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Modification of Jet Fuels to Decrease the Fire Hazard in Survivable Aircraft Crashes

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This paper is directed to the modification of jet fuels to reduce the inherent fire hazard of such fuels. Some of the problems and compromises involved in this development program are discussed. The theoretical concept pursued is outlined and some of the physical properties of the final compromise modified fuel are shown.

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INTRODUCTION

Aviation fuels have presented a fire hazard throughout aviation history. Many different safety concepts have been investigated to minimize this hazard inherent in hydrocarbon fuels. However, the practical solutions employed to date have been to require safe fuel-handling practices and upgrade the safety engineering in aircraft design. This total effort has resulted in an exceptionally good safety record for aviation, but the aviation fuel itself has continued to be a target for safety improvement.

BACKGROUND

This paper is directed to the modification of jet fuels to reduce the inherent fire hazard of such fuels. Some of the problems and compromises involved in this development program are discussed. The theoretical concept pursued is outlined and some of the physical properties of the final compromise modified fuel are shown.

The development of the jet engine required a change in aviation fuels, from gasoline to kerosene types of fuel. In Table 1¹, the aviation fuels currently being utilized are listed along with a few of the physical properties of such fuels.

There appears to be a fair amount of difference of opinion among aviation people as to the fire hazards associated with these various aviation fuels. In discussing this subject, one must be alert for the individuals point of reference, i.e.: (a) the USAF may be referring to the fire explosion hazard from gunfire, (b) the U. S. Army referring to the fire explosion from vertical impact of helicopters, (c) the U. S. Navy referring to accidental fuel fires aboard ship, and (d) commercial transport people referring to passenger plane crashes where the passengers would

have survived if severe fuel fires had not occurred. It should also be noted that each group is generally using a different fuel as his reference point, i.e.: (a) USAF and Army -- JP-4, (b) U. S. Navy -- JP-5, and (c) Commercial Transport -- Jet A or A-1.

DEFINING THE PROBLEM

All of the aviation fuels obviously have one common characteristic -- the ability to form an explosive mixture when combined with air. The specific fire hazard must, therefore, be defined in terms of the environment in which the hazard is expected to occur. This has been an area of frustrated investigation due to the extensive environmental variables.

Several years ago, programs were initiated by certain government agencies to explore again the feasibility of modifying aviation fuels to obtain a less hazardous fuel. This resulted in what we will term the "thickened fuels" program. The object was to thicken the fuel by some means, normally gellation or emulsification, so that the fuel would not cause violent explosions or rapid flame spread when subjected to certain simulated crash or gunfire environments. (Aircraft retrofit systems, such as reticulated foam and fuel containment, were also investigated but will not be a subject for discussion here.) The practical utilization of such thickened fuels in existing aircraft was not overlooked but the general assumption was made that, if such fuels gave the desired safety performance, then a practical method to utilize such fuels would be developed. This assumption was invalid, but the early feasibility studies on less fire hazardous fuels served to stimulate various researchers to develop more practical fuels.

Dow became interested in the thickened fuel programs in 1967 due to proprietary technology in thickening and modifying various liquid ali-

¹ Numbers in parentheses designate References at end of paper.

Table 1 Physical Properties of Various Aviation Fuels (1)

Fuel type	Freeze point, deg F	Flash point, deg F	Vapor pressure, psi	Average specific gravity, 60/60 F	Approximate distillation range, ^a deg F
AVGAS 100/130	-76		6.0	0.71	150-338
JP-4	-76	-10	2.5	0.77	140-470
JP-5	-55	140	0.1	0.83	365-550
JP-6	-65	90		0.81	250-550
JP-8	-51	116	0.1	0.80	320-550
JET A	-40	110	0.1	0.80	330-550
JET A-1	-58	110	0.1	0.80	330-550
JET B	-60		2.5	0.78	140-470

^a Lower limit is usually not indicated in military specifications and appears here as an approximate figure.

phatic and aromatic hydrocarbons. The Dow approach to thickened fuels was to modify a commercial jet fuel with a hydrocarbon additive that would change the fuel into a pseudoplastic gel structure. Through the cooperation of the FAA (NAFEC), Atlantic City, New Jersey, numerous tests were run to determine the resistance to fire explosion when subjected to a misting condition in the presence of an ignition source.

Fig. 1 shows a diagram (2) of the crash fire hazard test facility at NAFEC where one gallon of test fuel, contained in a polyethylene bag in a foam cartridge, is propelled at 90 mph into a screen which sprays the fuel over the fire pots. Jet fuel thickened with this polymer provided a significant reduction in the fire explosion hazard (Radiometer readings of 0.0 to 0.5 versus 12 to 14 for unmodified Jet A-1), would thin rapidly with shear and thus perform as fuel to run a jet engine (actual tests conducted), and also showed a very slow flame spread rate. Although this polymer additive could not be considered practical (it contained undesired sodium ions), these tests served as a benchmark for future development.

Dow was successful in making a new polymer that does not contain metallic ions and gave the familiar pseudoplastic gellation characteristics to kerosene-type jet fuels.

Feasibility studies were continued by the

FAA until it became apparent that such highly viscous fluids would not be acceptable for use in existing aircraft (3).

One of the major problems with the thickened fuels was the slow flow rate under static conditions, indicating a high percentage of residual fuel would remain in aircraft fuel tanks at practical pump-out rates.

In March 1970, the FAA (NAFEC) issued a Request for Proposal titled "Chemical and Physical Study of Gelled Hydrocarbon Fuels." Dow was awarded a contract, and part of the data reported here is taken from the work done under this contract, Report No. FAA-RD-71-34 (4).

Although the primary problem to be solved is elimination or significant reduction of the fire hazard, many other criteria must be met in order for a modified fuel to be of any commercial significance. Even the fire hazard problem must be defined in rather specific terms in order to take steps to solve it.

In Table 2 are a few statements and assumptions made to attempt to define the fire hazard problem in commercial transport jet fuel (Jet A or A-1).

In approaching the problem of modifying the base jet fuel, some rather basic requirements must be considered. Table 3 suggests some of these requirements for the modified fuel.

Obviously, this is not a complete list of require-

Table 2 Defining the Fire Hazard Problem

- 1 Explosive fuel mist is formed in or around an aircraft during a survivable crash and is usually ignited.
- 2 Passengers could escape uninjured or with minor injuries if no fuel explosions occurred.
- 3 A reduction in the flame spread rate of the fuel would give passengers more time to evacuate the aircraft.
- 4 The fire hazard reduction can be measured by currently used test methods and will correlate with actual survivable aircraft crash environments.
- 5 Modifying the fuel misting characteristics will reduce the fire explosion hazard.

ments but should point out that modifying a jet fuel to achieve reduction in fire hazard is not without complications and compromises.

SOLVING THE PROBLEM

Proprietary work at Dow has demonstrated that the fluidity and rheological characteristics of jet fuel, thickened with a Dow hydrocarbon polymer, can be significantly changed by the addition of trace quantities of certain materials, such as glycols, alcohols, ethers, bases, etc. (patent pending). With the knowledge that the rheological profile of jet fuel gelled with the Dow polymer could be significantly changed and still maintain a major reduction in the fire hazard, efforts were taken to obtain a satisfactory compromise between fluidity and fire hazard.

Simple flow equipment shown in Figs. 2, 3, and 4 were used to obtain initial data with actual pump-out tests conducted on certain modified fuels, Fig. 5. The container is inclined 4° over the 9-in. width and 6° over the 14-in. length with a 0.5-in. orifice in the lower corner. The flow rate and residual fuel were measured to compare fuels. In Fig. 2 the Ford Cup was modified by removing the die thus giving an orifice opening of 0.335 in. The weight of fuel versus head pressure was plotted to compare flow rates of various fuels. Figs. 3 and 4 show the visual difference in flow between a thick fuel, Fig. 3, and a viscosity modified fuel, Fig. 4. Fire hazard ratings were obtained in cooperation with NAFEC using the facilities previously shown

Table 3 Some Basic Requirements for a Modified Jet Fuel

- 1 Reduce misting and/or flammable characteristic of misting in a specific shear range.
- 2 Maintain or increase fuel's calorific value (18,400 Btu/lb).
- 3 Readily atomize and combust in burner can.
- 4 Maintain adequate flow rates in fuel system.
- 5 Have acceptable residual fuel weight.
- 6 Produce no corrosion problems (aircraft and engine components).
- 7 No increase in current fuel contamination problems.
- 8 Reduce flame spread rate.
- 9 Easy and reliable method of addition of fuel modifiers.
- 10 Will not increase ecological problems.
- 11 Will not increase fire fighting problems.
- 12 Must not significantly increase cost.

in Fig. 1. Apparent viscosity and rheological phenomena were determined using a variety of instruments such as those shown in Figs. 6, 7, 8, 9, and 10. The Brookfield RVT and Rotovisco viscometers have proven to be the most useful instruments for our work to date.

A brief mention of some basic rheology is appropriate in order to describe the rheological characteristics we are dealing with in this modified fuel. Fig. 11 shows some flow curves for various ideal rheological bodies (5).

The ratio of applied shearing stress to rate of shear is called the coefficient of viscosity, or simply viscosity for Newtonian fluids, and apparent viscosity for nonlinear stress-versus-shear-rate curves.

$$\frac{\text{Shearing Stress}}{\text{Shear Rate}} = \text{Viscosity in poises (dynes-sec/sq cm)}$$

The curves in Fig. 11 are described as:

- A = Newtonian, the viscosity is constant.
- B = Pseudoplastic, the apparent viscosity decreases with shear rate.

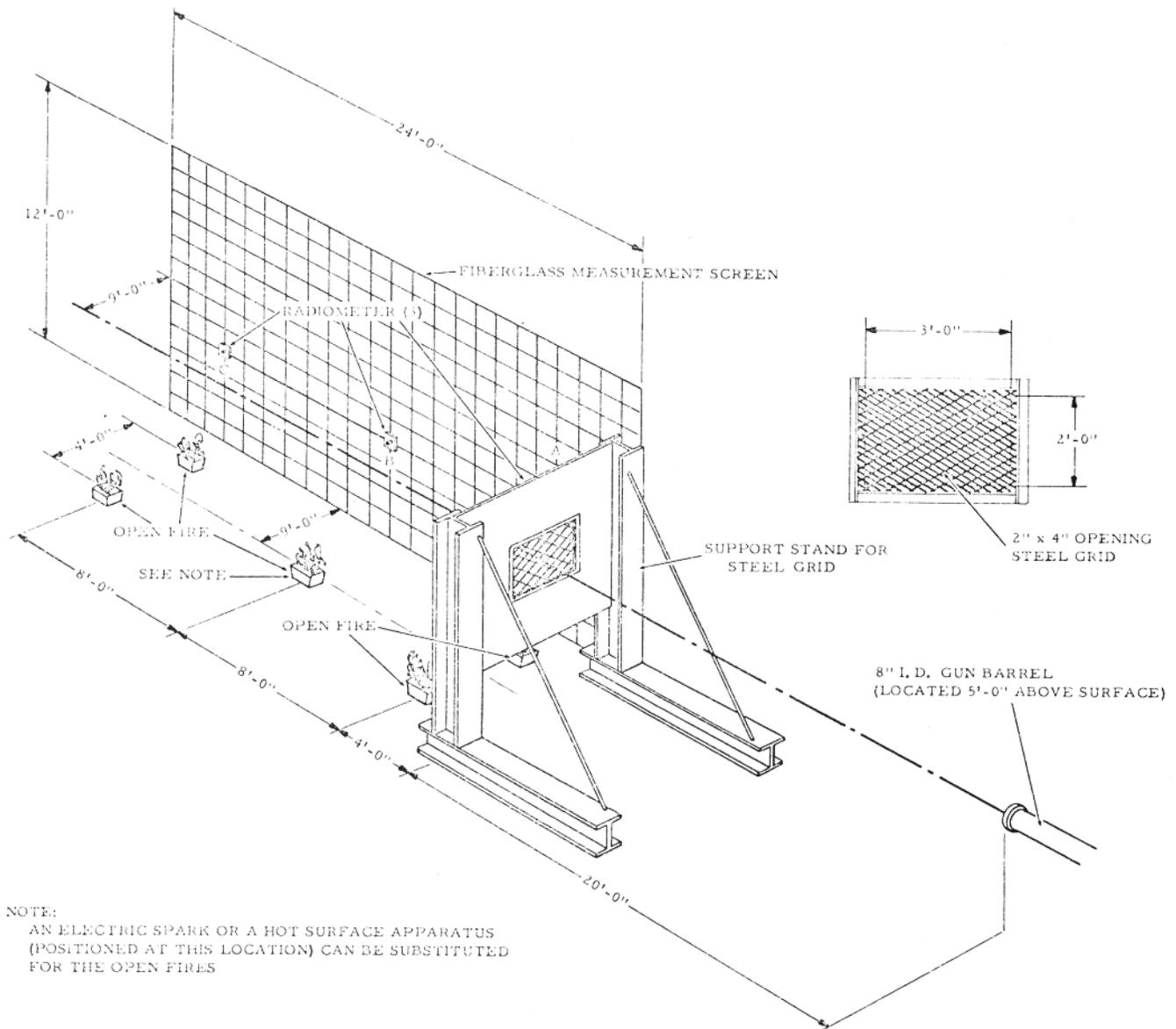


Fig. 1 Crash fire hazard test facility at FAA
(NAFEC), Atlantic City, New Jersey

- C = Dilatant, the apparent viscosity increases with shear rate.
- D = Pseudoplastic with yield value.
- E = Dilatant with yield value.

In considering the optimum design of a modified fuel with reduced fire hazard, we theorized that the rheological profile should ideally be similar to the example curve shown in Fig. 12.

This type of flow curve indicates a fluid that would readily flow under static, gravity conditions, resist misting under relatively low shear conditions, and then readily flow under high shear conditions such as would exist during atomization at the burner can.

Following this hypothesis, a modified jet

fuel was formulated with the flow characteristics indicated in Fig. 12. This modified jet fuel based on Jet A-1 has been designated Experimental Jet Fuel XD-7129.02FAA and is being extensively tested for practical utility. A typical flow curve for XD-7129.02FAA is shown in Fig. 13 (4) compared with unmodified Jet A-1. Fig. 14 (4) shows viscosity versus shear rate.

RESULTS

Some of the typical characteristics of XD-7129.02FAA are shown in the following tables and graphs. Table 4 shows that the heat of combustion value is essentially unchanged in the modified fuel.



Fig. 2 Modified No. 4 Ford cup equipment



Fig. 3 Inclined pan gravity flow equipment (thick gel)

Table 4 Heat of Combustion (ASTM D2382-65) (4)

<u>Fuel</u>	<u>Cal/g.</u>	<u>Btu/lb gross</u>	<u>Btu/lb net</u>
Jet A-1	11,020	19,840	18,570
Experimental jet fuel XD-7129.02FAA	11,000	19,800	18,530

Table 5 shows that the low shear viscosity is affected by aging at different temperatures.

Table 5 Effect of Temperature on Viscosity Stability of XD-7129.02FAA (4)

<u>Aging temperature (24 hr), deg F</u>	<u>Viscosity at 75 F (Brookfield RVT, 10 rpm No. 3 spindle, cps)</u>
-65	400
0	300
75	300
135	120

This is essentially a conditioning test where the fuel is held at the various temperatures for 24

hr, then aged at 75 F for 24 hr for recovery to room temperature. The viscosity-versus-shear-rate curve from the Rotovisco Viscometer, Fig. 15 (4), shows the effect in a higher shear-rate range.

Table 6 shows the Brookfield viscosity at various temperatures and indicates a significant change in low shear viscosity from high to low temperatures.

The thermal conductivity of XD-7129.02FAA is essentially unchanged over a temperature range of 120 C to -40 C. In Fig. 16 are curves plotting thermal conductivity versus temperature (4).

Note that the thermal conductivity of unmodified Jet A-1 increases as the temperature decreases; however, this may also be true of XD-



Fig. 4 Inclined pan gravity flow equipment
(modified thickened fuel: thin gel)

Table 6 Effect of Temperature on Viscosity

Temperature (deg F)	Viscosity (Brookfield RVT, 10 rpm, No. 3 spindle)	
	Sample 1, cps	Sample 2, cps
135	30-40	
75	110-250	
0	140-480	
-40	270-450	

Table 7 Viscosity Stability (4)

Aging time at room temperature, days	Viscosity (Brookfield RVT No. 3 spindle, 10 rpm)	
	Sample 1, cps	Sample 2, cps
1	370	320
21	210	200
28	200	
42		190

7129.02FAA if tested under dynamic conditions.

There is some data now available that indicates that the viscosity of XD-7129.02FAA will drift downward during long-term storage, Table 7. At room temperature (75 F) aging under static conditions, the low shear viscosity drifted about 40 to 46 percent after one to one and a half months, but the trend is toward stabilization after about two weeks.

The fire hazard appears to be significantly reduced in Experimental Jet Fuel XD-7129.02FAA. Three different tests have been performed in an effort to predict the fire hazard in simulated aircraft crash environments. Extensive testing at the FAA, NAFEC has consistently shown excellent fire explosion resistance (fuel misting in the presence of an ignition source) using the NAFEC air gun explosion test equipment.

A number of test results are shown in Table 8.

Table 8 Fire Explosion Test Data (4)

Fuel	Radiometer reading, Btu/sqft/sec		
	A	B	C
Jet A-1	8.0	12.1	7.1
XD-7129.02FAA	0.4	0.1	0.3
XD-7129.02FAA	0.6	0.4	0.4
XD-7129.02FAA	0.1	0.0	0.0
XD-7129.02FAA	0.05	0.14	0.12
XD-7129.02FAA	0.0	0.09	0.12
XD-7129.02FAA	0.27	0.27	0.06
XD-7129.02FAA	0.27	0.27	0.12
XD-7129.02FAA	0.37	0.59	0.30
XD-7129.02FAA	0.05	0.18	0.12

Tests conducted by the Bureau of Mines showed XD-7129.02FAA to have definite resistance to fire and fire explosion compared to base Jet A. These tests were vertical and 60-deg angle drop tests using 5-gal containers of fuel impacted near ignition sources (6).

The fire and fire explosion resistance of XD-7129.02FAA gave excellent results in a simulated crash test conducted by Dynamic Sciences, Inc. for the U. S. Army. In this test, 13 gal of XD-7129.02FAA (at 100 F) were impacted at 44 mph against a 45-deg angle cement wall, the tank ruptured, and the fuel was sprayed over different types of ignition sources. No fire or fire explosion occurred in these tests.

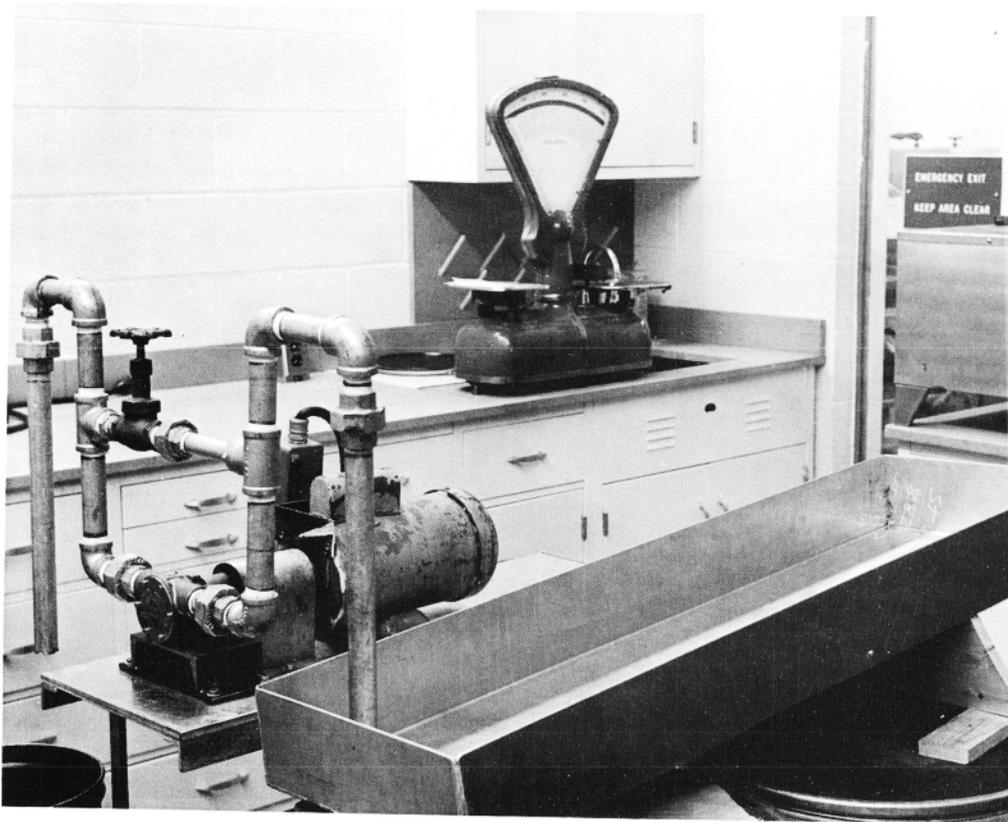


Fig. 5 Pump-out test equipment

CONCLUSIONS

In this paper, we have very briefly reviewed some of the highlights of the development of modified jet fuels. Perhaps another look at the suggested requirements for a modified jet fuel shown previously in Table 3 will serve as a guide to arrive at some conclusions.

1 The misting tendency has been reduced in the shear range assumed to be encountered in a survivable aircraft crash environment.

2 The fuel's calorific value has not been decreased.

3 Preliminary tests at NAFEC show adequate combustion in the burner can. Extensive testing is required.

4 Flow rates have been increased significantly compared to the former thick gels and emulsions. Extensive testing is also required to determine whether or not serious problems remain.

5 The residual fuel weight will probably be greater than unmodified fuel, since existing aircraft fuel systems were designed to control unmodified fuel. The true significance of this problem requires extensive testing.

6 Previous corrosion test data on similar systems showed no problems with various grades of aluminum, magnesium, brass, titanium, and steel. No serious problems are, therefore, anticipated with XD-7129.02FAA.

7 Most fuel contaminants are of higher specific gravity than the fuel and, therefore, settle to the bottom. The same observation has been made with XD-7129.02FAA, since this modified fuel has no yield value. However, the viscosity is greater; therefore, the rate of settling will probably be slower. Water contamination is currently a major problem with unmodified jet fuels and probably will not be any less with XD-7129.02FAA.

8 A noticeable decrease in flame spread rate is achieved with XD-7129.02FAA.

9 The polymer additive is a fine powder and can readily be dispersed in the jet fuel with agitation at ambient temperature. The additional flow modifiers are liquid and likewise readily mix with the base fuel.

10 No additional ecological problems are anticipated since the fuel modifiers will produce carbon monoxide and water when decomposed during combustion.

11 Preliminary fire fighting tests indicate

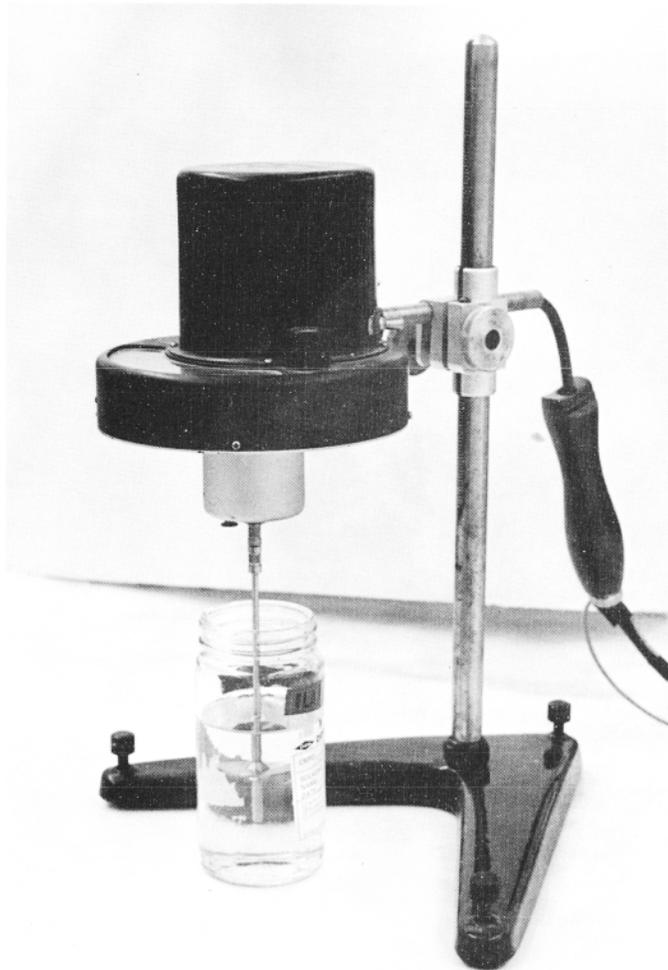


Fig. 6 Brookfield RVT viscometer

no change required in conventional methods.

12 It should be obvious that there will be additional costs incurred with a modified jet fuel. Since this project is still in the early feasibility development stage, it is premature to discuss this problem.

Although there are many problems yet to be solved, we believe that significant progress has been made in the development of a practical, less hazardous jet fuel.

ACKNOWLEDGMENTS

Many people within Dow and the FAA have made valuable contributions to this project. The cooperation of NAFEC personnel in scheduling and conducting tests has been excellent. Likewise within Dow, the contribution of rheological data and consultation by T. Alfrey, B. J. Meister, and T. Selby have been invaluable. We also acknowledge and appreciate the work done by various

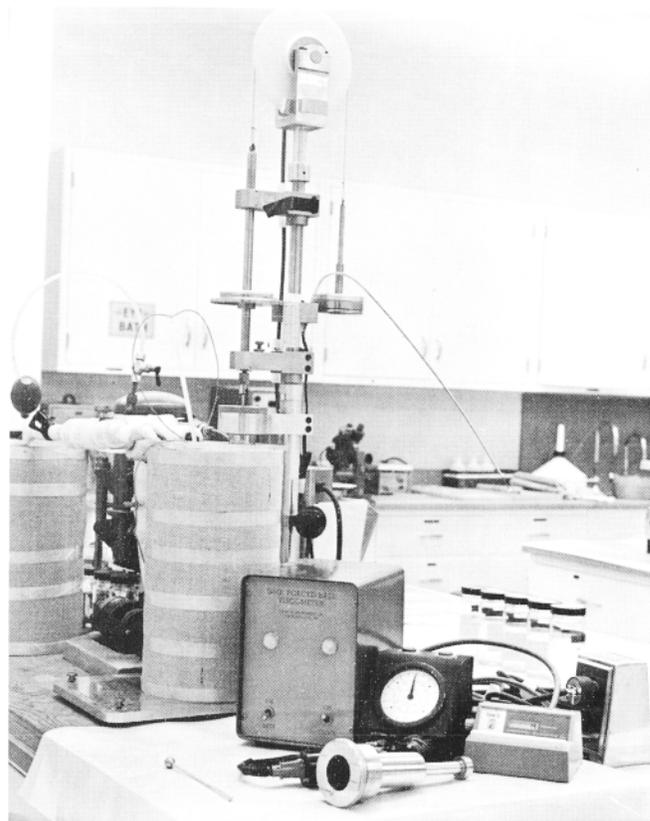


Fig. 7 Forced ball viscometer

Dow laboratories to obtain necessary key data.

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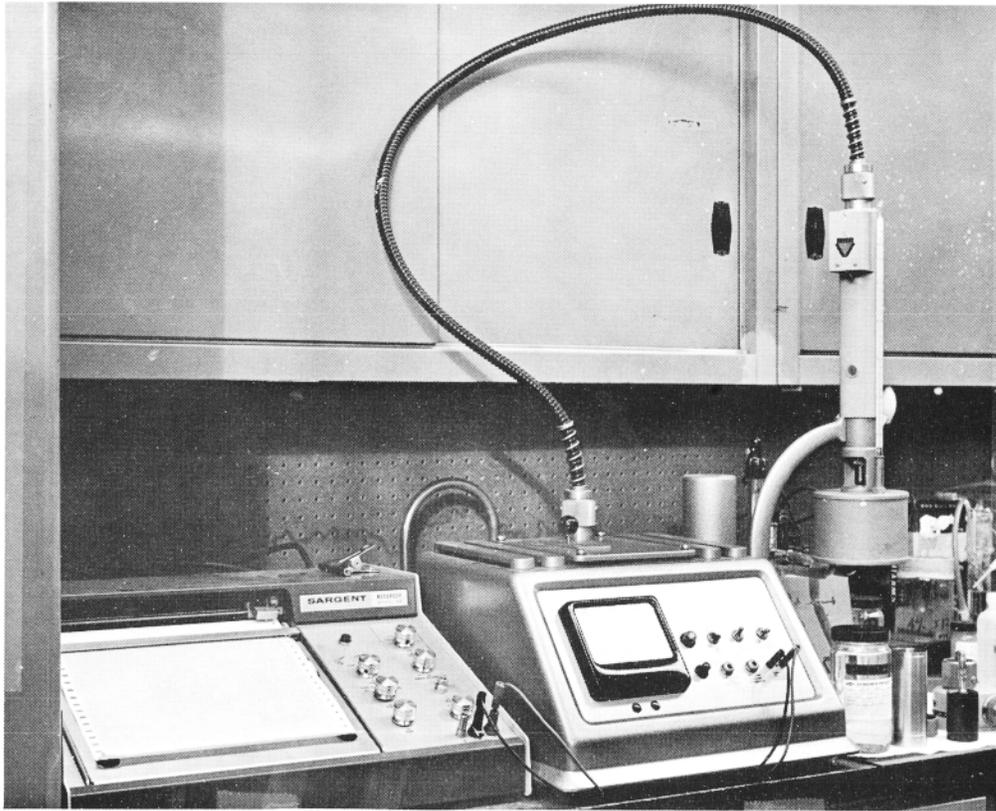


Fig. 8 Rotovisco viscometer

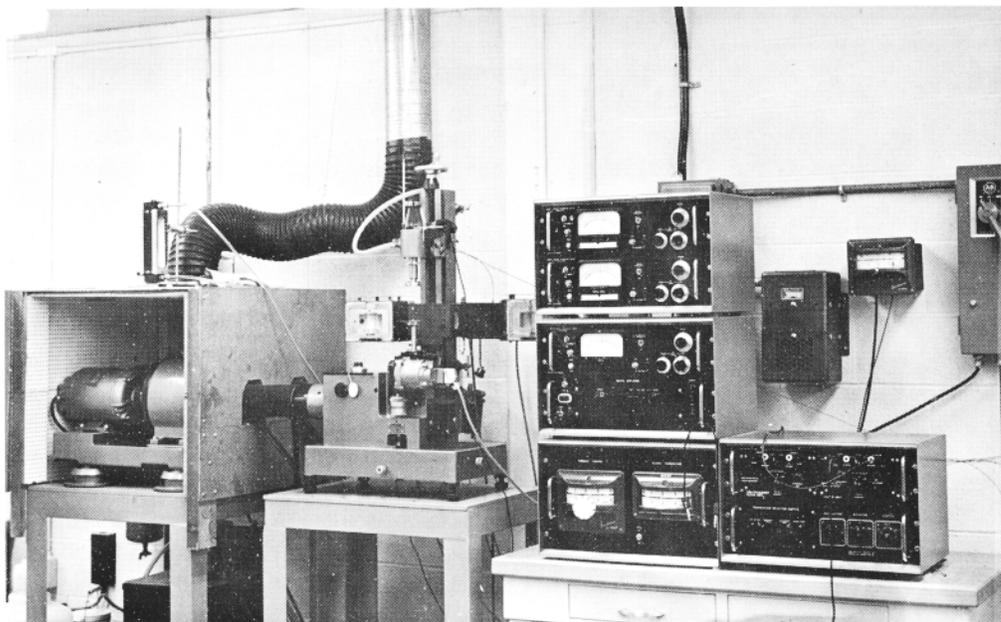


Fig. 9 Weissenberg rheogoniometer

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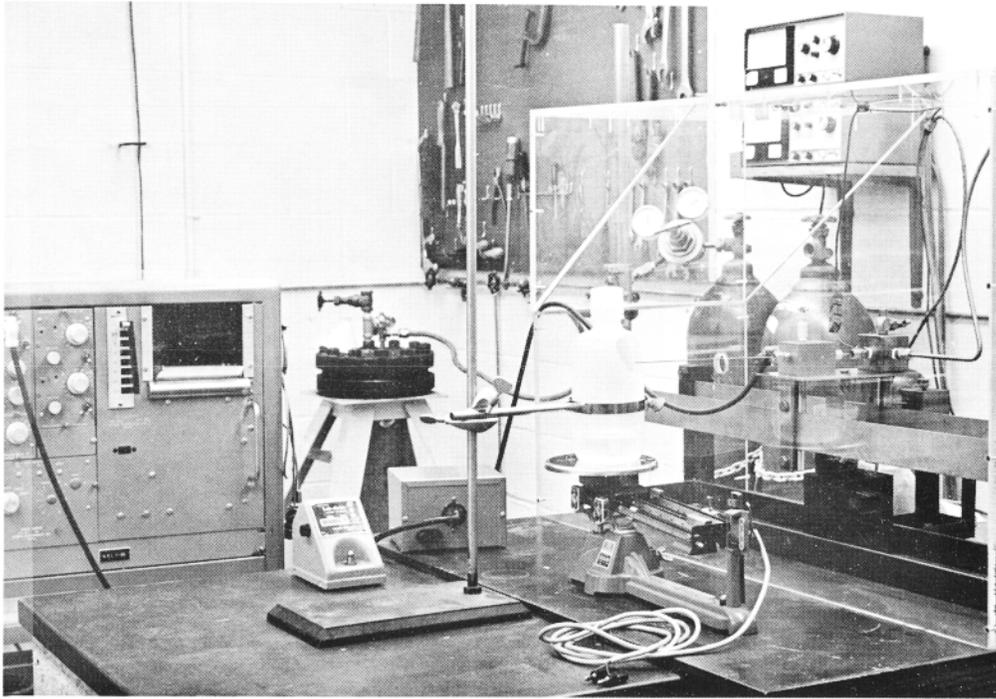


Fig. 10 Thrust jet instrument

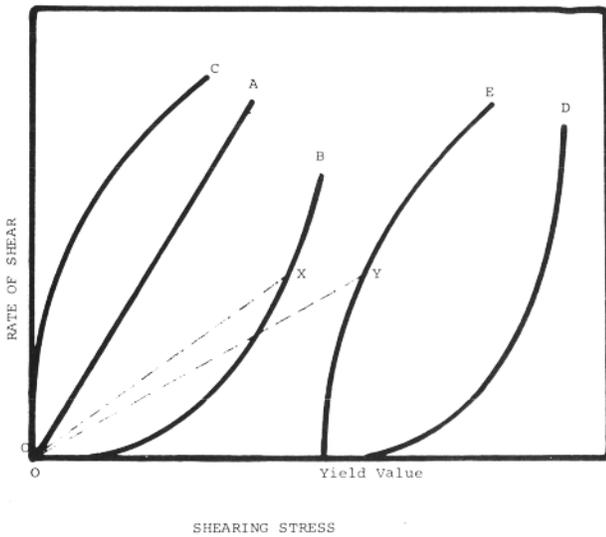


Fig. 11 Flow curves for various ideal rheological bodies

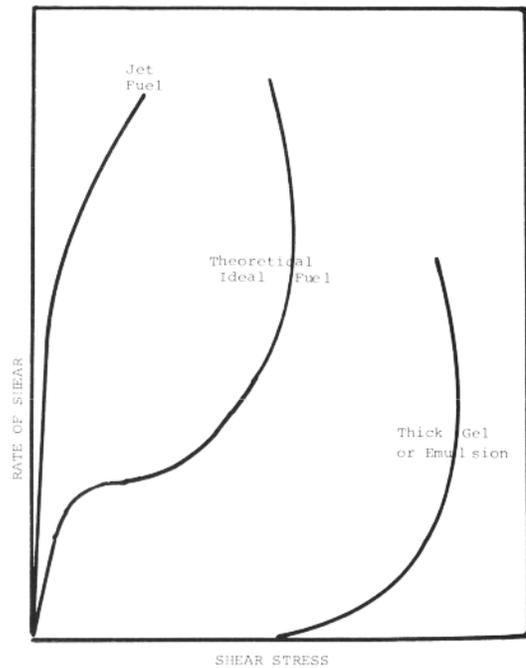


Fig. 12 Theoretical flow curve for modified jet fuel

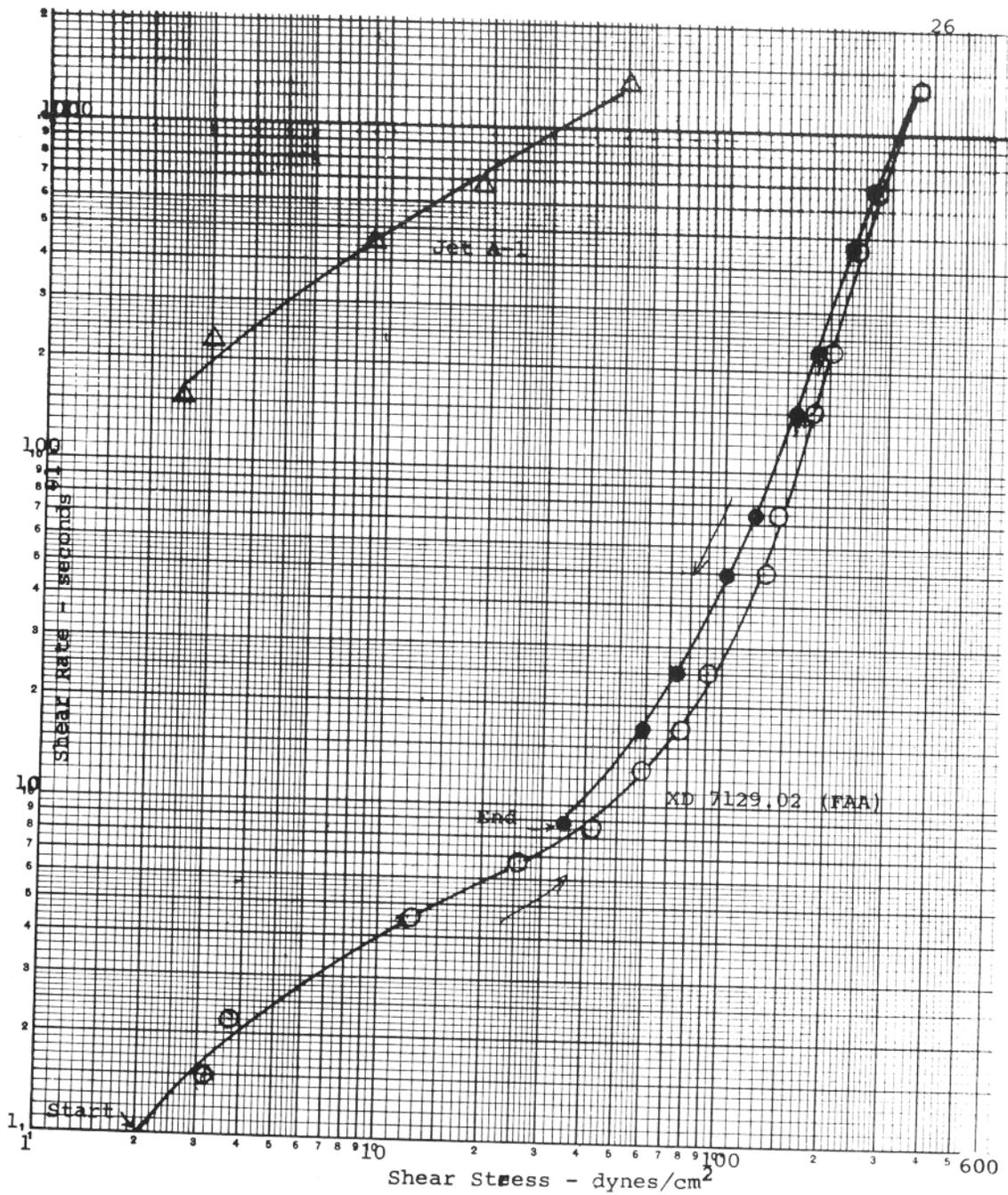


Fig. 13 Shear rate versus shear stress (rotovisco viscometer) experimental jet fuel XD-7129.02 (FAA)

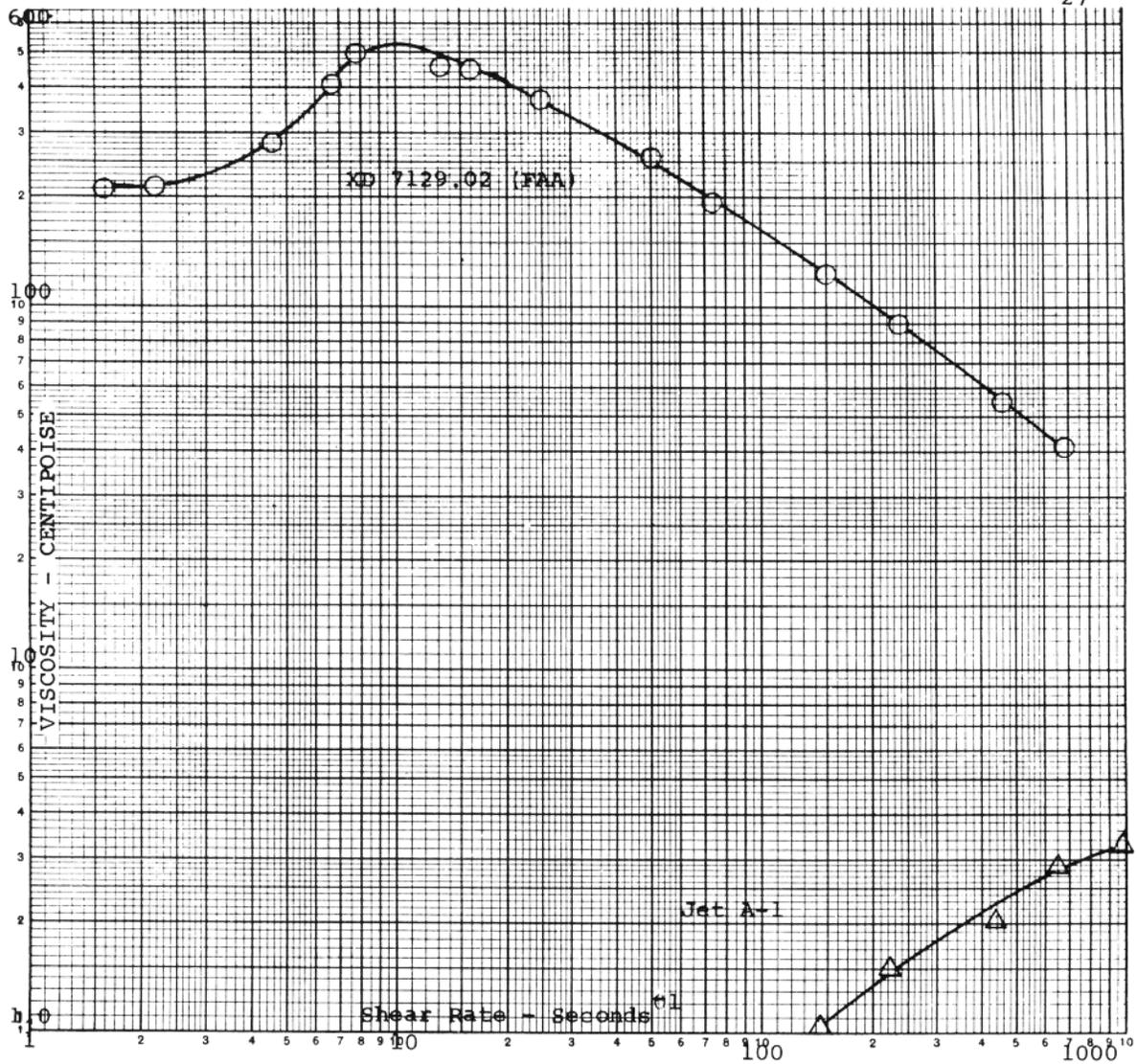


Fig. 14 Viscosity versus shear rate (rotovisco viscometer) experimental jet fuel XD-7129.02 (FAA)

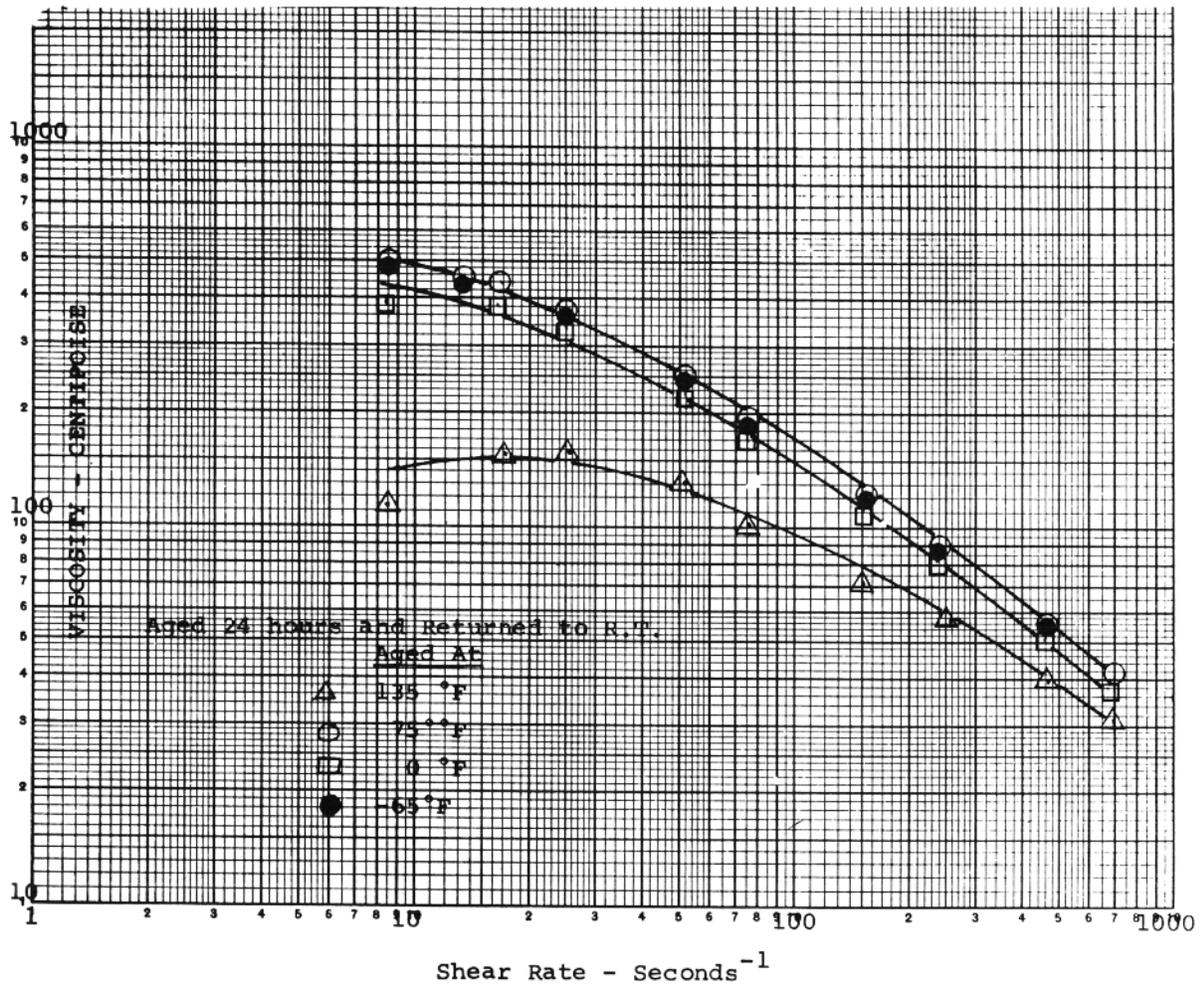


Fig. 15 Viscosity versus shear rate (rotovisco viscometer) experimental jet fuel XD-7129.02 (FAA) aged at various temperatures

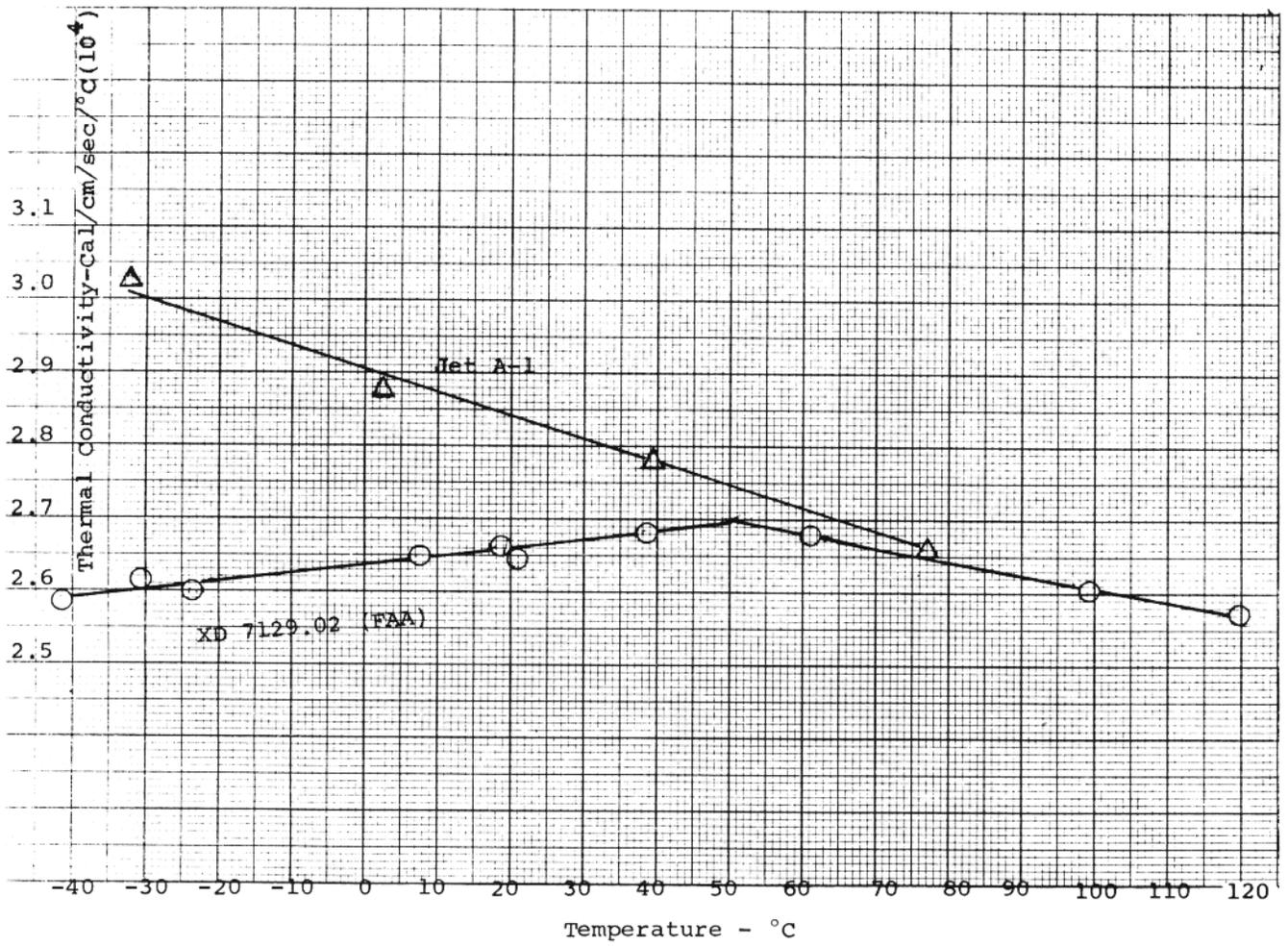


Fig. 16 Thermal conductivity versus temperature experimental jet fuel XJ-7129.02 (FAA)