The Highs and Lows of Engine Lubrication: Part I - Low Temperature, Low Shear Pumpability Studies Using the Scanning Brookfield Technique.

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INTRODUCTION

The subject of engine lubrication has occupied the minds and efforts of a significant number of scientists and engineers ever since the automobile became an important source of locomotion for the world. Despite the attention given to this particular type of lubricant - often compared to the lifeblood of a human being - the effects of engine oil and the dependence of these effects on its composition of base stocks and additives, still are being unravelled. It is the author's intent to focus on certain critical aspects of todays engine lubricants and to further encourage technical dialogue on a subject of great importance to this mobile society.

As, indeed, our society is highly dependent on the automobile and the engine oil is the lifeblood of the source of its power for locomotion, then the subject is important beyond question and worthy of continuing close attention.

This particular paper has as its subject the low-temperature, low-shear response of an engine oil. The rheological response of an engine oil to this condition has a direct bearing on the ability of the engine oil to be pumped. As the automobile and truck have become more and more critical to our lifestyle, the expectation of service from these devices has extended to lower and lower temperatures and it is of value to place our present technical position in the framework of near-history regarding pumpability and its measurement.

But before we can put the subject into perspective, we must first view and appreciate the interrelationship of pumpability and startability.

HISTORY - Startability

Earlier in the development of the engine - during the '30s, '40s, '50s and '60s - the low-temperature problem was one of starting the engine. Adequate batteries, starting systems, carburetion and fuels were some of the very important points of technical concentration. But after these were resolved, there still was one area requiring understanding - the rheological properties of the engine oil and what effect these properties had on the degree of success in engine starting at temperatures below +10 F (-12 C).

For a considerable time gross errors in technical judgement were caused by the assumption that it was possible to predict low-temperature effects of the oil on starting by extrapolation of viscometric values obtained at much higher temperatures. However, slowly, much information was won at the laboratory bench and in the cold-room about the true properties of engine oils at low temperatures. The consequence was that startability was extended to lower temperatures and became considerably less of a problem at temperatures of -10 and even -20 F (-23 to -29 C).

HISTORY - Pumpability

Development of engines easier to start at low temperatures was a strong forward step for the use of the automobile. However, each step of progress usually reveals some other factor which then needs attention. Some warnings came well before the resolution of the startability problem. In 1948, Appeldoorn (1), considering the role of the engine oil on cold-starting, investigated the effect of wax on startability. Finding that wax in the oil had little effect on startability, he went on to comment on another potential effect of wax in an engine oil:

> "We therefore conclude that the effect of wax on cold starting is negligible. This does not mean that the presence of wax in motor oil can be neglected. Wax may not affect cold starting, but it can affect pumpability. --- The result is oil starvation, a high rate of wear, and eventual engine failure."

In 1962, the question of engine oil pumpability and its lack was reopened in an ASLE paper by Moyer (2). In this paper he showed that extrapolated viscosities would not explain the actual low-temperature response and air-binding of several engine oils in a pumping test rig using automotive pumps and supply tubes.

In 1963, the author's rework (3) of Moyer's data was made with a special viscometer using reblends of the oils Moyer had used. It was found that the measured values of viscosity for Moyer's oils at low shear rate corresponded very well with his experimental results. Moreover, the results obtained on the special viscometer could be calculated from the dimensions of Moyer's equipment. From this information and the rheological knowledge of oil gelation caused by wax and wax-polymer interactions gained earlier from low-temperature studies of engine oils for cranking/starting considerations, the author noted the possible air-binding effects possible through such gelation - and the attendent implications for engines capable of being started:

> "By any viewpoint, a highly gelated oil is undesirable, especially if the gelation exists at temperatures at which the engine may be started. --- Since gelation can be controlled either by proper dewaxing techniques, base stock selection or additive treatment, it would seem that any

> engine oil marketed should provide adequate lubrication under all the environmental conditions for which it is offered."

However, pumpability was at that time simply not considered to be a problem despite the increased ability to start the engine at low temperatures. For understandable reasons, the completion of the technical task and the development and accreditation of suitable measuring equipment was of more immediate importance. Thus, engine oil effects on cranking and starting continued to occupy the attention of the technical community involved in low-temperature engine oil viscometry problems.

The call to study pumpability was muted until 1970. As a result of a very limited and quickly rectified field experience in Canada and the concerns of one of the automobile manufacturers regarding the implications of this incident, the Society of Automotive Engineers conducted a survey to determine the level of interest in a method to measure the pumpability of engine oil. Early in 1971, on receiving a positive response from those questioned, the SAE sent a letter (4) requesting the ASTM to

> "--- develop a simple laboratory test to measure the ability of an oil to flow to the engine oil pump inlet in a manner relatable to engine conditions, and to consider the relationship between low-temperature oil properties and the supply from the pump to critical engine parts."

This request unleased a powerful effort to determine the properties of oils connected with pumpability (4 - 28). In the process 13 Pumpability Reference Oils (PRO) were developed and run in seven full-scale North-American test engines, five engine pumpability rigs, and a variety of bench tests. The latter were very important tests prefacing the choice of a bench test device or devices around which to build an ASTM Test Method. Subsequently, the CEC in Europe conducted similar tests (20) using eight representative European engines with virtually identical results reported on four of the ASTM Pumpability Reference Oils.

Yet, during all of this work there was an undercurrent of feeling that pumpability tests were an unnecessary burden to bear since the engine oils available had, to that time, shown no sign of giving field problems (with the exception of the poorly documented oil initially triggering the pumpability effort). While producing conditions in an engine which would be very prejudicial to engine longevity, the ASTM Pumpability Reference Oils were not considered representative of engine oils likely to be encountered in the field. To append an unnecessary new test on the already cumbersomely footnoted SAE Classification System, J-300, seemed a bit much - particularly with other changes having more evident need such as the extension of the temperature range over which to determine the cranking/starting characteristics of the oil.

The ASTM work, however, forged ahead. In the process it was shown that different engine designs had different levels of susceptibility to pumpability problems, particularly in regard to those oils showing 'air-binding' response of the sort anticipated 10 years earlier. With such oils of the PRO series, the oil would form a gelated mass in the crankcase and when the oil pump began to remove oil from the crankcase, the gelated oil was pulled from a volume immediately surrounding the pump inlet. As this occurred, atmospheric pressure forced the overcover of oil down to replace that drawn into the inlet. When the immediate overcover of fluid had been exhausted, a hole now extended through the fluid mass to the pump inlet causing the pump to air-bind. This occurance of air-binding in the test rigs and engines was observed through ports in the oil pan and photographed (7,10). The experimental verification of the phenomenon of air-binding predicted from the studies a decade earlier supported the implications of the earlier papers that, indeed, it would be possible to start engines under conditions where gelated engine oil would simply not permit the engine to be supplied with lubricant for some time after such starting, a condition virtually assuring heavy engine damage.

The ASTM completed their initial work on the pumpability project in 1978 with balloting and approval of the Mini-Rotary Viscometer as ASTM Method D-3829. In addition, the way was left clear for other pumpability methods that might be developed to be evaluated and ballotted by the ASTM and subsequently submitted to the SAE. Two of these methods on which research continued, used the Brookfield Viscometer in conjunction with a programmable liquid bath (21,27).

In early 1979, the SAE balloted and accepted the redesigned Viscosity Classification System, which incorporated D-3829, and called for it to become official in September of 1980.

HISTORY - Pumpability: Recent Past; Dramatic Change

After all of this work by the ASTM and the SAE, immediately after the new SAE Viscosity Classification, J300 Sep80, was in official effect, the method was found inadequate in detecting the sources of a serious outbreak of pumpability failures. During the winters of '80-'81 and '81-'82, a number of automobile owners experienced field engine failures which seemed, according to the symptoms reported by the owners, to be largely caused by oil starvation induced by air-binding - that is, oil gelation. Unfortunately, where samples of the oils could be obtained and tested, most of these failing oils could not be detected as such by ASTM Method D-3829 or other methods under development using the Brookfield Viscometer and, as a consequence, the methods were reluctantly thrown into disrepute, at least as far as detecting potential air-binding oils were concerned. The situation was highly confusing and very stimulating to new studies to determine the cause of failure as well as a suitable method of detecting such oils before more engines were ruined.

BREAKTHROUGH IN PUMPABILITY PROGRESS

The desired breakthrough in determining the cause was made by Stambaugh and O'Mara (29) in a series of engine cold room tests conducted with the same temperature profile that had been experienced in a region, Sioux Falls, South Dakota, December 1-2, 1980, a day which was known to produce engine failures at this location. When the so-called 'Sioux Falls' cooling cycle shown in Table 1 was used, the results were very similar to those associated with the air-bound condition of earlier experiences in the ASTM studies.

Next to producing failure conditions by simulating a certain field temperature cycle, the most interesting feature of the test was the narrow soak temperature 'window' within which the engine oil had to be held constant to produce the failing results. Raising or lowering the soak and/or the pumping temperatures by only a matter of a few degrees would cause the adverse behavior of the oil in the engine to appear and disappear. A third interesting product of the study was that the MiniRotary Viscometer - of D-3829 development - when exposed to the same cold-room conditions with the engine gave similar results in that high 'yield stresses' were shown when the engine was producing air-binding responses. The only difference between the treatment of the oils put in the engines and the oils put in the stripped MRV was in not preheating the oils in the latter.

DEVELOPMENT OF THE SCANNING BROOKFIELD TECHNIQUE

Basis of Study -

After the engine failure experiences of the winter '80-'81, when it was finally recognized and admitted that all the previous pumpability tests were inadequate, the author and his associates elected to follow a path hinted at during some of their capillary work at low temperatures. This capillary work with diesel fuels indicated that when there was a tendency for the fuel to form crystals at some given temperature, the tendency was amplified by moving the fuel back and forth through the capillary and measuring the viscosity at each pass to determine the rate of crystallization by its effect on the fuel viscosity. In effect, the technique was a varient of the use of nucleation techniques in superconcentrated solutions.

In developing a laboratory test, the author and his associates felt that there were several criteria to be met if the test were to be most effective in predicting the pumpability response of engines to the engine oil:

the desired test should

1) correspond with the field results producing pumpability failure,
2) be repeatable and reproducible,
3) be as short as possible commensurate with conditions 1 and 2,
4) be relatively simple to set up and run, and unambiguous in interpretation;

particularly in the light of the results of Stambaugh and O'Mara (29), the method should

5) have only one test mode and not require either prior information as to proper test temperatures or the use of multiple tests to identify a potential failure condition.

(The latter condition was one of the early shortcomings of the application of D-3829 as a pumpability test method in that testing for flow-limited and air-binding behavior required two different test approaches. Further, D-3829 requires that possible air-binding response be sought at two higher temperatures for an oil indicated at a lower temperature to be flow-limited (30).)

Prior to the development of the Scanning Brookfield technique, direct imitation of Nature was conceived to be the only approach to pumpability methods. That is, the oil was to be held quiescent as possible (as in the engine sump) and be exposed to some cooling condition believed to be reflective of what happened in the field. An ultimate example of this method of approach was mentioned earlier where Stambaugh and O'Mara (29) used a stripped down (i.e. non-insulated) MiniRotary Viscometer in the cold-room alongside of the engine in the evaluation of the response of the engine oil to the Sioux Falls cycle. (While they were not recommending the approach, the experiment was successful in showing that the MRV could be responsive to oils with air-binding properties if the proper temperature conditions and time of exposure were chosen.)

In contrast to the prior art of determining pumpability response of an engine oil through imitation of Nature, the author viewed the need as more the encouragement of Nature to respond to nucleation conditions if an engine oil were gelation-prone. It was considered that the ability of an oil to form some degree of gelation is related to four factors:

1) the concentration of oil components capable of forming a structure in the oil,
2) the rate at which these components become available to form a structure as a result of change of temperature,
3) the degree of opportunity for these components to associate in structure-building processes, and
4) the vulnerability of the structure to degradation if shearing conditions are present.

The first is, of course, the predominant factor in whether there will be a structure-building process at all. The second and third factors are rate-controlling in the building of a structure and the fourth factor is rate-controlling in the destruction the structure and, obviously opposed to the second and third processes of structure building. In the practice of prior art, the process of structure nucleation and growth - the second and third factors (which are encouraged by fluid motion) - were perforce inhibited by trying to eliminate the third factor.

From past experience with engine oil/additive structure formation (31), the author considered that the rate of formation of a structure for an air-binding oil might predominate over the rate of degradation of the structure and, under any circumstances, the 'shards' of the degraded structure would still affect the viscosity of the continuous liquid phase. Thus, the beginning and extent of structure formation should be manifest if the measuring technique were sufficiently sensitive. It was considered that the engine oil to be studied should be taken relatively slowly through the low-temperature range of interest while being stirred continuously to encourage the interaction of structure-building components. Simply stirring the sample was not considered sufficiently informative since a much better approach would be to use the rotor of a Couette-type viscometer as the stirrer and, thus, to be able to continuously measure the effects of such stirring.

First Results -

Accordingly, the author and his associates set up an experiment using a Siverso programmable liquid bath for producing and regulating the necessary low temperature program at 6 degrees Celcius per hour, a Brookfield Rheolog Viscometer (the predecessor to the Brookfield Digital unit used in later studies) for measuring and recording viscosity continuously, and a special test cell comprising a stator made out of a test tube and relatively close-fitting Brookfield rotor. The oils selected for contrast were a known Newtonian low-temperature calibration oil and the other was a sample of a field failing oil quite similar to one of those used by Stambaugh and O'Mara (29). The first results of the test, shown in Figure 1, were immediately gratifying. The result with the field-failing oil showed a dramatic 'break' from the normal curve expected with Newtonian behavior. Moreover, the break occurred at essentially the same temperature, ~+15 F (-10 C), indicated by Stambaugh and O'Mara to be the 'window' at which the oil in question gave such adverse air-binding performance. These results plus some evidence of a good degree of repeatability - repeat curves showing variations of less than 1 degree Celcius - were presented by the author (32) as a discussion of the Stambaugh, O'Mara paper (29) in early 1982.

When first reported, the Scanning Brookfield results elicited surprise in some technical quarters in that it showed definite evidence of the lack of necessity to hold engine oils quiescent before relevant analysis of pumpability was made. Quite the contrary, the study showed that shearing the engine oil could produce information not otherwise available. Particularly important was the fact that the technique seemed to clearly identify the temperature 'window' shown by Stambaugh and O'Mara to be critical to failure of the oils. Further, the technique produced a form of analysis which, if applicable to other field-failing oils, required only one technique and no prejudgement of an oils low temperature response point nor did it require multiple temperatures of analysis. Thus, the Scanning Brookfield technique immediately met several of the five test criteria mentioned earlier.

Developmental Efforts -

Further work on the Scanning Brookfield technique to determine and optimize the factors influencing the method was reported in the fall of 1982 (33). This work showed that the Scanning Brookfield technique

1) was repeatable
2) correctly diagnosed the air-binding, field-failed oils then available - PRO-21 to PRO-28 (Table 2)
3) correctly diagnosed the original ASTM PRO set, PRO-1 to PRO-16 (Table 3) with the exception of PRO-03 which was indicated by the Scanning Brookfield technique to have a tendency toward air-binding and PRO-09 which had been contaminated with water.

The result on PRO-03 will be discussed later in this paper.

In 1982 and 1983 the Scanning Brookfield technique was applied in a series of studies by Ford Motor Company through the efforts of Florkowski (later of Standard Oil of Ohio), Groh and Misangyi. This study was of certain field-failed oils which had given inconsistent results in other pumpability tests including D-3829, Stable Pour Point, and a Ford Method, BJ20-1. As a consequence of positive experience through relatively extensive evaluation, in 1983 the Scanning Brookfield technique was made a tentative Ford Method, BJ27-1, and in late 1984 was made a world-wide specification for Ford factory-fill engine oils and Ford Motorcraft Engine Oils. In 1985 the Scanning Brookfield technique, as BJ27-1, was made a part of the Cummins Engine Company's requirements.

Also in 1982, the Scanning Brookfield technique was formally made a part of the activities of the ASTM Task Force on Liquid Bath Brookfield Viscometry but only relatively recently were there enough active participants to mount a round-robin study. That study is now virtually complete with five sets of analyses submitted and four more in advanced stages. Repeatability and reproducibility look encouraging and a report on the effort is planned for the June ASTM meeting.

With this extensive history of the status of pumpability and the associated Scanning Brookfield technique now in perspective, further considerations of the method can now be presented.

PRESENT CONSIDERATIONS OF PUMPABILITY RELATED TO THE SCANNING BROOKFIELD TECHNIQUE

CONFIGURATIONS OF THE EQUIPMENT

The present instrumental setup has taken three forms in the hands of different investigators as a result of interest in the method. One of these forms, developed by K.O. Henderson of Ethyl Additives uses one source of coolant to transfer refrigerant to insulated outboard cells each of which records its own temperature/viscosity relationship. Asoke Deysarkar of Pennzoil Products uses a device which locks the stator to the Brookfield Viscometer head for ease of assembly and repeatable positioning of the rotor within the stator. J.H. O'Mara of Rohm and Haas uses a similar approach but a different rotor/stator geometry. Each of these investigators would undoubtably prefer to speak of their own approaches but, it should be noted that, when using the same rotor/stator geometry, each approach seems to give results within the reproducibility and repeatability of the technique.

The standard geometry of the rotor/stator is shown in Figure 2.

Most Common Configuration -

The most common setup for Scanning Brookfield viscometry is one like that shown in Figure 3 using a Brookfield Viscometer head, Model LVTD-5X and the Siverso programmable liquid bath, Model 410. While only slightly different, the setup of the author and his associates employes two Brookfield heads and a two-channel recorder (Figures 4a and 4b) to double the productivity of the Siverso programmable liquid bath. It will be noted that the glass cap over the test cell, shown more clearly in Figure 5 in position and in Figure 6 in an exploded view, is used to cover the cell and provide an injection port for dry nitrogen gas to sweep the inner cell air volume. This forestalls precipitation on the cold inner surfaces of the cell during humid days.

PRESENT TEST TECHNIQUE

Analysis -

Essentially the test technique is one of heating the test engine oil to between 80 and 90 degrees C for an hour with or without stirring. Then the test cell, filled with about 20cc of the oil, is placed in the coolant held at 15 degreees Celcius.

The rotating rotor position is then adjusted until it registers least output of torque. At this point the rotor speed is turned down to 0.3 RPM and the bath is quickly lowered to -5 degrees C, and held until the rotor torque output has stabilized. When the torque output has stabilized, the test cell cooldown at 1 degree per hour is initiated. The test is terminated when the capacity of the Brookfield head to record torque is exceeded. The resultant curve taken from a strip chart or recorded digitally is then analyzed.

Calibration -

Calibration of the test cell is quite similar in approach except that a known Newtonian oil is chosen and only five or six temperature steps are used to establish the viscosity/torque reading relationship. To assist in reading the raw data, the author and his associates have followed the practice of spanning the chart pen output so that the chart reading is proportional to viscosity and the chart can be roughly read directly.

ANALYSIS OF THE DATA PRODUCED

Depending on the purpose of using the Scanning Brookfield technique, analysis of the resultant data can take several forms. The data that result from a Scanning Brookfield analysis are first evident on the strip chart paper as a continuous line. A smooth curve with no abrupt changes, as is shown in Figure 1 for the satisfactory oil. Any departure from the smooth curve is evidence that some other process is operative and the temperature of the occurance may likewise be of interest. Sometimes the departure is abrupt and continuous as in the case of the poor fluid of Figure 1. At other times the abrupt change may soften and the curve revert to previous change although at a higher level of viscosity as a consequence of the initial abrupt change.

When the raw data from the strip chart or other recorder are then plotted on ASTM/Walther paper (a Log-Log viscosity versus Log absolute temperature coordinate paper), the data now yield further information depending on the degree of departure from a straight line on this logarithmic paper. In any case in which an abrupt change is evident on the strip chart or other recorder, that change will also be evident on the ASTM/Walther plot. The following section will discuss the significance of these points.

'Newtonian' versus Non-Newtonian Viscosity/Temperature Curves -

In the absence of any suitable way to refer to a viscosity/temperature curve on ASTM/Walther (log-log viscosity versus log absolute temperature) paper, and noting that mineral oil and their formulated products generally seem to exhibit Newtonian behavior at low shear rates whenever the curve forms a straight line on such paper, the author will use the term 'Newtonian Viscosity/Temperature Curve' or 'Newtonian VTC' to signify this simplistic form of flow behavior. Any other curve will be called 'non-Newtonian' with or without further definition.

The comparison between Newtonian VTC response and non-Newtonian behavior when rendered on ASTM/Walther paper is shown in Figure 7 for the two oils of Figure 1. With these as an example, the meaning of 'Newtonian VTC' and 'non-Newtonian' or 'structural' become virtually self-evident. Between these extremes are an infinite number of responses. Examining the ASTM/Walther curves for the original flow-limited PRO series, shown in Figure 8, some of this variety becomes apparent. Here there is evidence of completely Newtonian VTC response as well as gentle departures from it. However, there is no extreme departure from the Newtonian VTC.

In strong contrast to the Newtonian VTC response, the non-Newtonian curves associated with air-binding are produced when structure-building phenomena strongly manifest their presence as shown in Figure 9 for the air-binding oils of the same original PRO series. Again, one is struck by the range of non-Newtonian response of these original PRO air-binding series and by the fact that the engine tests themselves show much variation in whether they respond in an air-binding manner. Clearly, there is much to be understood in the involved engine/oil-pumpability relationship.

From the foregoing, it is evident that engine oils may or may not exhibit non-Newtonian behavior in low-shear, low-temperature flow under the stimulus of the Scanning Brookfield technique. Almost without exception, when there is a non-Newtonian curve generated on the ASTM/Walther plot, the curve has an 'ogee' or s-shaped pattern or, at least a portion of the pattern. In some cases the departure from the simple Newtonian VTC is quite mild and is associated with flow-limited behavior; in other cases the departure is quite abrupt and associated with air-binding behavior; in still other cases the response is mixed where the ogee pattern associated with structure appears but without the level of abruptness characteristic of the field-failed oils.

DETECTION OF POTENTIAL FIELD-FAILING ENGINE OILS

Flow-Limited Oils -

Flow-limited behavior is the simplest rheological property of an oil to measure and predict. Any of the various applied or proposed viscometric pumpability tests have thus far showed clear response to flow-limited oils as well as agreement with one another, including the D-3829 MRV and the Scanning Brookfield technique.

For example, information from a North American engine oil collection and analysis program contained data permitting comparison of 175 low-temperature results from D-3829 and Scanning Brookfield analyses of marketed engine oils (34). The data showed that, at the test temperature required by J300 for the SAE grade involved, more than 80% of the MRV single point values fell within 2 degrees C of the Scanning Brookfield curve and for 55% of those MRV data, the values fell on the Scanning Brookfield curve. Moreover, of those remaining oils which showed poorer agreement between the MRV and the Scanning Brookfield several (20%) had evidence of strong gelation, characteristic of air-binding oils which characteristic, as previously noted, more strongly affects the sensitive Scanning Brookfield in its results.

As shown in Tables 2 and 3, the temperature at which an oil reached 40 Pa.s or 40,000 cP was found to be effective in predicting conformity with SAE J300. The temperature at which an oil reaches this viscosity is called the Critical Pumping Temperature, or CPT, and this single criterion applies to both flow-limited and air-binding oils.

A recent paper by Stambaugh (35) indicated that the so-called 'flow curves' generated by the Scanning Brookfield technique, had poor correlation with the 'oiling times' observed in certain engines and at certain test temperatures using three experimental oils fully formulated to meet the requirements of J300 FEB84. The three oils were made with three different VI Improver systems: polymethacrylate (PMA), olefin copolymer (OCP), and hydrogenated styrene/isoprene, (HSI). This observation of a lack of correlation between the Scanning Brookfield 'flow curves' and the 'oiling times' led Stambaugh to suggest that the Scanning Brookfield may be a poor method for ranking flow-limited oils. While this may be true, the data of reference (34) previously discussed do not seem to support his suggestion. Rather, it shows relatively close correlation between the results of method D-3829 and the Scanning Brookfield with the exception of a few oils some of which were strongly non-Newtonian.

The work he generated, however, has additional value in further understanding the engine pumpability relationship particularly since his work calls several assumptions into question and it is well to consider these questions even if they cannot be answered at this point.

First is the question of whether the oils used by Stambaugh are 'non-Newtonian', as the term is defined in this paper. That is, do they individually or collectively have structure-forming characteristics. Scanning Brookfield tests on the three oils reported in two Rohm and Haas presentations to the automotive industry (35) indicates that at least the PMA-containing oil is non-Newtonian as denoted by an ogee curve. If one or more of these oils is non-Newtonian, then the second question is one of whether there is or should be a parallel between the curve generated by the Scanning Brookfield and the curve generated by 'oiling times'.

The third question is in regard to the Sioux Falls cooling cycle and whether it is a universal engine cooling technique for detecting the air-binding propensity of oils. If one or more of the three oils were actually capable of air-binding response and the Sioux Falls cycle were not a universal discriminator of air-binding response in engines, then perhaps other cycles should be evaluated.

The latter point was amplified recently when the application of the Scanning Brookfield technique of BJ27-1 led to the finding of a 15w40 on the market which, as shown in Figure 10, gave strong evidence of potentially failing in the field under certain temperature conditions. Both the MRV at -20 degrees C and the Cold-Cranking Simulator at -15 degrees C gave acceptable results. Without engine tests, however, the temperature conditions leading to possible pumping problems were not known beyond the fact that the Scanning Brookfield indicated that initiation of structure-building was about -10 degrees C (+15 degrees F). Corroboration of the Scanning Brookfield results was obtained using a TP-1 MRV cycle which is a another proposed ASTM method for determining pumpability utilizing the MRV and a modified cooling cycle (36). However, in the cold-room engine tests, the oil would not fail with the Sioux Falls cycle (and several variants). The oil finally was brought to failure by imitating the TP-1 cycle at which point the oil failed in the engine in a very evident manner. It can be concluded that the nature of the cold-room cycle is also critical in regard to effectively testing an oils pumping response and the Sioux Falls cycle, while very significant, is not a universally applicable cycle to detect air-binding potential.

This, of course, brings back the question of whether or not any or all of the three engine oils blended and tested by Stambaugh might, in their oiling curves, only reflect the Sioux Falls response while the Scanning Brookfield technique might be giving information concerning temperature effects likely to produce structure over the entire temperature range of interest. Perhaps, had some other cooling cycle for the engine tests on the three oils been made, say similar to the TP-1 cycle, the results reported might have fallen in a different order.

The latter results also call into question the original engine tests for pumpability. Had these engine tests been cold-soaked for different lengths of time, or cooled down more slowly to the test temperature, the results might have been more uniform among the engines and some oils which first appeared flow-limited, would then appear air-binding. Perhaps this is the reason why, with the Scanning Brookfield approach, PRO-03 would seem to be more of an air-binding oil. This behavior of PRO-03, which was reported, as noted earlier in this paper, in an SAE presentation in 1982 (33), was recently confirmed by Henderson, et al., in a study using new MRV methods (36).

Air-binding Oils -

The most insidious form of pumpability failure is air-binding, probably because with a flow-limited oil - if the oil is too viscous to pump - it is too viscous to start.

As previously detailed, this structure-building, non-Newtonian form of flow constraint was the primary cause of much engine damage in the winters of '80-'81 and '81-'82 in both North America and in Europe. It was also the primary cause of the development of the Scanning Brookfield technique which, although expected to be effective in detecting flow-limited behavior, was primarily intended to be a method of detecting air-binding response across the broad band of temperatures to which engines are exposed. The method was to be singular - that is, only one method should be required, if possible, with no multiple determinations to 'hunt' possible failure nor other data to narrow the search. While other pumpability methods presently being developed have much to commend them, as far as is known to the author, the Scanning Brookfield is still the only method which meets the important criteria above with sufficient sensitivity and precision.

The most outstanding characteristic of potentially air-binding oils in the Scanning Brookfield test is the relatively abrupt change in rate of increase in viscosity at some critical temperature. If that rate of change continues until the viscometer torque read-out is driven off-scale, the chances are very good that the oil will air-bind in a sensitive engine under some low-temperature exposure conditions. At present there have been no exceptions to this experience. For example, note the sequence of ASTM/Walther curves for the field-failing series PRO-21 to PRO-28 in Figures 11 and 12; all of the Scanning Brookfield non-Newtonian curves for this series are essentially vertical after forming a brief first leg of the ogee curve. The exception is PRO-26 which, although quite vertical during the second leg of the ogee, does begin to form the third leg before exceeding the 40,000 cP limit at about -17.5 degrees C. It is of interest that PRO-26 is a European engine oil which failed there during the winter of '80-'81.

On the other hand, PRO-26 shows that there are varying degrees of non-Newtonian response and this is amplified when the various Scanning Brookfield curves for the original series of air-binding PROs are viewed as in Figure 9. The question becomes one of determining the minimum non-Newtonian curve which will still result in air-binding failure.

The need seems to be met by PRO-29, a field-failing engine oil from the winter of '82-'83. It is a subtle oil which frequently passes the stable pour point - the pumpability nemesis of a number of other field-failing oils. Recent studies with the

Scanning Brookfield equipped with the standard rotor/stator geometry are shown in Figure 13. The results show that PRO-29 is clearly non-Newtonian with a pronounced ogee curve and has a Critical Pumpability Temperature of -24.3 to -25.4 degrees C which is definitely borderline for a 10w40 oil. From the original strip chart data it was apparent that PRO-29 started the second leg of the ogee curve somewhat lower in temperature than the other members of the notorious PRO-2X series.

Following the experimental lead of Ken Henderson of Ethyl Additives (37), the author had a smaller diameter (0.5 in.) rotor made with which PRO-29 was again tested. The resultant strip chart curve, while showing a first break at about the same temperature, gave a much longer second leg before tipping into the final leg. As shown in the ASTM/Walther plot of Figure 14, the Critical Pumpability Temperature was raised to -21.7 degrees C, a definite failure. These results suggest that, despite good correlation with air-binding oils with the standard rotor/stator geometry, much is available to be learned by modifications of the Scanning Brookfield technique.

Considerations Regarding the Causes and Effects of the Scanning Brookfield Technique -

One of the first considerations in applying the Scanning Brookfield technique is that regarding sharp non-Newtonian behavior typical of air-binding immediately beyond the chosen temperature of classification. In other words, is a propensity for air-binding acceptable below the specifically chosen temperature of test? It would seem that, as deadly as air-binding is to the life of the engine and as expensive as engines are today, that perhaps some thought should be given to avoiding serious air-binding potential at temperatures 10 or 15 degrees C below the lowest temperature at which the engine is expected to start.

In the same vein, what of the wide variety of single grade oils on the market and in vehicles? Because they are not classified for low-temperature service, should they not have some minimum standards of pumpability standards for lower temperature starting. Paraphrasing a statement quoted earlier in the paper (3), it would seem that the engine oil would be expected to protect the engine at whatever temperature the engine could be started without assistance. However,in the final analysis, even if the engine were given some form of starting aid assistance, the oil could be strongly structured and air-binding unless some provision were made for heating the engine oil or otherwise preventing the consequences of air-binding.

Correction of Air-Binding Tendencies in Motor Oils -

Considering the various possible causes of the occurance of air-binding, the question arises about correction of the tendency without the waste of the product. Further, what is a reasonable goal for such correction?

While much knowledge and understanding concerning the role and mechanism of pour point depressants is important in the treatment of formulated products, a relatively simple experiment showed that, at least in some cases, air-binding can be effectively terminated.

Figure 14 shows the consequences of an effort to correct an unsuccessfully pour-point depressed base oil shown as Sample F. This base oil showed all the symptoms of air-binding potential in the Scanning Brookfield analysis. Treatment with Pour-Point Depressant A produced Sample G - an obvious improvement but still an oil capable of causing air-binding. Treatment with Pour-Point Depressant B produced Sample H - an oil with a Newtonian VTC.

CONCLUSIONS

While this paper has had the overtones of a techno-historical essay, there are conclusions to be drawn.

The subject of pumpability and its control is becoming more and more of a serious problem as a consequence of the greater variety of sources and treatment of refined base oils. Efforts to extend the quantities of the lighter neutral base oils by raising the dewaxing temperatures has also caused concern. In the face of this situation, the problem is compounded by the recent emphasis on marketing 5w30 oils. Such a move will place even greater demands on low-viscosity base stocks and greater efforts to try to utilize the full content of the distillates yielding these basestocks. If less dewaxing for such oils is chosen as one path of increasing yield, the techniques of pour-point depressancy will be given a great stimulus in research, development and application. Alternative paths include the serious consideration of synthetic basestocks.

The Scanning Brookfield technique is really representative of many techniques utilizing the concept of measuring the change in a lubricant property while stressed by changes in applied conditions. At this time, the technique seems to stand alone in producing relevant information concerning pumpability of oils across the broad low-temperature range of interest. The technique is obviously capable of many modifications to meet this problem area and others of similar nature.

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TABLE 1

HOURLY TEMPERATURES
SIOUX FALLS, S.D.
DEC. 1-2, 1980

Time	Temperature, °F
2 PM	8
3	6
4	5
5	5
6	5
7	5
8	5
9	5
10	5
11	5
MIDNIGHT	5
1	4
2	4
3	3
4	2
5	0
6	-2
7	-5
8	-9

TABLE 2

COMPARISON OF NEW PRO OILS INCLUDING THE SCANNING TECHNIQUE

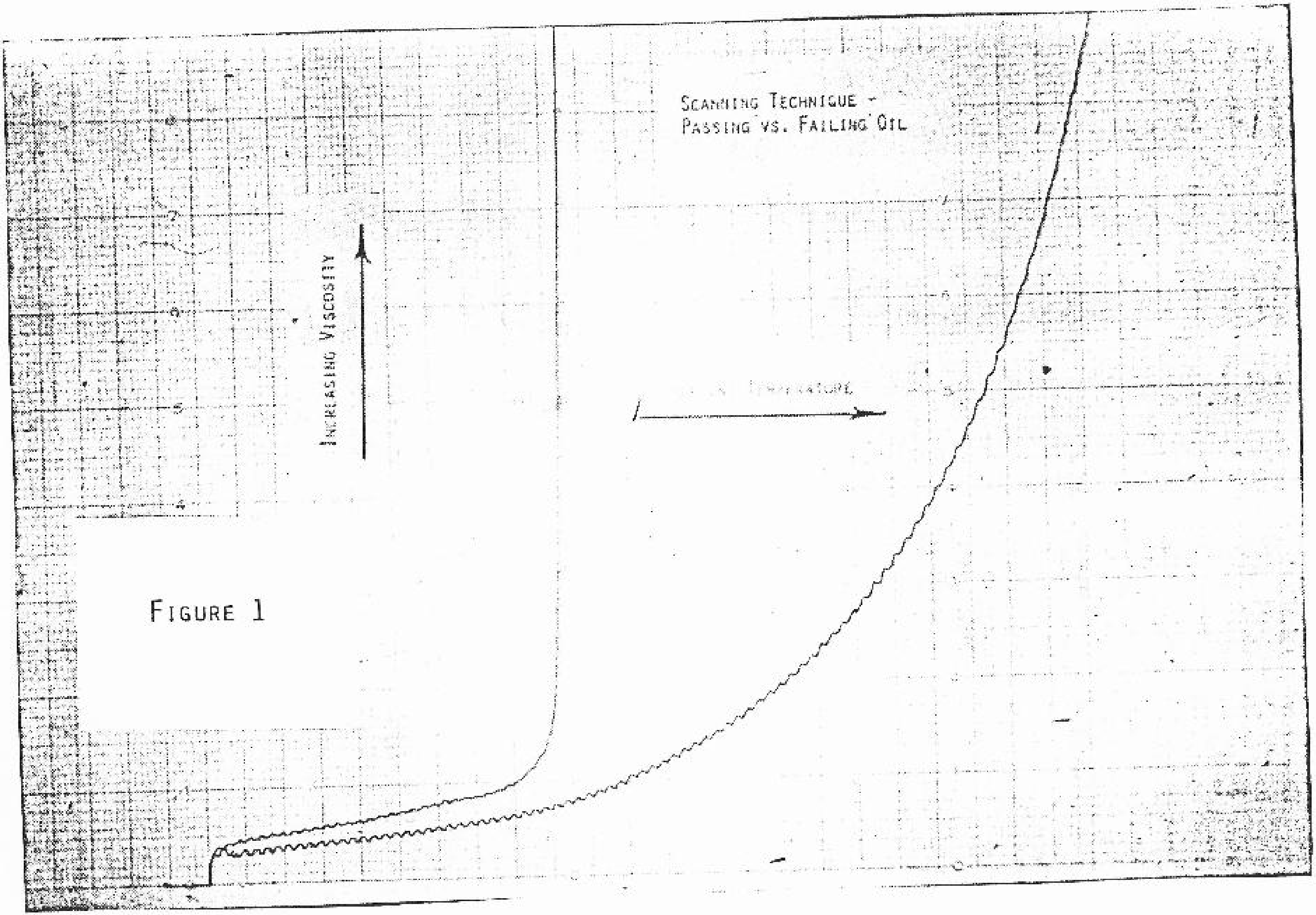
PRO OILS	SAE GRADE	D-3829 @ 30 PA·S	SAE J-300	FIELD DATA	SCANNING TECHNIQUE @ 30 PA-S	SCANNING TECHNIQUE @ 40 PA-S
21	10W-30	-13	FAIL	FAIL	FAIL	FAIL
22	10W-30	-17	FAIL	FAIL	FAIL	FAIL
23	10W-40	-29	PASS	FAIL	FAIL	FAIL
24	10W-40	-26	PASS	FAIL	FAIL	FAIL
25	10W-40	-22	FAIL	FAIL	FAIL	FAIL
26	10W-40	-27	PASS	FAIL	FAIL	FAIL
27	10W-40	-29	PASS	FAIL	FAIL	FAIL
28	10W-40	-27	PASS	FAIL	FAIL	FAIL

TABLE 3

COMPARISON OF ORIGINAL PRO OILS INCLUDING THE SCANNING TECHNIQUE

PRO OILS	SAE GRADE	D-3829 @ 30 PA·S	SAE J-300	7-ENG. AVG./ FIELD DATA	SCANNING TECHNIQUE @ 30 PA·S	SCANNING TECHNIQUE @ 40 PA·S
1	5w-30	-36	PASS	PASS	PASS	PASS
3	10w-40	-27	PASS	PASS	FAIL	FAIL
5	10w-40	-18	FAIL	FAIL	FAIL	FAIL
6	20w-50	-23	PASS	PASS	PASS	PASS
7	20w-20	-27	PASS	PASS	PASS	PASS
8	20w-20	-28	PASS	PASS	PASS	PASS
9	10w-40	-26	PASS	PASS	FAIL*	FAIL*
10	5w-40	-32	PASS	PASS	PASS	PASS
11	10-w40	-30	PASS	PASS	PASS	PASS
12	10w-50	-28	PASS	PASS	PASS	PASS
13	10w-40	-33	PASS	PASS	FAIL	BORDERLINE PASS
15	10w	-34	PASS	PASS	PASS	PASS
16	20w	-23	PASS	PASS	PASS	PASS

* = CONTAMINATED OIL



Scanning Technique - Passing vs. Failing Oil

Figure 1

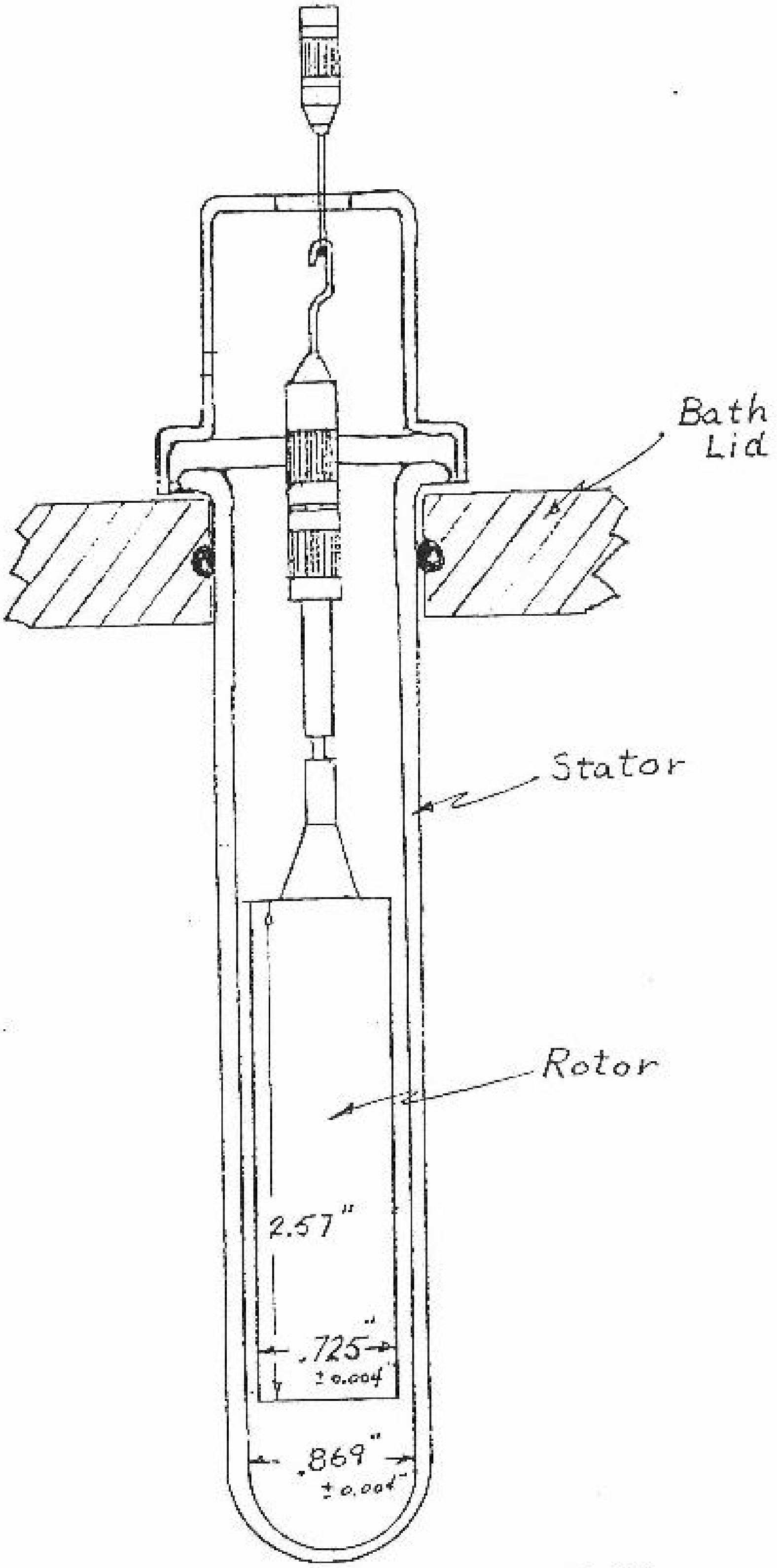


FIGURE 2

STS 851

FIGURE 3

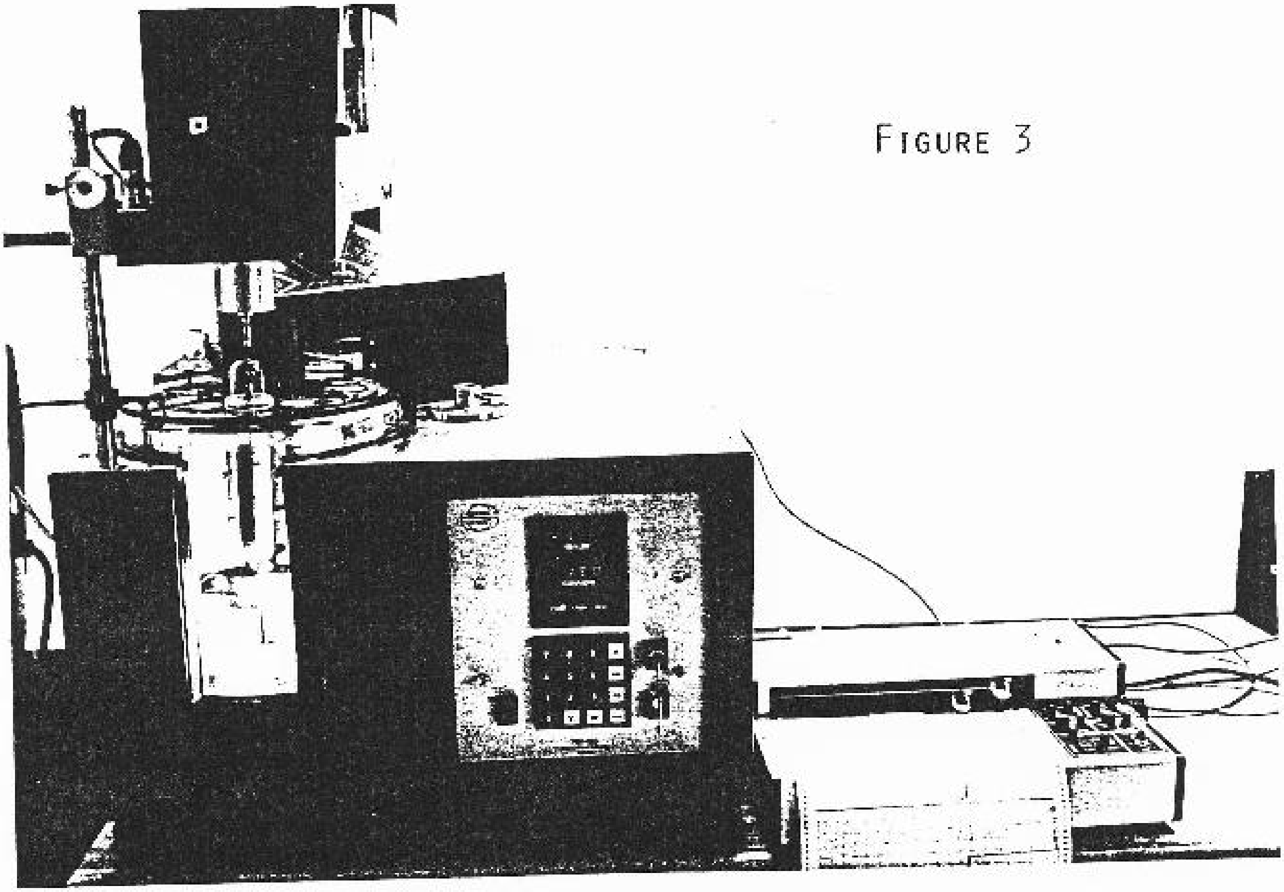
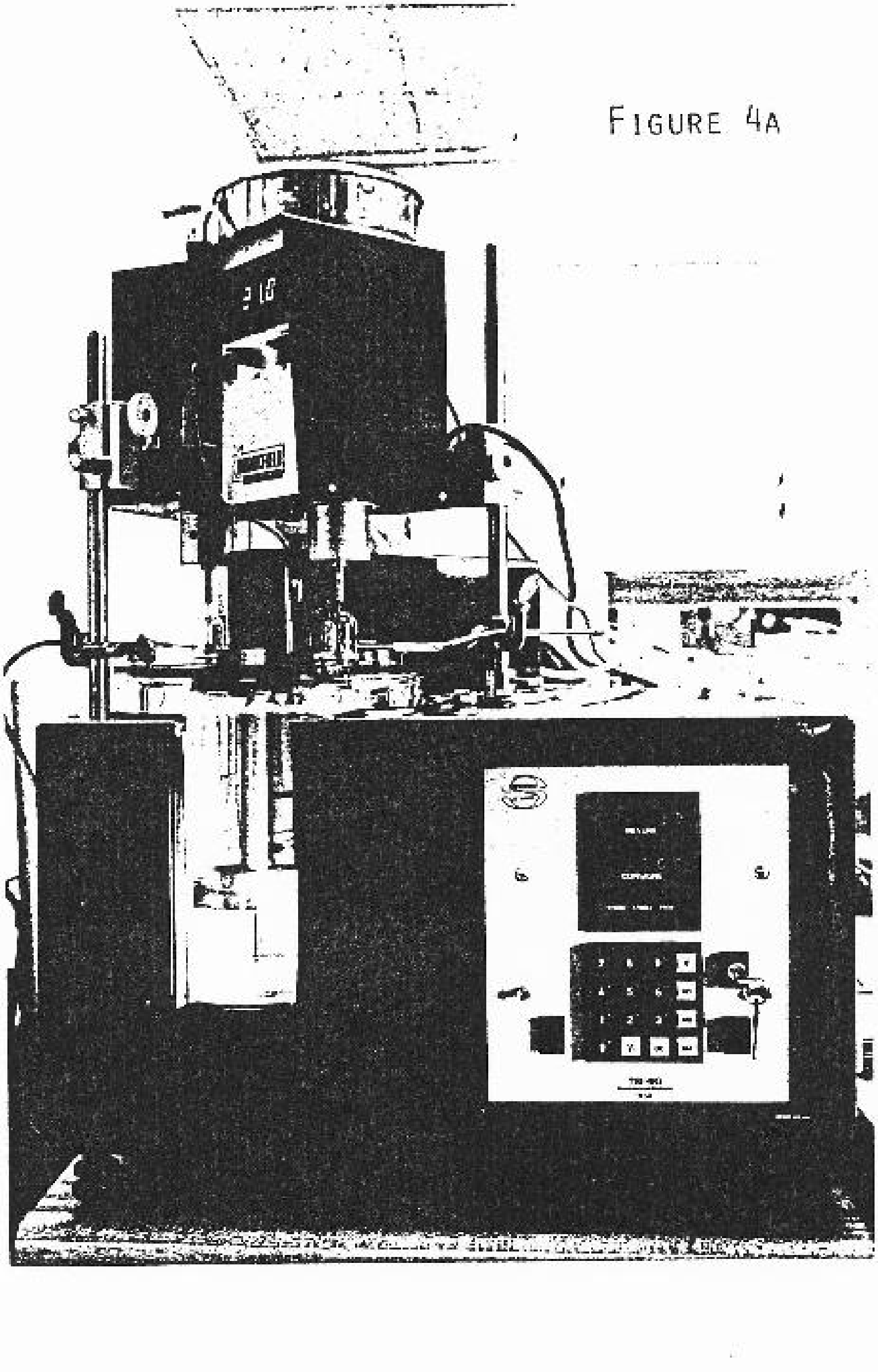


FIGURE 4A



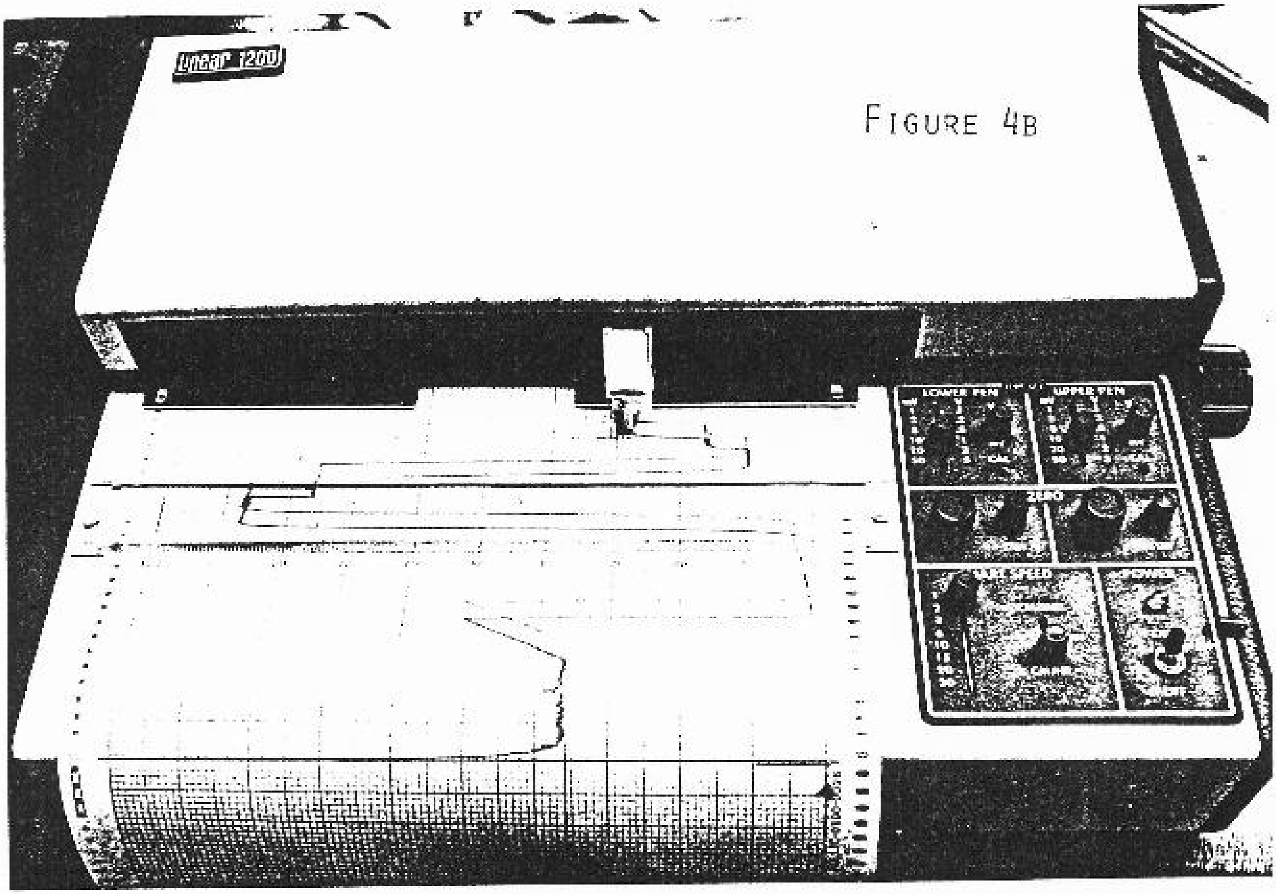
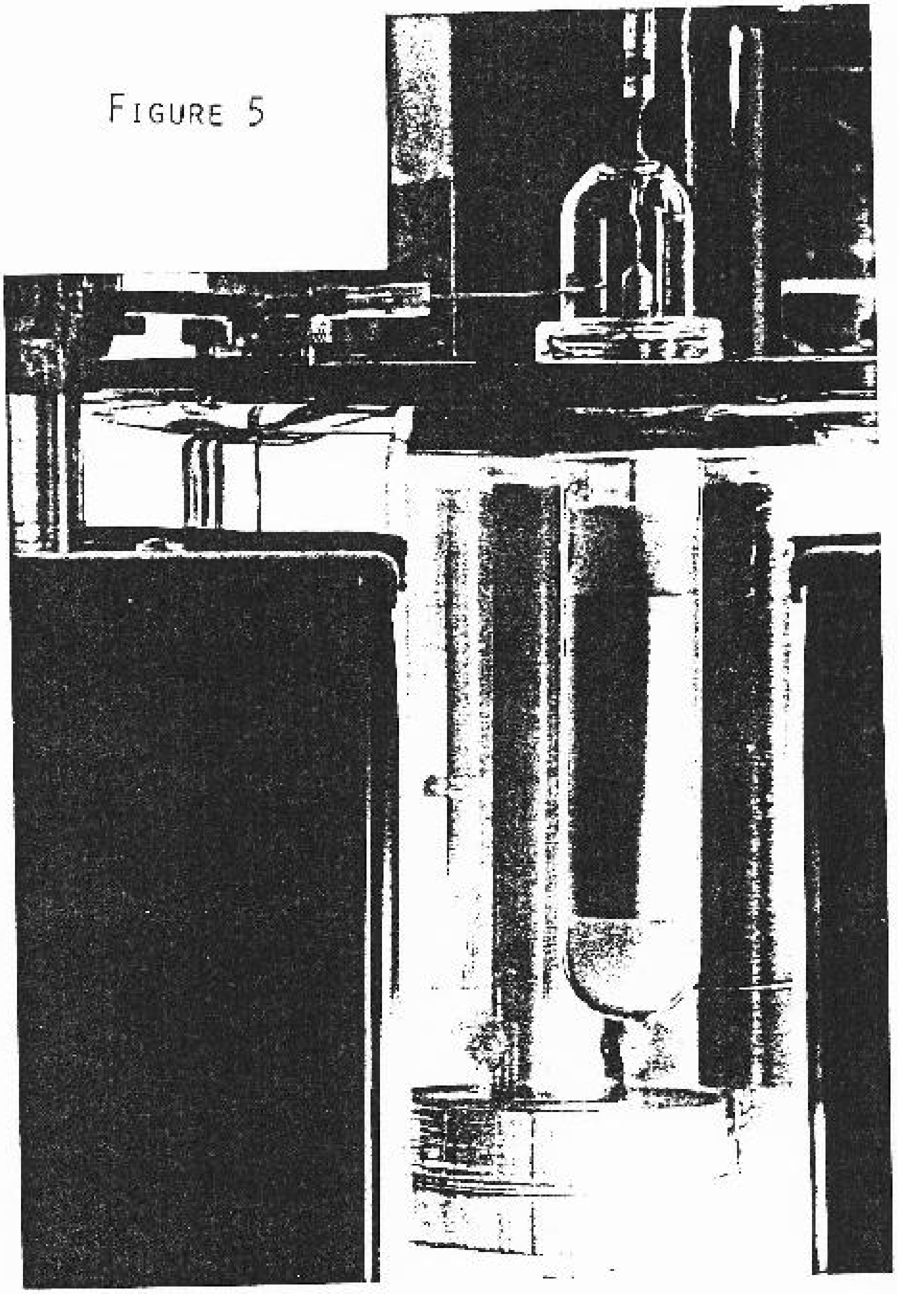


FIGURE 4B

FIGURE 5



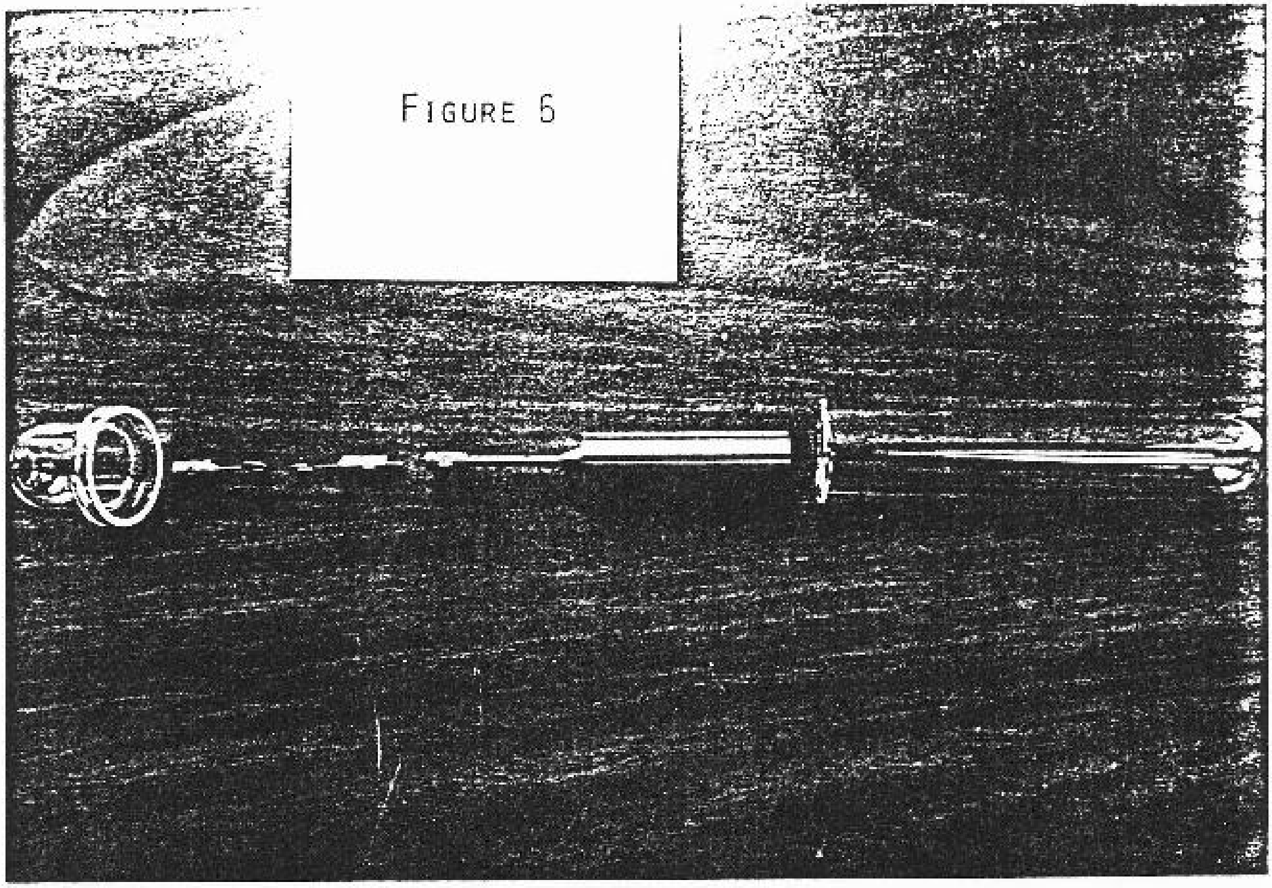


Figure 6

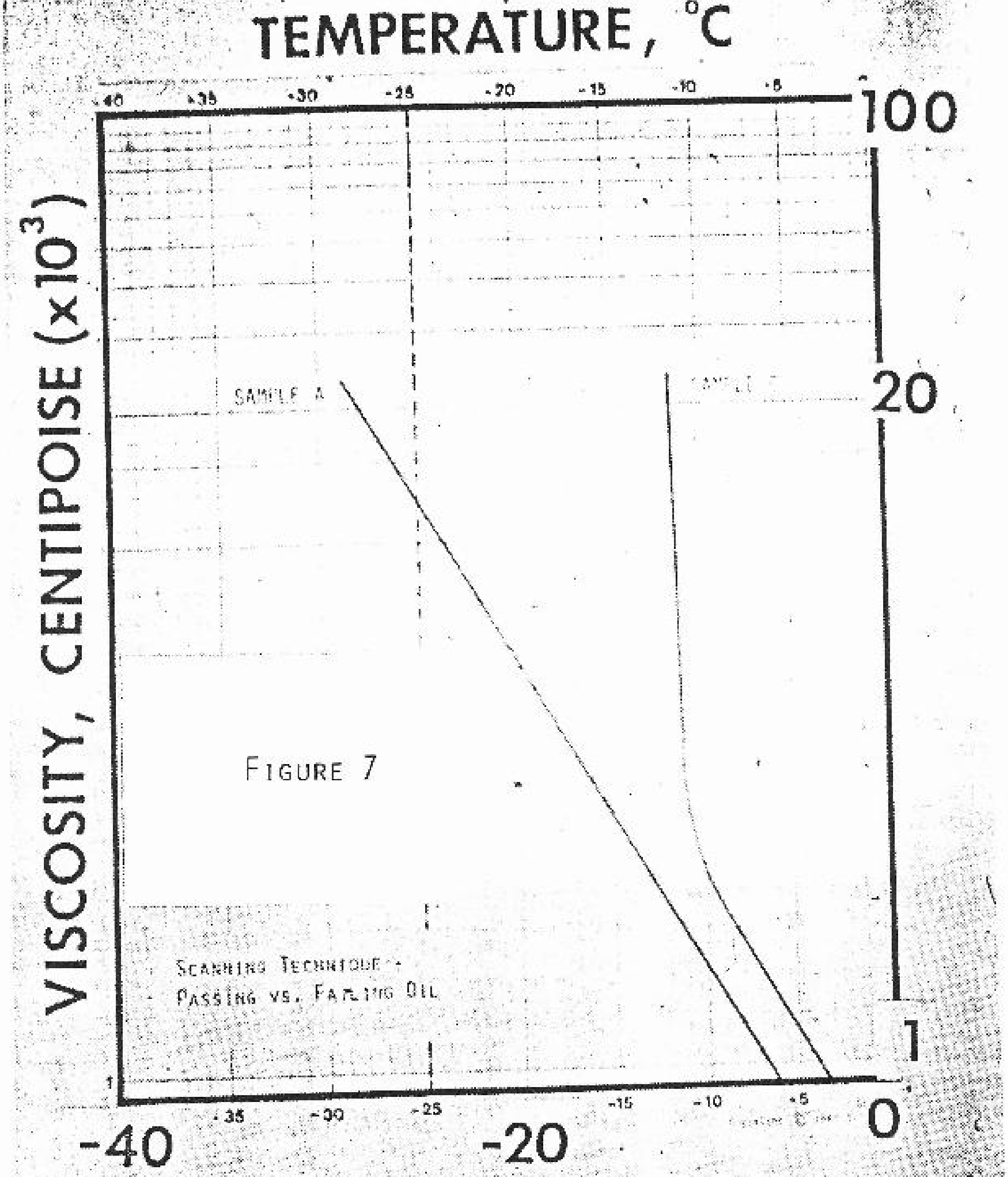


FIGURE 7

SCANNING TECHNIQUE – PASSING VS. FAILING OIL

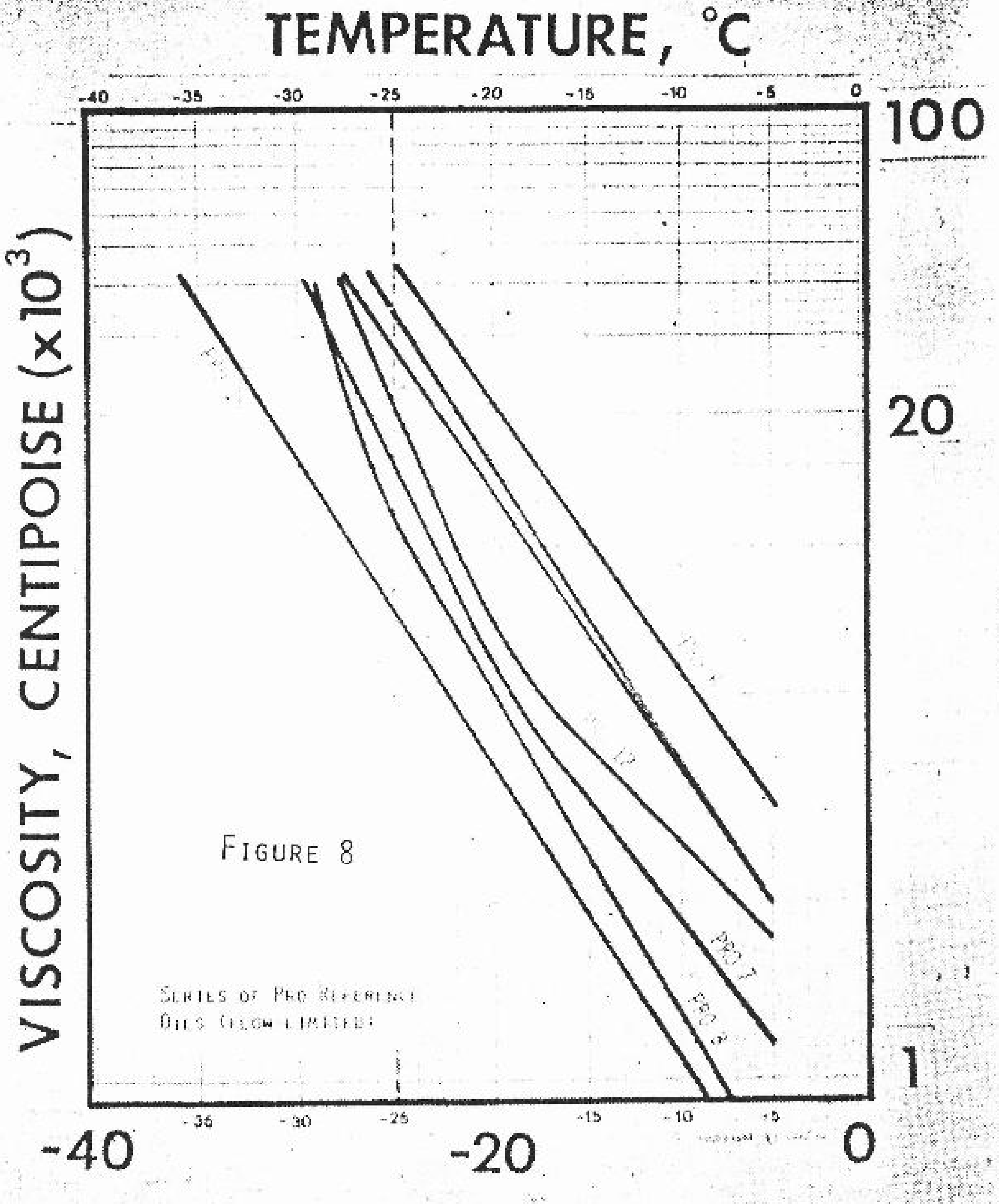

TEMPERATURE, °C
-40
-35
-30
-25
-20
-15
-10
-5
0
VISCOSITY, CENTIPOISE (x10³)
100
20
1
-40
-20
0
PRO 7
PRO 2
SERIES OF PRO REFERENCE
OILS (FLOW LIMITED)

FIGURE 8

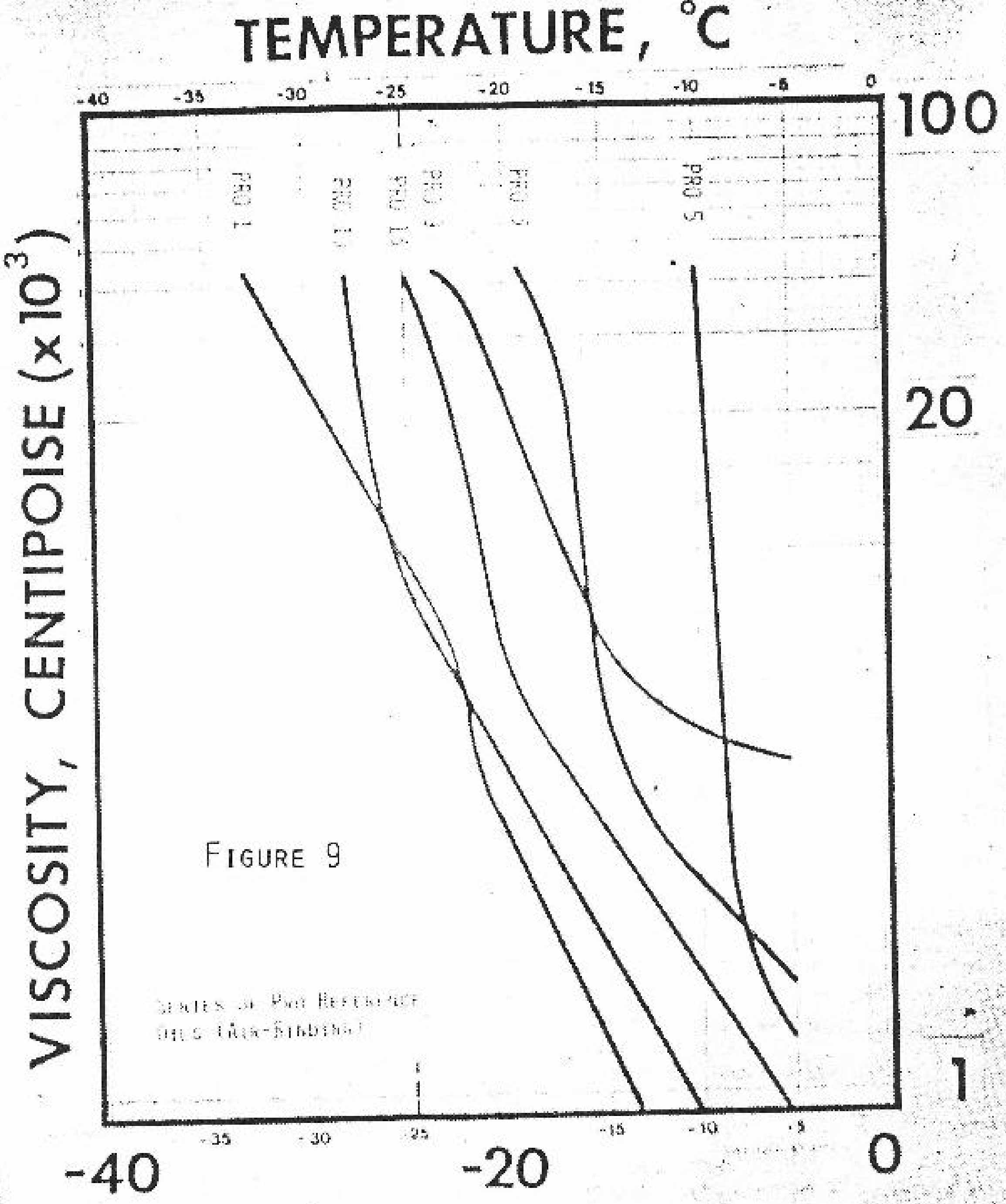
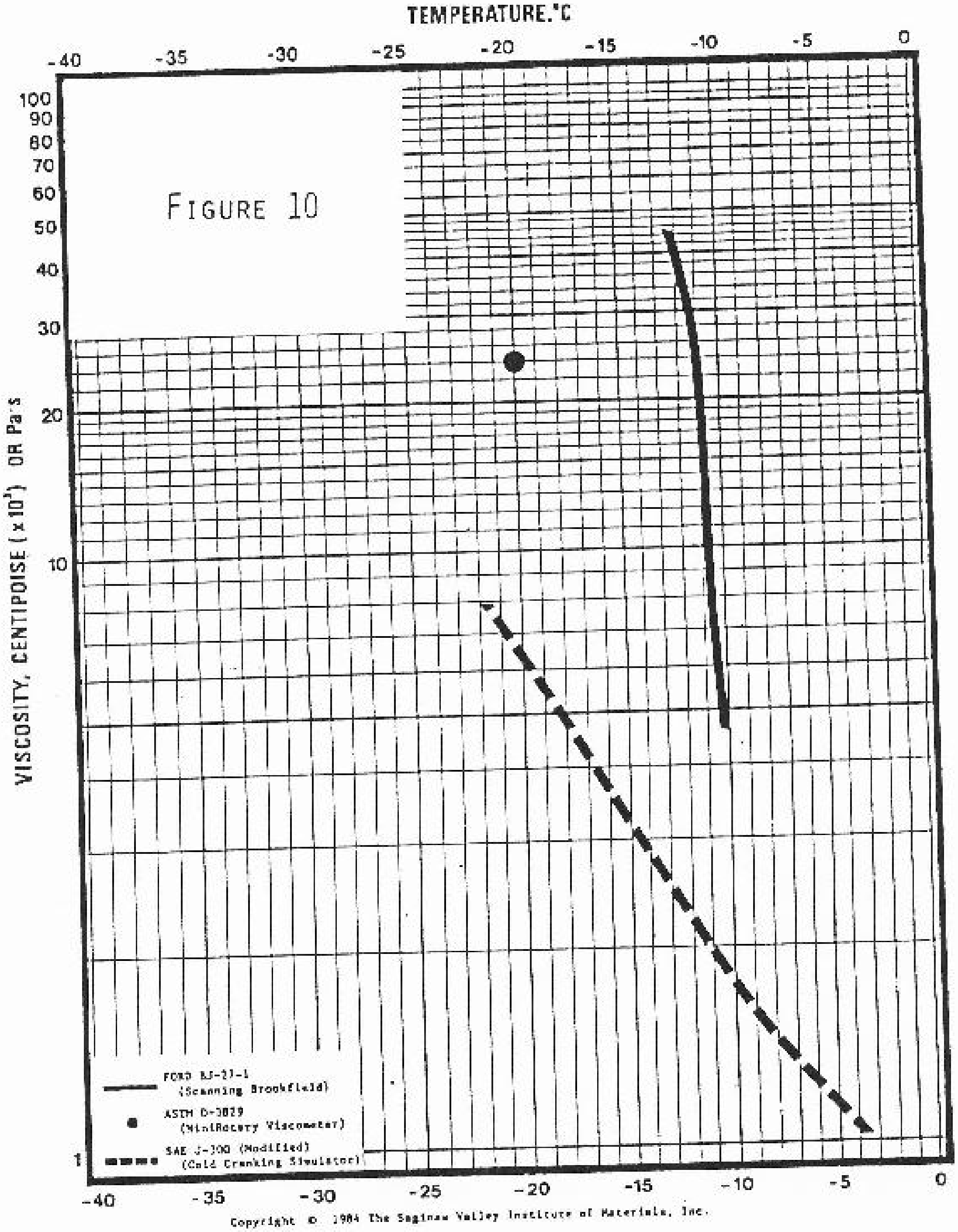

TEMPERATURE, °C
-40
-35
-30
-25
-20
-15
-10
-5
0
VISCOSITY, CENTIPOISE ($\times 10^3$)
100
20
1
-40
-20
0
PAO 1
PAO 10
PAO 15
PAO 4
PAO 6
PAO 5
Series of PAO Reference
Oils (Air-Binding)

FIGURE 9

FIGURE 10


TEMPERATURE,°C
-40
-35
-30
-25
-20
-15
-10
-5
0
VISCOSITY, CENTIPOISE ($\times 10^3$) OR Pa·s
100
90
80
70
60
50
40
30
20
10
1
FORD BJ-27-1
(Scanning Brookfield)
ASTM D-3829
(MiniRotary Viscometer)
SAE J-300 (Modified)
(Cold Cranking Simulator)

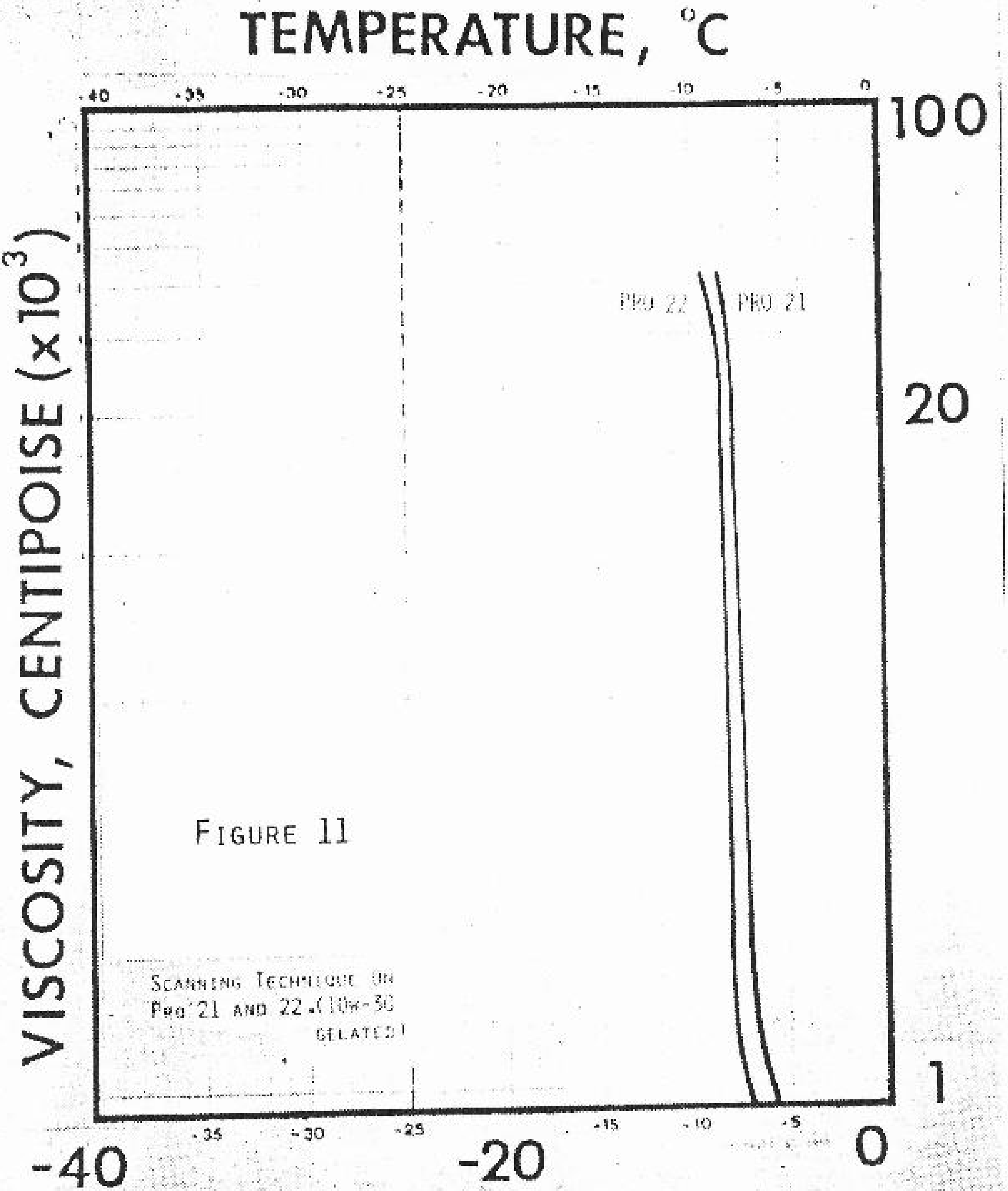


FIGURE 11

SCANNING TECHNIQUE ON PRO 21 AND 22 (10W-30 GELATED)

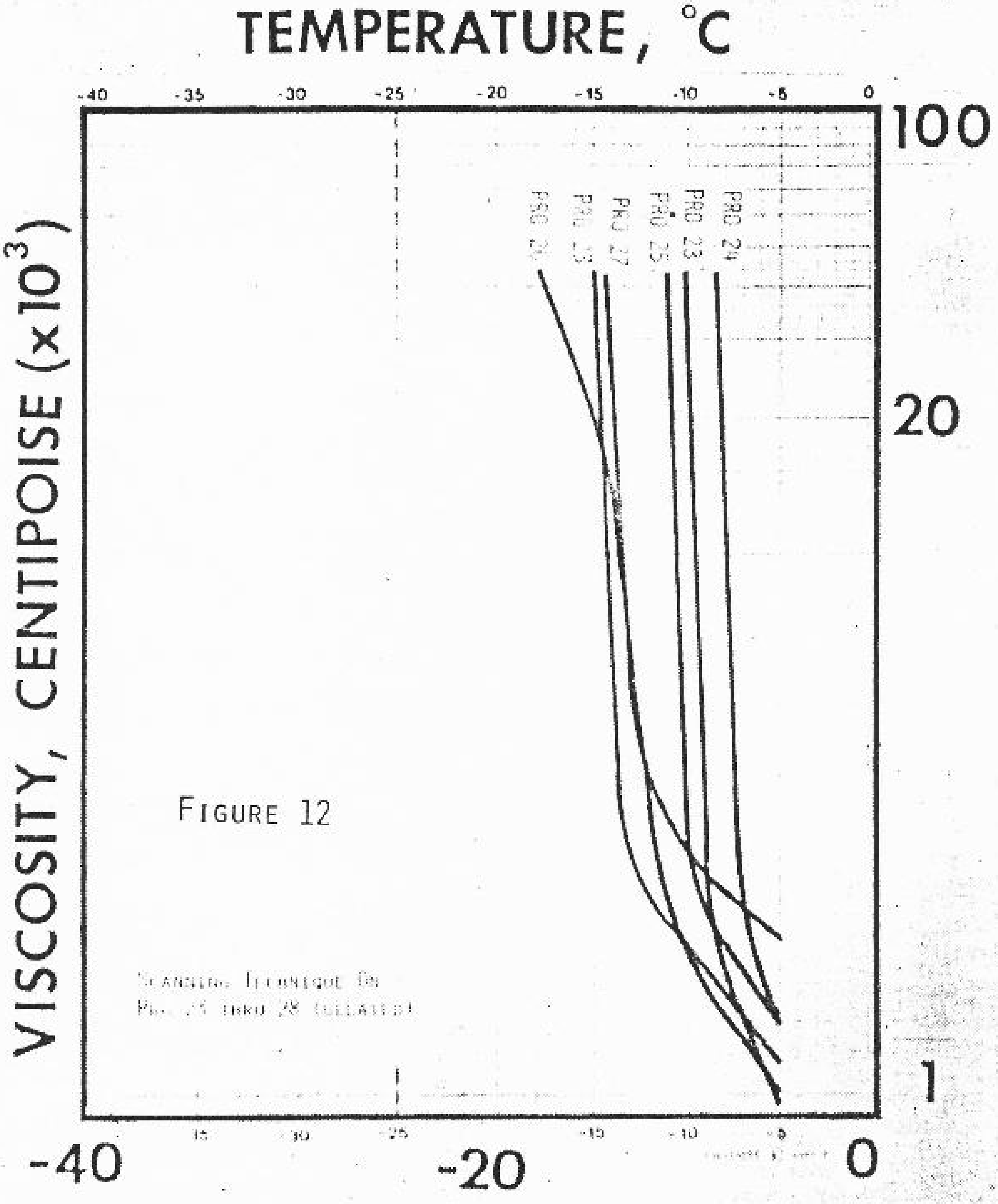


FIGURE 12

Scanning Technique On
Pro. 23 thru 28 (Gelated)

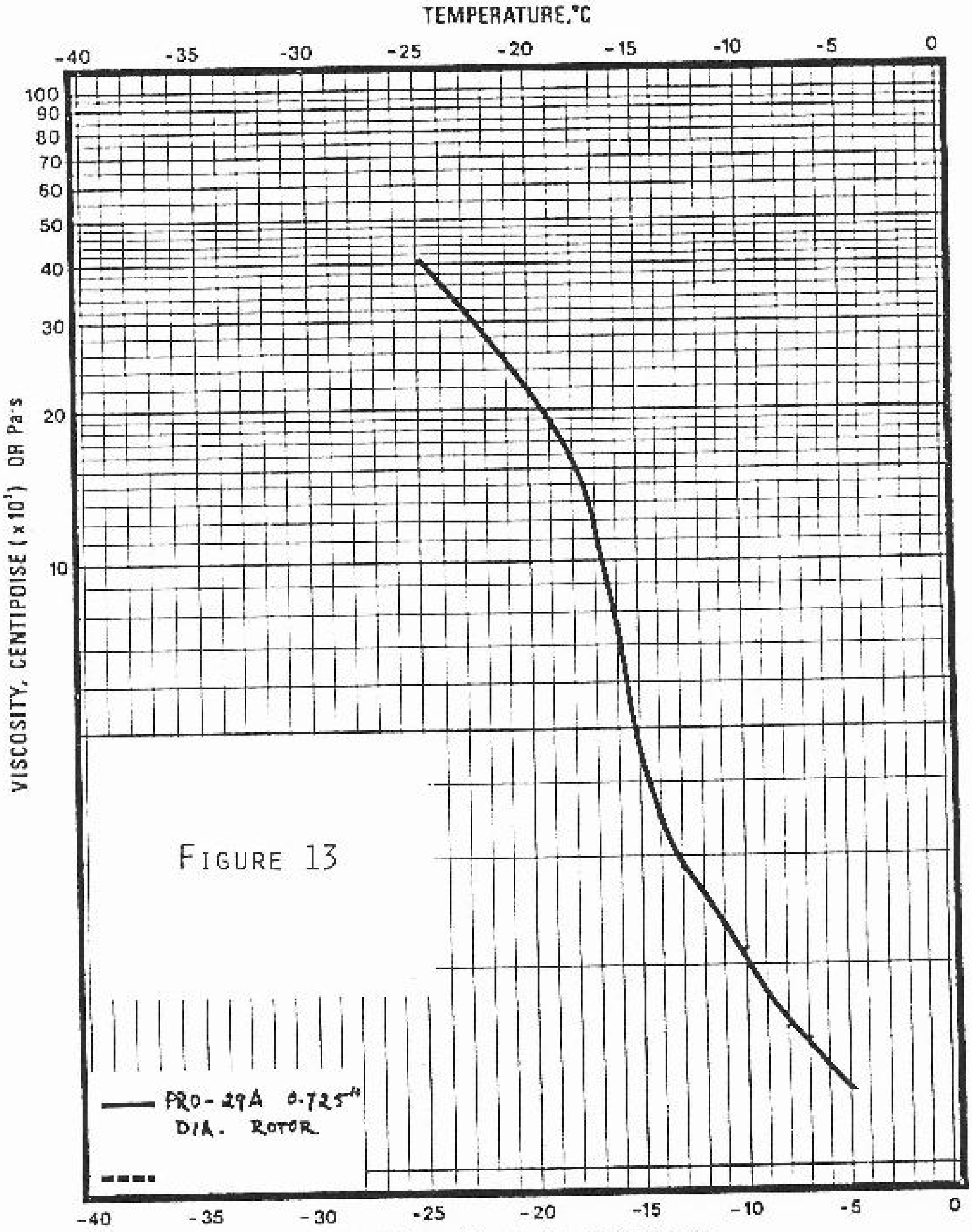

TEMPERATURE,°C
-40
-35
-30
-25
-20
-15
-10
-5
0
100
90
80
70
60
50
40
30
20
10
VISCOSITY, CENTIPOISE (x 10³) OR Pa·s
— PRO-29A 0.725" DIA. ROTOR
-40
-35
-30
-25
-20
-15
-10
-5
0

FIGURE 13

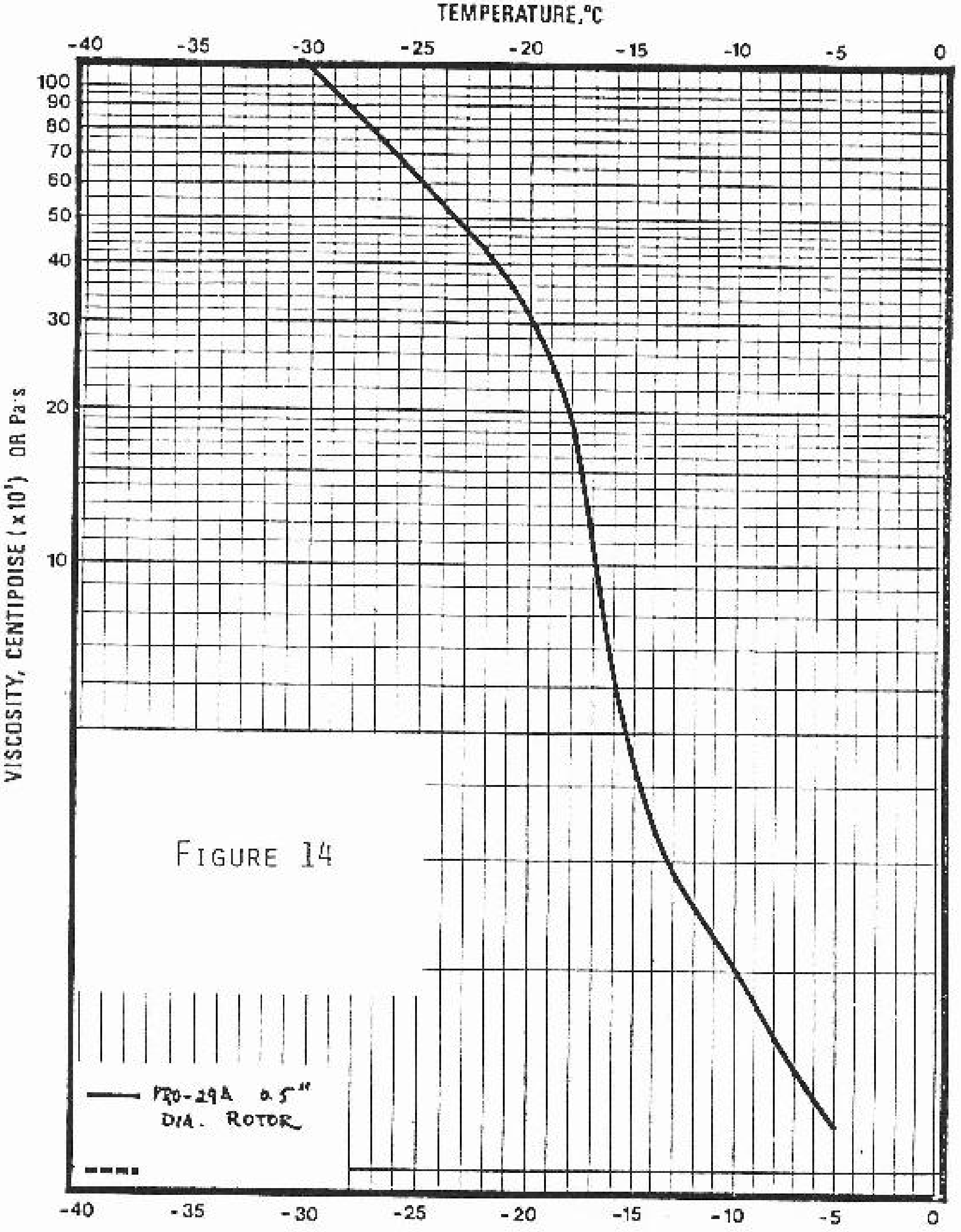

TEMPERATURE,°C
-40
-35
-30
-25
-20
-15
-10
-5
0
VISCOSITY, CENTIPOISE (x10³) OR Pa·s
100
90
80
70
60
50
40
30
20
10
PRO-29A 0.5" DIA. ROTOR

FIGURE 14

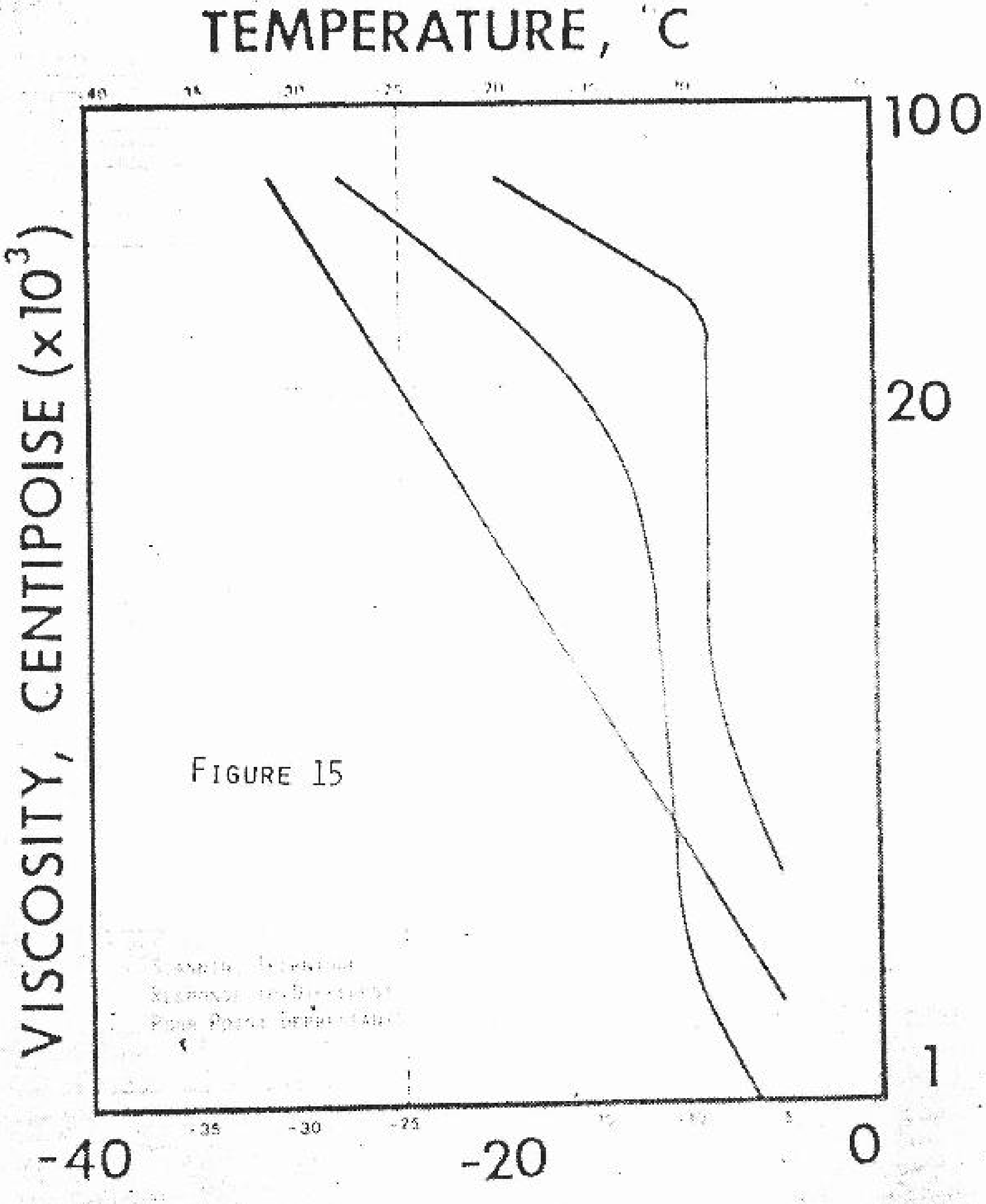


FIGURE 15