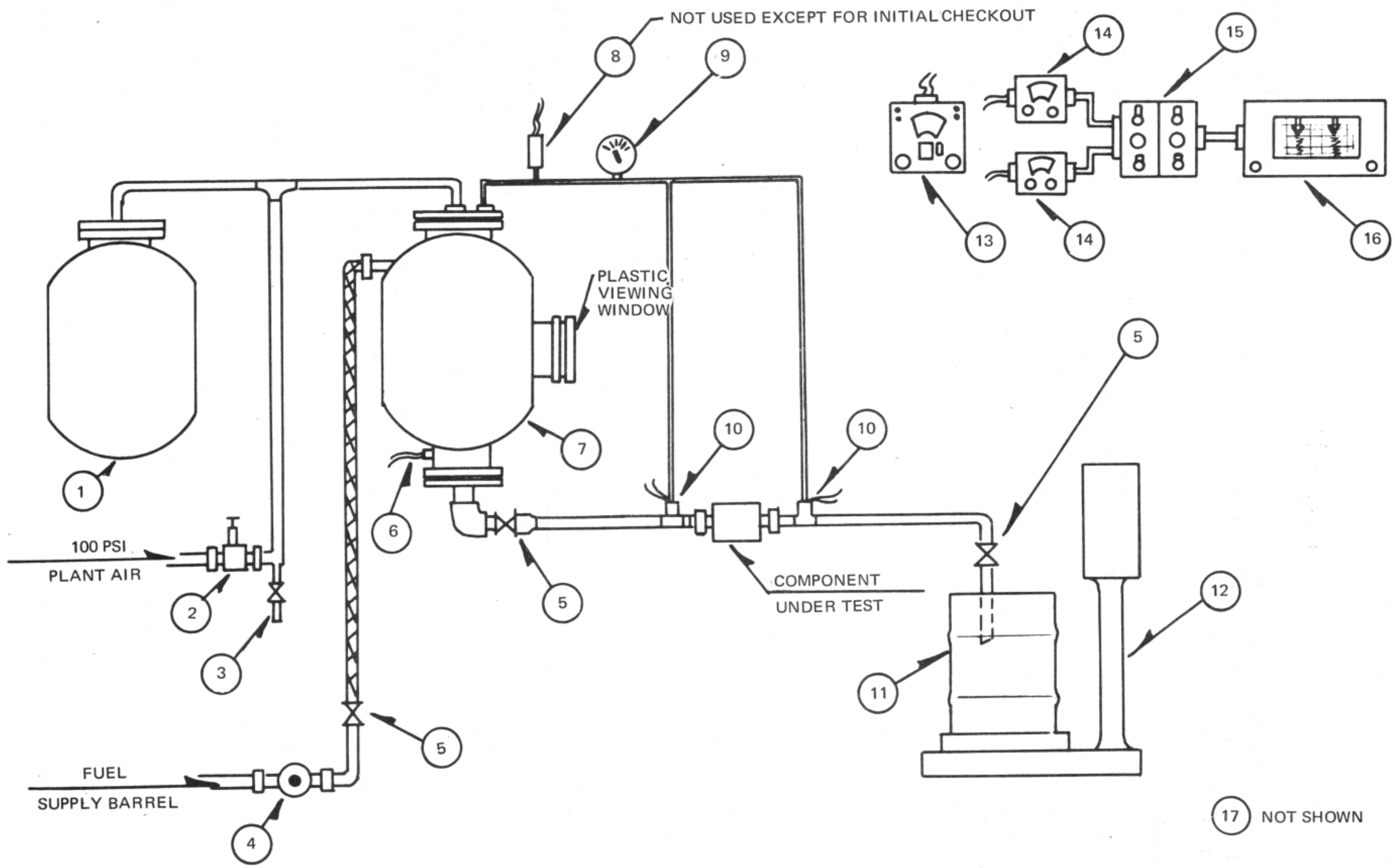


FIGURE 2.1
COMPONENT PRESSURE DROP TEST FACILITY

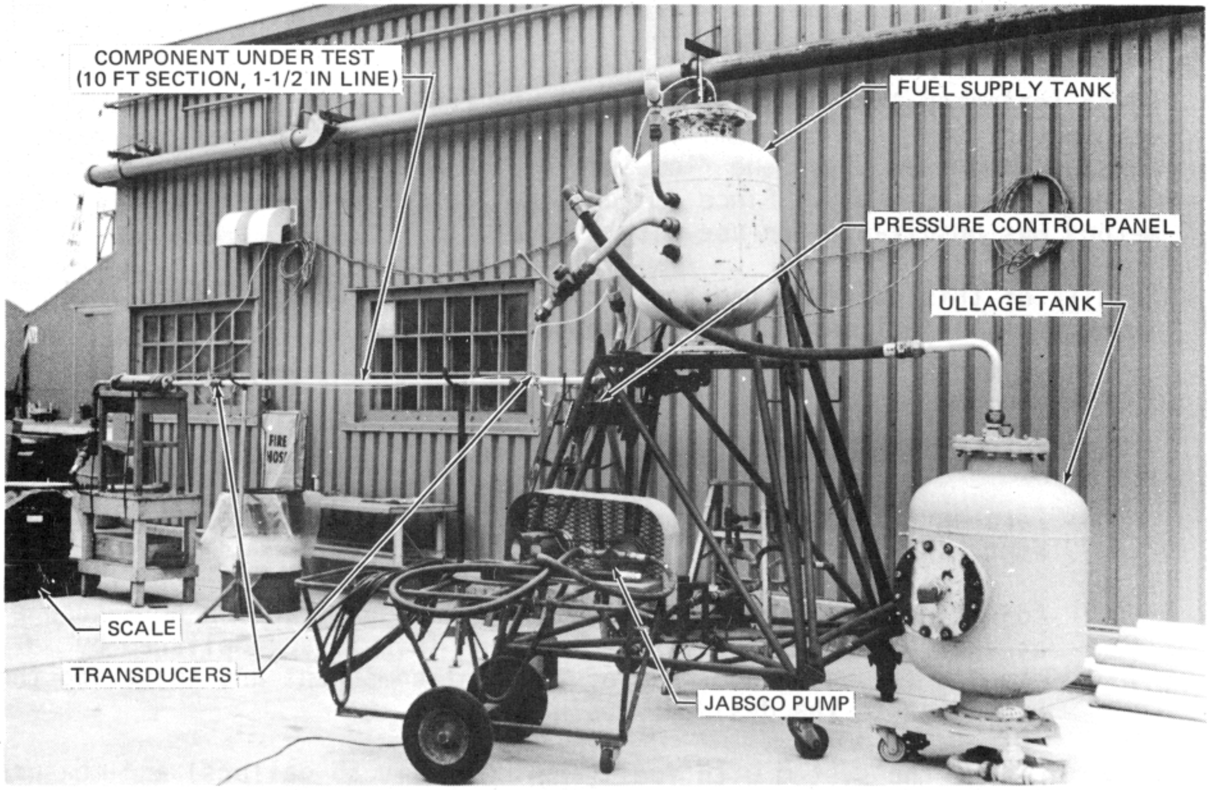


FIGURE 2.2
FUEL COMPONENT FLOW TEST FIXTURE

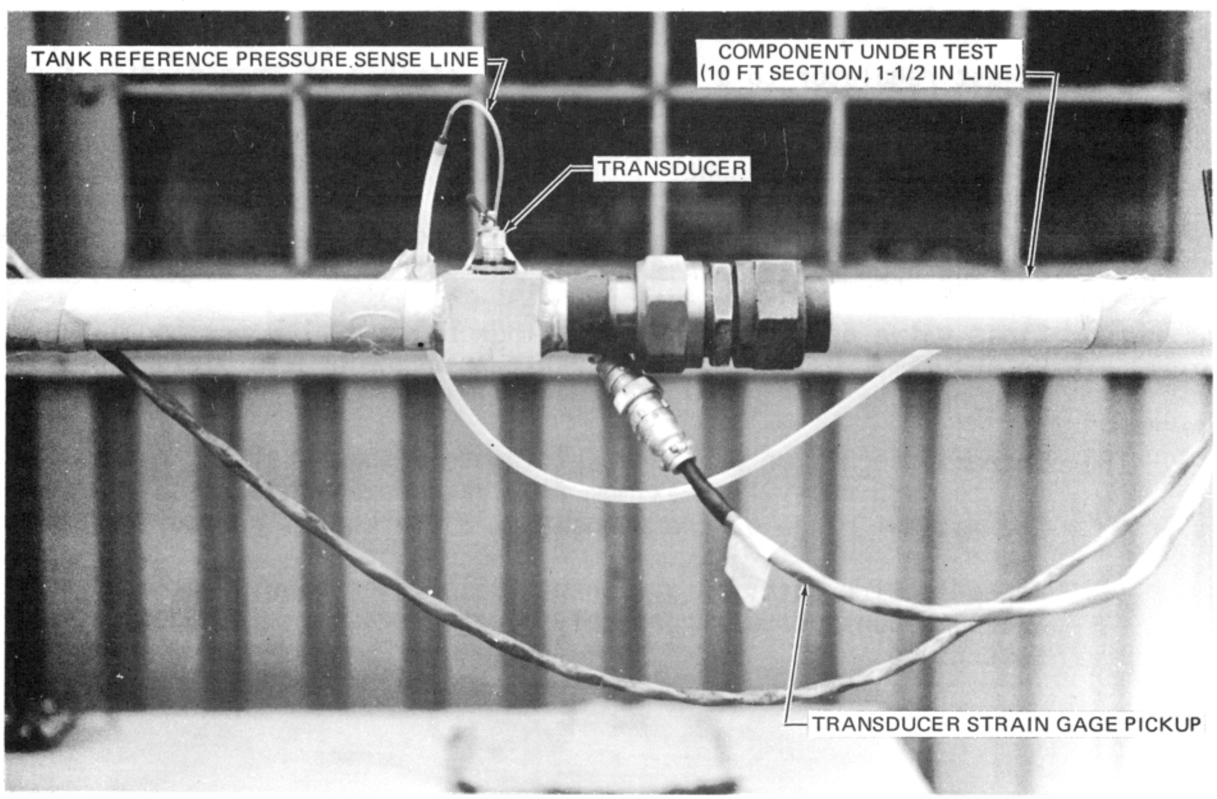


FIGURE 2.3
TRANSDUCER INSTALLATION

which indicated the effect of pressure and fuel head decay was within the accuracy of the test program. Yield stress of the emulsified fuel was obtained before and after the flow test by the ASTM D217 Pentrometer with a 30 gram cone assembly. Since gel does not have a true yield stress, this method was unsuitable for use with the gel.

Results of this phase of the test program are recorded on Tables 1-II through 11-II included at the end of this section.

PROCEDURE

(A) Install equipment as shown in Figure 2.1.

(B) Zero each transducer signal received by the recorder with system empty and vented.

(C) Adjust recorder span to achieve simultaneous trace on both channels at various transfer pressure levels. This is accomplished by closing the valve upstream of the test component and adjusting the regulator to the desired pressure.

(D) Charge the system with fuel (approximately 55 gallons) and measure fuel temperature and yield stress. Particular care must be taken to dispell any air which might become trapped in the transfer line or component.

(E) Adjust regulator to a pressure level capable of transferring fuel through the component. This is initially accomplished by incrementally increasing the transfer pressure and cycling the valve downstream of the component.

(F) Zero scale and timer, start recorder and simultaneously start timer and the open valve downstream of the component.

(G) Close valve downstream of the component when flow period elapses. Record time, weight of fuel transferred and obtain yield stress reading.

(H) Increase regulator pressure setting to a new level and repeat steps (A) through (H). The maximum flow rate obtainable was dictated by the maximum range of the downstream differential pressure transducer.

(I) Repeat entire test for different fuels under consideration, system and components to be thoroughly cleaned prior to introducing new test fluid.

TEST APPARATUS

The test apparatus used to determine pressure drop of the components noted previously is schematically presented in Figure 2.1. Equipment items located therein are specified below.

Item	Name	Description
1	Ullage Tanks	Butane Tank Corp., Serial #32286 125 PSI max., 14 ft^3 capacity
2	Regulator	C.A. Norgren Co., 1" orifice, 0-125 PSI output
3	Bleed Valve	Schaible Co., Model #125, 3/4" pipe size
4	Pump	Jabsco Pump Div., ITT Corp., Model #777-37, 1" pipe size
5	Lever Valve	Lunkenheimer Corp., Model #175, 2" pipe size
6	Thermocouple	Cu.-Const., ISA Type J - 0° to 500°F
7	Fuel Tank	Butane Tank Corp., Serial #32287 125 PSI max., 14 $ft.^3$ capacity
8	Pressure Transducer	Statham Instruments Inc., Model P24-100A-350, 0-100 PSIA range
9	Pressure Gage	Helicoid Gage Co., Model GW-60 1/2 0-60 PSI range
10	Differential Pressure Transducer	Statham Instruments Inc., Model PM 131TC $\pm$ 25 - 350, 0-25 PSID range
11	Drum	55 gallon capacity coated steel drum
12	Scale	Toledo Scale Co., 0-1000 lbs. capacity. 1 lb. graduations
13	Temperature Potentiometer	Leeds & Northrup Co., Cat. #8693
14	Power Supply	Endevco Corp., Model #SR200EP
15	Bridge Balance & Control Unit	McDonnell Douglas Corp. P/N Z4887694
16	Recorder	Leeds & Northrup Co., Model: Speed-Omax W/L, Chart #490221
17	Timer	Minerva Stopwatch

TEST COMPONENTS

Pressure drop data was determined on the following articles using the fuels under consideration. Photographs of these components are included on Figures 2.4 through 2.11.

Check Valve	2.4	Gladden Corp., P/N 313880, 2 inch
Fuel Level Control Shut-off Valve	2.5	Koehler Corp., P/N 7-89615-1, 2 inch
Selector Valve	2.6	Gladden Corp., P/N 413800, 2 inch
Poppet Check Valve	2.7	Parker Aircraft Corp., P/N 1112-578216 (modified with 6 PSI spring), 1-1/2 inch
Heat Exchanger	2.8	AiResearch Corp., P/N SK21412, 1-1/2 inch
Filter	2.9	Pall Corporation, P/N MCS 1001G16 (with 40 micron SS element), 1-1/2 inch
Bulkhead Check Valve	2.10	Parker Aircraft Corp. P/N 566620, 2 inch
Refueling Nozzle	2.11	Parker Aircraft Corp., P/N F110
Refueling Adapter	2.11	Parker Aircraft Corp., P/N F406B
Tube	-	1-1/2" dia. - .035 Al tubing, 10' long.
Tube	-	2" dia. - .035 Al tubing 10' long
Tube	-	1-1/2" dia. - .035 Al tubing 10' long with std. 90° bend

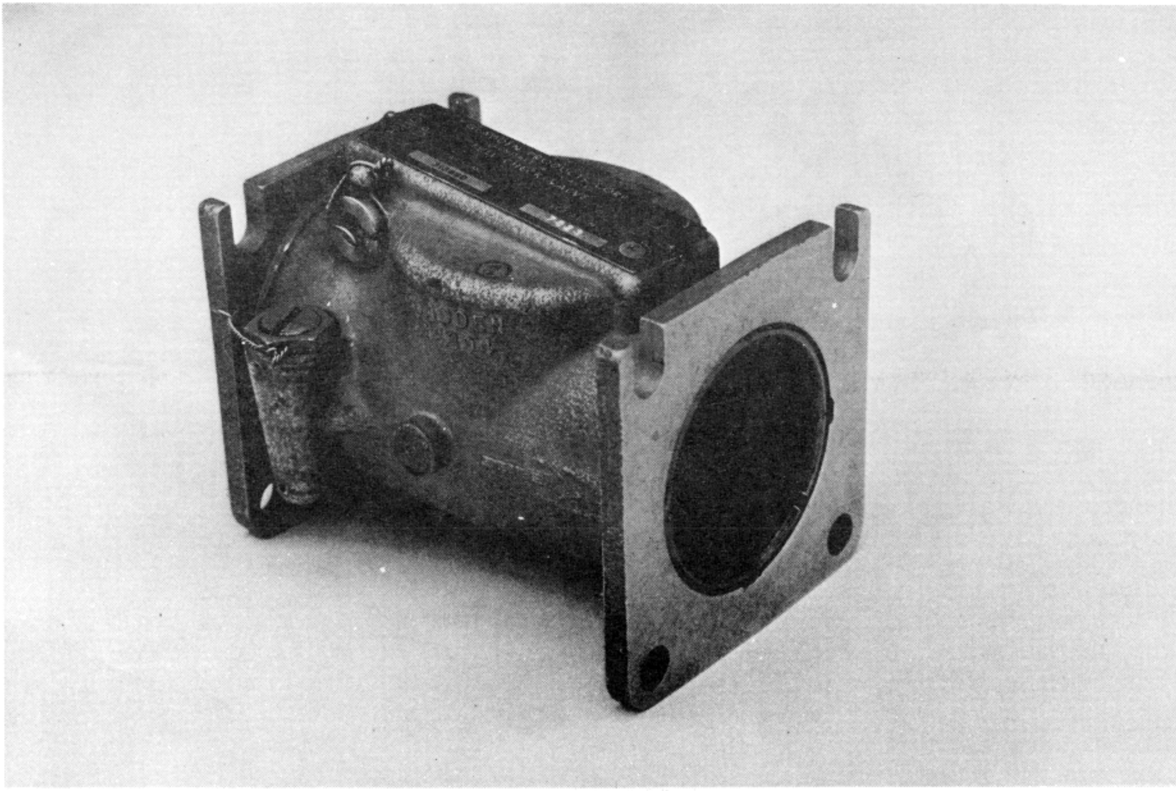


FIGURE 2.4
CHECK VALVE

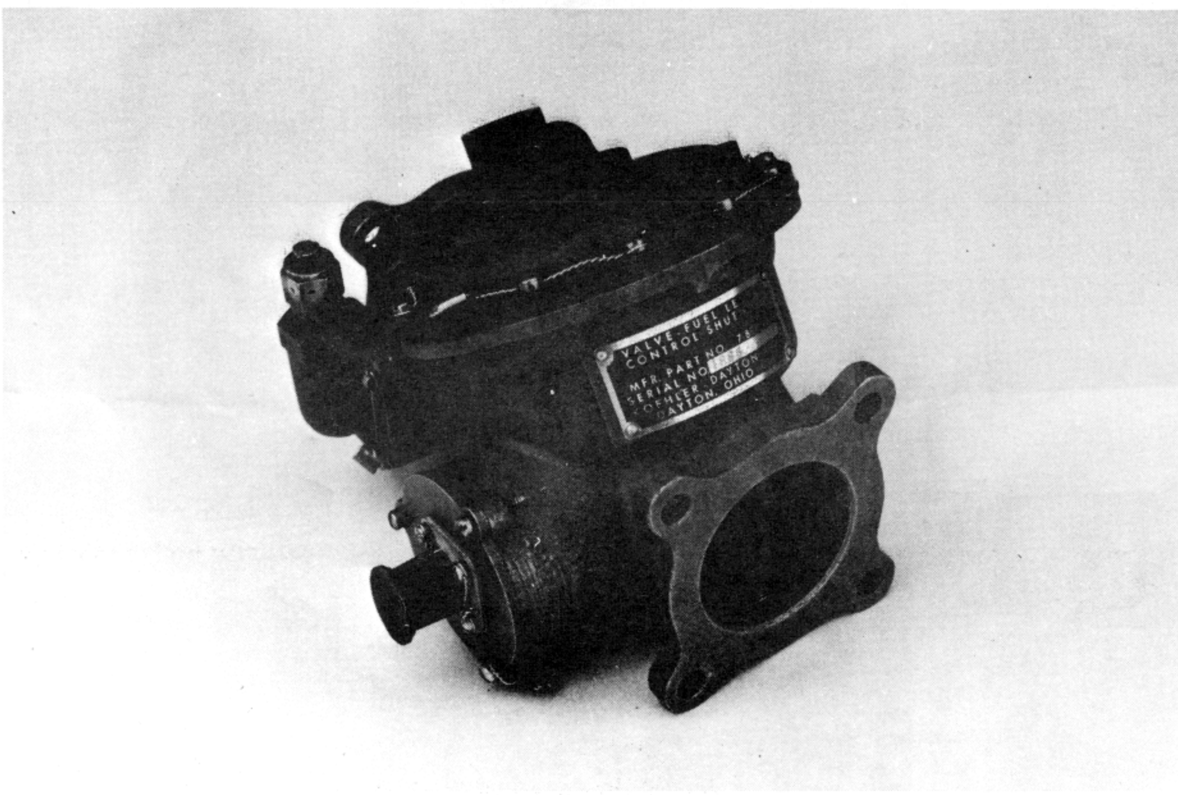


FIGURE 2.5
FUEL LEVEL CONTROL SHUTOFF VALVE

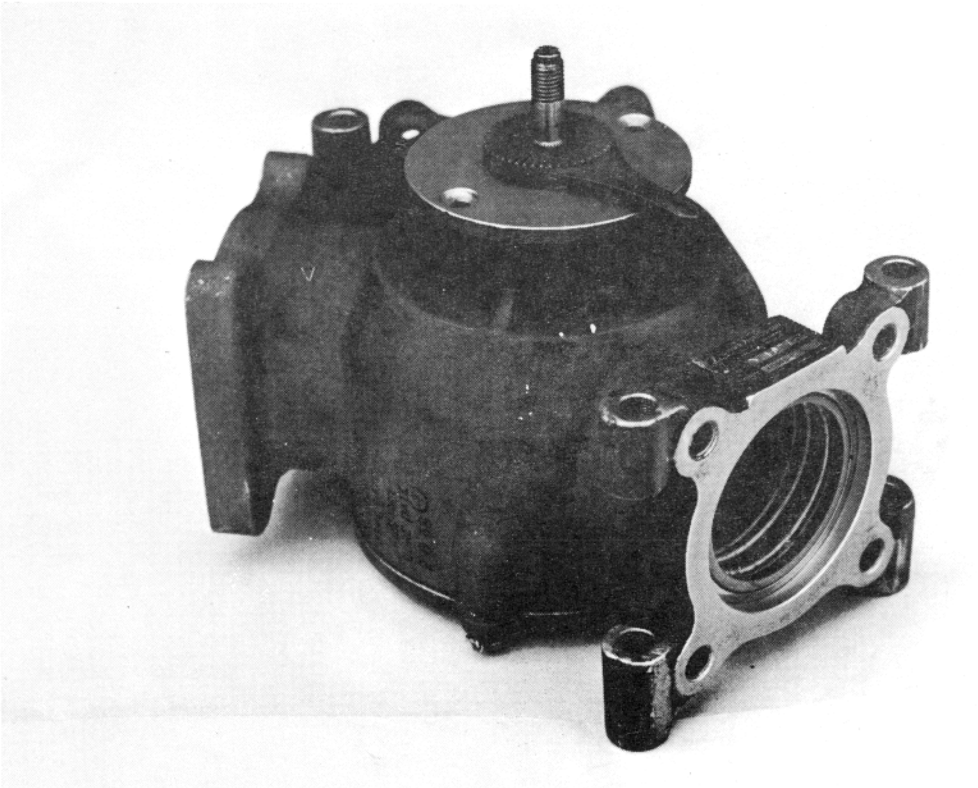


FIGURE 2.6
SELECTOR VALVE

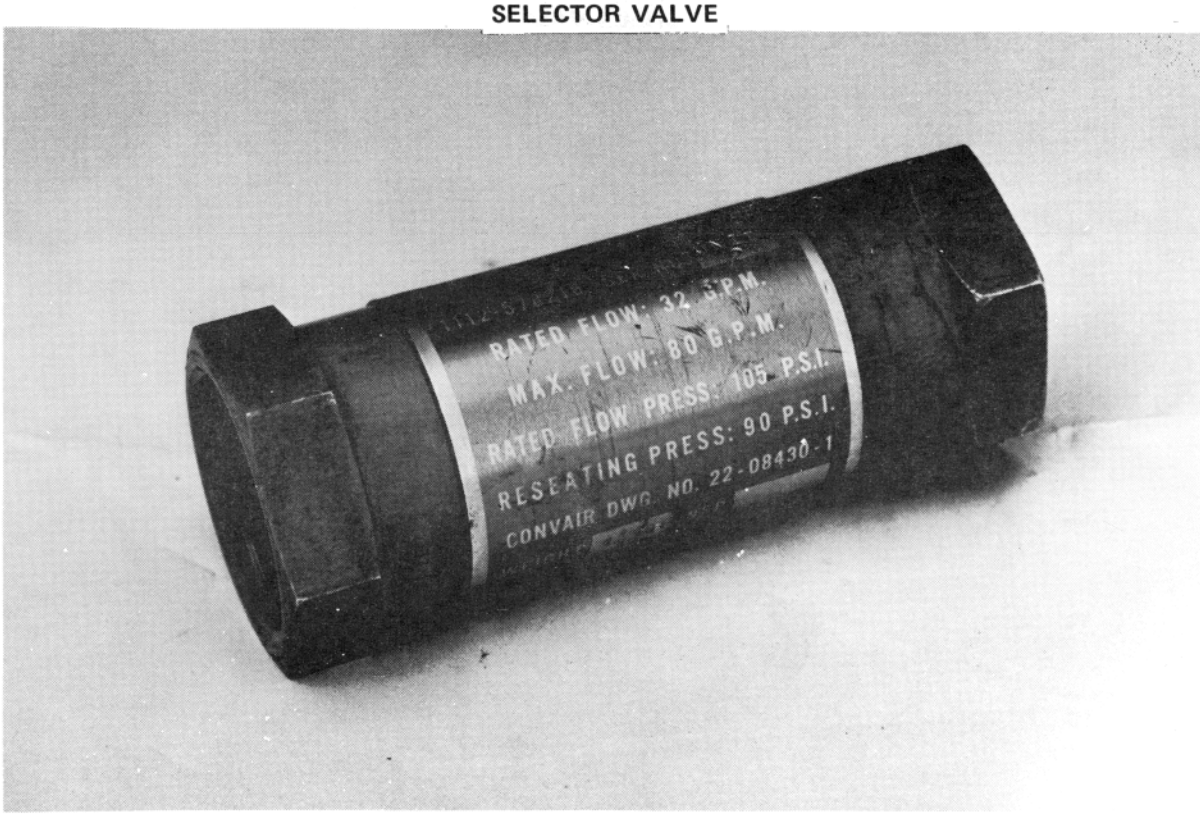


FIGURE 2.7
POPPET CHECK VALVE

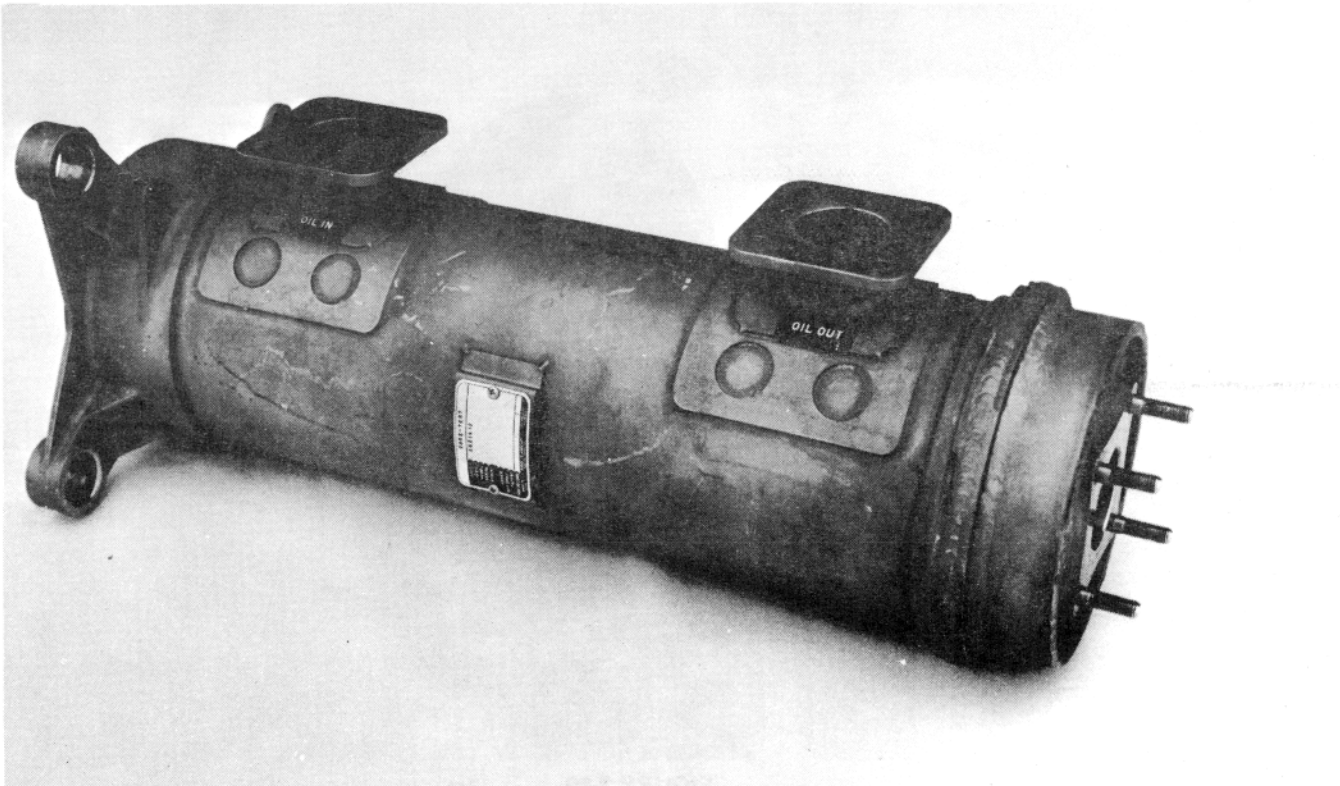


FIGURE 2.8
HEAT EXCHANGER

FIGURE 2.9
FILTER

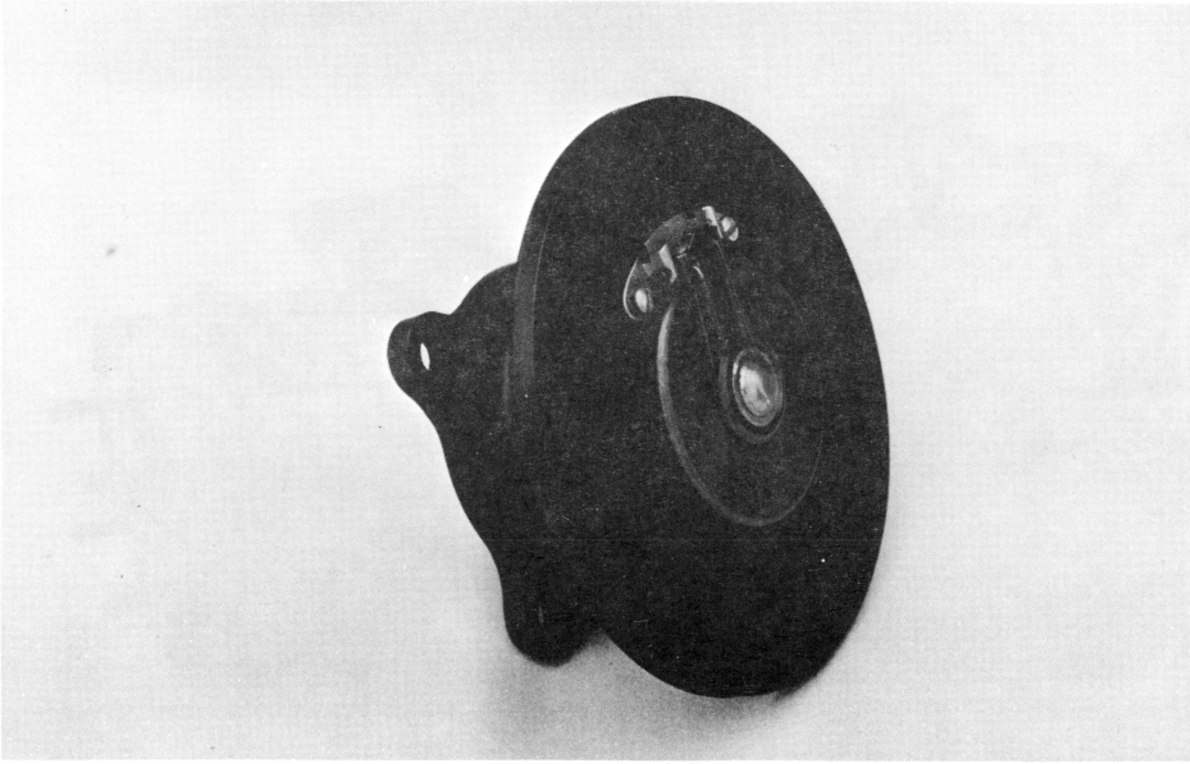


FIGURE 2.10
BULKHEAD CHECK VALVE

FIGURE 2.11
REFUELING ADAPTER (L) AND NOZZLE (R)

TABLE 1-II

COMPONENT FLOW TEST DATA

Gladden P/N 313880 Check Valve

FUEL TEMP (°F)	FLOW RATE (lbs per min)	PRESSURE DROP (lbs per in^2)	STRESS LEVEL BEFORE (Dynes/cm^2)	STRESS LEVEL AFTER (Dynes/cm^2)
JP-4				
72.5	304	.15	-	-
72.5	316	.15	-	-
72.5	638	.23	-	-
73.0	810	.45	-	-
74.0	910	.60	-	-
74.0	1030	.86	-	-
74.0	1120	1.01	-	-
FUEL G				
78.0	210	.69	-	-
78.0	345	.75	-	-
76.0	594	.86	-	-
78.0	680	.93	-	-
78.0	720	.94	-	-
78.0	890	.99	-	-
76.0	1000	1.04	-	-
FUEL B				
56.0	20	.35	945	990
56.0	80	.60	945	-
56.0	200	.87	945	-
56.0	320	1.25	945	1075
56.0	548	1.75	945	1090
56.0	757	2.35	945	-
56.0	968	2.70	945	1150
57.0	780	.96	860	900
57.0	924	1.30	860	910
57.0	348	.75	960	914
57.0	505	1.35	960	1075
57.0	660	1.84	960	1085
57.0	816	2.32	960	1075

TABLE 2-II

COMPONENT FLOW TEST DATA

Koehler P/N 7-89615 Fuel Level Control
Shut-Off Valve

FUEL TEMP (°F)	FLOW RATE (lbs per min)	PRESSURE DROP (lbs per in^2)	STRESS LEVEL (Dynes/cm^2) BEFORE	STRESS LEVEL (Dynes/cm^2) AFTER
JP-4				
73.0	310	.14	-	-
74.0	590	.96	-	-
74.0	748	1.47	-	-
74.0	880	2.01	-	-
74.0	990	2.60	-	-
74.0	1100	3.15	-	-
FUEL G				
83.0	250	.55	-	-
83.0	303	.64	-	-
83.0	316	.60	-	-
78.0	499	.93	-	-
77.0	650	1.35	-	-
77.0	800	1.83	-	-
78.0	900	2.28	-	-
FUEL B				
56.0	50	.75	990	990
56.0	134	1.10	990	1080
56.0	266	1.65	990	1300
56.0	510	2.64	990	1220
56.0	720	3.40	990	1390
56.0	920	3.95	990	-
56.0	1190	4.02	990	1300

TABLE 3-II

COMPONENT FLOW TEST DATA

Gladden P/N 413800 Selector Valve

FUEL TEMP (°F)	FLOW RATE (lbs per min)	PRESSURE DROP (lbs per in^2)	STRESS LEVEL (Dynes/cm^2) BEFORE	STRESS LEVEL (Dynes/cm^2) AFTER
JP-4				
63.5	386	.38	-	-
64.5	382	.42	-	-
64.5	670	1.05	-	-
64.5	830	1.50	-	-
64.5	835	1.53	-	-
66.0	960	2.04	-	-
66.0	1090	2.43	-	-
67.0	1140	2.73	-	-
FUEL G				
69.0	90	.20	-	-
68.0	132	.27	-	-
68.0	290	.45	-	-
67.0	728	1.14	-	-
67.0	920	1.50	-	-
69.0	949	1.43	-	-
69.0	1050	1.76	-	-
FUEL B				
54.0	90	.40	840	840
54.0	120	.40	840	840
54.0	230	.75	840	840
54.0	430	1.60	840	860
54.0	590	2.35	840	860
56.0	780	3.05	840	840
56.0	960	3,75	840	840
56.0	1180	4.10	840	840

TABLE 4-II

COMPONENT FLOW TEST DATA

Parker Aircraft P/N 1112-578216 Poppet
Check Valve

FUEL TEMP (°F)	FLOW RATE (lbs per min)	PRESSURE DROP (lbs per in^2)	STRESS LEVEL (Dynes/cm^2) BEFORE	AFTER
JP-4				
70.0	15	7.43	-	-
71.0	75	11.16	-	-
71.0	141	13.20	-	-
71.0	243	16.00	-	-
71.0	273	12.75	-	-
FUEL G				
60.0	24	6.60	-	-
57.0	27	7.28	-	-
57.0	33	7.60	-	-
60.0	36	7.25	-	-
60.0	51	9.28	-	-
57.0	54	9.28	-	-
57.0	93	10.70	-	-
60.0	294	11.74	-	-
FUEL B				
60.0	24	6.0	785	760
60.0	30	7.0	785	-
60.0	126	10.2	785	940
60.0	102	12.8	785	1300
60.0	168	12.6	785	-
60.0	174	12.8	785	1325
60.0	288	14.0	785	1500
-	24	8.92	1235	1270
-	54	10.32	1235	1220
-	162	12.68	1235	1430
-	306	16.28	1235	1380

TABLE 5-II

COMPONENT FLOW TEST DATA

AiResearch P/N SK21412 Heat Exchanger

FUEL TEMP (°F)	FLOW RATE (lbs per min)	PRESSURE DROP (lbs per in^2)	STRESS LEVEL (Dynes/cm^2) BEFORE	STRESS LEVEL (Dynes/cm^2) AFTER
JP-4				
63.0	126	.53	-	-
63.0	139	.75	-	-
63.0	270	1.95	-	-
63.0	270	2.23	-	-
63.0	334	2.73	-	-
63.0	410	4.35	-	-
63.0	480	5.36	-	-
63.0	530	5.88	-	-
63.0	570	6.03	-	-
FUEL G				
58.0	6	2.72	-	-
58.0	15	3.68	-	-
58.0	110	5.48	-	-
65.0	163	7.12	-	-
65.0	248	8.55	-	-
65.0	329	9.68	-	-
FUEL G VIRGIN				
67.0	12	4.38	-	-
67.0	15	4.72	-	-
67.0	33	5.35	-	-
67.0	36	5.44	-	-
67.0	87	6.95	-	-
67.0	144	8.64	-	-

TABLE 5-II (Cont)

COMPONENT FLOW TEST DATA

AiResearch P/N SK21412 Heat Exchanger

FUEL TEMP (°F)	FLOW RATE (lbs per min)	PRESSURE DROP (lbs per in^2)	STRESS LEVEL (Dynes/cm^2) BEFORE	STRESS LEVEL (Dynes/cm^2) AFTER
FUEL G - USED ONCE FOR TEST ABOVE				
67.0	82	5.38	-	-
67.0	198	8.68	-	-
67.0	272	10.08	-	-
FUEL B				
60.0	12	13.54	785	825
60.0	24	16.00	785	875
60.0	36	18.30	785	960
-	48	6.80	1025	1025
-	66	8.20	1025	990
-	114	10.60	1025	1235
-	192	12.66	1025	1265

TABLE 6-II

COMPONENT FLOW TEST DATA

Pall Corp. P/N MCS 1001G16 Filter
With 40μ Element

FUEL TEMP (°F)	FLOW RATE (lbs per min)	PRESSURE DROP (lbs per in^2)	STRESS LEVEL BEFORE (Dynes/cm^2)	STRESS LEVEL AFTER (Dynes/cm^2)
JP-4				
79.0	65	.45		
79.0	68	.64		
79.0	124	2.40		
79.0	140	2.40		
80.0	166	4.07		
80.0	220	5.13		
74.0	60	.38		
74.0	180	5.52		
74.0	230	7.29		
87.0	148	4.20		
87.0	172	5.64		
87.0	230	8.10		
FUEL G				
63.0	18	1.87		
62.0	54	3.33		
63.0	57	3.36		
62.0	96	5.15		
63.0	108	5.33		
65.0	144	7.20		
63.0	153	7.40		
63.0	174	9.21		
65.0	174	9.02		
63.0	186	9.21		
63.0	210	10.98		
63.0	228	12.07		
63.0	240	13.10		

Cont'd...

TABLE 6-II (Cont.)

COMPONENT FLOW TEST DATA

Pall Corp. P/N MCS 1001G16 Filter

With 40μ Element

FUEL TEMP (°F)	FLOW RATE (lbs per min)	PRESSURE DROP (lbs per in^2)	STRESS LEVEL BEFORE (Dynes/cm^2)	STRESS LEVEL AFTER (Dynes/cm^2)
FUEL B				
60.0	24	1.74	760	
60.0	48	3.16	760	965
60.0	78	4.50	760	1080
60.0	126	7.10	760	1125
60.0	201	11.70	760	1250
60.0	216	12.00	760	1250
60.00	243	15.06	760	1265
-	66	2.16	1125	1165
-	132	5.00	1125	1300
-	216	9.00	1125	1650
-	276	14.56	1125	1550

TABLE 7-II

COMPONENT FLOW TEST DATA

Parker P/N 565520 Bulkhead Check Valve

FUEL TEMP (°F)	FLOW RATE (lbs per min)	PRESSURE DROP (lbs per in^2)	STRESS LEVEL (Dynes/cm^2) BEFORE	STRESS LEVEL (Dynes/cm^2) AFTER
JP-4				
67.0	520	.09	-	-
67.0	840	.08	-	-
67.0	920	.15	-	-
67.0	1060	.20	-	-
67.0	1160	.18	-	-
67.0	1340	.18	-	-
FUEL G				
69.0	198	.15	-	-
69.0	414	.38	-	-
69.0	570	.33	-	-
69.0	780	.27	-	-
69.0	880	.20	-	-
FUEL B				
54.0	130	.15	910	910
54.0	310	.35	910	910
54.0	680	.50	910	870
54.0	1000	.70	910	885
54.0	1440	1.00	910	870

TABLE 8-II

COMPONENT FLOW TEST DATA

Parker Aircraft P/N F110 Refueling Nozzle
and P/N F406B Adapter

FUEL TEMP (°F)	FLOW RATE (lbs per min)	PRESSURE DROP (lbs per in^2)	STRESS LEVEL (Dynes/cm^2) BEFORE	STRESS LEVEL (Dynes/cm^2) AFTER
JP-4				
65.0	420	.07	-	-
65.0	740	.36	-	-
65.0	820	.36	-	-
72.0	1080	.75	-	-
72.0	1170	1.13	-	-
74.0	1240	1.35	-	-
74.0	1300	1.40	-	-
FUEL G				
69.0	76	.68	-	-
73.0	81	.66	-	-
73.0	100	.75	-	-
73.0	300	.84	-	-
73.0	520	1.12	-	-
73.0	530	1.02	-	-
73.0	900	1.45	-	-
73.0	970	1.50	-	-
73.0	990	1.57	-	-
FUEL B				
64.0	160	1.55	760	760
64.0	182	1.40	760	790
64.0	320	2.00	760	-
64.0	460	2.58	760	960
64.0	510	2.50	760	-
64.0	720	3.85	760	-
64.0	950	5.00	760	-
56.0	60	.80	760	760
56.0	178	1.26	760	870
56.0	420	2.20	760	-

TABLE 9-II

COMPONENT FLOW TEST DATA

1-1/2" - .035 Wall Straight Al Tube, 10' Long

FUEL TEMP (°F)	FLOW RATE (lbs per min)	PRESSURE DROP (lbs per in^2)	STRESS LEVEL (Dynes/cm^2) BEFORE	STRESS LEVEL (Dynes/cm^2) AFTER
JP-4				
80.0	168	.38	-	-
82.0	340	1.61	-	-
82.0	348	1.60	-	-
82.0	470	2.34	-	-
82.0	490	2.40	-	-
82.0	520	3.33	-	-
82.0	650	4.13	-	-
82.0	650	4.18	-	-
82.0	740	5.04	-	-
82.0	760	5.04	-	-
82.0	810	5.82	-	-
FUEL G				
73.0	22	1.52	-	-
73.0	40	1.52	-	-
73.0	147	2.24	-	-
73.0	170	2.24	-	-
73.0	408	2.72	-	-
73.0	475	2.82	-	-
73.0	578	2.90	-	-
73.0	610	3.24	-	-
73.0	720	3.47	-	-
73.0	750	3.55	-	-
FUEL B - VIRGIN				
64.0	19	1.55	785	-
64.0	30	1.35	785	-
64.0	30	2.35	785	-
64.0	38	1.65	785	-
64.0	40	2.35	785	-
64.0	90	4.15	785	-
64.0	110	5.16	785	-
64.0	120	4.40	785	-
64.0	126	5.00	785	-
64.0	150	5.05	785	-
64.0	164	4.50	785	-
64.0	200	5.75	785	-

TABLE 9-II (Cont.)

COMPONENT FLOW TEST DATA

1-1/2" - .035 Wall Straight Al Tube, 10' Long

FUEL TEMP (°F)	FLOW RATE (lbs per min)	PRESSURE DROP (lbs per in^2)	STRESS LEVEL (Dynes/cm^2) BEFORE	AFTER
FUEL B - VIRGIN (Cont)				
67.0	12	3.46	1475	1475
67.0	21	4.60	1475	1475
67.0	42	8.28	1475	1580
67.0	45	8.32	1475	-
67.0	48	7.34	1475	1540
67.0	57	10.94	1475	1600
67.0	68	10.26	1475	1565
67.0	85	9.60	1475	-
67.0	122	12.54	1475	1600
67.0	130	12.94	1475	1630
67.0	132	13.04	1475	-
67.0	276	11.68	1475	-
67.0	282	11.40	1475	1500
FUEL B - USED				
65.0	66	4.00	1850	1850
65.0	66	4.60	1850	-
65.0	92	4.40	1850	-
65.0	232	5.30	1850	1850
65.0	306	6.14	1850	1760
65.0	330	6.00	1850	1760
FUEL B - EXTENSIVELY USED				
74.0	39	.62	1475	-
74.0	42	.76	1475	-
74.0	45	.77	1475	-
74.0	87	1.00	1475	1610
74.0	123	.96	1475	1580
74.0	147	1.00	1475	-
74.0	288	.96	1475	1530
74.0	300	.90	1475	1475
74.0	324	.98	1475	-

TABLE 10-II

COMPONENT FLOW TEST DATA

1-1/2" - .035 Wall Al Tube, 10' Long
with STD 90° Bend

FUEL TEMP (°F)	FLOW RATE (lbs per min)	PRESSURE DROP (lbs per in^2)	STRESS LEVEL (Dynes/cm^2) BEFORE	STRESS LEVEL (Dynes/cm^2) AFTER
JP-4				
83.0	183	.43	-	-
79.0	390	1.57	-	-
79.0	490	2.36	-	-
79.0	582	3.15	-	-
79.0	680	4.20	-	-
83.0	781	5.37	-	-
FUEL G				
80.0	9	2.25	-	-
80.0	18	2.70	-	-
80.0	27	2.89	-	-
78.0	43	2.85	-	-
80.0	59	3.36	-	-
78.0	123	3.60	-	-
78.0	253	3.98	-	-
80.0	254	4.20	-	-
80.0	446	4.80	-	-
80.0	624	5.28	-	-
FUEL B				
64.0	35.5	8.20	785	875
64.0	66	9.38	785	925
64.0	234	10.40	785	-
64.0	270	11.44	785	-
64.0	280	11.20	785	-
64.0	345	12.00	785	-

TABLE 11-II

COMPONENT FLOW TEST DATA

2" - .035 Wall Straight Al Tube, 10' Long

FUEL TEMP (°F)	FLOW RATE (lbs per min)	PRESSURE DROP (lbs per in^2)	STRESS LEVEL (Dynes/cm^2) BEFORE	AFTER
JP-4				
76.0	204	.24	-	-
76.0	550	1.01	-	-
76.0	580	.98	-	-
76.0	680	1.23	-	-
76.0	740	1.50	-	-
76.0	860	1.77	-	-
76.0	860	1.88	-	-
76.0	1000	2.28	-	-
FUEL G				
69.0	35	1.95	-	-
69.0	40	2.10	-	-
69.0	78	2.70	-	-
69.0	90	2.85	-	-
69.0	156	3.00	-	-
69.0	192	3.00	-	-
69.0	270	2.62	-	-
69.0	510	2.78	-	-
69.0	660	3.00	-	-
69.0	810	3.15	-	-
FUEL B				
76.0	69	3.25	1250	-
76.0	99	4.15	1250	-
76.0	132	4.00	1250	1455
76.0	141	4.59	1250	-
76.0	396	6.60	1250	1375
76.0	546	6.25	1250	1360

APPENDIX III

This section provides a more detailed discussion of the pumpdown test program than that included in the main text. Results of this phase of the test program have been extrapolated to yield the data compiled on Figures 3.4 through 3.12 presented later in this section. A synopsis of this data is presented in Tables IV, V and VI, included in the main text.

PURPOSE

Wing fuel tanks conventionally constructed of stringers, spars and bulkheads offer resistance to the flow of thickened fuels. Some fuel is unavailable to the engines due to entrapment by the structure. Ideally, 100% recovery is desired. This phase of the test program is designed to assist in determining the unavailable volume of the gel and emulsion under consideration.

DISCUSSION

In an attempt to maintain compatibility between the pumpdown test and other phases of this test program, considerable effort was taken to simulate a portion of a DC-8 wing fuel tank. The tank configuration within two inboard bays; that including and adjacent to the pump inlet, were chosen for this test. Figures 3.1 and 3.2 show the tank configuration which was used for the pumpdown tests.

Stringers were fashioned and located according to basic DC-8 design requirements. Bulkhead lightening and drain hole configuration was made to duplicate the production article. A production foot valve and piping was installed to simulate suction feed requirements. The test program itself was basic and consisted of filling the fuel tanks with emulsion or gel and initiating pumping. The surface slope and flow patterns were to be photographed and measured at the time of pump cavitation. From this, general rules of tank depletion were formulated. The pump cooling flow, although collected and weighed separately, was included in the utilization. The complete breakdown of the fuel and the location of the cooling flow outlet with respect to the pump inlet made this assumption reasonable.

PROCEDURE

(A) Set up test equipment as shown in Figure 3.1 or 3.2.

(B) Fill fuel test tank to a depth of ten inches as measured from foot valve inlet.

(C) Position pump outlet valve partially open. Start pump and determine flow rate by a time-weight method. Adjust valve to obtain 10,000 pounds/hour (See steps (D) or (E)).

(D) If desired flow rate can not be achieved, remove foot valve and position inlet 3/4" above tank floor. Repeat Step (C).

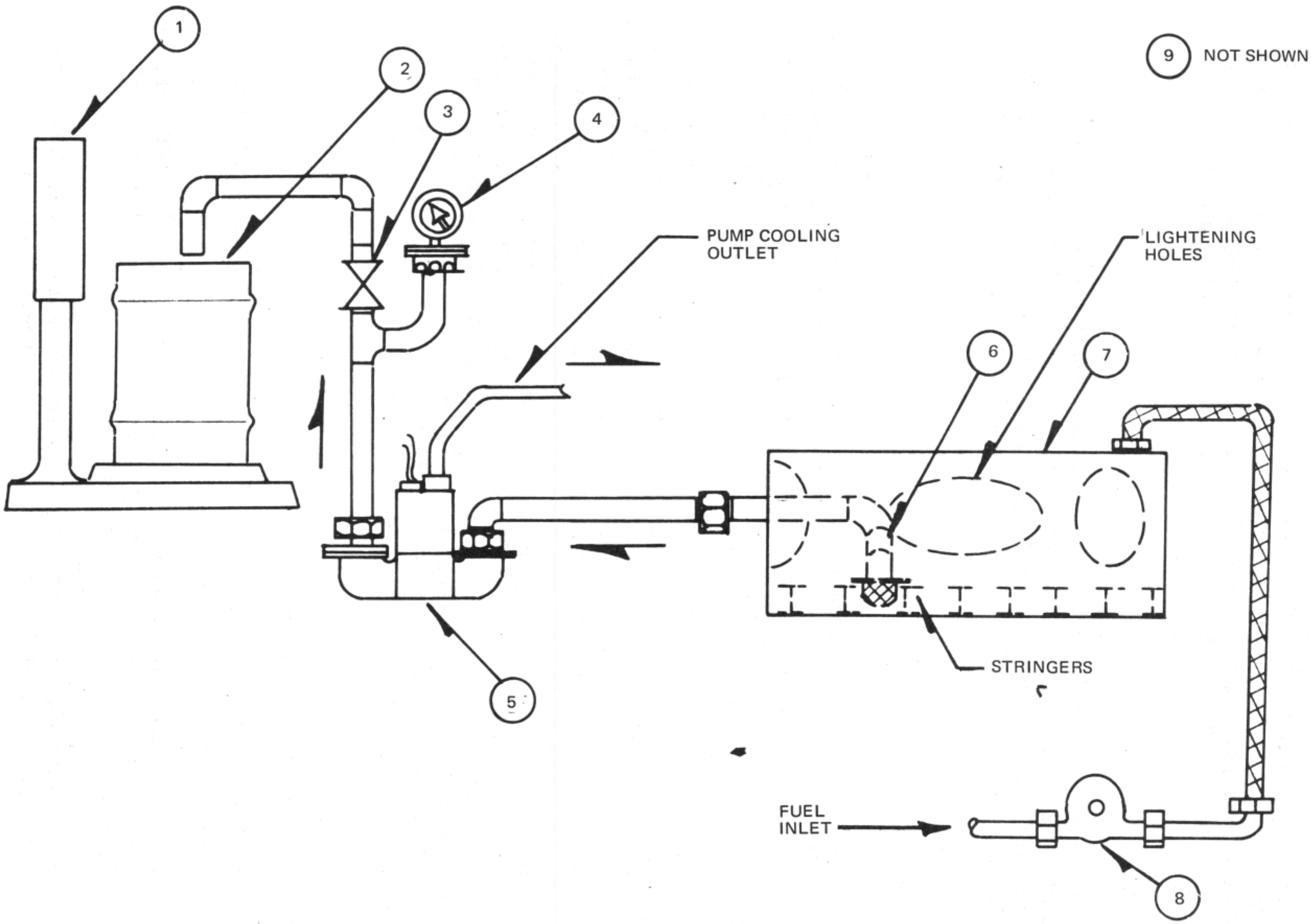


FIGURE 3.1
UNUSABLE FUEL TEST FACILITY

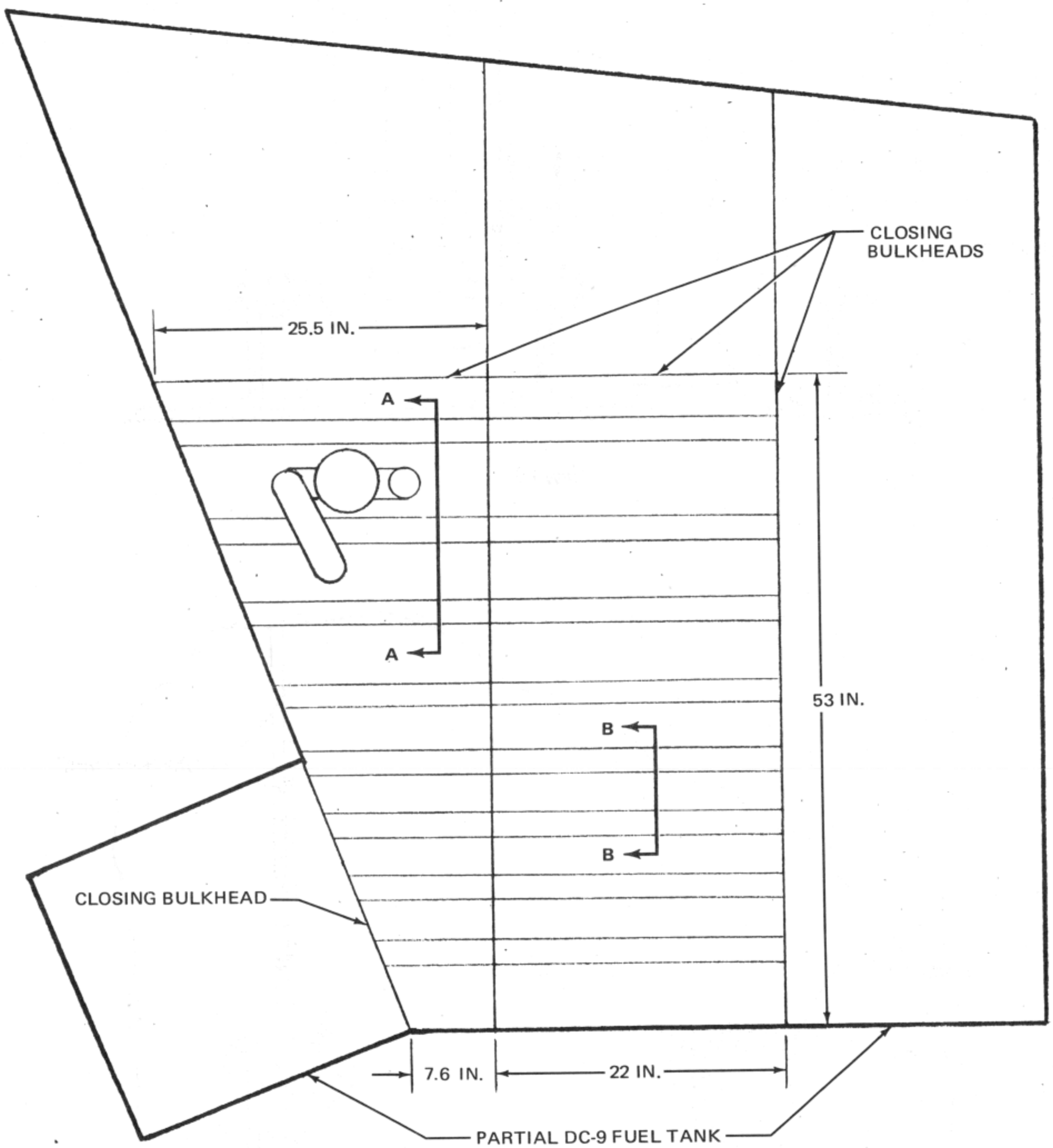
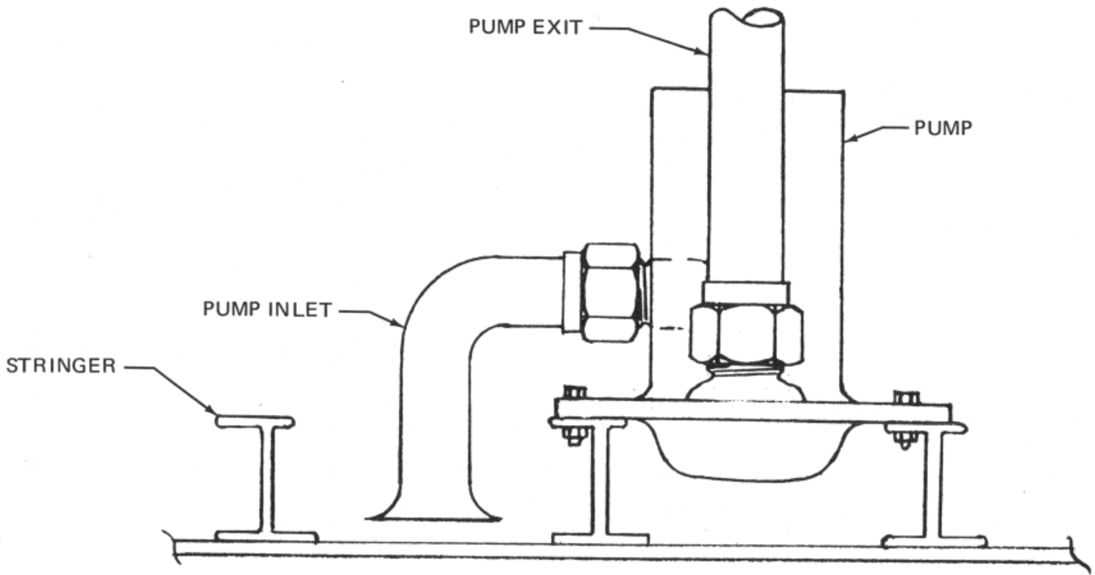
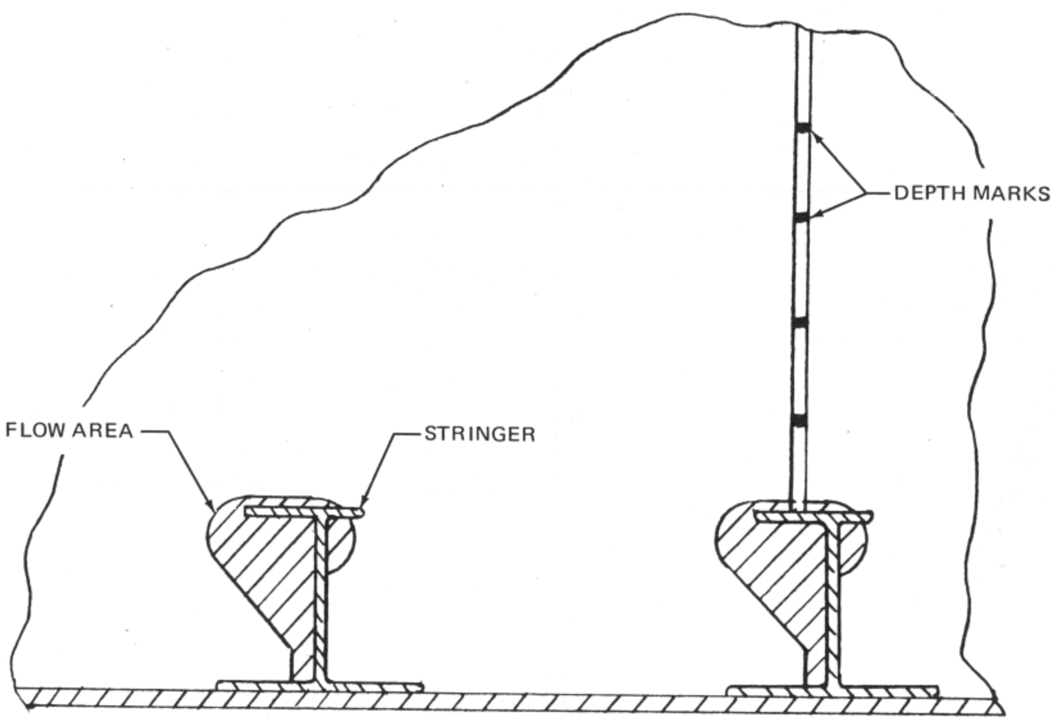


FIGURE 3.2
FUEL TANK FIXTURE



VIEW A-A



SECTION B-B

FIGURE 3.3
FUEL TEST TANK DETAILS

(E) If desired flow rate can not be achieved, remove inlet piping and relocate pump within fuel tank with inlet positioned 3/4" above tank floor. Repeat step (C).

(F) Refill tank to the 10 inch mark and determine temperature and yield stress.

(G) Simultaneously start timer and fuel pump. Obtain pictures of the fuel surface during pumpdown.

(H) Shut off pump and timer at cavitation.

(I) Record time, fuel weight transferred, temperature, depth of fuel at various points within the tank, slope of fuel adjacent to pump inlet.

(J) Repeat steps (B) through (I) at 3,000 pounds/hour fuel flow rate.

(K) Repeat entire test for different fuels under consideration. System and components to be thoroughly cleaned prior to introducing new test fluid.

TEST APPARATUS

The test apparatus used to determine unusable fuel is schematically presented in Figure 3.1. The following list details the specifications of the equipment utilized in this test. Item numbers refer to Figure 3.1.

Item	Name	Description
1	SCALE	Toledo Scale Co., 0 - 1000 lbs. capacity, 1 lb. graduations
2	DRUM	55 gallon capacity coated steel drum.
3	VALVE	Lunkenheimer Corp., 2" globe valve
4	GAUGE	Acragage, 0 - 30 psi
5	PUMP	Pesco Prod. Div., Borg-Warner Corp., P/N 112-303
6	FOOT VALVE	Gladden Corp., P/N 414275
7	TANK	McDonnell Douglas, P/N Z 7829601 Simulated DC-8 fuel tank
8	PUMP	Jabsco Pump Div., ITT Corp. Model #777-37
9	TIMER	Minerva Stopwatch

DATA

The results of this phase of the test program as used in the analysis are graphically illustrated on Figures 3.4 through 3.12. Each figure represents an elevation view of the tanks sections identified in Figure 40 in the main text. Reading from top to bottom, the first set of boxes represent fuel utilization with the existing DC-8 fuel pump arrangement. In most cases, none of the fuel that was loaded aboard the aircraft was usable for engine operation. The next set of boxes represents the same subsection of tanks except that each remote pump inlet has been fitted with a pump in order to eliminate suction piping. This configuration is known as Modification #1. The figures illustrate that the systems are operable with either fuel but that Fuel B usage is lower.

The last set of boxes represent fuel utilization with a more extensive modification of the aircraft fuel system. Known as Modification #2, this configuration is where a small scavaging pump is installed between each bulkhead. These pumps transfer fuel directly to the inlet of the fuel boost pumps. Obviously, the addition of in excess of one-hundred scavaging pumps provides the best utilization.

Figures 3.13 and 3.14 are representative of the amount of emulsion and gel which remained in the test tank after completion of the take-off flow rate (10,000 lb/hr) test run.

Table 1-III documents viscosity degradation of Fuel G during the pumpdown test program. This data was obtained with the Brookfield Viscometer within a period of one day from the time the sample was taken. As described in the main text, the fuel utilized in the pump-down test was stabilized with an additive introduced by the vendor prior to testing. The effect of high shear by a throttled centrifical pump is obvious from the cruise pumpdown curve shown in Figure 3.15.

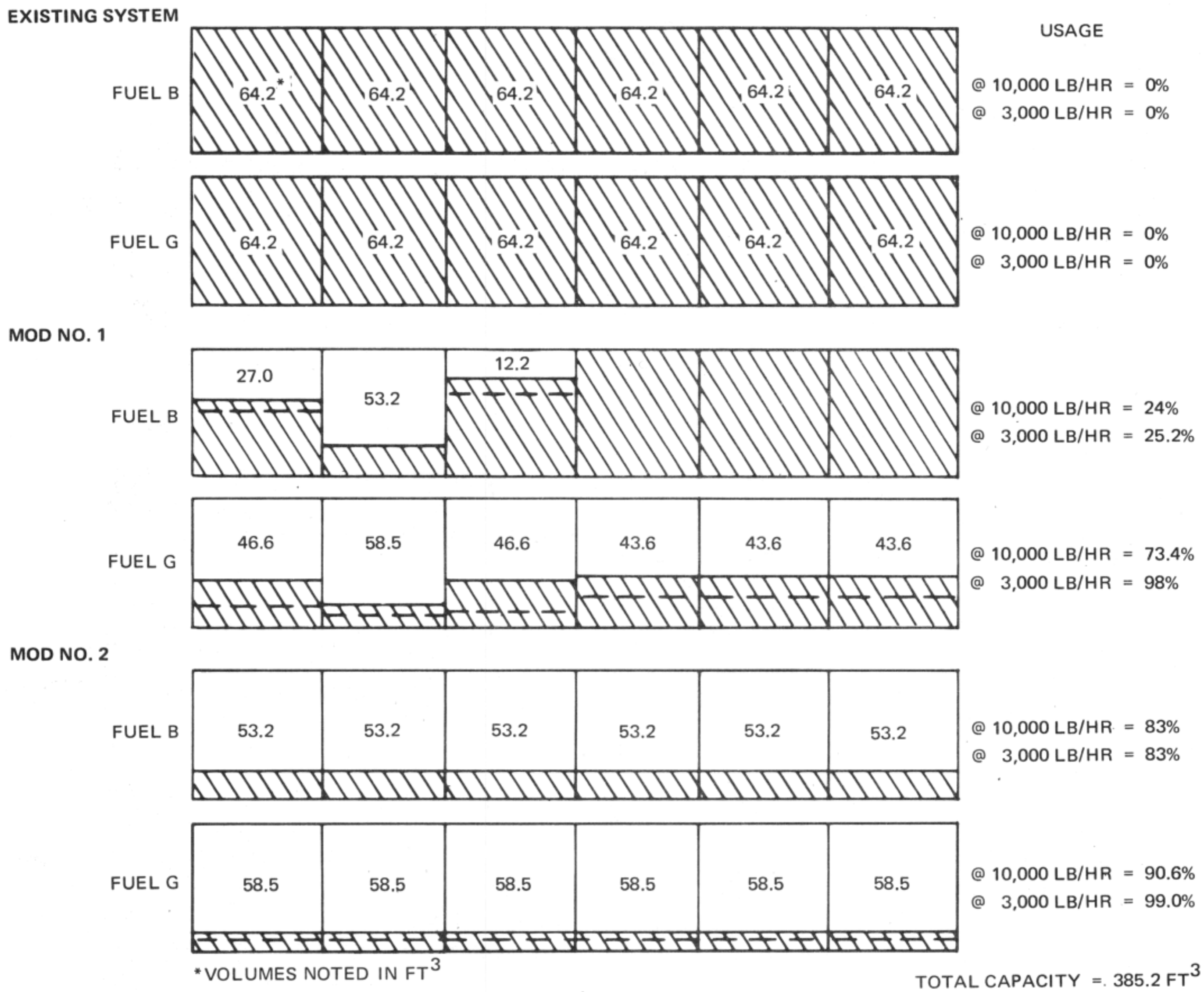


FIGURE 3.4
FRONT CENTER WING SECTION

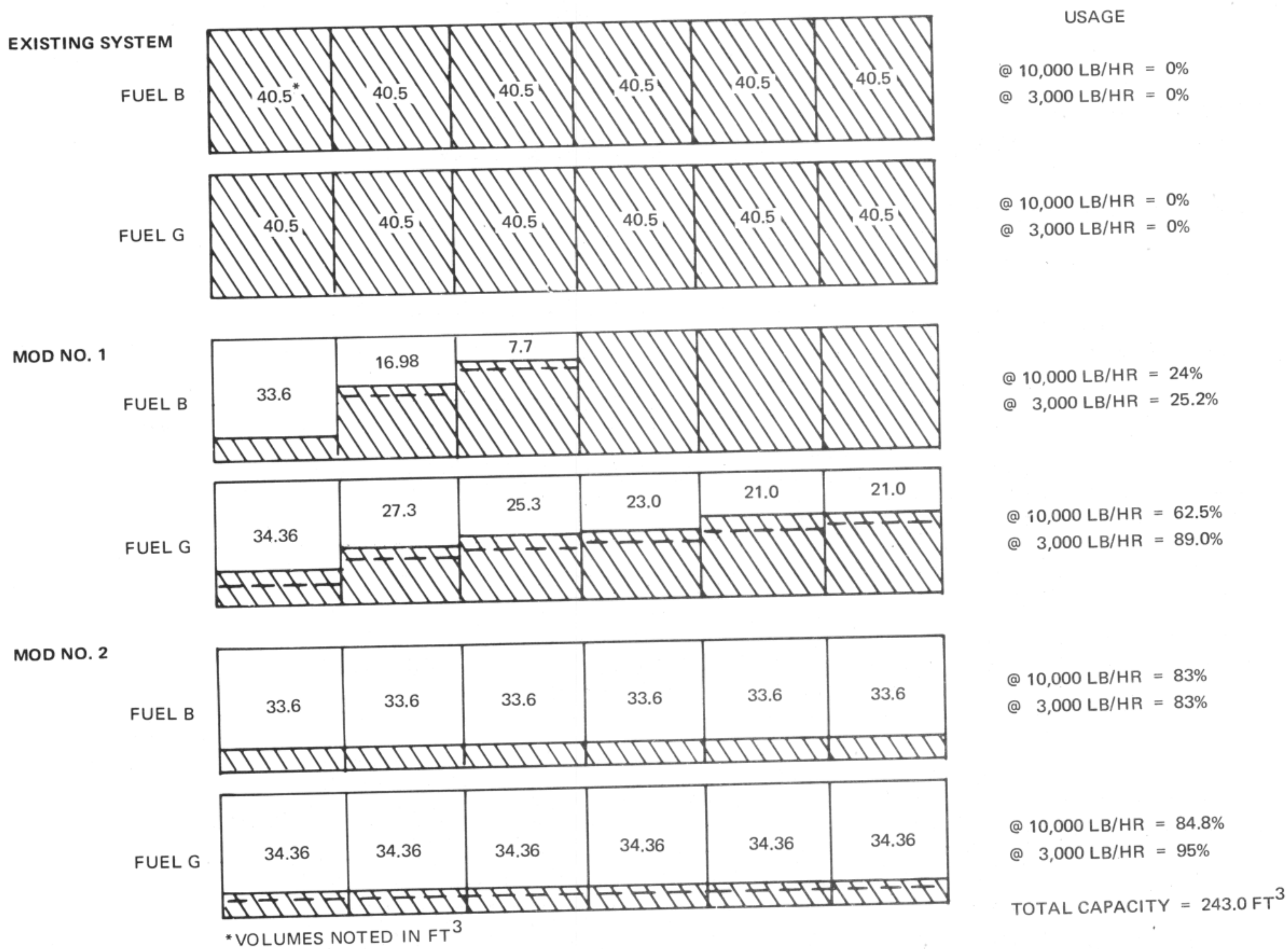


FIGURE 3.5

REAR CENTER WING SECTION

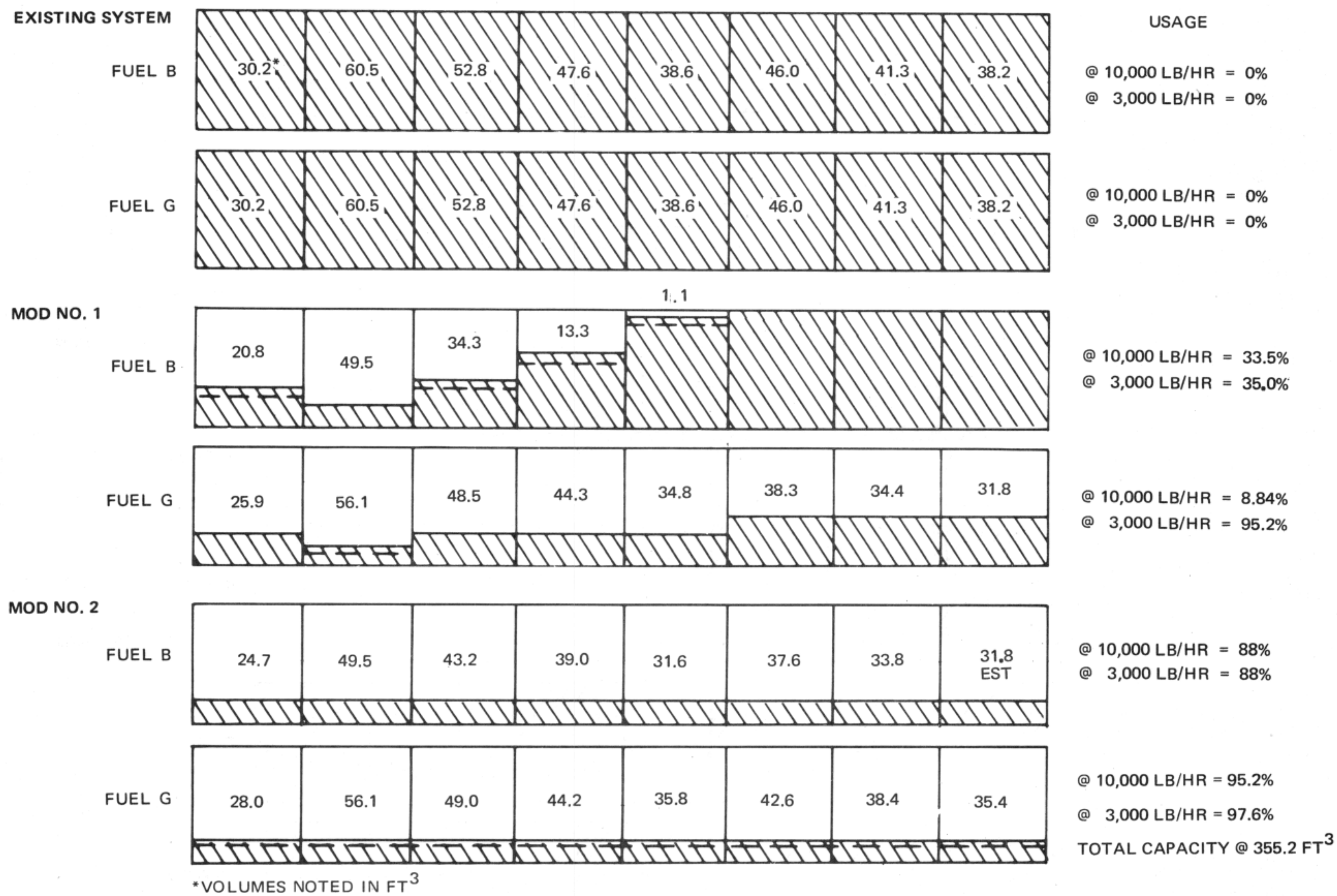


FIGURE 3.6
FRONT INBOARD MAIN

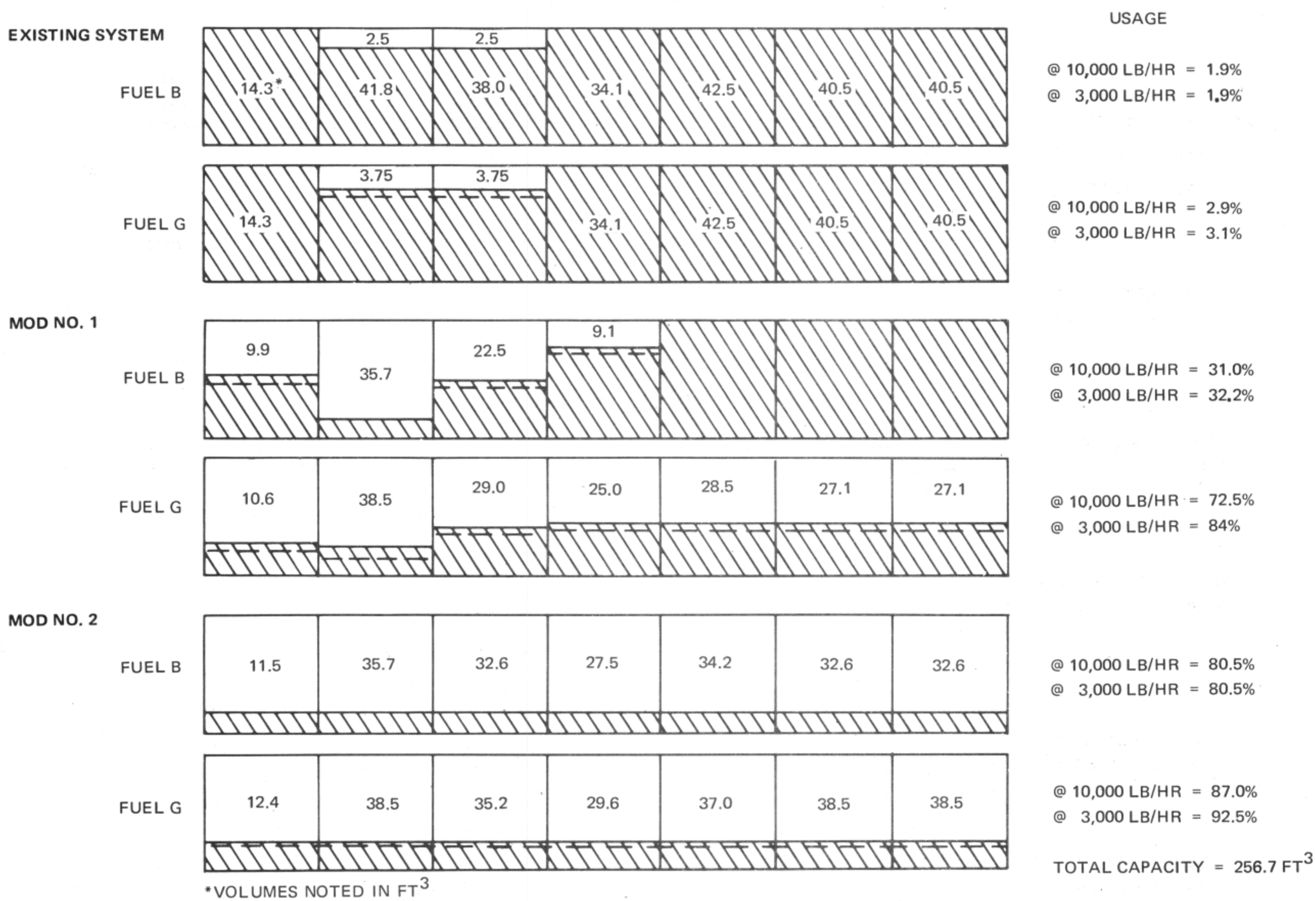


FIGURE 3.7
REAR INBOARD MAIN

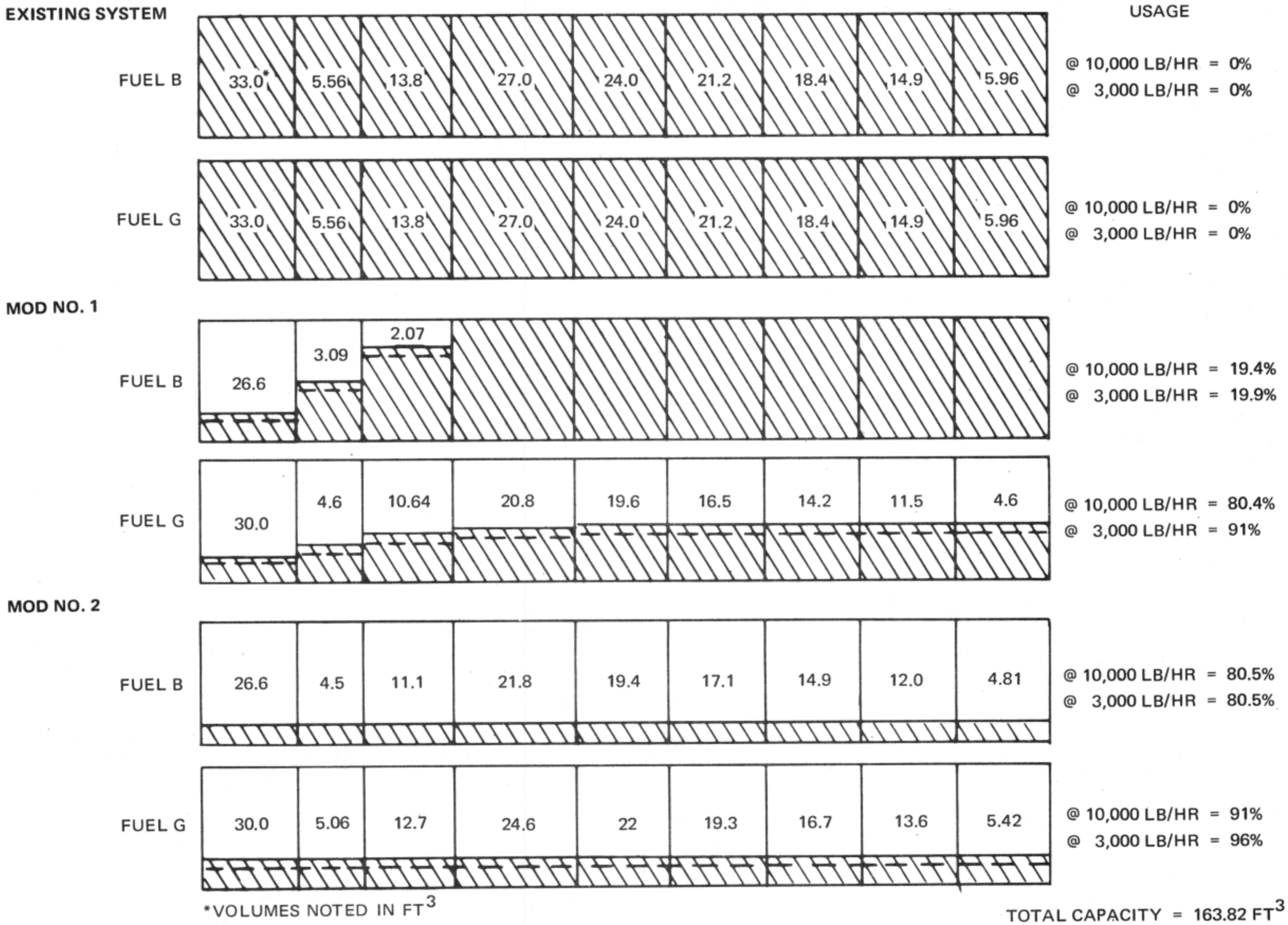


FIGURE 3.8

FRONT OUTBOARD MAIN SECTION

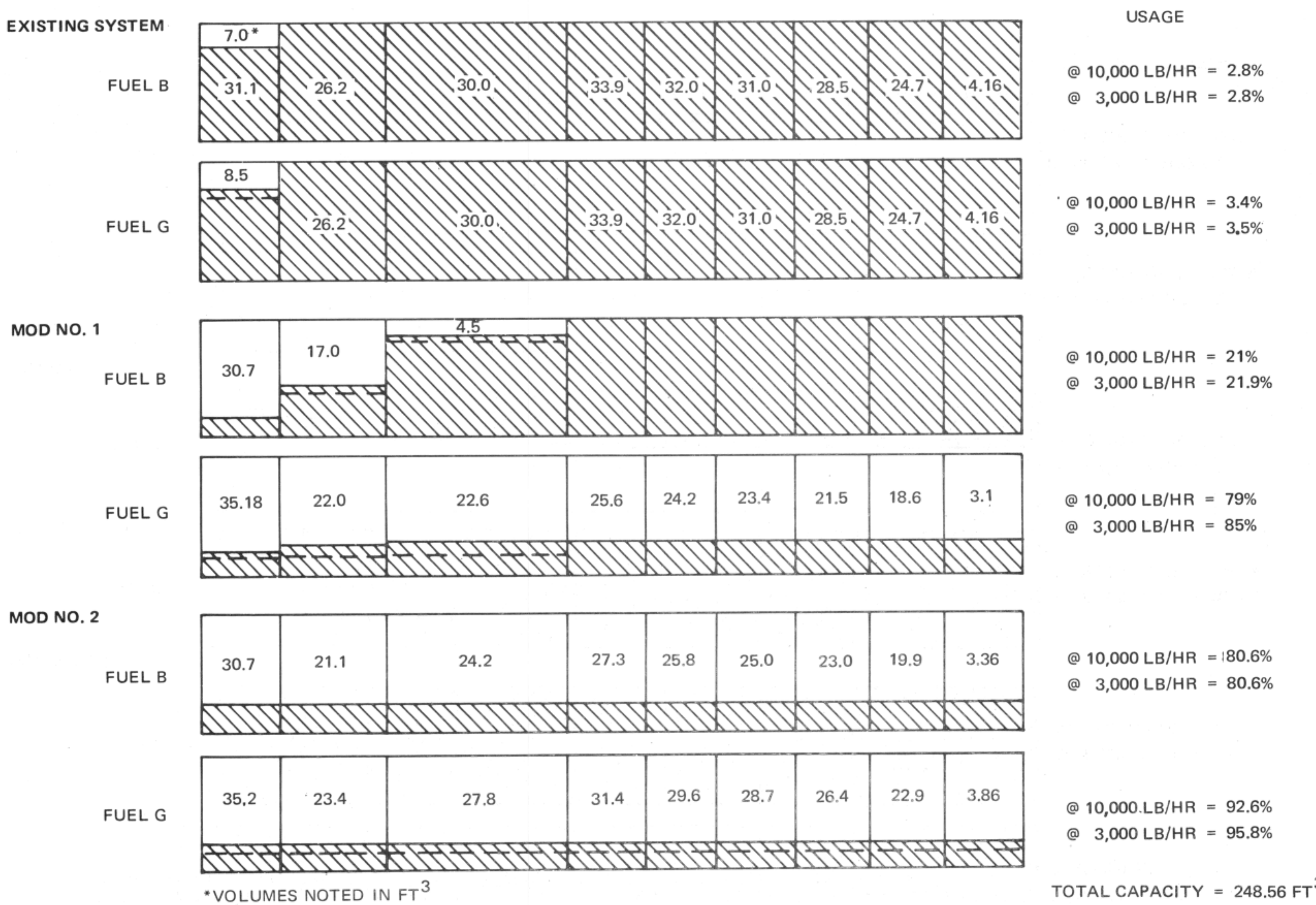


FIGURE 3.9

REAR OUTBOARD MAIN SECTION

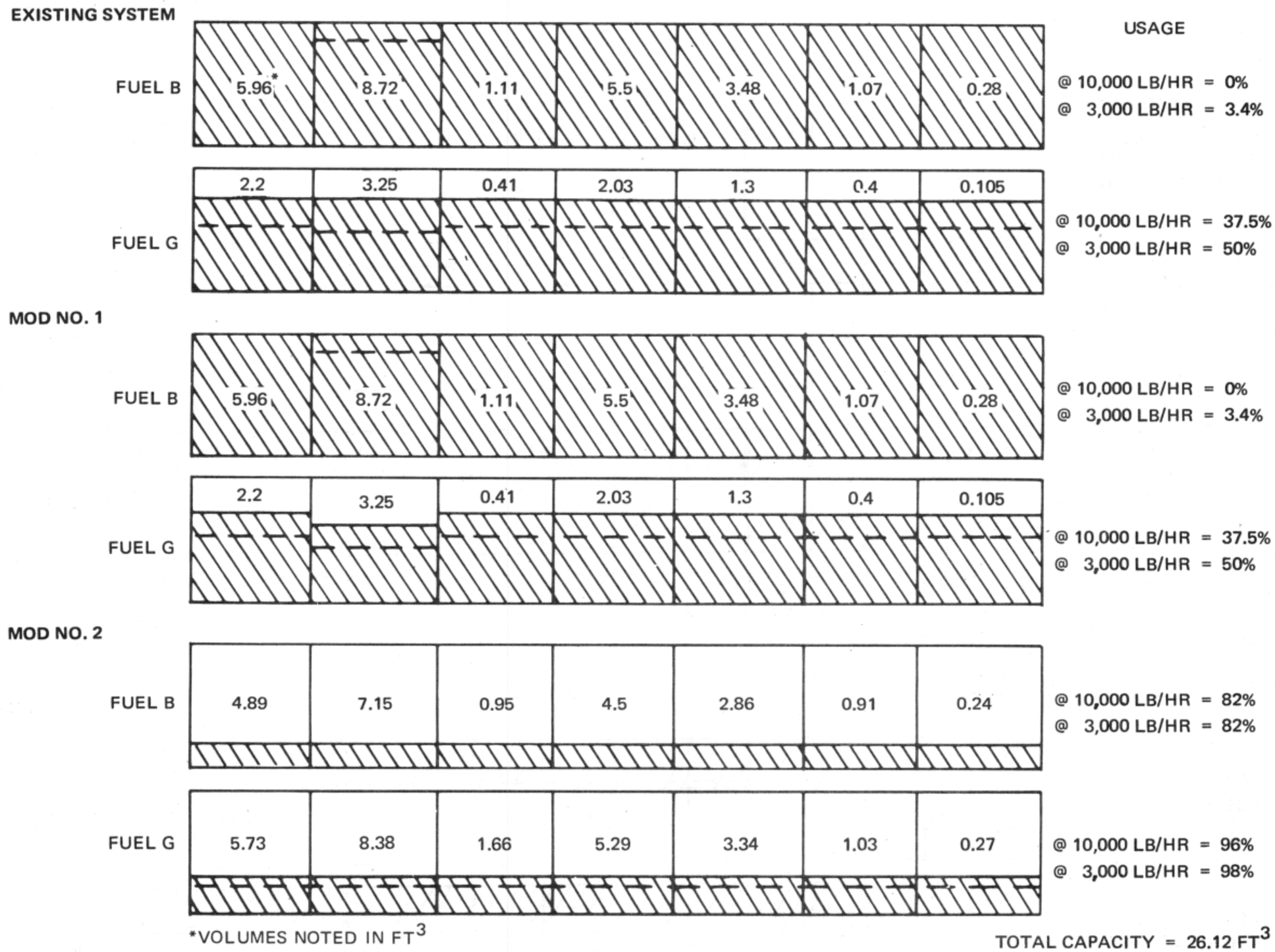


FIGURE 3.10
FRONT ALT

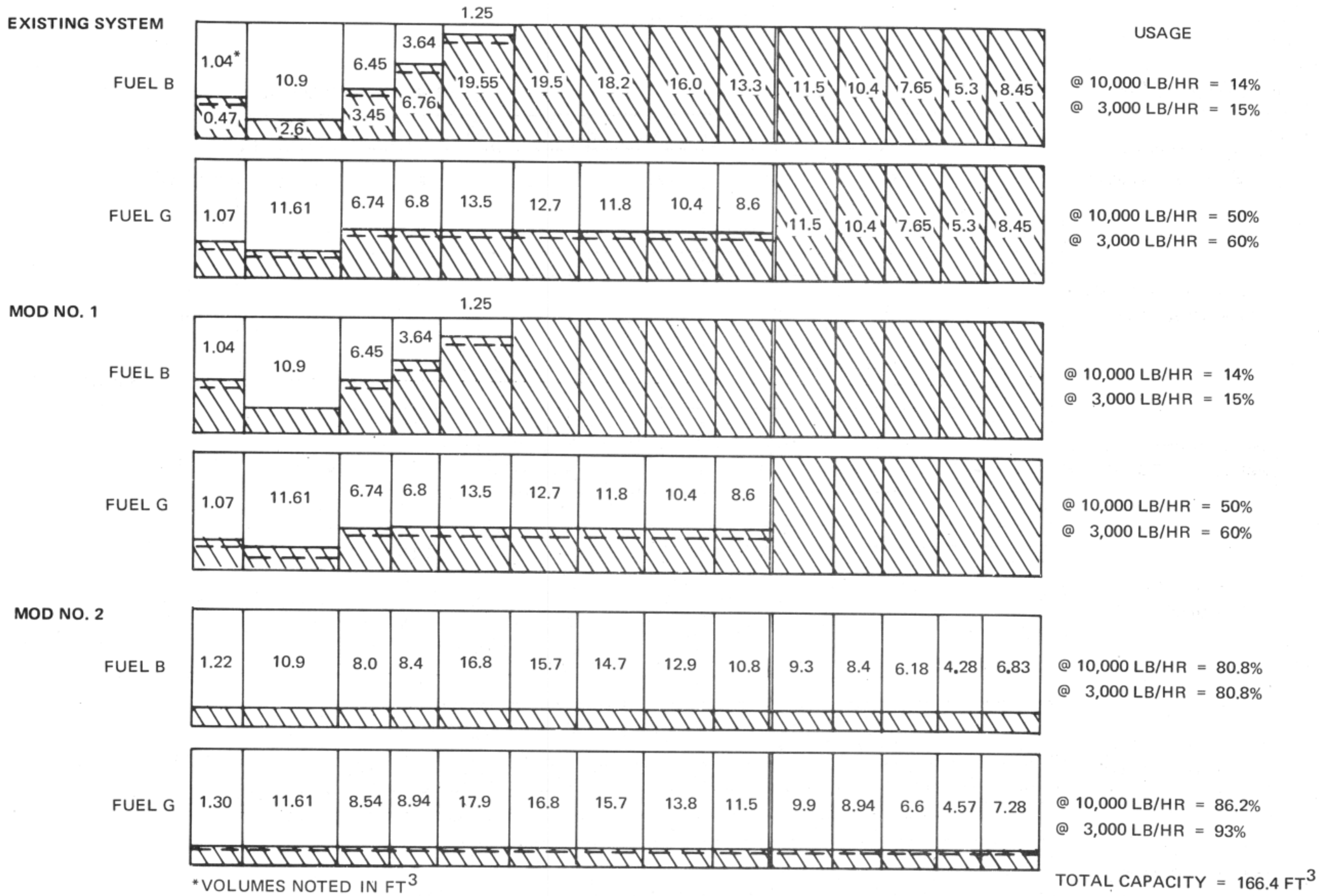


FIGURE 3.11
REAR ALT (INCL TIP)

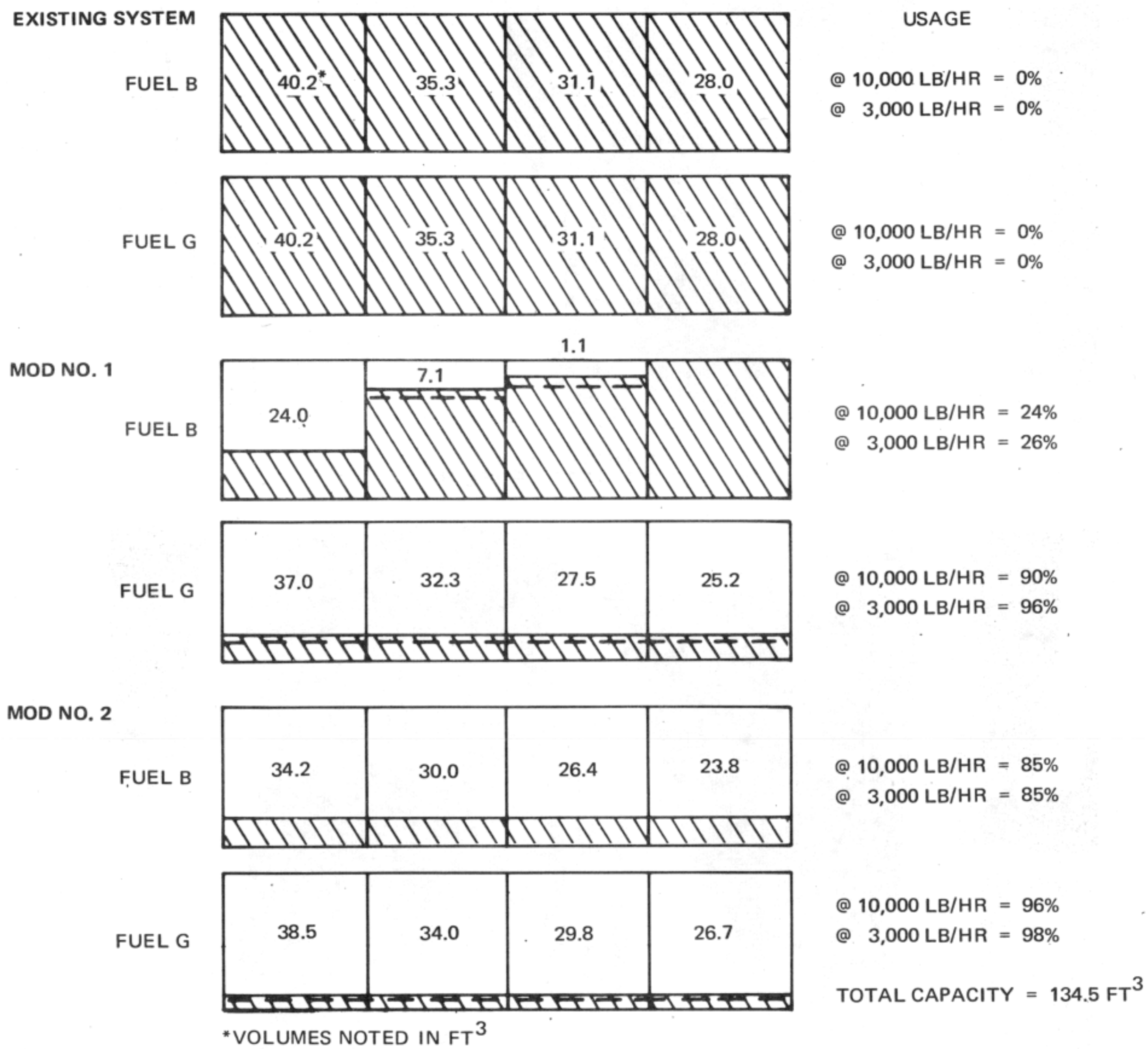


FIGURE 3.12
LEADING EDGE TANK

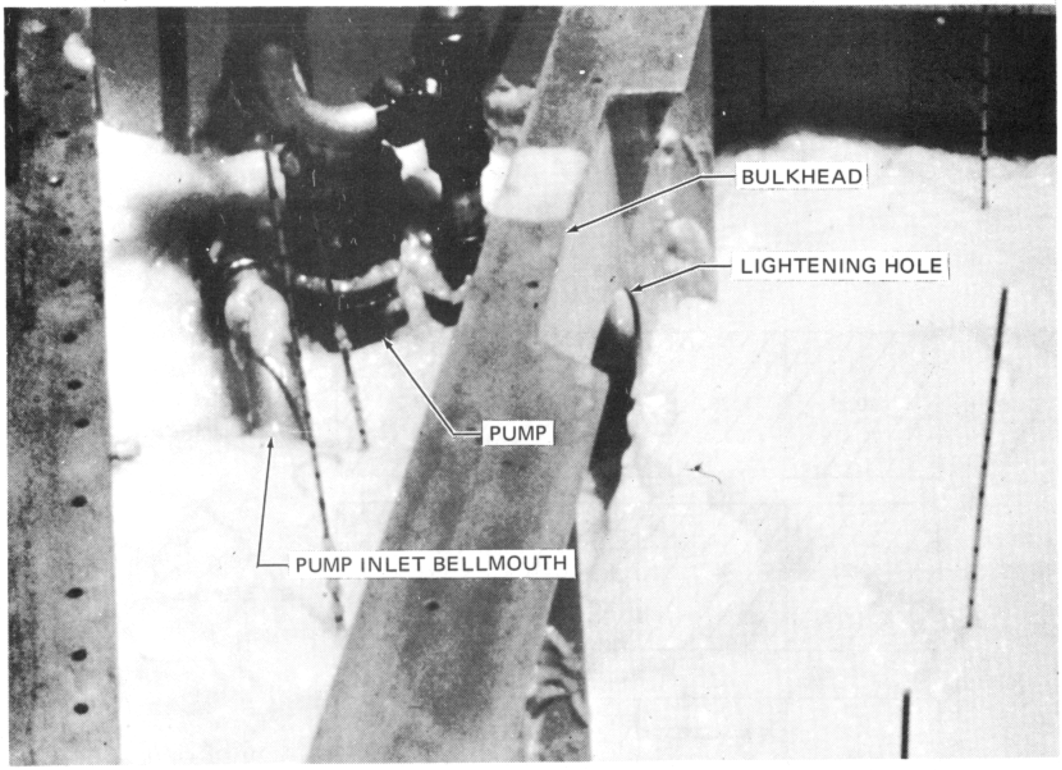


FIGURE 3.13
PUMP DOWN TEST - FUEL B

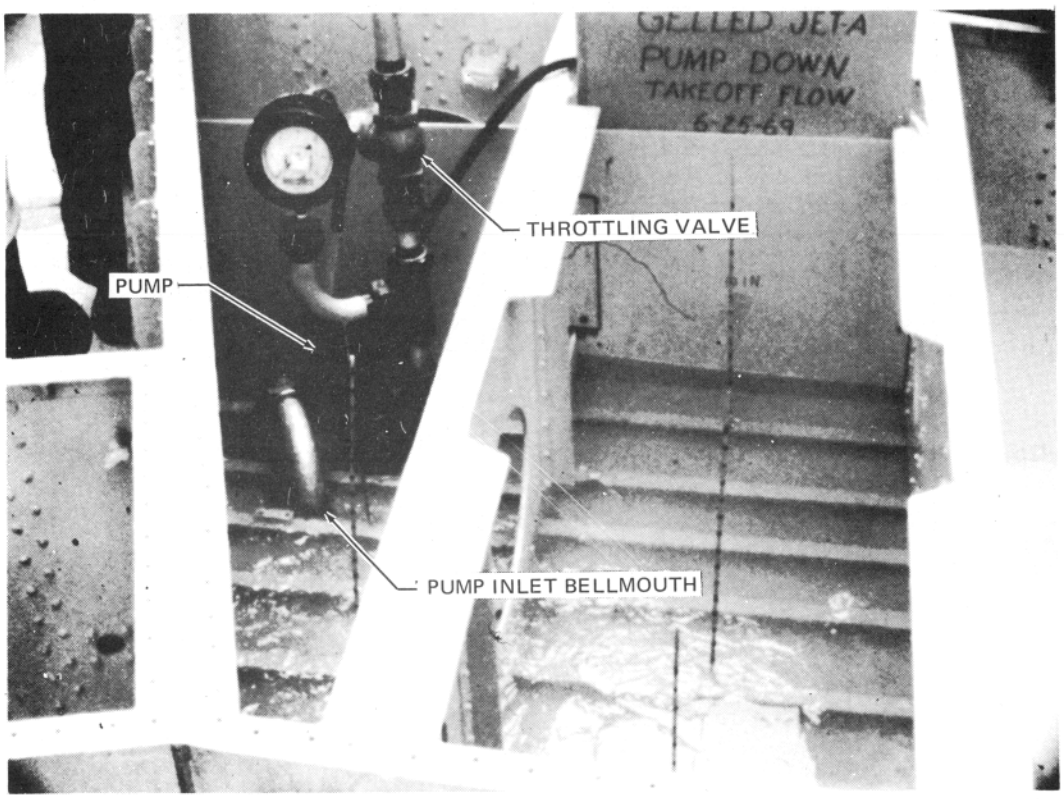


FIGURE 3.14
PUMP DOWN TEST - FUEL G

TABLE 1-III

GEL DEGRADATION DATA

FUEL G

1. From takeoff pumpdown supply tank (with stabilization additive)

Test Date: June 25, 1969
Brookfield: RVF
Spindle: #6
Temp: 73°F
Guard: None
Container: 1 Quart Can

Speed RPM	Reading % Full Scale	Time Second	Viscosity Contipoise
2	10.0	120	50,000
4	12.2	240	30,500
10	17.0	360	17,000
20	19.3	480	9,650

2. From takeoff pumpdown receiver barrel

Test Date: June 25, 1969
Conditions: Same as above

2	6.2	120	31,000
4	10.4	240	26,000
10	11.3	360	11,300
20	15.8	480	7,900

3. From 2nd cruise pumpdown supply tank

Test Date: June 25, 1969
Conditions: Same as above

2	1.8	120	9,000
4	3.3	240	8,250
10	3.8	360	3,800
20	8.0	480	4,000

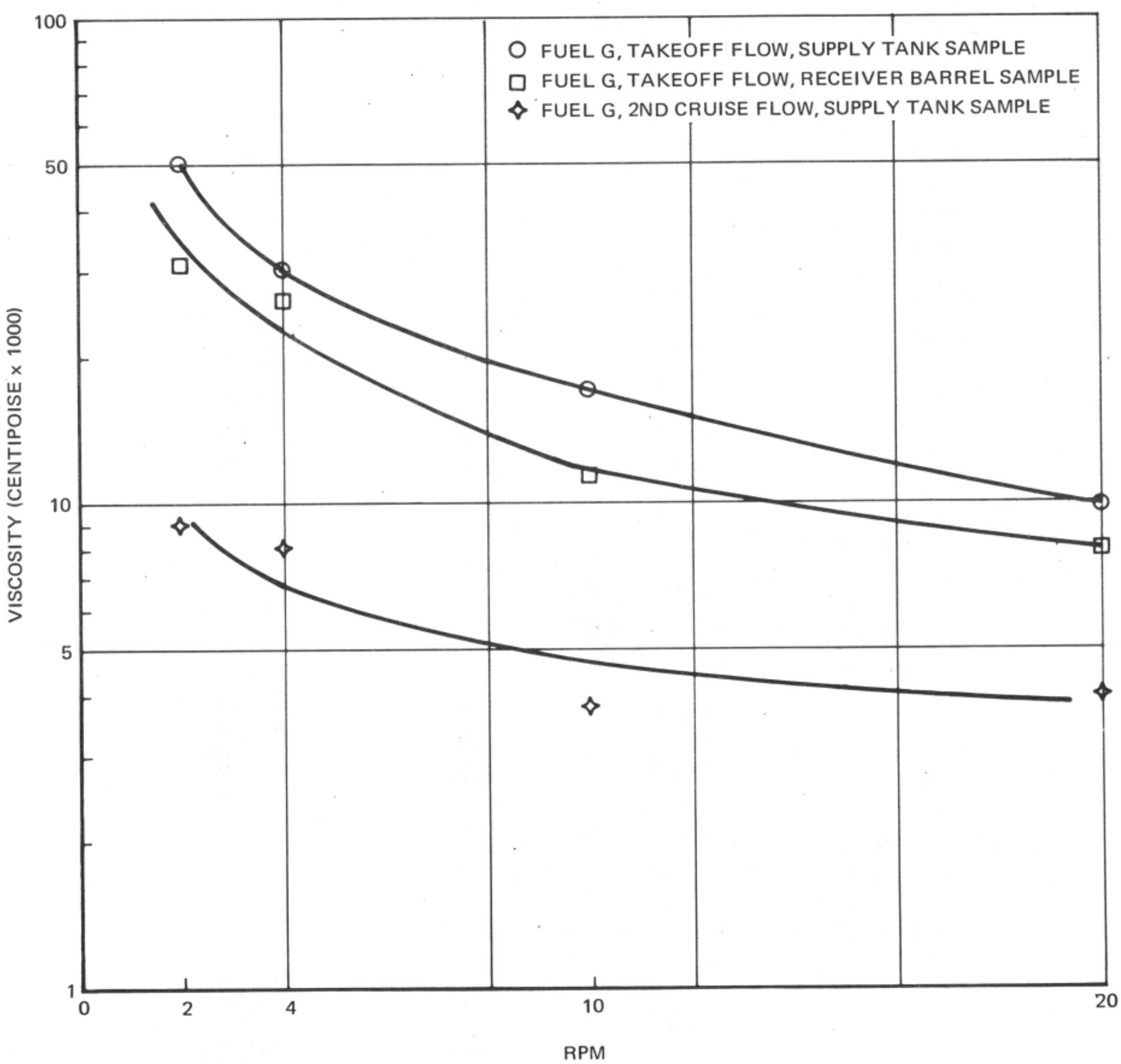


FIGURE 3.15
GEL DEGRADATION

APPENDIX IV

This section provides a more detailed discussion of the orifice test program than that included in the main text. The test data tabulated in this section is summarized in Figures 21 through 30.

PURPOSE

This phase of the gelled and emulsified fuel test program was performed specifically to estimate flow resistance through various size perferations in aircraft fuel tank bulkheads. The aircraft wing bulkhead is pierced with numerous holes intended for conventional fuel passage and for lightening the aircraft. By this test, fuel head requirements could be ascertained and thereby provide the basis for calculating unusable fuel volumes.

DESCRIPTION

The test equipment utilized in this test is schematically shown in Figure **4.1.** A total of ten orifice plates were fabricated with holes representative of that normally found through a bulkhead. By scaling, addition or subtraction, flow rates of other hole configurations could be estimated.

The following orifice configurations were tested:

(A) 4 inch diameter

(B) 3 inch diameter

(C) 2 inch diameter

(D) 1 inch diameter

(E) 1/2 inch diameter

(F) 4 inch x 2 inch rectangle

(G) 3 inch x 1 inch rectangle

(H) 4 inch x 1/2 inch rectangle

(I) 4 inch x 1 inch rectangle

(J) 6 inch x 1 inch rectangle

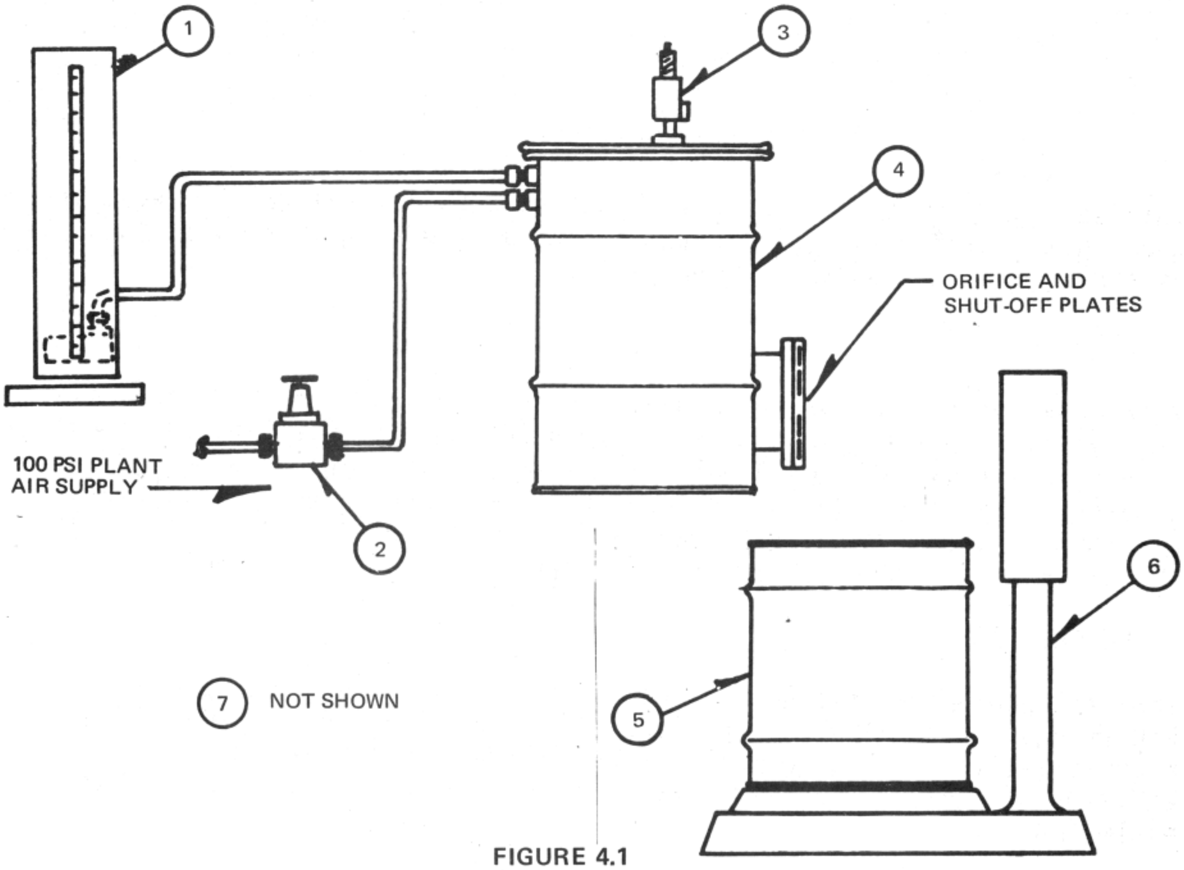


FIGURE 4.1
ORIFICE FLOW TEST

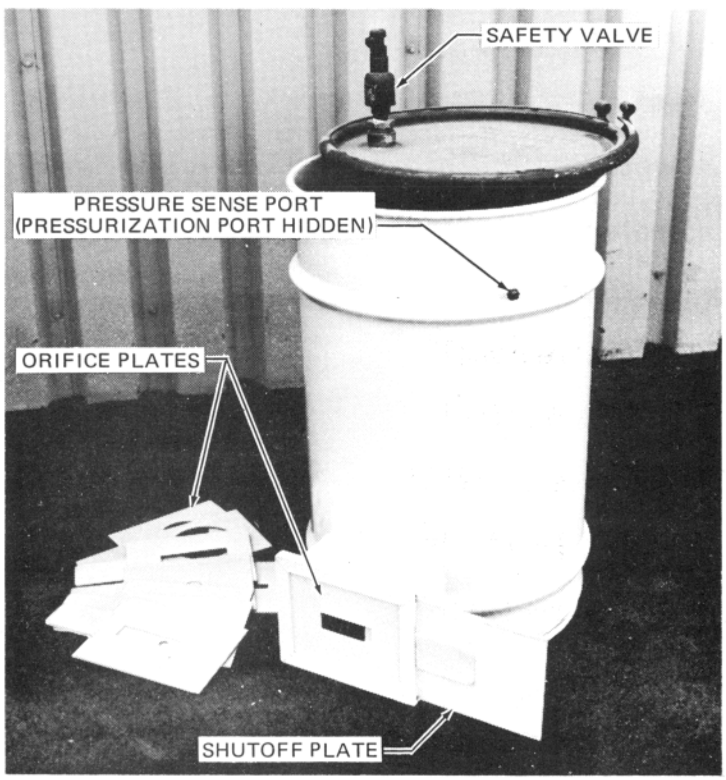


FIGURE 4.2
ORIFICE TEST FIXTURE

TEST APPARATUS

The test apparatus used to determine orifice flow rates is schematically presented in Figure 4.1. A photograph of the orifice test fixture is included on Figure 4.2. The following list details the specifications of the equipment utilized in this test program.

Item	Name	Description
1	PRESSURE MANOMETER	Meriam Inst. Co. 0 - 30" water tube
2	REGULATOR	C. A. Norgren Co., 0 - 25 psi output press.
3	SAFETY VALVE	Lunkenheimer Corp., 3/4" safety set 5 psig
4	ORIFICE TEST DRUM	McDonnell Douglas Corp., P/N Z 7829674
5	DRUM	20 gal. capacity steel drum
6	SCALE	Toledo Scale Co., 0 - 500 lbs. capacity, 1 lb. graduations
7	TIMER	Minerva Stopwatch

PROCEDURE

(A) Set up flow test apparatus as shown in Figure 4.1.

(B) Select orifice plate and install a slot provided in test drum. Also install shutoff plate.

(C) Fill test drum with sufficient quantity of fuel for duration of the flow test. Install cover on drum and pressurize drum to predetermined value.

(D) Simultaneously remove orifice shutoff plate and start timer.

(E) Allow sufficient flow time to accurately gauge the flow rate, then simultaneously reinstall orifice shutoff plate and stop timer.

(F) Record initial depth of fuel, yield stress, temperature, pressure, flow time, final depth and weight of fuel transferred.

(G) Repeat (A) through (F) at various pressures or initial fuel depth.

(H) Repeat entire test for different fuels under consideration. System to be thoroughly cleaned prior to introducing new test fluid.

TABLE 1-IV

ORIFICE FLOW TEST DATA - FUEL G

RUN NO.	ORIFICE SIZE (in)	STRESS	TIME secs	TOTAL WT. #	INITIAL HEAD in/fuel	HEAD CORR in/fuel	ELEVATED CORR in/fuel	H_2O CORR in/H_2O	H_2O CORR in/fuel	AVG HEAD in/fuel	AVG PRESS psid	FLOW RATE #/min
1	1/2	-	5	.6	9.75	.05	3.0	-	-	6.70	.185	7.2
2	1/2	-	5	.55	9.50	.05	3.0	-	-	6.45	.178	6.6
3	1/2	-	5	.4	7.37	.04	3.0	-	-	4.33	.1195	4.8
4	1/2	-	10	.4	6.37	.04	3.0	-	-	3.33	.092	2.4
5	1/2	-	15	.4	5.37	.04	3.0	-	-	2.33	.0643	1.6
6	1/2	-	15	.2	4.87	.01	3.0	-	-	1.86	.0514	.8
7	1/2	-	120	.6	4.37	.05	3.0	-	-	1.32	.0364	.3
7A	1/2	-	∞	-	4.25	-	3.0	-	-	1.25	.0346	Very Slow
8	1	-	5	4.6	9.75	.42	2.75	-	-	6.58	.182	55.2
9	1	-	5	6.15	15.37	.56	2.75	-	-	12.06	.332	73.8
10	1	-	5	-	14.25	-	-	-	-	-	-	-
11	1	-	5	5.7	14.0	.52	2.75	-	-	10.73	.296	68.4
12	1	-	5	5.6	12.37	.51	2.75	-	-	9.11	.252	67.2
13	1	-	5	4.2	9.75	.38	2.75	-	-	6.62	.183	50.4
14	1	-	5	3.1	7.78	.28	2.75	-	-	4.75	.131	37.2
15	1	-	5	2.6	6.75	.24	2.75	-	-	3.76	.104	31.2
16	1	-	5	2.0	5.62	.18	2.75	-	-	2.69	.0742	24.
17	1	-	5	1.8	5.00	.16	2.75	-	-	2.09	.0578	21.6
18	1	-	5	1.1	4.5	.10	2.75	-	-	1.65	.0455	13.2
19	1	-	5	.9	4.25	.08	2.75	-	-	1.42	.0392	10.8
20	1	-	5	.8	4.0	.07	2.75	-	-	1.18	.0326	9.6

TABLE 1-IV (Cont'd)

ORIFICE FLOW TEST DATA - FUEL G

RUN NO.	ORIFICE SIZE (in)	STRESS	TIME secs	TOTAL WT. #	INITIAL HEAD in/fuel	HEAD CORR in/fuel	ELEVATED CORR in/fuel	H_2O CORR in/H_2O	H_2O CORR in/fuel	AVG HEAD in/fuel	AVG PRESS psid	FLOW RATE #/min
18	1	-	120	1.2	3.62	.11	2.75	-	-	.76	.021	.6
19	2	-	5	28.6	13.37	2.62	2.25	-	-	8.50	.235	.343
20	2	-	5	-	-	-	-	-	-	-	-	-
21	2	-	5	7.2	5.12	.66	2.25	-	-	2.21	.061	86.5
22	2	-	2	3.	4.0	.27	2.25	-	-	1.48	.0408	90.0
23	2	-	2	2.3	3.62	.21	2.25	-	-	1.16	.032	69.0
24	2	-	2	1.5	3.25	.13	2.25	-	-	.87	.024	45.0
25	2	-	2	.5	3.0	.045	2.25	-	-	.71	.0196	15.
25A	2	-	∞	-	2.75	-	2.25	-	-	.50	.0137	None
26	1/2 x 4	-	5	5.75	5.25	.52	3.00	-	-	1.73	.0478	69.0
27	1/2 x 4	-	5	4.0	4.25	.36	3.00	-	-	.89	.0246	48.0
27A	1/2 x 4	-	∞	-	3.00	-	3.00	-	-	0	0	None
28	1/2 x 4	-	5	3.1	3.62	.28	3.00	-		.34	.0094	37.2
29	1/2 x 4	-	5	1.2	3.12	.11	3.00	-		.01	.0002	14.4
30	1/2 x 4	-	5	11.6	9.12	1.06	3.00	-		5.06	.14	139.0
31	1 x 3	-	5	12.35	7.0	1.13	2.75	-		3.12	.086	148.0
32	1 x 3	-	5	5.7	4.25	.52	2.75	-		.98	.027	68.3
33	1 x 3	-	5	3.2	3.87	.29	2.75	-		.83	.0229	38.4
34	1 x 3	-	∞	-	2.75	-	2.75	-		0	0	None

TABLE 1-IV (Cont'd)

ORIFICE FLOW TEST DATA - FUEL G

RUN NO.	ORIFICE SIZE (in)	STRESS	TIME secs	TOTAL WT. #	INITIAL HEAD in/fuel	HEAD CORR in/fuel	ELEVATED CORR in/fuel	H_2O CORR in/H_2O	H_2O CORR in/fuel	AVG HEAD in/fuel	AVG PRESS psid	FLOW RATE #/min
35	1 x 4	-	5	19.6	8.50	1.78	2.75	-		3.97	.109	235.0
36	1 x 4	-	5	8.6	5.0	.79	2.75	-		1.46	.0402	103.0
37	1 x 4	-	5	2.6	3.5	.24	2.75	-		.51	.0141	31.2
38	1 x 6	-	3	24.3	9.5	2.23	2.75	-		4.52	.125	486.0
39	1 x 6	-	3	10.6	5.12	.94	2.75	-		1.43	.0398	212.0
40	1 x 6	-	3	3.1	3.5	.28	2.75	-		.47	.013	62.0
41	2 x 4	-	3	22.45	10.75	2.06	2.25	-		6.44	.1775	449.0
42	2 x 4	-	2	13.4	6.62	1.23	2.25	-		4.14	.114	402.0
43	2 x 4	-	2	7.3	4.25	.67	2.25	-		1.33	.0367	219.0
44	2 x 4	-	2	2.9	3.12	.26	2.25	-		.61	.0168	87.0
44A	2 x 4	-	∞	-	2.37	-	2.25	-		.12	.0033	None
45	3	-	2	18.0	8.25	1.65	1.75	-		4.85	.134	540.0
46	3	-	2	10.1	5.0	.92	1.75	-		2.33	.0643	303.0
47	3	-	2	3.85	3.37	.35	1.75	-		1.27	.035	115.5
48	3	-	2	1.55	2.75	.14	1.75	-		.86	.0238	46.5
48A	3	-	∞	-	1.75	-	1.75	-		0	0	None
49	4	-	1	14.0	8.25	1.28	1.25	-		5.72	.158	840.0
50	4	-	1	8.55	5.75	.78	1.25	-	-	3.72	.103	513.0

TABLE 1-IV (Cont'd)
ORIFICE FLOW TEST DATA - FUEL G

RUN NO.	ORIFICE SIZE (in)	STRESS	TIME secs	TOTAL WT. #	INITIAL HEAD in/fuel	HEAD CORR in/fuel	ELEVATED CORR in/fuel	H_2O CORR in/H_2O	H_2O CORR in/fuel	AVG HEAD in/fuel	AVG PRESS psid	FLOW RATE #/min
51	4	-	1	8.25	4.25	.75	1.25	-	-	2.25	.062	495.0
52	4	-	1	1.9	2.87	.17	1.25	-	-	1.45	.040	114.0

TABLE 2-IV

ORIFICE FLOW TEST DATA   FUEL B (BATCH #1)

RUN NO.	ORIFICE SIZE (in)	STRESS dynes/ cm^2	TIME secs	TOTAL WT. #	INITIAL HEAD in/fuel	HEAD CORR in/fuel	ELEVATED CORR in/fuel	H_2O CORR in/H_2O	H_2O CORR in/fuel	AVG HEAD in/fuel	AVG PRESS psid	FLOW RATE #/min
1	1/2	1180	60	.2	9.25	.02	3.0	2.75	3.6	9.83	.271	.2
1A	1/2	1180	Start	-	9.25	-	3.0	2.50	3.27	9.52	.262	Steady
2	1/2	1180	120	.1	9.25	-	3.0	2.5	3.27	9.52	.262	.05
3	1/2	1180	60	.55	9.0	.05	3.0	5.0	6.54	12.49	.344	.55
4	1	1180	60	.7	8.5	.06	2.75	3.0	3.92	9.61	.265	.75
4A	1	1180	Start	-	8.5	-	2.75	2.5	3.27	8.02	.222	Steady
5	1	1180	10	1.1	8.5	.10	2.75	4.5	5.89	11.54	.319	6.6
6	2	1180	30	.7	9.0	.06	2.25	1.75	2.29	8.98	.248	1.4
6A	2	1180	Start	-	9.0	-	2.25	1.50	1.96	8.71	.240	Steady
7	2	1180	10	7.7	11.0	.71	2.25	3.0	3.92	11.96	.33	46.2
8	1/2 x 4	1180	30	.3	11.0	.02	3.0	1.0	1.31	9.29	.256	.6
8A	1/2 x 4	1180	Start	-	11.0	-	3.0	.75	.98	8.98	.248	Steady
9	1/2 x 4	1180	10	.6	10.0	.05	3.0	2.0	2.62	9.57	.264	3.6
10	1/2 x 4	1180	10	1.6	9.5	.14	3.0	3.0	3.92	10.28	.286	9.6
11	1/2 x 4	1180	2	2.0	9.0	.18	3.0	5.5	7.2	13.02	.359	50.0
12	1/2 x 4	1180	2	1.1	8.5	.10	3.0	5.0	6.54	11.94	.33	33.0
13	1 x 3	1180	10	.5	11.5	.05	2.75	-	-	8.70	.24	3.0
13A	1 x 3	1180	Start	-	10.5	-	2.75	-	-	7.75	.214	Steady
14	1 x 3	1180	30	.5	11.0	.05	2.75	-	-	8.20	.226	1.0

TABLE 2-IV (Cont'd)

ORIFICE FLOW TEST DATA - FUEL B (BATCH #1)

RUN NO.	ORIFICE SIZE (in)	STRESS dynes/ cm^2	TIME secs	TOTAL WT. #	INITIAL HEAD in/fuel	HEAD CORR in/fuel	ELEVATED CORR in/fuel	H_2O CORR in/H_2O	H_2O CORR in/fuel	AVG HEAD in/fuel	AVG PRESS psid	FLOW RATE #/min
15	1 x 3	1180	10	1.4	10.5	.12	2.75	1.0	1.31	8.94	.247	8.4
16	1 x 4	1180	Start	-	9.5	-	2.75	-	-	6.75	.186	Steady
17	1 x 4	1180	5	1.2	9.5	.11	2.75	1.0	1.31	7.95	.219	14.4
18	1 x 4	1180	5	3.7	9.0	.34	2.75	2.25	2.94	8.85	.244	44.4
19	1 x 6	1180	30	.7	7.75	.06	2.75	.9	1.18	6.12	.169	1.4
19A	1 x 6	1180	Start	-	7.75	-	2.75	.8	1.05	6.05	.167	Steady
19B	1 x 6	1180	∞	0	8.25	-	2.75	-	-	5.00	.137	None
20	1 x 6	1180	5	2.2	8.0	.20	2.75	2.0	2.62	7.67	.212	26.4
21	2 x 4	1180	5	.5	7.0	.05	2.25	1.0	1.31	6.01	.166	6.0
21A	2 x 4	1180	Start	-	7.0	-	2.25	1.0	1.31	6.06	.167	Steady
21B	2 x 4	1180	∞	-	7.5	-	2.25	-	-	5.25	.145	None
22	2 x 4	1180	10	5.0	8.0	.46	2.25	.5	.66	5.95	.164	30.0
23	3	1180	5	.3	7.0	.03	1.75	1.0	1.31	6.53	.180	3.6
23A	3	1180	Start	-	7.0	-	1.75	.75	.98	6.23	.172	Steady
23B	3	1180	∞	0	7.0	-	1.75	-	-	5.25	.145	None
24	3	1180	5	2.8	7.25	.26	1.75	1.5	1.96	7.20	.199	33.6
25	4	1180	5	.7	6.5	.06	1.25	.6	.785	5.97	.165	8.4
25A	4	1180	Start	-	6.5	-	1.25	.5	.66	5.91	.163	Steady

TABLE 2-IV (Cont'd)

ORIFICE FLOW TEST DATA - FUEL B (BATCH #1)

RUN NO.	ORIFICE SIZE (in)	STRESS dynes/ cm^2	TIME secs	TOTAL WT. #	INITIAL HEAD in/fuel	HEAD CORR in/fuel	ELEVATED CORR in/fuel	H_2O CORR in/H_2O	H_2O CORR in/fuel	AVG HEAD in/fuel	AVG PRESS psid	FLOW RATE #/min
25B	4	1180	∞	0	6.5	-	1.25	-	-	5.25	.145	None
26	4	1180	5	8.0	9.75	.73	1.25	.5	.66	8.43	.233	96.0
27	1/2	770	40	.4	8.5	.04	3.00	-	-	5.46	.151	.6
27A	1/2	770	Start	-	8.0	-	3.00	-	-	5.00	.137	Steady
27B	1/2	770	∞	0	7.35	-	3.00	-	-	4.35	.120	None
28	1/2	770	15	.3	7.35	.03	3.00	1.5	1.96	6.28	.173	1.2
29	1/2	770	10	.3	7.25	.03	3.00	2.0	2.62	6.84	.189	1.8
30	1/2	770	30	.25	7.00	.02	3.00	1.0	1.44	5.42	.150	.5
31	1	770	10	.8	6.00	.07	2.75	1.0	1.31	4.49	.124	4.8
31A	1	770	Start	-	6.75	-	2.75	-	-	4.00	.11	Steady
31B	1	770	∞	0	6.00	-	2.75	-	-	3.25	.090	None
32	1	770	30	.25	5.5	.02	2.75	.5	.66	3.39	.093	.5
33	1	770	10	.20	5.5	.02	2.75	.75	.98	3.71	.102	1.2
34	2	770	5	3.3	7.5	.03	2.25	-	-	5.22	.144	39.6
34A	2	770	Start	-	5.25	-	2.25	-	-	3.00	.083	Steady
34B	2	770	∞	0	4.75	-	2.25	-	-	2.50	.069	None
35	2	770	5	1.7	6.75	.15	2.25	-	-	4.35	.120	20.4
36	2	770	5	.8	6.0	.07	2.25	-	-	3.68	.102	9.6
37	1 x 3	770	5	2.4	7.25	.22	2.75	-	-	4.78	.132	28.8

TABLE 2-IV (Cont'd)

ORIFICE FLOW TEST DATA - FUEL B (BATCH #1)

RUN NO.	ORIFICE SIZE (in)	STRESS dynes/ cm^2	TIME secs	TOTAL WT. #	INITIAL HEAD in/fuel	HEAD CORR in/fuel	ELEVATED CORR in/fuel	H_2O CORR in/H_2O	H_2O CORR in/fuel	AVG HEAD in/fuel	AVG PRESS psid	FLOW RATE #/min
68	4	770	3	.6	4.0	.10	1.25	-	-	2.65	.073	12.0
69	4	770	3	.1	3.87	-	1.25	-	-	2.62	.072	2.0
69A	4	770	Start	-	4.0	-	1.25	-	-	2.75	.076	Steady
69B	4	770	∞	0	3.75	-	1.25	-	-	2.50	.069	None

TABLE 3-IV

ORIFICE FLOW TEST DATA - FUEL B, Batch 2

RUN NO.	ORIFICE SIZE (in)	STRESS	TIME secs	TOTAL WT. #	INITIAL HEAD in/fuel	HEAD CORR in/fuel	ELEVATED CORR in/fuel	H_2O CORR in/H_2O	H_2O CORR in/fuel	AVG HEAD in/fuel	AVG PRESS psid	FLOW RATE #/min
					(+)	(-)	(-)			(+)		
1	1/2	780	300	.1	7.5	-	3.0	-	-	4.5	.123	.02
2	1	780	60	.4	7.5	.04	2.75	-	-	4.71	.130	.4
3	2	780	30	3.5	7.0	.32	2.25	-	-	4.43	.114	7.0
4	2	780	15	5.7	7.75	.52	2.25	-	-	4.98	.137	22.8
5	2	780	10	7	8.0	.64	2.25	-	-	5.11	.141	42
6	2	780	3	4.1	8.5	.38	2.25	-	-	5.77	.159	82.0
7	1/2x4	780	2	1.3	8.25	.12	3.0	-	-	5.13	.141	39.0
8	1/2x4	780	2	.7	8.0	.06	3.0	-	-	4.94	.135	21
9	1 x 3	780	1 1/2	1.4	7.75	.13	2.75	-	-	4.87	.133	56
10	1 x 3	780	2	2.1	7.5	.19	2.75	-	-	4.56	.126	63
11	1 x 3	780	2	2.2	7.25	.2	2.75	-	-	4.30	.119	66
12	1 x 4	780	2	5.4	8.5	.49	2.75	-	-	5.26	.143	162
13	2 x 4	780	2	5.8	7.5	.53	2.25	-	-	4.72	.13	174
14	2 x 4	780	1	5.4	8.25	.5	2.25	-	-	5.50	.151	324
15	2 x 4	780	1	5.1	8.25	.47	2.25	-	-	5.53	.153	306
16	3	780	1	4.3	7.5	.4	1.75	-	-	5.35	.148	258
17	3	780	1	5.3	8.25	.48	1.75	-	-	6.02	.161	318
18	1 x 6	780	1	4.1	7.75	.37	2.75	-	-	4.63	.128	248
19	1 x 6	780	1	3.5	7.5	.32	2.75	-	-	4.43	.122	210
20	1 x 6	780	1	3.5	7.5	.32	2.75	-	-	4.43	.122	210
21	4	780	1	9.5	8	.87	1.25	-	-	5.88	.162	570

TABLE 3-IV (Cont'd)

ORIFICE FLOW TEST DATA - FUEL B, Batch 2

RUN NO.	ORIFICE SIZE (in)	STRESS	TIME secs	TOTAL WT. #	INITIAL HEAD in/fuel	HEAD CORR in/fuel	ELEVATED CORR in/fuel	H_2O CORR in/H_2O	H_2O CORR in/fuel	AVG HEAD in/fuel	AVG PRESS psig	FLOW RATE #/min
54A	2 x 4	1290	Start	-	10.0	-	2.25	.5	.654	8.40	.232	Steady
55	2 x 4	1290	3	2.5	9.0	.23	2.25	2.5	3.27	9.79	.27	50
56	3	1290	3	2.5	10.5	.23	1.75	1.5	1.96	10.48	.289	50
56A	3	1290	Start	-	8.0	-	1.75	1.5	1.96	8.21	.226	Steady
57	3	1270	3	.6	10.0	.05	1.75	1.0	1.31	9.51	.262	12
58	3	1250	2	.4	10.0	.04	1.75	1.0	1.31	9.52	.262	12
59	3	1250	2	.2	10.0	-	1.75	.5	.654	8.90	.246	6
60	3	1250	2	.8	10.0	.07	1.75	1.0	1.31	9.49	.262	24
61	2 x 4	1250	2	.6	9.0	.05	2.25	1.0	1.31	8.01	.221	18
61A	2 x 4	1250	Start	-	9.0	-	2.25	.5	.654	7.40	.204	Steady
62	2 x 4	1240	2	.8	9.0	.07	2.25	1.0	1.31	7.99	.22	24
63	1 x 6	1240	2.2	1.5	10	.14	2.75	2.0	2.62	9.73	.268	38.7
63A	1 x 6	1240	Start	-	9.0	-	2.75	1.7	2.22	8.47	.234	Steady
64	1 x 6	1240	2	.9	9.0	.08	2.75	2.0	2.62	8.79	.242	27
65	4	1220	10	1.4	9.5	.13	1.25	-	-	8.12	.224	8.4
65A	4	1220	Start	-	9.0	-	1.25	-	-	7.75	.214	Steady
66	-	-	-	-	-	-	-	-	-	-	-	-
67	1/2	1850	10	.1	11.0	-	3.0	12.0	15.7	23.7	.654	.6
67A	1/2	1850	Start	-	11.0	-	3.0	9.5	12.4	20.4	.563	Steady
68	1/2	1850	10	.1	11.0	-	3.0	12.0	15.7	23.7	.654	.6
69	1/2	1830	10	1.2	11	.10	3.0	18.0	23.5	31.4	.865	7.2

TABLE 3-IV (Cont'd)

ORIFICE FLOW TEST DATA - FUEL B, Batch 2

RUN NO.	ORIFICE SIZE (in)	STRESS	TIME secs	TOTAL WT. #	INITIAL HEAD in/fuel	HEAD CORR in/fuel	ELEVATED CORR in/fuel	H_2O CORR in/H_2O	H_2O CORR in/fuel	AVG HEAD in/fuel	AVG PRESS psig	FLOW RATE #/min
70	1	1810	10	1.8	10	.17	2.75	12.0	15.7	22.78	.628	10.8
70A	1	1810	Start	-	10	-	2.75	9.0	11.8	19.05	.525	Steady
71	1/2x4	1780	10	4.6	11.75	.42	3.0	10.0	13.1	21.43	.591	27.6
71A	1/2x4	1780	Start	-	11.75	-	3.0	5	6.54	15.29	.421	Steady
72	1/2x4	1780	10	4.3	10	.4	3.0	10	13.1	19.7	.544	25.8
73	2	1760	5	.6	13	.05	2.25	5	6.54	17.24	.476	7.2
74	2	1760	10	.9	13	.08	2.25	5	6.54	17.21	.475	5.4
75	2	1730	5	5.7	11	.52	2.25	7	9.15	17.38	.479	68.4
76	1 x 4	1710	5	.6	11.75	.05	2.75	5	6.54	15.49	.427	7.2
76A	1 x 4	1710	Start	-	12.75	-	2.75	3.5	4.58	14.58	.402	Steady
77	1 x 4	1700	5	.7	11.5	.06	2.75	5	6.54	15.23	.42	7.2
78	1 x 3	1700	5	.9	12.75	.08	2.75	5	6.54	16.46	.454	10.8
78A	1 x 3	1700	Start	-	-	-	2.75	4	5.23	15.23	.42	Steady
79	1 x 3	1650	5	2.7	12.0	.24	2.75	6.5	8.5	17.51	.483	32.4
80	1 x 6	1650	5	.9	11.0	.08	2.75	5.0	6.54	14.71	.406	10.8
80A	1 x 6	1650	Start	-	11.0	-	2.75	4.0	5.23	13.48	.372	Steady
81	1 x 6	1630	5	3.4	12.0	.32	2.75	5.0	6.54	15.47	.427	40.8
82	1 x 6	1580	5	1.9	11.0	.17	2.75	5.0	6.54	14.62	.403	22.8
83	2 x 4	1580	5	7.6	13.0	.70	2.25	3.0	3.92	13.97	.385	91.2
83A	2 x 4	1580	Start	-	13.0	-	2.25	2.0	2.62	13.37	.268	Steady
84	2 x 4	1580	5	4.4	13.0	.40	2.25	2.5	3.27	13.62	.376	52.8

TABLE 3-IV (Cont'd)

ORIFICE FLOW TEST DATA - FUEL B, Batch 2

RUN NO.	ORIFICE SIZE (in)	STRESS	TIME secs	TOTAL WT. #	INITIAL HEAD in/fuel	HEAD CORR in/fuel	ELEVATED CORR in/fuel	H_2O CORR in/H_2O	H_2O CORR in/fuel	AVG HEAD in/fuel	AVG PRESS psig	FLOW RATE #/min
85	3	1580	5	.6	12.0	.05	1.75	3.0	3.92	14.12	.390	7.2
85A	3	1580	Start	-	12	-	1.75	2.5	3.27	13.52	.373	Steady
86	3	1560	5	2.1	12	.19	1.75	4.0	5.23	15.29	.421	25.2
87	4	1560	5	4.4	11.5	.4	1.25	3.0	3.92	13.77	.38	52.8
87A	4	1560	Start	-	11.5	-	1.25	2.0	2.62	12.87	.355	Steady
88	4	1550	5	3.3	10.5	.3	1.25	3.0	3.92	12.87	.355	39.6
89	1/2	1970	10	.3	14.0	.02	3.0	12.0	15.7	26.68	.736	1.8
89A	1/2	1970	Start	-	14.0	-	3.0	8.5	11.1	22.1	.61	Steady
90	1/2	1920	10	2.0	14.0	.18	3.0	20.0	26.2	37.02	-	12
91	1	1900	10	2.0	13.0	.18	2.75	12.0	15.7	25.77	.71	12
91A	1	1900	Start	-	14.0	-	2.75	8.25	10.8	22.05	.608	Steady
92	1	1850	10	6.7	12.0	.64	2.75	15.0	19.6	28.21	.78	41.4
93	1/2x4	1780	10	14.5	13.5	1.34	3.0	11.0	14.4	23.56	.65	87
93A	1/2x4	1780	Start	-	13.5	-	3.0	6.26	8.17	18.67	.515	Steady
94	1/2x4	1740	10	3.0	13.0	.27	3.0	8.0	10.46	20.19	.557	18
95	2	1800	5	3.9	12.0	.35	2.25	7.0	9.15	18.55	.512	46.8
95A	2	1800	Start	-	12.0	-	2.25	5.5	7.18	16.93	.467	Steady
96	2	1690	5	1.5	11.0	.14	2.25	7.0	9.15	17.76	.49	18
97	1 x 3	1690	5	.5	12.0	.04	2.75	6.0	7.85	17.06	.47	6
97A	1 x 3	1650	Start	-	13.5	-	2.75	4.1	5.36	16.11	.445	Steady
98	1 x 3	1630	5	1.4	11.5	.12	2.75	7.0	9.15	17.78	.49	16.8

TABLE 3-IV (Cont'd)

ORIFICE FLOW TEST DATA - FUEL B, Batch 2

RUN NO.	ORIFICE SIZE (in)	STRESS	TIME secs	TOTAL WT. #	INITIAL HEAD in/fuel	HEAD CORR in/fuel	ELEVATED CORR in/fuel	H_2O CORR in/H_2O	H_2O CORR in/fuel	AVG HEAD in/fuel	AVG PRESS psig	FLOW RATE #/min
99	1 x 3	1580	5	6.9	11.5	.13	2.75	6.0	7.85	16.47	.454	82.8
100	-	-	-	-	-	-	-	-	-	-	-	-
101	1 x 3	1920	5	4.6	13.0	.41	2.75	7.0	9.15	18.99	.524	55.2
101A	1 x 3	1920	Start	-	13.0	-	2.75	4.0	5.23	15.48	.427	Steady
102	1 x 4	1880	5	2.1	11.0	.19	2.75	7.0	9.15	17.21	.475	25.2
102A	1 x 4	1880	Start	-	12.0	-	2.75	6.0	7.85	17.10	.472	Steady
103	1 x 4	1850	5	1.9	10.5	.17	2.75	7.0	9.15	16.73	.462	22.8
104	1 x 6	1790	5	5.2	12.75	.48	2.75	5.0	6.53	16.05	.443	62.4
104A	1 x 6	1790	Start	-	12.75	-	2.75	4.0	5.23	15.23	.42	Steady
105	1 x 6	1730	5	2.2	12.0	.20	2.75	5.0	6.53	15.58	.43	26.4
106	2 x 4	1700	5	5.9	12.5	.54	2.25	4.0	5.23	14.94	.412	70.8
106A	2 x 4	1700	Start	-	13	-	2.25	1.5	1.96	12.71	.351	Steady
107	2 x 4	1670	5	.8	11.5	.07	2.25	3.0	3.92	13.10	.362	9.6
108	2 x 4	1650	5	3.8	14.5	.35	2.25	2.3	3.01	14.91	.411	45.6
109	3	1650	5	4.0	13.5	.36	1.75	4.0	5.23	16.62	.459	48.0
109A	3	1650	Start	-	13.5	-	1.75	3.0	3.92	15.67	.432	Steady
110	3	1620	5	3.0	12.0	.27	1.75	4.0	5.23	15.21	.42	36.0
111	4	1620	5	2.7	12.0	.25	1.25	2.0	2.62	13.12	.362	32.4
111A	4	1620	Start	-	12.0	-	1.25	1.5	1.96	12.71	.351	Steady
112	4	1610	5	2.9	11.0	.26	1.25	2.0	2.62	12.11	.335	34.8
113	4	1610	5	.2	9.0	-	1.25	2.0	2.62	10.37	.286	2.4

APPENDIX V

This section provides a more detailed discussion of the pump performance test program than that included in the main text. The test data tabulated herein is graphically summarized in Figure 31.

PURPOSE

This phase of the gelled and emulsified fuel test program was performed in order to establish comparative pump performance curves using the fuels under discussion. With this information, in conjunction with component and line pressure drop data, existing fuel system performance could be calculated. The pump inlet configuration was identical to that of the pump-down test i.e., minimum length of inlet piping since previous tests proved the pump would not prime with additional flow resistance.

DESCRIPTION

The test equipment utilized in this test is identical to that shown in Appendix III Figure 3.3 with the exception that the pump was located within a 55 gallon steel drum and that a simple bellmouth inlet was installed. By incrementally opening the outlet valve prior to each run the data tabulated in Table 1-V was recorded.

TEST APPARATUS

The test apparatus used to determine pump performance is schematically presented in Figure 3.3. The following list of equipment applies to this portion of the test program.

Item	Name	Description
1	SCALE	Toledo Scale Co., 0 - 1000 lbs, capacity, 1 lb. graduations
2	DRUM	55 gallon capacity coated steel drum
3	VALVE	Lunkenheimer Corp., 2" globe valve
4	GAUGE	Acragage, 0 - 30 psi
5	PUMP	Pesco Prod. Div., Borg-Warner Corp. P/N 112-303
6	INLET	Standard 2 inch flared bellmouth
7	DRUM	55 gallon capacity coated steel drum
8	PUMP	Jabsco Pump Div., ITT Corp. Model #777-37
9	TIMER	Minerva Stopwatch

TABLE 1-V

PUMP TEST

FUEL B

YIELD STRESS. 810 DYNES/CM2
TEMP. 88°F

RUN #	WEIGHT FLOW (lbs)	TIME (secs)	GAGE PRESS. (psi)	HEAD (inches) BEFORE	HEAD (inches) AFTER	AVG. HEAD (inches)	HEAD CORR. (psi)	FLOW RATE (lbs/hr x 10^3)	OUTPUT PRESS. (psi)
1	0	-	20.	29.	29.	29.00	.014	0	20.01
2	6.5	31.8	19.75	29.	28.5	28.75	.021	0.74	19.77
3	11.0	16.0	18.75	28.5	27.5	28.00	.041	2.48	18.79
4	13.0	12.0	12.25	27.5	26.5	27.00	.069	3.90	12.32
5	14.5	9.4	10.25	26.5	23.5	25.00	.123	5.56	10.37
6	19.0	11.0	10.25	23.5	21.5	22.50	.192	6.22	10.44
7	16.0	5.8	9.75	21.5	19.5	20.50	.246	9.93	10.00
8	20.0	5.3	7.0	19.5	18.0	18.75	.294	13.60	7.29
9	18.0	5.8	7.5	18.0	15.5	16.75	.349	11.20	7.85
10	19.5	5.8	7.0	15.5	13.5	14.50	.411	12.10	7.41
11	21.0	5.8	6.75	13.5	11.5	12.50	.466	13.05	7.22
12	13.5	4.5	6.75	11.5	10.0	10.75	.514	10.80	7.26
13	30.0	13.8	9.25	12.5	10.0	11.25	.501	7.83	9.75

TABLE 1-V (Cont'd)

PUMP TEST

JP-4 TEMP. 98°F

RUN #	WEIGHT FLOW (lbs)	TIME (secs)	GAGE PRESS. (psi)	HEAD (inches) BEFORE	HEAD (inches) AFTER	AVG HEAD (inches)	HEAD CORR (psi)	FLOW RATE (lbs/hr x 10^3)	OUTPUT PRESS. (psi)
1	0		21.	27.	27.00	27.	.068	0	20.82
2	14.0	6.5	17.25	27.0	26.0	26.50	.082	7.75	17.33
3	8.0	6.2	18.5	26.0	25.0	25.50	.109	4.65	18.61
4	10.0	4.8	17.0	25.0	23.5	24.25	.143	7.51	17.14
5	12.0	4.8	16.0	23.5	22.25	22.87	.183	9.00	16.18
6	17.0	5.7	15.0	22.25	20.5	21.37	.221	10.72	15.22
7	20.0	5.85	14.25	20.5	18.25	19.37	.276	12.30	14.53
8	16.0	5.1	14.0	18.25	16.5	17.37	.330	11.30	14.33
9	21.0	5.1	12.5	16.5	14.25	15.37	.384	14.83	12.88
10	22.0	4.6	11.0	14.25	12.00	13.12	.445	17.20	11.45
11	21.0	4.0	9.0	12.0	10.50	11.25	.496	18.90	9.50
12	19.0	3.15	7.3	18.5	16.00	17.25	.333	21.75	7.63
13	21.0	3.5	7.3	16.0	14.00	15.00	.394	21.60	7.69
14	18.0	3.0	6.4	14.0	11.75	12.87	.453	21.60	6.85
15	20.0	3.1	5.6	11.75	9.50	10.67	.512	23.20	6.11
16	16.5	2.3	5.0	9.50	8.00	8.75	.564	25.80	5.56
17	17.5	2.3	5.0	11.50	9.50	10.5	.517	27.40	5.52

TABLE 1-V (Cont'd)

PUMP TEST

FUEL G

TEMP. -100°F

RUN #	WEIGHT FLOW (lbs)	TIME (secs)	GAGE PRESS. (psi)	HEAD (inches) BEFORE	HEAD (inches) AFTER	AVG. HEAD (inches)	HEAD CORR. (psi)	FLOW RATE (lbs/hr x 10^3)	OUTPUT PRESS. (psi)
1	0	-	21.5	29.5	29.0	29.25	.007	0	21.50
2	9.0	11.6	20.5	29.0	27.0	28.0	.043	2.79	20.54
3	16.0	9.3	19.5	27.0	25.5	26.25	.093	6.19	19.59
4	17.5	6.2	16.5	25.5	23.5	24.5	.143	10.20	16.64
5	7.5	3.8	16.25	23.5	23.0	23.25	.178	7.10	16.43
6	16.0	4.6	14.8	23.0	21.25	22.12	.210	12.50	15.01
7	14.0	4.2	13.8	21.25	19.5	20.37	.260	12.00	14.06
8	19.0	3.7	10.7	19.5	17.75	18.63	.310	18.50	11.01
9	24.0	4.2	7.7	17.75	15.25	16.50	.370	20.60	8.07
10	20.	3.0	6.5	15.25	13.5	14.37	.432	24.00	6.93
11	16.5	2.3	6.6	13.5	11.75	12.63	.480	25.80	7.08
12	16.	2.7	6.4	11.75	10.25	11.00	.527	21.40	6.93
13	19.	3.3	5.8	16.0	14.0	15.00	.414	20.75	6.21
14	18.	3.1	5.8	14.0	12.0	13.0	.470	20.90	6.27
15	20.	3.0	6.2	12.0	10.25	11.12	.524	24.00	6.72
16	11.0	4.7	17.2	10.25	9.25	9.75	.563	8.43	17.76