AN EVALUATION OF
A COLD CRANKING SIMULATOR
FOR OIL VISCOSITY DETERMINATION
AT SUB-ZERO TEMPERATURE

BY

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SCOPE AND CONTENTS:

AN EXPERIMENTAL EVAULATION OF THE COLD CRANKING SIMULATOR AT -20°F IS REPORTED IN THIS THESIS. THE EVALUATION WAS MADE ON EIGHT SPECIAL RESEARCH ENGINE OILS, RANGING IN VISCOSITY GRADE FROM SAE 5W TO SAE 20W, INCLUDING MULTIGRADE OILS, AND SEVEN SPECIALLY BLENDED 5W30 OILS OF COMMERCIAL NATURE. REPEATABILITY AND ACCURACY WERE ANALYZED STATISTICALLY AND CORRELATIONS WERE MADE WITH OTHER VISCOSITY MEASUREMENTS ON THE SAME OILS, INCLUDING AN ENGINE CRANKING EVALUATION OF THE OILS. THE VISCOSITIES DETERMINED BY THE COLD CRANKING SIMULATOR WERE FOUND TO CORRELATE WELL WITH THOSE FROM THE ENGINE CRANKING TESTS AND A RELATIONSHIP BETWEEN MEASURED VISCOSITY AND ENGINE CRANKING SPEED WAS ESTABLISHED.

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NOMENCLATURE

ABBREVIATIONS

ASTM	-	American Society for Testing Materials
CCS	-	Cold Cranking Simulator
CRC	-	Coordinating Research Council
FHP	-	Frictional Horsepower
GM	-	General Motors of Canada
GMR	-	General Motors Research
IHP	-	Indicated Horsepower
SAE	-	Society of Automotive Engineers
SUS	-	Saybolt Universal Second (unit of kinematic viscosity)
VI	-	Viscosity Index

SYMBOLS

σ	-	Standard Deviation
μ	-	Dynamic Viscosity
F	-	Fahrenheit
I	-	Current
K	-	Constant (including lower case and superscripted notation)
M	-	Torque
N	-	Rotational speed (rpm)
P	-	Power
R	-	Resistance
V	-	Potential

NOMENCLATURE (CONTINUED)

TERMS (CONTINUED)

VISCOMETER (CONTINUED)

- FERRANTI-SHIRLEY - BASED ON THE TORQUE REQUIRED TO ROTATE A SHALLOW CONE WITH A FILM OF OIL SEPARATING IT FROM A STATIONARY PLATE.
- FORCED-BALL - BASED UPON THE TIME REQUIRED FOR A SPHERE TO PASS A GIVEN DISTANCE THROUGH A SLEEVE FILLED WITH OIL, UNDER A CONSTANT LOAD.
- HAAKE ROTOVISCO - BASED ON THE TORQUE REQUIRED TO ROTATE A SHALLOW CONE IN THE PRESENCE OF A FLUID NEAR A STATIONARY PLATE.
- P.R.L. CAPILLARY - BASED UPON THE TIME REQUIRED FOR A GIVEN QUANTITY OF FLUID TO FLOW THROUGH A CAPILLARY TUBE.
- S.O.D. PRESSURE - BASED UPON THE TIME REQUIRED FOR A GIVEN QUANTITY OF FLUID TO FLOW THROUGH A CAPILLARY TUBE UNDER PRESSURE.

NOMENCLATURE (CONTINUED)

TERMS

MULTIGRADE	-	HAVING PROPERTIES OF DIFFERENT SAE VISCOSITY GRADES AT 0°F AND 210°F.
NEWTONIAN	-	HAVING VISCOMETRIC PROPERTIES UNAFFECTED BY SHEAR RATE.
NON-NEWTONIAN	-	HAVING VISCOMETRIC PROPERTIES WHICH VARY AS A FUNCTION OF SHEAR RATE.
POISE	-	A UNIT OF DYNAMIC VISCOSITY $\left(\frac{\text{DYNE SEC.}}{\text{CM}^2}\right)$
STOKE	-	A UNIT OF KINEMATIC VISCOSITY $\left(\frac{\text{CM}^2}{\text{SEC}}\right)$
VISCOMETER	-	A DEVICE FOR DETERMINING VISCOSITY, EITHER DIRECTLY OR INDIRECTLY; SOME TYPES ARE: - - BARBER CONCENTRIC CYLINDER ROTATIONAL - BASED ON TORQUE REQUIRED TO ROTATE A CYLINDER IN A CYLINDER. - BROOKFIELD - BASED ON TORQUE REQUIRED TO ROTATE A ROD IN A FLUID FREE FROM ANY WALLS. - COLD CRANKING SIMULATOR - BASED ON SPEED ATTAINED BY A ROTATING CYLINDER IN A CYLINDER WITH HIGH SHEAR RATES AND NEAR CONSTANT POWER INPUT.

I

INTRODUCTION

Historically, it has been necessary to determine the low temperature cranking performance of an engine oil by actual testing in an engine. Such tests were required because the Society of Automotive Engineers (SAE) specified procedure for establishing engine oil viscosities at low temperatures was based on values extrapolated from viscosities measured at 100°F and 210°F, and was not meaningful for multigrade engine oils. Similarly, no laboratory devices were available which could accurately predict an oil's effect on the cranking effort of an engine at low temperatures. For the past ten years multiple attempts have been made to develop laboratory viscometers for this purpose. In order to evaluate these instruments, a number of engine cranking tests have been conducted, in different engines for comparison.

Only one of these instruments appeared capable of predicting the results of the engine cranking tests, to a high degree of accuracy, at 0°F. This device was the Cold Cranking Simulator, (CCS) an indirect measuring viscometer, which was first made public in 1965. As a result of encouraging initial tests a complete evaluation of the device, at 0°F, was conducted by the Coordinating Research Council (CRC) and the American Society for Testing Materials (ASTM). The results of this evaluation confirmed the suitability of the device for predicting cranking performance.

Because of the severity of winter weather conditions encountered by Canadian motorists, General Motors of Canada required satis-

FACTORY ENGINE PERFORMANCE TO A TEMPERATURE OF -20°F IN ITS PRODUCTS. SINCE THE COLD CRANKING SIMULATOR HAD BEEN EVALUATED ONLY AT 0°F IT WAS STILL NECESSARY TO CONDUCT ENGINE CRANKING TESTS TO DETERMINE -20°F PERFORMANCE OF ENGINE OILS. FURTHERMORE, THE 0°F EVALUATION OF THE VISCOMETER WAS MADE IN COMPARISON WITH THE AVERAGE RESULTS OF TWELVE DIFFERENT ENGINE CRANKING PROGRAMS. SINCE THE CRANKING ABILITY OF DIFFERENT ENGINES VARIES CONSIDERABLY, GOOD CORRELATION WITH THE AVERAGE RESULTS DOES NOT NECESSARILY GUARANTEE THE SAME DEGREE OF CORRELATION WITH A SPECIFIC ENGINE.

THE TEST PROGRAM DISCUSSED IN THIS THESIS WAS INITIATED TO EVALUATE THE ABILITY OF THE COLD CRANKING SIMULATOR TO PREDICT THE ENGINE CRANKING PERFORMANCE OF AN ENGINE OIL AT A TEMPERATURE OF -20°F. SPECIFICALLY, THE PURPOSE OF THE PROJECT WAS TO DETERMINE THE FEASIBILITY OF RELATING COLD CRANKING SIMULATOR RESULTS DIRECTLY TO THE CRANKING SPEED OF A SPECIFIC ENGINE, AT -20°F.

IN ORDER TO EVALUATE THE DEVICE A QUANTITY OF TEST OILS WAS OBTAINED AND TESTED AT -20°F IN BOTH THE COLD CRANKING SIMULATOR AND A 250 CUBIC INCH SIX CYLINDER CHEVROLET ENGINE. STANDARD CALIBRATION OILS WERE USED IN BOTH TEST APPARATUS. IN ORDER TO INSURE REPRESENTATIVE RESULTS FROM THE VISCOMETER A SERIES OF TESTS WAS ALSO CONDUCTED AT 0°F AND THE RESULTS COMPARED TO THOSE OF THE ASTM EVALUATION. ALL RESULTS WERE ANALYZED STATISTICALLY FOR REPEATABILITY AND CORRELATION. CORRELATIONS WERE ALSO MADE BETWEEN THESE TWO TEST PROGRAMS AND OTHER ENGINE CRANKING TESTS TO ILLUSTRATE THE RANGE OF POSSIBLE RESULTS. A SPECIFIC RELATIONSHIP WAS ESTABLISHED BETWEEN THE COLD CRANKING SIMULATOR MEASUREMENTS AND THE CRANKING SPEED OF THE CHEVROLET TEST

ENGINE. COLD CRANKING SIMULATOR DETERMINATIONS WERE ALSO MADE FOR A VARIETY OF COMMERCIALLY AVAILABLE ENGINE OILS TO ILLUSTRATE THE ADVANTAGE OF THIS METHOD OF LOW TEMPERATURE EVALUATION.

IN THIS THESIS THE LITERATURE PERTINENT TO THE FIELD OF LOW TEMPERATURE ENGINE OIL VISCOSITY IS REVIEWED. A BRIEF HISTORY OF THE DEVELOPMENTS LEADING UP TO THE CURRENT PROBLEMS AND INITIATIONS OF THIS PROJECT IS ALSO PRESENTED. SUBSEQUENTLY THE TEST APPARATUS AND TEST METHODS ARE DESCRIBED IN DETAIL. AN EXTENSIVE ANALYSIS OF THE TEST RESULTS IS INCLUDED AND THESE RESULTS ARE DISCUSSED WITH REGARD TO THEIR REASONS AND SIGNIFICANCE. FINALLY, THE CONCLUSIONS AND RECOMMENDATIONS DERIVED FROM THE PROJECT ARE PRESENTED.

II

HISTORY

The problem of determining the viscosity of engine oils at low temperatures is a very practical one. Rather than being primarily research oriented, it is of immediate importance to both the automotive and petroleum industries, particularly in Canada. Traditionally, cold Canadian winters have resulted in starting problems for motor vehicles used in this climate. Engine oil viscosity is one important factor which affects an engine's starting ability.

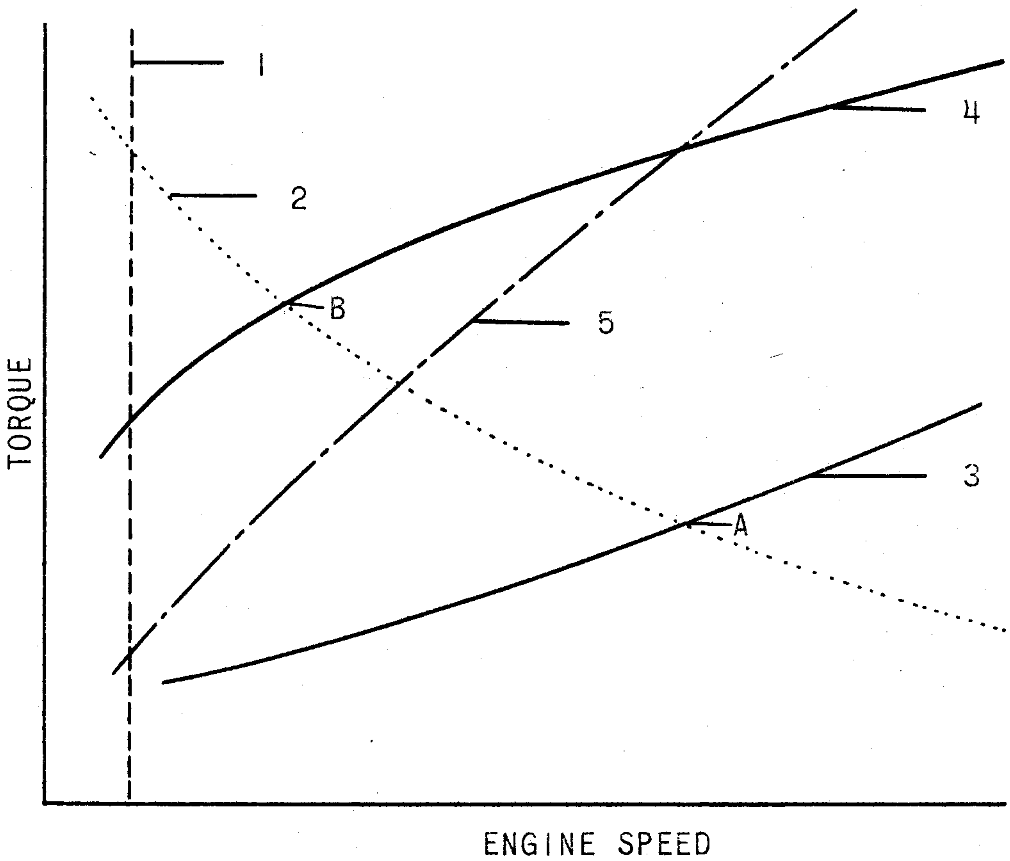
There are several parameters which determine whether or not an engine can be started. A sufficient amount of fuel-air mixture, in the correct ratio, must be inducted into the combustion chambers and a spark of sufficient energy must be fired at the correct instant in order to support combustion. Once firing has commenced, the engine must be able to produce sufficient indicated horsepower (IHP) to overcome its own frictional horsepower (FHP) requirements or it will stall. Engine cranking speed is an important factor in supplying these requirements.

The importance of engine cranking speed may be seen in Figure 1, page 6. A number of relationships between engine speed and torque for a typical engine are shown. Curve 1 indicates a minimum cranking speed which is required to assure sufficient distribution of the fuel-air mixture to all the cylinders. This minimum speed is independent of torque, as shown. Curve 2 shows the maximum available cranking motor torque output as a function of speed. This maximum will decrease

WITH THE STATE OF CHARGE OF THE BATTERY AND WITH DETERIORATION OF THE MOTOR THROUGH USE. THE CRANKING TORQUE REQUIRED BY AN ENGINE LUBRICATED WITH A LOW VISCOSITY OIL, SUCH AS AN SAE 10W, IS SHOWN IN CURVE 3. A SIMILAR CURVE FOR AN ENGINE WITH A HIGH VISCOSITY OIL, SUCH AS AN SAE 30, IS SHOWN IN CURVE 4. IT MAY BE SEEN THAT THE CRANKING TORQUE REQUIRED, WHICH IS A FUNCTION OF FHP, IS GREATER AT ANY SPEED WHEN HIGH VISCOSITY OIL IS USED THAN IT IS WHEN LOW VISCOSITY OIL IS USED. IN CURVE 5, THE RUNNING TORQUE OF THE ENGINE, A FUNCTION OF IHP, IS PLOTTED. FROM THESE CURVES AN UNDERSTANDING OF THE RELATIONSHIPS BETWEEN CRANKING SPEED AND STARTING MAY BY ACQUIRED.

THE CRANKING SPEEDS WHICH MAY BE OBTAINED WITH LOW AND HIGH VISCOSITY OILS ARE INDICATED AT POINTS A AND B RESPECTIVELY. THESE POINTS ARE OBTAINED AT THE INTERSECTIONS OF THE CRANKING TORQUE AVAILABLE CURVE WITH THE CRANKING TORQUE REQUIRED CURVES. SINCE BOTH SPEEDS ARE GREATER THAN THE MINIMUM FUEL DISTRIBUTION SPEED THE ENGINE SHOULD START TO FIRE IN EITHER CASE, PROVIDED THAT THE CARBURETION AND IGNITION SYSTEMS ARE FUNCTIONING PROPERLY. SINCE POINT A IS BELOW THE RUNNING TORQUE LINE THERE IS SUFFICIENT ENGINE TORQUE AVAILABLE TO ACCELERATE FROM THIS SPEED WHEN THE CRANKING TORQUE IS REMOVED, SO THE ENGINE WILL KEEP RUNNING. POINT B, HOWEVER, IS ABOVE THE RUNNING TORQUE LINE. WHEN THE CRANKING MOTOR TORQUE IS REMOVED, IN THIS CASE, THE RUNNING TORQUE IS NOT SUFFICIENT TO OVERCOME THE TORQUE REQUIREMENTS OF THE ENGINE SO IT WILL STALL. FROM THIS ILLUSTRATION THE IMPORTANCE OF OIL VISCOSITY TO STARTING ABILITY CAN BE READILY UNDERSTOOD.

AT NORMAL AMBIENT TEMPERATURES STARTING PROBLEMS DO NOT OCCUR BECAUSE OF HIGH OIL VISCOSITIES. PETROLEUM BASED OILS, HOWEVER, ARE



1.- - - - MINIMUM FUEL DISTRIBUTION SPEED

2. ·········· CRANKING MOTOR TORQUE

3.——— ENGINE TORQUE REQUIRED - LOW VISCOSITY OIL

4.——— ENGINE TORQUE REQUIRED - HIGH VISCOSITY OIL

5.———·— ENGINE TORQUE DEVELOPED

FIGURE 1 - CRANKING TORQUE AND SPEED RELATIONSHIPS

TEMPERATURE DEPENDENT WITH REGARD TO VISCOSITY, WHICH INCREASES AS TEMPERATURE DECREASES. AT VERY LOW (SUB-ZERO) AMBIENTS, THE VISCOSITY OF THE ENGINE OIL CAN INCREASE TO THE POINT WHERE IT AFFECTS STARTING. IT SHOULD ALSO BE NOTED THAT THE CURVES, SHOWN IN FIGURE 1, WILL VARY FROM ENGINE TO ENGINE DUE TO THE EFFECTS OF DESIGN DIFFERENCES AND PRODUCTION TOLERANCES. THEREFORE THE EFFECT OF OIL VISCOSITY ON STARTING WILL BE DIFFERENT FROM ENGINE TO ENGINE. IN GENERAL, HOWEVER, IMPROVING CRANKING SPEED ALSO TENDS TO IMPROVE STARTING PROBABILITY.

THE EFFECT OF OIL VISCOSITY ON CRANKING SPEED, AND THUS ON STARTING ABILITY, BECAME APPARENT IN THE EARLY DAYS OF THE AUTOMOBILE. IT BECAME COMMON PRACTICE TO USE LOW VISCOSITY OILS, OR OILS DILUTED WITH KEROSENE, IN ENGINES WHICH HAD TO OPERATE AT LOW TEMPERATURES. ATTENDANT WITH THE USE OF LOW VISCOSITY OILS IN THESE APPLICATIONS, HOWEVER, WERE THE PROBLEMS OF HIGH OIL CONSUMPTION AND HIGH WEAR. OIL CONSUMPTION INCREASED BECAUSE OF THE ABILITY OF LOWER VISCOSITY OIL TO FLOW WHERE HIGHER VISCOSITY OIL COULD NOT. IN THIS WAY THE AMOUNT OF OIL, BOTH BURNED AND LEAKED, INCREASED. INCREASED WEAR RESULTED FROM THE FACT THAT THE LOAD CARRYING ABILITY OF ANY FLUID IS DECREASED AS VISCOSITY IS DECREASED. AS A RESULT OF THESE PROBLEMS IT WAS RECOGNIZED THAT THERE WAS A NEED FOR OIL HAVING LOWER VISCOSITY AT LOW TEMPERATURES, FOR STARTING, WITHOUT SACRIFICING THE MUCH NEEDED HIGHER VISCOSITY AT HIGH TEMPERATURES, FOR GOOD CONSUMPTION AND LOW WEAR.

IN ORDER TO COMPARE THE VISCOSITY-TEMPERATURE RELATIONSHIPS BETWEEN OILS THE CONCEPT OF VISCOSITY INDEX (VI) WAS INTRODUCED BY DEAN AND DAVIS IN 1941[1]. AT THAT TIME PENNSYLVANIA (PARAFFINIC) BASE OILS WERE KNOWN TO HAVE RELATIVELY LOW VISCOSITIES AT LOW TEMPERATURES with respect to their viscosities at high temperatures. The Dean and Davis VI system made use of an arbitrary Pennsylvania base oil to which all other oils were compared. The VI of this oil was arbitrarily set at 100. Other oils were related to this standard by the expression:

$$VI = \frac{L-U}{D}$$ Where:

U is the viscosity at 100°F of the test oils;

L is the viscosity at 100°F of a standard oil having 0 VI and the same viscosity at 210°F as the test oil;

H is the viscosity at 100°F of a standard oil having 100 VI and the same viscosity at 210°F as the test oil;

and D is L-H.

This method was adopted by the ASTM as standard D-567.[2] Tables were provided to determine the values of L and D for a variety of 210°F viscosities.

In 1933[3], it was learned that by adding small amounts of certain polymers to petroleum oils the viscosity-temperature relationships could be altered significantly. The additional viscosity of the solution due to the polymer was proportionately greater at high temperature than at low. By reducing base stock viscosity so that the new solution had a similar low temperature viscosity to the previously used low viscosity oils a much higher viscosity at high temperatures could be obtained. Since the viscosity index was raised significantly in these solutions the polymeric additives were appropriately called VI improvers.

The use of VI improvers in commercial oils became widespread about 1953.[26] They brought with them new problems however. Because the Walther equation, which was the accepted method for determining low temperature viscosity, was based on non-VI-improved oils it did not necessarily hold true for the new oils. Using this technique it was possible, as shown in Figure 2, page 10, to add VI improver to a base oil and result in a solution having a lower extrapolated viscosity than the base oil at low temperature, as specified by the Walther equation. Obviously this was an impossible situation. The SAE established limits for viscosity grades, as shown in Table I, page 11, were based on extrapolated viscosities for 0°F determinations. Thus it was common to find an oil which could be classified as an SAE 10W30 but which in reality was an SAE 20W30 or perhaps even an SAE 30, as shown in Figure 3, page 12. Because of this situation, attempts were made to measure the low temperature viscosity of oil rather than extrapolating it.

When low temperature viscosity measurements were made it was found that, for VI improved oils, different values were obtained depending upon the instrument used. This situation added more confusion in the field of VI improved oils. The fact that VI improved oils are non-Newtonian in nature, and therefore exhibit different viscosities under different shear rates, as shown in Figure 4, page 13, explained the discrepancies to some extent. Since the factor which was of primary concern was the cranking ability of the engine the SAE decided to evaluate a number of oils in a variety of engines, and then to develop a laboratory viscometric technique to correlate with the engine results. The Coordinating Research Council (CRC) was assigned the

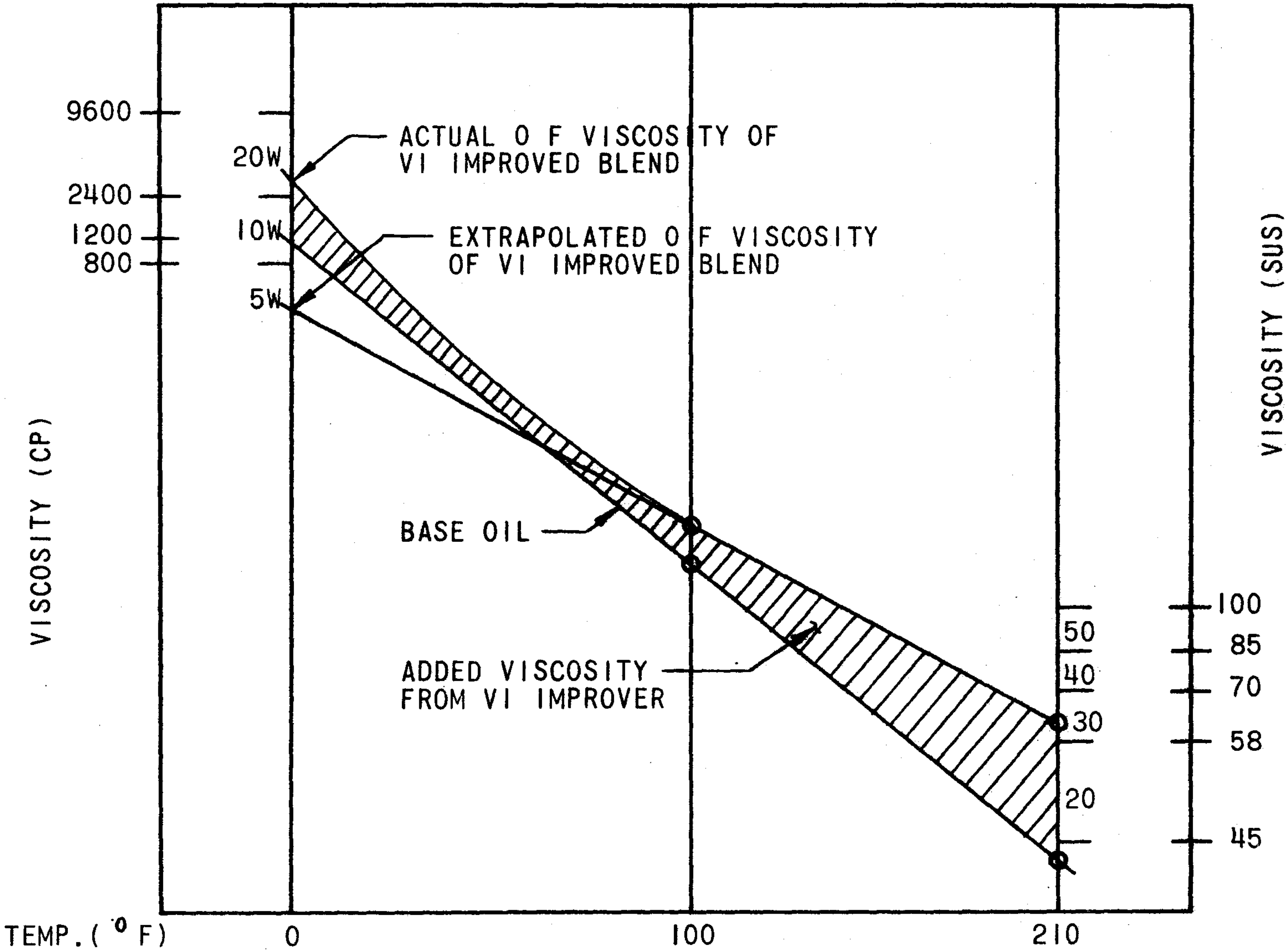


FIGURE 2 - EFFECT OF VI IMPROVERS ON BASE OIL

TABLE I

SAE VISCOSITY VALUES FOR CRANKCASE OILS*

* As Specified in SAE J300, 1967 SAE Handbook

SAE Viscosity Number	Viscosity Range - Saybolt Universal Seconds			
	At 0°F		At 210°F	
	Min.	Max.	Min.	Max.
5W	—	4000	—	—
10W	6000[A]	less than 12000	—	—
20W	12000[B]	48000	—	—
20	—	—	45	less than 58
30	—	—	58	less than 70
40	—	—	70	less than 85
50	—	—	85	110

A Minimum viscosity at 0°F may be waived provided viscosity at 210°F is not below 40 SUS

B Minimum viscosity at 0°F may be waived provided viscosity at 210°F is not below 45 SUS

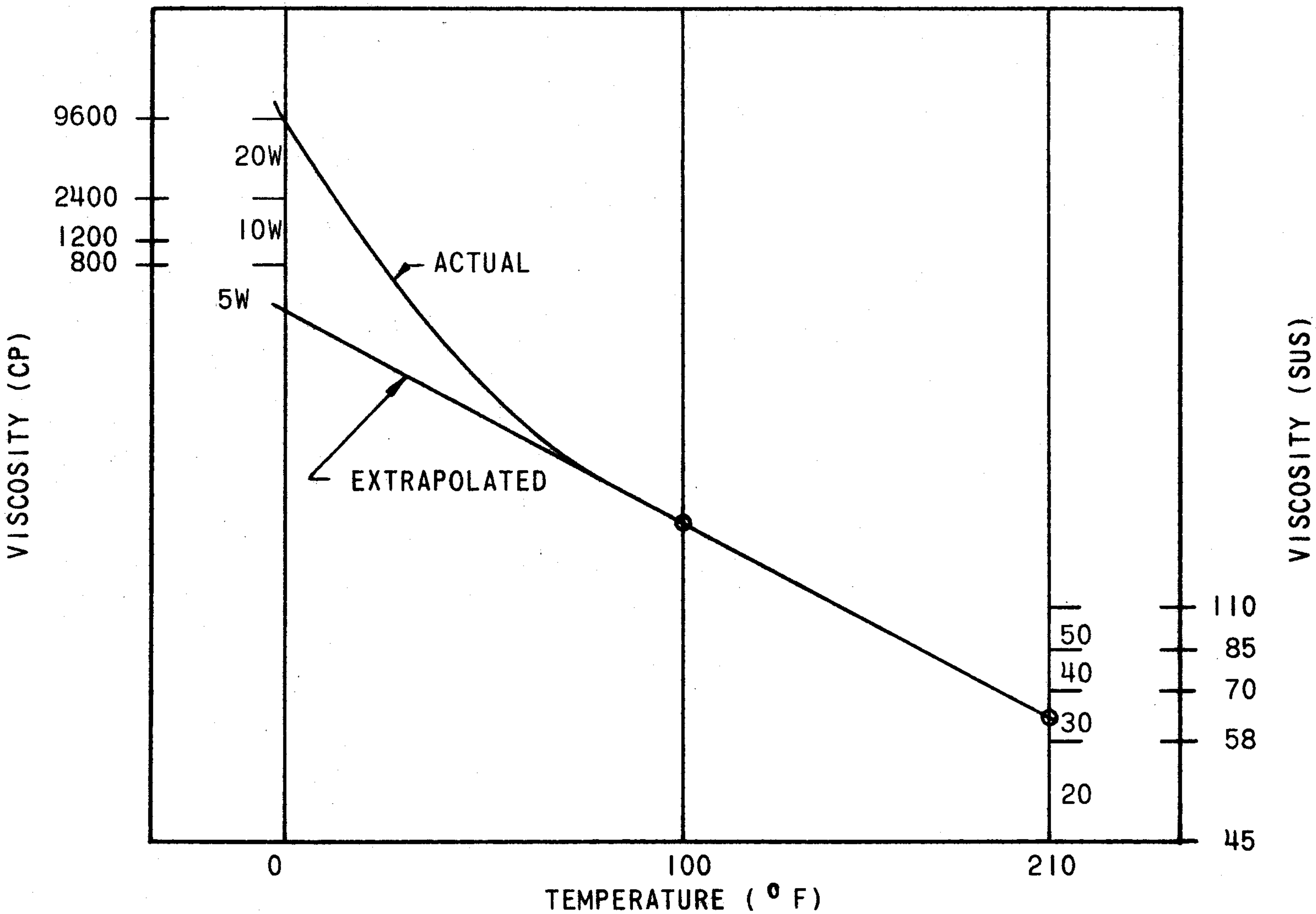


FIGURE 3 - EXTRAPOLATION METHOD OF VISCOSITY DETERMINATION

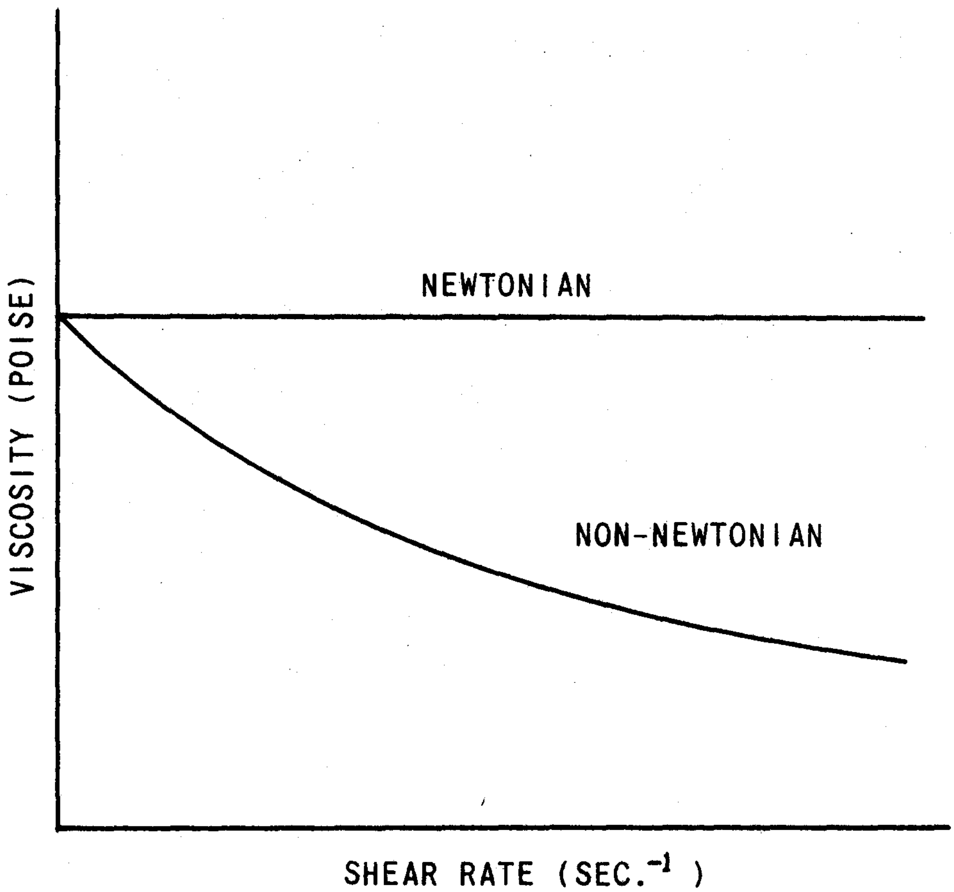


FIGURE 4 - VISCOSITY-SHEAR RATE RELATIONSHIPS

first phase of the project and the American Society for Testing Materials (ASTM), the latter.

A CRC test procedure was developed whereby oil viscosity, as experienced in an engine, was determined from engine cranking speed or cranking torque at 0°F. Round robin tests were conducted on the same oils in up to twelve different engines and all data were pooled into a single set of results. These results verified the fact that the viscosities of VI improved oils, as determined by an engine, differed considerably from their extrapolated viscosities.

Similar series of round-robin tests were conducted by the ASTM on a variety of different laboratory devices, most of which were developed specifically for the purpose. The results from these viscometers were compared with those from the CRC engine tests. Although a few of these instruments showed promise in predicting viscosities as the engines did none of these were very practical for a variety of reasons.

In 1965 a new instrument the Cold Cranking Simulator, (CCS) was introduced.(4) The basis of operation for this device was its similarity of concept to a cold cranking engine and its development of high shear rates, which were known from previous work, to promote good correlation with engine tests. Preliminary tests of this instrument showed excellent promise and a subsequent ASTM evaluation, at 0°F, substantiated the superiority of the simulator over the other viscometers tested.(5)

III

LITERATURE SURVEY

THE RELATIONSHIP BETWEEN ENGINE OIL VISCOSITY AND CRANKING TORQUE WAS NOTED QUITE EARLY IN THE HISTORY OF THE AUTOMOBILE. AS EARLY AS 1913 WILSON(6) MADE REFERENCE TO THE FACT THAT ENGINES WERE HARDER TO START WHEN COLD BECAUSE OF THE INCREASED VISCOSITY OF THE ENGINE OIL.

IN 1928, WILKIN, OAK, AND BARNARD(7) DETERMINED THAT THE CRANKING TORQUE OF ANY ENGINE SEEMED TO DEPEND ENTIRELY ON THE VISCOSITY OF THE CRANKCASE OIL BUT THAT IT WAS NOT A DIRECT PROPORTIONALITY FUNCTION. THEY ALSO STATED THAT THE CRANKING CHARACTERISTICS OF A NEWTONIAN, OR NEAR-NEWTONIAN ENGINE OIL COULD BE ESTIMATED WITH FAIR RELIABILITY FROM SUITABLE VISCOSITY-TEMPERATURE DATA PLOTTED ON A HERSCHEL DIAGRAM(8).

DR. A. E. BECKER,(9) IN 1931, RELATED ENGINE OIL VISCOSITY TO ENGINE STARTING BY INDICATING THAT THE RELATIONSHIP OF FRICTIONAL HORSEPOWER, WHICH WAS A FUNCTION OF OIL VISCOSITY, TO STARTER POWER AND ENGINE POWER AT LOW SPEEDS IS THE CONTROLLING FACTOR IN LOW TEMPERATURE STARTING.

ALSO IN 1931, BLACKWOOD AND RICKLES(10) ARRIVED AT THE SAME CONCLUSION. THEY FOUND THAT THE FRICTIONAL RESISTANCE OF THE CRANKCASE LUBRICANT AT LOW TEMPERATURES MAY BE HIGHER THAN THE TOTAL TORQUE WHICH THE ENGINE CAN PRODUCE. WHEN THIS IS THE CASE STARTING IS IMPOSSIBLE.

GRAVES, MOUGEY AND UPHAM,(11) IN 1934, EXPERIMENTED WITH WINTER GRADE (10W AND 20W) ENGINE OILS UNDER COLD STARTING AND NORMAL OPERATING

CONDITIONS. THEY ESTABLISHED THAT THERE IS A MINIMUM CRANKING SPEED BELOW WHICH AN ENGINE CANNOT START BECAUSE IT IS NOT BEING CRANKED FAST ENOUGH TO PERMIT SATISFACTORY DISTRIBUTION OF THE FUEL MIXTURE TO THE CYLINDERS. IN ORDER TO INSURE CRANKING SPEEDS ABOVE THIS MINIMUM VALUE THEY RECOMMENDED THE USE OF 10W OR 20W ENGINE OILS, STATING ALSO THAT THESE OILS WERE SATISFACTORY FOR USE IN ALL DRIVING CONDITIONS, INCLUDING HIGH SPEED DRIVING. THEIR EXPERIMENTS ALSO SHOWED THAT ALTHOUGH OIL CONSUMPTION INCREASED WITH THE USE OF LOWER VISCOSITY OILS THE PRIMARY FACTOR AFFECTING OIL CONSUMPTION WAS ENGINE SPEED.

FURTHER VALIDATION OF THE MINIMUM CRANKING SPEED THEORY WAS GIVEN BY BLACKWOOD(12) IN 1935. HE FOUND THAT AS TEMPERATURE DECREASES THERE IS AN INCREASE IN THE INTERNAL FRICTION OF AN ENGINE IN EXCESS OF THAT CAUSED BY OIL VISCOSITY ALONE. THIS INCREASE IS DUE TO PARTIAL FILM LUBRICATION AND POSSIBLY SOME METAL TO METAL CONTACT AT CERTAIN POINTS. HE ALSO FOUND THAT THERE IS A MINIMUM CRANKING SPEED NECESSARY TO DRAW FUEL OUT OF THE CARBURETOR BOWL AND DELIVER IT TO THE COMBUSTION CHAMBERS TO BE BURNED.

ALTHOUGH THE BENEFITS OF LOW VISCOSITY OILS IN COLD WEATHER STARTING WERE PROVEN, THERE WAS SOME CONCERN OVER THE PERFORMANCE OF SUCH OILS IN VARIED SERVICE. S. W. SPARROW,(13) IN 1938, AFTER STUDYING THE PERFORMANCE OF LOW VISCOSITY OILS, CONCLUDED THAT RATHER LOW VISCOSITIES MAY BE SAFE FOR BEARINGS IF AN ADEQUATE FLOW CAN BE INSURED. HE FOUND THAT A REDUCTION IN VISCOSITY DID EFFECT AN INCREASE IN FLOW RATE AT CONSTANT PRESSURE. HIS WORK ALSO SHOWED THAT REDUCING VISCOSITY IS AN EFFECTIVE METHOD OF INCREASING CRANKING SPEED AND ENGINE POWER DUE TO THE ACCOMPANYING DECREASE IN ENGINE FRICTION.

Working with diesel engines at sub-zero temperatures in 1943, H. L. Knudsen[14] conducted a number of tests to determine starting power requirements with different lubricating oils. He found that cranking power requirements can be reduced by diluting the lubricating oil with kerosene or gasoline. However, a more desirable means of assisting low temperature starting was found in the use of an immersion heater to raise oil temperature and in this manner decrease viscosity.

The practice of diluting engine oil with kerosene or commercial diluents was also investigated by Mougey and Upham[15] in 1948. They determined that although oil diluted in this manner did aid low temperature starting it became unstable as a lubricant. A stable engine oil with viscosity lower than 10W was needed, according to their findings.

In 1950 an investigation of the performance of engine oils having a high viscosity index (VI) was undertaken by Fleming, Geddes, Hakala and Weisel.[16] Their results supported previous work in that engine starting was found to depend in part on the viscosity of the crankcase oil at starting temperature, with low viscosity promoting better starting. However, they also showed that the low temperature starting properties of VI improved oils are identical to those of straight mineral oils, having the same winter viscosity grade, at the same temperature. Oil consumption was related to the high temperature viscosity of the oil, increasing as viscosity decreased, and consumption of VI improved oils was found to be the same as that of mineral oils having the same viscosity at 300°F. They concluded that high VI engine oils offered the readiest means of combining good low temperature

STARTING CHARACTERISTICS AND LOW OIL CONSUMPTION PROPERTIES IN A SINGLE LUBRICANT.

DeCarolis and Meyer,(17) at Penn State University, in 1956 investigated the factors which influence engine cranking at low temperatures. Their findings verified previous statements that the cranking torque of an engine is a function of oil viscosity only, increasing appreciably as viscosity increases. Their investigation also revealed that there is little difference in cranking torque with speed after the first few seconds of cranking with oil viscosities up to 23000 centistokes. With very high viscosity oils torque was found to drop as speed increased. Cranking torque was also found to decrease as time increased due to the heat generated in the oil, causing a subsequent decrease in viscosity.

A study of the relationships between low temperature cranking resistance and the viscosity characteristics of multigrade engine oils was carried out by Selby and Malone(18) in 1956. It was found that the low temperature performance of a multigrade oil was often not equivalent to that of a single grade oil with the same low temperature rating (i.e. a 10W30 was not equivalent to a 10W oil). They also showed that the accepted method of determining low temperature viscosity by using the empirical Walther equation was not accurate for multigrade oils and recommended that its use be restricted to that portion of the temperatures spectrum where it was known to apply. It was also their recommendation that classification of an engine oil for low temperature should be based on its measured viscosity at these temperatures and at a specified shear rate, preferably one comparable to the shear rates adjacent to the principal moving parts in an engine.

In a 1957 paper, Selby[19] explored the non-Newtonian characteristics of lubricating oils. His results showed that pure mineral oils become non-Newtonian below the cloud point while polymer containing oils exhibit non-Newtonian behaviour both above and below the cloud point. Non-Newtonian oils exhibit thixotropy which may be due to temporary distortion and orientation of polymer molecules or to permanent shear degradation. Polymer structures may multiply the base oil viscosity many times at low shear rates but, above the pour point, under high rates of shear, the viscosity of the polymer containing oil was found to approach that of the base oil. The effectiveness of different polymers was shown to vary with their physical and chemical natures and with the solvency and physical natures of the base stock. It was found that the General Motors Research (GMR) Forced-Ball Viscometer was capable of determining viscometric differences caused by different polymers at low temperatures. Selby suggested that more needed to be known about the load carrying ability of polymeric oils in view of the possibility of polymer degradation, and cautioned against the use of polymers which might create unpumpable structures at low temperatures.

Selby[20] continued his study of cranking speed and viscosity relationships and in 1958 reported that viscosities measured by the GMR Forced-Ball Viscometer at a shear rate of 2000^{-1} seconds were found to give significantly better correlation with cranking data than did extrapolated viscosities, or viscosities predicted using the method developed by Horowitz.[21] Correlations were made with engine cranking data taken from 250 cold cranking tests with three oils and at temperatures varying from +3°F to -35°F. Correlation analysis were made against the line $M = c(N)^B$, a relationship found by Barrington and Lutwysky(22) and confirmed by Arter(23) and by David(24). This relationship was found to hold true and "B" was shown to have a value of approximately 0.5. Other observations were that higher shear rates gave higher engine correlation, and that polymer gelation appeared to have an effect on engine cranking.

In a 1960 paper, Selby(25) summarized an ASTM Investigation of the low temperature viscometry of engine oils. The viscometers considered were: S.O.D. Pressure Viscometer; Ferranti-Shirley; Barber Concentric Cylinder Rotational; Brookfield Rotational; PRL Single Pass Capillary; and the GMR Forced-Ball. These viscometers are described in the Nomenclature. Three individual sets of cranking tests were also run on four Newtonian and two non-Newtonian reference fluids. The engine correlation data tended to favour the transient measurement devices. This relationship was explained by the fact that in continuous shear maximum orientation occurs before the reading is taken while in transient shear only partial orientation occurs. In reference to Barrington's(22) work Selby pointed out that 80% of an engine's cranking effort is developed in the cylinders where the oil is in transient shear. The need for further cranking tests was emphasized by Selby.

About the same time, Selby and Hunstad(26) presented a detailed paper on the Forced Ball Viscometer. A theoretical analysis of the shear rate was given and it was shown that the viscosity data obtained with the instrument agreed well enough with theoretical calculations to enable the forced-ball viscometer to be used as an absolute instrument. The instrument was found to be particularly useful in the study of non-Newtonian characteristics of engine oils. It was shown that the instrument made it possible to study thixotropy, polymer orientation phenomena, dilatancy, and complex flow systems exhibiting combination of these phenomena. The repeatability of results from initial studies with the instrument was found to be satisfactory.

Newingham and Ziegler,[27] in 1961, presented an analysis of cranking tests on a complete series of service station oils, both single and multi-graded. Their results tended to support previous findings in that extrapolated viscosity data did not correlate well with engine viscosity data. Measured viscosities determined with an ASTM pressure viscometer and a Brookfield viscometer, however, showed appreciably better correlation. The authors recognized, though, that due to the low shear rates involved, similar correlations could not necessarily be expected for oils compounded with different base oils and polymers.

In 1961 Selby[28] discussed a means of calculating cranking speed from engine oil viscosity at low temperatures. It was known from previous work that cranking torque requirement is a function of the square root of the product of cranking speed and engine oil viscosity ($M \propto (N\mu)^{\frac{1}{2}}$). The cranking torque required may then be represented by the expression $M = k(N\mu)^{\frac{1}{2}}$. By making the assumption that cranking power is constant ($P = NM = k_1$) the expression may be reduced to:

$$\frac{k_1}{N} = k(N\mu)^{\frac{1}{2}}$$

or

$$K = \frac{k_1^2}{k^2} = \mu N^3$$

By determining the torque requirement of an engine with an oil of known viscosity the value of K can be calculated. This value remains relatively constant for a given engine.

Selby, Verdura and Hunstad[29] in 1961, discussed a study of engine oils at low temperature in an improved cranking apparatus. It was shown that cranking with a conventional cranking motor had two disadvantages. Torque measurement was indirect and dependent upon cranking motor condition and cyclic torque variations made averaging very difficult. The improved GMR apparatus combined both motor driven and cranking motor systems and a gearbox provided multiple speed variations for the motor drive. It was noted that, as cranking speeds are increased a greater proportion of the torque requirement is used to overcome compression pressure due to decreased leakdown time. Poor correlation between bearing temperature fluctuation and cranking speed indicated that bearing friction is not of primary importance. The apparatus was shown to have good versatility and repeatability.

Munsell,[30] in 1962, pointed out that the Brookfield viscometer gave results that were too high for good correlation with engine cranking results. He explained that this poor correlation was due to the very low shearing action of the system. He also explained that oil consumption depends upon volatility and used oil viscosity and that increased oil consumption due to the use of lighter base stocks with increased volatility may be offset by use of VI improvers having low breakdown. Temporary viscosity loss for most commercial VI improvers was found to be approximately 50% of the increase due to polymer thickening.

In 1963, in a presentation before the Sixth World Petroleum Congress in Frankfurt, Germany, Selby(3) made a detailed review of the problems, developments, and research concerned with viscosity and the cranking resistance of engine oils at low temperatures up to that time. He traced the development of polymer containing and multigrade oils and pointed out the shortcomings of the Walther extrapolation technique for determining the low temperature viscosity of these oils. The effects of polymer and gel structures at low temperatures were discussed and a number of experimental studies of these effects were reviewed. Selby also covered the subject of oil supply at low temperatures. He showed that for a given oil pump design there is a critical viscosity above which an oil would cause air-binding of the pump, and stoppage of flow. The temperature at which the oil pump will become air-bound with a given oil was shown to be dependent on the low shear viscosity of the oil and the dimensions and depth of immersion of the oil pump inlet tube. From a standpoint of oil supply at low temperatures highly gelated oils were shown to be undesirable. In discussing viscosity and cranking speed relationships Selby demonstrated that the theories of hydrodynamic lubrication may be applied to the lubrication of an engine. Both empirical and theoretical expressions relating torque, speed, and viscosity were reviewed and shown to agree. Selby then presented a simplified relationship based on the assumption that, over a considerable range of cranking speed, cranking motor power may be considered nearly constant. A brief summary of the work of the ASTM with laboratory instruments was given, as well as a more detailed account of a series of engine viscosity determinations co-ordinated by the CRC. The tech-

NIQUE USED FOR DETERMINING ENGINE VISCOSITY, CRC L-49 PROCEDURE, WAS FOUND TO BE BOTH REPEATABLE AND REPRODUCIBLE. IN SUMMARY, SELBY NOTED THAT PROGRESS WAS BEING MADE THROUGH THE WORK OF A SUCCESSION OF SCIENTISTS AND ENGINEERS WORKING INDIVIDUALLY AND COLLECTIVELY.

SELBY,[31] LATER IN 1963, CONDUCTED A STUDY TO SEPARATE THE EFFECTS OF OIL VISCOSITY AND CRANKING SPEED ON COLD-WEATHER STARTING. HE LEARNED THAT CHANGING CRANKING SPEED ALONE HAD VERY LITTLE EFFECT ON STARTING. CHANGING OIL VISCOSITY ONLY, HOWEVER, SHOWED A MUCH MORE PRONOUNCED EFFECT ON STARTING. IT APPEARED THAT THE CRITICAL FACTOR IN STARTING WAS WHETHER OR NOT THE ENGINE WAS CAPABLE OF PRODUCING ENOUGH POWER TO OVERCOME THE TORQUE REQUIREMENT RESULTING FROM THE VISCOUS DRAG OF THE OIL. CRANKING SPEED, ON THE OTHER HAND, APPEARED TO BE SIMPLY A REFLECTION OF THE IMPORTANCE OF OIL VISCOSITY. IN VIEW OF THESE FINDINGS SELBY SUGGESTED THAT, ALTHOUGH IT WOULD SEEM TECHNICAL SOUND TO IMPROVE COLD-STARTING PROBLEMS BY REDUCING ENGINE OIL VISCOSITY, THERE IS LITTLE TO BE GAINED IN INCREASING CRANKING SPEED BY INCREASING THE CAPACITY OF THE STARTING SYSTEM.

REIN AND CORDELL,[32] IN 1964, PRESENTED A STATISTICAL ANALYSIS OF THE RESULTS OF VISCOMETRIC TESTS ON A VARIETY OF OILS USING A CRANKING ENGINE AND A NUMBER OF LABORATORY VISCOMETERS. IN THEIR ANALYSIS THEY ALSO CONSIDERED THE POSSIBLE EFFECTS OF PHYSICAL PROPERTIES OTHER THAN OIL VISCOSITY ON ENGINE CRANKING. THEIR FINDINGS SUBSTANTIATED PREVIOUS WORK IN THAT EXTRAPOLATED VISCOSITY SHOWED POOR CORRELATION WITH ENGINE VISCOSITY. THE BEST CORRELATION OF VISCOSITY ONLY WAS FOUND WITH DATA FROM A FERRANTI-SHIRLEY ROTATIONAL VISCOMETER OPERATED AT HIGH SHEAR RATE. HOWEVER, WHEN THE EFFECTS OF OTHER PROPERTIES WERE considered the best correlation was found with information based on Forced Ball viscometer data and shear rate, pour point, 100°F kinematic viscosity, and viscosity index. In neither case was the correlation sufficiently good to precisely predict engine viscosity. The authors suggested that in order to predict engine viscosity from use of a laboratory instrument it would be necessary to gain a much better understanding of the complex flow processes in a cold engine.

In 1964, Lowther, Meyer, Selby and Vick(33)(34) reported on the development of a research technique for determining the low-temperature cranking characteristics of engine oils. The project, co-ordinated by the CRC, made use of engine cranking tests data on a number of research engine oils as determined by eleven different laboratories in twelve different engines. After an initial series of tests a second series was conducted using a more standardized test procedure. This procedure was proven to be able to differentiate between different multi-viscosity oils having similar extrapolated viscosity but different composition. It was also found to have adequate repeatability although reproducibility from lab to lab was not as satisfactory. Some variation was found to be dependent on the displacement of the engine used. A detailed paper explaining the development of the test procedure, CRC L-49 -663, and analyzing the results of the program was issued by the Coordinating Research Council in 1964.(35)

In commenting on the work of Selby(31), Rein and Cordell(32), and the CRC(33)(34), Munsell(36) gave evidence that viscosity data obtained with a Ferranti-Shirley rotational viscometer showed better correlation with engine viscosity than did results from other laboratory instruments. Twenty-three multi-grade and four single grade oils were used in the test program which produced these results. Munsell recognized, however, that although the Ferranti-Shirley instrument gave good correlation, its initial cost, temperature effects and other minor problems would preclude its use as a commercial instrument. He proposed that an instrument could be designed, using the same principle of operation, which would minimize the undesirable features of the Ferranti-Shirley.

Later in 1964 Vick[37] summarized the progress which had been made in the cold cranking of motor oils. His presentation served to clarify the findings of several investigators and to relate them to each other. He noted that the ASTM extrapolation technique for determining low temperature viscosity was inaccurate for multi-grade oils, partially because the low shear viscosity of polymer containing oils is not a linear function of temperature and partially because polymer thickened oils show a temporary viscosity loss under high shear rates and stresses. He observed that the CRC -L49-663 cranking tests showed good repeatability in viscosity determination. He also pointed out the agreement between Selby's[31] findings, with regard to the effect of oil viscosity on starting and Becker's[9] findings 32 years previous. Vick concluded that viscosity measured by a laboratory instrument would serve as a more satisfactory basis for SAE viscosity classification than does extrapolated viscosity but noted that any instrument considered for this purpose should be judged on the basis of its ability to predict cranking performance.

In 1964 the Coordinating Research Council [38] published a

REPORT ON THE PREDICTION OF LOW TEMPERATURE CRANKING CHARACTERISTICS OF ENGINE OIL BY USE OF LABORATORY VISCOMETERS. THE REPORT OUTLINED THE RESULTS OF A SERIES OF TESTS WHICH WERE CONDUCTED IN A NUMBER OF DIFFERENT LABORATORIES AND RELATED TO THE RESULTS OF ENGINE CRANKING TESTS ON THE SAME OILS.[35] THE VISCOMETERS CONSIDERED WERE: FERRANTI-SHIRLEY CONE PLATE; GMR FORCED-BALL; BROOKFIELD; HAAKE ROTOVISCO; PRL SINGLE PASS CAPILLARY; SOD; MASON TORSION CRYSTAL; TEXACO HIGH RATE OF SHEAR ROTATIONAL; AND THE CANNON-MANNING PRESSURE VISCOMETER. THESE VISCOMETERS ARE DESCRIBED IN THE NOMENCLATURE. THE CONCLUSIONS REACHED WERE THAT THE FERRANTI-SHIRLEY AND GMR FORCED-BALL VISCOMETERS GAVE GOOD AGREEMENT WITH ENGINE CRANKING DATA AND THAT THE HAAKE ROTOVISCO AND PRL CAPILLARY VISCOMETERS SHOWED SOME PROMISE. THE OTHER VISCOMETERS WERE FOUND TO BE UNSUITABLE FOR CORRELATION WITH ENGINE CRANKING. IN GENERAL, THE BEST CORRELATION WAS FOUND FOR THE HIGHEST SHEAR RATES OR SHEAR STRESSES INVESTIGATED. CONTINUED INVESTIGATION WITH BOTH LABORATORY INSTRUMENTS AND ENGINE CRANKING RIGS WAS ENCOURAGED. THE RESULTS OF THIS PROGRAM WERE ALSO REPORTED BY VICK, MEYER, AND SELBY[39] IN 1965.

SELBY AND STAFFIN[40] IN 1965, PRESENTED A MUCH MORE DETAILED ACCOUNT OF THE TEST PROGRAM INVOLVING THE GMR FORCED-BALL VISCOMETER AND THE FERRANTI-SHIRLEY, AND HAAKE-ROTOVISCO CONE-PLATE VISCOMETERS. THEY EXPLAINED THE CONCEPT OF GEL CORRECTION WHICH WAS FOUND TO IMPROVE THE CORRELATION OF FORCED-BALL RESULTS. THE APPARENT VISCOSITY WAD ADJUSTED BY A "GEL VISCOSITY" WHICH WAS DETERMINED FROM THE AREA OF THE IRREVERSIBLE PORTION OF A VISCOSITY-SHEAR STRESS GRAPH, OVER THE RANGE OF SHEAR STRESS USED. A SIGNIFICANT IMPROVEMENT IN CORRELATION WITH ENGINE VISCOSITIES WAS REALIZED WHEN THE CONCEPT OF GEL CORRECTION WAS APPLIED to those oils which exhibited gel structures at the temperature of determination. The cone-plate viscometers were found to be most suited for use as relative viscometers. A standardized test procedure, which had been found to be satisfactory, was proposed for cone-plate viscometer use. Information was also given on an improved plate and temperature control system. Good correlation with engine data was found with the cone-plate viscometers.

A large portion of the cranking resistance in an engine is associated with its reciprocating motion. In view of this fact, Stewart, Lion, and Meyer(41), on 1965, made a study to develop and evaluate a reciprocating viscometer. Tests were made on a number of test oils in a cold cranking engine, three model airplane engines, and four reciprocating viscometers. Correlation for the model airplane engines with engine cranking was slightly lower than for the GMR Forced-Ball viscometer, or the Ferranti-Shirley cone-plate viscometer. The correlation for the reciprocating viscometers proved to be lower than for the model airplane engines. Improved correlation was found when higher shear rates were used. With further development the reciprocating viscometer showed promise of becoming a useful and accurate viscometric tool.

In 1965, West and Selby(42) made a study of the effect of engine operation on the viscometry of multigrade engine oils. It was found that polymer containing oils often lose a portion of their initial viscosity after lubricating the engine for a period of time. The used oil may, then, be more viscous than expected at low temperature and less viscous than desired at operating temperatures after a relatively short period of use. It was found that the major portion of the viscosity loss encountered occurs in the first 7 1/2 hours of operation. Engine speed was found to have a pronounced effect on viscosity loss but engine load had no apparent effect. Permanent viscosity loss after 7 1/2 hours ranged from 8% to 20% for a number of multigrade oils. Viscosity change was explained to be a function of four independent factors: degradation of the VI improver; gasoline dilution; distillation of volatile components; and oxidation. Based on this information it would appear that used oil viscosity would be a more accurate reflection of oil performance than would new oil viscosity.

In a prepared discussion of Stewart, Lion, and Meyer's paper(41) on the reciprocating viscometer, D. S. Kim(4) made public his development of a another new device, the Cold Cranking Simulator. The heart of the unit was a viscometric cell in which a sample is sheared in the small space between a rotating spindle, with two flattened sides, and a cooled cylinder. The coupled flats were described to provide a fluctuating, but continuous shearing actions and to produce a hydrodynamic shearing action. The rotor was driven by a series wound AC motor and the speed was measured from the output of a DC generator driven at rotor speed. The motor was driven at constant voltage so that speed was a function of viscosity. Preliminary tests conducted by Kim indicated that this unit, possibly, offered superior correlation with engine viscosities to other viscometers.

IV

EXPERIMENTAL APPARATUS

Two separate and independent pieces of experimental apparatus were used in this research project. The first device used was a cold cranking test engine, equipped to simulate actual field conditions in winter passenger car service. The second instrument was a laboratory viscometric device known as a Cold Cranking Simulator (CCS). The construction and principles of operation of these devices will be discussed in the following sections.

Cold Cranking Engine

It was learned, in 1956,[18] that the low temperature viscosity of a non-Newtonian oil, as determined by viscometers then available, was not a valid indication of the low temperature cranking performance of the oil in an engine. In order to evaluate the low temperature cranking performance of an oil it was necessary to conduct cranking tests in an engine. For this purpose a number of individual laboratories independently developed their own apparatus and procedures. In an effort to co-ordinate the work being done in this field, in 1961 the Co-ordinating Research Council (CRC), at the request of the Society of Automotive Engineers (SAE), initiated a program to develop a research technique for measuring the low temperature cranking performance of engine oils.

CRC Apparatus - The results of the CRC program were published in 1963.[35] As part of the approved procedure (CRC Designation L-49-

663) general specifications were placed on the apparatus. These specifications are shown in Appendix A. As may be noted a considerable amount of flexibility in equipment was provided to make the technique as broadly applicable as possible.

There are two basic types of apparatus allowed by the CRC. In either case a broken-in (1500 miles or equivalent) engine is used without an oil filter, transmission, power assist drives, and air conditioning. Solid valve lifters are recommended where available. The difference in the two lies in the power supply for cranking. One system uses a conventional cranking motor supplied by either a bank of batteries with high capacity, to give a constant voltage, or by a constant voltage power supply such as a rectifier. The more sophisticated alternative uses a constant speed drive motor to crank the engine through a torque sensing transducer. The significance of these differences with regard to the method of testing are discussed in Chapter V.

GM of Canada Apparatus - General Motors of Canada (GM), have traditionally used factory fill engine oils having SAE low-temperature viscosities lower than those used by GM divisions in the United States. The reason for using these oils was to insure satisfactory cranking performance in the subzero temperatures encountered in many parts of Canada. In view of the inability of the SAE viscosity system to predict this cranking performance an engine cranking test was needed to evaluate oils proposed for factory fill use.

As part of the program described in this thesis a cold cranking engine apparatus was developed at the General Motors of Canada Experimental Engineering Department. When work was initiated on this

APPARATUS NO ATTEMPT WAS MADE TO COMPLY DIRECTLY WITH THE CRC SPECIFICATIONS. RATHER, AN ATTEMPT WAS MADE TO SIMULATE, AS CLOSELY AS POSSIBLE, ACTUAL SERVICE CONDITIONS IN AN AUTOMOBILE.

A 250 CUBIC INCH DISPLACEMENT 1967 CHEVROLET SIX CYLINDER ENGINE WAS CHOSEN AS THE HEART OF THE APPARATUS. THIS TYPE OF ENGINE WAS CHOSEN BECAUSE IT, ALONG WITH A 283 CUBIC INCH V8 ENGINE, ACCOUNTED FOR THE MAJORITY OF GENERAL MOTORS PRODUCTION IN CANADA, AND BECAUSE OF ITS SIMPLICITY, COMPARED WITH THE V8. BEFORE BEING PUT INTO USE THE ENGINE WAS INSTALLED IN A VEHICLE WHICH WAS DRIVEN FOR 2000 MILES ON A PRESCRIBED SCHEDULE OVER A PRESCRIBED ROUTE, TO BREAK IT IN.

A TEST STAND WAS CONSTRUCTED TO HOLD THE ENGINE IN THE ATTITUDE SPECIFIED FOR INSTALLATION IN AN AUTOMOBILE. IN ORDER TO MAKE THE TEST STAND A SELF-CONTAINED UNIT IT WAS FITTED WITH A RADIATOR, A FUEL TANK, AND AN EXHAUST SYSTEM AND MUFFLER. AN INSTRUMENT PANEL WAS ALSO FITTED TO CONTAIN AN IGNITION SWITCH, VOLTAGE REGULATOR, AMMETER, OIL PRESSURE GAUGE, AND TEMPERATURE AND OIL PRESSURE TELL-TALE LIGHTS. THE TEST STAND WAS THEN WIRED TO DUPLICATE THE WIRING COMPONENTS OF AN AUTOMOBILE IGNITION SYSTEM.

SOME MODIFICATIONS WERE MADE TO THE ENGINE BEFORE IT WAS INSTALLED IN THE TEST STAND. A COPPER PIPE WAS WELDED INTO THE LOWEST POINT OF THE OIL PAN AND A PIPE VALVE WAS INSTALLED TO FACILITATE OIL CHANGING. BEFORE THE OIL PAN WAS REPLACED THE #4 MAIN BEARING CAP WAS REMOVED, FITTED WITH A THERMOCOUPLE AS ILLUSTRATED IN FIGURE 5, PAGE 33, AND REINSTALLED. A QUALIFIED CRANKING MOTOR WAS SUPPLIED BY DELCO REMY DIVISION, ANDERSON, INDIANA, AND WAS INSTALLED ON THE ENGINE. A REGULAR PRODUCTION 1967 PONTIAC (CANADIAN) ENGINE WIRING HARNESS WAS USED. IN

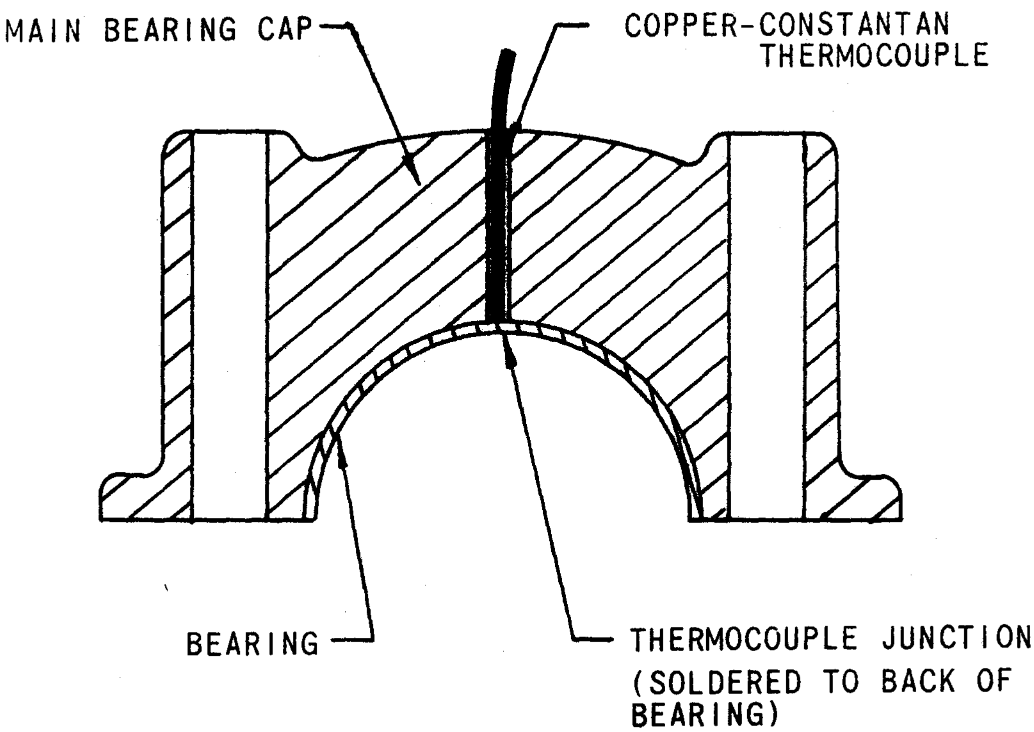


FIGURE 5 - THERMOCOUPLE IN MAIN BEARING CAP

ORDER TO SIMPLIFY THE ATTACHMENT OF BATTERY CABLES TWO QUICK CHANGE TERMINALS WERE CONSTRUCTED OF LOW RESISTANCE BRASS. THESE POSITIVE AND NEGATIVE TERMINALS (SEE FIGURE 6, PAGE 35) WERE ATTACHED TO THE CRANKING MOTOR, THROUGH A SHUNT RESISTOR, AND TO THE ENGINE BLOCK, RESPECTIVELY. THE OIL FILTER WAS REMOVED AND REPLACED WITH A BY-PASS CAN CONSTRUCTED FROM AN EMPTY OIL FILTER CAN.

IN ORDER TO INSTALL THE ENGINE IN THE TEST STAND IN THE DESIRED ATTITUDE IT WAS NECESSARY TO ATTACH A TRANSMISSION ASSEMBLY TO PROVIDE A REAR MOUNT. SINCE THE VISCOUS DRAG IN AN AUTOMATIC TRANSMISSION DURING CRANKING COULD ADD AN UNDESIRABLE VARIABLE TO THE TESTS, THE TORQUE CONVERTER WAS REMOVED FROM THE TRANSMISSION SO THAT IT COULD NOT CONTRIBUTE TO THE CRANKING REQUIREMENTS OF THE ENGINE. FOR THE SAME REASON, NO POWER STEERING, AIR CONDITIONING, OR AIR INJECTION PUMPS WERE INSTALLED ON THE ENGINE.

WHEN THE ENGINE WAS INSTALLED IN THE TEST STAND THE ENGINE WIRING HARNESS WAS CONNECTED TO THE TEST STAND HARNESS, THE OIL PRESSURE GAUGE WAS CONNECTED TO THE ENGINE, AND A FUEL LINE WAS INSTALLED FROM THE FUEL TANK TO THE FUEL PUMP. UPPER AND LOWER RADIATOR HOSES WERE INSTALLED WITH A THERMOCOUPLE IN THE UPPER HOSE TWO INCHES ABOVE THE ENGINE END. ANOTHER THERMOCOUPLE WAS INSTALLED IN THE OIL SUMP AT THE BASE OF THE OIL DIPSTICK.

THE EXTERNAL COMPONENTS OF THE SYSTEM CONSISTED PRIMARILY OF THE POWER SUPPLY AND RELATED PARTS. FROM PREVIOUS WORK IN THE EXPERIMENTAL DEPARTMENT COLD ROOM IT WAS LEARNED THAT, UNDER TYPICAL CRANKING CONDITIONS, AT -20°F, THE CRANKING VOLTAGE AVAILABLE FROM A PRODUCTION 12 VOLT BATTERY IS APPROXIMATELY FIVE TO SIX VOLTS. FOR CRANKING TESTS A

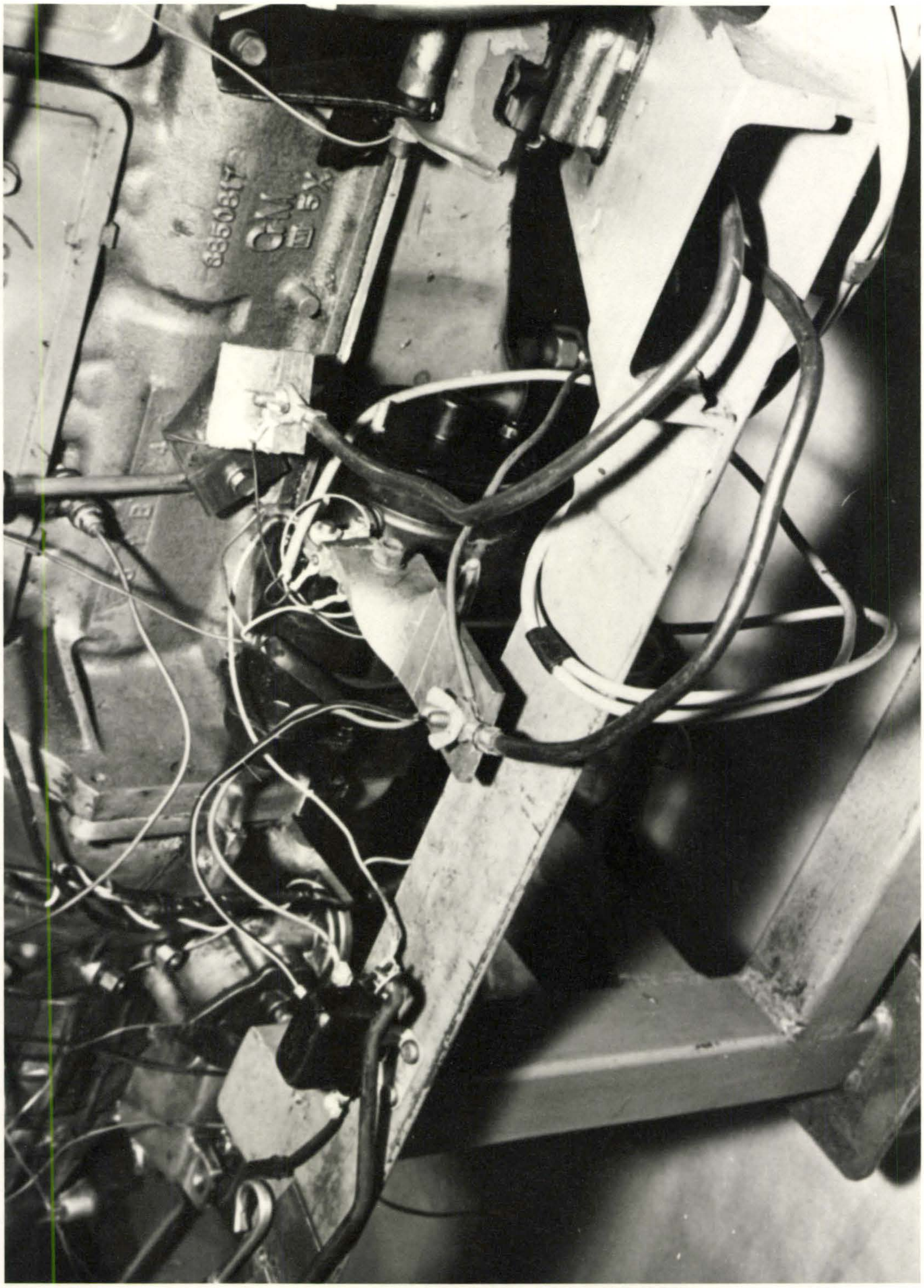


FIGURE 6.

relatively constant power supply was required. Therefore a battery of high capacity was needed. The power supply selected was a single Delco 12 volt diesel truck battery with a capacity of 205 ampere-hours. A three ampere battery charger was used to keep the battery fully charged. Figure 7, page 37, shows this unit. Two 15 foot long battery cables, with quick change terminals, were made to allow the power supply to remain outside the cold room. In order to minimize the resistance #1 gauge cable was used. As will be discussed later, some modifications to this power supply were to become necessary.

The heart of the instrumentation used for the cranking tests was a Sanborn chart recorder, shown in Figure 8, page 38. This instrument contains two amplifiers, two pre-amplifiers and a two channel chart recorder, and was used to record cranking voltage and current on a time scale. A self-balancing potentiometer, pictured in position on the cold room control console in Figure 9, page 39, was used to monitor temperatures at the thermocouples.

As a result of preliminary testing with this cranking apparatus some modifications were found to be necessary. Using the 12 volt power supply cranking voltage was found to be approximately 10 volts at -20°F. Since the purpose of this test was to simulate actual conditions and since it was known that in actual conditions, cranking voltage was approximately six volts, this power supply was unacceptable.

In order to reduce the cranking voltage to the desired level a variable carbon-pile resistor was installed in series with the positive battery cable. Although this system proved satisfactory for repeat tests on a single oil it was not repeatable for various oils.

FIGURE 7.

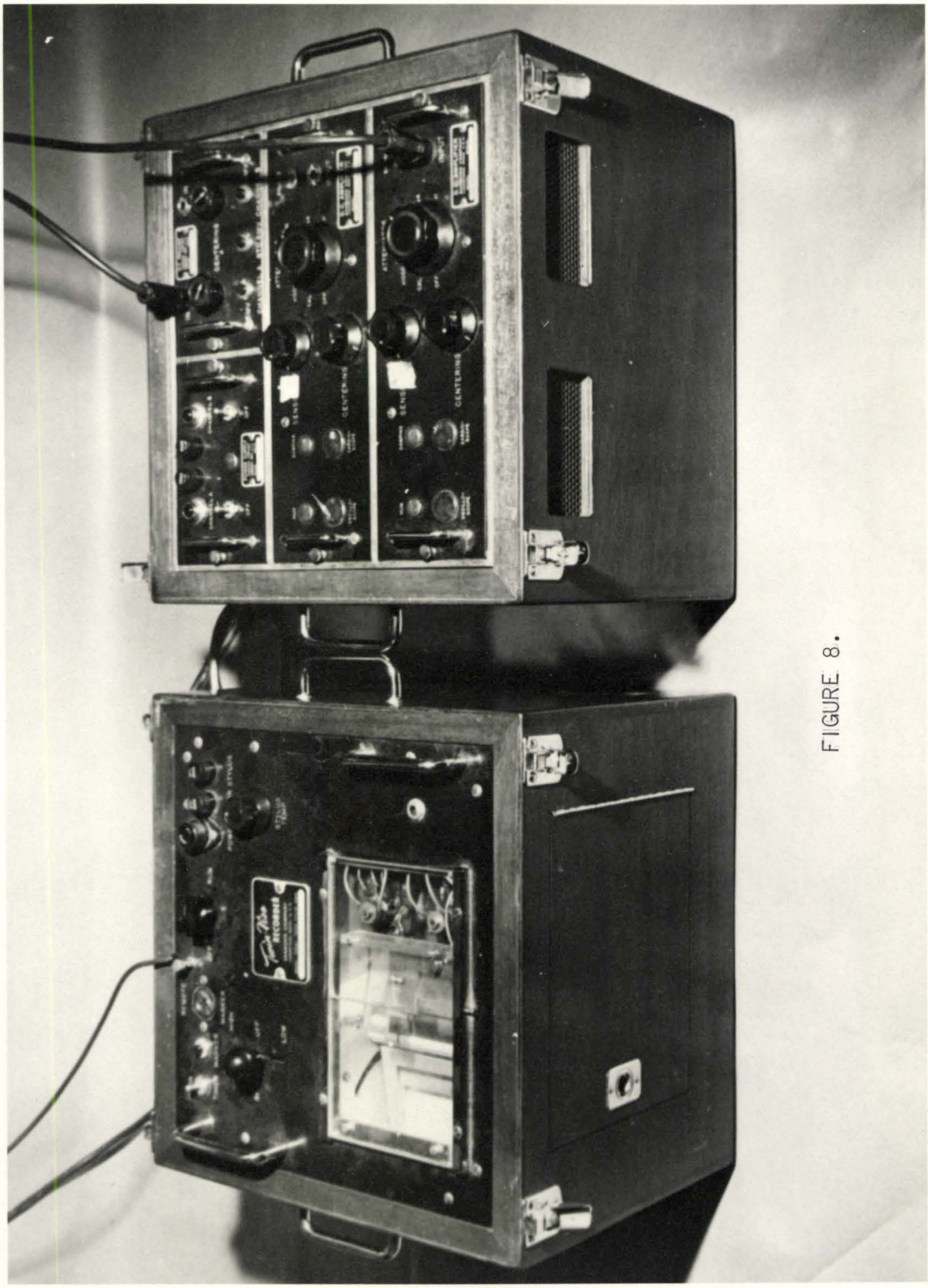


FIGURE 8.

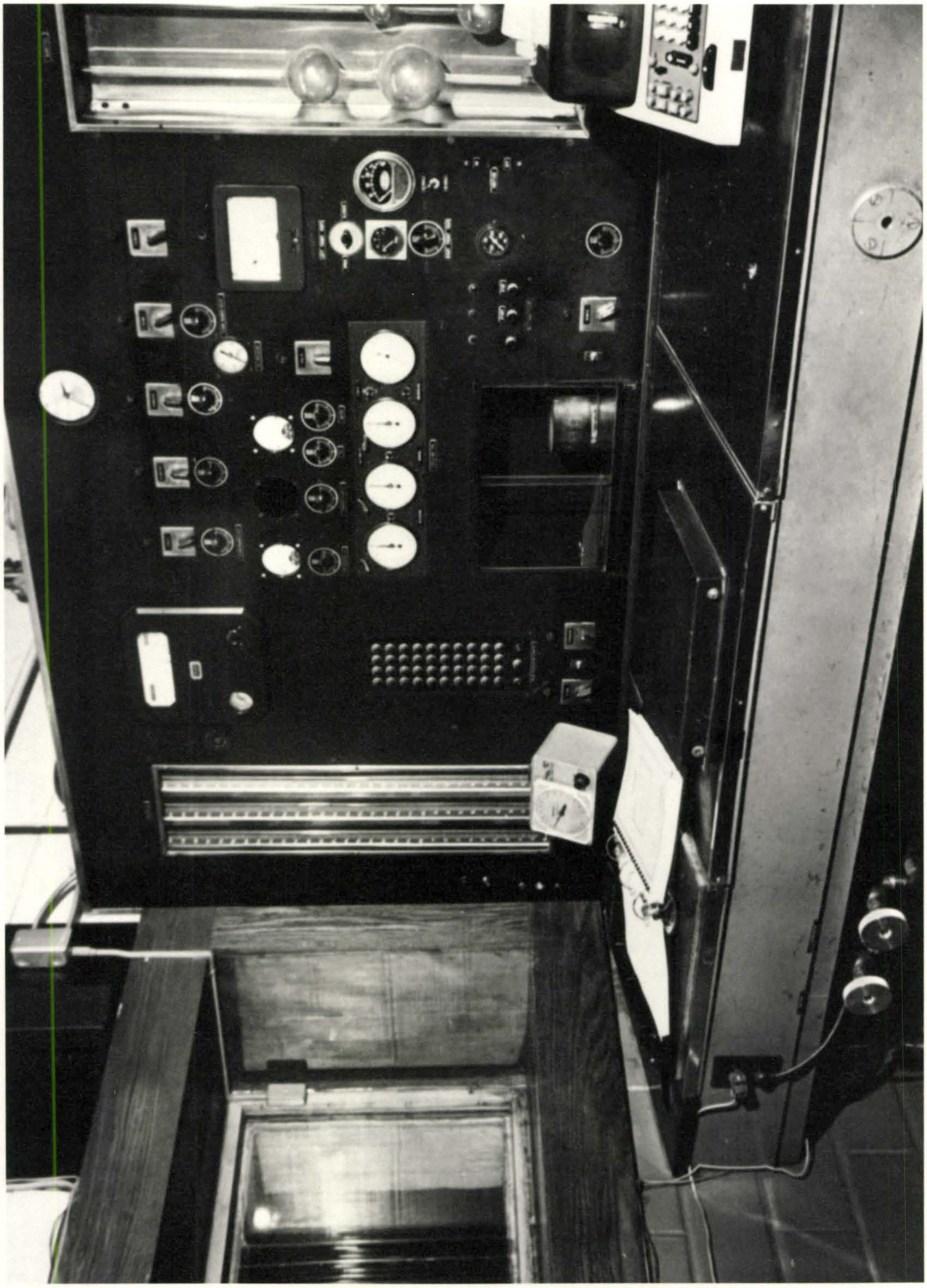


FIGURE 9.

With a single oil the cranking torque, and current requirements are relatively constant from one test to another, Considering Ohm's law then: V = IR, where I and R are constant so V = Constant. Cranking torque and current requirements vary, however, from one oil to another. If current is considered variable, then, by referring to Ohm's law it can be seen that, with a constant resistance the voltage will vary directly with the current. This situation indicated that the use of a resistor to reduce voltage was an unsatisfactory solution.

It was decided that a more desirable means of reducing cranking voltage would be to start with a reduced voltage power supply. An investigation of the six volt batteries available through General Motors Parts and Service revealed that the largest capacity unit available was a 160 ampere-hour industrial battery. In order to maximize the reserve power available four of these batteries were obtained and connected together in parallel to give a six volt power supply with a total capacity of 640 ampere-hours. This power supply, and an accompanying three ampere battery charger to keep the batteries at full charge, are shown in Figure 10, page 41. Preliminary tests with this power supply showed that cranking voltages in the range of 4.5 to 5.5 volts were obtained. Since this range more closely approximates actual cranking conditions this power supply was considered acceptable.

The second modification to the apparatus was made partially as a result of the change in power supply, and partially as a matter of convenience. One inconvenient facet of the test procedure required that one person enter the cold room and crank the engine by turning the ignition switch while a second person recorded the data in the

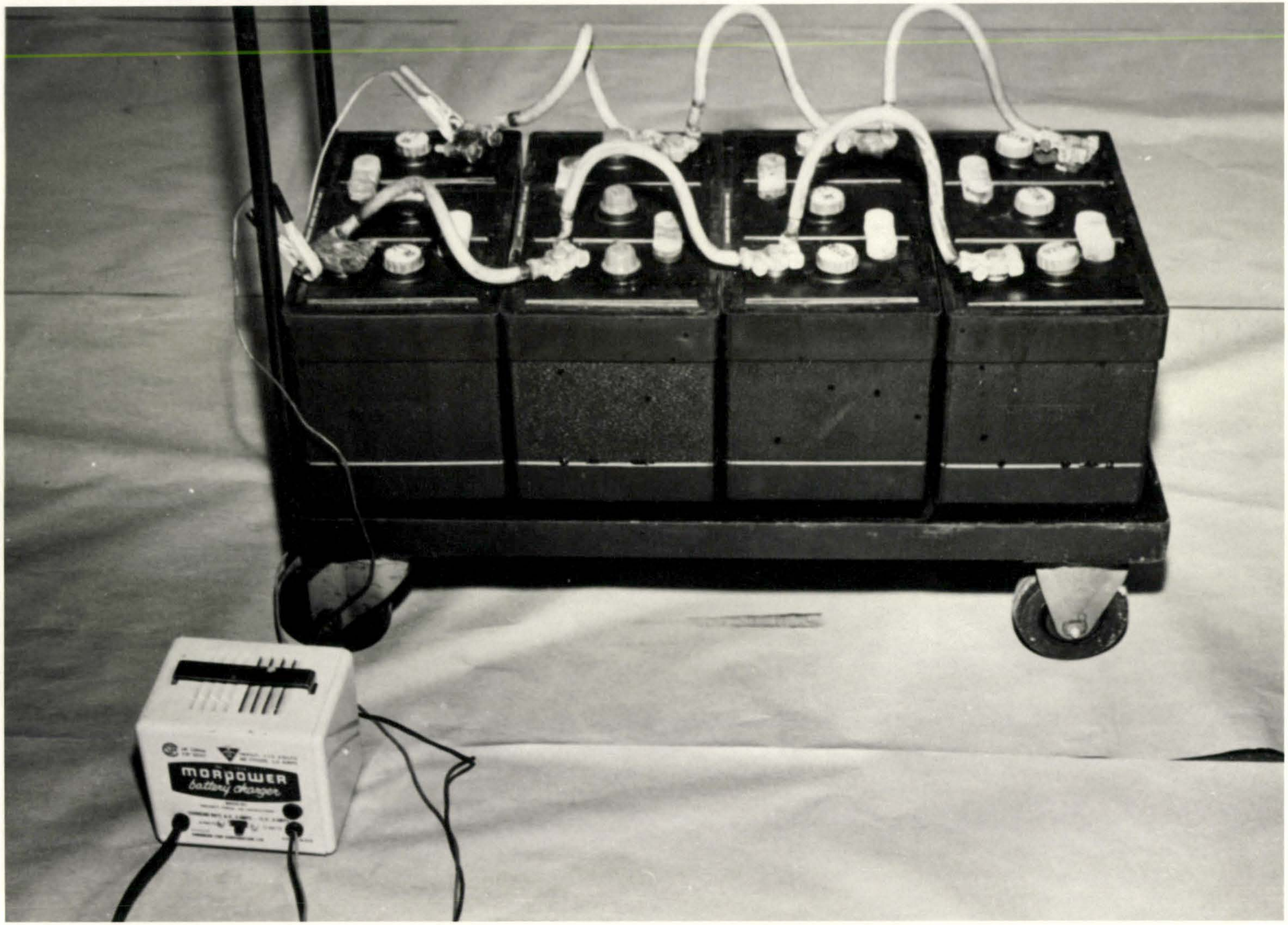


FIGURE 10.

CONTROL ROOM. BY MOVING THE CRANKING CONTROL SWITCH INTO THE CONTROL ROOM IT WOULD BE POSSIBLE FOR ONE PERSON TO CONDUCT THE TEST WITHOUT ENTERING THE COLD ROOM. BY MAKING THIS CHANGE, HOWEVER, THE IGNITION SYSTEM WOULD BE CHANGED FROM ACTUAL IN-CAR CONDITIONS.

WHEN THE 12 VOLT POWER SUPPLY WAS REPLACED BY THE 6-VOLT SUPPLY SOME DIFFICULTY WAS ENCOUNTERED IN CRANKING MOTOR OPERATION. OCCASIONALLY, THE VOLTAGE AVAILABLE TO THE STARTER SOLENOID WAS NOT SUFFICIENT TO PULL IN THE SOLENOID. THE MINIMUM SPECIFIED SOLENOID PULL-IN VOLTAGE, AT -20°F, FOR THE MOTOR USED WAS 5.5 VOLTS. IT WAS FOUND THAT BY BYPASSING THE PRODUCTION IGNITION WIRING SUFFICIENT VOLTAGE WAS AVAILABLE TO ENERGIZE THE SOLENOID. IN ORDER TO INSURE THAT THE SOLENOID WOULD PULL IN CONSISTENTLY AN AUXILIARY STARTING CIRCUIT, SHOWN IN FIGURE 11, PAGE 43, WAS DEVISED. SINCE THE STARTER SWITCH ONLY ENERGIZED A RELAY THROUGH WHICH ENERGY WAS TRANSFERRED TO THE SOLENOID, THE SWITCH COULD BE REMOVED AS FAR AS NECESSARY FROM THE TEST STAND WITHOUT AFFECTING THE VOLTAGE AVAILABLE TO THE SOLENOID. THE SWITCH, THEREFORE, WAS LOCATED INSIDE THE CONTROL ROOM, WITH THE ADDED ADVANTAGE THAT ONLY ONE PERSON WOULD NOW BE REQUIRED TO CONDUCT A TEST.

THE TEST APPARATUS WAS UNALTERED DURING THE TEST PROGRAM EXCEPT FOR THE REPLACEMENT OF THE ORIGINAL CRANKING MOTOR WITH A DUPLICATE WHEN THE ORIGINAL SHOWED A CHANGE IN CHARACTERISTICS, AS WILL BE FURTHER DISCUSSED IN CHAPTER VII. FIGURES 12 AND 13, PAGES 44 AND 45 RESPECTIVELY SHOW THE COMPLETE TEST APPARATUS.

COLD CRANKING SIMULATOR

THE COLD CRANKING SIMULATOR IS A LABORATORY VISCOMETRIC INSTRU-

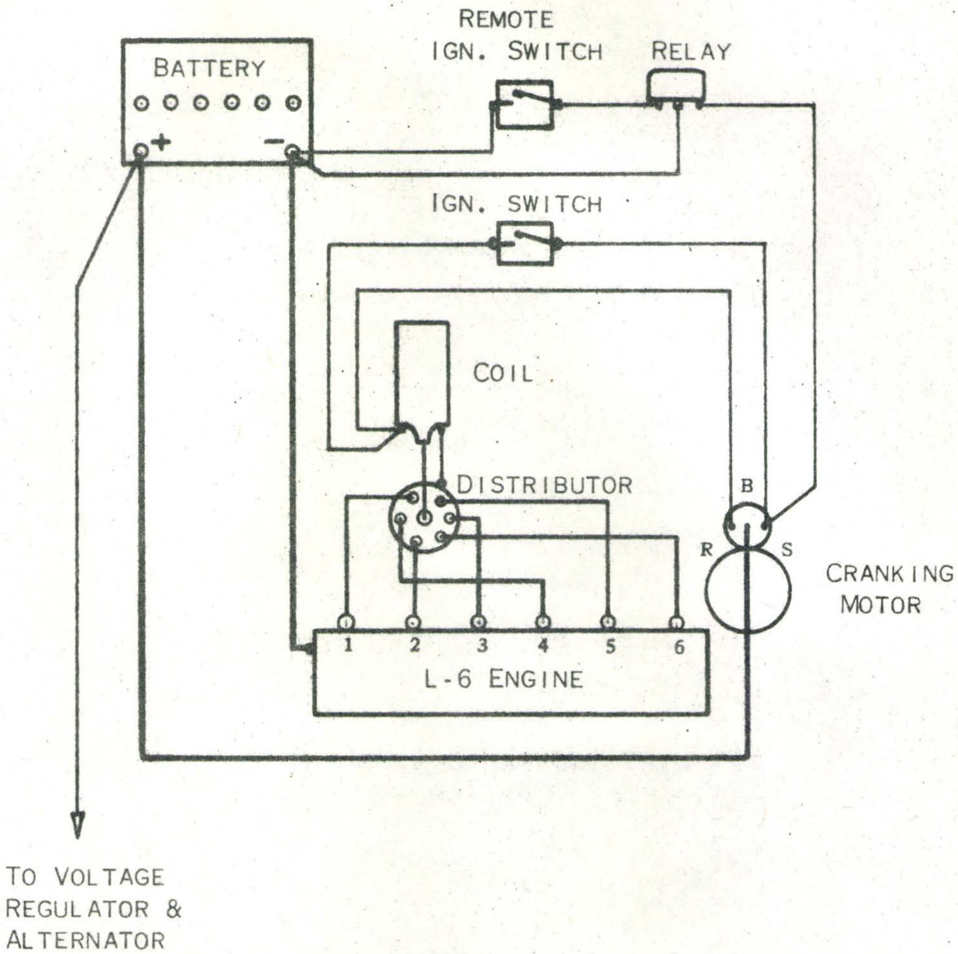


FIGURE II - SCHEMATIC DIAGRAM OF REMOTE STARTING CIRCUIT

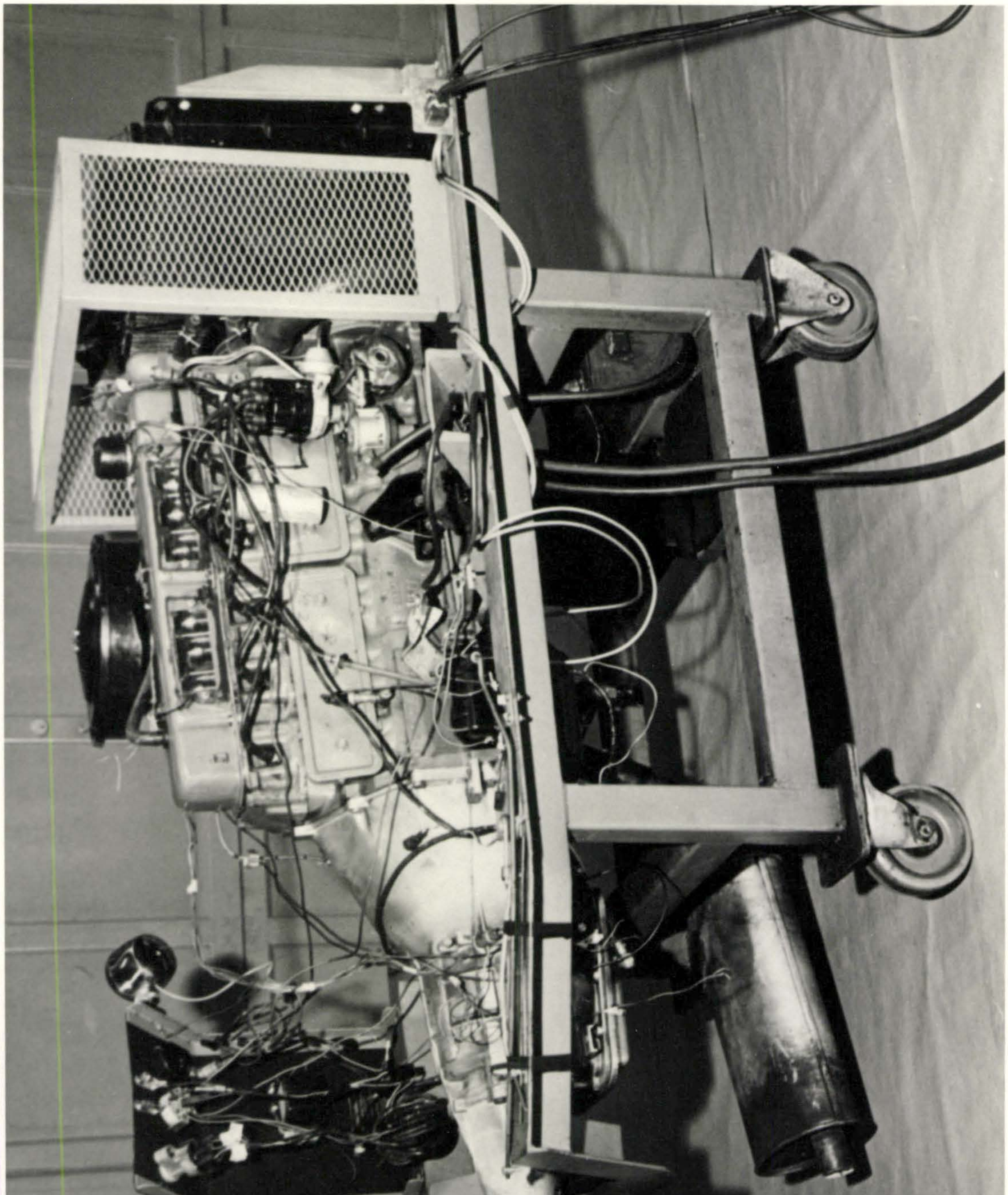


FIGURE 12.

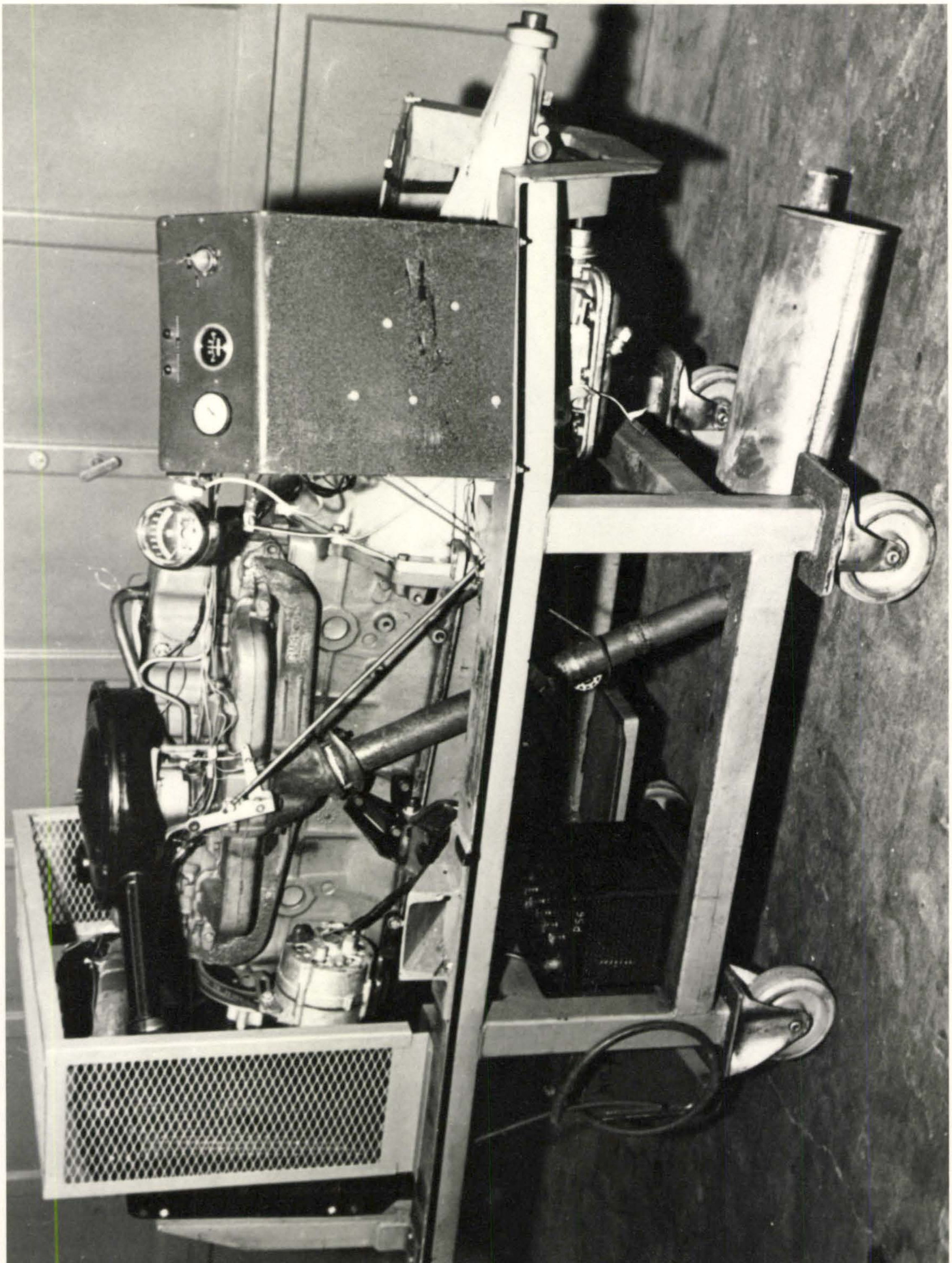


FIGURE 13

ment which is intended to simulate the operation of a cold cranking engine in its effect on an oil sample. The concept of the simulator is basically similar to that of an engine under cranking conditions. In each case an electric motor, activated by a constant voltage, is used to rotate a shaft and a bearing in a sample of oil. The controlled input is voltage and the measured output is shaft speed. The shaft speed is governed by the torque requirement of the shaft which is in turn governed by the viscosity of the oil.

Development - The results of experiments with previous viscometric devices indicated that correlation of laboratory test results with engine test results improved as shear rates were increased in the laboratory instruments. There was some evidence to suggest that the level of power input to the oil sample was equally as important as high shear rates alone. It was also indicated that continuous shearing of the sample is more desirable that intermittent shearing because of the fact that wax structures are broken up.

The prototype of the cold cranking simulator was developed by Dr. Dae Sik Kim of the Esso Research Laboratories, Linden, New Jersey to incorporate those features known to be desirable in a single instrument. The original apparatus was simply a journal bearing, driven at a constant speed with torque as the variable output[(43)]. This device was modified so that the horsepower input was fixed and shaft speed was the variable output. Clearances were designed to provide a shear rate in the order of 40,000 sec^{-1}. In order to maintain an oil film in the clearance volume flats were machined on the rotor to promote hydrodynamic lubrication and to provide a centering effect for the rotor. Preliminary tests on this apparatus were encouraging and were made public at the Chicago SAE meeting in May, 1965.[4]

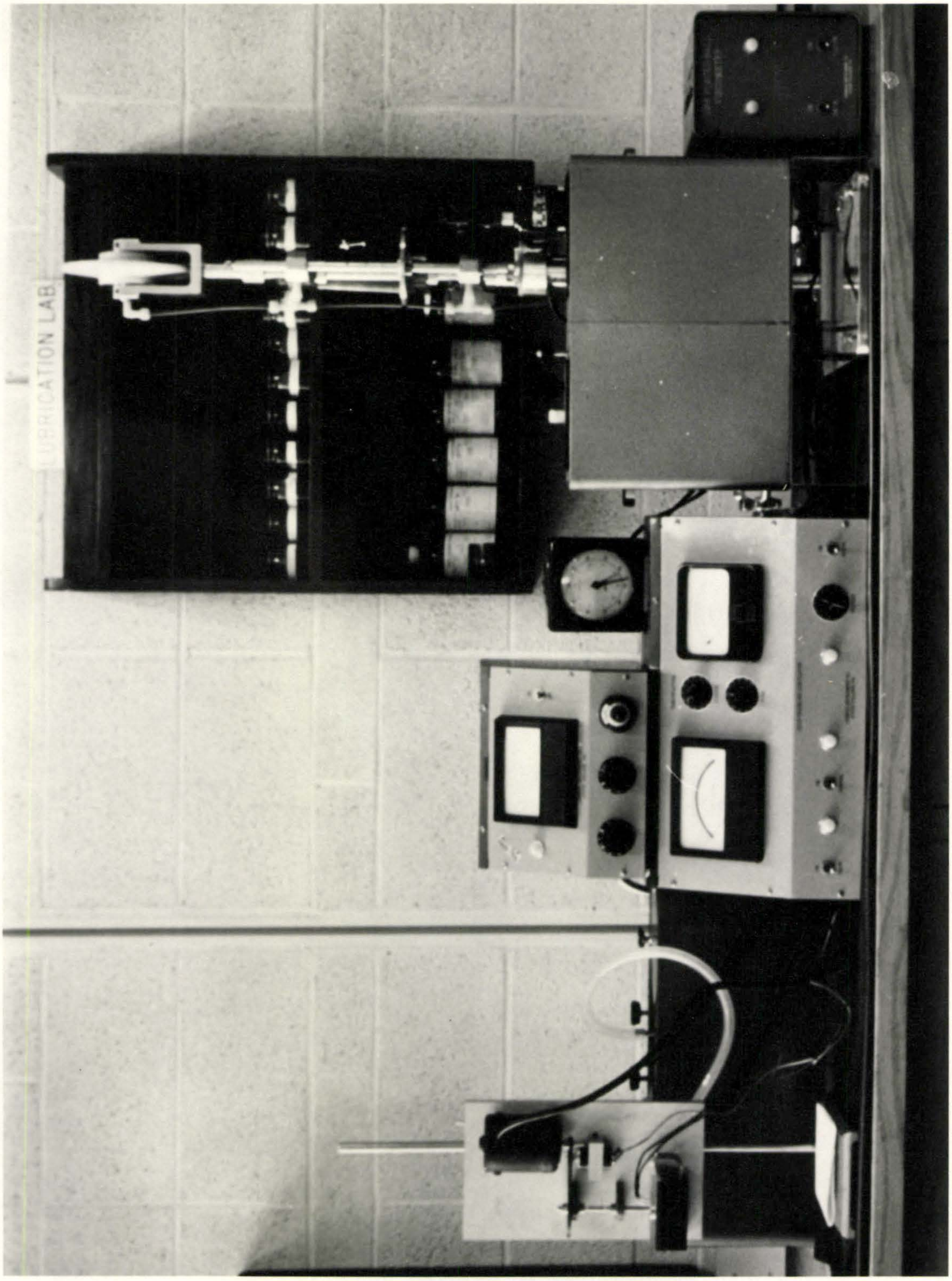
Further development work on the instrument was conducted by the Cannon Instrument Company. The original design was developed to the point where it could be manufactured as a complete, self-contained unit. At this stage a number of the units were built and made available to the ASTM for a series of round robin tests. The success of this round robin, conducted at 0°F, resulted in the instrument being put into production on a firm order basis.

Description - The cold cranking simulator used in this research program was the sixteenth unit built and one of the first to be delivered for use outside the round-robin.

Figure 14, page 48, shows the complete cold cranking simulator. Also apparent, to the right of the simulator is a GMR Forced-Ball Viscometer. The apparatus may be considered to have four major components, (a) a viscometric cell, (b) a control console, (c) a coolant circulator, and (d) an electronic thermometer.

The heart of the system is the viscometric cell, shown in Figure 15, page 49. The viscometric cell consists of a shearing head, an electric motor and a tachometer generator mounted on a flat plate which is in turn fixed to a stand.

The shearing head may be seen in Figure 16, page 50. The major components of this unit are a nylon insulator block, a copper stator, and a stainless steel rotor. These components are illustrated in cross-section, along with the detail components, in Figure 17, page 52. As indicated, the nominal clearance between the rotor and stator is 0.0008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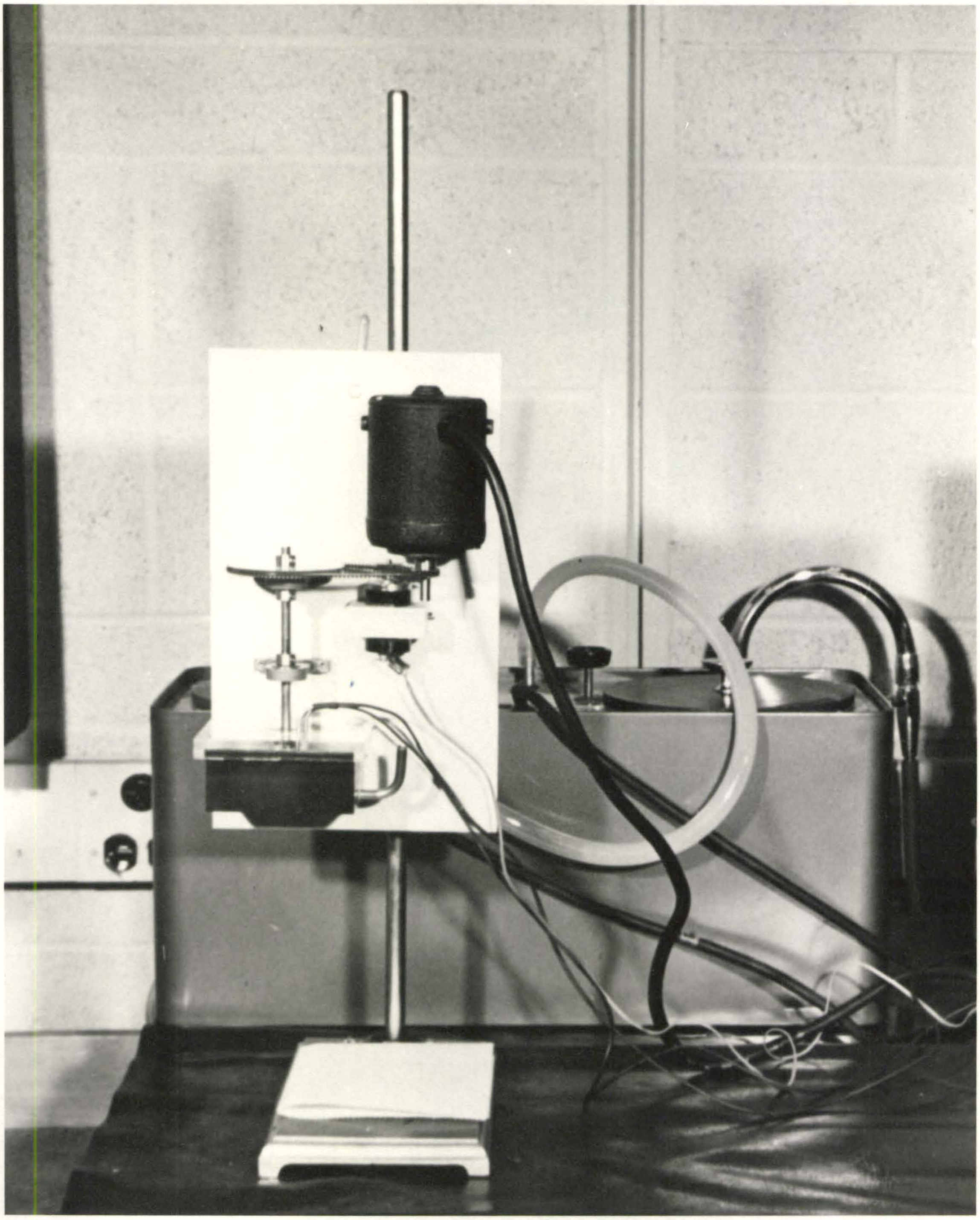


FIGURE 15.

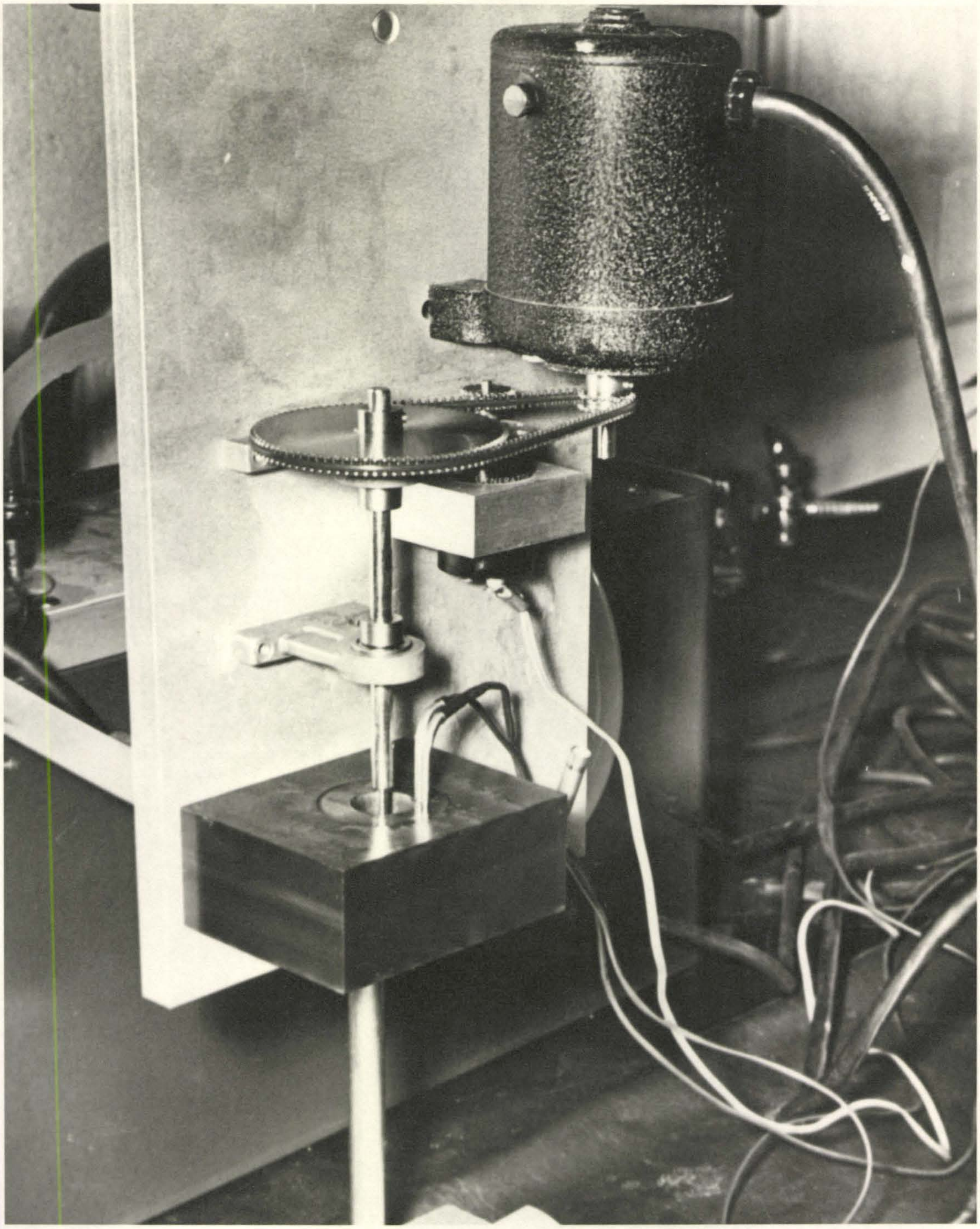


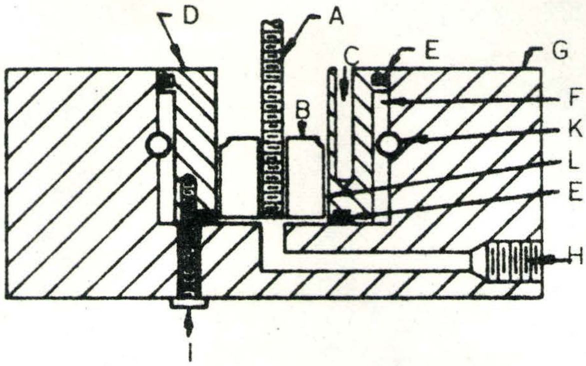
FIGURE 16.

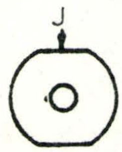
inches. The copper stator is surrounded by a coolant jacket through which coolant is circulated, as required, to maintain the desired temperature. The coolant inlet and outlet are located in the back of the nylon block. Another channel leads from the side of the block to the sample chamber beneath the rotor. The channel is tapped at the mouth to permit the attachment of a steel tube which is used as the filling tube for the test sample. The rotor is mounted on a stainless steel shaft with a short flexible section which allows for the self-centering feature of the rotor.

The electric motor is a series-wound AC-DC unit. A toothed drive belt is used to drive the rotor and tachometer generator. A speed reduction of 4.4:1 is used between the motor and rotor to maintain satisfactory motor speed under relatively high torque loads. The unique toothed belt may be seen in Figure 15, page 49. The tachometer generator is driven at motor speed and is rated at 7v/1000 rpm. By design the input voltage to the motor should be that required to turn the rotor at approximately 900 rpm in a fluid of 5.5 poise viscosity[43].

The control console, shown in Figure 18, page 53, contains the voltage supply for the motor, the temperature control unit for the coolant circulator, and the readout for the tachometer generator. On-off switches for the coolant flow, temperature control, and motor are also located on the console.

A rheostat control allows the voltage to the motor to be regulated and a meter on the console monitors the voltage. The recommended range of operation is 110 to 125 volts for most efficient operation. It is necessary to check the voltage and regulate it to the desired





ROTOR, BOTTOM VIEW

A FLEXIBLE SHAFT
B ROTOR
C THERMISTOR WELL
D STATOR
E O-RING
F COOLANT CHANNEL
G NYLON BLOCK
H SAMPLE PORT
I MACHINE SCREW
J ROTOR FLATS
K COOLANT INLET
L CLEARANCE - .0008 IN.

FIGURE 17 - CROSS-SECTION OF SHEARING HEAD (REPRINTED WITH PERMISSION FROM SAE 680067)


TEMPERATURE
COARSE
FINE
VOLTS
COLD-CRANKING SIMULATOR
VALVE
CONTROL

FIGURE 18.

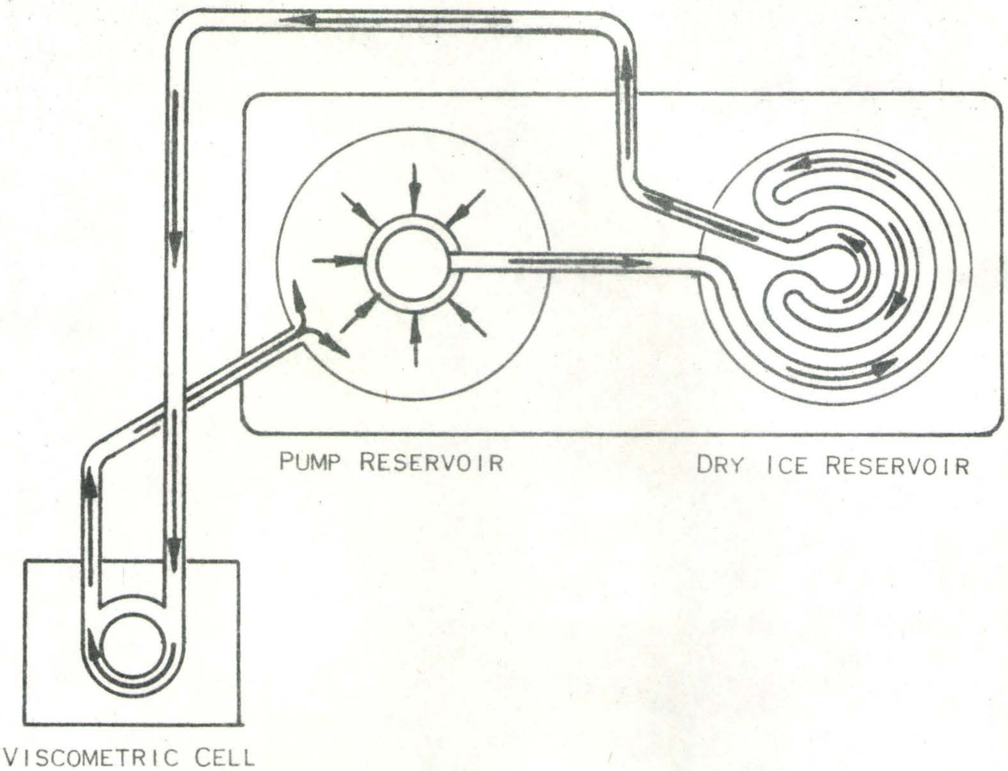


FIGURE 19 - SCHEMATIC DIAGRAM OF COOLANT CIRCUIT

value each time the motor is run since the voltage will vary with load.

The sensor for the temperature control system is a small bead thermistor located in a drilled hole in the stator (see Figure 17, page 52). The thermistor is in an a-c bridge circuit which is amplified to run a DPDT relay which controls the pulsing of coolant around the stator. A resistance is used in series with the thermistor to insure that the total resistance is greater than the "dead zone" of the controller. One pole of the relay is in parallel with the resistor so that at the control temperature the controller opens and closes at intervals of approximately 0.5 seconds. The other pole of the relay controls a solenoid valve in the coolant line and thus pulses the flow of coolant, thereby controlling temperature in the stator.

The coolant circulator consists of an insulated container housing two stainless steel reservoirs. The right hand reservoir houses a stainless steel coil which originates in the left hand reservoir. The left hand reservoir houses a pump whose outlet is connected to the inlet of the coil. The left hand reservoir is charged with methanol while the right hand is charged with methanol and dry ice. Methanol from the left chamber is pumped through the coil in the right chamber, where it is cooled, through a throttle valve and a solenoid valve, through the viscometric cell where it cools the stator, and back into the left hand reservoir. Figure 19, page 54, shows the path of the coolant flow.

The electronic thermometer is a d-c Wheatstone bridge circuit containing a thermistor and amplified by a solid state magnetic amplifier. The thermistor is located in a second drilled hole in the

STATOR. THE SENSITIVITY OF THE THERMOMETER MAY BE ADJUSTED TO APPROXIMATELY 1.5°F FULL SCALE, WITH A LEAST COUNT OF 0.03°F.

AN ADDITIONAL PIECE OF EQUIPMENT USED IN THIS PROGRAM AND PICTURED IN FIGURE 14, PAGE 48, WAS A STOP-CLOCK WHICH WAS A COMPONENT OF THE GMR FORCED BALL VISCOMETER MANUFACTURED BY CANNON INSTRUMENT COMPANY. THIS CLOCK WAS USED BECAUSE OF ITS AVAILABILITY AND CONVENIENCE RELATIVE TO A STOP-WATCH.

V

EXPERIMENTAL TEST PROCEDURES

Before the formal test program could be initiated it was necessary to develop reliable test procedures which could be used throughout the program with reasonable repeatability and accuracy. This chapter explains the test procedures which were used with each test apparatus.

Cold Cranking Engine

As mentioned in the previous chapter the GM of Canada cranking apparatus was developed independently of the CRC recommended apparatus for the specific purpose of evaluating the cold cranking performance of proposed factory fill engine oils in simulated field service conditions. For this reason the test procedure was also developed independently of the CRC recommended procedure.

The final test procedure, as used in this program, is detailed in Appendix B. This procedure is not, however, in its original form. Many changes were made based on experience and the results of a preliminary evaluation program.

Some revisions were made to the oil change procedure from its first form. Originally, only one flush was made when the oil was changed. Although no data was obtained to support the contention that one flush was insufficient the procedure was modified to provide for two flushes when the new test oil to be used was not identical to the previous test oil. This change was made on the advice of several

PEOPLE WHO HAD BEEN CONDUCTING SIMILAR TESTS IN THE CRC PROGRAM. ALTHOUGH THE NEED FOR THE SECOND FLUSH WAS NOT FIRMLY ESTABLISHED IT WAS CONSIDERED TO BE A WORTHWHILE INSURANCE STEP AGAINST CONTAMINATING THE TEST SAMPLE.

FOUR QUARTS OF OIL WERE ORIGINALLY USED IN THE FLUSH CHANGES. SINCE THE ENGINE RUNS SATISFACTORILY WHEN THE OIL LEVEL IS ONE QUART LOW THE PROCEDURE WAS REVISED TO SPECIFY THREE QUARTS ADDED FOR FLUSHINGS. THIS STEP WAS TAKEN AS AN ECONOMY MEASURE TO CONSERVE THE TEST OIL, SOME OF WHICH WAS IN SHORT SUPPLY.

FIFTEEN MINUTES WAS SPECIFIED AS THE RUNNING TIME TO WARM UP THE OIL BEFORE EACH DRAIN. SINCE THE ENGINE BLOCK DID NOT HAVE TIME TO COOL SIGNIFICANTLY BETWEEN DRAINS THE FRESH OIL WARMED UP MUCH MORE QUICKLY AFTER THE FIRST DRAIN. IN VIEW OF THIS FACT AND THE FACT THAT TIME WAS OFTEN AT A PREMIUM IN TEST PREPARATION THE RUNNING TIME WAS REDUCED TO FIVE MINUTES EXCEPT FOR THE INITIAL WARMUP.

IN THE PRELIMINARY PROCEDURE TEN MINUTE DRAIN PERIODS WERE SPECIFIED. IT WAS SOON APPARENT THAT THE AMOUNT OF OIL DRAINED IN THE LAST FIVE MINUTES WAS NEGLIGIBLE IN RELATION TO THE TOTAL QUANTITY. THEREFORE, IN THE INTEREST OF CONSERVING TIME THE DRAIN PERIODS WERE REDUCED TO FIVE MINUTES. IT WAS FELT THAT THE FLUSH CHANGES WOULD SUFFICIENTLY DILUTE ANY PREVIOUS TEST OIL STILL PRESENT SO THAT IT WOULD BE OF NO CONSEQUENCE.

INITIALLY, THE ENGINE WAS NOT CRANKED OR RUN AFTER THE TEST OIL WAS ADDED. IT WAS FELT THAT PART OF THE REPEATABILITY PROBLEM ENCOUNTERED AT THAT TIME COULD BE DUE TO INCONSISTENT AMOUNTS OF OIL IN THE BEARINGS OF THE ENGINE. FOR THIS REASON IT WAS DECIDED TO CRANK

THE ENGINE UNTIL THE OIL PRESSURE STABILIZED, AS INDICATED BY THE ATTACHED PRESSURE GAUGE, THUS INSURING THAT THE BEARINGS CONTAINED OIL. SOME PROBLEMS WERE ENCOUNTERED IN THAT, WITH CERTAIN OILS IT WAS NECESSARY TO CRANK FOR UP TO 30 SECONDS BECAUSE THE PRESSURE WOULD CONTINUE TO RISE RATHER THAN STABILIZING. UNDER THESE CIRCUMSTANCES THE CRANKING MOTOR HAD A TENDENCY TO OVERHEAT. IN A DOUBLE EFFORT TO PREVENT THE CRANKING MOTOR FROM BEING DAMAGED IN THIS MANNER THE CRANKING TIME WAS LIMITED TO 15 SECONDS, MAXIMUM, AND THE SPARK PLUGS WERE REMOVED DURING CRANKING TO REDUCE THE COMPRESSION FORCES IN THE CYLINDERS AND, THEREBY, THE LOAD ON THE CRANKING MOTOR. NO FURTHER OVERHEATING PROBLEMS WERE ENCOUNTERED.

DISCREPANCIES IN THE RESULTS OBTAINED WHEN THE ENGINE WAS CRANKED SEVERAL HOURS BEFORE BEING PLACED IN THE COLD ROOM PROMPTED THE STIPULATION THAT CRANKING MUST OCCUR WITHIN 30 MINUTES OF THE START OF THE COLD SOAK.

THERE WERE SIGNIFICANT CHANGES IN THE PROCEDURE WITH REGARD TO BATTERIES, PRIMARILY BROUGHT ABOUT BY CHANGES IN THE BATTERIES USED AS A POWER SUPPLY. THE ONLY DIFFERENCE BETWEEN THE INITIAL AND FINAL BATTERY PREPARATION PROCEDURE REFLECTS THE USE OF MULTIPLE SIX VOLT BATTERIES IN PARALLEL IN THE FINAL FORM AS OPPOSED TO ONE LARGE 12 VOLT BATTERY INITIALLY. AN INTERIM CHANGE HOWEVER REFLECTED THE NEED TO REDUCE THE VOLTAGE OF THE 12 VOLT BATTERY TO SIMULATE FIELD CONDITIONS AND SPECIFIED THE USE OF A VARIABLE CARBON-PILE RESISTOR FOR THIS PURPOSE. THE REPEATABILITY WITH THIS COMBINATION WAS TOTALLY UNACCEPTABLE. THE SIX VOLT BATTERY BANK WAS FOUND TO SUPPLY BOTH THE DESIRED VOLTAGE AND THE REQUIRED CAPACITY FOR CONSISTENT AND MEANINGFUL

RESULTS.

THE TEST METHOD PROPER RECEIVED RELATIVELY SLIGHT MODIFICATION FROM INITIAL TO FINAL FORM. FOR CONVENIENCE AND CONSISTENCY PROVISIONS WERE MADE TO LOCATE THE BATTERIES OUTSIDE THE COLD ROOM WHEN THE CHANGE TO 6 VOLTS WAS MADE. THE PROCEDURE WAS REVISED TO REFLECT THIS CHANGE. AT THE SAME TIME A REMOTE STARTER SWITCH WAS ADDED, ELIMINATING THE NEED FOR A SECOND OPERATOR TO CONNECT THE BATTERIES AND CRANK THE ENGINE FROM INSIDE THE COLD ROOM. THE TEST PROCEDURE WAS THUS SIMPLIFIED.

NO FURTHER CHANGES WERE FOUND TO BE NECESSARY AND THE TEST PROGRAM PROPER WAS CONDUCTED ACCORDING TO THE PROCEDURE DETAILED IN APPENDIX B.

IT IS OF INTEREST TO NOTE THE SIMILARITY BETWEEN THIS PROCEDURE AND THAT SPECIFIED BY THE CRC AS FOUND IN APPENDIX A. QUITE NATURALLY THIS PROCEDURE IS MUCH LESS GENERAL SINCE IT IS MEANT FOR A SPECIFIC APPLICATION. IN EVERY SENSE, HOWEVER, THIS PROCEDURE COMPLIES WITH THE MORE GENERAL GUIDE LINES LAID DOWN BY THE CRC. THE RESULTS OF TESTS CONDUCTED ACCORDING TO THIS GM OF CANADA PROCEDURE MAY THEN BE CONSIDERED LEGITIMATE CRC-L-49-663 TEST RESULTS. IT WAS THEREFORE POSSIBLE TO CALIBRATE THE ENGINE AND THUS ESTABLISH THE ENGINE VISCOSITY OF ANY GIVEN OIL AS WELL AS ITS CRANKING PERFORMANCE IN SIMULATED FIELD CONDITIONS.

COLD CRANKING SIMULATOR

A ROUND ROBIN SERIES OF TESTS WERE CONDUCTED WITH THE COLD CRANKING SIMULATOR, AT 0°F, BY THE ASTM. ONE OF THE RESULTS OF THIS ROUND ROBIN WAS THE ESTABLISHMENT OF AN ACCEPTABLE TEST PROCEDURE. THIS PROCEDURE, FOUND IN APPENDIX C, WAS SUPPLIED WITH THE OPERATING

MANUAL FOR THE APPARATUS. SINCE NO SPECIFIC PROCEDURE FOR TESTING AT TEMPERATURES LOWER THAN 0°F HAD BEEN SPECIFIED IT WAS NECESSARY TO DEVELOP A PROCEDURE FOR -20°F.

BEFORE ATTEMPTING TO RUN TESTS AT -20°F A PRELIMINARY PROGRAM WAS RUN AT 0°F TO BECOME FAMILIAR WITH THE EQUIPMENT. DURING THIS PRELIMINARY PROGRAM A NUMBER OF CHANGES WERE MADE TO THE RECOMMENDED PROCEDURE FOR 0°F AND A NUMBER OF CHANGES WERE DETERMINED TO BE NECESSARY FOR LOWER TEMPERATURES.

THE COOLANT SYSTEM WAS CHARGED AND THE CONTROL SYSTEM SET ACCORDING TO THE PROCEDURE SUPPLIED WITH THE EQUIPMENT. THE CONTROLS WERE FOUND TO FUNCTION SATISFACTORILY WITH THESE SETTINGS. THE ELECTRONIC THERMOMETER SETTING SPECIFIED FOR 0°F WAS FOUND TO BE APPROXIMATELY 2° IN ERROR HOWEVER. THE UNIT WAS CALIBRATED USING A CANNON CONSTANT TEMPERATURE BATH MONITORED BY AN ACCURATE ASTM -62°F THERMOMETER AND A NEW SETTING WAS DETERMINED FOR 0°F. A CONSIDERABLE AMOUNT OF TIME WAS ALSO SPENT IN DETERMINING A SUITABLE ADJUSTMENT FOR THE "PROPORTIONAL BAND" CONTROL WHICH GOVERNS THE SIZE OF THE TEMPERATURE CONTROL RANGE. EARLY ATTEMPTS WERE LIMITED TO A DEVIATION OF ±0.5°F FROM THE NOMINAL CONTROL TEMPERATURE. WITH EXPERIENCE, HOWEVER, THIS DEVIATION WAS REDUCED TO ±0.1°F MAXIMUM.

INITIAL TESTS SHOWED A COMPLETE INABILITY TO REPEAT RESULTS CONSISTENTLY WITH LESS THAN 10% DEVIATION. A THOROUGH STEP BY STEP CHECK OF THE POSSIBLE VARIABLES WHICH COULD CAUSE DEVIANT RESULTS WAS MADE AND THE PROBLEM APPEARED TO BE CENTERED IN THE CLEANING PROCEDURE. SEVERAL DAYS WERE SPENT EXPERIMENTING WITH VARIOUS CLEANING TECHNIQUES.

THE RECOMMENDED CLEANING SEQUENCE IS HOT WATER, NAPHTHA, AND

FIGURE 20.

ACETONE. ALL CLEANSERS ARE APPLIED FROM THE TOP OF THE SAMPLE CHAMBER WITH A VACUUM LINE ATTACHED TO THE SAMPLE INJECTION PORT, AS SHOWN IN FIGURE 20, PAGE 62, TO INSURE REMOVAL OF THE CLEANSING FLUIDS. USING THE RECOMMENDED FLUIDS AND PROCEDURE DEPOSITS WERE FOUND TO BE LEFT ON THE ROTOR AND STATOR AFTER THE COMPLETION OF THE CLEANING CYCLE. SEVERAL FACTORS WHICH COULD HAVE CAUSED THE FORMATION OF DEPOSITS WERE CONSIDERED AND CORRECTIVE MEASURES WERE TAKEN.

THE TEMPERATURE OF THE HOT WATER USED FOR RINSING WAS INCREASED FROM APPROXIMATELY 150°F TO APPROXIMATELY 200°F, AND THE AMOUNT OF WATER USED WAS INCREASED FROM 400 TO 600 MILLILITERS. THESE CHANGES WERE TO INSURE THAT THE TEMPERATURE OF THE ROTOR AND STATOR WERE RAISED SUFFICIENTLY HIGH TO PREVENT CONDENSATION OF THE CLEANSING FLUIDS IN THE SAMPLE CHAMBER.

IN ORDER TO INSURE THE COMPLETE AND RAPID REMOVAL OF THE CLEANSERS FROM THE SAMPLE CHAMBER THE VACUUM ON THE SAMPLE PORT WAS ALSO INCREASED.

A CHEMIST WAS CONSULTED WITH REGARD TO THE SUITABILITY OF CLEANING SOLVENTS USED. FOLLOWING THE HOT WATER RINSE IT WAS SUGGESTED THAT A METHANOL RINSE SHOULD BE INCLUDED TO ABSORB THE WATER WHICH MAY ENCAPSULATE OIL DROPLETS REMAINING IN THE CHAMBER. THEN AN OIL SOLVENT COULD EFFECTIVELY DISSOLVE AND CARRY AWAY THE OIL. IT WAS FOUND THAT THE NAPHTHA BEING USED WAS OF LOW PURITY AND COULD THEREFORE CONTRIBUTE TO DEPOSIT FORMATION. REAGENT GRADE CHLOROFORM WAS SUGGESTED AS A MORE SUITABLE SOLVENT. A FINAL RINSE WITH REAGENT GRADE ETHER WOULD THEN REMOVE ANY WATER WHICH MAY REMAIN, LEAVING CLEAN DRY SURFACES.

THIS CLEANSING SEQUENCE WAS FOUND TO WORK SATISFACTORILY AND was used throughout the entire test program. It is possible that other solvents could be used with similar results and unless excellent ventilation is available substitutes would be advisable. Where there is sufficient ventilation to safely use these solvents, however, they have proved to be completely satisfactory.

No other changes from the recommended procedure were found to be necessary at 0°F. The entire test program at 0°F was then conducted according to the procedure outlined here.

Following the successful completion of the 0°F testing program preliminary tests at -20°F were begun. The temperature control was calibrated using a Cannon constant temperature bath as reference. Considerable difference was noted in the time required to bring the sample to -20°F from that required to bring it to 0°F. Whereas 0°F could be reached in 30 to 45 seconds, -20°F was often not attained after three minutes.

In order to shorten this time to stabilization a number of steps were taken. The coolant reservoir was moved directly behind the viscometric unit, as seen in Figure 21, page 65. By moving the reservoir it was possible to shorten the inlet and outlet hoses to the viscometer from approximately 30 inches to 18 and 12 inches respectively, thus reducing the area available for heat transfer to the atmosphere. To further deter heat transfer the thinwall neoprene hose supplied with the viscometer was replaced by 3/16 inch inside diameter Tygon tubing having a wall thickness of 1/8 inch. This thick-wall Tygon tubing has excellent insulation properties and as a result of the above modifications, which may be seen in Figure 21, the time

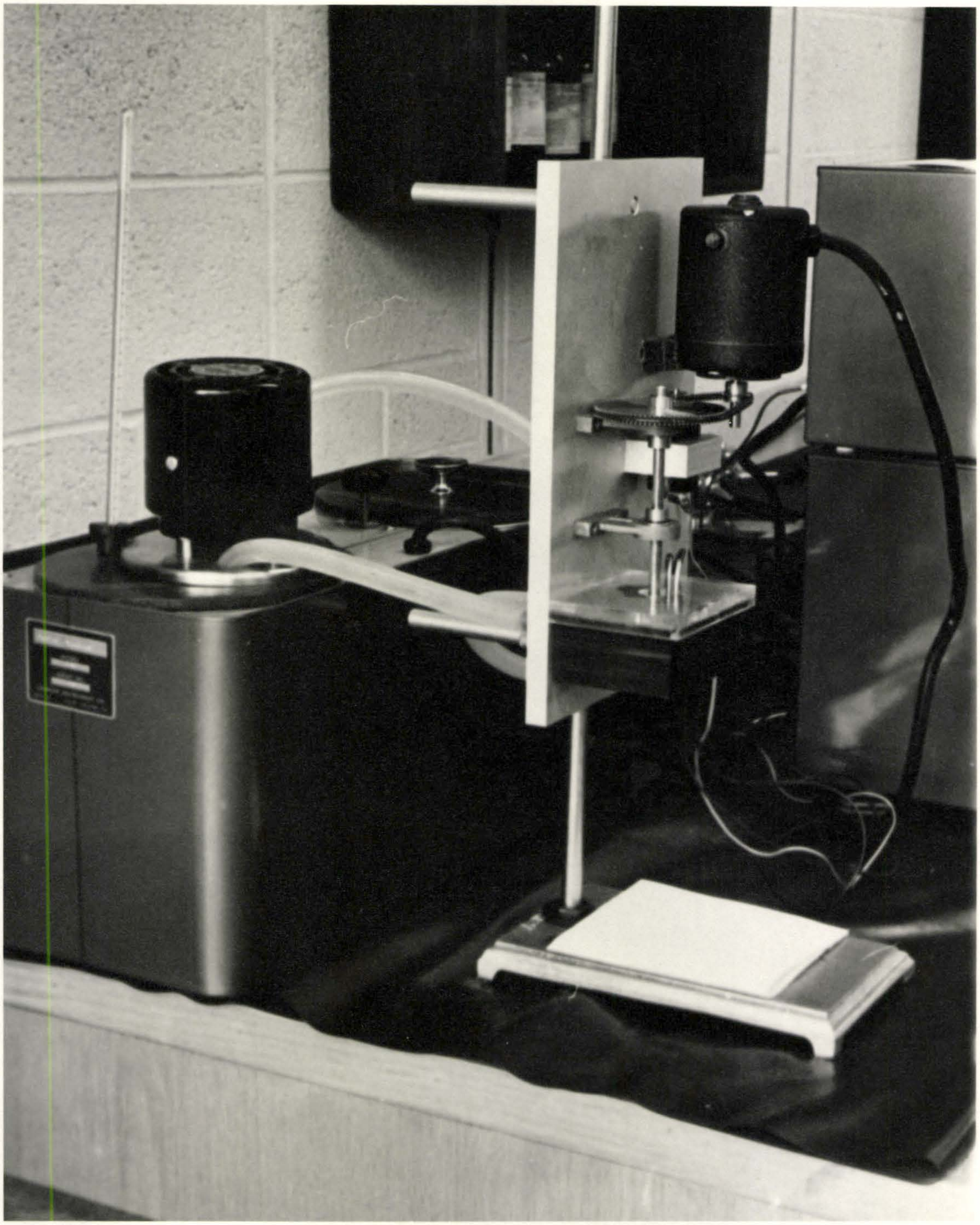


FIGURE 21.

REQUIRED TO REACH STABILIZED TEMPERATURE IN THE SAMPLE WAS REDUCED TO APPROXIMATELY ONE AND A HALF MINUTES.

A PROBLEM STILL EXISTED, HOWEVER, WHEN THE MOTOR WAS TURNED ON. THE SAMPLE WOULD HEAT UP ABOVE THE CONTROL TEMPERATURE AND THEN WOULD NOT RETURN TO THE DESIRED TEST TEMPERATURE. THIS SITUATION WAS PARTICULARLY CRITICAL WITH LOW VISCOSITY OILS, SUCH AS THE CALIBRATION OIL, N17L. FLOW THROUGH THE SYSTEM WAS CHECKED AND FOUND TO BE SATISFACTORY. IT APPEARED, THEN, THAT THE PROBLEM WAS AN INSUFFICIENT TEMPERATURE DIFFERENTIAL BETWEEN THE COOLANT AND THE SAMPLE, TO PROVIDE THE NECESSARY HEAT TRANSFER TO THE SAMPLE. A CHECK OF THE TEMPERATURE OF THE COOLANT RETURNING TO THE RESERVOIR REVEALED THIS TO BE THE CASE. THE TEMPERATURE VARIED FROM -22 TO -15 AT VARIOUS TIMES. DRY ICE WAS ADDED TO THE PUMP SIDE OF THE RESERVOIR A BIT AT A TIME TO DETERMINE THE EFFECT OF DECREASING TEMPERATURE. IT WAS FOUND THAT IF A TEMPERATURE OF -25°F, OR LOWER COULD BE MAINTAINED AT THE OUTLET OF THE VISCOMETER THERE WAS NO PROBLEM IN CONTROLLING THE SAMPLE TEMPERATURE AT -20°F.

THE DESIGN OF THE COOLING SYSTEM IS SUCH THAT THERE CAN BE NO CIRCULATION OF COOLANT WHILE THE VISCOMETRIC CELL IS BEING CLEANED. SINCE THIS OPERATION TAKES ABOUT TWICE AS LONG AS THE ACTUAL TEST DOES, THE COOLANT CIRCULATES ONLY ABOUT 1/3 OF THE TIME. THE COOLANT IN THE PUMP RESERVOIR, THEN, MAY BECOME SUFFICIENTLY WARMED DURING THIS TIME SO THAT IT CANNOT BE COOLED BELOW THE CONTROL TEMPERATURE DURING THE BRIEF TIME IT PASSES THROUGH THE COIL IN THE DRY ICE RESERVOIR. TO OVERCOME THIS SITUATION IT WOULD BE DESIRABLE TO RECIRCULATE THE COOLANT THROUGH THE DRY ICE RESERVOIR AND BACK INTO THE PUMP RESERVOIR WHILE THE VISCOMETRIC CELL IS BEING CLEANED. A TWO WAY VALVE WAS INSERTED

INTO THE OUTLET HOSE FROM THE RESERVOIR AND A SECOND RETURN LINE WAS ADDED FROM IT TO THE PUMP RESERVOIR. A SCHEMATIC OF THIS SYSTEM IS FOUND IN FIGURE 22, PAGE 68, AND A PHOTOGRAPH IN FIGURE 23, PAGE 69. AS MAY BE SEEN IN THE PHOTOGRAPH IT WAS NECESSARY TO INSULATE THE VALVE TO PREVENT EXCESSIVE HEAT TRANSFER RESULTING IN AN EXTERNAL FROST BUILDUP CAUSING THE VALVE TO BECOME INOPERATIVE.

USE OF THE VALVE TO RECIRCULATE COOLANT CONTINUOUSLY, BY BY-PASSING THE VISCOMETRIC CELL WHEN IT WAS BEING CLEANED, WAS SUCCESSFUL IN MAINTAINING A LOW TEMPERATURE IN THE PUMP RESERVOIR. THIS TEMPERATURE WAS NOT CONTROLLED, HOWEVER, AND WAS THUS INCONSISTENT, RESULTING IN INCONSISTENT TEMPERATURE CONTROL OF THE SAMPLE. THE SOLUTION, THEN, WAS NOT A SATISFACTORY ONE.

THE COOLANT IN BOTH RESERVOIRS HAD BEEN CHANGED ONCE DURING THE 0°F TEST PROGRAM BUT HAD NOT BEEN CHANGED AT THE BEGINNING OF THE -20°F PROGRAM. A CHEMIST WAS AGAIN CONSULTED TO DETERMINE WHETHER OR NOT THE HEAT TRANSFER CHARACTERISTICS OF THE METHYL ALCOHOL COOLANT COULD CHANGE AS THE FLUID AGED. IT WAS LEARNED THAT PROLONGED EXPOSURE TO AIR RESULTED IN A HIGH PERCENTAGE OF WATER BEING ABSORBED BY THE ALCOHOL, FROM THE ATMOSPHERE. THIS DILUTION RESULTED IN A SEVERE DROP IN THE ALCOHOL'S ABILITY AS A REFRIGERANT. THE COOLANT WAS DRAINED FROM THE RESERVOIRS AND THE SYSTEM FLUSHED AND CHARGED WITH FRESH METHYL ALCOHOL. NO FURTHER PROBLEM WAS EXPERIENCED WITH TEMPERATURE CONTROL AND IT WAS POSSIBLE TO REMOVE THE VALVE AND BYPASS LINES FROM THE SYSTEM.

FOLLOWING THIS EXPERIENCE, THE COOLANT WAS CHANGED WEEKLY, DURING CONTINUOUS OPERATION, AND BEFORE EVERY SERIES OF TESTS WHEN OPERATION BECAME INFREQUENT.

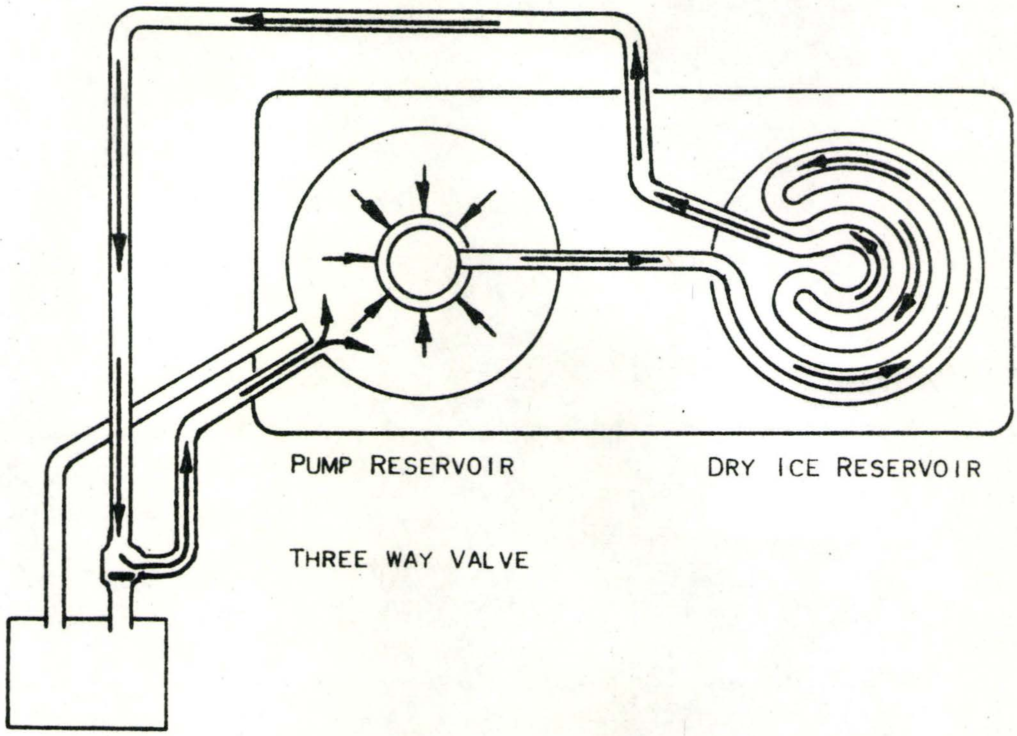


FIGURE 22 - SCHEMATIC DIAGRAM OF MODIFIED COOLANT CIRCUIT

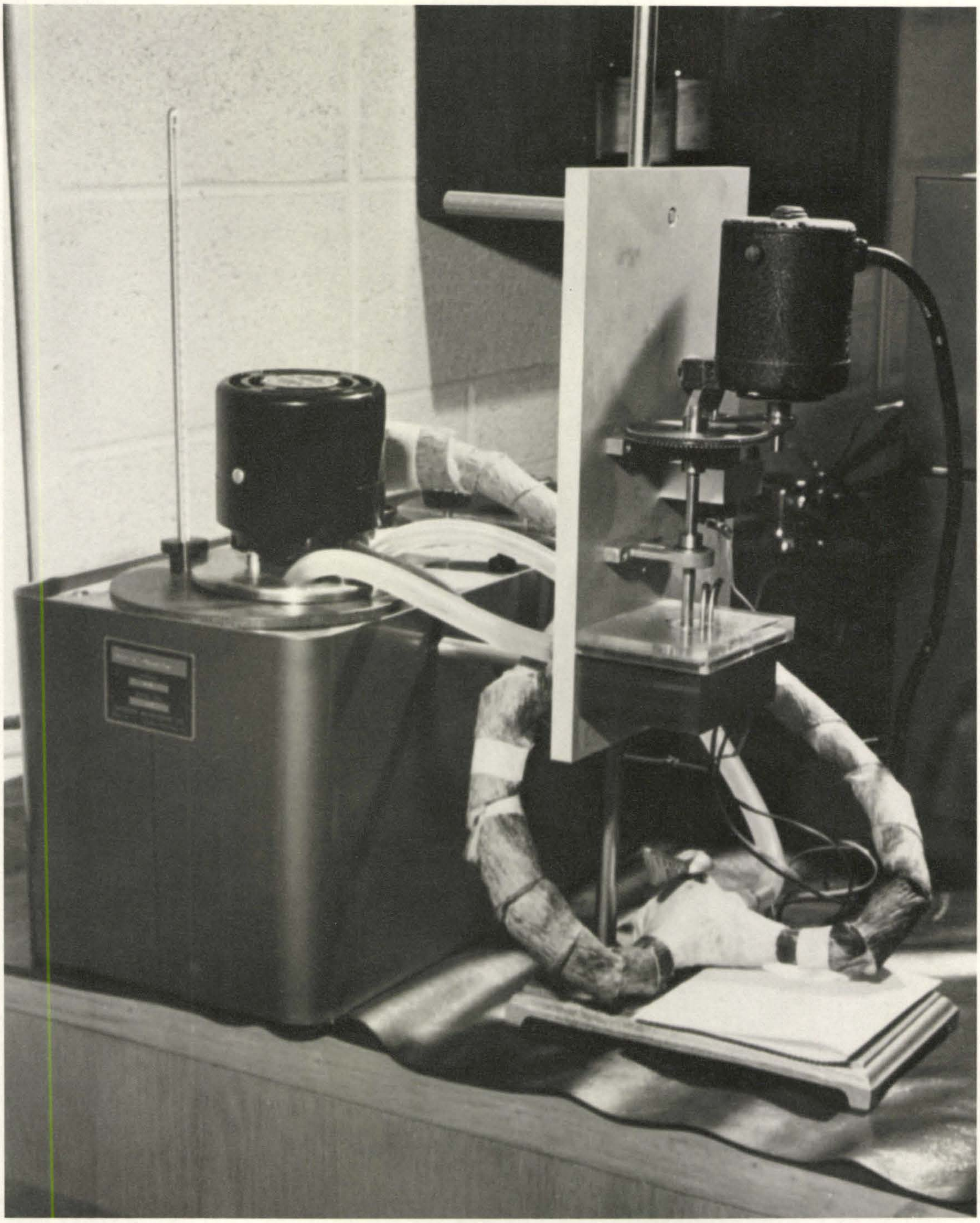


FIGURE 23.

Having solved the temperature control problem initial testing was begun. It was noticed that there was a significant frost build-up on the surface of the copper stator which had not been present at the higher operating temperature. Care was taken to fill the cup within approximately 1/32 of an inch of the top to prevent frost from forming on the inner wall and affecting the results. Frost formation on the top of the stator was such, however, that particles of frost often became very large and fell into the sample during the test. There was no evidence to indicate that these particles affected the results. It was decided, however, that a means should be devised to prevent them from doing so.

Figure 24, page 71, shows a frost shield which was developed to prevent frost buildup on the stator. The shield is constructed of 1/4 inch thick plexiglass and is covered with a 1/8 inch thick foam rubber pad where it contacts the surface of the viscometric cell. The unit was found to be completely satisfactory for preventing frost build-up and was used throughout the -20°F test program. A drawing of the frost shield may be seen in Figure 25, page 72. As will be described in a later chapter a further use for the shield was found during the program.

At this time some consideration was given to the effect of atmospheric conditions on the open, top surface of the sample. In particular, a question was raised as to whether significant heat transfer occurred there and whether or not this affected the results. A second frost shield was constructed, differing from the first in that this one enclosed the top of the sample cap. The cover may be seen in

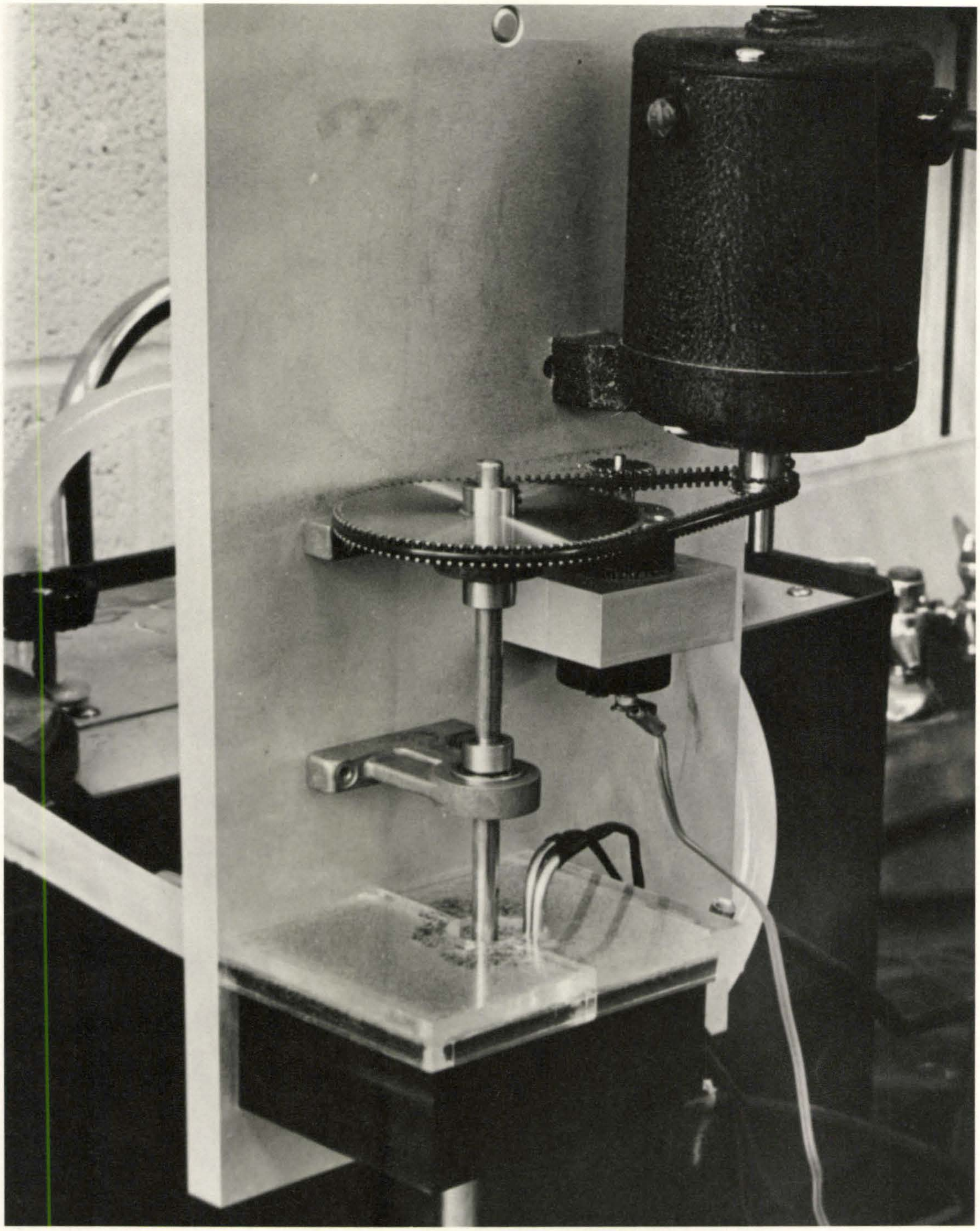


FIGURE 24.

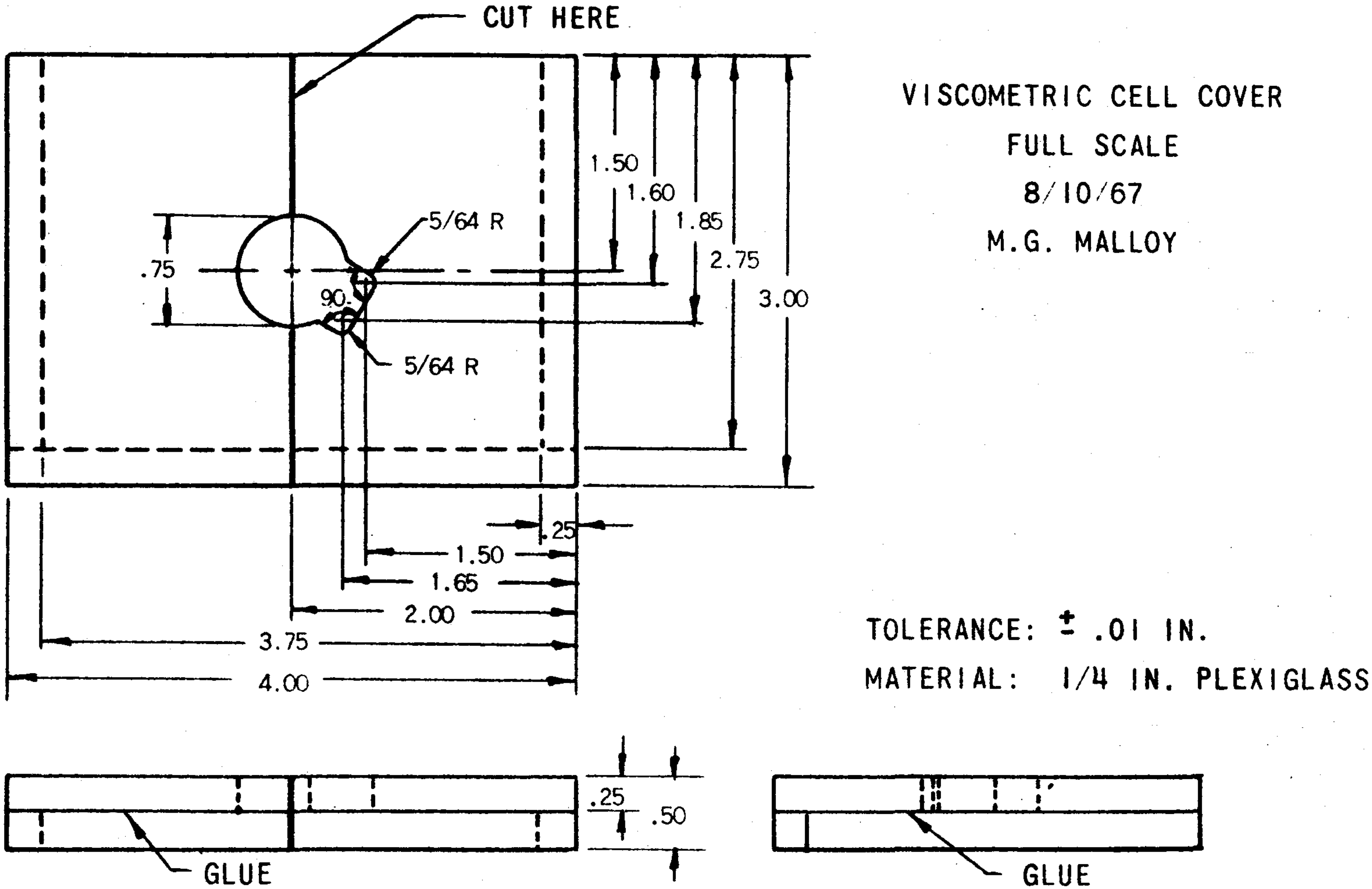


FIGURE 25 - FROST SHIELD DRAWING

Figure 26, page 74. A number of evaluation tests were run with and without the shield and no difference in results could be noted. Since the purpose of the project was primarily concerned with developing a good correlation with an engine rather than with theoretical justification of the instrument, no further work was conducted along this line. As will be shown later, further work illustrated the desirability of maintaining an open surface at the top of the cup.

No further complications arose and the -20°F test program was conducted using the procedure previously described (as found in Appendix C) for operation at 0°F with the modifications noted here. After a number of tests indicated that there was little value in continuing with a 120 second reading it was eliminated in order to speed up the procedure. A procedure for testing at both 0°F and -20°F has since been published by the ASTM as procedure D-2602 and may be seen in Appendix D. It may be noted that the procedures used in this program comply with the requirements of D-2602 although it was not published at the time of test.

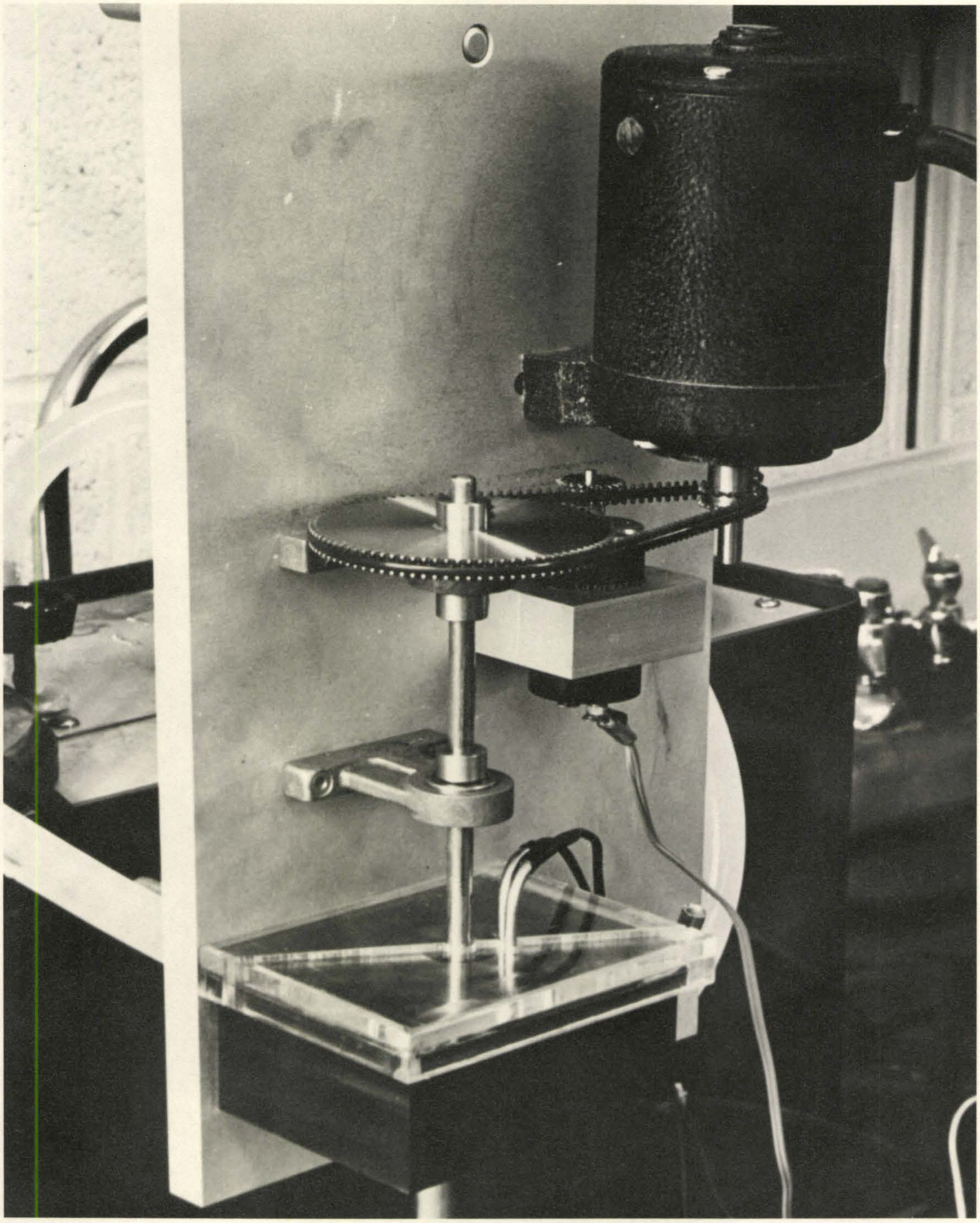


FIGURE 26.

VI

ANALYSIS OF EXPERIMENTAL RESULTS

The results of tests conducted with both the cold cranking engine and the cold cranking simulator were organized and analyzed statistically. An attempt was made to evaluate the repeatability and accuracy of both test procedures and to establish correlations with each other and with other instruments.

Cold Cranking Engine

The results of cranking tests made in the GM of Canada cold cranking engine were reduced to analyzable data, analyzed for repeatability, and correlated with results of a cold cranking round robin conducted by the CRC. A correlation was also made with the results of engine tests conducted by Shell Canada Research Laboratories.

Data Reduction - The static data obtained for each test were recorded on a Test Data sheet, as shown in Figure 27, page 76. The primary purpose for recording this data was to insure repeatability of test conditions. Any change in circumstances from day to day, which could affect the results, could be discovered in the daily records. The dynamic data, which were recorded on a recording oscillograph, were the significant data for analysis. Figure 28, page 77, shows a segment of an oscillograph trace, plotting cranking current and voltage against a time scale. Each peak on the current scale represents the peak of a compression stroke in the engine. Corresponding to the current peak is a valley on the voltage scale, since voltage and current are 180°

COLD CRANKING TEST DATA SHEET

DATE ______________________ TEST NO. ______________________

ENGINE TYPE ______________________

SERIAL NO. ______________________ CONDUCTED BY ______________________

WIRING HARNESS

ENGINE ______________________ CRANKING MOTOR ______________________

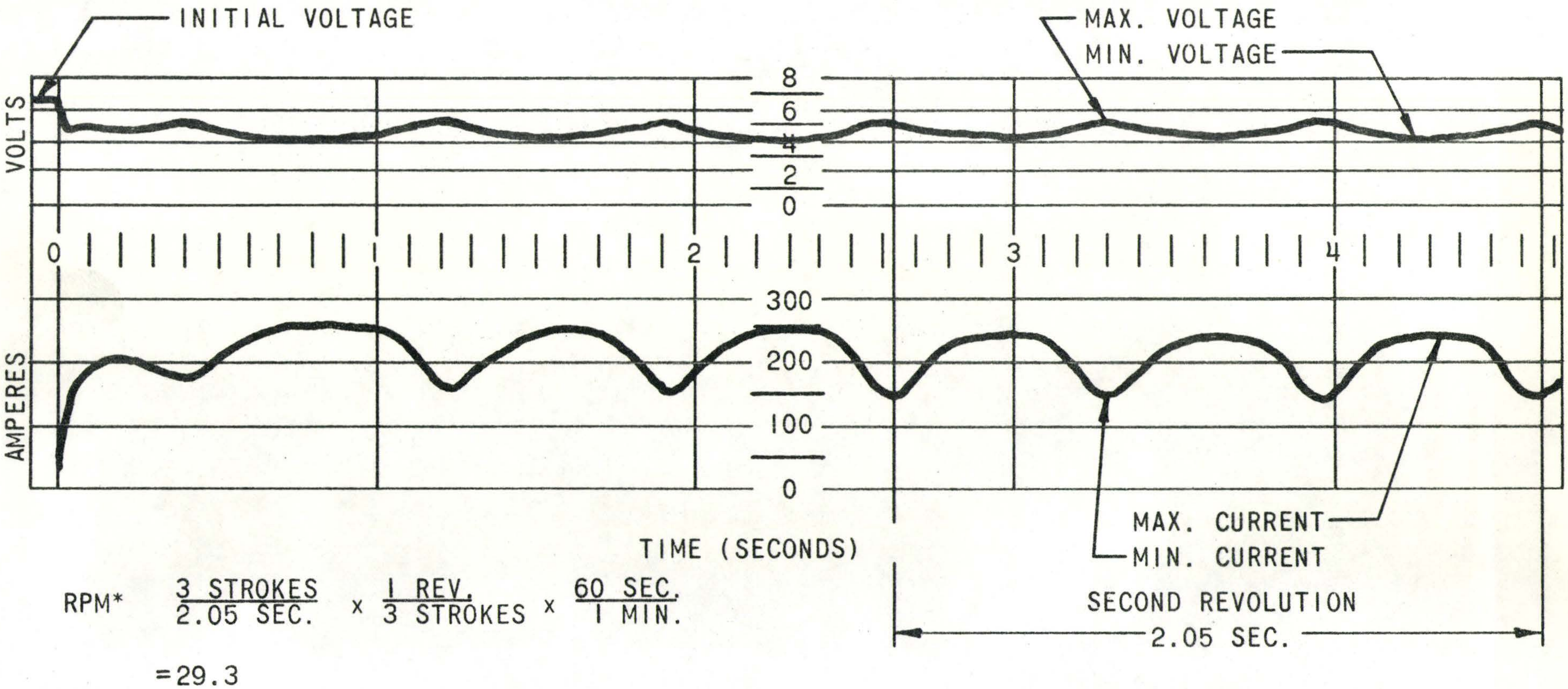
STAND ______________________

SWITCH ______________________ BATTERY CABLES ______________________

TEST OIL ______________________

	FIRST CRANK		SECOND CRANK		THIRD CRANK	
	BEFORE	AFTER	BEFORE	AFTER	BEFORE	AFTER
Cold Soak Time (Hrs.)						
Ambient Temp. (°F.)						
Oil Temp. (°F.) Sump						
Oil Temp. (°F.) Brg.						
Top Rad. Temp. (°F.)						
Bat. Spe. Grav.						
Initial Voltage (V)						
Cranking Time (Sec.)						
Cranking Speed (RPM)						
Viscosity at 100°F.						
Cranking Voltage (V)						
Cranking Current (A)						

FIGURE 27 - TEST DATA SHEET



* - FOR SECOND REVOLUTION ONLY

FIGURE 28 - TYPICAL OSCILLOGRAPH TRACE

OUT OF PHASE. THE DISTANCE BETWEEN PEAKS REPRESENTS THE TIME BETWEEN CONSECUTIVE STROKES, 120° OF CRANKSHAFT ROTATION IN THE CASE OF THE SIX-CYLINDER ENGINE USED. CRANKING SPEED FOR THE ENGINE WAS CALCULATED BY DETERMINING THE TIME REQUIRED FOR SIX STROKES AND CALCULATED AS FOLLOWS:

$$\frac{6 \text{ STROKES}}{(X) \text{ SECONDS}} \times \frac{2 \text{ REVOLUTIONS}}{6 \text{ STROKES}} \times \frac{60 \text{ SECONDS}}{1 \text{ MINUTE}} = \frac{(120)}{X} \text{ RPM}$$

FOR CONSISTENCY OF RESULTS THE CRANKING SPEED WAS CALCULATED FOR THE SECOND AND THIRD COMPLETE REVOLUTIONS, THAT IS, BEGINNING WITH THE SEVENTH STROKE. IN THIS WAY THE INCONSISTENCIES OF BREAKAWAY WERE AVOIDED.

THE MAXIMUM AND MINIMUM VALUES RECORDED FOR CURRENT AND VOLTAGE ARE SIMPLY THE VALUES INDICATED BY THE HIGHEST PEAK AND THE LOWEST VALLEY, RESPECTIVELY, OVER THE PERIOD OF CRANKING SPEED CALCULATION; THAT IS, THE SECOND AND THIRD FULL REVOLUTIONS.

REPEATABILITY - THE CRANKING SPEEDS, RESULTING FROM EACH TEST, WERE ANALYZED STATISTICALLY TO DETERMINE THE REPEATABILITY OF THE TEST METHOD.

ACCORDING TO THE STATISTICAL THEORY OF SMALL SAMPLE SIZE[(44)(45)] A "STUDENT'S t" DISTRIBUTION OF SAMPLE POPULATION WAS ASSUMED. A SAMPLE CALCULATION IS SHOWN IN APPENDIX E, AND THE COMPUTER PROGRAM WRITTEN TO FACILITATE THE NUMEROUS CALCULATIONS IS ALSO SHOWN IN THIS APPENDIX.

FOR EACH OIL THREE TESTS WERE RUN. EACH TEST CONSISTED OF THREE CRANKS AT ONE HOUR INTERVALS. THEREFORE, THERE WERE NINE ACTUAL CRANKS CONDUCTED ON EACH OIL AND THE CRANKING SPEEDS OBTAINED IN THESE NINE CASES WERE THE DATA ANALYZED FOR REPEATABILITY.

THE CRANKING SPEEDS OBTAINED FOR EACH OIL, IN EACH TEST, ARE found in Table II, page 80. The results of the statistical analysis, showing mean cranking speed and standard deviation and 95% confidence limits, for each oil, are summarized in Table III, page 82. As may be seen, the average standard deviation for 45 tests (135 sets of data) was 1.28 rpm. The relative significance of this value may be more readily understood when standard deviation is expressed as a percentage of the mean, as shown in column three of Table III. The average standard deviation for the cold cranking tests was 4.53% of the mean cranking speed. That is, if a large number (>30) of tests were repeated on the same oil it is statistically probable that 68.27% (the area represented by $\pm 1\sigma$ under a normal distribution curve) of the results would lie within $\pm 4.53\%$ of the mean cranking speed.

By comparison, the average standard deviation of the results of the CRC L-49 cold cranking tests[46], based on engine viscosity rather than cranking speed, was calculated to be 7.60% of the mean engine viscosity. Although the comparison is not direct, because the CRC tests were run at 0°F, it is an indication that the results of the engine test program were repeatable within reasonable expectations.

Column four of Table III represents the 95% confidence limits of the mean cranking speed. That is, we can be 95% confident that the actual mean of the population lies within $\pm$ the indicated amount of the sample mean. Specifically, in the case of oil Shell A, we can predict, with 95% confidence, that the mean cranking speed which is representative of the entire batch of oil from which the sample was taken, would lie between 30.41 and 32.37 rpm (31.39 ± 0.98).

Column five represents the 95% confidence limits in terms of

TABLE II

RESULTS OF ENGINE CRANKING TESTS

OIL	TEST	RUN 1	RUN 2	RUN 3	MEAN	MAX/MIN
SHELL A	1	32.8	33.6	29.8	32.1	
	2	31.5	31.8	31.8	31.7	1.055
	3	30.0	30.6	30.6	*30.4	
SHELL B	1	32.7	32.5	32.6	32.6	
	2	29.5	30.8	28.6	*29.6	1.100
	3	31.2	30.0	29.5	*30.2	
SHELL C	1	34.5	32.7	32.2	33.1	
	2	30.6	31.8	30.6	*31.0	1.068
	3	31.6	32.0	32.0	*31.9	
SHELL D	1	30.0	31.0	31.0	30.7	
	2	30.8	30.6	30.4	30.6	1.160
	3	27.4	26.0	26.0	*26.5	
SHELL E	1	29.5	31.2	31.0	30.6	
	2	29.2	30.8	30.8	30.3	1.080
	3	29.0	28.0	28.0	*28.3	
SHELL F	1	30.0	32.0	32.0	31.3	
	2	26.6	25.5	25.2	*25.8	1.235
	3	27.1	28.3	27.3	*27.3	
SHELL G	1	31.2	31.2	31.2	31.2	
	2	30.4	31.5	32.2	31.4	1.060
	3	29.8	29.6	29.5	*29.6	
REO 151	1	27.4	26.9	26.4	26.9	
	2	28.4	26.1	27.2	27.2	1.016
	3				27.1	
REO 153	1	17.5	19.0	18.5	18.3	
	2	19.4	19.6	19.2	19.4	1.069
	3	18.2	18.2	18.0	18.1	

TABLE II (CONT'D)

OIL	TEST	RUN 1	RUN 2	RUN 3	MEAN	MAX/MIN
REO 161	1	27.5	31.0	28.0	28.8	
	2	32.4	32.0	32.0	32.1	1.110
	3	29.5	30.4	30.4	30.1	
REO 162	1	18.0	18.5	19.5	18.7	
	2	19.8	20.0	19.9	19.9	1.111
	3	17.8	18.0	18.0	*17.9	
REO 158	1	29.4	31.5	32.0	31.0	
	2	24.0	26.0	26.4	*25.5	1.224
	3	24.2	25.8	26.0	*25.3	
REO 159	1	22.3	22.3	22.2	22.3	
	2	22.4	22.6	22.0	22.3	1.056
	3	20.6	21.5	21.2	*21.1	
REO 160	1	20.4	20.2	20.0	20.2	
	2	19.0	19.5	19.0	19.2	1.062
	3	18.6	19.2	19.2	*19.0	
REO 172	1	38.4	38.4	35.6	37.5	
	2	37.6	39.5	38.6	38.6	1.038
	3	36.5	37.5	37.5	*37.2	

TABLE III

REPEATABILITY ANALYSIS OF ENGINE CRANKING TESTS

Oil	Mean	Standard Deviation		95% Confidence Limits	
	RPM	RPM	% of Mean	± RPM	± % of Mean
REO 151-65	27.07	.74	2.52	.60	2.06
REO 153-65	18.60	.67	3.65	.55	2.98
REO 161-63	30.75	1.69	5.50	1.38	4.49
REO 162-63	18.84	.90	4.78	.74	3.90
REO 158-63	27.25	2.77	9.80	2.26	8.10
REO 159-63	21.90	.62	2.83	.51	2.31
REO 160-63	19.45	.58	2.98	.47	2.43
REO 172-65	37.73	1.11	2.95	.89	2.41
Shell A	31.39	1.20	3.82	.98	3.12
Shell B	30.82	1.42	3.69	1.16	3.01
Shell C	32.00	1.00	3.13	.82	2.55
Shell D	29.25	2.08	7.12	1.70	5.80
Shell E	29.72	1.20	4.04	.98	3.30
Shell F	28.22	2.48	8.78	2.03	7.15
Shell G	30.51	.74	2.42	.60	1.97
Mean	27.57	1.28	4.53	1.06	3.70

PERCENT OF MEAN CRANKING SPEED. THE AVERAGE OF THE CONFIDENCE LIMITS IS CALCULATED TO BE ±3.70%. THAT IS, WITH 95% PROBABILITY, THE MEAN OF THE ENTIRE POPULATION CAN BE CONSIDERED, ON THE AVERAGE, TO BE WITHIN ±3.70% OF THE MEAN OF THE SAMPLES (PROVIDED THREE SAMPLES ARE TESTED AS IN THE CASE OF THIS PROGRAM). THIS FIGURE MAY BE EXPRESSED IN TERMS OF A REPEATABILITY RATIO. AT THE 95% CONFIDENCE LEVEL TWO RESULTS COULD HAVE THE VALUES 96.3% AND 103.7% OF THE MEAN WITHOUT BEING SUSPECT. THE RATIO OF THESE TWO NUMBERS IS $\frac{103.70}{96.30} = 1.075$.

THEREFORE IN ANY SERIES OF TEST RESULTS, AT THE 95% CONFIDENCE LEVEL, THE RESULTS SHOULD NOT BE SUSPECT UNLESS THE RATIO OF THE GREATEST TO THE SMALLEST EXCEEDS 1.075.

REVIEWING THE DATA OF TABLE II REVEALS, IN COLUMN SIX, THAT THE TEST RESULTS FOR THE FOLLOWING OILS EXCEEDED THE REPEATABILITY RATIO CALCULATED ABOVE:

SHELL B
SHELL D
SHELL E
SHELL F
REO 158
REO 161
REO 162

IT WAS NOTED THAT IN EACH OF THESE CASES, WITH THE EXCEPTION OF REO 161, THERE WAS A TREND TOWARD DECREASING CRANKING SPEED WITH SUCCESSIVE TESTS. FURTHER INVESTIGATION REVEALED THAT THIS TREND BEGAN APPROXIMATELY MIDWAY THROUGH THE TESTING PROGRAM. ALL DATA OBTAINED AFTER THIS TIME ARE NOTED (*) IN TABLE II. PLANS WERE MADE TO REPEAT THESE TESTS AFTER SOME MODIFICATION TO THE TEST APPARATUS. IT WAS NOT POSSIBLE, HOWEVER, TO CARRY OUT THIS PROGRAM. THE SIGNIFICANCE

OF THIS SITUATION WILL BE DISCUSSED IN THE FOLLOWING CHAPTER.

Based on the data analyzed the repeatability of the cold cranking engine test can be expressed by the ratio 1.075 with 95% confidence.

Correlation - The results of a number of tests on REO oils were correlated with tests conducted on similar oils by participants in the CRC round robin. Only three common test oils were used, REO 158-63, REO 159-63, and REO 172-65.

In order to correlate results from the two series of tests it was necessary to use a common parameter. The cranking speed data from the G.M. of Canada cold cranking tests, therefore, were converted to viscosity values. The engine viscosities of the test oils were determined from the calibration curve shown in Figure 29, page 85. The engine viscosities of the test oils, at -20°F, were determined to be:

REO 158-63	8100 cp
REO 159-63	13500 cp
REO 172-65	2050 cp

These viscosities were correlated against the CRC average engine viscosities(47) according to the method outlined in Appendix F. Figure 30, page 86, shows the points in relation to the line of perfect correlation. Obviously, the greatest deviation is with oil REO 158.

A linear regression analysis was made to fit the points to a straight line, using the method of least square. Two straight line equations were used, for comparison. The results are indicated in Table IV, page 87. For the $Y = a_1 X$ the value of a_1 is 0.996 and the standard error of estimate is 1970 centipoise. When the line $Y = a_0 + a_1 X$ is used, a_0 is 897, a_1 is .914, and the standard error of estimate is 1860 centipoise. As may be seen in Figure 26, the lines do not

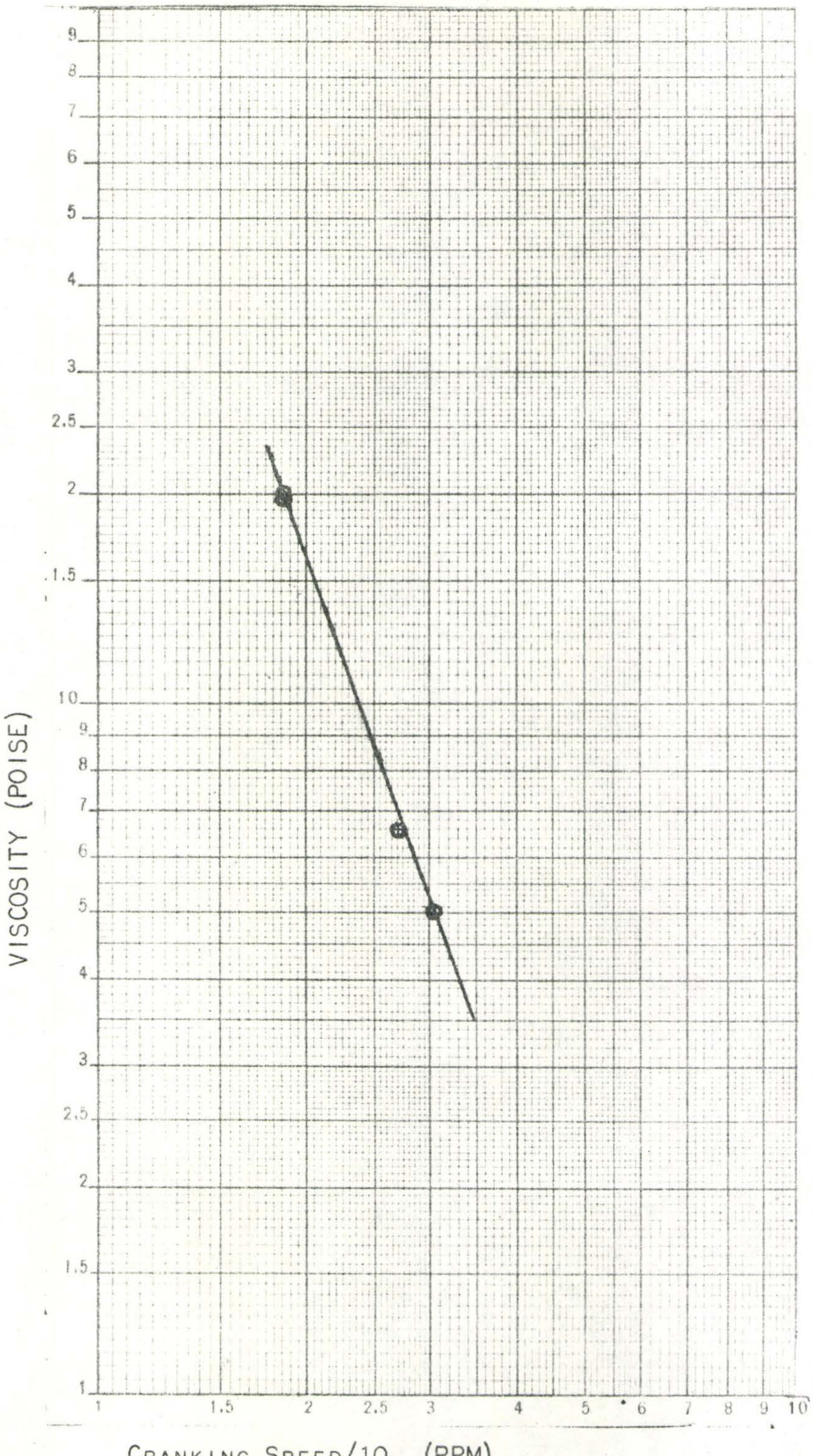


FIGURE 29 - ENGINE CALIBRATION CURVE

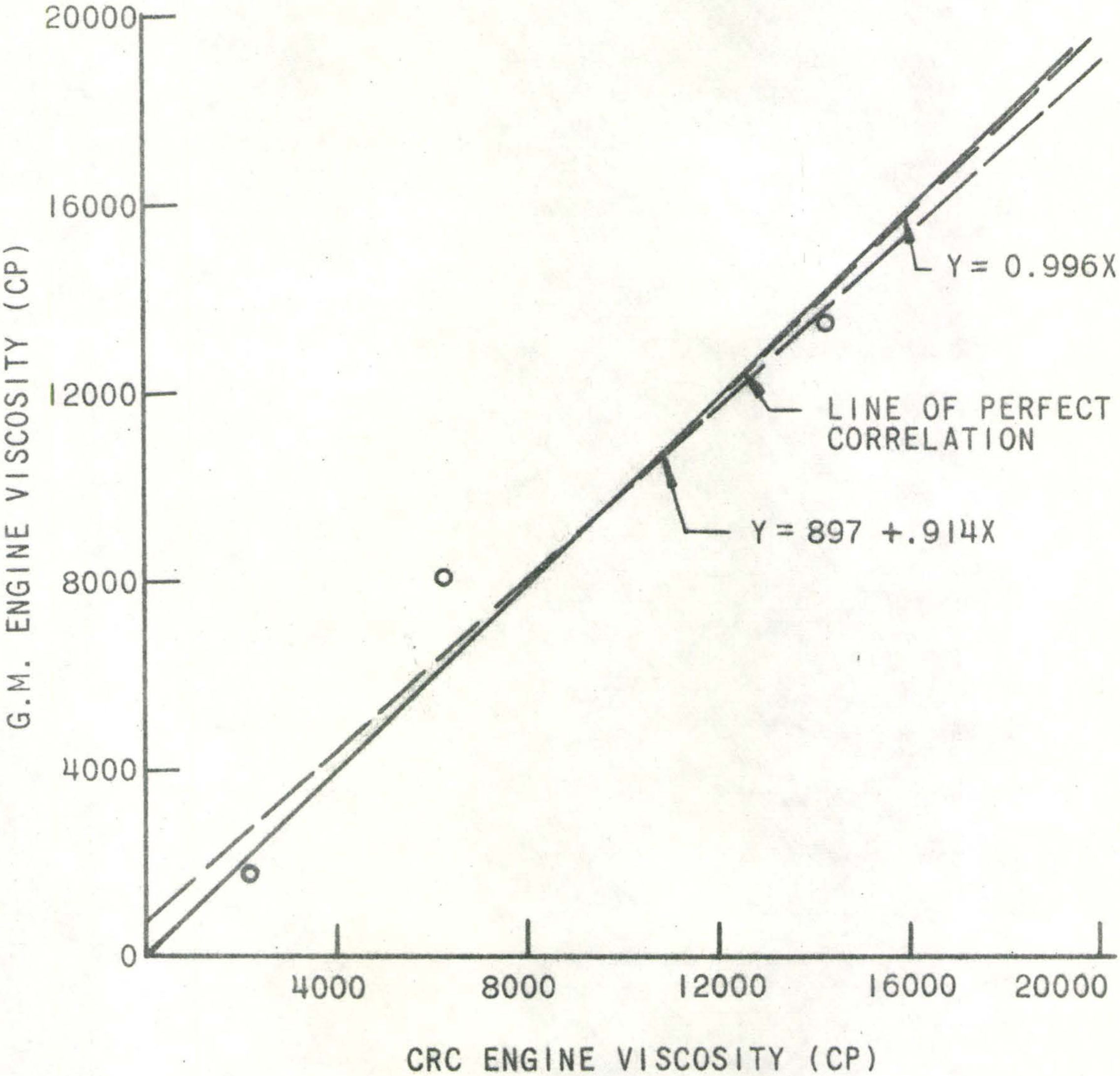


FIGURE 30 - CORRELATION OF G.M. ENGINE VISCOSITY WITH CRC ENGINE VISCOSITY AT -20°F

TABLE IV

COMPARISON OF REO OIL ENGINE VISCOSITIES AT -20°F

	Engine Viscosity (cp)	
Oil	GM Engine	CRC Engines(*)
REO 158-63	8100	6350
REO 159-63	13500	14300
REO 172-65	2050	2270

* 8 Engine Average[47]

correspond closely to the line of perfect correlation. The actual coefficient of correlation was calculated to be 0.917, indicating that the correlation is fair. It should be noted that for these calculations it was necessary to assume the CRC values to be accurate and exact.

The experimental Shell oils, A through G, were also tested, according to the CRC L-49 procedure, by the Shell Canada Research Laboratory(48). The results of the G.M. of Canada cranking tests were correlated with the results of these tests, using the same methods described above. The points are plotted in Figure 31, page 89, against the line of perfect correlation. Two least-square regression lines are also shown on this graph. For the forced line through the origin, $Y=a_1X$, a_1 was calculated to be 0.842 and the standard error of estimate was 635 centipoise. For the free line, $Y=a_0+a_1X$, a_0 was -45.6, a_1 was 0.848, and the standard error of estimate was 123 centipoise. The calculations are summarized in Table V, page 90. The correlation coefficient for this data was calculated to be 0.980, indicating good correlation. As was noted with the previous comparison, these calculations are based on the assumption that one set of data, in this case the Shell data, is accurate and exact.

In summary, the analysis of results from the G.M. of Canada engine cold cranking tests showed a reasonable level of repeatability, for a test of this nature, fair correlation with CRC test results, and good correlation with Shell test results.

Cold Cranking Simulator

Two separate programs were conducted with the Cold Cranking

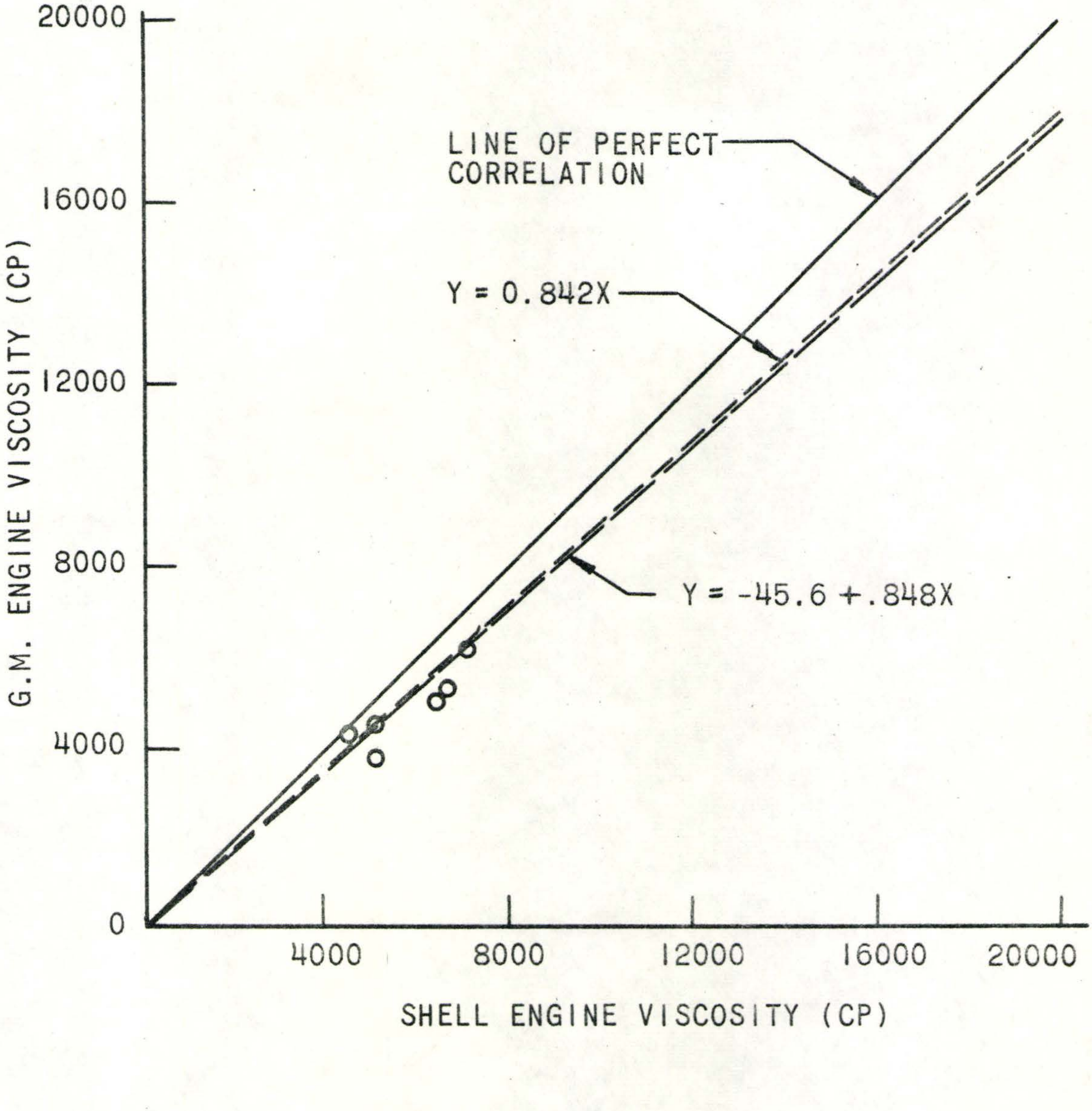


FIGURE 31 - CORRELATION OF G.M. ENGINE VISCOSITY WITH SHELL ENGINE VISCOSITY AT -20°F

TABLE V

COMPARISON OF SHELL OIL ENGINE VISCOSITIES AT -20°F

	Engine Viscosity (cp)	
Oil	GM Engine	Shell Engine
Shell A	4300	4400
Shell B	4400	4900
Shell C	3800	5000
Shell D	5300	6600
Shell E	5700	6600
Shell F	6100	7000
Shell G	5000	6400

Simulator (CCS), the first at 0°F, and the second at -20°F. In both cases the results were reduced to analyzable form and the data were analyzed for repeatability of results, at both temperatures. The results at 0°F, were then correlated with results obtained from the Shell engine tests, CRC engine tests and ASTM CCS tests also obtained at 0°F. Similarly, the results at -20°F were correlated with results from the G.M. of Canada engine tests, Shell engine tests, CRC engine tests, and ASTM CCS tests, also obtained at -20°F.

Data Reduction - At the beginning and end of each day's testing a calibration oil was run to insure against any large deviation in repeatability going unnoticed. In addition, at least two more calibration oils were run during the testing so that a calibation curve could be established each day. Whenever possible, a minimum of two runs on each oil were used to establish the curve. A typical calibration curve is represented by the solid line in Figure 32, page 92. The figure illustrates the method of determining the viscosity of a test oil from the calibration curve. The test oil showed a speed reading of 0.25 ma on the speed indicator. The line representing this speed is seen to intersect the calibration curve at a point equivalent to a viscosity of 7500 cp. This value, then, represents the CCS viscosity of the test oil.

One of the shortcomings of this method of determining viscosity is the possibility of error in constructing the calibration curve. Referring to the same data points in Figure 32, the two dotted lines represent smooth curves which could also reasonably be drawn through the data as calibration curves. It may be seen that, depending on which

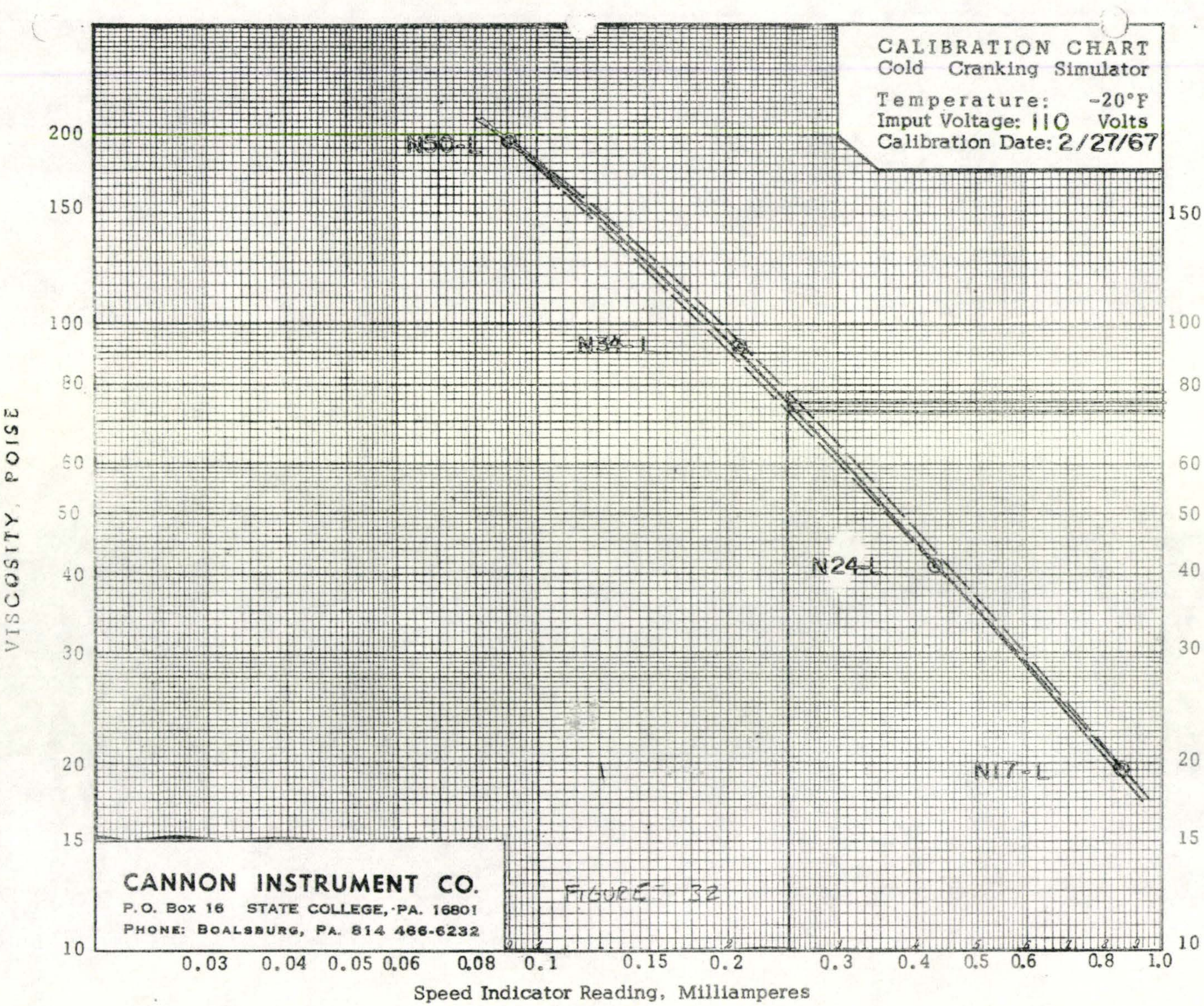


FIGURE 32 - COLD CRANKING SIMULATOR CALIBRATION CURVE

CURVE IS USED, THE VISCOSITY DETERMINED FOR THE TEST OIL COULD VARY CONSIDERABLY. IT IS CONCEIVABLE, THEN, THAT THE DEVIATION IN RESULTS DUE TO DIFFERENCES IN CALIBRATION CURVES DRAWN THROUGH THE SAME POINTS BY DIFFERENT PEOPLE, OR BY THE SAME PERSON AT DIFFERENT TIMES, COULD BE AS SIGNIFICANT AS ANY DEVIATION CAUSED BY INSTRUMENT VARIATION. THE DESIRABILITY OF A REPEATABLE AND CONSISTENT METHOD OF DETERMINING CALIBRATION CURVES IS OBVIOUS.

BECAUSE OF THE POSSIBLE INCONSISTENCIES IN THE USE OF CALIBRATION CURVES CONSIDERATION WAS GIVEN TO THE USE OF NUMERICAL, RATHER THAN GRAPHICAL METHODS TO ESTABLISH TEST OIL VISCOSITIES. A NUMBER OF TEST VISCOSITIES WERE DETERMINED USING SEVERAL CALIBRATION CURVES, BY BOTH GRAPHICAL AND NUMERICAL METHODS. THE GRAPHICAL RESULTS WERE DETERMINED PRIOR TO THE NUMERICAL RESULTS IN ORDER TO PREVENT ANY LOSS OF OBJECTIVITY WHICH COULD UNKNOWINGLY OCCUR IF THE NUMERICAL RESULTS WERE ALREADY KNOWN. A COMPARISON OF THE RESULTS IS SHOWN IN TABLE VI, PAGE 94. AS MAY BE SEEN, THERE IS NO DIFFERENCE IN RESULTS WHICH COULD NOT BE ACCOUNTED FOR BY THE ABILITY OF A PERSON TO READ DATA FROM A GRAPH. IT IS APPARENT THEN, THAT THE NUMERICAL METHOD PROVIDES THE DESIRED ACCURACY, AS WELL AS THE ADDITIONAL VALUE OF COMPLETE CONSISTENCY. AS LONG AS THE SAME DATA POINTS ARE USED THE ANSWER WOULD ALWAYS BE THE SAME. THIS METHOD OF NUMERICAL INTERPOLATION, AITKEN'S PROCESS, IS DESCRIBED FULLY IN APPENDIX G. ALTHOUGH THE METHOD WAS PROGRAMMED FOR CALCULATION BY COMPUTER, IN THIS CASE, IT IS READILY ADAPTABLE TO USE WITH A DESK CALCULATOR. THIS METHOD WAS USED TO DETERMINE THE TEST OIL VISCOSITIES FOR ALL TESTS RUN DURING BOTH TEST PROGRAMS. ALL CCS VISCOSITIES REFERRED TO IN THE REMAINDER OF THIS CHAPTER WILL BE THOSE

TABLE VI

-20°F EVALUATION OF NUMERICAL INTERPOLATION

	Viscosity (cp)#	
Oil	Graphical	Numerical
REO 151-65	6750	6700
REO 153-65	20100	20100
REO 161-63	4940	4940
REO 162-63	20100	20100
REO 158-63	6750	6700
REO 159-63	15200	15100
REO 160-63	19600	19500
REO 172-65	2140	2150
Shell A	4950	4950
Shell B	4950	4950
Shell C	4950	4950
Shell D	6400	6400
Shell E	6400	6400
Shell F	7300	7400
Shell G	4950	4950

Mean results of tests 1,2,3 and 4

determined by numerical interpolation. It should be noted that, for the numerical results, the practice of rounding off results was continued, as specified for the graphical method. Viscosities below 3000 cp were determined to the nearest 10 cp, those between 3000 and 6000 cp were determined to the nearest 50 cp, and those above 6000 cp were determined to the nearest 100 cp. Although the numerical calculations could be determined more accurately, thus improving precision, this practice was continued for the purpose of making comparisons with results determined graphically.

Repeatability at 0°F - For the Cold Cranking Simulator tests six calibration oils, supplied by Cannon Instrument Company, were used as standards. The test oils consisted of eight CRC, REO oils and seven experimental Shell oils. The REO oils covered SAE viscosity ranges from 5W to 20W, including both single and multigrade oils. All of the Shell oils were SAE 5W30's each with different characteristics. The physical properties of each of the oils used are detailed in Appendix H.

Five test sequences were run at 0°F. Each sequence consisted of one test on each oil and a calibration curve was developed for each sequence. The order of testing within each sequence was random, and is listed in Appendix J.

The data were analyzed for repeatability in the same manner described for the engine cranking tests. A "Student's t" distribution of sample was assumed and the method of analysis illustrated in Appendix E was applied. To facilitate the calculations all analyses were computerized.

The raw results, after conversion to viscometric units by the method of numerical interpolation described previously, are listed in Table VII, page 97. The results of the statistical analysis, showing mean viscosity, standard deviation, and 95% confidence limits for each oil, are summarized in Table VIII, page 98. The average standard deviation for the total of 75 tests was 26.5 centipoise. Because of the wide variation in viscosity of the oils tested this value is more meaningful when expressed as a percentage of the mean, since naturally the absolute value would be high for viscosity below the mean and low for viscosities above the mean. The average standard deviation for tests at 0°F was 1.41% of the mean. Thus, if a large number (>30) of tests were conducted on the same oil it is statistically probable that 68.27% (the area represented by $\pm 1\sigma$ under a normal distribution curve) of the results would lie within 1.41% of the mean viscosity.

As a means of evaluating the precision of the results the standard deviations for the eight REO oils were compared to those for the same oils as tested in the second ASTM round robin[43]. The comparison is shown in Table IX, page 99. The mean standard deviation of tests conducted in this program, on a percent of mean basis, was 1.59%, compared to 2.16% for the ASTM tests. The ASTM tests showed a lower standard deviation for only two oils, REO 153 and REO 162.

Column four of Table VIII represents the 95% confidence limits of CCS viscosity. That is, we can be 95% confident that the actual population mean lies within these limits ($\pm$ the indicated amount from the mean). Column five represents the same limits expressed as a percent of the mean. This figure may be expressed in terms of a repeat-

TABLE VII

COLD CRANKING SIMULATOR RESULTS AT 0°F

Oil	CCS Viscosity (cp)					
	Test 1	Test 2	Test 3	Test 4	Test 5	Mean
REO 151-65	1320	1310	1330	1320	1310	1320
REO 153-65	3550	3500	3300*	3400	3400	3430
REO 161-63	1050	1060	1040	1070	1090	1060
REO 162-63	3500	3400	3400	3250*	3400	3390
REO 158-63	1500	1560	1560	1560	1580	1550
REO 159-63	2450	2250*	2350	2400	2410	2370
REO 160-63	2960	2910	2860	2910	2920	2910
REO 172-65	670	660	670	660	680	670
Shell A	940	930	950	930	950	940
Shell B	1040	1040	1050	1040	1060	1050
Shell C	950	940	950	940	950	950
Shell D	1210	1180	1200	1190	1210	1200
Shell E	1170	1200	1190	1180	1230	1190
Shell F	1340	1340	1340	1300	1390	1340
Shell G	1130	1100	1090	1100	1120	1110

TABLE VIII

REPEATABILITY ANALYSIS OF CCS TESTS AT 0°F

		Standard Deviation		95% Confidence Limits	
Oil	Mean (cp)	(cp)	(% of mean)	(±cp)	(± % of mean)
REO 151-65	1320	7.49	0.49	10.4	.79
REO 153-65	3430	87.2	2.55	121	3.53
REO 161-63	1060	17.2	1.62	25.0	2.36
REO 162-63	3390	80.0	2.36	111	3.27
REO 158-63	1550	27.2	1.75	37.8	2.44
REO 159-63	2370	41.5	1.75	57.6	2.43
REO 160-63	2910	31.9	1.09	44.4	1.52
REO 172-65	670	7.49	1.12	10.4	1.55
Shell A	940	8.94	.95	12.4	1.32
Shell B	1050	8.24	.79	11.4	1.09
Shell C	950	4.9	.52	6.81	.72
Shell D	1200	11.7	.97	16.4	1.36
Shell E	1190	20.6	1.72	28.6	2.40
Shell F	1340	28.6	2.13	39.8	2.97
Shell G	1110	14.7	1.33	20.4	1.84
Mean	1632	26.5	1.41	36.9	1.97

TABLE IX

COMPARATIVE 0°F STANDARD DEVIATONS (% OF MEAN)

OIL	TEST	ASTM (13 LAB) (2ND ROUND)
REO 151-65	0.49	1.77
REO 153-65	2.55	2.35
REO 158-63	1.75	2.88
REO 159-63	1.75	2.56
REO 160-63	1.09	2.16
REO 161-63	1.62	1.80
REO 162-63	2.36	0.76
REO 172-65	1.12	3.00
MEAN	1.59	2.16

ABILITY RATIO. AT THE 95% CONFIDENCE LEVEL, TWO RESULTS COULD HAVE THE VALUES 98.03% AND 101.97% OF THE MEAN WITHOUT BEING SUSPECT. THE RATIO OF THESE TWO NUMBERS IS $\frac{101.97}{98.03} = 1.040$. THEREFORE, IN ANY SERIES OF TEST RESULTS, AT THE 95% CONFIDENCE LEVEL, THE RESULTS SHOULD NOT BE SUSPECT UNLESS THE RATIO OF THE GREATEST TO THE SMALLEST EXCEEDS 1.040. BY COMPARISON, THE REPEATABILITY RATIO DETERMINED BY THE ASTM WAS 1.06 [43] FOR 95% CONFIDENCE.

IN REVIEWING TEST RESULTS IT WAS NOTICED THAT THE RATIO OF THE GREATEST TO THE SMALLEST VALUE EXCEEDED THE PRESCRIBED REPEATABILITY RATIO IN A NUMBER OF CASES. A FURTHER REVIEW OF THE RAW DATA FOR THESE OILS INDICATED THAT IN MOST CASES, ONE OR TWO DETERMINATIONS DIFFERED CONSIDERABLY FROM THE OTHERS. THESE VALUES ARE NOTED (*) IN TABLE VII.

IN ORDER TO IMPROVE THE PRECISION OF RESULTS THESE DATA WERE DISCARDED AND REPEAT RUNS WERE MADE ON THE OILS INVOLVED TO OBTAIN REPLACEMENT VALUES FOR THOSE DISCARDED. TABLE X, PAGE 101, SHOWS THE REVISED RESULTS AND THE CORRESPONDING STATISTICAL ANALYSIS IS SHOWN IN TABLE XI, PAGE 102. THE IMPROVEMENT IN PRECISION WHICH RESULTED MAY BE SUMMARIZED AS FOLLOWS:

	ORIGINAL	REVISED
STANDARD DEVIATION (CP)	26.5	21.9
STANDARD DEVIATION (%)	1.41	1.21
95% CONFIDENCE LIMITS (± CP)	36.9	30.4
95% CONFIDENCE LIMITS (± %)	1.97	1.68
REPEATABILITY RATIO	1.040	1.034

THE RESULTS OF THE 0°F TEST PROGRAM INDICATED THAT THE REPEATABILITY OF THE COLD CRANKING SIMULATOR AND THE PROCEDURE USED WAS VERY

TABLE X

CORRECTED CCS RESULTS AT 0°F (NUMERICALLY INTERPOLATED)

	Viscosity (cP)					
Oil	Run 1	Run 2	Run 3	Run 4	Run 5	Mean
REO 151-65	1320	1310	1330	1320	1310	1320
REO 153-65	3550	3500	3400	3400	3400	3450
REO 161-63	1050	1060	1040	1070	1090	1060
REO 162-63	3500	3400	3400	3400	3400	3400
REO 158-63	1500	1560	1560	1560	1580	1550
REO 159-63	2450	2440	2350	2400	2410	2420
REO 160-63	2960	2910	2860	2910	2920	2910
REO 172-65	670	660	670	660	680	670
Shell A	940	930	950	930	950	940
Shell B	1040	1040	1050	1040	1060	1050
Shell C	950	940	950	940	950	950
Shell D	1210	1180	1200	1190	1210	1200
Shell E	1170	1200	1190	1180	1230	1190
Shell F	1340	1340	1340	1300	1390	1340
Shell G	1130	1100	1090	1100	1120	1110

TABLE XI

CORRECTED REPEATABILITY ANALYSIS OF CCS TESTS AT 0°F

		Standard Deviation		95% Confidence Limits	
Oil	Mean (cp)	(cp)	(%)	(cp)	(%)
REO 151-65	1320	7.49	0.49	10.4	.79
REO 153-65	3450	63.2	1.83	82.7	2.39
REO 161-63	1060	17.22	1.62	25.00	2.36
REO 162-63	3420	40.0	1.18	55.6	1.62
REO 158-63	1550	27.20	1.75	37.80	2.44
REO 159-63	2420	36.6	1.51	50.9	2.10
REO 160-63	2910	31.90	1.09	44.40	1.52
REO 172-63	670	7.49	1.12	10.4	1.55
Shell A	940	8.94	.95	12.4	1.32
Shell B	1050	8.24	.79	11.4	1.09
Shell C	950	4.90	.52	6.81	.72
Shell D	1200	11.7	.97	16.4	1.36
Shell E	1190	20.60	1.72	28.6	2.40
Shell F	1340	28.62	2.13	39.8	2.97
Shell G	1110	14.7	1.33	20.4	1.84
Mean	1637	21.9	1.21	30.4	1.68

HIGH, AND THE RESULTS OF PREVIOUS WORK AT THIS TEMPERATURE WERE SUBSTANTIATED IN THIS REGARD.

Correlation at 0°F - Engine cranking tests at 0°F had been conducted on the seven experimental Shell oils, used in the test, by Shell Canada. The results obtained in the CCS program at 0°F were correlated with the Shell engine test results using the methods previously discussed and outlined in Appendix F. Figure 33, page 104, shows the data plotted with respect to the line of perfect correlation (45°). Two lines were considered in correlating the results, $Y=a_1X$ and $Y=a_0+a_1X$. For the equation $Y=a_1X$, a_1 was calculated to be .929 and the standard error of estimate was 162 cp. For the equation $Y=a_0+a_1X$, a_0 was calculated to be 755 and a_1 to be .306. The standard error of estimate was 135. Calculations showed the coefficient of correlation to be .507. This low value indicates that the correlation between the two sets of values is almost random.

The results of the CCS test program were also correlated with the results of CRC engine cranking tests on the same oils. The CRC engine viscosities are the averages from twelve laboratories and are listed in Table XII, page 105. The data were analyzed according to the method of Appendix F. Figure 34, page 106, shows the correlation graphically. When the line $Y=a_1X$ was used the value of a_1 was calculated to be 1.032 and the standard error of estimate was calculated to be 288 cp. For the line $Y=a_0+a_1X$, a_0 was -47 and a_1 was 1.042. The standard error of estimate was 360 centipoise and the correlation coefficient was .931.

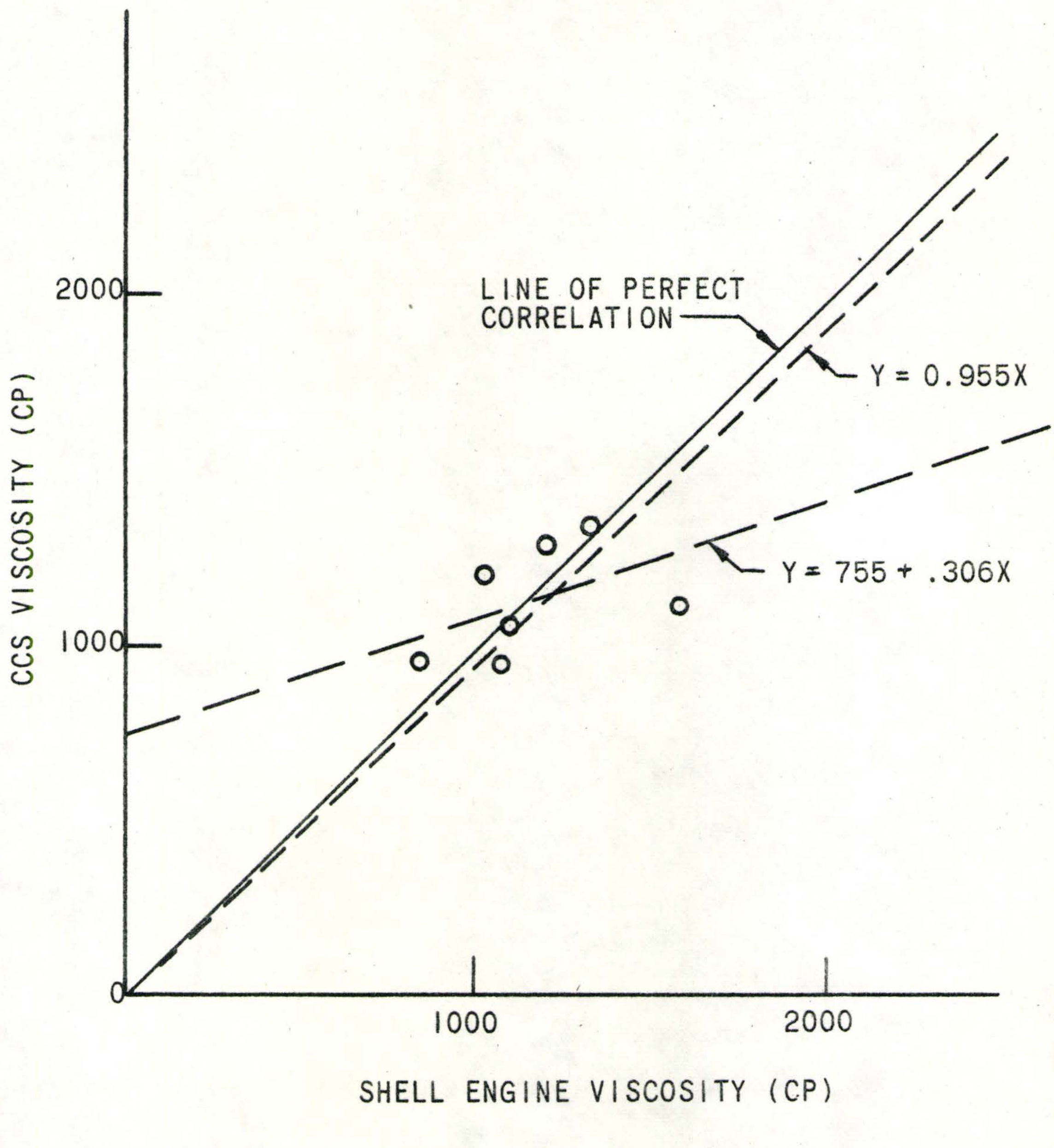


FIGURE 33 - CCS VISCOSITY vs SHELL ENGINE VISCOSITY AT 0°F

TABLE XII

CRC ENGINE VISCOSITIES AT 0°F

Oil	Engine Viscosity (cp)(*)
REO 161-63	990
REO 162-63	2740
REO 158-61	1780
REO 159-61	2510
REO 160-61	3040
REO 172-63	580

* 12 Engine Average.

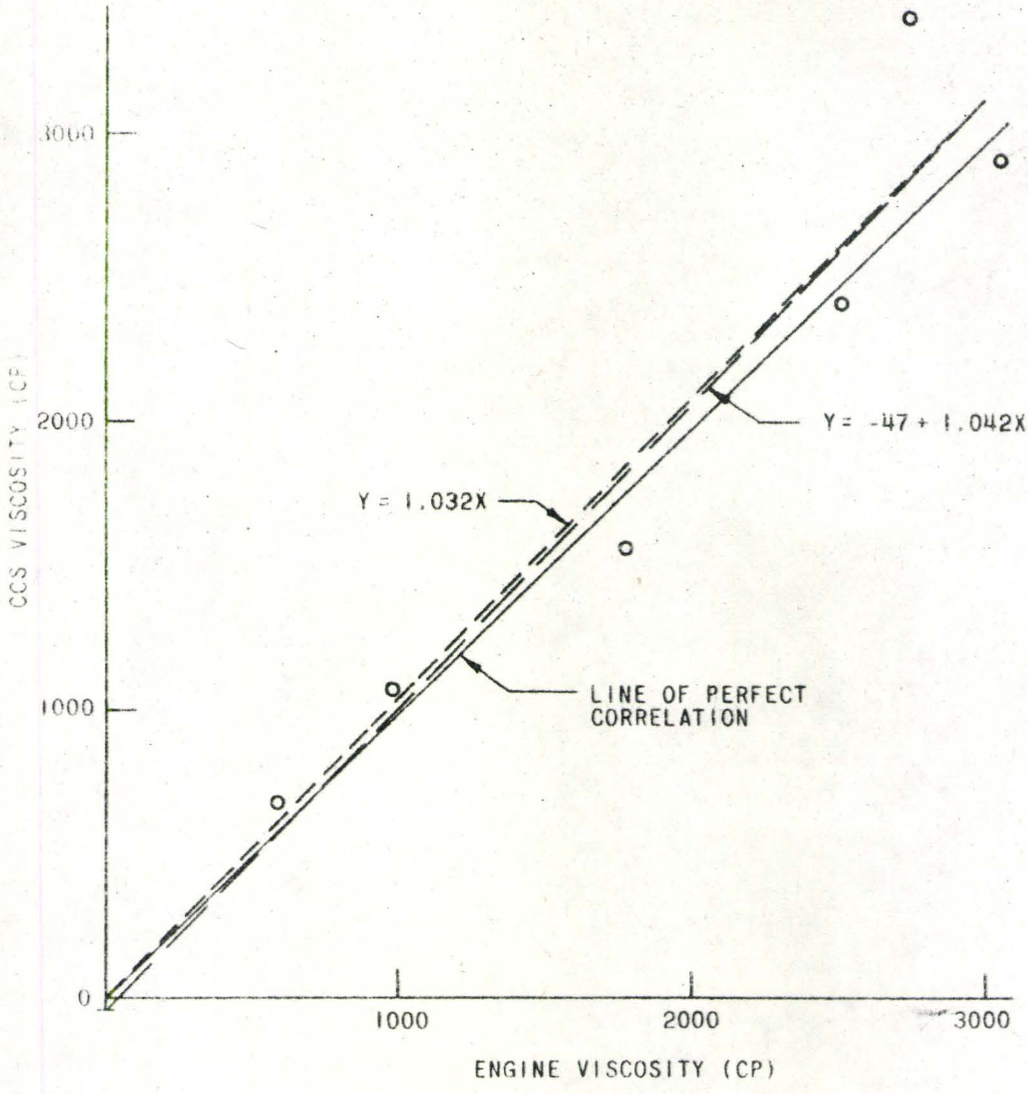


FIGURE 34 - CORRELATION OF CCS VISCOSITY WITH CRC ENGINE VISCOSITY AT 0°F

The ASTM conducted two round robin series of tests at 0°F, on REO oils, with the Cold Cranking Simulator. The results from this program, at 0°F, were correlated with the results from the second ASTM round robin at 0°F, both of which were conducted at approximately the same time. The ASTM results were assumed to be perfect for correlation purposes. Using the straight line equation $Y=a_1X$, the value of a_1 was calculated to be .957 and the standard error of estimate was 1060. For the more general straight line, $Y=a_0+a_1X$, the values for a_0 and a_1 were calculated as 73 and .930 respectively. The standard error of estimate was 186. A very high coefficient of correlation, .983, was determined, indicating that very little improvement could be made. Figure 35, page 108, is a graphic representative of the data and the correlation lines.

The correlation of data between the results of this program and those to which it was compared indicated that the particular instrument and procedure used gave results which were representative of cold cranking simulators, in general, at 0°F test temperature.

<u>Repeatability at -20°F</u> - For the Cold Cranking Simulator tests at -20°F, only the four least viscous calibration oils were used. All the test oils, used in the 0°F program, however, were also used in this program. Their physical properties are detailed in Appendix H.

Six test sequences were run at -20°F. As in the previous program, a sequence consisted of one test on each oil, and a calibration curve was developed for each sequence. The order of testing within each sequence was random and is listed in Appendix J.

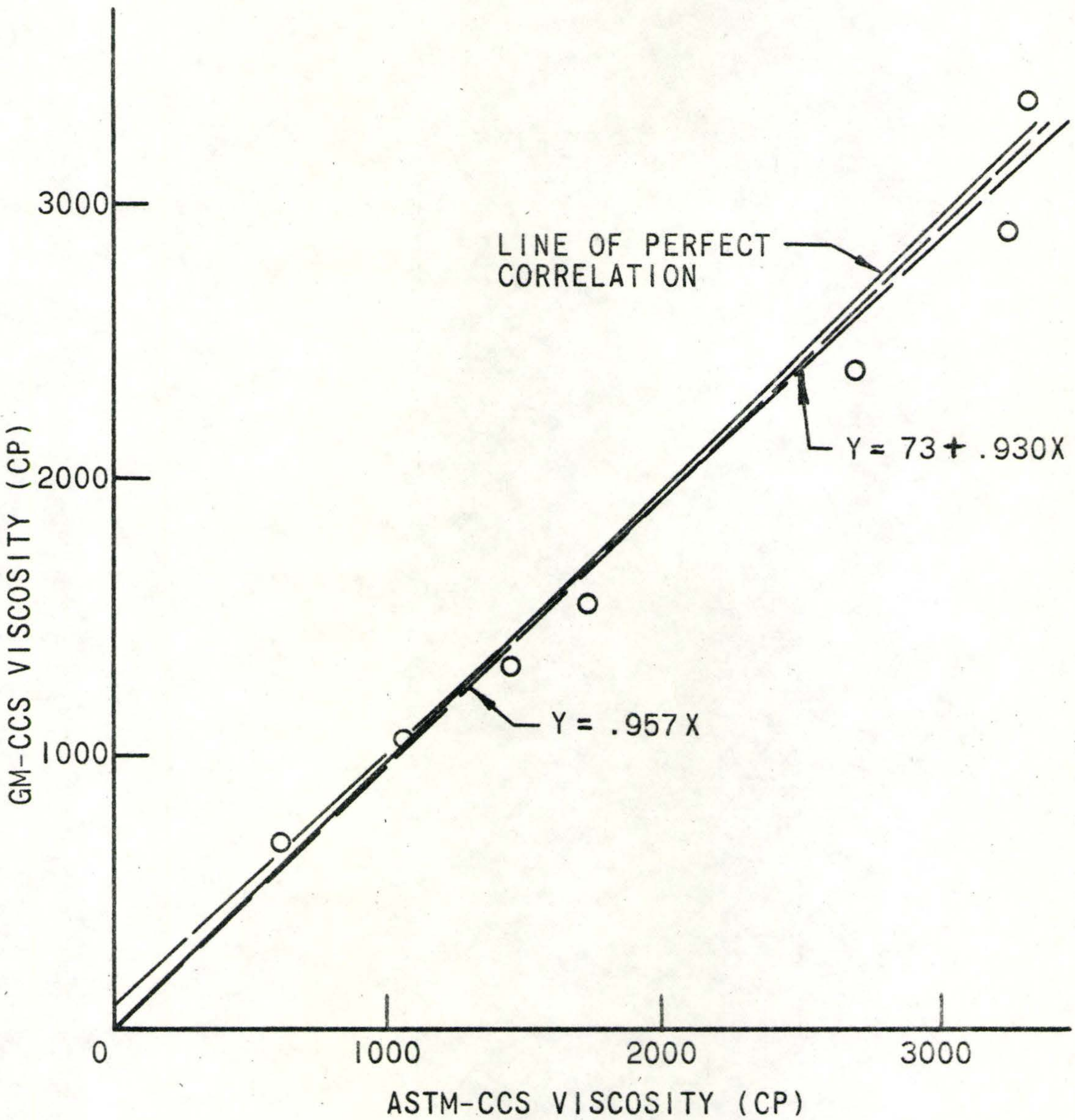


FIGURE 35 - CORRELATION OF C.C.S. VISCOSITY WITH A.S.T.M.-C.C.S. VISCOSITY AT 0°F

The data were analyzed for repeatability according to the "Student's t" method described in Appendix E. Computer analysis techniques were used to facilitate calculations.

The raw test results, converted to viscometric units by the use of Aitken's interpolation process, are listed in Table XIII, page 110. Table XIV, page 111, summarizes the mean viscosity, standard deviation, and 95% confidence limits for each oil. The average standard deviation was 214 centipoise for the total of 90 tests conducted. A more meaningful expression of standard deviation is the coefficient of variation, the standard deviation expressed as a percentage of the mean. This value, for the -20°F tests, was 2.31% of the mean. Therefore, if a large number (>30) of tests were conducted on the same oil it is statistically probable that 68.27% (the area represented by $\pm 1\sigma$ under the standard distribution curve) of the results would lie within $\pm 2.31\%$ of the mean viscosity.

The 95% confidence limits of the -20°F CCS measured viscosity are shown in column four of Table XIV. With 95% confidence the actual population mean lies within these specified limits of the sample mean. These same limits expressed as a percent of the mean, are found in column five. A repeatability ratio, for 95% confidence, may be defined as the ratio of the maximum to the minimum limiting values. The average repeatability ratio for this program, therefore, was $\frac{102.31}{97.69} = 1.047$. Several readings for the same sample, then, should not be suspect at the 95% confidence level, unless the ratio of the greatest to the least is in excess of 1.047.

A review of test results indicated a number of cases where the

TABLE XIII

COLD CRANKING SIMULATOR RESULTS AT -20°F

Oil	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Mean
REO 151-65	6500	6900*	6900*	6500	6700	6500	6670
REO 153-65	20800	20800	20000	18800*	19800	19600	20200
REO 161-63	4750	4950	5200	4850	5100	5200	5080
REO 162-63	20800	21600*	19400*	19600	20600	20300	20400
REO 158-63	6700	6500	6800	6700	6800	6700	6700
REO 159-63	15200	14900	14900	15400	14500*	15400	15050
REO 160-63	20100*	19200	19200	19400	18900	19000	19300
REO 172-65	2080	2150	2180*	2180*	2050	2080	2120
Shell A	4750*	5000	5200	4850*	5050	5200	5000
Shell B	4750*	5000	5200	4850*	5050	5200	5000
Shell C	4750*	5000	5200	4850*	5050	5200	5000
Shell D	6200	6400	6500	6500	6400	6300	6400
Shell E	6300	6400	6600	6400	6600	6500	6500
Shell F	7400	7200	7500	7200	7400	7400	7350
Shell G	4750*	5000	5200	4850*	5050	5200	5000

TABLE XIV

REPEATABILITY ANALYSIS OF CCS TESTS AT -20°F

		Standard Deviation		95% Confidence Limits	
Oil	Mean (cp)	(cp)	(%)	(±cp)	(±%)
REO 151-65	6670	72.8	1.09	82.9	1.25
REO 153-65	20200	464	2.29	527	2.59
REO 161-63	5080	57.0	1.12	64.8	1.28
REO 162-63	20400	740	3.62	840	4.12
REO 158-63	6700	100	1.49	1.14	1.70
REO 159-63	15050	313	2.08	356	2.32
REO 160-63	19300	391	2.03	450	2.33
REO 172-65	2120	52.0	2.45	59.1	2.83
Shell A	5000	172	3.42	196	3.92
Shell B	5000	172	3.42	196	3.92
Shell C	5000	172	3.42	196	3.92
Shell D	6400	100	1.56	114	1.78
Shell E	6500	115	1.77	131	2.02
Shell F	7350	112	1.53	127	1.76
Shell G	5000	172	3.42	196	3.92
Mean	9051	214	2.31	243	2.64

repeatability ratio of the data exceeded the allowable value. These cases are noted (*) in Table XIII. In order to improve the precision of results these data were discarded and repeat runs were made to obtain replacement values. Table XV, page 113, shows the revised results and the corresponding statistical analysis is shown in Table XVI, page 114. The imrovement in precision may be summarized as follows:

	Original	Revised
Standard Deviation (cp)	214	157
Standard Deviation (%)	2.31	1.73
95% Confidence Limits (± cp)	243	178
95% Confidence Limits (%)	2.64	1.97
Repeatability Ratio	1.047	1.040

A comparison of repeatability values between the tests at -20°F and those at 0°F is shown in Table XVII, page 115. It may be seen that the repeatability is, in general, slightly poorer at -20°F than at 0°F.

Correlation at -20°F - Engine cranking tests were conducted, using the G.M. of Canada engine cranking tests apparatus, on the same oils which were tested in the cold cranking simulator. Four of these, however, were used as calibration oils in the engine and could not, therefore, be considered in correlation studies. The results obtained in the CCS tests at -20°F were correlated with the engine cranking test results, using straight lines of the form $Y = a_1 X$ and $Y = a_0 + a_1 X$. The method of correlation described in Appendix F was used. The engine test results

CORRECTED CCS RESULTS AT -20°F (NUMERICALLY INTERPOLATED)

VISCOSITY (CP)

OIL	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	RUN 6	MEAN
REO 151-65	6500	6600	6600	6500	6700	6500	6570
REO 153-65	20800	20800	20000	20100	19800	19600	20200
REO 161-63	5200	4950	5200	4850	5100	5200	5080
REO 162-63	20800	20300	19800	19600	20600	20300	20200
REO 158-63	6700	6500	6800	6700	6800	6700	6700
REO 159-63	15200	14900	14900	15400	14800	15400	15100
REO 160-63	18900	19200	19200	19400	18900	19000	19100
REO 172-65	2080	2150	2050	2130	2050	2080	2090
SHELL A	5250	5000	5200	5250	5050	5200	5130
SHELL B	5250	5000	5200	5250	5050	5200	5130
SHELL C	5250	5000	5200	5250	5050	5200	5130
SHELL D	6200	6400	6500	6500	6400	6300	6400
SHELL E	6300	6400	6600	6400	6600	6500	6500
SHELL F	7400	7200	7500	7200	7400	7400	7400
SHELL G	5250	5000	5200	5250	5050	5200	5130

TABLE XVI

CORRECTED REPEATABILITY ANALYSIS OF CCS TESTS AT -20°F

		Standard Deviation		95% Confidence Limits	
Oil	Mean (cp)	(cp)	(%)	(±cp)	(±%)
REO 151-65	6570	75.4	1.15	86	1.37
REO 153-65	20200	464	2.30	530	2.62
REO 161-63	5080	116	2.28	132	2.56
REO 162-63	20200	420	2.08	477	2.37
REO 158-63	6700	100	1.49	1.14	1.70
REO 159-63	15100	245	1.62	279	1.86
REO 160-63	19100	182	0.95	205	1.05
REO 172-65	2090	35.6	1.70	40.5	1.92
Shell A	5130	96.5	1.88	110	2.14
Shell B	5130	96.5	1.88	110	2.14
Shell C	5130	96.5	1.88	110	2.14
Shell D	6400	100	1.56	114	1.78
Shell E	6500	115	1.77	131	2.02
Shell F	7350	112	1.53	127	1.76
Shell G	5130	96.5	1.88	110	2.14
Mean	9054	157	1.73	178	1.97

TABLE XVII

COMPARISON OF CCS REPEATABILITY AT 0°F AND -20°F

	0°F	-20°F
Standard Deviation (cp)	21.9	157
Standard Deviation (%)	1.21	1.73
95% Confidence Limits (±cp)	30.4	178
95% Confidence Limits (±%)	1.68	1.97
Repeatability Ratio	1.034	1.040

were assumed to be perfect for correlation purposes. For the line through the origin, $Y=a_1X$, a_1 was calculated as 1.076 and the standard error of estimate was 1710 centipoise. Similarly, for the line $Y=a_0+a_1X$, a_0 was 431, a_1 was 1.036, and the standard error of estimate was 962 centipoise. A correlation coefficient of .980 was calculated, indicating near perfect correlation. Figure 36, page 117, illustrates the data points and correlation lines graphically.

The seven Shell experimental oils, tested in the cold cranking simulator, were also evaluated at -20°F in a cold cranking engine by the Shell Canada Research Laboratory. The CCS results from this program were correlated with the results from the Shell engine tests. For the purpose of correlation it was assumed that the engine test data were correct. Using a straight line of the form $Y=a_0+a_1X$, a_0 was determined to be 1718, a_1 to be .706, and the standard error of estimate to be 610 centipoise. The correlation coefficient for these two sets of results was calculated to be .700. The data and correlation lines are graphically portrayed in Figure 37, page 118.

Engine cranking tests at -20°F were conducted by ten laboratories in a round robin organized by the CRC. Several REO oils were used in the program, three of which were common to the CCS tests conducted in this program. A correlation was developed between these sets of data with the engine test results taken as the independent variable. For the straight line $Y=a_1X$, a_1 was found to be 1.044 and the standard error of estimate was found to be 191 centipoise. For the more general straight line, $Y=a_0+a_1X$, a_0, a_1 and the standard error of estimate were calculated to be -290, 1.070, and 91.7 centipoise, respectively.

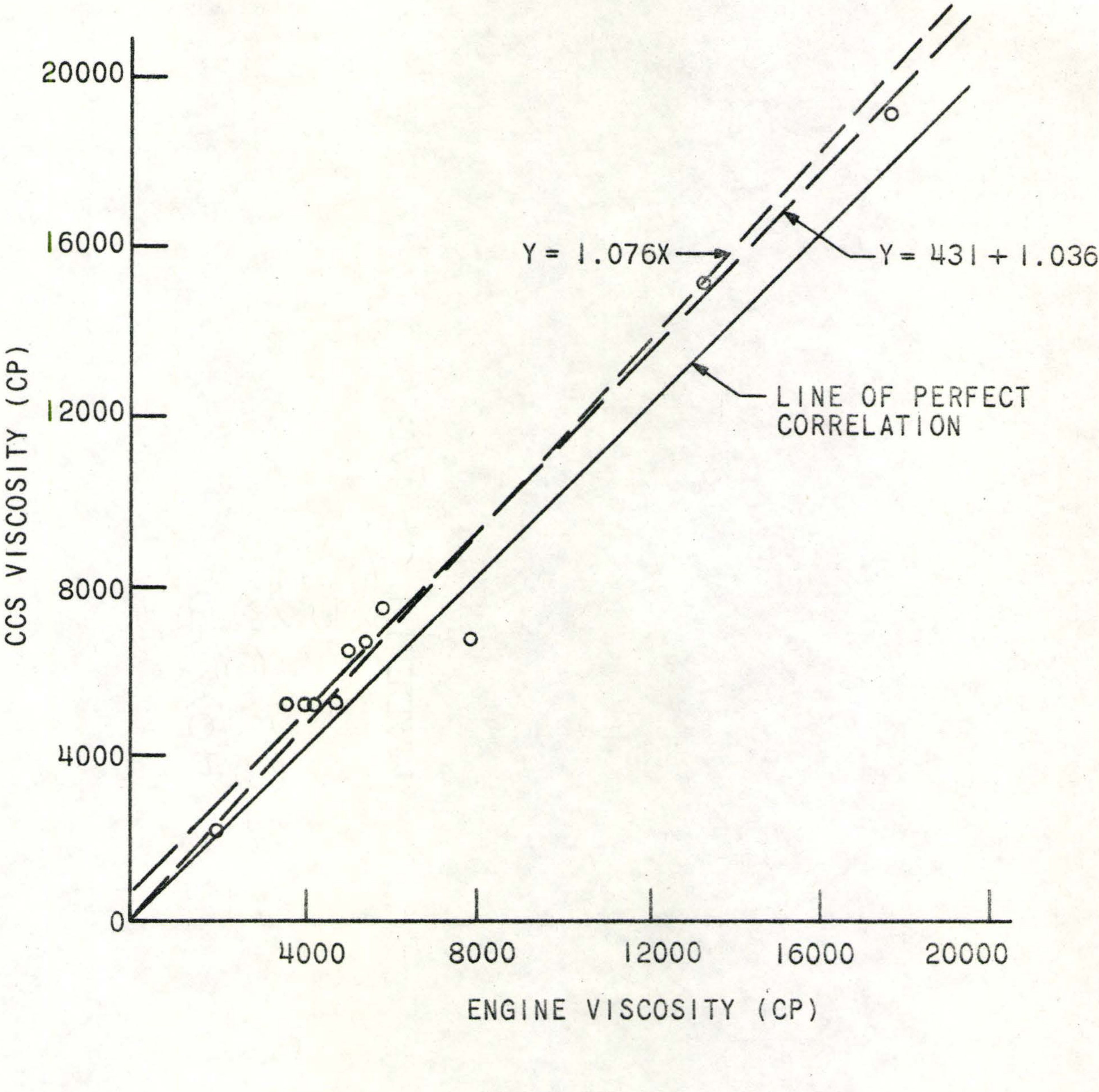


FIGURE 36 - CORRELATION OF CCS VISCOSITY WITH GM ENGINE VISCOSITY AT -20°F

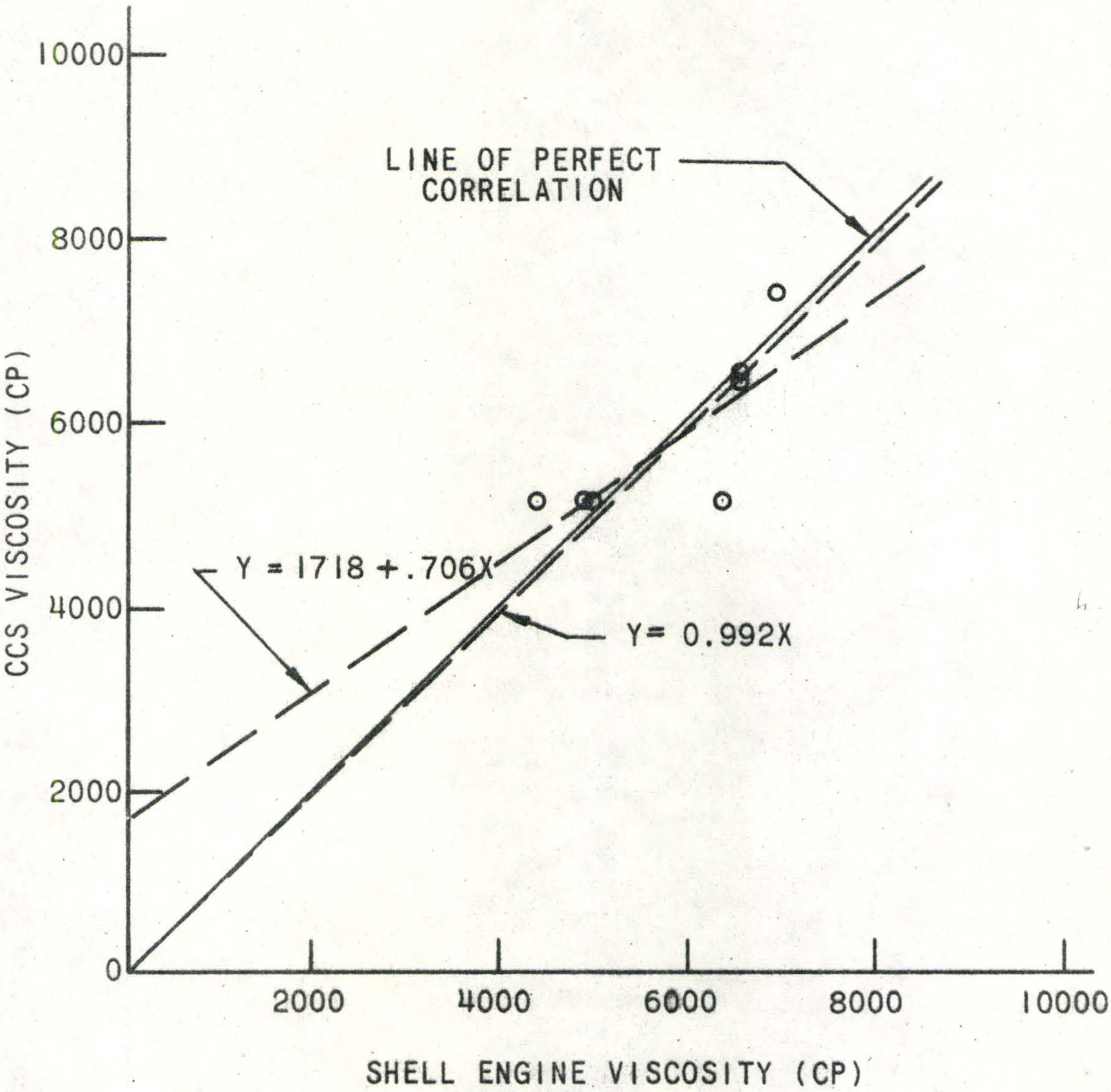


FIGURE 37 - CCS VISCOSITY vs SHELL ENGINE VISCOSITY AT -20°F

The coefficient of correlation, in this case was determined to be .999. The data and correlation lines are plotted in Figure 38, page 120.

During the time this program was being conducted a round robin series of tests was being conducted, at -20°F, under the direction of the ASTM, to study the use of the cold cranking simulator at sub-zero temperatures. The results of the round-robin tests on six REO oils were correlated with the corresponding results from this program, the former being set as the independent variable. For the straight line through the origin, a_1 was calculated as 1.035 and the standard error of estimate as 319 centipoise. For the general straight line the values of a_0, a_1 and the standard error of estimate were calculated to be -170, 1.046, and 359 centipoise, respectively. The correlation coefficient was calculated to be .989. Figure 39, page 121 shows the data and correlation lines plotted graphically.

A summary of the correlation data, for CCS tests at both 0°F and -20°F as well as for engine cranking tests, is found in Table XVIII page 122. There was an excellent correlation between cold cranking simulator test results and engine cranking test results at -20°F. The correlation between the instrument used in this test program and similar instruments used by other laboratories was also shown to be extremely high.

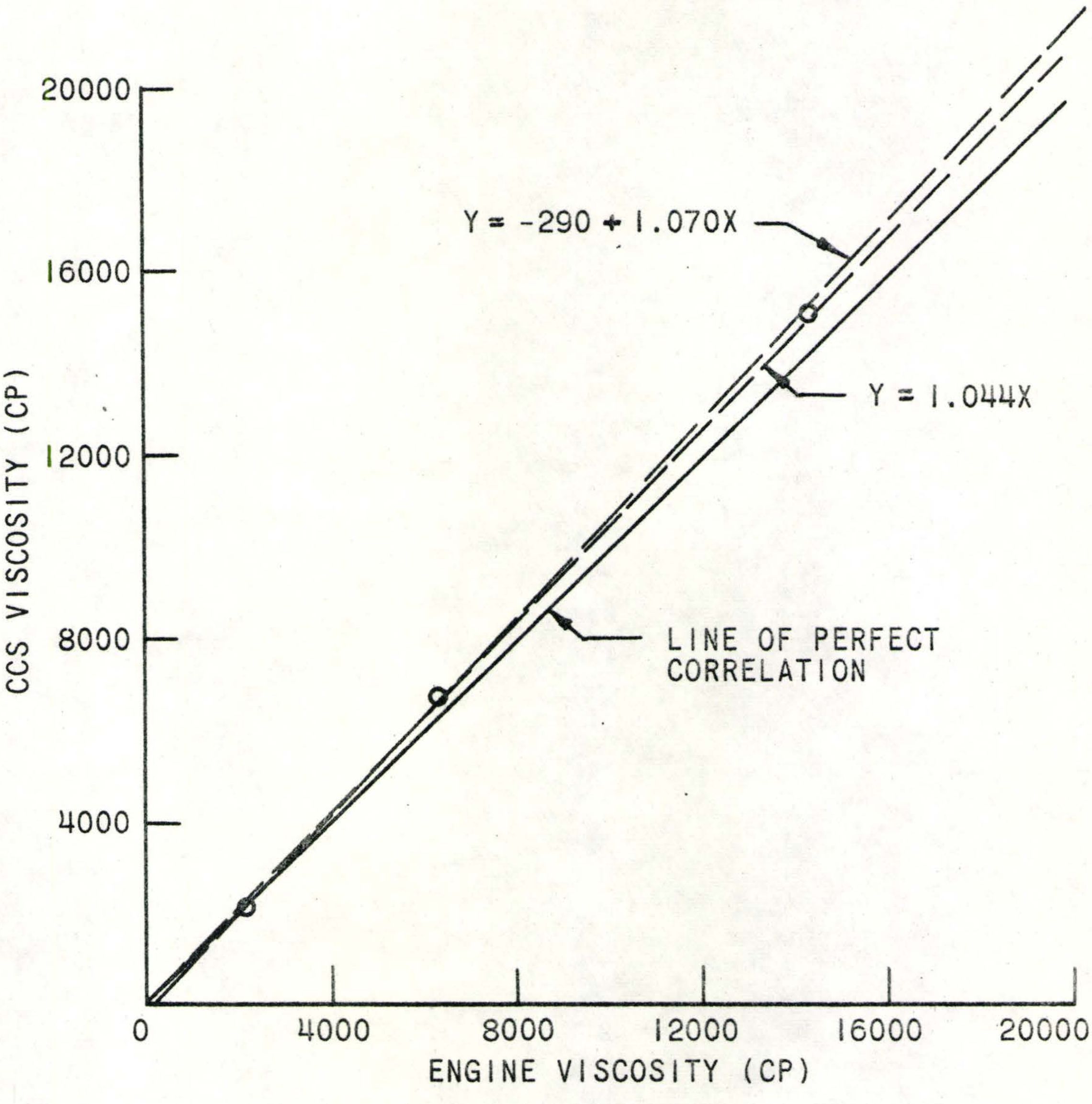


FIGURE 38 - CORRELATION OF C.C.S. VISCOSITY WITH C.R.C. ENGINE VISCOSITY AT -20°F

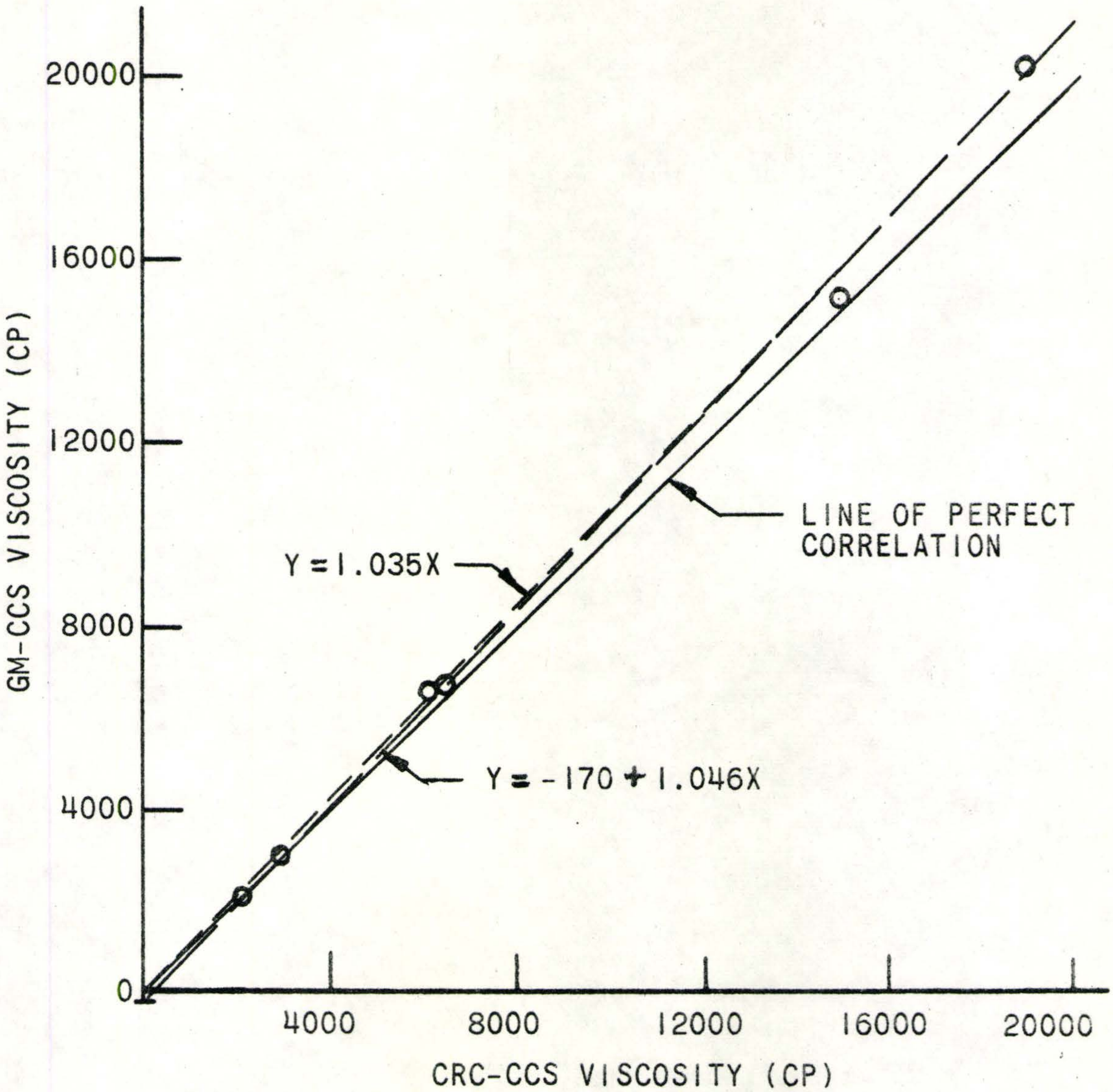


FIGURE 39 - CORRELATION OF CCS VISCOSITY WITH ASTM CCS VISCOSITY AT -20°F

SUMMARY OF CORRELATION DATA

Parameters		$Y = a_1X$		$Y = a_0 + a_1X$			
X	Y	a_1	S_{YX}	a_0	a_1	S_{YX}	"r"
GM-CCS-0°F	Shell L-49-0°F	0.929	162	755	0.306	135	.507
GM-CCS-0°F	CRC L-49-0°F	1.032	288	-47	1.042	360	.931
GM-CCS-0°F	ASTM-CCS-0°F	0.957	1060	73	0.930	186	.983
GM-CCS--20°F	GM L-49--20°F	1.076	1710	431	1.036	962	.980
GM-CCS--20°F	Shell L-49--20°F	0.992	587	1718	0.706	610	.700
GM-CCS--20°F	CRC L-49--20°F	1.044	191	-290	1.070	91.7	.999
GM-CCS--20°F	ASTM CCS--20°F	1.035	319	-170	1.046	359	.989
GM L-49--20°F	CRC L49--20°F	.996	1970	897	.914	1860	.917
GM L-49--20°F	Shell L49--20°F	.842	635	-45.6	.848	123	.990

VII

DISCUSSION OF EXPERIMENTAL RESULTS

THE RESULTS OF THE TEST PROGRAMS CONDUCTED ON BOTH THE COLD CRANKING ENGINE AND THE COLD CRANKING SIMULATOR ARE DISCUSSED IN THIS CHAPTER. AN ATTEMPT IS MADE, IN EACH CASE, TO EXPLAIN THE REASONS FOR THE RESULTS WHICH WERE OBTAINED.

COLD CRANKING ENGINE

DATA REDUCTION - BECAUSE OF THE DYNAMIC NATURE OF THE TEST DATA RECORDED, DATA REDUCTION WAS NECESSARY, AS DESCRIBED IN THE PREVIOUS CHAPTER, IN ORDER TO PROVIDE READY COMPARISONS. THE ACCURACY OF THE RESULTS CAN BE GREATLY AFFECTED BY THE ACCURACY OF THIS INTERPRETATION. THE ABILITY TO ACCURATELY CALCULATE CRANKING SPEED FROM THE CHART RECORDINGS DECREASES AS CRANKING SPEED INCREASES, SINCE THE POSSIBLE ERROR IS MUCH GREATER, ON A PERCENT BASIS, WHEN VERY SMALL TIME INTERVALS MUST BE DETERMINED. FOR THE CRANKING SPEEDS ENCOUNTERED IN THIS PROGRAM, HOWEVER, THE TIME INTERVAL WAS RELATIVELY LARGE ($>$3.0 SECONDS), SO THE POSSIBLE ERROR (WITH A LEAST COUNT OF .02 SECONDS) SHOULD HAVE BEEN RELATIVELY SMALL. IT COULD REASONABLY BE ASSUMED, THEN, THAT NO SIGNIFICANT DEVIATION IN RESULTS OCCURRED DUE TO DATA REDUCTION CALCULATIONS.

REPEATABILITY - A REGULAR MASS-PRODUCED PASSENGER CAR ENGINE, WITH ALL THE INHERENT LACK OF PRECISION ASSOCIATED WITH MASS-MANUFACTURING PROCESSES, WAS USED AS THE BASIS FOR THE TEST APPARATUS. CONSIDERING THE

COMPLEXITY OF THE SYSTEM, AND THE POSSIBLE NUMBER OF VARIABLES WHICH COULD NOT BE CONTROLLED, IT IS REASONABLE TO EXPECT THAT TEST REPEATABILITY WOULD BE RATHER POOR. IT WAS SURPRISING, THEN, TO FIND THE AVERAGE STANDARD DEVIATION OF THE TEST RESULTS TO BE LESS THAN 5% OF THE MEAN. SIMILARLY THE LIMITS OF THE POPULATION MEAN WERE CALCULATED TO BE WITHIN LESS THAT ±5% OF THE MEAN AT THE 95% CONFIDENCE LEVEL, INDICATING THAT A HIGH DEGREE OF REPEATABILITY IS POSSIBLE WITH THE TEST APPARATUS AND PROCEDURE USED.

THE MAJOR PARAMETERS WHICH WERE CONTROLLED FOR THESE TESTS WERE THE POWER SUPPLIED TO THE CRANKING MOTOR, AND THE STABILIZED TEMPERATURE OF THE ENGINE COOLANT AND OIL. THE PREPARATION AND TEST PROCEDURES ESTABLISHED WERE ALSO RIGIDLY FOLLOWED. THE HIGH RELATIVE REPEATABILITY INDICATES THAT THESE PARAMETERS ARE THE MAJOR ONES AFFECTING CRANKING SPEED, EXCEPT FOR THE VARIABLE OF OIL VISCOSITY WHICH WAS BEING EVALUATED. THE SIGNIFICANCE OF THIS HIGH LEVEL OF REPEATABILITY LIES IN THE FACT THAT A HIGH DEGREE OF CONFIDENCE CAN BE PLACED IN THE RESULTS OF ANY SINGLE TEST.

IN COMPARISON WITH RESULTS FROM CRC ENGINE TESTS AT 0°F, THE REPEATABILITY OF THIS TEST PROGRAM WAS SIGNIFICANTLY BETTER. A NUMBER OF POSSIBLE FACTORS COULD ACCOUNT FOR THE IMPROVEMENT. IN THE CRC PROGRAM 12 DIFFERENT ENGINES OF DIFFERENT TYPES AND SIZES WERE USED, INCLUDING A NUMBER OF VERY HIGH DISPLACEMENT ENGINES. EACH TYPE OF ENGINE, AS WELL AS EACH INDIVIDUAL ENGINE, HAS ITS OWN CHARACTERISTICS. SOME ENGINES, THEREFORE, COULD HAVE MUCH HIGHER, OR LOWER, REPEATABILITY THAN OTHERS. SIMILARLY, VARIOUS POWER SOURCES, COLD ROOMS, AND, TO SOME EXTENT, PROCEDURAL DEVIATIONS WERE USED IN THE PROGRAMS, all of which could affect repeatability. The importance of the comparison is that the relative level of repeatability, for the engine cranking tests conducted in this program, was at least as good as for similar tests conducted by various laboratories under CRC coordination. The use of these results as representative cranking data, for the engine-oil combinations used, is therefore justified.

The determination of a repeatability ratio, 1.075, served as a check for subsequent tests, and will continue to do so in the future. When two tests are conducted, supposedly on the same variable and under the same conditions, and the results differ by a factor greater than 1.075, with 95% probability a portion of the deviation is due to some cause other than experimental error. The system should be checked, then, for changes which could account for the excessive deviation.

As mentioned in the previous chapter, about midway through the test program a trend toward decreasing cranking speed with successive tests, on the same variable, developed. By making use of the repeatability ratio this trend was discovered, as previously discussed. Investigation revealed that a change had occurred in the characteristics of the cranking motor, resulting in a lower cranking speed to torque relationship than when the tests were initiated. The cranking motor used was a specially calibrated one supplied by Delco-Remy Division of General Motors. In order to duplicate the original conditions a new cranking motor, to duplicate the original one, was obtained and tests were scheduled to repeat all those which resulted in low cranking speeds, previously. Two tests were completed on the development of a new calibration when the cold room facilities being

USED SUFFERED A BREAKDOWN. REPAIRS TO THE REFRIGERATION PLANT COULD NOT BE MADE IN TIME FOR CONTINUATION OF THE PROGRAM. ALL DATA USED FOR COMPARISON AND CORRELATION PURPOSES, THEREFORE, REFLECT THE INFLUENCE OF THE CHANGE IN CRANKING MOTOR PERFORMANCE. IT IS REASONABLE TO EXPECT THAT AN IMPROVEMENT IN BOTH ACCURACY AND REPEATABILITY WOULD HAVE BEEN REALIZED IF THE TESTS WHICH WERE SUSPECT COULD HAVE BEEN REPEATED.

CORRELATION - A ROUND ROBIN SERIES OF ENGINE CRANKING TESTS AT -20°F WAS COORDINATED BY THE CRC. THREE OILS TESTED IN THE ROUND ROBIN WERE ALSO USED IN THIS TEST PROGRAM. THE BEST CORRELATION OF RESULTS BETWEEN THE TWO PROGRAMS, AS SHOWN IN FIGURE 30, PAGE 86, WAS OBTAINED WITH THE LINE $Y = 897+.914X$. THIS LINE INDICATES THAT THE DIFFERENCE BETWEEN OILS, AS DETERMINED BY THE 250 L-6 ENGINE IN THIS PROGRAM, IS NOT AS GREAT AS THAT DETERMINED BY THE CRC TESTS. THE COEFFICIENT OF CORRELATION, .917, INDICATES THAT THERE IS A DEFINITE, IF NOT PRECISE, CORRELATION BETWEEN THE TWO PROGRAMS. THE MAJOR DEVIATION IN RESULTS OCCURRED WITH OIL REO-158. THIS OIL HAS A HISTORY OF POOR REPRODUCIBILITY AMONG LABORATORIES, IN VARIOUS VISCOMETRIC DEVICES[38]. THE DEVIATION IN THIS CASE IS, THEN, NOT UNEXPECTED ALTHOUGH IT IS UNEXPLAINED. SPECULATION SUGGESTS THAT, SINCE THE OIL TESTED WAS BLENDED IN 1963, AGING MAY HAVE AFFECTED ITS PROPERTIES. THERE IS NO TECHNICAL EVIDENCE TO SUPPORT THIS THEORY, HOWEVER. ANOTHER POSSIBLE EXPLANATION MAY BE PROMPTED BY THE FACT THAT THE OIL HAS A RELATIVELY HIGH (-10°F) POUR POINT, INDICATING THAT A GREATER DEGREE OF WAXINESS IS PRESENT THAN IN THE OTHER OILS TESTED. AT -20°F, WHERE THE TESTS WERE CONDUCTED, THE CHARACTERISTICS OF THE OIL COULD BECOME INCONSISTENT DUE

TO VARIATIONS IN THE WAX STRUCTURE FORMED DURING COOLDOWN. IT IS ALSO PROBABLE THAT, IN THE WAXY STATE, THE OIL CEASES TO ACT AS A FLUID IN THE ENGINE. THESE THEORIES MAY, IN WHOLE OR IN PART, ACCOUNT FOR SOME OF THE PROBLEMS ENCOUNTERED IN REPRODUCING TEST RESULTS WITH THIS OIL.

FOR CORRELATION PURPOSES IT IS NECESSARY TO ASSUME THAT ONE SET OF DATA IS CORRECT. IN THIS CASE THE ASSUMPTION WAS MADE FOR THE CRC DATA. THE ASSUMPTION IS NOT VALID, HOWEVER. THE CRC DATA ARE THE AVERAGES FROM A NUMBER OF TESTS IN A NUMBER OF (IN THIS CASE EIGHT) DIFFERENT ENGINES. THE DEVIATION IN RESULTS AMONG THESE LABORATORIES IS SO GREAT THAT IN REPORTING THE DATA[43] NO REPRODUCABILITY RATIO WAS CALCULATED. IT IS POSSIBLE, THEN, THAT THE RESULTS FROM ANY ONE OF THE PARTICIPATING LABORATORIES, IF CORRELATED AGAINST THE AVERAGE RESULTS, COULD DEVIATE AS MUCH AS OR MORE THAN THE RESULTS OF THIS PROGRAM. IT IS IMPORTANT THAT THE VALIDITY OF THE CRC DATA BE KEPT IN PERSPECTIVE, AND THAT THEY BE TREATED AS AVERAGES INDICATING THE RELATIVE COLD CRANKING PERFORMANCE OF OILS RATHER THAN ABSOLUTE VALUES OF VISCOSITY. IF THE TESTS WERE REPEATED BY THE SAME LABORATORIES, USING ENGINES OF DIFFERENT TYPES AND SIZES IT IS PROBABLE THAT THE RELATIVE PERFORMANCE WOULD BE THE SAME, BUT THE NUMERICAL VISCOSITY VALUES COULD DIFFER. THE DEGREE OF CORRELATION BETWEEN THE RESULTS OF THIS PROGRAM AND THOSE OF THE CRC PROGRAM IS INDICATIVE, THEN, OF THE GENERAL DEVIATIONS WHICH EXIST IN ENGINE VISCOSITY MEASUREMENTS.

THE EXPERIMENTAL SHELL OILS USED IN THIS PROGRAM WERE TESTED IN A COLD CRANKING ENGINE BY THE SHELL CANADA RESEARCH LABORATORY. THE ENGINE USED WAS A CHEVROLET 230 L-6 SIMILAR IN DESIGN TO THE 250 L-6 USED IN THIS PROGRAM. THE SHELL RESULTS WERE DETERMINED IN A

MANNER SLIGHTLY DIFFERENT THAN THAT SPECIFIED BY THE CRC, IN THAT, THE CRANKING TORQUE WAS MEASURED AND CONVERTED TO VISCOSITY ACCORDING TO THE PROCEDURE OF APPENDIX K. THE RESULTS OF THIS PROGRAM WERE CORRELATED WITH THOSE OF THE SHELL PROGRAM. THE LINE OF BEST FIT, AS SHOWN IN FIGURE 31, PAGE 89, WAS FOUND TO BE $Y= -45.6+.848X$. THE DEVIATION OF THIS LINE FROM THAT OF PERFECT CORRELATION INDICATES THAT THE TESTS CONDUCTED IN THIS PROGRAM SHOWED A SMALLER DIFFERENCE BETWEEN OILS THAN DID THE SHELL TESTS. THE COEFFICIENT OF CORRELATION, .990, SHOWS THAT CORRELATION IS VERY GOOD, BETTER THAN WITH THE CRC ENGINE AVERAGES. AN IMPROVEMENT OVER THE CRC ENGINE TEST CORRELATION COULD BE EXPECTED BECAUSE OF THE SIMILARITY IN THE ENGINES USED IN THIS CASE. THE LOWER APPARENT VISCOSITIES DETERMINED IN THIS PROGRAM COULD BE DUE TO ONE OR A COMBINATION OF MANY FACTORS, INCLUDING ENGINE DIFFERENCES, CRANKING MOTOR DIFFERENCES, POWER SUPPLY DIFFERENCES AND PROCEDURAL DIFFERENCES.

THE SAME COMMENTS MADE WITH REGARD TO THE ASSUMPTION OF CORRECTNESS FOR THE CRC ENGINE TESTS HOLD TRUE IN THIS CASE. THE SHELL TEST RESULTS WERE ASSUMED CORRECT FOR CORRELATION PURPOSES. THERE ARE, HOWEVER, NO "CORRECT", OR ABSOLUTE, ENGINE VISCOSITIES. THE IMPORTANCE OF THE CORRELATION, THEN, IS NOT IN THE FACT THAT ONE TEST PROGRAM GIVES LOWER ENGINE VISCOSITIES THAN THE OTHER, BUT IN THE FACT THAT THE DEVIATION IS CONSISTENT AND PREDICTABLE.

IN SUMMARY, THE RESULTS OF CRANKING TESTS CONDUCTED IN THIS PROGRAM WERE IN RELATIVE AGREEMENT WITH THOSE OBTAINED IN SIMILAR TESTS ON THE SAME OILS.

Cold Cranking Simulator

Data Reduction - As described in the previous chapter, calibration oils were run to develop a curve each day. The problems inherent in the use of graphical calibration curves were also described in the previous chapter. Aitken's process, a numerical interpolation method was used to determine the viscosities of all test oils, using the calibration oil results as the standard. By using the method of numerical interpolation all inconsistencies in the calculation of test oil viscosities were eliminated. The element of human error involved was reduced to that in reading the speed indication from the milliammeter. Human errors in fitting the calibration curves and determining test results from them were completely eliminated.

The use of the numerical interpolation method would be particularly valuable for comparing viscometric results from different tests conducted by different people, in different instruments, or at different times. In making such comparisons using the graphical method some error due to human variables is likely to occur. Use of the numerical method insures against the occurrence of such errors. Furthermore, there is an opportunity to improve upon the precision of the results, although the opportunity was not taken in this program. Because of limitations in reading the log-log calibration graphs all readings below 3000 cp were rounded off to the nearest 10 cp, those between 3000 and 6000 cp were rounded off to 50 cp, and those greater than 6000 cp were rounded off to the nearest 100 cp. This practice was specified by the ASTM in the cold cranking simulator procedure (Appendix D). In order to make

VALID COMPARISONS WITH OTHER RESULTS THE PRACTICE WAS ADHERED TO FOR THIS PROGRAM AS WELL. THE NUMERICAL METHOD, HOWEVER, PROVIDES WHATEVER PRECISION IS REQUIRED. THE ADDED PRECISION AVAILABLE WITH THIS METHOD COULD BE OF PARTICULAR IMPORTANCE IN COMPARING TWO VERY SIMILAR OILS. FOR EXAMPLE, TWO OILS TESTED IN A SUBSEQUENT PROGRAM WERE FOUND TO HAVE CALCULATED VISCOSITIES OF 3217 AND 3230 CENTIPOISE. USING THE GRAPHICAL METHOD THESE READINGS WOULD BE 3200 AND 3250 CENTIPOISE, RESPECTIVELY. WITH THE GRAPHICAL METHOD THERE APPEARS TO BE A DIFFERENCE IN THE OILS WHICH DOES NOT EXIST WHEN THE RESULTS AND DETERMINED NUMERICALLY.

IT IS PROBABLE THAT THE AMOUNT OF ERROR IN THIS TEST PROGRAM WAS REDUCED BY THE USE OF NUMERICAL INTERPOLATION IN DETERMINING TEST OIL VISCOSITIES.

<u>REPEATABILITY AT 0°F</u> - A FULL SCALE TEST PROGRAM WAS CONDUCTED AT 0°F IN PREPARATION FOR THE FORMAL TEST WORK AT -20°F. THE REPEATABILITY OF THE TEST PROGRAM WAS DETERMINED TO BE VERY HIGH, WITH A STANDARD DEVIATION 1.21% OF THE MEAN, AND 95% CONFIDENCE LIMITS $\pm$1.68% OF THE MEAN. THE REPEATABILITY RATIO OF 1.04 COMPARED FAVOURABLY WITH THAT OF 1.06 DETERMINED FOR THE ASTM SECOND ROUND ROBIN. THE COMPARISON INDICATED THAT THE REPEATABILITY OF THE COLD CRANKING SIMULATOR AND THE METHOD USED IN THIS PROGRAM WAS REPRESENTATIVE OF OTHER COLD CRANKING SIMULATORS USED IN THE ROUND ROBINS.

THE HIGH REPEATABILITY OF THE TEST PROGRAM INDICATED THAT THE INITIAL PROBLEMS ENCOUNTERED IN CLEANING THE VISCOMETER, AS DESCRIBED IN THE DEVELOPMENT OF TEST PROCEDURE, WERE OVERCOME. THE PROCEDURE used was apparently satisfactory for operation at 0°F.

Certain readings, of the original test program, were found to be out of line when the repeatability ratio established was applied to them. When these readings were discarded and repeat tests were made the repeat results fell within the repeatability limits. The reason for the erroneous results could not be determined. There was, however, 95% probability that some cause other than experimental error was responsible. Possible sources of error could have been poor temperature control or contamination in the sample although neither of these were apparent at the time of test.

Correlation at 0°F - Engine cranking tests at 0°F were conducted on the seven experimental Shell oils by the Shell Research Laboratory. The same method of engine viscosity determination previously discussed (Appendix K) was used in this case. A correlation of the cold cranking simulator results from this program with the Shell program resulted in a correlation coefficient of .507. The line Y= 755+.306X was found to be the best fit, as shown in Figure 33, page 104.

Similarly, a correlation was made with the results of the original CRC engine cranking program at 0°F. The correlation coefficient was determined to be .931, and the line of best fit, shown in Figure 34, page 106, was Y=1.032X.

In both cases the engine viscosities were considered to be correct. This assumption has been previously explained to be invalid. In the case of the Shell data, conversation with personnel involved in the tests revealed that a number of problems were encountered with cranking motors during the program. Although no raw data or statistical analysis was available for this data knowledge of the problems encountered cast suspicion on the validity of the results.

A possible cause of deviation between the CCS and CRC engine viscosities in some cases may be noted in Table XIX, page 133. The original engine tests were conducted on research oils blended in 1961 and 1963. In the meantime supplies of some of these oils were depleted and duplicate batches were blended. Although the second and third batches were blended to have the same physical properties as the first, some variations were possible. In the cases where the tests were not on the same batch small deviations could occur due to oil differences.

In order to evaluate the accuracy of the results of this program a correlation was also made with the cold cranking simulator results obtained in the ASTM second round robin. The best fit line was $Y=73+.930X$ with the ASTM data assumed correct. The coefficient of correlation was .983. The high coefficient of correlation and low deviation, as shown in Figure 35, page 108, indicate that the accuracy of this test program was equivalent to that of the ASTM program.

In summary, the correlation results, as well as the repeatability results, at 0°F, showed that the test instrument and procedure used gave equivalent results to cold cranking simulators in prior use, and that the repeatability and accuracy of the instrument were comparable to those determined by others.

<u>Repeatability at -20°F</u> - A full scale test program, with six tests on each oil, was conducted at -20°F using the procedure described in Experimental Procedures. Some problems in repeatability were encountered

TABLE XIX

BLENDING DATES OF REO OILS TESTED

TEST PROGRAM

OIL	GM - CCS	GM L-49	ASTM CCS (0°)	ASTM CCS (-20°)	CRC L-49(0°)	CRC L-49(-20°)
REO -151	'65	'65	'61	'65	'61	-
REO -153	'65	'65	'61	'65	'61	'65
REO -161	'63	'63	'63	-	'63	-
REO -162	'63	'63	'63	-	'63	-
REO -158	'63	'63	'61	'63	'61	'63
REO -159	'63	'63	'61	'63	'61	'63
REO -160	'63	'63	'61	-	'61	-
REO -172	'65	'65	'63	'65	'63	'65

which were not apparent in the Analysis of Results.

During -20°F tests of the experimental oil Shell G, a strange phenomenon was noted. The sample was cooled according to the established procedure and the motor was started. The speed indicator stabilized normally but before the specified sixty seconds had elapsed for a reading to be taken, the speed indicator reading jumped to an abnormally high value. Sometimes the reading would stabilize at this high value while other times it would fluctuate between the original and high values. Accompanying the change in indicator reading was a change in the physical location of the sample in the viscometric cell. The diagram in Figure 40, page 135, show the distorted profile of the sample. In examining the action closely the sample was noted to climb up the center shaft of the rotor, distorting the remaining sample in the cup until the oil was rapidly separated from the wall of the stator and formed into a ball around the rotor shaft. Movies of the phenomenon were made and proved to be beneficial in isolating the stages of the occurrence. A photograph of the sample in its final "balled up" stage is shown in Figure 41, page 136.

During the program a number of commercial engine oils were tested in the instrument and the same phenomenon was noted in four of these products. In all cases the phenomenon occurred with 5W30 oils of "Super Premium" quality. From information gained from the manufacturers of these oils it appeared that all had very high polymer content although the actual type of polymer used could not be disclosed. In the case of the Shell oils the polymer content appeared to be the only major deviation from the other 5W30 oils. It appeared, then, that

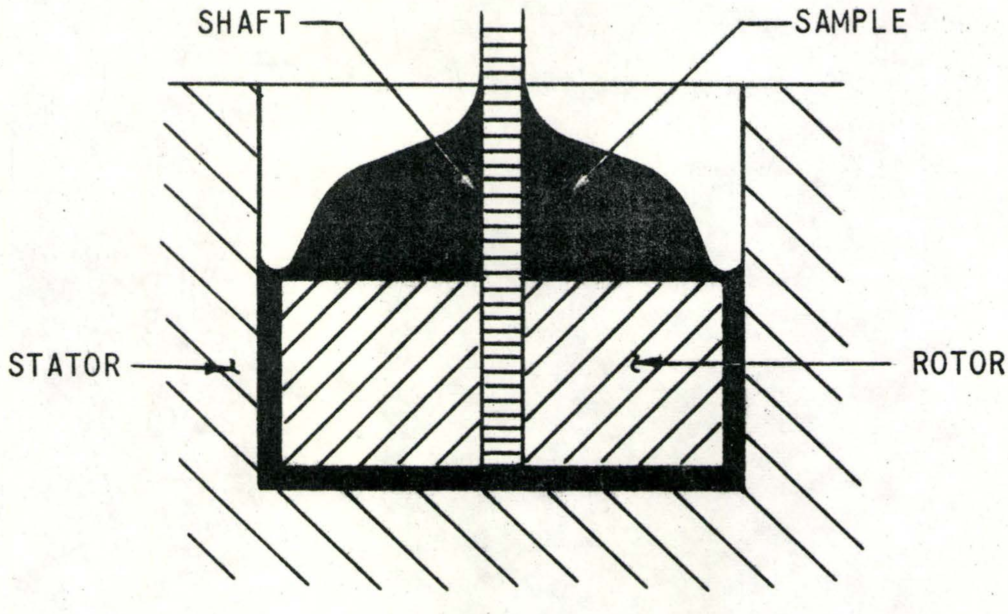


FIGURE 40 - BALLING EFFECT OF OIL SAMPLE

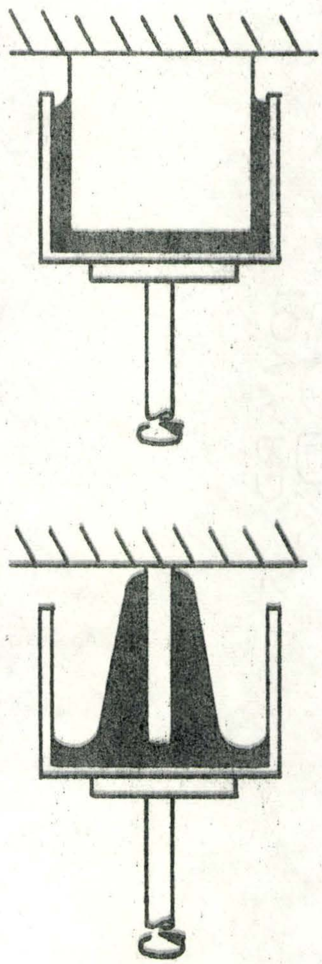
FIGURE 41.

MULTIGRADE OILS WITH VERY HIGH AMOUNTS OF POLYMER WERE SUSCEPTIBLE TO "BALLING UP" IN THE COLD CRANKING SIMULATOR AT -20°F.

IN DISCUSSING THE PHENOMENON WITH PERSONNEL FROM ONE OF THE OIL COMPANIES WHOSE PRODUCT WAS INVOLVED, SIMILAR OCCURRENCES IN OTHER APPLICATIONS WERE RECALLED. THESE OCCURRENCES HAD BEEN DESCRIBED AS THE "WEISSENBERG EFFECT" ALTHOUGH THE PRECISE MEANING OF THE TERM COULD NOT BE EXPLAINED. A BRIEF LITERARY STUDY REVEALED CONSIDERABLE INFORMATION IN THIS REGARD.

IN 1947, DR. K. WEISSENBERG[(40) (50)] OBSERVED THAT A GREAT VARIETY OF RHEOLOGICAL PHENOMENA OCCURRED WHEN FLUIDS OF DIFFERENT KINDS WERE SUBJECTED TO MECHANICAL ACTIONS. IN A MACROSCOPIC STUDY OF THESE PHENOMENA SEVEN FORMS OF MECHANICAL ACTION WERE INVESTIGATED. IT WAS LEARNED THAT, IN AN ACTION SIMILAR TO THAT OF THE COLD CRANKING SIMULATOR, THE COMBINED ACTIONS OF THE SHEAR IMPOSED AT THE BOUNDARIES, AND THE FORCES OF GRAVITY AND INERTIA (CENTRIFUGAL FORCES), THE LIQUID EXECUTES A STATIONARY LAMINAR SHEARING MOVEMENT SUCH THAT THE STRESS HAS ITS STRENGTH DISTRIBUTED OVER THE VARIOUS DIRECTIONS IN SPACER TO COMPRISE, IN ADDITION TO THE SHEAR STRESS COMPONENTS, A PULL ALONG THE LINES OF FLOW. WHEN THE LINES OF FLOW ARE CLOSED CIRCLES, AS IN THIS CASE, THE PULL ALONG THESE LINES STRANGULATES THE LIQUID AND FORCES IT IN AGAINST THE CENTRIFUGAL FORCES AND UPWARDS AGAINST THE FORCE OF GRAVITY. THIS CONDITION IS ILLUSTRATED IN FIGURE 42, PAGE 138, FOR THE TWO CONDITIONS WHICH COMPRISE THE ACTION OF THE COLD CRANKING SIMULATOR.

WEISSENBERG'S FINDINGS WERE REINFORCED AND EXPANDED BY RIVLIN (51) (52) (53) WHO MADE SOME STUDIES OF THE EFFECT ON NORMAL STRESS OF POLYMER CONCENTRATIONS AND TEMPERATURE. ONE OF THE POLYMERS USED WAS



FIXED CYLINDER
ROTATING CUP (HIGH SPEED)
SMALL SIDE GAP

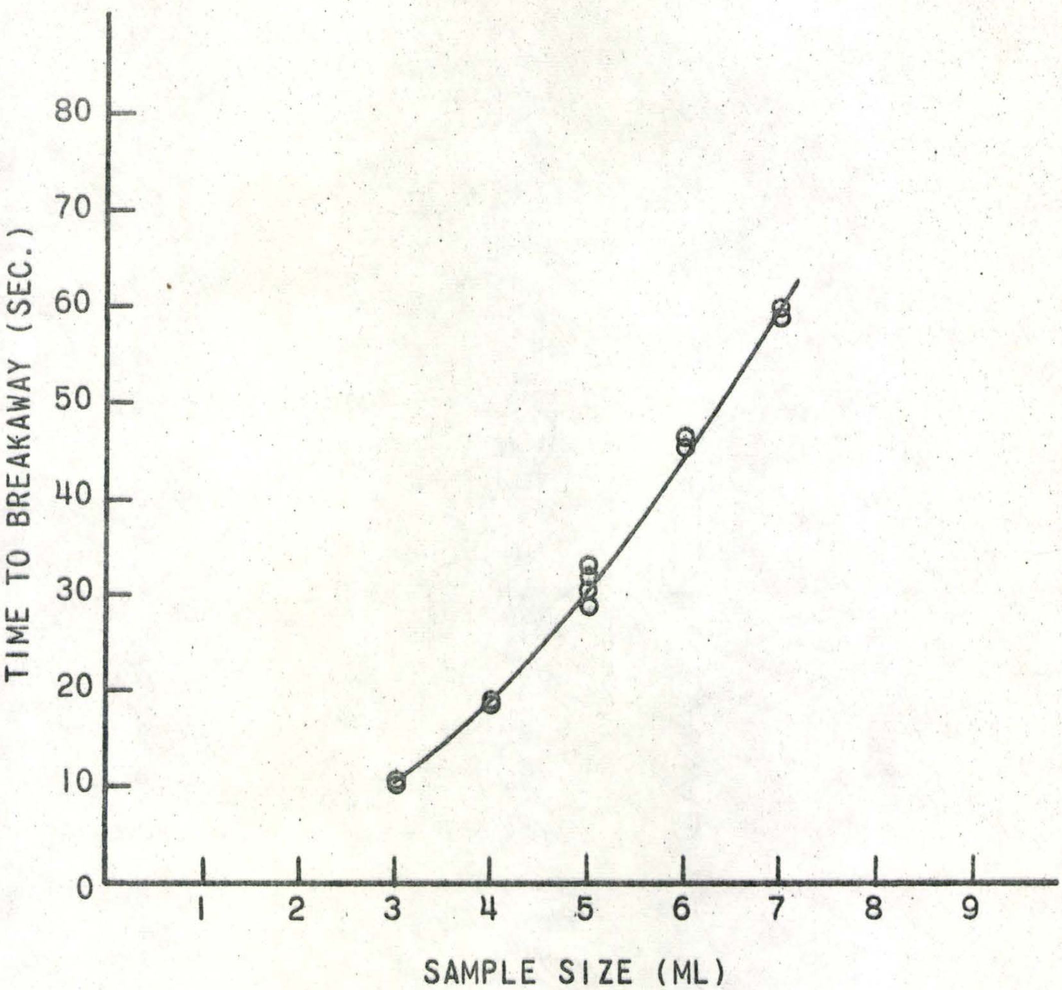
FIXED ROD
ROTATING CUP (HIGH SPEED)
LARGE SIDE GAP

FIGURE 42 - WEISSENBERG EFFECT

POLYISOBUTYLENE, WHICH IS ALSO A COMMONLY USED VI IMPROVER IN ENGINE OILS. NORMAL STRESSES WERE FOUND TO INCREASE ALMOST DIRECTLY WITH INCREASED POLYMER CONCENTRATION AND, CONVERSELY TO DECREASE ALMOST DIRECTLY WITH INCREASED TEMPERATURE.

A NUMBER OF STEPS WERE TAKEN, EXPERIMENTALLY, TO LEARN MORE ABOUT THE PHENOMENON. THE SIZE OF THE SAMPLE PLACED IN THE CUP WAS VARIED, AND THE RESULTING EFFECT ON BALLING WAS NOTED. THE TIME REQUIRED FROM MOTOR START-UP UNTIL THE BALL WAS FORMED AND THE OIL WAS BROKEN AWAY FROM THE STATOR WAS FOUND TO INCREASE AS THE SAMPLE SIZE WAS INCREASED, AS SHOWN IN FIGURE 43, PAGE 140. THE SIZE OF THE CUP LIMITED THE SAMPLE SIZE TO A MAXIMUM OF SIX MILLILITERS. THIS QUANTITY WAS NOT SUFFICIENTLY LARGE TO EXTEND THE TIME BEFORE BALLING BEYOND THE SIXTY SECOND LIMIT SO THAT A READING COULD BE TAKEN. EXTRAPOLATING THE GRAPH OF FIGURE 43, IT APPEARED THAT AN 8 ML SAMPLE WOULD EXTEND THE TIME TO BALL-UP BEYOND 60 SECONDS.

THE USE OF A FROST SHIELD TO INHIBIT FROST FORMATION WAS DESCRIBED IN EXPERIMENTAL PROCEDURES. THIS SAME SHIELD WAS ALSO UTILIZED IN AN ATTEMPT TO PROVIDE LARGER SAMPLE CAPACITY TO PREVENT BALLING. THE SAMPLE CUP WAS FIRST FILLED TO THE TOP WITH THE TEST OIL. A FILM OF TEST OIL WAS THEN PLACED OVER THE TOP OF THE COPPER STATOR TO ACT AS A SEAL, AND THE FROST SHIELD WAS SET IN PLACE AND SECURELY CLAMPED. MORE TEST OIL WAS THEN ADDED UNTIL THE LEVEL REACHED THE TOP OF THE FLEXIBLE PORTION OF THE ROTOR SHAFT. THE TEST WAS THEN CONDUCTED ACCORDING TO THE NORMAL PROCEDURE. AS EXPECTED, NO BALLING OF THE SAMPLE OCCURRED AND STEADY, STABILIZED SPEED READINGS WERE OBTAINED. THIS TECHNIQUE, ALTHOUGH MESSY, PROVED TO BE VERY SUCCESSFUL AND WAS USED



COMMERCIAL OIL F-5W30 WAS USED TO DEVELOP THIS RELATIONSHIP

FIGURE 43 - EFFECT OF SAMPLE SIZE ON THE BALLING PHENOMENON

throughout the -20°F program whenever an oil balled up with the standard (5 ml) sample size.

Another technique was employed by one of the oil companies in an attempt to eliminate balling, and was found to be similarly successful. A small sample (3 ml) was used in the viscometric cell for cooldown and temperature stabilization. Immediately after the motor was started the remaining two ml of warm test sample were added. The result was a stabilized, steady reading without balling of the sample. This method was duplicated and compared to that of increased sample size. Over three tests the difference in results between the two methods was so negligible that it could not be read on the milliammeter speed indicator scale.

In both methods the reason for improvement appeared to be the same. In both cases a volume of oil was present at the top of the sample which was warmer than that beneath it, either because there was not cooling around that part of the sample or because there was not sufficient time after it was added to cool it to test temperature.

From the results of Rivlin's[51] work a decrease in normal shear stress was found with an increase in temperature. The temperature deviation, then, caused a decrease in normal shear stress at the top of the sample which prevented the Weissenberg effect from occurring.

Once the problem of balling was overcome the remainder of the -20°F test program was conducted without further mishap. A repeatability analysis was carried out on the six sets of data for each oil, using the method of Appendix E. The coefficient of variation, or standard deviation expressed as a percent of the mean, was found to be

1.73%, an exceptionally low value. Similarly, the 95% confidence limits were found to be ±1.97% of the mean, also extremely low. These low values are indicative of the high level of repeatability achieved in the test program.

Table XVII, page 115, compared the repeatability results obtained in the -20°F program with those from the 0°F program. Although the results at 0°F were more repeatable the difference was not large. The added severity of the -20°F conditions plus the added possibility of irregularities in the samples at this temperature would support the expectation that poorer repeatability would result.

As mentioned previously a round-robin series of -20°F tests was conducted concurrently under the organization of the ASTM. Although different oils, in different viscosity ranges, were used, for the most part, in the two programs, the repeatability results obtained compared favourably with each other, indicating the consistency which can be expected with the cold cranking simulator.

In summary, the cold cranking simulator was found to have excellent test repeatability at -20°F. If two test runs are made on an oil and the results are found to be within a ratio of 1.04 to 1.00 of each other, then the test viscosity can be established as being in the range of these results with 95% confidence.

Correlation at -20°F - The results of the cold cranking simulator test program at -20°F were correlated with those of the cold cranking engine program at -20°F for the seven experimental Shell oils and four REO oils. The line of best fit, as shown in Figure 36, page 117, was found

TO BE Y=431+1.036X AND THE COEFFICIENT OF CORRELATION WAS .980. THE CAUTIONS WHICH WERE PREVIOUSLY DISCUSSED, WITH REGARD TO THE TREATMENT OF ENGINE VISCOSITIES AS RELATIVE RATHER THAN ABSOLUTE VALUES, ARE ALSO APPLICABLE TO THIS CASE.

A COMPARISON OF VISCOSITIES MEASURED BY THE COLD CRANKING SIMULATOR AND BY THE ENGINE, IN TERMS OF THE STANDARD DEVIATION OF THE TEST DETERMINATION, SHOWS THAT, THE VISCOSITY VALUES DEFINED BY THE LIMITS ± ONE STANDARD DEVIATION FROM THE MEAN, ARE CONFINED TO A MUCH NARROWER BAND WHEN DETERMINED BY THE COLD CRANKING SIMULATOR THAN BY THE ENGINE CRANKING TESTS. THIS CONDITION ILLUSTRATES THE SHORTCOMINGS OF CORRELATING LABORATORY VISCOSITY WITH ENGINE VISCOSITY. THE PARAMETERS TO WHICH THE VARIABLES ARE BEING COMPARED ARE THEMSELVES MORE VARIABLE THAN THE DATA BEING EVALUATED. IT IS CONCEIVABLE, THEN, THAT POOR CORRELATION COULD OCCUR BECAUSE THE LABORATORY VISCOMETER WAS TOO PRECISE. IN THE CASE OF THE CORRELATION DISCUSSED HERE, HOWEVER, THE COEFFICIENT OF CORRELATION WAS NOT ADVERSELY AFFECTED.

A CORRELATION WAS ALSO MADE WITH ENGINE CRANKING TESTS CONDUCTED ON THE SHELL OILS, AT -20°F, BY THE SHELL RESEARCH LABORATORY. THE LINE OF BEST FIT WAS Y=.992X, AS SHOWN IN FIGURE 37, PAGE 118, BUT THE COEFFICIENT OF CORRELATION WAS ONLY .700 INDICATING THAT THE CCS DATA DID NOT CORRESPOND AS WELL WITH THE SHELL ENGINE CRANKING DATA AS WITH THE ENGINE CRANKING DATA OF THIS PROGRAM.

NOTING THE DISTRIBUTION OF DATA ON FIGURES 36 AND 37 IT IS APPARENT THAT THERE ARE FOUR OILS WHICH HAVE THE SAME VISCOSITY, WHEN MEASURED BY THE COLD CRANKING SIMULATOR BUT HAVE DIFFERENT VISCOSITIES DETERMINED BY THE ENGINES. THE FACT THAT BOTH ENGINES DIFFERENTIATED between the oils cast doubt upon the CCS determinations. Another suspicious fact noted was that the values determined for these four oils were identical within each sequence, even though they varied from one sequence to another. It was also noted, during supplementary tests of a number of commercial oils, that the viscosity of several 5W30 oils showed the same readings.

A review of possible procedural variations which could affect the results, in this manner, revealed nothing. Similarly, no property which was common to these oils only could be discovered, with the exception that their viscosities probably were only slightly different. It appeared then, that some characteristic of the instrument was responsible for the identical results.

The manufacturer was contacted with regard to this phenomenon and provided a probable explanation. The AC-DC electric motor used on the viscometer had a characteristic tendency to become synchronous at a motor speed in the range of 600 rpm. This speed corresponds to a rotor speed of 136 rpm which is achieved at 0°F by oils having viscosities in the middle of the SAE 20W range. At -20°F, however, this speed is reached by oils in the SAE 5W range. The phenomenon is best explained graphically, as illustrated in the calibration curve of Figure 44, page 145. It may be seen from the curve that oils having viscosities in the approximate range of 4400 to 5600 cp will all show the same viscosity.

In order to prevent the synchronous speed effect from affecting results an alternative method of operation was developed by the manufacturer. This method requires a conversion of the console to pro-

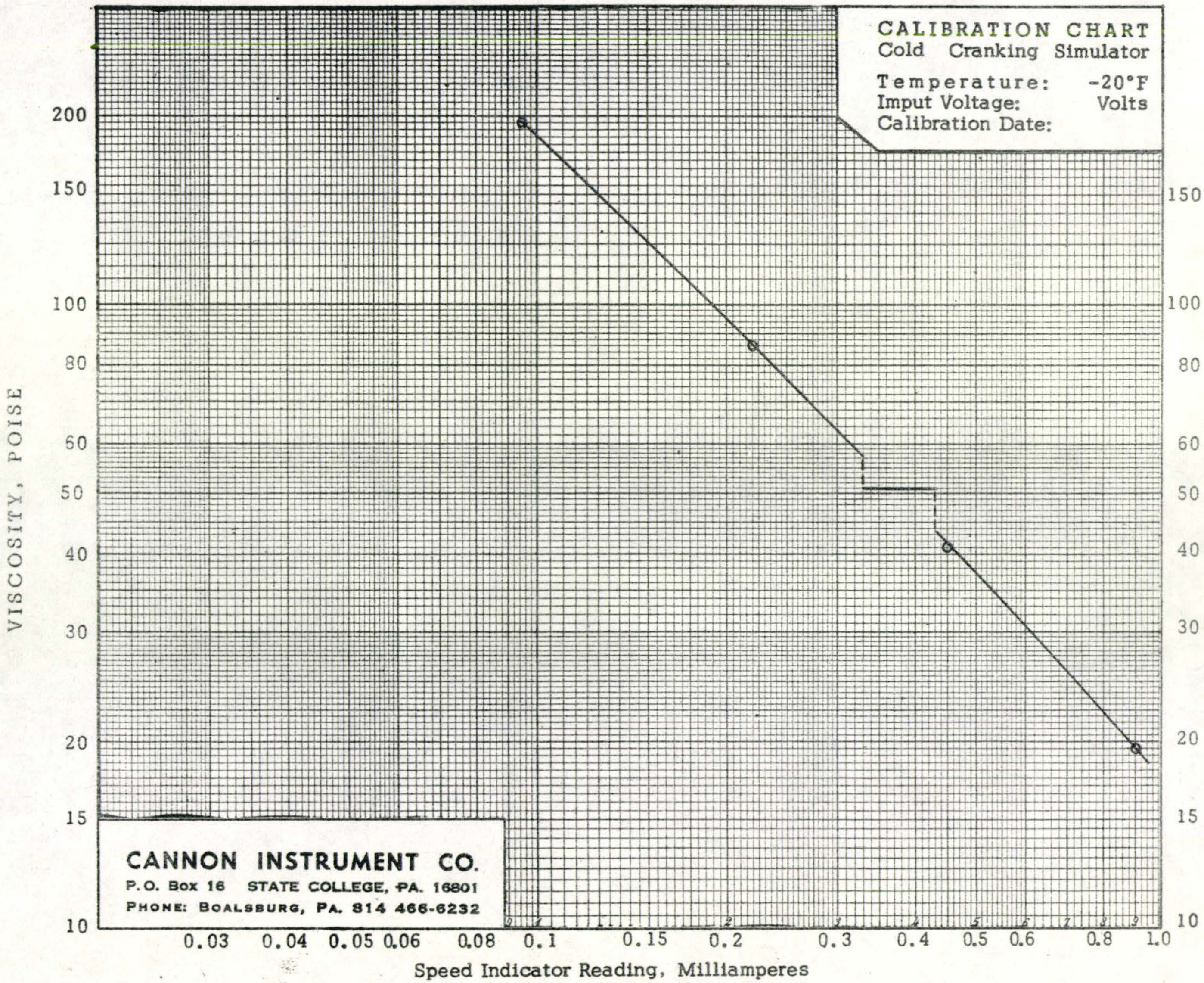


FIGURE 44 - CALIBRATION CURVE - SYNCHRONOUS EFFECT

vide a DC power supply. The motor is then driven on DC and no synchronous effect is encountered. The method of operation with the DC program is described in Appendix L. The control console was returned to the manufacturer for conversion to DC. The test program was completed prior to the conversion, however, and no comparative data were obtained using DC control.

An ASTM procedure, D-2602, has been established for testing, using the AC method, but no provision was made for the DC method. Since current SAE specifications specify viscosity measurement only at 0°F, where the synchronous effect is of little concern, the use of DC control is being provided only for the purpose of research work at this time.

Correlation of the cold cranking simulator results from this program with those from the ASTM round robin, at -20°F, showed a correlation coefficient of .9990. The line of best fit, as shown in Figure 39, page 121, was found to be Y=1.035X. The high correlation obtained indicates excellent reproducability of results between various cold cranking simulators.

In order to illustrate the superiority of Cold Cranking Simulator measured viscosities over the traditional extrapolated viscosities, as limiting standard for SAE winter viscosity grade oils, a number of commercially available engine oils were tested in the simulator. The oils tested are listed in Table XX, page 147, and the results are in Table XI, page 148. All of these oils were necessarily below the SAE winter grade maximum viscosity limits, 800 cp and 2400 cp at 0°F for 5W and 10W respectively, as determined by extrapolation. The CCS viscosities, however, did not necessarily comply. For 5W base oils, considering the

TABLE XX

COMMERCIAL OILS TESTED IN CCS

BRAND	SAE VISCOSITY GRADES TESTED
B-A Durafilm	5W20, 10W30
B-A G.M. Factory Fill	5W20, 10W30
B-P Viscostatic	5W30
Castrol Castrolite	10W30
CTC Superoyl	5W30
Ford Rotunda	5W30
Imperial Uniflo	5W30
Imperial Esso Extra	5W20
Imperial G.M. Factory Fill	5W20(2),10W20, 10W30 (2)
Royalite	5W20, 10W
Shell Super	5W30 (2)
Shell X-100	5W, 5W20, 10W, 10W30
Shell G.M. Factory Fill	5W20 (2), 10W30
Sunoco Special	5W30, 10W40 (2)
Supertest Multigrade	10W30
Texaco Havoline	5W20, 10W30

TABLE XXI

RESULTS OF COMMERCIAL OIL CCS TESTS

SAE GRADE	OIL IDENTIFICATION	CCS VISCOSITY (CP) 0°F	CCS VISCOSITY (CP) -20°F
5W	A	720	2690
5W20	B	600	2380
	C	660	2710
	D	660	3100
	E	740	2900
	F	780	3100
	G	800	3550
	H	810	3450
	I	980	3300
	J	1060	4850
5W30	K	920	4850
	L	980	4850
	M	1010	4850
	N	1020	4850
	O	1030	4850
	P	1050	4850
	Q	1270	4850
10W	R	1410	6600
	S	2100	11000
10W20	T	1480	8000
10W30	U	1250	6000
	V	1350	6950
	W	1640	8200
	X	1680	9400
	Y	1750	9400
	Z	1950	10300
	AA	2100	12100
	BB	2250	14700
	CC	2640	14700
10W40	DD	2050	9100
	EE	2290	14000

800 cp maximum limit, only 5 of 16 oils tested were true 5W oils, and all of these were of the 5W20 type. Considering a recent change in SAE specifications to establish 1200 cp, as measured by the Cold Cranking Simulator, as the maximum limit for 5W oils, all but one of the oils, a 5W30 met the requirements. Figure 45, page 150 illustrates this condition.

The correlation of CCS and engine viscosities has been noted. In order to eliminate the necessity to convert cranking speed to viscosity an attempt was made to relate the engine cranking speed directly to CCS viscosity. The data points and resulting curve are shown in Figure 46, page 151.

It has been previously noted[28] that the general equation for cranking an engine is $M = \kappa (\mu N)^{\frac{1}{2}}$. For the cranking system used on the test engine, and for the speeds obtained, it is reasonable to assume a constant power input to the engine during cranking:

$$P = MN\kappa' = K'$$

or
$$MN = \frac{K'}{\kappa'} = K$$

and
$$M = \frac{K}{N} .$$

Then;
$$\frac{K}{N} = \kappa (\mu N)^{\frac{1}{2}}$$

$$\frac{K^2}{N^2} = \kappa^2 \mu N$$

$$\frac{K^2}{\kappa^2} = \mu N^3$$

or
$$K'' = \mu N^3$$

and
$$\mu = \frac{K''}{N}$$

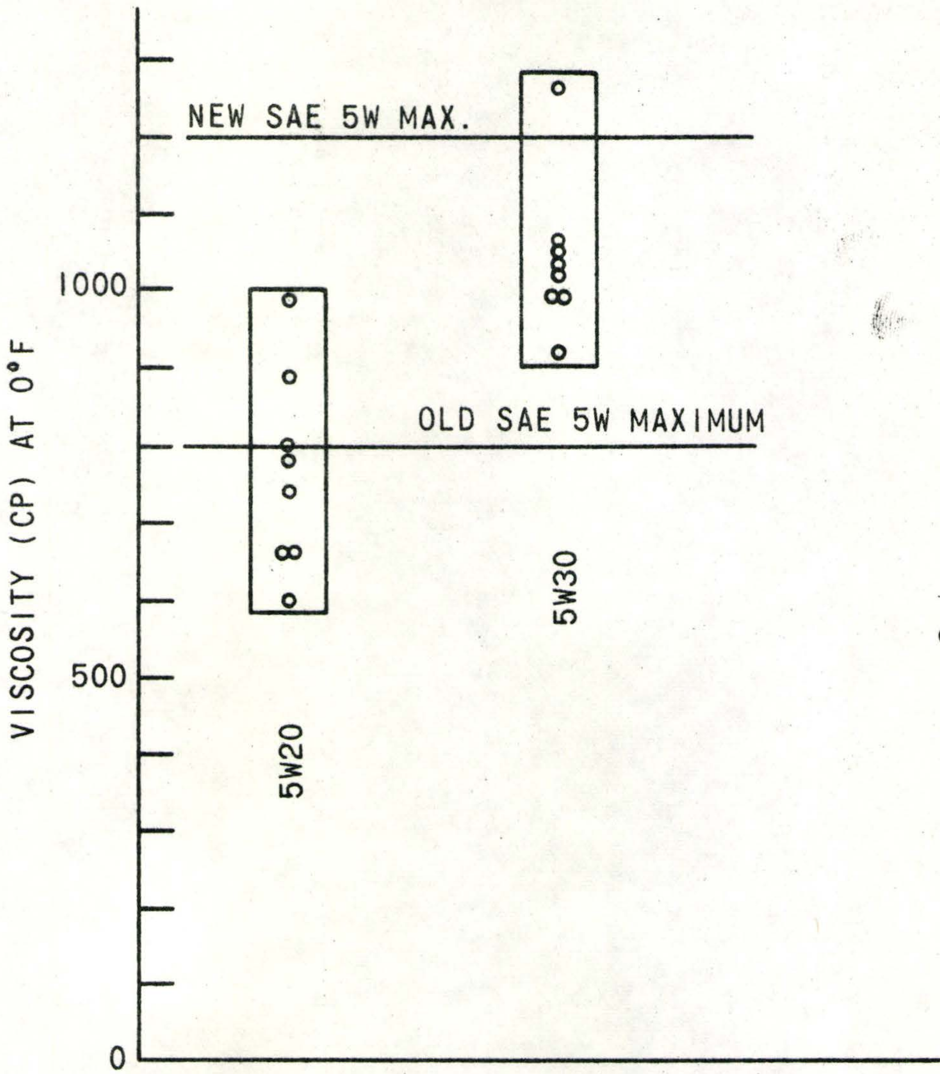


FIGURE 45 - VISCOSITY RANGES OF COMMERCIAL 5W20 AND 5W30 ENGINE OILS

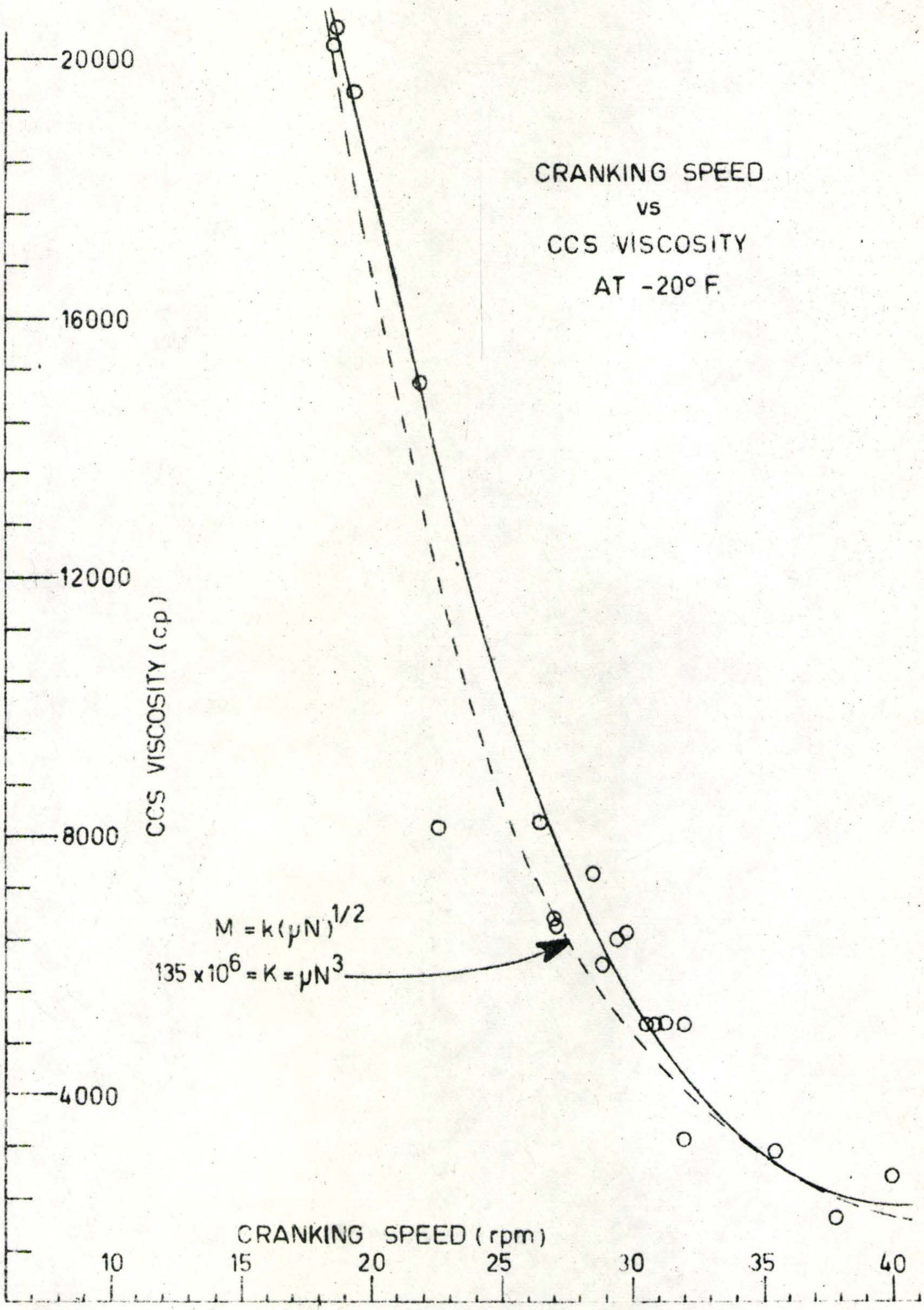

CRANKING SPEED
vs
CCS VISCOSITY
AT -20° F
20000
16000
12000
8000
4000
CCS VISCOSITY (cp)
M = k(μN)^1/2
135 x 10^6 = K = μN^3
CRANKING SPEED (rpm)
10
15
20
25
30
35
40

FIGURE 46

The engine viscosity, then, may be calculated as a function of cranking speed when the engine constant K'' is known. For this engine the engine constant was calculated to be 135×10^6 rev.^{3} cp/min. The curve then, is $\mu = 135 \times 10^6 / N^3$ where μ is viscosity in cp and N is the cranking speed in rpm. As shown in Figure 46, this curve fits the empirically determined curve amost exactly, and may be used, therefore as a good approximation of the cranking speed-viscosity relationship. Similar curves could be determined for other engines by determining the engine constant from a number of calibration tests.

VIII

CONCLUSIONS AND RECOMMENDATIONS

Based on the results analyzed and discussed in the two previous chapters the following conclusions were drawn and recommendations were made. The conclusions will be summarized first, followed by the recommendations.

Conclusions

1. The repeatability of test results from the cold cranking engine at 0°F, as obtained using the test procedure of this program, is sufficiently high to insure meaningful results, when three tests are conducted on a given variable.
2. Although different engines tend to rank oils differently, with regard to numerical viscosity, they tend to rank them in the same order, relatively.
3. The use of numerical methods, specifically Aitken's interpolation process, for determining test oil viscosities relative to those of standard calibration oils, provides consistent and accurate results.
4. The Cold Cranking Simulator used in this program provided 0°F results which were representative of those obtained from Cold Cranking Simulators in general.
5. The Cold Cranking Simulator, when used according to the method of this program, provides a high degree of repeatability at -20°F, only slightly poorer that at 0°F.

6. With some engine oils, having a high polymer content, it is necessary to "overfill" the sample cup in order to obtain significant test results by preventing the occurrence of the Weissenberg effect.

7. Use of the AC method of operation of the Cold Cranking Simulator results in inaccurate viscosity determinations over a small range of viscosities near 5000 centipoise, due to synchronous effect of the drive motor.

8. The correlation between Cold Cranking Simulator and Cold Cranking Engine viscosities is sufficiently high to warrant their use interchangeably, provided the precise conditions of the engine tests are explained as a parameter of the engine viscosity.

9. The correlation of Cold Cranking Simulator and Cold Cranking Engine test results, at -20°F, for oils in the SAE 5W range, could be improved by use of the DC method of simulator operation.

10. The viscosities determined from Cold Cranking Simulator tests, at -20°F, can be related directly to the cranking speed of a specific engine, approximately according to the relationship $M = K(\mu N)^{\frac{1}{2}}$, where M is cranking torque, K is an engine constant, μ is the viscosity, and N is the cranking speed.

11. Use of the Cold Cranking Simulators as the standard of measurement for SAE recommended, 0°F maximum viscosities will insure compliance of all oils, both single and multigrade with the specified winter grade viscosity limitations,

AND WILL ELIMINATE THE INEQUITIES POSSIBLE WITH THE EXTRAPOLATION METHOD.

Recommendations

1. A minimum of three tests should be conducted on any test oil, in either the Cold Cranking Simulator or Cold Cranking Engine, in order to insure statistically significant results.
2. Numerical methods should be used, in preference to graphical methods, to determine the viscosity of a test oil from a calibration curve for either the Cold Cranking Simulator or Cold Cranking Engine.
3. Cold Cranking Simulators destined for use at -20°F should be modified to provide a sample capacity of at least 8 ml., with coolant circulated only around the area cooled in the current models.
4. The DC method of Cold Cranking Simulator operation, as specified in Appendix L, should be used for all tests conducted at -20°F.
5. In order to predict the cranking performance of a given engine for a variety of oils, an engine constant, K, should be determined by conducting cranking tests on a minimum of three calibration oils, and then predicting the cranking speeds from the relationship $M = K(\mu N)^{\frac{1}{2}}$.
6. In order to insure the necessary cranking performance of SAE winter grade motor oils in the 5W range, specifications should be established to limit viscosity at -20°F according to the Cold Cranking Simulator DC method.

IX

APPENDICES

A	Test Procedure - CRC-L49-663
B	Test Procedure - GM 66L-14-44
C	Test Procedure - ASTM CCS Tentative
D	Test Procedure - ASTM - D2602-67
E	"Student's" t Method of Analysis
F	Correlation Method
G	Aitken's Interpolation Process
H	Test Oil Properties
J	Random Order of Tests
K	Shell Method of Engine Viscosity Determination
L	DC Method of CCS Operation

APPENDIX A

RESEARCH TECHNIQUE FOR DETERMINING THE LOW-TEMPERATURE CRANKING CHARACTERISTICS OF ENGINE OILS

(CRC Designation L-49-663)

A. PURPOSE

This research technique has been formulated by the Group on Relationship Between Oil Characteristics and Engine Cranking of the CRC Motor Vehicle Fuel, Lubricant, and Equipment Research Committee for guidance in evaluating the low-temperature cranking properties of motor oils by mean of actual cranking tests in a multicylinder automotive engine in the laboratory. A considerable amount of flexibility in procedure and equipment has been provided for in this technique to make it as broadly applicable as possible. Wherever more than one procedure is available, a discussion of the relative merits of each has been included.

B. TEST EQUIPMENT

1. Engine - A modern, multicylinder automotive engine should be used. The oil filter should be removed; also, the transmission, power assist drives, and air conditioner (if any) should be removed or disengaged. Other items such as the fan, water pumps, generator, and fuel pump may be either removed or retained in accordance with the particular installation involved. Spark plugs should be in place while cranking. Where solid valve lifters are available, it is recommended that they be used in place of hydraulic valve lifters to eliminate cranking inconsistencies that might be encountered due to lifter leakdown.

   The engine should have been run the equivalent of at least 1500 miles under cycling speed and load conditions prior to its use on the test stand. It is then necessary to conduct five low-temperature cranking test cycles in order to further break in the engine and insure reproducibility. A number of investigators have reported a gradual trend in cranking effort which may persist beyond 20 tests. Therefore, a common reference oil should be run approximately every five tests to monitor the repeatability of the results. It has also been reported that repeatability is generally poorer during the early tests on an engine.

2. Cranking Power Supply - Two alternative methods may be employed for cranking the engine. The engine may be cranked by its own starting motor or by a suitably sized electric motor and gear train.

B. TEST EQUIPMENT (Cont'd)

a. Cranking with Starter Motor: Repeatability of cranking tests when using the engine's starting motor is dependent in large part upon the starter motor and supply of d-c used to power the motor. Good brush contact on the commutator of the starter motor is essential. The brushes should therefore be seated onto the commutator. This can be done by placing a fine abrasive compound (such as that used for lapping in valves on an engine) on the commutator and running the starter motor. After enough of the brush has been removed so that it conforms closely to the commutator, the starter motor should be cleaned thoroughly of all traces of abrasive.

A d-c source of appropriate voltage should be available. This power supply should have a high enough capacity to supply a power greater than that obtainable from the fully charged battery normally used with the engine in question. The power supply should be capable of maintaining the current and voltage under high power outputs with little change over a period of 15 seconds. The power supply should be consistent from crank to crank and day to day. Two such sources have been found to be suitable: six or more heavy-duty, lead-acid storage batteries in parallel at 50-100°F, and a transformer rectifier power supply. It has generally been found that a single lead-acid storage battery at 0°F or below is not as reproducible a source of power for cranking tests as the two methods outlined.

If the above power supplies are used directly, somewhat higher cranking speeds will be encountered than with a single battery at 0°F. The reason for this is that the battery at 0°F has an appreciable internal resistance which causes the voltage at the starter motor to drop as more current is drawn. It is permissible to simulate the characteristics of a battery at 0°F by inserting a suitably sized resistor into the circuit in series with power supply. As a result, lower cranking speeds will be produced but the spread in cranking speeds between different oils will also be reduced.

The engine, power supply, and associated equipment should be chosen such that oils in the range of interest will not be cranked below 35 rpm since cranking results become progressively more erratic in a lower speed range. Low cranking speeds also tend to reduce the spread obtained between different oils and thus make it difficult to distinguish between them. Very high cranking speeds should also be avoided because of a possible loss of sensitivity as the cranking motor approaches its maximum speed. Data available to date have shown no clear advantage for cranking in any particular portion of the 35-200 rpm range.

B. TEST EQUIPMENT (Cont'd)

The engine may also be equipped with an additional electric motor and drive capable of turning the engine over at 400–600 rpm at an oil sump temperature of 140–180°F for at least 15 minutes.

b. Cranking by Dynamometer or External Electric Motor: In this procedure, the engine is cranked at constant speed and the torque required is measured. The preferable method employs a synchronous a-c motor with a power rating well in excess of the cranking requirements of the engine. The torque can be measured by cradling the motor-gear train or by suitably placed strain gauges.

3. Low-Temperature Chamber – A chamber large enough to accommodate the engine and its auxiliary equipment must be provided. If the engine is removed periodically from the chamber, provision should be made to return it each time as nearly as possible to the same location. The temperature of the room should be controlled to ±1° F for periods of at least 18 hours.

C. INSTRUMENTATION

1. Temperature Measurement – Engine temperatures should be measured in the bulk oil in the crankcase, and in the water jacket. These measurements should be performed with a remote reading device so that the cold room does not have to be entered. A continuous record of the oil sump temperature should be obtained during the cool-down and cold soak periods.

2. Cranking Effort Using Starter Motor – Provision should be made to measure and record continuously the following during a cranking test:

a. Current flow through the starter (amp).

b. Accurate measure of time elapsed.

c. Torque, if measured independently of the above current measurement.

Note: Cranking speed can be obtained from the above data as discussed in Section F, item 1a.

It is desirable but not essential to measure and record continuously the following:

d. Potential drop at the starter terminals (volts).

e. Open circuit potential of the power supply before and after cranking.

C. INSTRUMENTATION (Cont'd)

3. Cranking Effort Using Dynamometer or External Electric Motor - Provision should be made to measure and record continuously the following during a cranking test:

   a. Torque.

   b. Speeds (should be monitored to insure uniformity for each test).

D. REFERENCE OILS

Four reference oils*-- REO-151, REO-152, REO-153, and REO-154--are to be used for calibrating the engine.

E. TEST PROCEDURE

1. Bring the water jacket or oil sump temperature to 90°F minimum and drain the previous test oil.

2. For first flush, charge the next test oil, using one quart less than the capacity of the crankcase in order to conserve oil. Run or motor the engine for 15 minutes at an oil sump temperature of 140-180°F. If fuel is used, run the engine at 1500 rpm. If fuel is not used, motor the engine at a minimum of 400 rpm. If an external pump is used to circulate oil from the sump to the oil gallery of the engine, lower motoring speeds may be employed.

3. For second flush, repeat Step 2 but run or motor for only 10 minutes.

4. Charge a quantity of oil equal to the capacity of the crankcase for the test. Repeat Step 3 but run or motor for only 5 minutes. If fuel is used, stop the engine by allowing the carburetor to run dry. Drain the carburetor of all fuel. Do not pump the throttle during Step 4 in order to prevent injecting raw fuel into the cylinders which might dilute oil on the cylinder walls. It is permissible to disconnect the carburetor accelerator pump prior to starting Step 4.

5. If fuel is used, the engine may then be motored at a minimum of 400 rpm for 15 minutes at an oil sump temperature of 140-180°F. This procedure tends to replace any oil on the cylinder wall which has become diluted with fuel to a greater extent than the bulk oil in the sump.

* These reference fluids represent low pour point, non-waxy straight mineral oils. They were made available to the CRC test program by the Esso Research and Engineering Company, Linden, New Jersey.

E. TEST PROCEDURE (Cont'd)

6. Obtain a 4-ounce sample of bulk oil from the engine for kinematic viscosity determinations as specified in Section F (3) below. Additional quantities up to a total of 1 quart may be removed for other studies if desired. It is recommended that the same size sample be withdrawn during each test.

7. Bring the room and the engine to the test temperature as rapidly as possible.

8. Allow the engine to soak at the test temperature for a minimum of 10 hours after the sump reaches within 1°F of the test temperature. The sump and water jacket temperatures must be within 1/2°F of each other before cranking is started.

   Note: Extra long soak periods such as 64 hours (over the weekend) have been found to adversely affect repeatability of the procedure and should be avoided.

9. Crank the engine for ten seconds or four revolutions, whichever is greater. Both the throttle and choke should be open during the cranking test.

10. Repeat Step 9 at least once at intervals of not less than 1 hour or more than 12 hours. Further cranks can be made with a consequent improvement in repeatability. However, it is important that the same number of cranks be made and averaged together (see Section G) for each test. It has been noted that some engines show a consistent change from crank to crank within a test. Thus, comparing tests involving different numbers of cranks could introduce additional variability in the results.

11. During cranking, record the data specified in Section C, item 2 or 3, depending upon whether the starting motor or external electric motor is used.

F. DATA TO BE OBTAINED

1. Cranking With Starter Motor

   a. Obtain cranking speed for two complete revolutions from the amperes and time recordings. The compression stroke for each cylinder is readily apparent on the amperes trace, and can be used to calculate cranking speed. Data should not be taken at cranking speeds below 35 rpm.

   b. Determine average current flow for two complete revolutions.

   c. If obtained, determine average torque for two complete revolutions.

APPENDIX B

GM of CANADA

TEST PROCEDURE 66L-14-44

Engine Cold Cranking - Oil Analysis

Procedure:

A. Oil Change

1. Connect slave battery.
2. Start and run engine for 15 minutes at fast idle.
3. Shut off engine.
4. Drain oil for five minutes.
5. Remove, clean, rinse, and reinstall oil filter by-pass can.
6. Close oil drain valve.
7. Add three imperial quarts of test oil.
8. Start and run engine for five minutes at fast idle.
9. If test oil is not identical to previous test oil repeat steps 3, 4, 6 and 7.
10. Shut off fuel supply.
11. When engine stops pump throttle twice and restart.
12. Keep engine running as long as possible by pumping throttle.
13. When engine stops drain oil for five minutes.
14. Remove spark plugs from engine and coil wire from distributor.
15. Close oil drain valve.

16. Add four imperial quarts of test oil.

17. Within 30 minutes of start of cold soak crank engine until oil pressure stabilizes (maximum 15 seconds).

18. Replace spark plugs.

19. Disconnect slave battery.

20. Install test apparatus in cold room for cold soak.

21. Connect instrumentation and power supply.

B. Battery Preparation

1. Turn on 3-amp battery charger when apparatus is installed in cold room.

2. Turn off battery charger one hour before beginning test.

3. If water is added to batteries charge for ten minutes at 20 amps to insure mixing.

4. Check and record specific gravity of center cell in each battery immediately before test.

5. If batteries fall below full charge recharge at 20 hour rate.

C. Test Method

1. Connect chart recorder to monitor cranking voltage and current on a time scale.

2. Connect battery cables to batteries (batteries must be at room temperature).

3. Record initial coolant, oil sump, main bearing and ambient temperatures.

4. Conduct test after engine has cold soaked for 16 hours ($\pm$ 30 minutes).

5. Turn on recorder.
6. Crank engine for 10 seconds using remote starter control.
7. Stop recorder.
8. Cold soak engine for one hour.
9. Repeat steps 3, 5, 6 and 7.
10. Cold soak engine for one hour.
11. Repeat steps 3, 5, 6 and 7.
12. Disconnect battery cable from batteries.
13. Disconnect instrumentation and power supply from engine.
14. Remove engine from cold room.
15. Prepare engine for next test.

APPENDIX C

May, 1966

PROPOSED METHOD OF TEST FOR APPARENT VISCOSITY OF MOTOR OILS AT LOW TEMPERATURE USING THE COLD CRANKING SIMULATOR(1)

This is a proposed method and is published for information only. Comments are solicited and should be addressed to the American Society for Testing Materials, 1916 Race Street, Philadelphia 3, Pa.

Scope

1. This method of test describes a laboratory procedure for determining the apparent viscosity of motor oils at 0°F and high shear rates. The results are related to the engine cranking characteristics of the motor oil. Utility of the method for oils with a viscosity less than 6 poise or greater than 55 poise has not been demonstrated.

Summary of Method

2. A universal motor run at constant voltage drives a rotor which is closely fitted inside a stator. A small sample of motor oil fills the space between rotor and stator, which are maintained at 0°F. The speed of the rotor is a function of the viscosity of the oil; from a calibration curve and the measured speed of the rotor with the oil under test, the viscosity of the test oil is determined.

Significance

3. This method is used for measuring the apparent viscosity of engine oils at low temperature at high rates of shear by simulating the engine cold-cranking process. While the rheological properties of engine oils can be quite complex, it has been shown that this technique demonstrated good capability for predicting low-temperature, engine-cranking characteristics of engine oil.[2,3,4]

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(1) Under the standardization procedure of the Society, this method is under the jurisdiction of the ASTM Committee D-2 on Petroleum Products.

(2) CRC Report No. 374, "Development of Research Technique for Determining the Low Temperature Cranking Characteristics of Engine Oils, January, 1964."

(3) CRC Report No. 381, "Prediction of Low Temperature Cranking Characteristics of Engine Oils by Use of Laboratory Viscometers, March, 1965."

(4) Kim, D.S., Prepared Comments at Cold-Cranking Session, SAE Meeting, Chicago, May 18, 1965. Also see the Supplement to this Method.

Definitions

4. (a) The Viscosity (often called Dynamic or Absolute Viscosity, η), of a liquid is a measure of the internal friction of the liquid in motion. Viscosity is defined as the ratio of shear stress to shear rate. The cgs unit of dynamic or absolute viscosity is the poise, which has the dimensions grams per centimeter per second. For a non-Newtonian liquid, the ratio of shear stress to shear rate varies with changing shear stress or shear rate. For a Newtonian liquid, the viscosity is constant at all shear rates.

(b) The Apparent Viscosity is the determined viscosity in poise obtained by use of the method under description. Since many motor oils are not Newtonian at low temperature, apparent viscosity may vary with shear rate.

(c) Density (ρ) is the weight in vacuo, (that is, the mass) of a unit volume of oil at any given temperature. In this method the unit of mass is the gram and the unit of volume, the cubic centimeter.

(d) The Kinematic Viscosity is defined as the quotient of dynamic viscosity divided by the density, η/ρ, both at the same temperature. The unit of kinematic viscosity, ν, is the stoke, which has the dimensions, square centimeters per second.

(e) A Newtonian Oil or Fluid is one in which the rate of shear is proportional to the shearing stress.

(f) Calibration Oils are those oils used for establishing the instrument's reference framework of apparent viscosity vs. speed from which the apparent viscosities of test oils are determined Calibration oils, which are essentially Newtonian fluids, are available commercially with a range of 5 to 80 poise at 0°F.

(g) Test Oil is any oil for which the apparent viscosity is to be determined by use of the test method under description.

(h) Speed Readings are scale readings (arbitrary units) obtained at the drive motor input voltage used. This voltage is suggested for each instrument by the manufacturer.

Apparatus

5. (a) Cold Cranking Simulator[5] consisting of a universal motor (run at constant voltage input) driving a rotor inside a stator; a tachometer indicates the rotor speed.

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(5) Manufactured by Cannon Instrument Company, P. O. Box 16, State College, Pa. 16801.

(b) Calibrated thermistor, thermocouple, or other temperature sensor for insertion near the inside surface of the stator, and temperature control system for control of temperature to ±0.2°F during measurement.

(c) Circulating system for supplying suitable liquid coolant to stator and suitable means for maintaining coolant at desired temperature.

Reference Materials

6. Calibration Oils[6] are low cloud point mineral oils of known kinematic viscosity and density. Extrapolated viscosities at 0°F are obtained from 210°F/10°F kinematic viscosities using the Walther equation. The defined viscosities in poise are then calculated by multiplying the extrapolated kinematic value by the density. Defined viscosities at 0°F for the calibration oils are listed in Table I.

Table I

Calibration Oils

Calibration Oils	Approximate Defined Viscosity* @ 0°F (poise)
N-17L	5
N-24L	10
N-34L	20
N-50L	40
N-61L	60
N-72L	80

* Consult supplier for specific values.

Sampling

7. A representative sample of test oil is necessary to obtain valid results. In order to insure homogeneity, agitation and warming of the test oil at approximately 120°F is required before making a determination.

---

(6) The calibration oils are available from Cannon Instrument Company, State College, Pennsylvania, 16801.

Calibration

8. (a) Using a minimum of five calibration oils covering the test range of 5 to 80 poise at 0°F, determine the Speed Reading for each oil using the Procedure 9(a) through 9(f).[7]

(b) On log-log coordinate graph paper plot the viscosity of the standard as a function of Speed Reading, and draw a smooth curve. See Figure 1 for a typical curve.

(c) From time to time through a test sample series, run a calibration oil to be sure there is no change in calibration.

Procedure

9. It is recommended to check the calibration of the temperature sensor before each series of runs. It is also recommended that the calibration curve be established for each series of runs (see paragraph 8).

(a) The test sample (2-4 ml inserted by syringe or eye-dropper) should fill the gap between the rotor and stator with an excess of about 6 mm depth of liquid above the rotor. The rotor should be turned by hand to insure complete wetting of the surface of the stator and rotor.

(b) Turn temperature control and coolant flow on, and allow stator to cool. Note the time that coolant flow was turned on (stop watch or other means of counting by seconds). Control temperature should be attained in 30-90 seconds. Wait until 180 seconds[8] after the <u>coolant</u> <u>flow</u> was turned on, and then turn on the rotor drive.

(c) Adjust motor input voltage to within $\pm$0.2 volts of the calibration voltage.

(d) Read Speed Reading at 60$\pm$5 seconds from when the rotor was turned on, record value, and turn off rotor drive and coolant flow.

---

(7) If only a narrow viscosity range of test liquids is to be measured, a minimum of three calibration oils (spanning that range) may be used.

(8) Any time from 180 to 200 seconds may be used, but the same time must be used consistently for each determination. Exception to this rule may be necessary for oils like REO 155 and REO 158 which tend to climb out of the rotor-stator gap during shear. For them, it may be necessary to turn on the rotor as soon as the control temperature is attained in order to get any steady Speed Reading at all. Rotor design is being examined to see if it is possible to minimize this problem.

(e) Clean Cold Cranking Simulator by the following steps:

(1) Attach vacuum hose (with trap) to the fill tube where the syringe or eyedropper normally is inserted.

(2) Pour approximately 300 ml hot water (140-150°F) on the rotor-stator assembly to heat it quickly above ambient temperature.

(3) Next wash the assembly with petroleum naphtha and finally with acetone, using the vacuum to dry the assembly. On humid days, dry air or nitrogen above the rotor will help prevent moisture condensation. Turn the rotor several revolutions by hand during final drying with vacuum to ensure that the gap between rotor and stator is clean.

Calculation

10. The apparent viscosity of the test sample at 0°F is obtained from the calibration curve (paragraph 8b) and the Speed Reading (paragraph 9d).

Report

11. Report the apparent viscosity to the nearest 0.1 poise at 0°F as determined in paragraph 10.

Precision

12. The following criteria should be used for judging the acceptability of the results (95% probability):

(a) Repeatability - Repeat determinations by the same operator should not exceed the ratio 1.14 (larger value divided by the smaller).

(b) Reproducibility - Determinations from two different laboratories should not be suspect unless they exceed the ratio 1.20 (larger value divided by the smaller).

APPENDIX D

December 14, 1966

TENTATIVE METHOD OF TEST FOR APPARENT VISCOSITY OF MOTOR OILS AT LOW TEMPERATURE USING THE COLD CRANKING SIMULATOR(1)

ASTM Designation: D2602-67T

Issued, 1967

This Tentative Specification has been approved by the sponsoring committee and accepted by the Society in accordance with established procedures, for use pending adoption as standard. Suggestions for revisions should be addressed to the Society at 1916 Race St., Philadelphia, Pa. 19103.

Scope

1. This method of test describes a laboratory procedure for determining the apparent viscosity of motor oils at 0°F and high shear rates. The apparent viscosities so determined are related to the engine cranking characteristics of the motor oil (Notes 1&2). Utility of the method at 0°F for oils with a viscosity less than 6 Poise or greater than 55 Poise has not been demonstrated.

Note 1. The detailed relations between the apparent viscosities determined by this Method and engine cranking performance as determined by the CRC L-49 test are shown in Appendix I. It is important to be aware that the CRC L-49 test is much less standardized and precise than this Method. Therefore, apparent viscosity values obtained by this Method may not predict accurately the engine cranking viscosities in individual engines, even though the correlation with average engine results is satisfactory.

Note 2. Since this Method was developed solely for use in relation to engine cranking of motor oils, the apparent viscosity values obtained should not be used to predict other types of performance.

(1) Under the standardization procedure of the Society, this method is under the jurisdiction of the ASTM Committee D-2 on Petroleum Products.

(h) Speed Readings are scale readings (arbitrary units) obtained at the drive motor input voltage used. This voltage is suggested for each instrument by the manufacturer.

Apparatus

4. (a) Cold Cranking Simulator[2] consisting of a universal motor (run at constant voltage input) driving a rotor inside a stator; a tachometer indicates the rotor speed. See Figure 1.

(b) Calibrated thermistor, thermocouple, or other temperature sensor for insertion in a well near the inside surface of the stator.[3] This unit indicates the test temperature.

(c) Circulating system for supplying suitable liquid coolant to stator and suitable means for maintaining coolant at desired temperature.[3]

Reference Materials

5. Calibration Oils[4] are low cloud point mineral oils of known kinematic viscosity and density. Extrapolated viscosities at 0°F are obtained from 210°F/10°F kinematic viscosities using the Walther equation. The defined viscosities in poise are then calculated by multiplying the extrapolated kinematic value by the density. Defined viscosities at 0°F for the calibration oils are listed in Table I.

Table I

Calibration Oils

Calibration Oils	Approximate Defined Viscosity* @ 0°F (poise)
N-17L	5
N-24L	10
N-34L	20
N-50L	40
N-61L	60
N-72L	80

*Consult supplier for specific values

(2) Manufactured by Cannon Instrument Company, P.O.Box 16, State College, Pa. 16801.

(3) Cannon Instrument Company also manufactures units for these functions. The coolant control circuit is ordinarily an integral part of the main simulator unit.

(4) The calibration oils are available from Cannon Instrument Company, State College, Pennsylvania 16801.

Sampling

6. A representative sample of test oil is necessary to obtain valid results. In order to insure homogeneity, warming and agitation of the test oil at approximately 120°F is required before making a determination.

Calibration

7. (a) Using a minimum of five calibration oils covering the test range of 5 to 80 poise at 0°F, determine the Speed Reading for each oil using the Procedure 8(a) through 8(f)(5). The span of the Speed Reading meter should be adjusted so that the 5 Poise oil gives a reading of about 0.95.

(b) On log-log coordinate graph paper plot the viscosity of the standard as a function of Speed Reading, and draw a smooth curve. Reasonable care should be taken to get the best fit to the points found. Careless use of commercial drawing curves can lead to errors of several per cent. See Figure 2 for a typical curve.

(c) From time to time through a test sample series, run a calibration oil to be sure there is no excessive change in calibration. Excessive change is a value outside the repeatability limit of the test.

Procedure

8. It is recommended that the calibration of the temperature sensor be checked before each series of runs. It is also recommended that the calibration curve be established for each series of runs (see paragraph 7).

(a) The test sample (5 ml inserted by eyedropper) should fill the gap between the rotor and stator with an excess of about 6-8 mm depth of liquid above the rotor. The rotor should be turned by hand to insure complete wetting of the surface of the stator and rotor.

(b) Turn temperature control and coolant flow on, and allow stator to cool. Note the time that coolant flow was turned on (stop watch or other means of counting by seconds). Control temperature should be attained in about 30 seconds. Wait until 180 seconds after the coolant flow was turned on, and then turn on the rotor drive.

---

(5) If only a narrow viscosity range of test liquids is to be measured, a minimum of three calibration oils (spanning that range) may be used.

(c) Adjust motor input voltage to within ±0.2 volts of the calibration voltage.

(d) Read Speed Reading at 60±5 seconds from when the rotor was turned on, record value, and turn off rotor drive and coolant flow.

(e) Clean Cold Cranking Simulator by the following steps:

(1) Attach vacuum hose (with trap) to the fill tube where the syringe or eye-dropper is normally inserted.

(2) Pour sufficient hot water (about 150°F) on the rotor-stator assembly to heat it above ambient temperature (Note 3).

(3) Next, wash the assembly with petroleum naphtha and finally with acetone, using the vacuum to dry the assembly. Care should be taken that evaporative cooling of the acetone does not lower the temperature of the assembly below the dew point. Turn the rotor several revolutions by hand during final drying with vacuum to ensure that the gap between rotor and stator is clean.

Note 3. The water may be poured on from a container such as a beaker. A more convenient supply consists of an elevated hot water reservoir and a siphon tube with control valve and nozzle to direct the water into the stator well.

Calculation

9. The apparent viscosity of the test sample at 0°F is obtained from the calibration curve (paragraph 7b) and the Speed Reading (paragraph 8d).

Report

10. Report the apparent viscosity as determined in paragraph 9 as Poises at 0°F. Because a logarithmic scale is used for reading viscosities, the following rule for interpolation should be used.

Report to Nearest	if Viscosity is
0.1 Poise	below 30 Poise
0.5 Poise	30-60 Poise
Poise	above 60 Poise

Precision

11. The following criteria should be used for judging the acceptability of the results (95% probability).

a. Repeatability - Two determinations by the same operator should not exceed the ratio 1.06 (larger value divided by the smaller). This statement is approximately equal to the following:

> Two determinations by the same operator should not differ by more than ±3% of the mean.

b. Reproducibility - Determinations from two different laboratories should not exceed the ratio 1.14 (larger value divided by the smaller). This statement is approximately equal to the following:

> Determinations from two different laboratories should not differ by more than ±6.5% of the mean. (Note 4)

Note 4. If viscosities are to be used for referee purposes, each lab should make two determinations. This will help avoid the occasional random error.

APPENDIX E

"Student's" t Distribution

$$t = \frac{\bar{x} - \mu}{s}\sqrt{N-1}$$

where: $\bar{x}$ is sample mean

μ is population mean

s is standard deviation*

n is number of samples

$$* \; s = \sqrt{\frac{\Sigma(x-x)^2}{n}}$$

The values of t for a variety of probabilities and degrees of freedom (ν = n-1) are tabulated in the attached table.

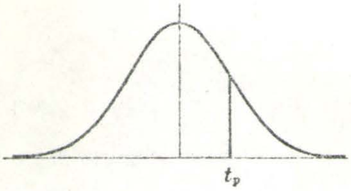
95% Confidence Interval:

$$= t_{.975} < \frac{\bar{x} - \mu}{s}\sqrt{N-1} < t_{.975}$$

i.e. the 95% confidence limits for μ are $x \pm t_{.975} \frac{s}{\sqrt{N-1}}$

Appendix

PERCENTILE VALUES (t_p) for STUDENT'S t DISTRIBUTION with ν degrees of freedom (shaded area = p)



ν	$t_{.995}$	$t_{.99}$	$t_{.975}$	$t_{.95}$	$t_{.90}$	$t_{.80}$	$t_{.75}$	$t_{.70}$	$t_{.60}$	$t_{.55}$
1	63.66	31.82	12.71	6.31	3.08	1.376	1.000	.727	.325	.158
2	9.92	6.96	4.30	2.92	1.89	1.061	.816	.617	.289	.142
3	5.84	4.54	3.18	2.35	1.64	.978	.765	.584	.277	.137
4	4.60	3.75	2.78	2.13	1.53	.941	.741	.569	.271	.134
5	4.03	3.36	2.57	2.02	1.48	.920	.727	.559	.267	.132
6	3.71	3.14	2.45	1.94	1.44	.906	.718	.553	.265	.131
7	3.50	3.00	2.36	1.90	1.42	.896	.711	.549	.263	.130
8	3.36	2.90	2.31	1.86	1.40	.889	.706	.546	.262	.130
9	3.25	2.82	2.26	1.83	1.38	.883	.703	.543	.261	.129
10	3.17	2.76	2.23	1.81	1.37	.879	.700	.542	.260	.129
11	3.11	2.72	2.20	1.80	1.36	.876	.697	.540	.260	.129
12	3.06	2.68	2.18	1.78	1.36	.873	.695	.539	.259	.128
13	3.01	2.65	2.16	1.77	1.35	.870	.694	.538	.259	.128
14	2.98	2.62	2.14	1.76	1.34	.868	.692	.537	.258	.128
15	2.95	2.60	2.13	1.75	1.34	.866	.691	.536	.258	.128
16	2.92	2.58	2.12	1.75	1.34	.865	.690	.535	.258	.128
17	2.90	2.57	2.11	1.74	1.33	.863	.689	.534	.257	.128
18	2.88	2.55	2.10	1.73	1.33	.862	.688	.534	.257	.127
19	2.86	2.54	2.09	1.73	1.33	.861	.688	.533	.257	.127
20	2.84	2.53	2.09	1.72	1.32	.860	.687	.533	.257	.127
21	2.83	2.52	2.08	1.72	1.32	.859	.686	.532	.257	.127
22	2.82	2.51	2.07	1.72	1.32	.858	.686	.532	.256	.127
23	2.81	2.50	2.07	1.71	1.32	.858	.685	.532	.256	.127
24	2.80	2.49	2.06	1.71	1.32	.857	.685	.531	.256	.127
25	2.79	2.48	2.06	1.71	1.32	.856	.684	.531	.256	.127
26	2.78	2.48	2.06	1.71	1.32	.856	.684	.531	.256	.127
27	2.77	2.47	2.05	1.70	1.31	.855	.684	.531	.256	.127
28	2.76	2.47	2.05	1.70	1.31	.855	.683	.530	.256	.127
29	2.76	2.46	2.04	1.70	1.31	.854	.683	.530	.256	.127
30	2.75	2.46	2.04	1.70	1.31	.854	.683	.530	.256	.127
40	2.70	2.42	2.02	1.68	1.30	.851	.681	.529	.255	.126
60	2.66	2.39	2.00	1.67	1.30	.848	.679	.527	.254	.126
120	2.62	2.36	1.98	1.66	1.29	.845	.677	.526	.254	.126
∞	2.58	2.33	1.96	1.645	1.28	.842	.674	.524	.253	.126

Source: R. A. Fisher and F. Yates, *Statistical Tables for Biological, Agricultural and Medical Research* (5th edition), Table III, Oliver and Boyd Ltd., Edinburgh, by permission of the authors and publishers.

```
$JOB            003733 M.G.MALLOY
$IBJOB          NODECK
$IBFTC
C
C       CONFIDENCE LIMIT DETERMINATION XXING STUDENT'S T AT 95 PC LEVEL
C
        DIMENSION  X(6),DIF(6),X2(6)
        READ(5,1) M
1       FORMAT(I3)
        DO 50 J=1,M
        WRITE(6,2)
2       FORMAT(13X,4HMEAN,13X,9HSTD. DEV(,13X,6HLIMITS//)
        N=6
        READ(5,3)(X(I),I=1,N)
3       FORMAT(8F10.3)
        SUM=0.0
        DO 10 I=1,N
10      SUM=SUM+X(I)
        AVG=SUM/6.0
        DO 20 K=1,N
        DIF(K)=ABS(AVG-X(K))
20      X2(K)=DIF(K)*DIF(K)
        SUMX2=0.0
        DO 30 L=1,N
30      SUMX2=SUMX2+X2(L)
        S=SQRT(SUMX2/6.0)
        CLIM=S*1.136
        WRITE(6,40) AVG,S,CLIM
40      FORMAT(2(10X,F10.3),6X,4H+/- ,F//.3/)
        WRITE(6,45)
45      FORMAT(1H1)
50      CONTINUE
        CALL EXIT
        END
```

APPENDIX F

Correlation Method

$Y = a_1 X$:

$$a_1 = \frac{\Sigma XY}{\Sigma X^2}$$

Standard error of estimate Syx -

$$Syx = \sqrt{\frac{Y^2 - a_1 \Sigma XY}{N}}$$

$Y = a_o + a_1 X$

$$a_1 = \frac{\Sigma (X-X)\ (Y-Y)}{\Sigma (X-X)^2}$$

$$a_o = \bar{Y} - a_1\bar{X}$$

Standard error of estimate Syx -

$$Syx = \sqrt{\frac{Y^2 = a_o \Sigma Y - a_1 \Sigma XY}{N}}$$

Coefficient of Correlation

$$r = \sqrt{1 = \frac{S^2XY}{S^2Y}}$$

```
C $IBFTC MAIN
C
C       FITTING A STRAIGHT LINE THRØUGH VISCØSITY DATA AS DETERMINED BY
C       DIFFERENT METHØDS
C
        DIMENSIØN X(100), Y(100)
C
C       N IS THE NUMBER ØF DATA PAIRS ØF X AND Y READ
C
        READ(5,5) NUM
    5   FØRMAT(I3)
        DØ 10 ISET=1,NUM
        READ (5,3) N
        READ(5,1) (X(I) , I=1,N)
        READ(5,2) (Y(I) , I=1,N)
 1      FØRMAT(8F10.3)
 2      FØRMAT(8F10.3)
 3      FØRMAT(I3)
        WRITE(6,200)
    200 FØRMAT(13X, 1HX,12X,1HY,14X,4HSUMX,12X,4HSUMY, 9X,3HPXY,14X,4HSP
     1,14X,3HSX2 ,12X, 3HSY2    ///)
 201    SUMX=0.0
        SUMY=0.0
        SPXY=0.0
        SX2=0.0
        SY2=0.0
        DØ 4 I = 1,N
        SUMX=SUMX+X(I)
        SUMY=SUMY+Y(I)
        PXY=X(I)*Y(I)
        SPXY=SPXY+PXY
        SX2=SX2+X(I)*X(I)
        SY2=SY2+Y(I)*Y(I)
        WRITE(6,300) X(I),Y(I),SUMX,SUMY,PXY,SPXY,SX2,SY2
    300 FØRMAT(8X,F8.2,6X,F8.2,4X,F12.2,4X,,F12.3, 3X,F12.3,1X,F15.3,2X,
     15.3,2X,F15.3)
      4 CØNTINUE
        SMX2=SUMX*SUMX
        WRITE(6,400) SMX2
    400 FØRMAT(1H0, //, 10X, 6HSMX2=  ,E18.8     ////)
        DENØM=FLØAT(N)*SX2-SMX2
        IF(DENØM.EQ.0.0) GØ TØ 10
C
C       A1 IS THE GRADIENT ØF THE ST. LINE ,WHILE A0 IS THE CØNSTANT.
C
        AØ=(SUMY*SX2-SUMX*SPXY)/DENØM
        A1=(FLØAT(N)*SPXY-SUMX*SUMY)/DENØM
        SYX=SQRT((SY2-AØ*SUMY-A1*SPXY)/FLØAT(N))
        WRITE(6,600)
    600 FØRMAT(10X, 96HTHE EQUATIØN ØF THE STRAIGHT LINE IS GIVEN BY
     1                          Y = A1 * X . + AØ, WHERE    //)
        WRITE(6,500) AØ,A1
    500 FØRMAT(30X,3HAØ=  ,F12.8 / 30X, 3HA1=  ,F12.8  ///)
C
C       SYX IS THE STANDARD ERRØR ØF ESTIMATE , GIVEN BY
```



```
C                          S(Y,X) = SQRT((SY2-A0*SUMY-A1*SPXY) /N )
C
        WRITE(6,700) SYX
    700 FØRMAT(10X,37HTHE STANDARD ERRØR ØF ESTIMATE SYX =    ,E18.8  //)
        WRITE(6,800)
    800 FØRMAT(1H1)
     10 CØNTINUE
   5000 STØP
        END
```

```
$JOB            003733 M.G.MALLOY
$IBJOB          NODECK
$IBFTC
C       NUMERICAL INTERPOLATION OF CCS CALIBRATION CURVE AT 0 F
C
C       DATA FOR REO AND SHELL OILS AT -20F
C
        DIMENSION X(20), Y(20,20), D(100)
        READ(5,1) NUM
1       FORMAT(I4)
        DO 6 ISET=1,NUM
        READ (5,10) N,M
10      FORMAT (2I4)
        READ (5,11) (X(II),II=1,N),(Y(II,1),II=1,N)
11      FORMAT (8F10.3)
        READ (5,12) (D(L),L=1,M)
12      FORMAT (8F10.3)
        DO 13 II=1,N
        X(II)=ALOG10(X(II))
13      Y(II,1)=ALOG10(Y(II,1))
        DO 6 L=1,M
        Z=ALOG10(D(L))
        DO 100 K=2,N
        DO 100 I=K,N
        J=K-1
100     Y(I,K)=(Y(J,J)*(X(I)-Z)-Y(I,J)*(X(J)-Z))/(X(I)-X(J))
        W=10.0**Z
        Y(N,N)=10.0**Y(N,N)
        WRITE (6,5) W,W,Y(N,N)
5       FORMAT(1H-,34HTHE INTERPOLATED VALUE OF Y FOR X=,F9.6,6H IS
       16,2H)=,F10.3)
6       CONTINUE
        CALL EXIT
        END
```

APPENDIX H

Test Oil Properties *

Oil	Viscosity (sus) 210°F.	Extrapolated Viscosity (cp) 0°F.	Extrapolated Viscosity (cp) -20°F.	Pour Point (°F.)
REO-151-65	38.9	1390	6320	-35
REO-153-65	42.4	3500	19800	-35
REO-161-63	42.0	1080	—	-20
REO-162-63	48.2	3190	—	-25
REO-158-63	67.1	1910	5630	-10
REO-159-63	65.7	1990	5880	-30
REO-160-63	66.9	1900	—	-35
REO-172-65	52.6	790	2180	-20
Shell A	62.3	564	—	-40
Shell B	62.9	624	—	-35
Shell C	63.8	624	—	-35
Shell D	66.5	758	—	-35
Shell E	63.6	800	—	-35
Shell F	64.3	880	—	-35
Shell G	67.5	630	—	-45

*As Specified by Manufacturers

APPENDIX J

Random Order of Testing

REO 161	REO 153	Shell G
REO 153	Shell G	Shell D
REO 162	REO 159	REO 160
REO 151	REO 160	REO 172
Shell F	Shell A	Shell C
Shell C	REO 151	REO 162
REO 158	REO 172	REO 158
REO 159	REO 161	Shell A
REO 160	Shell D	Shell B
Shell G	REO 158	Shell E
Shell E	Shell B	REO 159
Shell A	Shell F	REO 161
REO 172	Shell C	REO 153
Shell B	Shell E	REO 151
Shell D	REO 162	Shell F

Shell F	REO 160	REO 153
Shell C	REO 172	Shell G
REO 158	Shell B	REO 160
REO 162	REO 159	REO 158
REO 160	Shell F	Shell A
REO 151	Shell A	Shell F
REO 159	REO 151	REO 151
Shell E	Shell G	Shell D
REO 161	REO 161	REO 162
Shell G	REO 158	REO 159
REO 172	Shell E	Shell B
Shell A	Shell C	Shell C
REO 153	REO 153	REO 172
Shell B	Shell D	Shell E
Shell D	REO 162	REO 161

APPENDIX K

Shell Method of Viscosity Determination

$$M = K \mu N \qquad (1)$$

where:

M = torque

K = engine constant

μ = viscosity

N = cranking speed

so, equation 1 can be treated graphically as

$$\frac{M}{N} = K\mu$$

and K is the slope of the calibration line

APPENDIX L

D-C Method

Instructions - Model CCS1 Cold-Cranking Simulator

Special Note Concerning D.C. Operation

The initial development and testing of the Cold-Cranking Simulator has been with a constant (±0.2 volt) A.C. voltage applied to the simulator motor.

Subsequent experience by Cannon Instrument Company indicates that operation of the simulator motor by direct current at constant current produces more precise readings and equally good correlation with CRC fluids. The direct current is adjusted as described above, and it is automatically controlled by means of power transistors and a reference Zener diode.

The only modification in the procedure is that the control of voltage is not necessary.

Also, under this direct current operation, the graphical method of plotting a calibration curve and subsequent reading of test results can be replaced by an analytical method, as follows:

$$\text{Viscosity in poise} = \frac{\text{Constant}}{\text{Speed Indicator Reading}}$$

Calculate the constant by multiplying the viscosity of the standard in poise by the speed indicator reading. The constants so obtained from standards should agree within the repeatability of this method.

If low and high readings are obtained as outlined above, one constant (low range) can correspond to 5W and 10W oils, and is obtained with standards N17L, N24L, N34L and N50L; the high range corresponding to 20W oils at 0°F is calibrated as above with N34L, N50L, N61L and N72L standards.

X

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