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OF AVIATION FUELS
I. A COMPARISON OF TEST METHODS

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J.R. Coleman and L.D. Gallop

DEFENCE RESEARCH ESTABLISHMENT OTTAWA
REPORT 919

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ABSTRACT

Six bench scale test methods were assembled, which provide various measures of the lower limits of usability of aviation fuels. One of these was designed to measure fuel flow through reticulated polyurethane foams, used as a flame suppressant in aircraft fuel tanks. These tests were employed with fuels ranging from specification Jet A-1 to middle distillate blends of elevated freeze point containing No. 2 Diesel.

A series of comparisons of results by the several methods is presented. A small amount of work was conducted using two flow improvers with several of the higher-freezing blends.

RÉSUMÉ

Six méthodes d'essai au banc ont été élaborées, qui fournissent diverses mesures des limites inférieures d'utilisation des carburants d'aviation. Une de celles-ci a été conçue pour mesurer l'écoulement de carburant à travers les mousses de polyuréthane réticulé, employées comme agent extincteur dans les réservoirs de carburant d'aéronef. Ces essais ont été faits avec des carburants allant du Jet A-1 au mélanges de distillation moyenne à point de congélation élevé et contenant du diesel n^{o} 2.

Une série de comparaisons des résultats émanant de plusieurs méthodes est présentée. Une petite partie du travail a été exécuté qui comprenait l'emploi de deux améliorant l'écoulement dans plusieurs des mélanges à point de congélation élevé.

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1.0.0 INTRODUCTION

One consequence of the petroleum supply disruption of recent years is a move toward the inclusion of heavier, higher-boiling middle distillate fractions in aviation turbine fuels with the attendant result of higher freeze points. Specifications for the commercial aviation fuel, Jet A-1, established when petroleum was relatively plentiful and inexpensive, made provision for aircraft operation at low ambient temperatures by stipulating a freeze point sufficiently low (-50°C) that in almost no circumstances could fuel begin to solidify in the tanks. In the test method (ASTM D2386 (1)) prescribed in the specification, a sample of fuel is cooled with stirring to the point of wax separation and then rewarmed, and the freeze point taken as the temperature at which the last trace of wax redissolves; thus, at the freeze point so defined the fuel is entirely liquid. It has become clear that this method is extremely conservative (2,3); it was demonstrated that it is possible, even after appreciable phase separation, to pump part or all of the semi-solid fuel out of an aircraft fuel tank. Partly frozen kerosene is to an unusual degree thixotropic,(4) that is, once it has begun to collapse, the gel-like structure breaks down, and flow becomes still easier, so that initiation of flow in the semi-rigid structure may be the main obstacle to fuel delivery. Once the fuel reaches the booster pump, the remaining structure is further broken down by the pump impeller blades.

Refiners have secured small relaxations in the D 2386 freeze point for Jet A-1, to alleviate supply problems. In addition, there has been some revival of interest during the last few years in dynamic low temperature tests, which measure the mobility of two phase fuel systems, and attempts, using these tests, to establish more realistic criteria for low temperature usability limits (5,6).

We were interested in the possible use of pour depressants, or cold flow improvers, in alleviating low temperature performance problems that could arise with heavier aviation fuels. These additives have in the last twenty years found extensive use in diesel and home heating fuels. Added in fractional percentages, they can change the crystal form of the wax separating from the fuel, from an interlocking network of needles or platelets to compact non-cohering granules that pass through filters and do not impede flow.

Secondly, in certain military aircraft the fuel tanks are fitted with reticulated polyurethane foams, primarily to serve as fire suppressants. These are open-celled materials of large void volume, approaching 99%. It appears possible that with high freeze fuels the foam network might entrap wax crystals and cause fuel holdup; and again, that cold flow improvers might be of assistance by promoting a more compact, free-flowing wax deposit. The only previous examination of this aspect of foam use involved JP 4 and aviation gasoline (7); and as might be expected from the extremely low freeze point of these fuels, no drainage problems were encountered down to -51°C (-60°F).

In this work we examined the low temperature behaviour of fuels and fuel blends, using a variety of bench scale test methods. For most of these, published descriptions and procedures were followed. One, described here in detail, was devised to examine fuel flow in the presence of polyurethane foam. We also studied, in a preliminary way, the effects of two cold flow improvers, added at several levels, on three high freezing fuels and blends. Pour points, which would have been of interest with the higher freezing fuels, were not determined due to lack of test facilities. The main purpose of the work was to compare the test methods, using a number of diverse fuels, and gain some understanding of their limitations.

Succeeding sections of this report describe:

a. the fuels
b. the apparatus and procedure for each test
c. a summary and comparison of results by the different methods
d. Observations on the test methods, and on certain anomalous results.

2.0.0 EXPERIMENTAL

2.1.0. Fuels

Eight fuels and fuel blends from various sources were used, and are listed below, with the D 2386 freeze point for each.

FUEL	SOURCE	SPECIFICATION	D 2386 F.P.
JP 5	Imperial	3-GP-24	-48.9
Jet A-1	Shell	CAN 2-3.23	-59.5
JP 8 (shale)	USAF	F-44 (NATO)	-47.8
ERBS-3	NASA	(8)	-23.4
Kerocut	Suncor		-46.3
No. 2 Diesel	Gulf		-18.7
3:2 JP 5-Diesel			-28.0
1:1 Jet B-Diesel			-27.0

JP 5, with a high flash point, is designed for shipboard use; Jet A-1 is the standard fuel used nearly universally by commercial airlines. JP 8 was prepared from Colorado oil shale to meet a military specification that closely resembles Jet A-1.

ERBS (Experimental referee broadened specification) fuel was proposed by NASA as a reference for combustion and engine studies. It represented their estimate of the form aircraft gas turbine fuels might assume if trends then observed in the petroleum situation were to continue. It is generally felt now that changes in fuel properties will not be as drastic as envisaged in the ERBS description (9); thus, the freeze point of this material, near -25°C, is too high to be acceptable in commercial use, but it represents a useful extreme case fuel.

Kerocut, the kerosene fraction from the Suncor Fort McMurray operation, resembles JP 5 in many ways, though not conforming to the specification in all details. Like the other Suncor tar sands products, it is unusually low in wax (n-paraffins) and consequently has good low temperature properties.

Two additional fuels of elevated freeze point were made by blending a locally procured No. 2 Diesel with the JP 5 described above and with a Jet B (wide cut) fuel. The limited work with cold flow improvers was conducted with these two blends and with the ERBS-3. One source of uncertainty is that the origin of the No. 2 Diesel could not be traced exactly; if produced for a winter market, as seems probable, it was presumably flow improved. Thus the additive effects noted here might have been still larger with an untreated fuel.

Table I lists all the fuel and fuel-additive combinations used here. Lubrizol 8052[1] and Paradyne 25[2] were selected to illustrate the effect of flow improvers.

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[1] Exxon Chemical Company, Houston, Texas

[2] Lubrizol Corporation, Wickliffe, Ohio

The specification fuels have a narrower distillation range and hence a narrower wax (n-paraffin) distribution than ERBS or the diesel blends. This is illustrated by the analytical data of Table II, showing weight per cent of paraffins.

It is expected that with specification fuels wax separation will occur over a relatively narrow temperature interval, and thus that end point phenomena will set in more abruptly than with the ERBS or diesel blends. Examples of this will be given later.

2.2.0 TESTS

2.2.1 ASTM D 2386

This test measures something approximating a fundamental equilibrium property, namely the temperature of dissolution of the last trace of wax during gradual rewarming. Hence it is nearly unaffected by the presence in small weight or molar proportion of another material such as a flow improver. All the other tests are dynamic - the fluid is displaced under the stress of an applied force, air pressure or gravity, and for each test a critical temperature is defined at which some property related to fluidity or resistance to motion reaches a preassigned value. Here the presence of flow improvers can profoundly affect the end point.

2.2.2 Setapoint Detector

This apparatus was introduced a few years ago by Stanhope Seta, and has been accepted as an ASTM test method for aviation fuels (D 4305) (10).

Its operation (see Fig. 1) is based on the pumping of a sample of the test fuel back and forth across a 325 mesh metal screen, separating the inner and outer chambers of a transparent test cell. The apparatus is cooled in a programmed manner, and the pressure that builds up due to resistance to fuel passage at the screen (blockage by wax) is recorded. The temperature at which this pressure exceeds one cm Hg for one second is taken as the "stop flow" point. On subsequent rewarming the "flow" temperature is that at which this Δp-duration criterion is no longer met. In interlaboratory comparisons with 18 specification fuels the "flow" point was consistently 2°C lower than the D 2386 freeze point. It is presumably for this reason that D 4305 has not been adopted as a specification test.

The makers of the apparatus have suggested that there is a correlation between the "stop flow" point and the cold filter plugging point (11) for diesel fuels. Both stop flow and resume flow are reported here.

2.2.3 BP Pulse Test

This is a modification of a procedure to examine the flow behaviour of aviation fuels, developed about 20 years ago by British Petroleum (12). It is referred to here by this name in acknowledgement of its origin. Details of the test were never published, and we are indebted to one of the authors of the report for a description (13).

In the original arrangement (Fig. 2) the test cell was a glass tube (3 mm i.d., 135 cm in length) folded on itself accordion fashion for compactness. Ten ml of the fuel was drawn into this vessel, connected at one end to an air reservoir from which pressure could be applied by opening a stopcock, and at the other to an indicator tube (2 mm i.d.) having a horizontal section filled with water, and marked off in 1/8 inch divisions. The motion of an air bubble in this water column gave a direct measure of the displacement of the fuel when air pulses were applied to it.

The test cell was placed in a stirred isooctane bath and cooled at roughly 1°C per minute by additions of dry ice. At 1°C intervals air pressure (2 cm Hg) was applied to the fuel and the resulting motion of the air bubble followed. At first, while the fuel was still fluid, momentary application of a pulse resulted in an instantaneous rapid excursion of the bubble followed by an immediate return to the initial position. As the temperature fell, bubble motion became more sluggish, requiring longer air pulses, and the end-point was taken as the temperature at which the fuel either seized up completely or became extremely viscous by certain criteria - a fifteen second pulse for a bubble displacement of one scale division (1/8 inch) or a recovery time of greater than one minute.

The principal modification was the replacement of the stopcock by a solenoid and timing circuit, so that the pulse length required to displace the bubble a suitable distance (2-10 cm) along the scale could be measured. For convenience in treating results we calculated for all points during a run the pulse duration corresponding to an arbitrarily chosen bubble displacement of 2.5 cm. This arithmetic manipulation permitted us to compare behaviour of different fuels on a common basis, as seen in Fig. 3, which depicts results with two specification fuels, Jet A-1 and JP 5, and the 1:1 blend of Jet B and diesel. The first two fuels show a very slight increase in this calculated pulse length, and then a vertical rise as they suddenly became completely immobile over a 1°C interval. The onset of this end-point is unmistakeable. With the Jet B diesel blend no such holdup occurred, but rather a gradual increase in sluggishness, and the end-point (-58°C) was established by a criterion similar to that of the original method - a long application of air pressure, 15 seconds to produce a displacement of 3 mm or less.

The BP and similar tests that are related to yield stress in a thixotropic fluid have been criticized (14) as dependent on previous working of the fluid and hence not repeatable. We encountered no difficulty of this sort in the test as we conducted it.

2.2.4 Thornton Cold Flow Test

In some circumstances, as mentioned above, the ability to withdraw fuel from a tank may depend on whether, in the partly frozen state, it can collapse under its own weight and begin to flow toward the pump. The Thornton cold flow test (15) was devised to measure this property. The apparatus is a cylindrical vessel consisting of two chambers, one mounted above the other, the orifice between them closed by a precision fitted poppet valve. 100 ml of the test fluid is measured at room temperature into the upper chamber, and the vessel is then cooled to the desired temperature in a bath. When equilibrium is reached, the valve is opened for ten seconds, reclosed, and the vessel removed from the bath and allowed to warm up. During the ten second interval the fuel will, in the temperature region of interest, begin to slump and fall through the orifice into the lower chamber; and the per cent of the fuel remaining in the upper chamber, measured at room temperature, is defined as the per cent holdup. The experiment is repeated at a series of temperatures, and curves such as those of Fig. 4 are plotted up. By interpolation the temperature corresponding to a given percentage holdup (30% in the original description) is obtained, and is used as a measure of this aspect of the fuel's low temperature behaviour. Fig. 4 shows data for JP 8, ERBS 3 and Jet B-diesel.

2.2.5 Fuel Drainage Through Foam

One object of the present work was to study the passage of fuel, particularly after partial freezing, through polyurethane foam, and the effect of flow improvers. The most direct method would be a tank to tank drainage experiment, comparing flows in the presence and absence of foam. Such an apparatus has since been devised, but was not available when the other tests were being conducted. A simpler alternative method was developed: instead of draining fuel through immobile foam positioned in a tank, we slowly withdrew the foam itself from a vessel containing fuel, and measured how much fuel was left in it. The foam employed was Type IV Polyether[1].

The apparatus is depicted in Fig. 5. A one-liter graduated cylinder was cut off at a convenient height to fit into a Thermotron S-4 environmental chamber. The hatched area in the figure represents in cross section a cylindrical piece of foam cut so as to slip fit easily into the graduate. A thermocouple in a glass well measures fuel temperature. A stiff wire with an eyelet at the upper end passes concentrically through the foam, and is then crossed back and forth several times across the base of the cylinder to give good support to the foam during the lift. The foam is raised by means of a constant speed motor, mounted on top of the Thermotron, which winds up, at the rate of 2.5 - 3 cm/minute, a cord passing through the ceiling of the Thermotron chamber and engaging the foam cylinder as shown in the figure.

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[1] Scott Paper Company, Foam Division, Chester,Pa.

The graduate was filled to the 300 ml mark with fuel at room temperature, and the foam lowered carefully into it, dislodging any entrapped air-bubbles. The graduate was then placed in the cold chamber and connected to the lift mechanism. When fuel and chamber had come to equilibrium at the desired temperature, the motor was switched on for four minutes, a time sufficient to lift the foam clear of the fuel. The volume of fuel draining back into the cylinder could be read directly on the graduations, through the Thermotron window. This experiment was repeated at a succession of temperatures, and a volume drained-vs-temperature curve constructed. Several expedients - simultaneous cooling of a number of the test vessels shown in Figure 5, and judicious undercooling of the chamber with the aid of the auxiliary air thermocouple also shown in the figure - accelerated attainment of a series of decreasing final temperatures. In this way a succession of foam pulls could in favourable circumstances be conducted at intervals of little more than an hour, and a complete curve obtained for a fuel in about one and a half days.

While the initial volume (300 ml) was measured at ambient, drainage volumes were measured at the test temperature, with no correction for volume changes. For a temperature difference of say +20°C to -40°C, each absolute drainage volume will be in error by 4-5%, but this will not affect noticeably the shape of the volume-temperature curve nor any numbers derived from the curve.

An example of the results obtained with this method is shown in Fig. 6 for 1:1 Jet B-diesel, untreated and with three levels of added Lubrizol 8052. This was the first system investigated; it was not known where holdup might begin, and a good many unnecessary points were taken, particularly in the preliminary cooldown of the unadditized fuel. Examining this curve (solid circles), drainages of 275-280 ml were nearly constant from -20°C almost to -50°C. With an initial fuel volume at room temperature of 300 ml, this signifies practically complete drainage. Beginning at a sharply defined temperature, drainage fell off over an interval of several degrees to about 40 ml.

A more typical experiment is shown in Fig. 7, ERBS-3 alone and with three levels of Lubrizol 8052. It is seen that with experience the drainage - temperature relation could be established with much greater economy of effort.

Drainage - temperature curves were analyzed most usefully in terms of a breakpoint, the point of intersection of the initial nearly linear cooldown with the line of best fit through the points of the holdup region.

Results are quite reproducible. For Jet B - diesel, the right band curve of Fig. 6, a set of repeat runs was carried out after a lapse of several days with a fresh batch of fuel-plus-flow improver. These points, falling in the critical region of rapidly increasing holdup, and indicated by modified symbols, lie satisfactorily on the same curve as the points of the first determination.

2.2.6 Air Probe Flow Monitor (APFM)

This device, presently under development by the Shell Thornton Research Centre, became available after the bulk of the experimental work had been done (5). A stream of air bubbles is periodically released into the fuel from a capillary. Resistance to passage of air increases with falling temperature, as viscosity increases and wax formation begins, and the end point is taken as the temperature at which air can no longer be expelled from the capillary.

With the APFM the end point is recorded automatically, but it was evident from our preliminary work that there is room for the exercise of judgement in setting the controls, and that operator experience and familiarity with the type of fuel being investigated can play a role. Like the Setapoint apparatus, the APFM appears to give most unequivocal results with specification aviation fuels.

3.0.0 RESULTS

All experimental data are collected in Table III.

D 2386 results are reported only for the eight basic fuels. D 2386 freeze points were in fact determined for several of the fuel-flow improver combinations; these came out the same as for the untreated fuels, within the accuracy of the test. For the remaining tests, Table III lists results for each of the 20 fuel additive combinations.

Examination of Table III shows that all experimental data for specification fuels lie within a span of 6-7°C. With one or two exceptions the BP and Thornton test results are lower than those obtained by the other procedures, and the D 2386 freeze point is in every case the highest figure. With some of the non-specification fuels the spread between D 2386 and the remaining tests is as much as 30 C. The effect of these differences is seen when the correlation plots are examined.

3.1.0 Relation of D 2386 to the Other Tests

The data are plotted in Figs. 8 to 13. Results with the three specification fuels (and with kerocut) are circled in these figures.

a. For the four fuels noted just above (see Fig. 8) results for D 2386 average 2°C higher than by D 4305 (Setapoint flow) in agreement with the D 4305 precision statement (10).

b. The preliminary results comparing D 2386 and the APFM (Fig. 9) suggest a bias of about 4°C, the APFM readings falling lower. There is one badly deviant point, however, and it is too early to draw any conclusions about the APFM on the basis of such scanty data.

c. The most obvious feature is the great discrepancy, for non-specification fuels, between D 2386 and all the other tests; the extent of this is shown in Figs. 8 to 13 by the distance of experimental points below the 45° line, which would correspond to exact agreement between the two methods being compared.

3.1.1 Correlations Among Results of Remaining Tests

In Figs. 14 to 20, these results are plotted against each other in pairs. Fig. 14 compares results by the BP and Thornton tests, which as stated above gave lower values than the others. The agreement is rather satisfactory, as might be expected, except for the four heavier fuels (ERBS-3, No. 2 Diesel, Jet B-diesel and JP 5-diesel) used with no flow improver.

In the same way, Figs. 15 and 16 compare results by the other three tests methods, foam pull breakpoint and the two Setapoint measurements. Again fairly good agreement is seen. Errant points (circled) are observed with several non-specification fuels with the lowest level (0.025%) flow improver, and with the diesel alone, which had probably been flow improved. At higher added levels of flow improver the agreement is considerably better. The conclusion reached (see discussion below) was that for certain combinations of mid-distillate fuel and flow improver used here, the Seta apparatus gave intrinsically erratic and irreproducible results, for reasons connected with the physical form of the separated wax.

A few representative plots, comparing results of the BP and Thornton tests ("low" measurements) with Setapoint and foam pull are shown in Figures 17 to 20. There is evidently considerable divergence between these sets of results, experimental points lying well off the 45° line.

3.1.2 Effect of Cold Flow Improvers

Looking at the upper half of Table III, it is seen that with the three fuels tested, addition of flow improver depresses the end point temperature in all measurements. With JP 5-diesel and Jet B-diesel the effect increases with additive level; judging by the extent of depression, the additive was roughly twice as effective with the Jet B-diesel as with JP 5-diesel.

ERBS-3 is also sensitive to flow improvers, but saturates at a low level, hardly any further improvement being observed between concentrations of 0.025% and 0.1%.

It was mentioned that the narrow wax distribution of specification fuels can be expected to lead to more rapid onset of wax deposition over a narrow temperature range. It is presumably for this reason that the results for all tests using these fuels are compressed into a narrow range, as was seen above from the inspection of Table III; and also that in the individual tests the end-points appear suddenly. Instances of this were seen in Figures 3 and 4, where a difference was apparent in the behaviour of specification fuels and fuels with a more broadly based wax distribution.

These observations are in line with the findings of Knepper and Hutton (16) who studied the action of flow improvers on model systems, using pour point depression as a measure of effectiveness. They blended combinations of n-paraffin hydrocarbons into a wax-free base solvent to produce systems with various types of wax distribution. Those with a sharply peaking wax distribution were relatively insensitive to addition of flow improvers, which were unable to cope with the large quantities of wax precipitated over a range of only a few degrees. With a broad spectrum of waxes separation occurs gradually, and the additive is more effective in dealing with it. This is probably the reason also for the difference in response to additives of the JP 5-diesel and Jet B-diesel blends noted above. The JP 5 is present in 60% concentration and contains only three waxes (C_{11} to C_{13}) in sizable amount; hence flow improver effects in the various tests are relatively small. Jet B, however, has little wax above C_{11}, so that the response of this blend to the flow improver is that of the diesel alone.

3.1.3 Observations on the Setapoint Method

Certain blends and fuel-additive combinations did not behave reproducibly with the Seta apparatus. Results varied from day to day, or run to run, and appeared to depend critically on instrument settings (i.e., cooling rate) and sometimes even on initial fuel distribution between inner and outer chambers (Fig. 1). Some of these phenomena came to light in another investigation, to be reported separately, in which an array of cold flow improvers were used to treat both "natural" fuels e.g., ERBS, and synthetic blends of isooctane plus a distribution of n-paraffins. Certain of these combinations, in particular ERBS with, it appeared, either insufficient flow improver or an ineffective one, deposited wax in the form of clots or plates, which could be seen moving about in the field of vision. Erratic behaviour was in some cases shown by direct observation to be due to blocking and unblocking of the metal screen by these fragments.

In the present work we observed that reproducible results were always obtained with specification fuels, and with diesel blends and ERBS-3 with high levels of flow improver. In the former case wax formation set in rather suddenly, and the fluid became immobile after a relatively small number of pump strokes, much of the fluid remaining clear. In the latter case a fine milky or cloudy suspension usually formed, but the pumping remained vigorous even after the solution had become opaque; then over a short period viscosity increased and the end point was reached. Under these circumstances results were repeatable and consistent for both stop and resume flow. However, with the Jet B-diesel and ERBS, treated with 0.025% Lubrizol 8052, the irregularities noted above were observed; results were poorly reproducible and as seen in Figs. 15 and 16 these tests gave results out of line with other fuels.

4.0.0 SUMMARY

Of the correlations examined, two, the BP-Thornton and the Seta stop flow-foam pull were the best. From Figs. 15 and 17, the agreement was satisfactory considering the variety of materials tested. At the same time, the BP test was relatively insenitive to flow improver presence or level, and certain fuel-additive combinations behaved anomalously in the Seta apparatus. This latter test, and the APFM, are evidently geared primarily to specification aircraft fuels. It is recognized that all the dynamic tests are empirical, in their dependence on arbitrarily chosen dimensional factors - a tubing or chamber diameter, mesh or foam pore size, or time of application of a stress; alteration of any of these will displace the end point temperature. Several tasks remain to be investigated - the Air Probe Flow Monitor, development of tank-to-tank foam drainage experiments, and re-examination of the methods using more realistic high freeze point fuels than the diesel blends which were available when this work was commenced.

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TABLE I

3:2 JP 5:DF2
+A
+B
+C

1:1 JB:DF
+A
+B
+C

1:1 JB:DF
+D
+E
+F

ERBS-3
+A
+B
+C

JP 5
No. 2 Diesel
Jet A-1

JP 8 (Shale)
Kerocut

DF 2 : No. 2 Diesel
JB ; Jet B

A : + 0.025% w/w Lubrizol 8052
B : + 0.05% w/w Lubrizol 8052
C : + 0.10% w/w Lubrizol 8052

D : + 0.025% w/w Paradyne 25
E : + 0.05% w/w Paradyne 25
F : + 0.10% w/w Paradyne 25

TABLE II

Wax (n-paraffin) Composition of Fuels Employed in Study in Weight per cent of Total

	ERBS-3	JET A-1	JP 5	KEROCUT	JET B	NO. 2 DIESEL
C_7	0.01	0.01	0.00	0.00	2.89	0.00
C_8	0.02	0.34	0.20	0.13	3.66	0.14
C_9	0.51	2.56	0.65	0.49	3.54	0.56
C_{10}	2.33	6.65	2.67	0.73	3.12	1.50
C_{11}	5.15	7.58	6.24	1.86	3.28	2.07
C_{12}	6.55	5.53	6.80	3.30	2.47	1.70
C_{13}	5.35	1.91	5.01	2.56	1.23	1.56
C_{14}	2.68	0.42	2.01	1.95	0.61	1.82
C_{15}	1.17	0.16	0.69	1.30	0.20	1.69
C_{16}	0.88	0.09	0.14	0.50	0.04	1.15
C_{17}	0.72	0.09	0.04	0.10	-	1.09
C_{18}	0.60	0.05	0.02	0.02	-	0.74
C_{19}	0.50	0.04	0.01	-	-	0.76
C_{20}	0.32	0.02	-	-	-	0.41
C_{21}	0.18	0.01	-	-	-	0.25
C_{22}	0.09	-	-	-	-	0.13
C_{23}	0.03	-	-	-	-	0.05
C_{24}	0.01	-	-	-	-	-
C_{25}	0.00	-	-	-	-	-
TOTAL	27.10	25.48	24.50	12.95	21.04	15.62

TABLE III

Summary of Test Results

FUEL BLENDS	D 2386 FREEZE POINT	AIR PROBE FLOW MONITOR	SETAPOINT		FOAM PULL BREAKPOINT	B.P. PULSE NO FLOW	THORNTON COLD FLOW 30% HOLDUP
			NO FLOW	RESUME FLOW			
3:2 JP 5 : DF2	-28.0	-42.8	-45.4	-43.7	-45.1	-52	-46.0
+A			-50.6	-47.1	-49.8	-52	-52.4
+B			-52.0	-49.1	-51.3	-53	-53.6
+C			-52.4	-50.0	-53.1	-54	-55.2
1:1 JB : DF2	-27.0	-30.9	-45.6	-44.4	-47.1	-58	-47.9
+A			-51.8	-49.7	-57.8	-63	-62.7
+B			-59.0	-54.9	-58.6	-64	-67.8
+C			-63.7	-60.3	-62.3	-68	-71.0
+D			-57.5	-52.9	-59.6	-60.5	-63.9
+E			-59.5	-57.5	-62.4	-63	-65.7
+F			-60.0	-58.9	-63.2	-66	-67.9
ERBS-3	-23.4	-26.4	-31.5	-31.1	-32.8	-43.5	-34.6
+A			-40.3	-38.2	-47.3	-48	-46.9
+B			-47.5	-44.1	-47.5	-49.5	-50.1
+C			-47.9	-44.6	-48.0	-49.5	-51.2
JP 5	-48.9	-50.0	-50.7	-48.4	-51.0	-53	-52.8
NO. 2 DIESEL	-18.7	-22.6	-29.4	-26.9	-35.1	-40	-35.2
JET A-1	-59.5	-62.1	-63.8	-62.7	-63.7	-66	-65.1
JP 8 (SHALE)	-47.8	-52.1	-51.9	-49.6	-52.4	-56	-54.1
KEROCUT	-46.3	-50.2	-50.9	-49.4	-49.9	-58	-55.1

DF2 : NO. 2 DIESEL JB : JET B
ERBS : EXPERIMENTAL REFEREE BROADENED SPECIFICATION AVIATION TURBINE FUEL
A : + 0.025% w/w Lubrizol 8052 D : + 0.025% w/w Paradyne 25
B : + 0.05% w/w Lubrizol 8052 E : + 0.05% w/w Paradyne 25
C : + 0.10% w/w Lubrizol 8052 F : + 0.10% w/w Paradyne 25

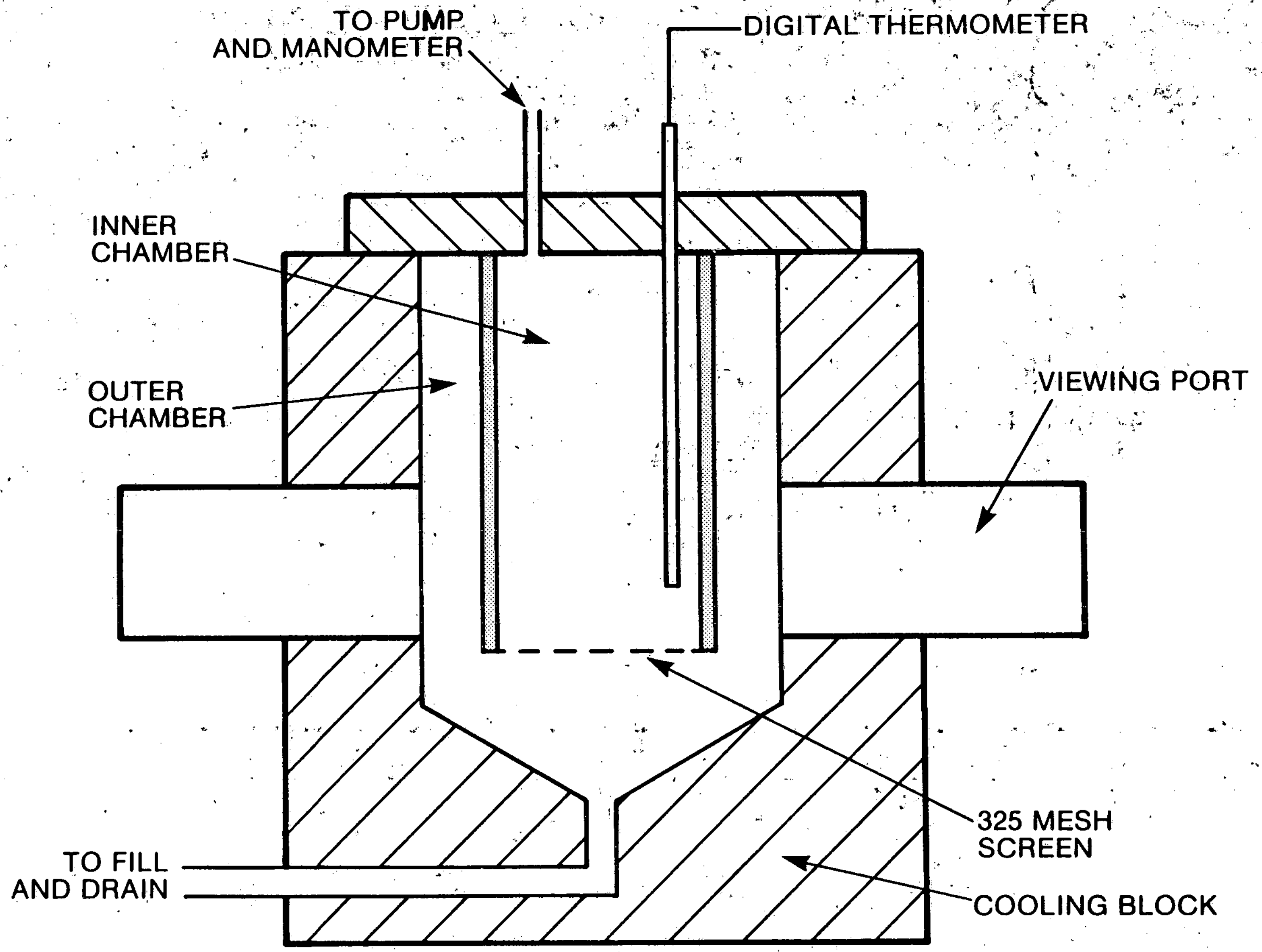

FIGURE 1. Test Cell of the Setapoint Detector, Schematic

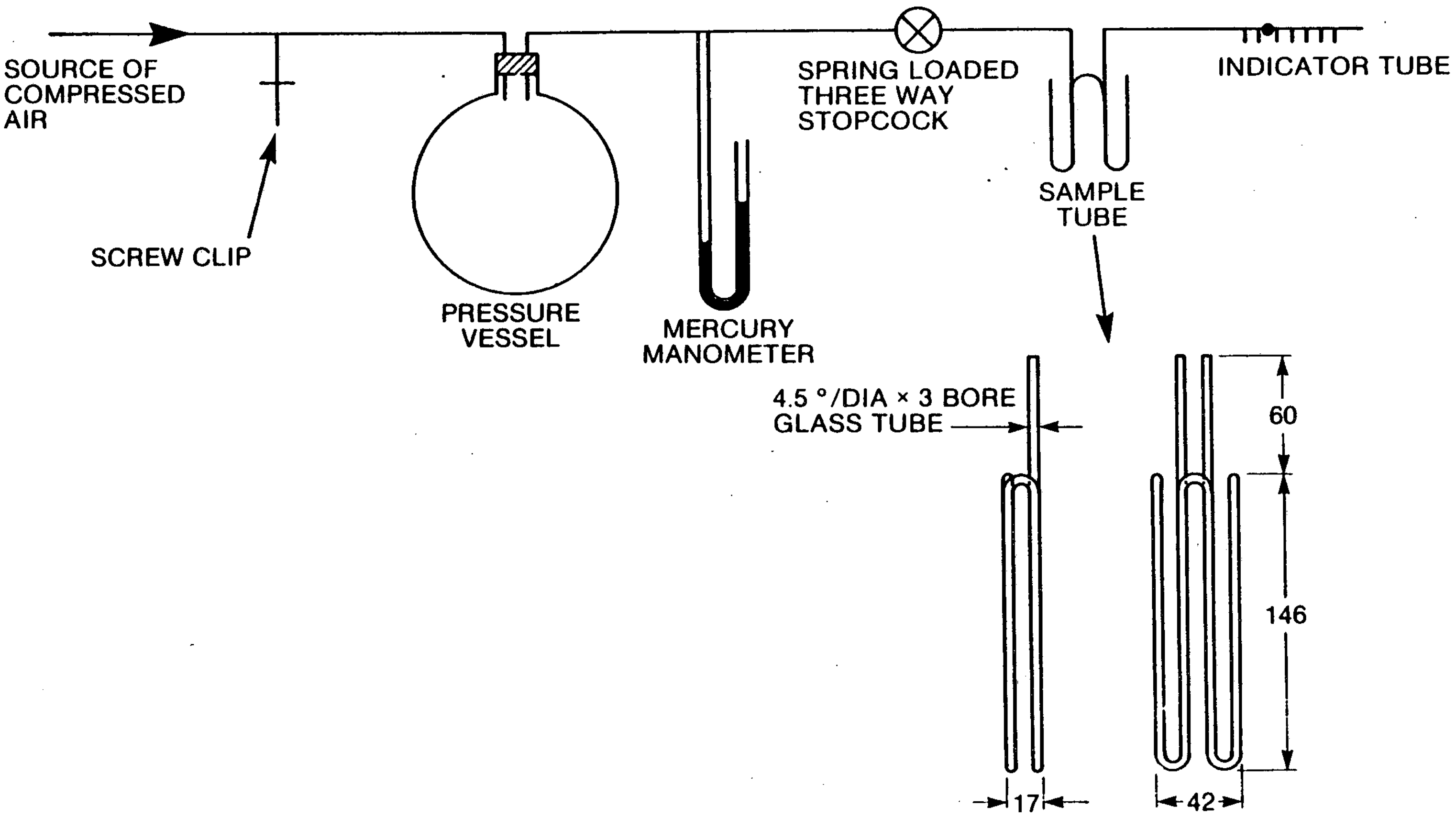

FIGURE 2. BP Pulse Test Apparatus in Original Version

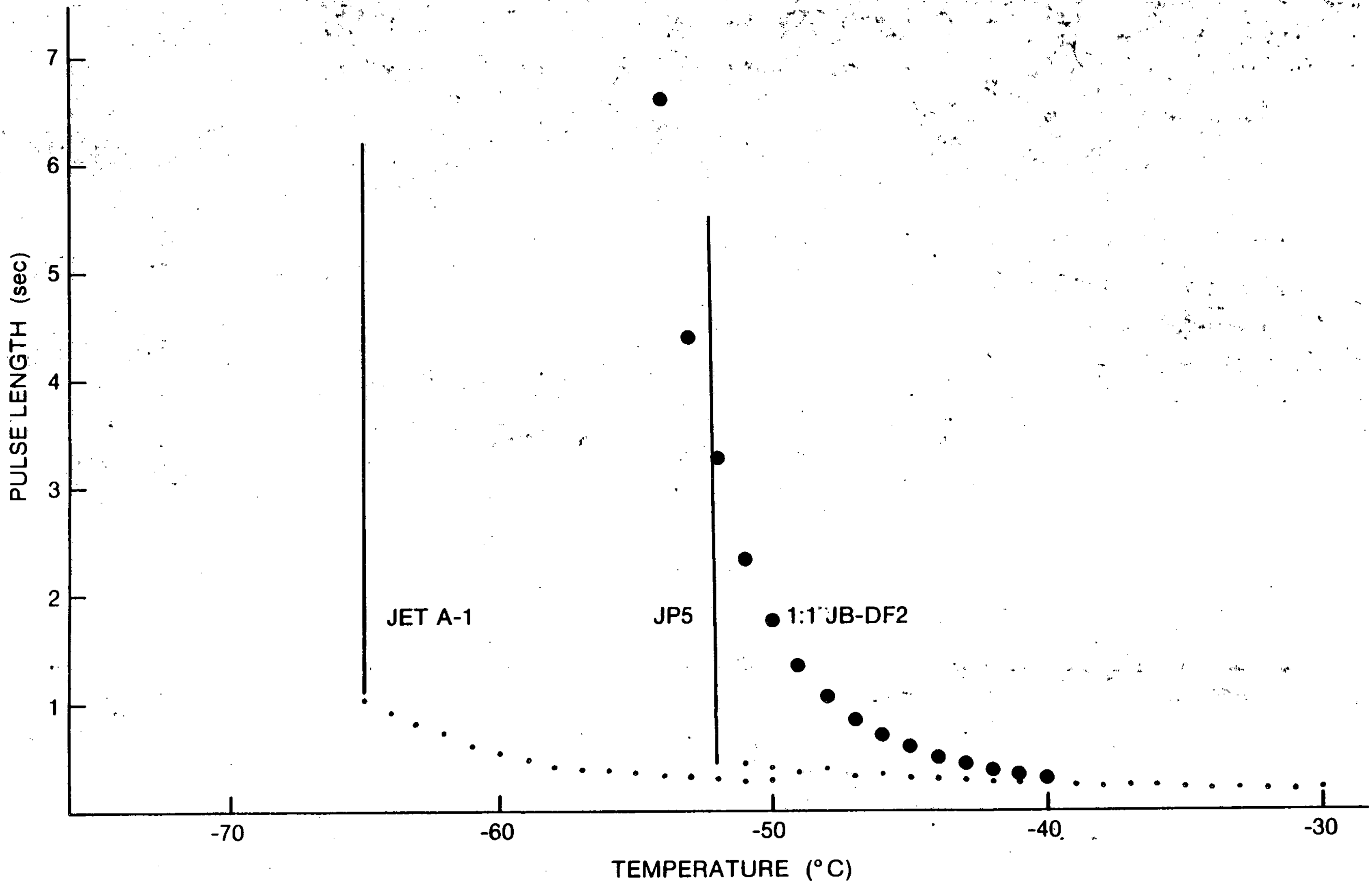

FIGURE 3. Behaviour of Three Fuels in the BP Pulse Test

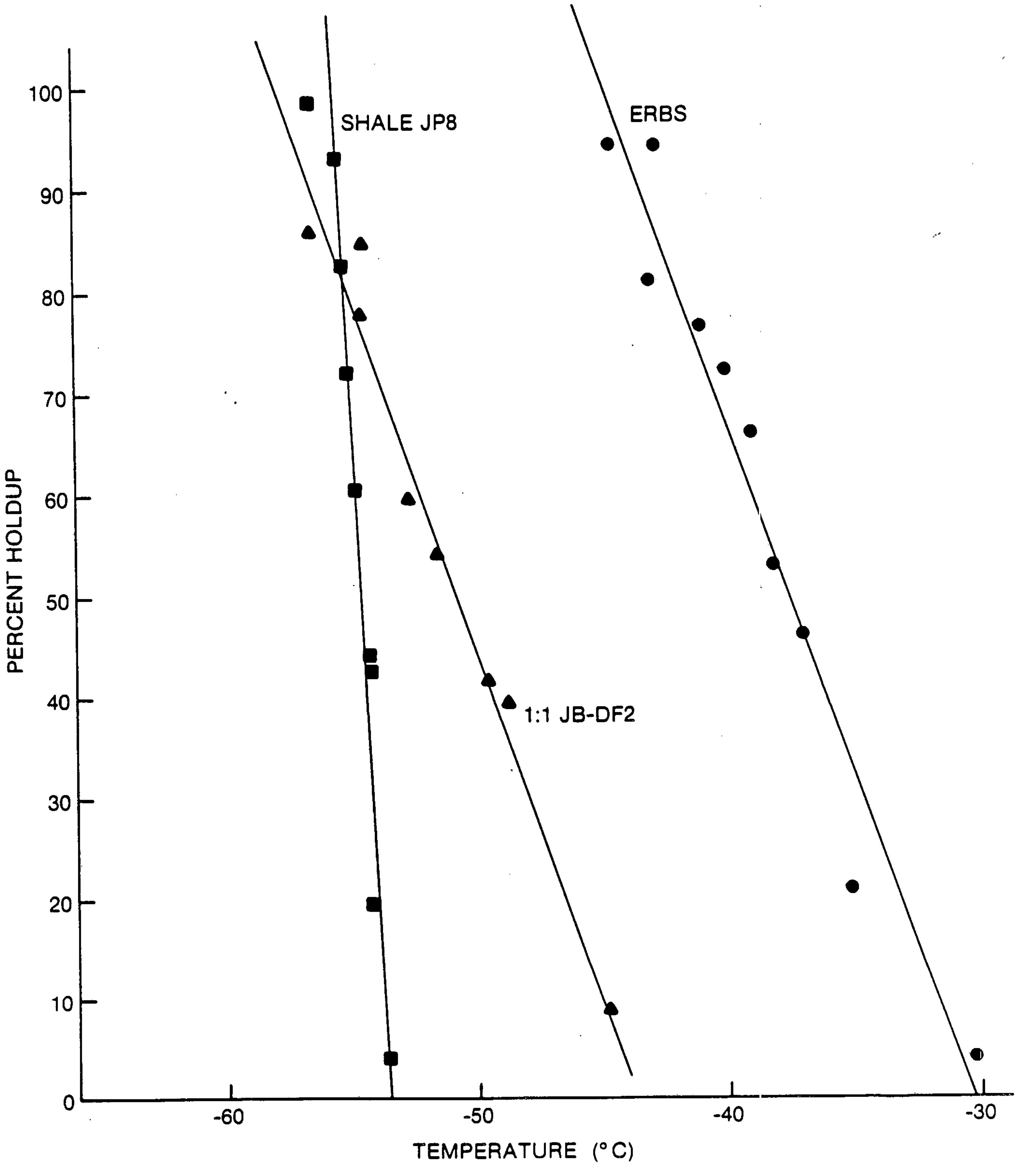

FIGURE 4. Thornton Cold Flow Test Results for Three Fuels

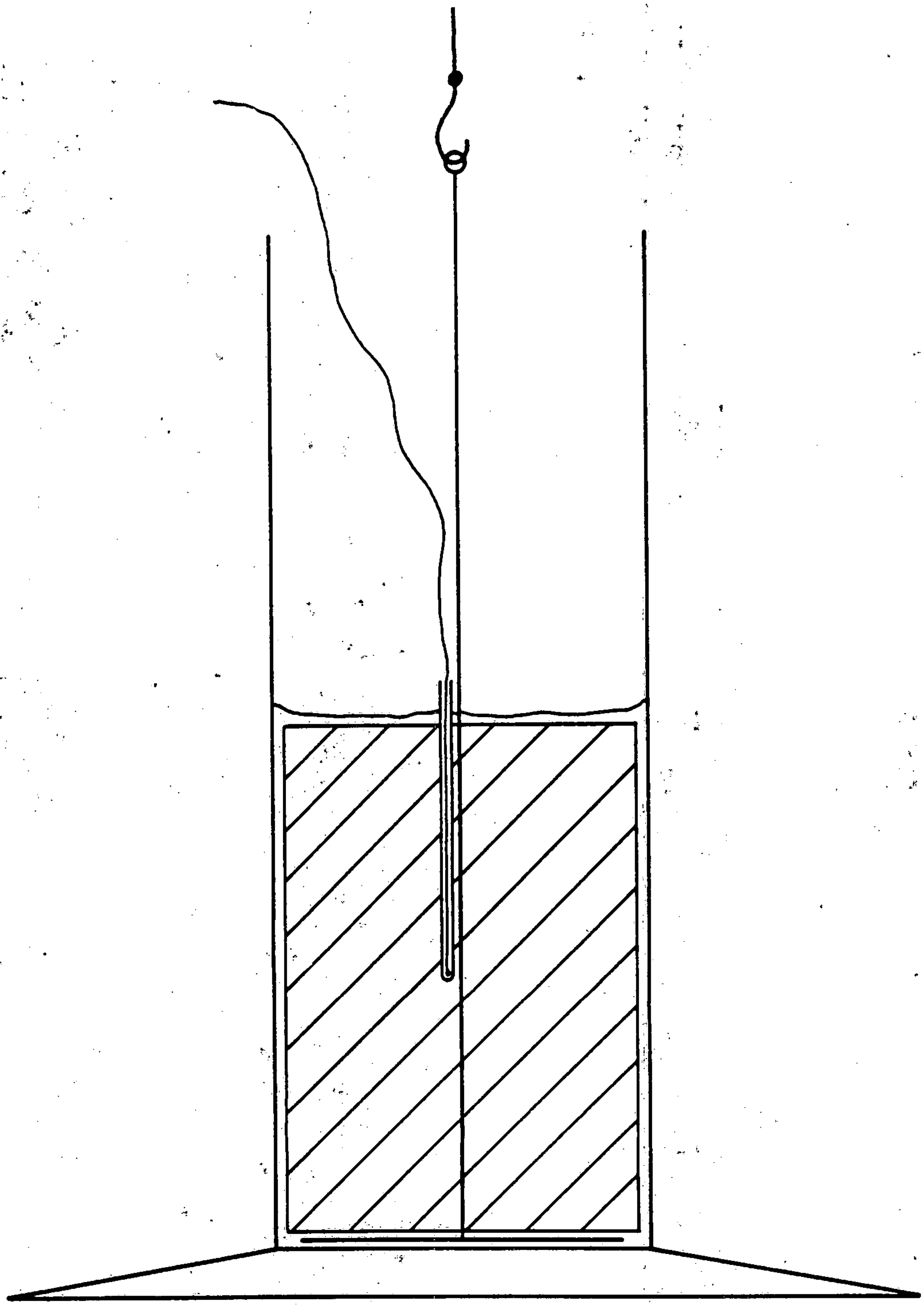

FIGURE 5. Schematic of Apparatus for Measuring Fuel Drainage Through Polyurethane Foam

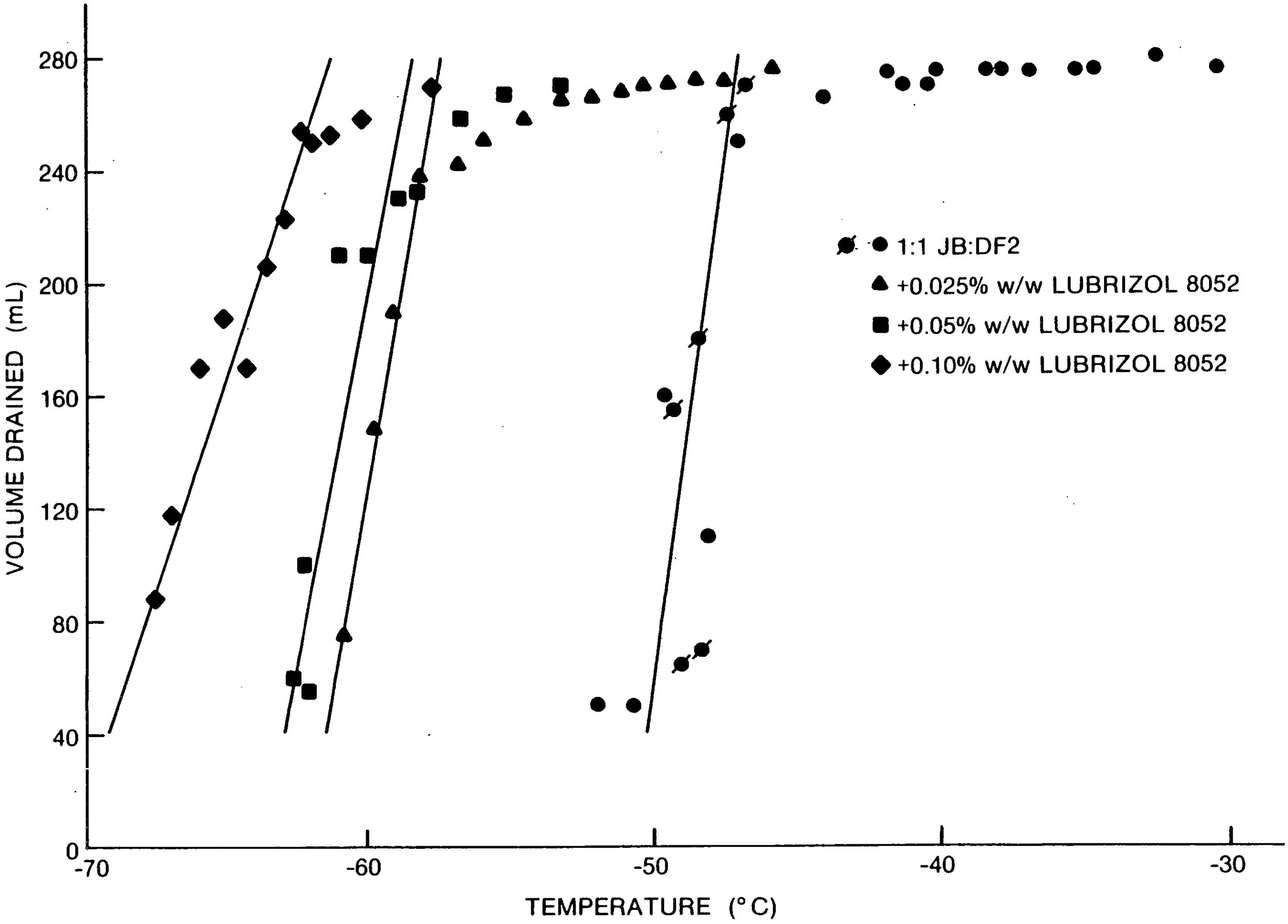

FIGURE 6. Fuel Drainage Through Foam as a Function of Temperature
Jet B - Diesel Alone and at Three Levels of Lubrizol 8052

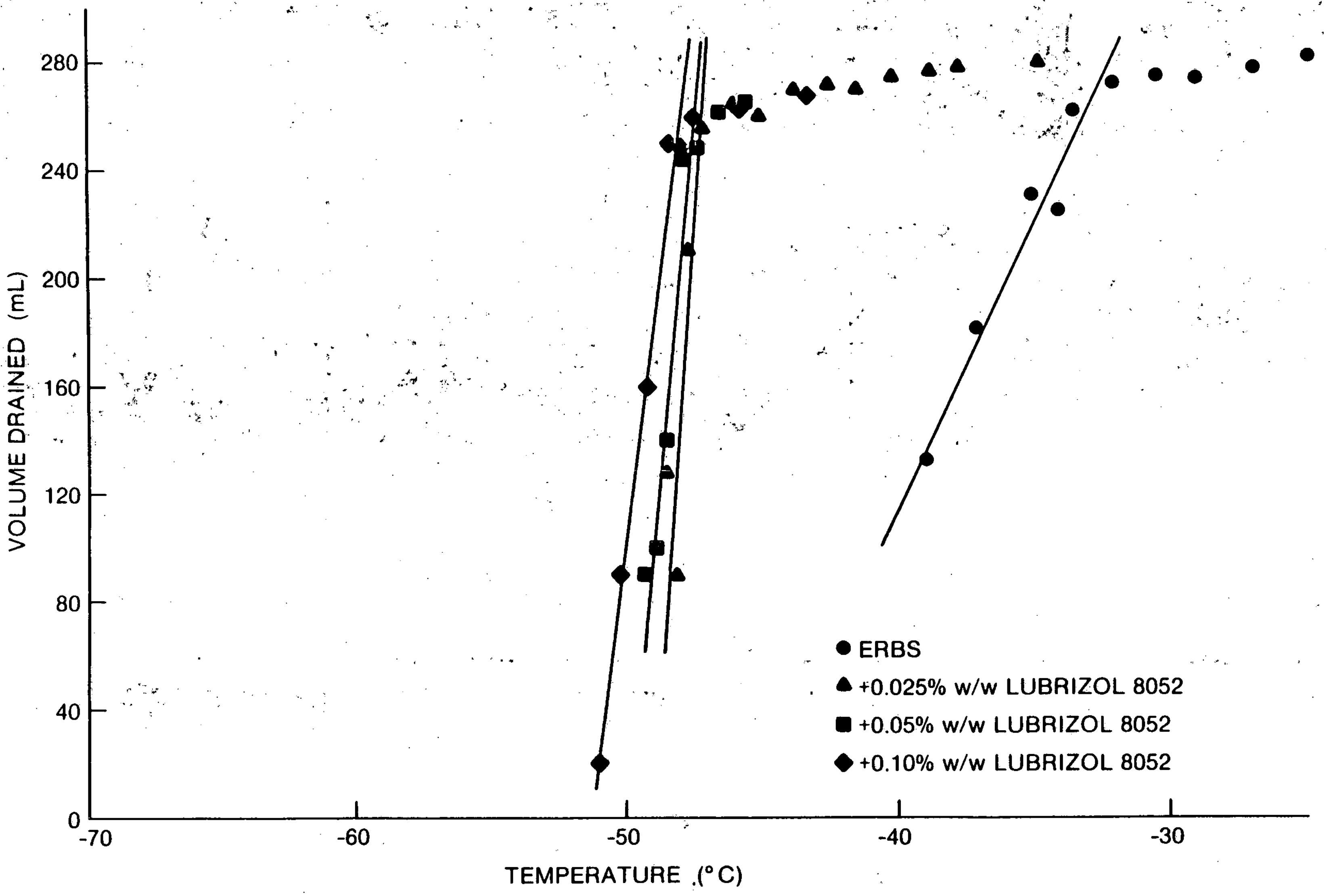

FIGURE 7. Fuel Drainage Through Foam as a Function of Temperature - ERBS 3 Alone and at Three Levels of Lubrizol 8052

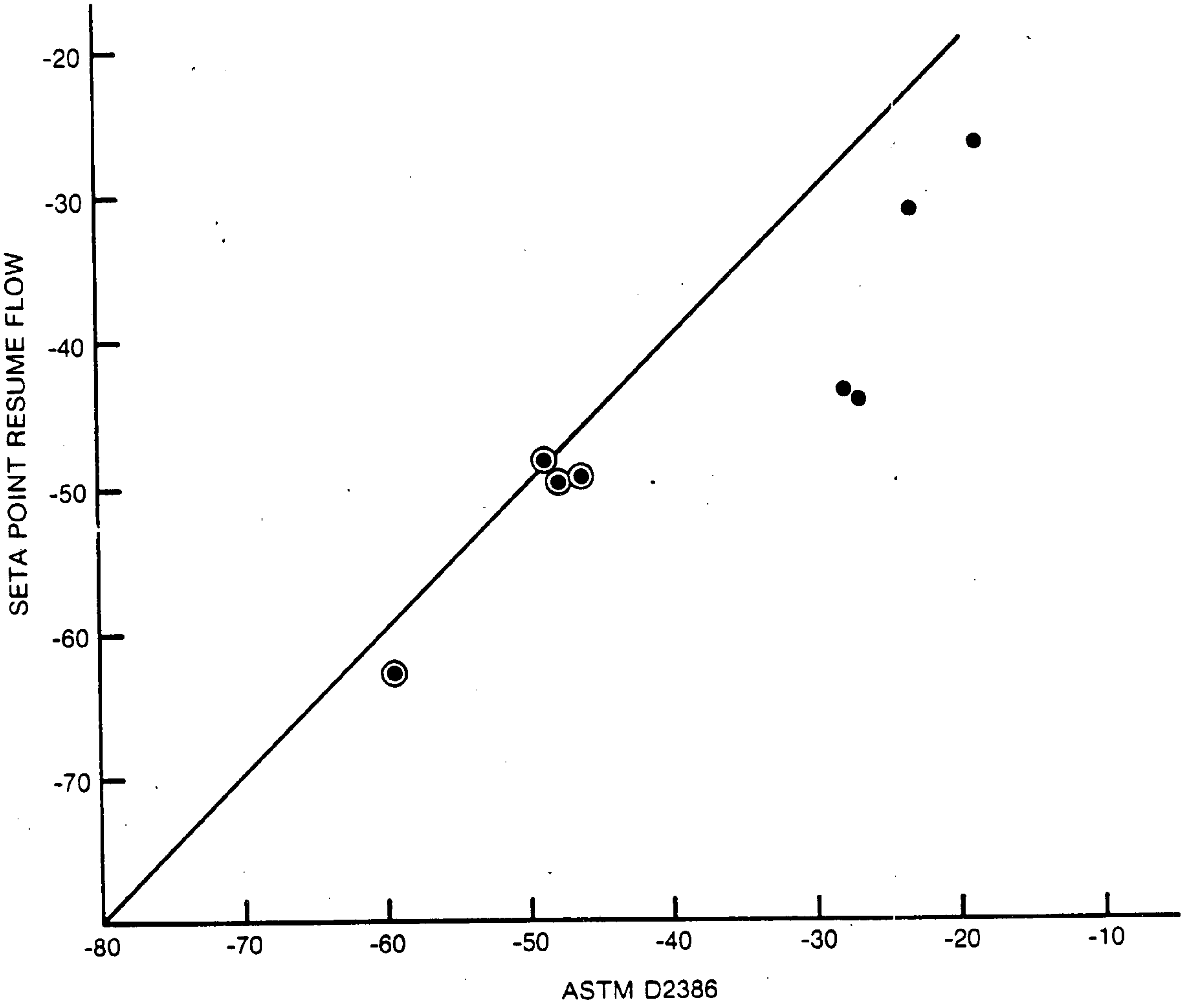

FIGURE 8. Setapoint Resume Flow vs D 2386 Circled points in Figs. 8 to 13 are for JP 5, Jet A-1, JP 8 and Kerocut

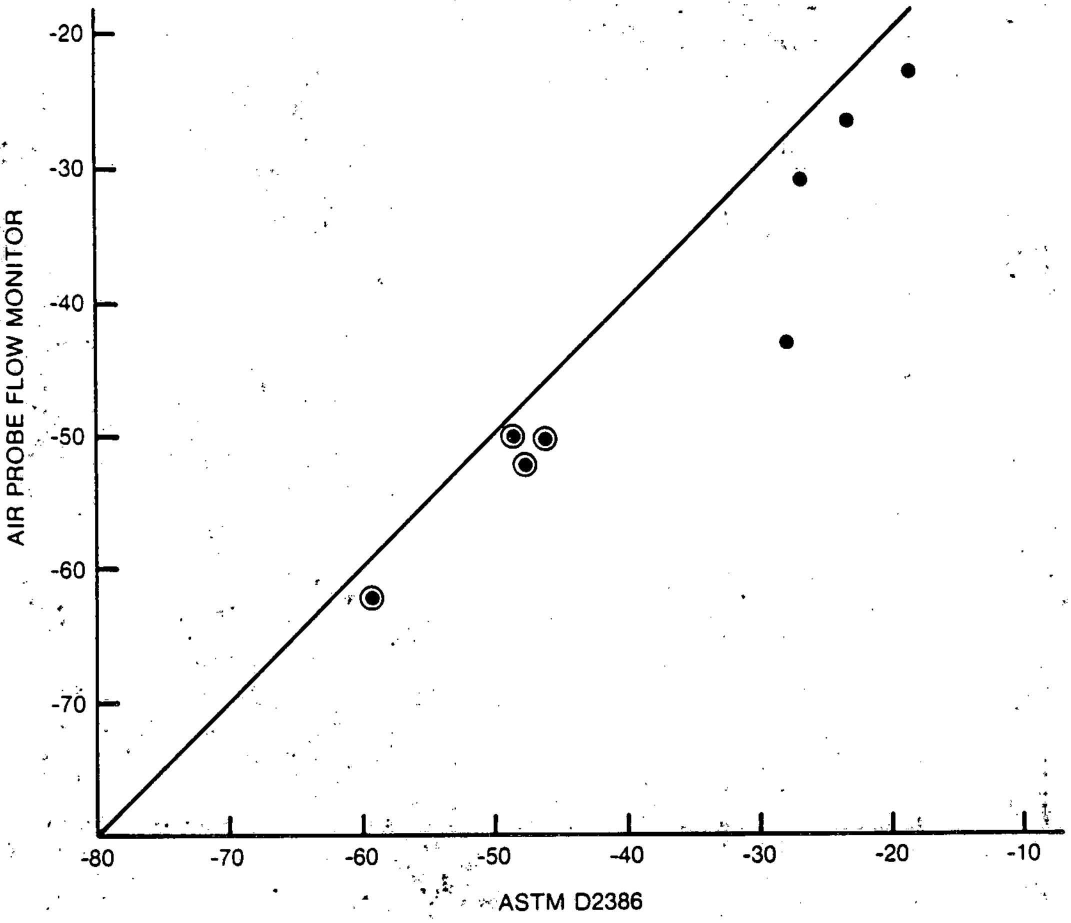

FIGURE 9. APFM End Point vs D 2386

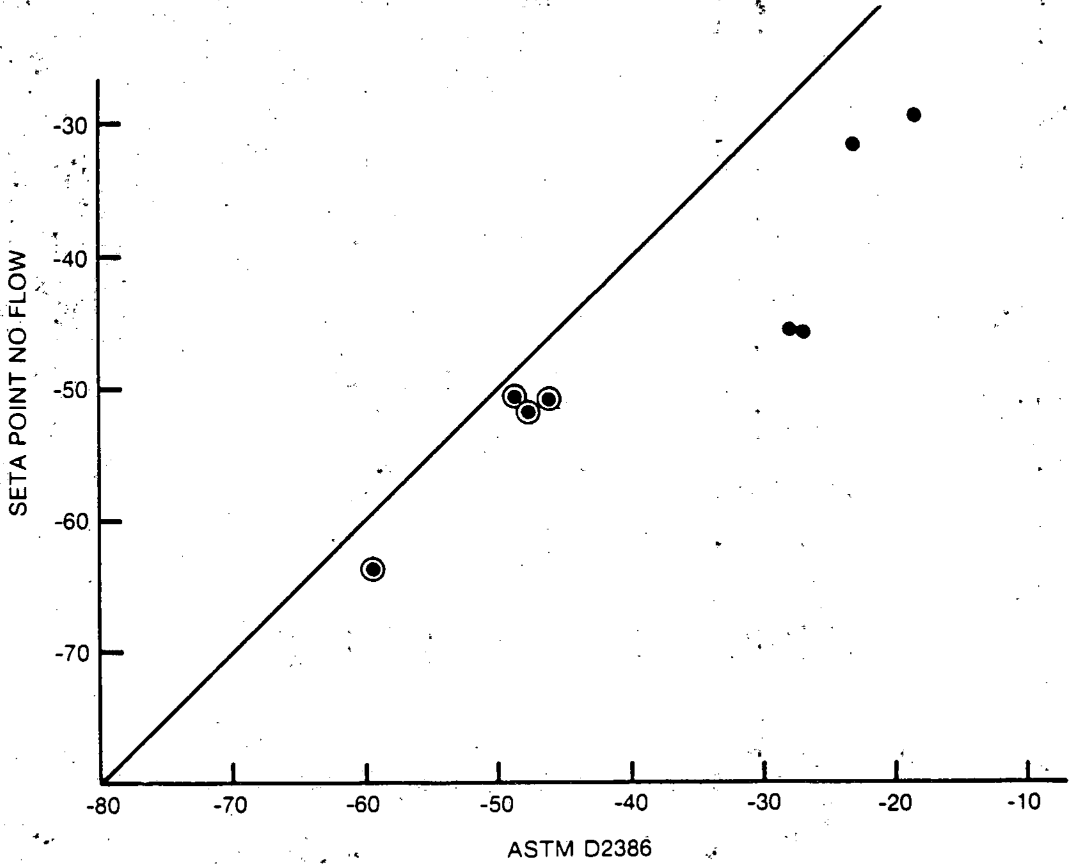

FIGURE 10. Setapoint no Flow vs D 2386

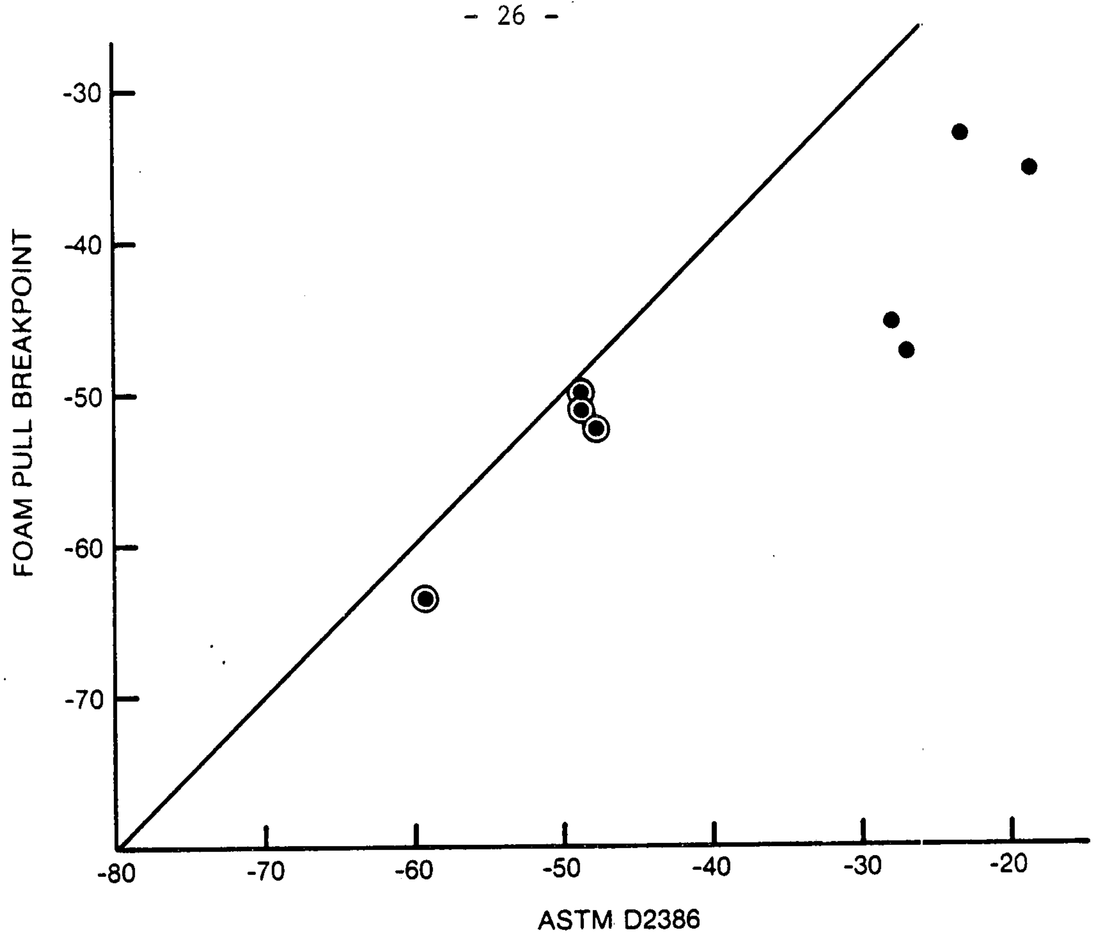

FIGURE 11. Foam Pull Breakpoint vs D 2386

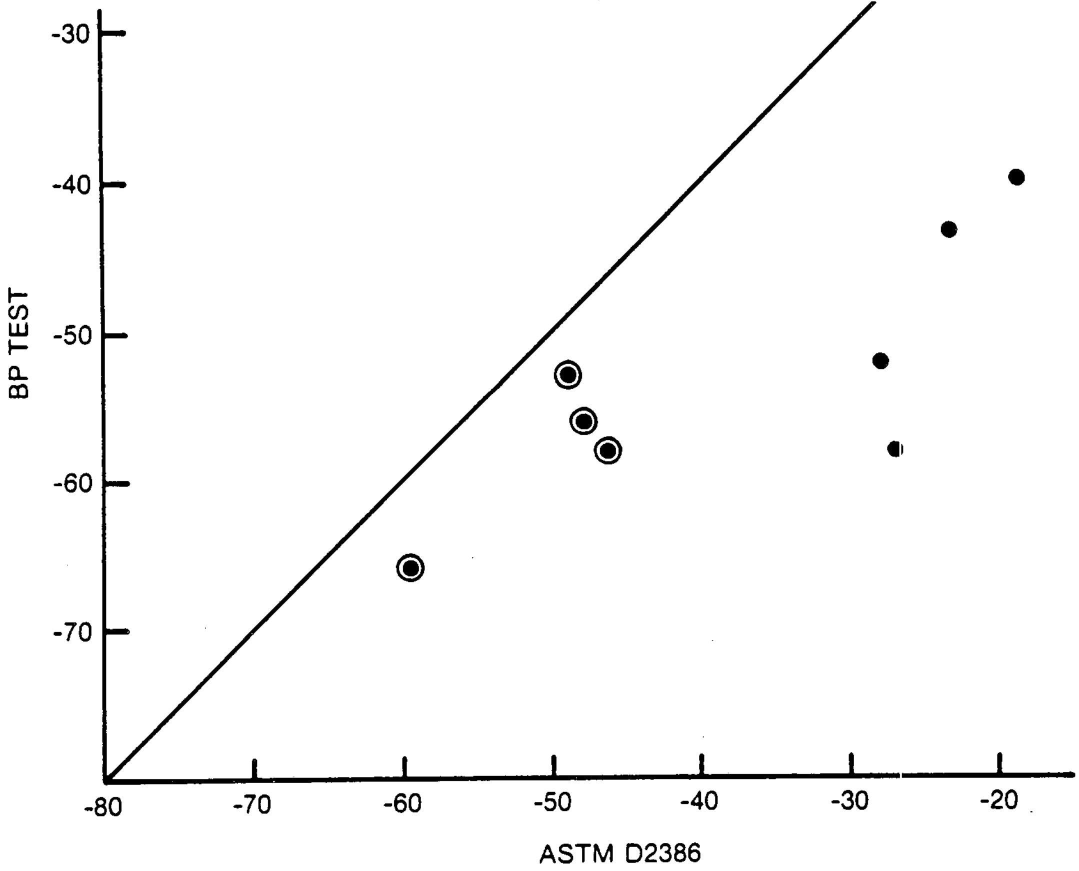

FIGURE 12. BP Test Stop Flow Point vs D 2386

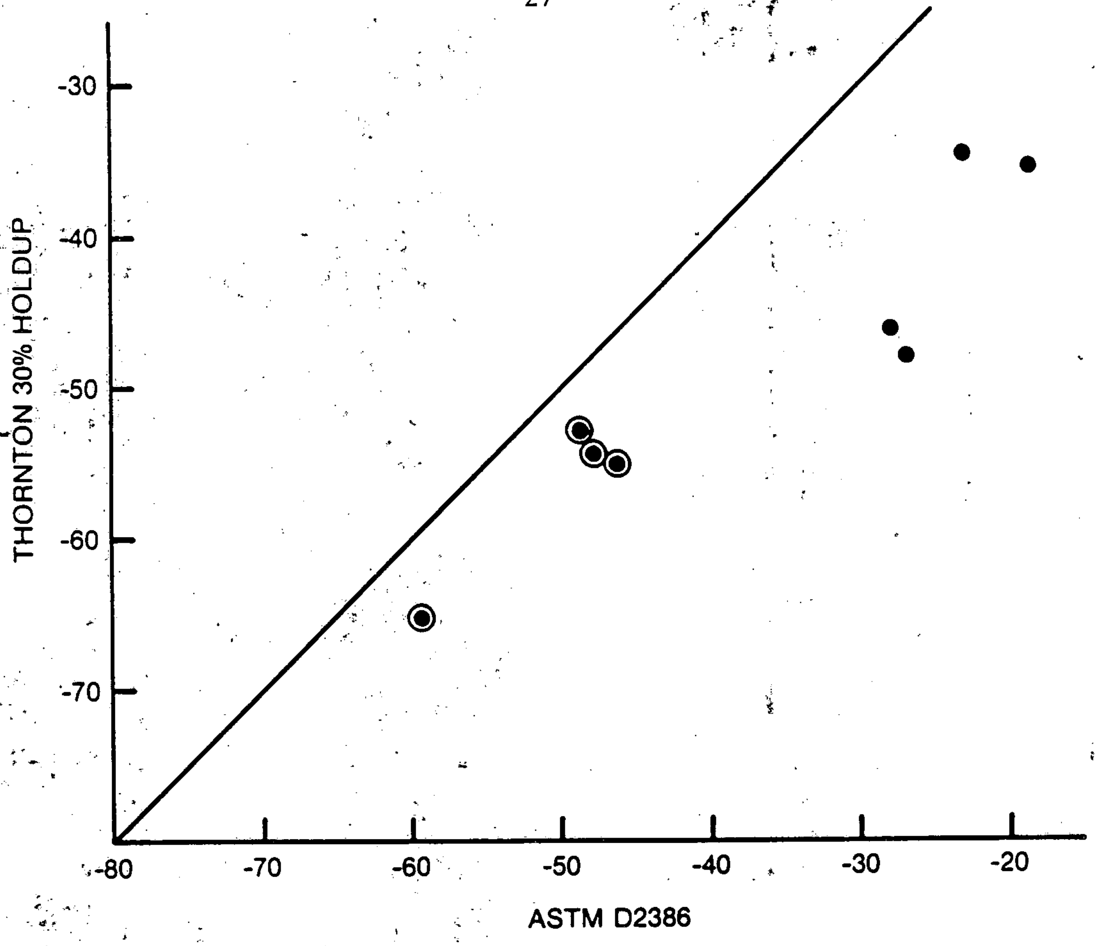

FIGURE 13. Thornton Cold Flow 30% Holdup Point vs D 2386

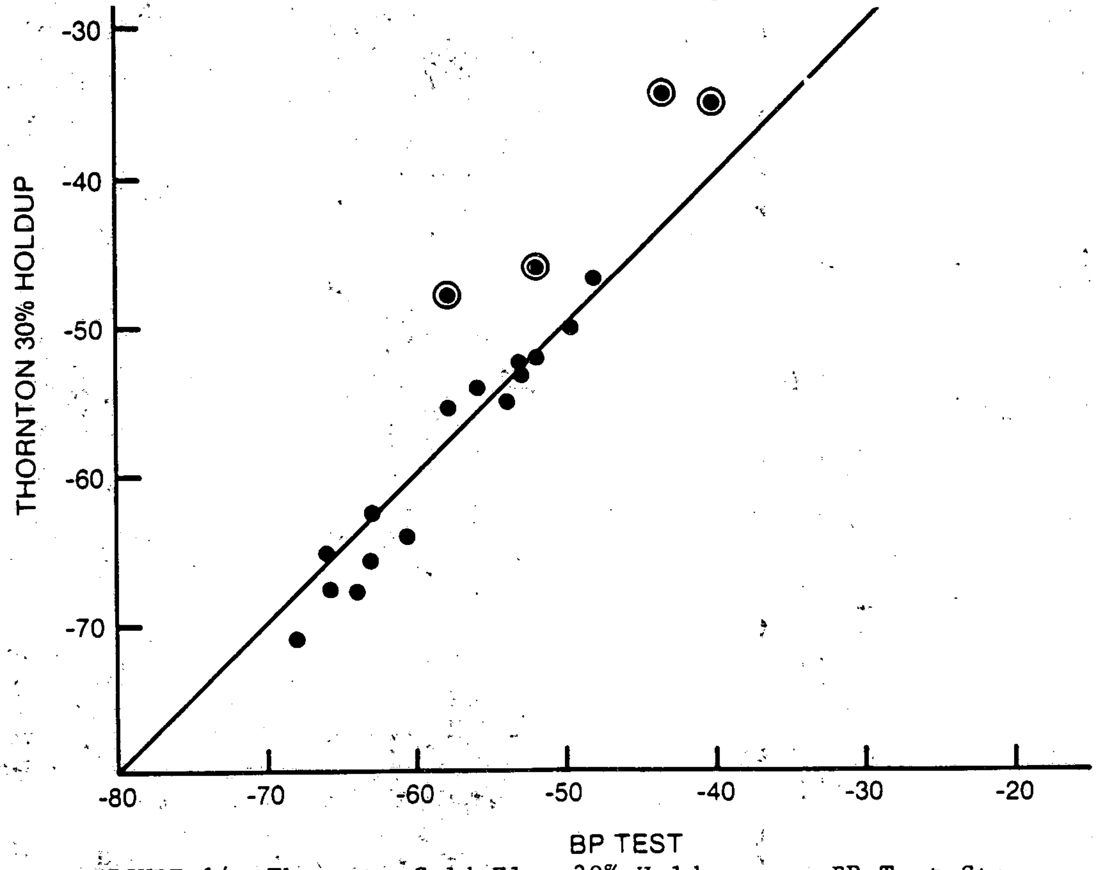

FIGURE 14. Thornton Cold Flow 30% Holdup vs BP Test Stop Flow Point (Circled points referred to in Text)

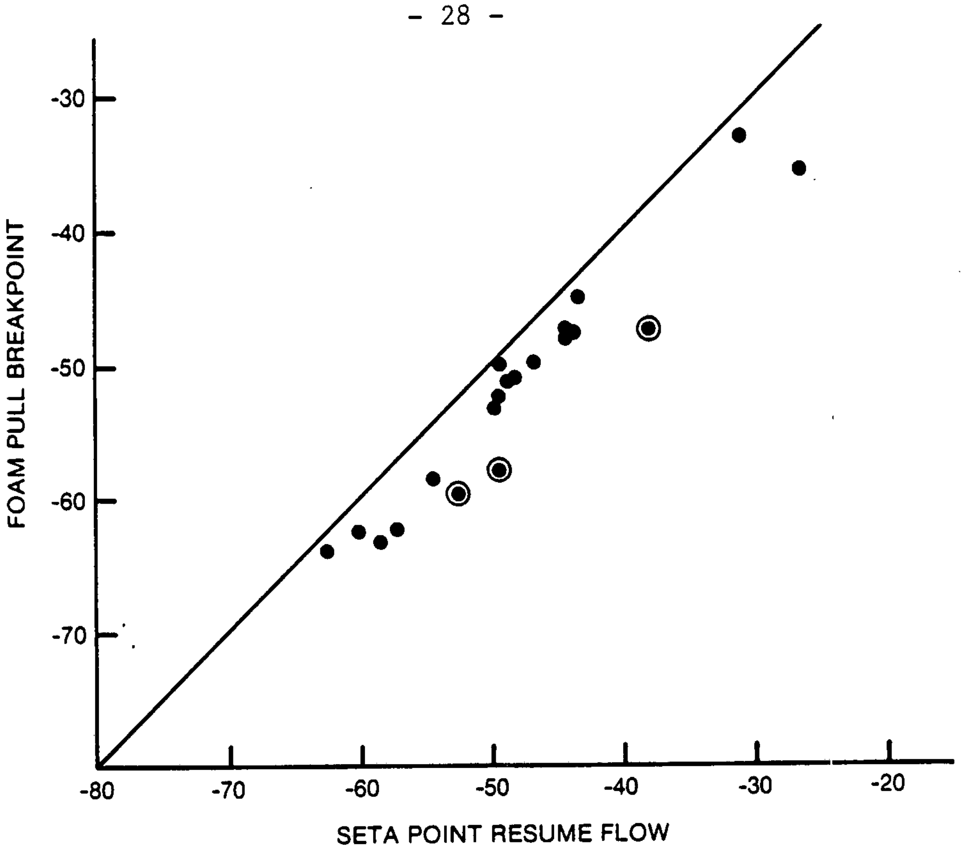

FIGURE 15. Foam Pull Breakpoint vs Setapoint Resume Flow (Circled Points, Figs. 15 to 18 are Jet B-Diesel and ERBS with Lowest Level Improver Flow (0.025%)

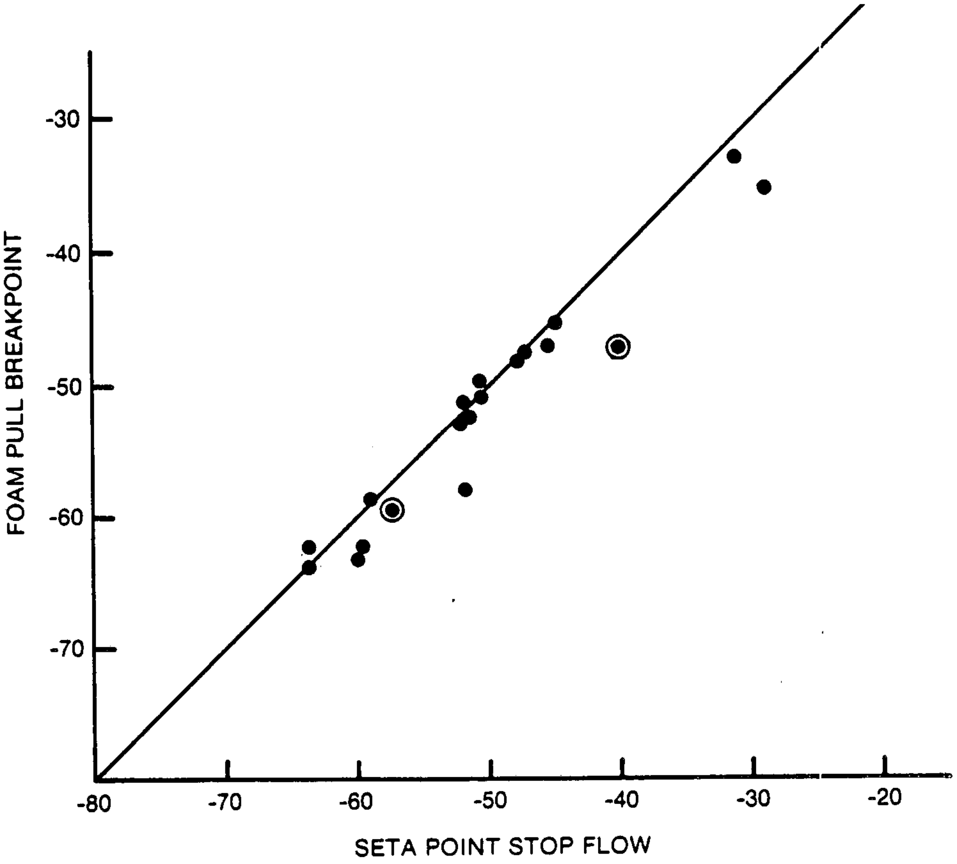

FIGURE 16. Foam Pull Breakpoint vs Setapoint Stop Flow

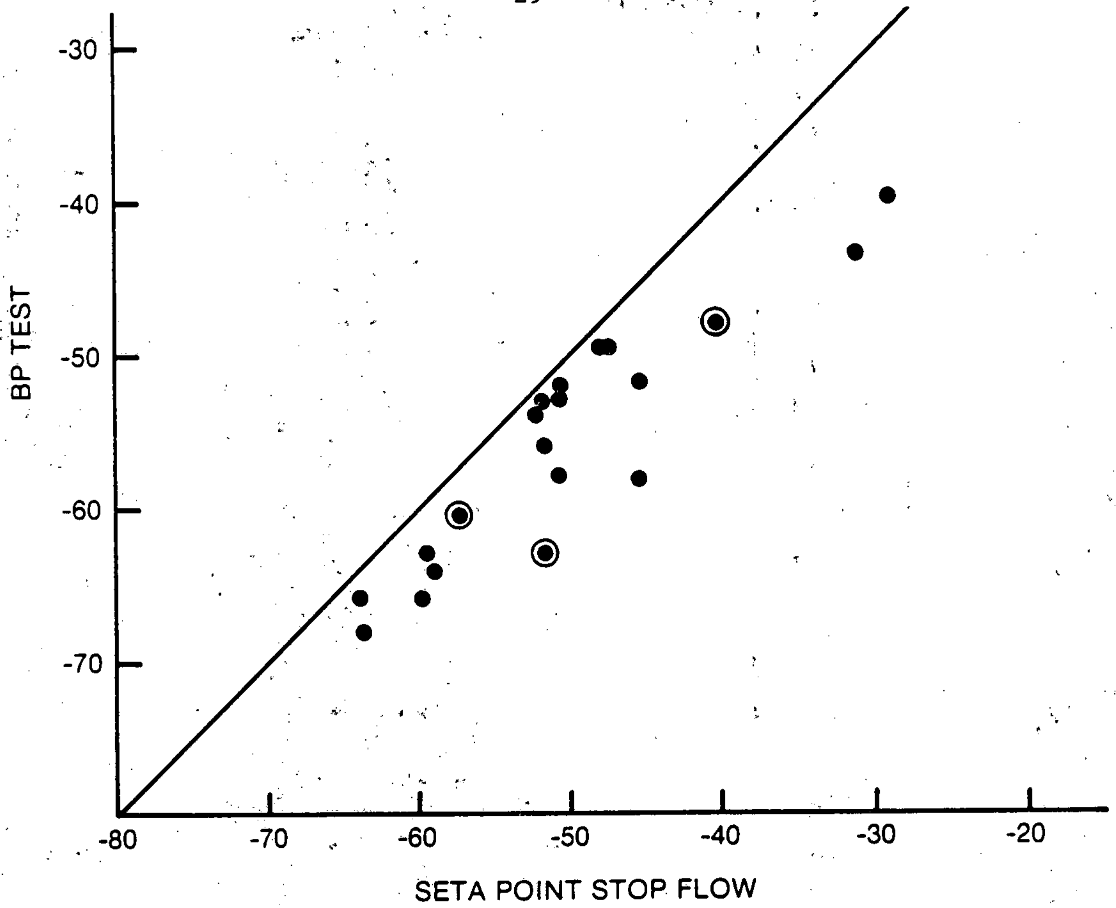

FIGURE 17. BP Test Stop Flow Point vs Setapoint Stop Flow

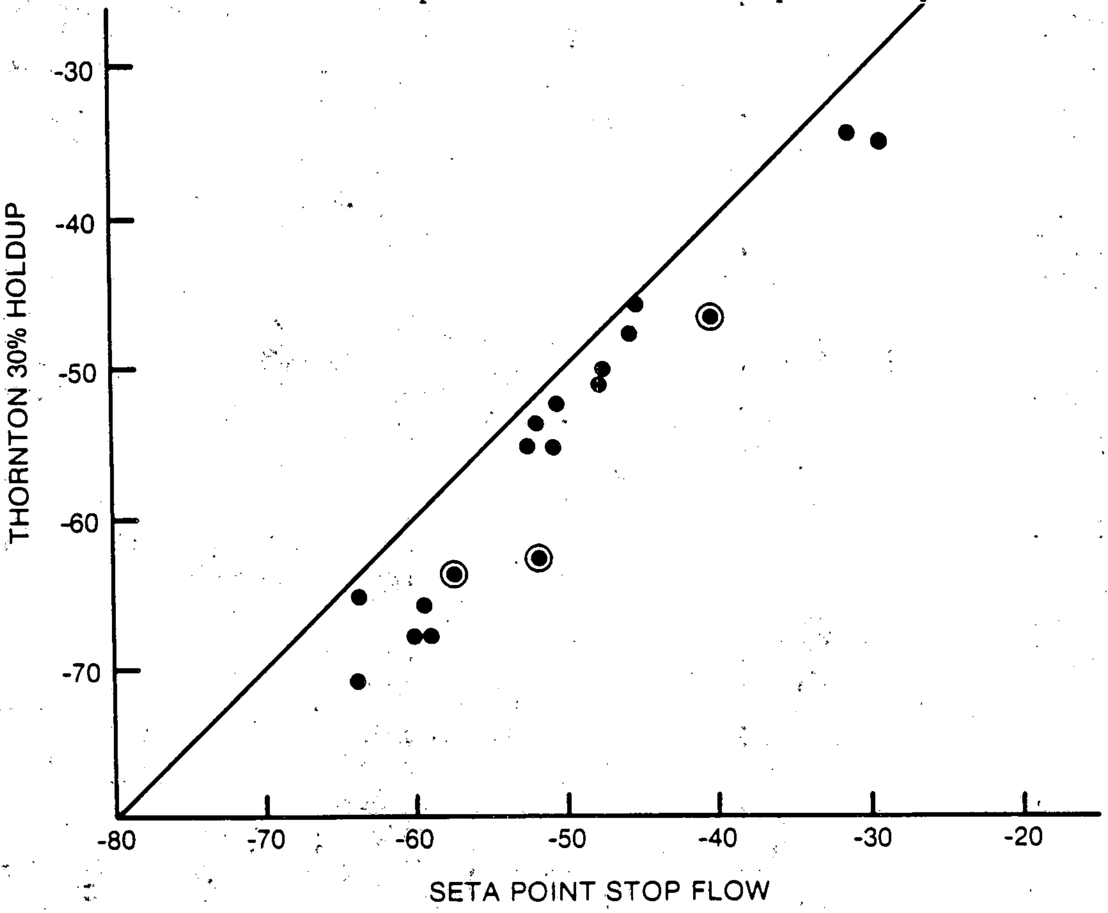

FIGURE 18. Thornton Cold Flow 30% Holdup Point vs Setapoint Stop Flow

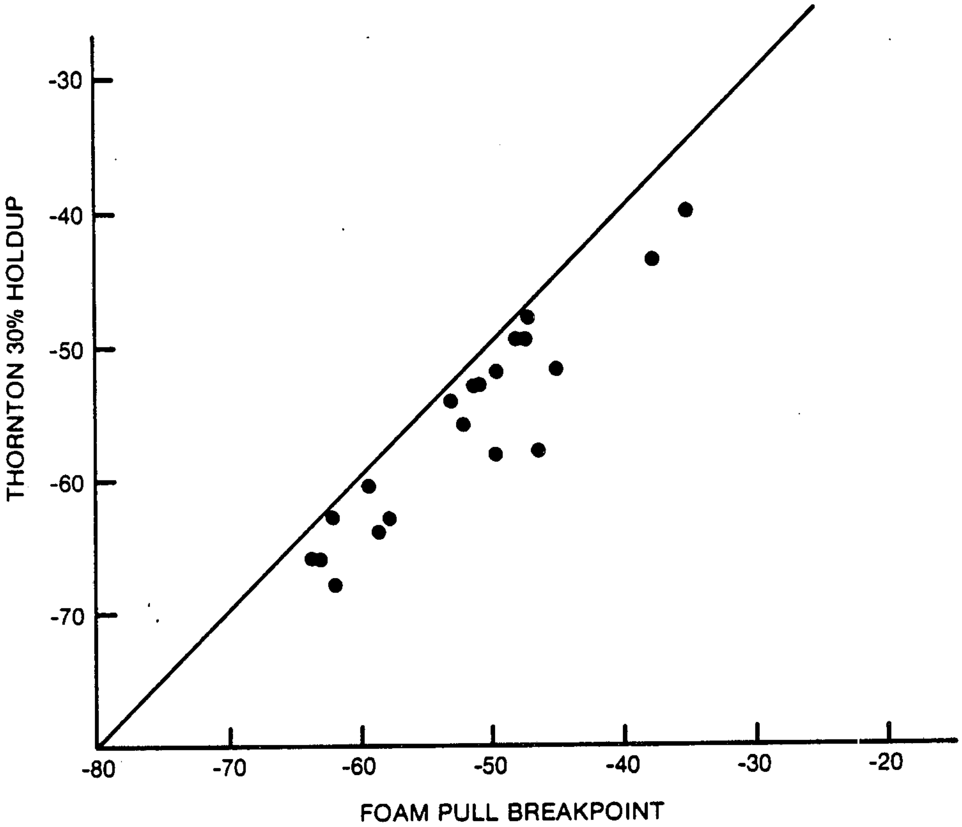

FIGURE 19. BP Test Stop Flow Point vs Foam Pull Breakpoint

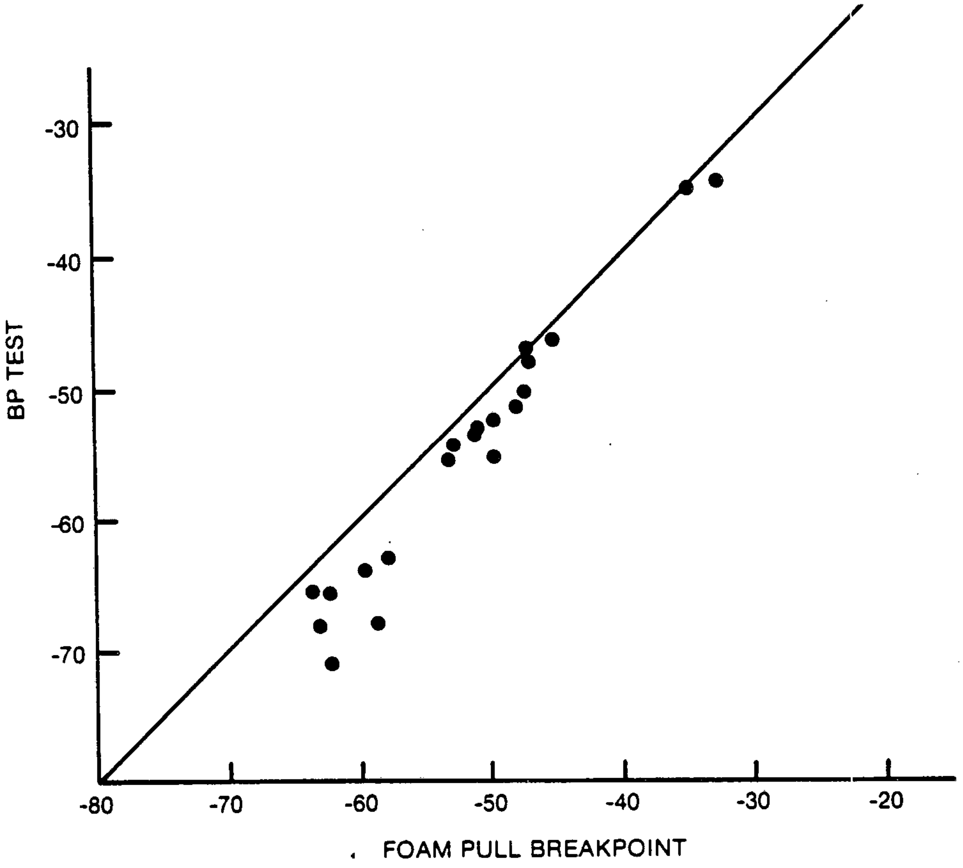

FIGURE 20. Thornton Cold Flow 30% Holdup Point vs Foam Pull Breakpoint

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Six bench scale test methods were assembled, which provide various measures of the lower limits of usability of aviation fuels. One of these was designed to measure fuel flow through reticulated polyurethane foams, used as a flame suppressant in aircraft fuel tanks. These tests were employed with fuels ranging from specification Jet A-1 to middle distillate blends of elevated freeze point containing No. 2 Diesel.

A series of comparisons of results by the several methods is presented. A small amount of work was conducted using two flow improvers with several of the higher freezing blends.

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KEY WORDS

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freeze point
fluidity
ASTM D 2386
Setapoint
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cold flow improvers
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