



Analysis of liquids from Savage, Montana lignite
by Ralph Frederick Speakman

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE in CHEMICAL ENGINEERING

Montana State University

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It was found that the product properties depended only slightly on the reaction conditions.

The maximum yield of oil is obtained at the most extreme set of variable reaction conditions studied: 475°C, a catalyst concentration equal to 4.0% by weight of the coal treated (moisture and ash free basis), and a run length of 4 hours.

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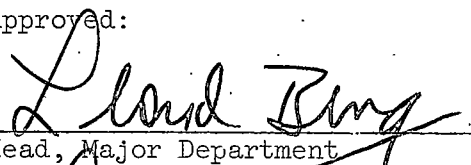
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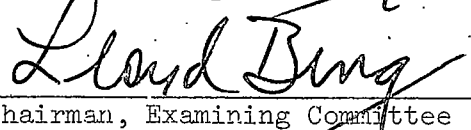
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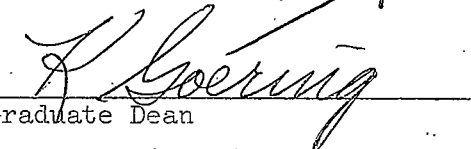
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VITA

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ABSTRACT

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It was found that the product properties depended only slightly on the reaction conditions.

The maximum yield of oil is obtained at the most extreme set of variable reaction conditions studied: 475°C, a catalyst concentration equal to 4.0% by weight of the coal treated (moisture and ash free basis), and a run length of 4 hours.

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I. INTRODUCTION

Coal hydrogenation to produce a liquid product is not a new process. In World War II, the Germans used a high temperature, high pressure process to supply synthetic fuel for the war effort. Since that time Russia has done extensive work on coal hydrogenation (1).

In the United States, work has been directed toward producing both synthetic fuels and organic chemicals by hydrogenating coal.

The most notable of this work are projects by Union Carbide Corporation and Consolidated Coal Company. The Union Carbide process study has been completed. The Consolidated Coal project at Cresap, West Virginia is sponsored by the Office of Coal Research and is directed toward converting coal to liquid fuels (2). No report is yet available.

Until recently, little work had been done on the hydrogenation of coals from the western United States. The Fort Union Coal Region (Figure 1) in Montana and adjacent states contains an estimated reserve of 460 billion tons of lignite and 240 billion tons of sub-bituminous coal (3), marking it as the United States' largest single coal field.

If a process for the conversion of coal to liquid products can be found that would be economically attractive, the coal reserves of the western United States could be the source of a large supply of synthetic liquid fuels to meet the increased energy demands predicted for the future. The economic attractiveness of this process would depend upon the quantity of the fuel produced and upon the quality of the finished product.

II. OBJECTIVES OF THE RESEARCH

The objective of the coal hydrogenation research currently being carried out at Montana State University is to hydrogenate Savage, Montana lignite to liquid products at moderate conditions and economically attractive costs.

The primary objective of this research was to determine the quality of the oils produced by the hydrogenation of Savage, Montana lignite. The change in physical properties of the oil as functions of the variable hydrogenation conditions of temperature, catalyst concentration, and run length were to be determined.

Secondary objectives were to determine reaction conditions that give optimum oil quality and to determine if the products contained the same type of compounds that have been reported in the products of other hydrogenations, namely a high percentage of aromatic hydrocarbons.

III. EQUIPMENT AND PROCEDURES

A. Production of an Oil from Lignite

Lignite coal can be hydrogenated to a liquid product in a single-stage batch operation (4). The equipment used to perform the hydrogenation consists of a main reactor and the peripheral equipment necessary for introducing the coal slurry, hydrogen, and catalyst to the reactor, and removing and separating the reaction products (Figure 2).

Coal is mixed in a 20% by weight slurry with anthracene oil and is preheated to 150°C before being introduced into the main reactor. The slurry is pressured to the reactor and hydrogen is added to 2500 psig. The catalyst is elutriated into the main reactor from a fluidized bed in the hydrogen feed line. The temperature of the reaction mixtures is raised to 425, 450, or 475°C.

The catalyst used in all runs is Harshaw 4401-E, which contains 6% nickel and 19% tungsten on a silica-alumina support.

After a desired reaction time, the reaction mixture is pressured to a cooling reactor where the gaseous products are taken off. The liquid products are separated from the solids (unreacted coal, ash, and catalyst) by means of a centrifuge.

The oily product is taken as that part of the total liquid product that boils below 325°C at one atmosphere pressure. This boiling range (up to 325°C) is typical of diesel fuels. The liquid remaining after the oily product is removed is used as the slurry base for the next cycle of hydrogenations.

Three cycles of hydrogenations were considered. The J series used anthracene oil, from which the portion boiling below 325°C had been

removed, as the slurry medium. A total of 12 runs were made in this series.

The products boiling below 325°C were removed following each run and the composite of the remaining liquid was used as the slurry medium for the 8 runs of the K series. The same method was used to generate the slurry medium for the L series from the liquid product boiling above 325°C obtained from the K series.

This procedure of using the liquids of the previous series as the slurry base was used in an effort to minimize the effects of the anthracene oil on the oily product.

The runs of the J, K, and L series were made at two temperatures (425°C and 475°C) and three catalyst concentrations (0, 0.8, and 3.6% by weight of the moisture and ash free coal charged per run). (6) The J series also contained runs at 450°C. The effects of these factors were studied from the results of the runs of these three series. All runs had a reaction time of 4 hours.

Four runs from the O series were added to the study to determine the effects of run length. These runs were for 1 and 2 hours and were used with data from the K series, with which the O series corresponds.

B. Determination of Product Quality

The quality of the liquid product was studied as a function of the three reaction variables of temperature, catalyst concentration and reaction time (run length). The effect of pressure was not studied as it is an accepted theory that increased pressure produces increased amounts of liquid reaction product. Therefore, only the highest available pressure was used.

The product was thought of as a diesel fuel, and as such the proper method of evaluating it would be by using the standard laboratory tests used by the major refining companies to determine and specify the quality of their diesel fuels.

The basic specifications for diesel fuels are set by the American Society for Testing and Materials (5). The ASTM tests specifications (Table II) were supplemented with several other tests not specifically required for diesel fuels.

A total of 12 tests were run on the product samples. These tests, along with their ASTM designations are shown in Table I.

The tests were run in the order shown in Table I. Due to the small amounts of oil product obtained from the runs (frequently less than 150 grams), separate samples could not be used for each test. A test sequence was set up that would minimize the influence of the tests in the first part of the sequence on the tests at the latter part of the sequence. Tests which would consume or change the nature of the material were placed at the end of the sequence, with the exception of the test for Reid Vapor Pressure which can be easily changed by any change in the material and is to be the first test run on any sample according to ASTM procedures. Where the vapor pressure test would consume too much material to allow other tests to be run, it was omitted.

A brief description of each test procedure and the knowledge obtained from the test results is required for interpretation of the test results:

1. Refractive Index: The refractive Index is the ratio of the

velocity of light in air to its velocity in the substance under examination. For hydrocarbons, a high refractive index indicates an aromatic substance, while a low refractive index indicates a paraffinic substance as shown by the indices of three reference compounds: 1.39 for 2,2,4-trimethylpentane, 1.42 for methylcyclohexane, and 1.49 for toluene.

2. Reid Vapor Pressure: The Reid Vapor Pressure is defined as the absolute vapor pressure of a volatile petroleum product at 100°F. The vapor pressure is an indication of the volatility of the hydrocarbon mixture. Volatility increases with increasing vapor pressure.

3. API Gravity: The API Gravity is used by the petroleum industry to measure the density of crude oils and liquid petroleum products. The small amounts of material available did not allow use of the regular ASTM procedure for determining gravity by means of hydrometers and cylinders. The densities of known volumes of product were determined and converted to the corresponding API gravity. A low API gravity indicates a high density and a high API gravity indicates a low density.

4. Flash Point: The flash point is the lowest temperature at which application of a test flame causes the vapor above the sample to ignite. The sample is heated at a constant rate until the composition of the vapor above the sample reaches the lower limit of flammability as determined by application of a test flame into the vapor space.

5. Saybolt Viscosity: The Saybolt viscosity is measured as the efflux time in seconds of 60 ml of sample through a calibrated orifice under specified conditions. The viscosity in Saybolt Universal Seconds was converted to viscosity in centistokes.

6. ASTM Distillation: A 100. ml sample is distilled under conditions specified by the nature of the material. Temperature readings are taken at specified intervals, usually volumes of condensate recovered.

7. Total Sulfur: A sample of the oil is burned in a lamp. The gases are collected and the sulfur oxides are absorbed and oxidized to sulfuric acid by hydrogen peroxide solution. The sulfur is determined by titration with sodium hydroxide solution. The sulfur content of the oil gives an indication of the possible corrosiveness of the oil and indicates what further refining processes might be required to remove the sulfur.

8. Pour Point: The pour point is the lowest temperature at which an oil sample will flow. The sample is cooled and inspected at regular temperature intervals for its flow characteristics.

9. Bromine Number: The bromine number is the number of grams of bromine consumed by 100 grams of the sample when reacted under certain conditions. The magnitude of the bromine number is an indication of the quantity of bromine active constituents, not an identification of the constituents and should not be taken as a measure of the olefinic unsaturation of the sample.

10. Aniline Point: The aniline point is the lowest temperature at which equal volumes of aniline and sample are miscible. The aniline point gives an indication of the type of compounds in the sample.

11. Average Molecular Weight: The average molecular weight of the sample was determined with the aid of a correlation developed by Rhodes Engineering Corporation. The ASTM method D2502 for determining the average molecular weight was not used because it required the viscosity of the

sample at 210°F which is above the flash point of all the samples. It was feared that the collection of this data could affect the results of tests following that for viscosity in the test sequence.

12. Calculated Cetane Index: The general method for rating diesel fuels is by the cetane number, which is analogous to the more familiar octane number ratings for gasoline. The cetane number is generally determined by direct ignition in a test engine, but when a test engine is not available or the sample size is too small (both are limitations in this case), the cetane number may be estimated from a correlation using the API gravity and the mid-boiling point of the ASTM distillation. This was the procedure which was followed.

IV. INTERPRETATION OF RESULTS

The data obtained from the application of the tests is presented in Tables V, VI, VII, VIII, and IX.

In cases where there appeared to be definite relationships between the data and the reaction conditions graphs were drawn to present the dependency in a clear manner. In many cases there was no relationship that could be determined between the test results and the reaction conditions.

A. Operating Variables

The products obtained were subjected to the 12 tests listed above. The results of the tests were studied to determine the dependency of the data on the three operating variables of temperature, catalyst concentration, and run length. The temperatures studied were 425°C and 475°C; the catalyst concentrations were 0, 0.8, and 3.6 weight percent of the moisture and ash free coal charged per run; and the run lengths were 1, 2, and 4 hours.

B. Reaction Product

The effects of catalyst concentration, reaction temperature, and run series on the amount of liquid product obtained are shown in Figures 3 and 4.

There is a slight increase in product with an increase in catalyst concentration.

There is an increase of approximately 100 grams of product when the reaction temperature is raised from 425°C to 475°C.

There is a general decrease in reaction product as the hydrogenation proceeds from the J series to the K series and from the K series to the L series. This indicates that some of the product obtained in the J

series (and possibly the K series) came from the anthracene oil slurry medium.

The reaction product increases with run length (Figure 5). The product yield increases most rapidly in the early stages of the run.

C. Refractive Index

The refractive indices of all the products are close to 1.6. This indicates a very aromatic product, probably of the condensed ring type.

There is no correlation with run conditions for this data.

D. Reid Vapor Pressure

The Reid vapor pressures of the samples are all below 1.0 psia.

There is no correlation of vapor pressure data with the reaction conditions.

E. API Gravity

There is no correlation of API gravity data with reaction temperature or catalyst concentration. However, there is a decrease in gravity with increased run length (Figure 6). Most gravity measurements are between 6 and 10 °API.

F. Flash Point

Flash points for the samples ranged from 100°F to 180°F, with most above the minimums of 100°F for No. 1 diesel and 125°F for No. 2 diesel set by the ASTM standards.

G. Viscosity

The viscosity data was converted from Saybolt Universal Seconds to centistokes. There was no correlation of the viscosity data with reaction conditions. The viscosity measurements ranged from 2.86 to 5.91 centistokes.

H. ASTM Distillations

The effect of increased reaction temperature is to lower the distillation curve, indicating a lower boiling product is produced at the higher temperature (Figures 7 - 12).

There is no effect of catalyst concentration on the distillation.

The effect of reaction time is to raise the curve as the reaction proceeds (Figures 13 and 14). A higher boiling product is produced as the reaction proceeds.

The 90% distillation temperatures are above the maximum allowable of 550°F for No. 1 diesel, but are within the limits of 540°F and 640°F for No. 2 diesel.

I. Total Sulfur

The total sulfur analysis is below 0.1% by weight for 26 of the 30 samples. This compares favorable with the 0.5% minimum allowed for No. 1 diesel and 0.7% allowed for No. 2 diesel. There is no correlation of the total sulfur (wt%) with any of the reaction conditions.

J. Pour Point

The pour points were all determined to be below -20°C (-4°F). All samples still flowed easily when cooled to -20°C.

K. Bromine Number

There was no correlation of the bromine numbers, which ranged from 11.6 to 35.4, with the reaction conditions. There are some bromine active constituents in the products.

L. Aniline Point

The aniline points for all of the samples were below -10°C (14°F).

The freezing point of pure aniline is -6.2°C , indicating that the products are very aromatic because the aniline does not crystallize out when cooled below its freezing point.

M. Average Molecular Weight

The average molecular weight of the diesel fuel products ranged from 143 to 167.

There is a slight increase in average molecular weight with increased catalyst concentration (Figures 15, 16, and 17).

As the reaction temperature is increased, there is a decrease in the average molecular weight of the product (Figures 15, 16, and 17). This agrees with the data of the ASTM distillations.

Figure 18 shows that there is an increase in average molecular weight for increased run length.

N. Calculated Cetane Index

The cetane index of each product was calculated from the API gravity and the mid-boiling point of the ASTM distillation.

The cetane indices were negative for all but one sample (L-NT-L-5). This indicates a poor ignition quality diesel fuel.

The cetane ratings are below the minimums set by the ASTM standards of 40 for No. 1 and No. 2 diesel fuels and 30 for No. 4 diesel fuel.

V. SUMMARY AND CONCLUSIONS

a) Increasing the reaction temperature increases the amount of oily product that is produced. At the higher temperature, a lighter product is produced.

b) Increasing the catalyst concentration increases the yield of oily product. A high catalyst concentration produces a heavier product.

c) Increasing the run length produces more product in the diesel fuel range and produces a heavier product.

d) Catalyst concentration appears to have less effect on the product quality than does reaction temperature or run length.

e) There is no detectable effect on product quality due to the series of the hydrogenation reaction. The products of all three series (J, K, and L) seem to be of nearly the same quality. The amount of oily product obtained decreases as the hydrogenation cycles proceed.

f) The products are highly aromatic. This is not desirable for diesel fuels.

g) The average oil produced by hydrogenation of Savage, Montana lignite has the physical properties shown in Table I below. These can be compared with a typical No. 1 diesel fuel produced by Continental Oil Company at Billings, Montana.

TABLE I. Average Physical Properties of Reaction Products

	<u>Hydrogenation Product Oil</u>	<u>Conoco No. 1 Diesel</u>
Refractive Index	1.60	1.48
Reid Vapor Pressure (psi)	0.5	-
API Gravity	9.5	41
Flash Point (°F)	132	142
Vixcosity (cst)	3.8	2.0
Total Sulfur (wt%)	0.06	0.04
Pour Point (°F)	below -4	-55
Bromine Number	22	-
Aniline Point (°F)	below 14	142
Average Molecular Weight	152	-
Cetane Index	-4.4	48

VI. RECOMMENDATIONS

There appears to be little difference in the quality of the oily products obtained at various sets of reaction conditions. Therefore, the reaction conditions should be chosen to produce the maximum yield of oily product. These would be a temperature of 475°C , a catalyst concentration of 4.0% by weight of the moisture and ash free coal, and run length of 4 hours.

As the catalyst concentration is the reaction factor that has the least influence on the reaction product, other catalysts could be studied in an effort to develop one that would produce a product more suitable for diesel fuel.

VII. APPENDIX

TABLE II. ASTM Test Procedures

Test	ASTM Designation	Material Required (ml)	Material Consumed (ml)
Refractive Index	D 1218	2	2
Reid Vapor Pressure	D 323	30	30
API Gravity	None	15	0
Flash Point	D 93	70	0
Saybolt Viscosity	D 88	70	0
ASTM Distillation	D 86	100	0
Total Sulfur	D 1266	5	5
Pour Point	D 97	5	0
Bromine Number	D 1158	1	1
Aniline Point	D 1012	5	5
Average Molecular Weight	None	0	0
Calculated Cetane Index	D 976	0	0

TABLE III Limiting ASTM Requirements for Diesel Fuel Oils (5)

Grade of Diesel Fuel Oil	Flash Point (°F)	Pour Point (°F)	90% Distillation Temperature (°F)		Viscosity at 100°F (cst)		Sulfur % by Weight	Cetane Number
	Min	Max	Min	Max	Min	Max	Max	Min
No. 1 - D	100	a	-	550	1.4	2.5	0.5	40
No. 2 - D	125	a	540	640	2.0	4.3	0.7	40
No. 4 - D	130	a	-	-	5.8	26.4	2.0	30

a. Pour point determined by operating conditions of use

TABLE IV. Runs and Reaction Conditions

Run Number	Catalyst Concentration (wt % of MAF Coal)	Pressure (psig)	Temperature (°C)	Run Length (hours)
L-NT-J-1	3.56	2500	425	4
L-NT-J-2	3.40	2500	475	4
L-NT-J-3	0.76	2500	425	4
L-NT-J-4	0.76	2500	475	4
L-NT-J-5	3.80	2500	450	4
L-NT-J-6	0.00	2500	425	4
L-NT-J-7	0.00	2500	450	4
L-NT-J-8	0.00	2500	475	4
L-NT-J-9	0.60	2500	450	4
L-NT-J-10	0.68	2500	475	4
L-NT-J-11	3.88	2500	475	4
L-NT-J-12	0.72	2500	450	4
L-NT-K-1	0.68	2500	425	4
L-NT-K-2	3.72	2500	475	4
L-NT-K-3	0.64	2500	450	4
L-NT-K-4	3.64	2500	425	4
L-NT-K-5	0.68	2500	475	4
L-NT-K-6	0.00	2500	425	4
L-NT-K-8	0.00	2500	475	4
L-NT-L-1	0.00	2500	475	4
L-NT-L-2	0.60	2500	425	4
L-NT-L-3	3.48	2500	475	4
L-NT-L-4	0.60	2500	450	4
L-NT-L-5	3.68	2500	425	4
L-NT-L-6	0.72	2500	475	4
L-NT-L-7	0.00	2500	425	4
L-NT-O-2	3.76	2500	475	2
L-NT-O-5	0.64	2500	425	2
L-NT-O-7	0.60	2500	425	1
L-NT-O-8A	3.92	2500	475	1

TABLE V. Test Results for J Series Products

Run Number	Product (grams)	Reid Vapor Pressure (psia)	Refractive Index	Gravity (°API)	Flash Point (°F)	Viscosity (cst)
L-NT-J-1	186.9	0.40	1.5948	7.40	-	5.32
L-NT-J-2	315.2	0.45	1.5980	8.75	105	3.17
L-NT-J-3	170.9	0.45	1.5941	8.20	160	4.94
L-NT-J-4	255.8	0.80	1.6016	8.30	115	3.29
L-NT-J-5	301.7	0.25	1.5893	10.00	100	4.00
L-NT-J-6	133.8	0.45	1.5944	8.50	150	4.88
L-NT-J-7	216.0	0.40	1.6013	7.50	150	3.75
L-NT-J-8	247.3	0.60	1.6093	6.25	125	3.47
L-NT-J-9	251.1	0.60	1.6086	6.10	155	4.09
L-NT-J-10	287.5	0.45	1.6058	6.50	125	2.86
L-NT-J-11	342.3	0.85	1.5996	8.80	130	2.89
L-NT-J-12	241.2	0.65	1.6030	6.90	155	4.09

Run Number	Total Sulfur (wt%)	Pour Point (°C)	Bromine Number	Aniline Point (°C)	Average Molecular Weight	Calculated Cetane Index
L-NT-J-1	0.051	below -20°C	34.9	below -10°C	167	-23.5
L-NT-J-2	0.074	below -20°C	22.5	below -10°C	151	-4.7
L-NT-J-3	0.087	below -20°C	17.7	below -10°C	158	-4.3
L-NT-J-4	0.125	below -20°C	20.8	below -10°C	148	-6.4
L-NT-J-5	0.072	below -20°C	11.6	below -10°C	150	-3.9
L-NT-J-6	0.084	below -20°C	35.4	below -10°C	150	-4.8
L-NT-J-7	0.191	below -20°C	10.2	below -10°C	152	-6.6
L-NT-J-8	0.108	below -20°C	17.0	below -10°C	149	-7.9
L-NT-J-9	-	below -20°C	23.0	below -10°C	154	-7.3
L-NT-J-10	-	below -20°C	26.1	below -10°C	146	-10.0
L-NT-J-11	0.028	below -20°C	20.4	below -10°C	143	-6.1
L-NT-J-12	0.033	below -20°C	20.2	below -10°C	148	-6.1

TABLE VI. Test Results for K Series Products.

Run Number	Product (grams)	Reid Vapor Pressure (psia)	Refractive Index	Gravity (°API)	Flash Point	Viscosity (cst)
L-NT-K-1	129.5	0.35	1.6004	6.75	190	5.85
L-NT-K-2	272.4	0.35	1.5992	6.75	180	4.02
L-NT-K-3	176.6	0.50	1.5929	8.30	160	5.82
L-NT-K-4	129.5	0.45	1.5832	9.40	145	4.78
L-NT-K-5	221.0	0.45	1.5988	8.10	100	3.29
L-NT-K-6	84.0	-	1.5956	7.90	160	4.97
L-NT-K-8	178.9	0.70	1.5986	8.45	120	5.13

Run Number	Total Sulfur (wt%)	Pour Point (°C)	Bromine Number	Aniline Point (°C)	Average Molecular Weight	Calculated Cetane Index
L-NT-K-1	0.027	below -20°C	20.1	below -10°C	166	-24.2
L-NT-K-2	0.056	below -20°C	24.8	below -10°C	155	-8.6
L-NT-K-3	0.057	below -20°C	23.8	below -10°C	151	-6.8
L-NT-K-4	0.033	below -20°C	19.5	below -10°C	157	-1.7
L-NT-K-5	0.022	below -20°C	27.2	below -10°C	149	-6.8
L-NT-K-6	0.043	below -20°C	19.9	below -10°C	153	-4.7
L-NT-K-8	0.038	below -20°C	21.4	below -10°C	144	-8.0

TABLE VII. Test Results for L Series Products

Run Number	Product (grams)	Reid Vapor Pressure (psia)	Refractive Index	Gravity (°API)	Flash Point (°F)	Viscosity (cst)
L-NT-L-1	172.9	-	1.5987	8.45	130	3.05
L-NT-L-2	86.5	-	1.5888	9.85	135	4.34
L-NT-L-3	238.8	-	1.5965	8.45	120	2.98
L-NT-L-4	144.5	-	1.5871	10.30	135	3.78
L-NT-L-5	145.1	-	1.5882	9.60	150	5.07
L-NT-L-6	175.3	-	1.5892	10.30	120	3.05
L-NT-L-7	88.0	-	1.5912	9.20	135	4.63

Run Number	Total Sulfur (wt%)	Pour Point (°C)	Bromine Number	Aniline Point (°C)	Average Molecular Weight	Calculated Cetane Index
L-NT-L-1	0.019	below -18°C	17.7	below -10°C	146	-7.4
L-NT-L-2	0.066	below -18°C	18.4	below -10°C	153	-3.1
L-NT-L-3	0.070	below -18°C	19.0	below -10°C	150	-7.7
L-NT-L-4	0.051	below -18°C	23.0	below -10°C	147	-4.7
L-NT-L-5	0.039	below -18°C	27.9	below -10°C	162	+0.1
L-NT-L-6	0.068	below -18°C	27.6	below -10°C	148	-4.8
L-NT-L-7	0.038	below -18°C	27.0	below -10°C	156	-3.1

TABLE VIII. Test Results for O Series Products

Run Number	Product (grams)	Reid Vapor Pressure (psia)	Refractive Index	Gravity (°API)	Flash Point (°F)	Viscosity (cst)
L-NT-O-2	267.0	-	-	6.75	145	4.38
L-NT-O-5	80.7	-	-	7.80	165	5.91
L-NT-O-7	38.5	-	-	8.30	175	-
L-NT-O-8A	138.4	-	-	8.95	140	4.28

Run Number	Total Sulfur (wt%)	Pour Point (°C)	Bromine Number	Aniline Point (°C)	Average Molecular Weight	Calculated Cetane Index
L-NT-O-2	0.070	below -20°C	14.4	below -10°C	155	-3.6
L-NT-O-5	0.085	below -20°C	19.9	below -10°C	157	-3.6
L-NT-O-7	0.253	below -20°C	33.2	below -10°C	-	-
L-NT-O-8A	0.027	below -20°C	25.1	below -10°C	147	-7.3

TABLE IX. ASTM Distillation Data

ASTM	IBP	% Recovered											EP
		5	10	20	30	40	50	60	70	80	90	95	
J-1	331	392	414	449	478	506	530	548	561	587	618	636	636
2	170	301	360	400	431	463	484	506	534	564	585	-	636
3	180	347	380	422	451	469	494	510	536	562	616	628	634
4	-	291	349	390	425	449	475	496	520	546	606	-	614
5	-	297	354	394	427	459	475	514	532	550	573	587	612
6	-	329	355	400	433	459	486	506	528	552	571	597	589
7	170	327	368	406	435	463	486	572	536	558	583	-	632
8	-	254	348	400	433	459	488	508	532	556	626	-	644
9	190	398	376	410	441	469	496	518	540	566	597	-	640
10	170	276	346	390	421	437	470	496	526	558	587	-	636
11	-	246	331	384	410	443	471	494	518	542	568	585	628
12	170	291	366	402	437	469	496	522	538	556	583	599	630
K-1	190	368	402	443	480	518	532	560	573	587	607	623	644
2	170	376	398	421	443	465	475	510	532	560	583	-	618
3	190	341	374	400	429	459	471	506	528	550	573	579	609
4	170	317	366	402	441	476	502	518	540	558	585	604	618
5	170	304	358	398	425	449	474	496	522	554	589	-	626
6	170	331	368	402	435	465	496	522	540	560	577	581	593
8	-	305	346	384	410	435	459	482	504	542	573	-	618
L-1	170	305	352	386	410	437	463	484	514	552	587	-	626
2	190	301	368	396	427	457	484	506	534	552	585	597	610
3	-	307	348	386	415	443	461	506	528	552	573	-	630
4	196	298	356	388	412	437	465	490	512	540	560	583	620
5	196	333	378	425	461	490	514	534	550	564	591	612	632
6	186	319	358	394	419	443	463	488	512	536	568	593	624
7	196	344	382	408	437	473	492	516	534	554	587	598	604
O-2	210	340	378	423	465	494	520	540	556	583	606	-	664
5	170	348	378	406	441	475	506	542	556	575	589	599	605
7	-	-	-	-	-	-	-	-	-	-	-	-	-
8A	190	317	360	382	406	433	459	490	532	560	-	-	600



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Figure 1. The Fort Union Coal Region in Montana and Adjacent States. Also shows other coal areas in Montana. (3)

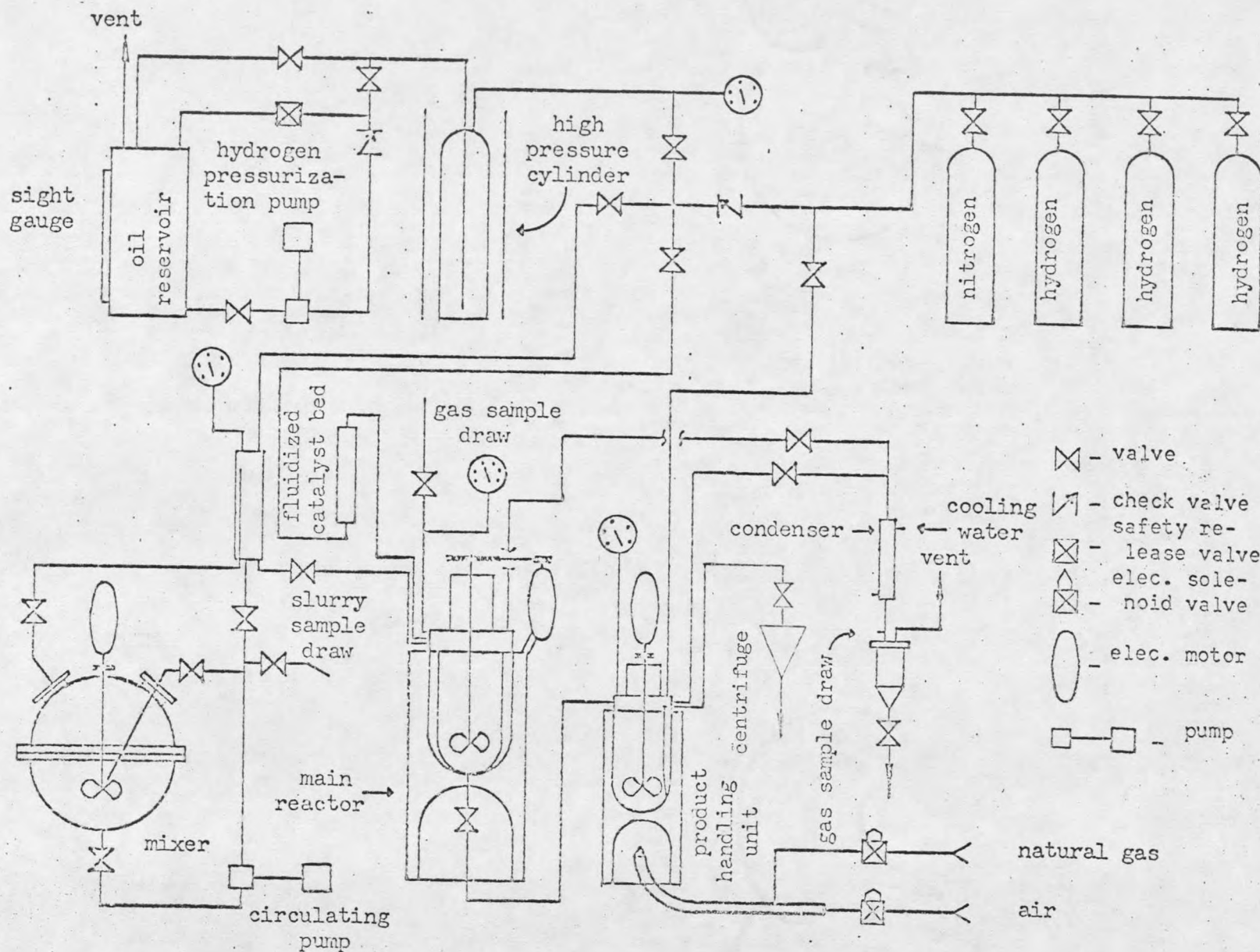


Figure 2. Schematic Diagram of Hydrogenation System.

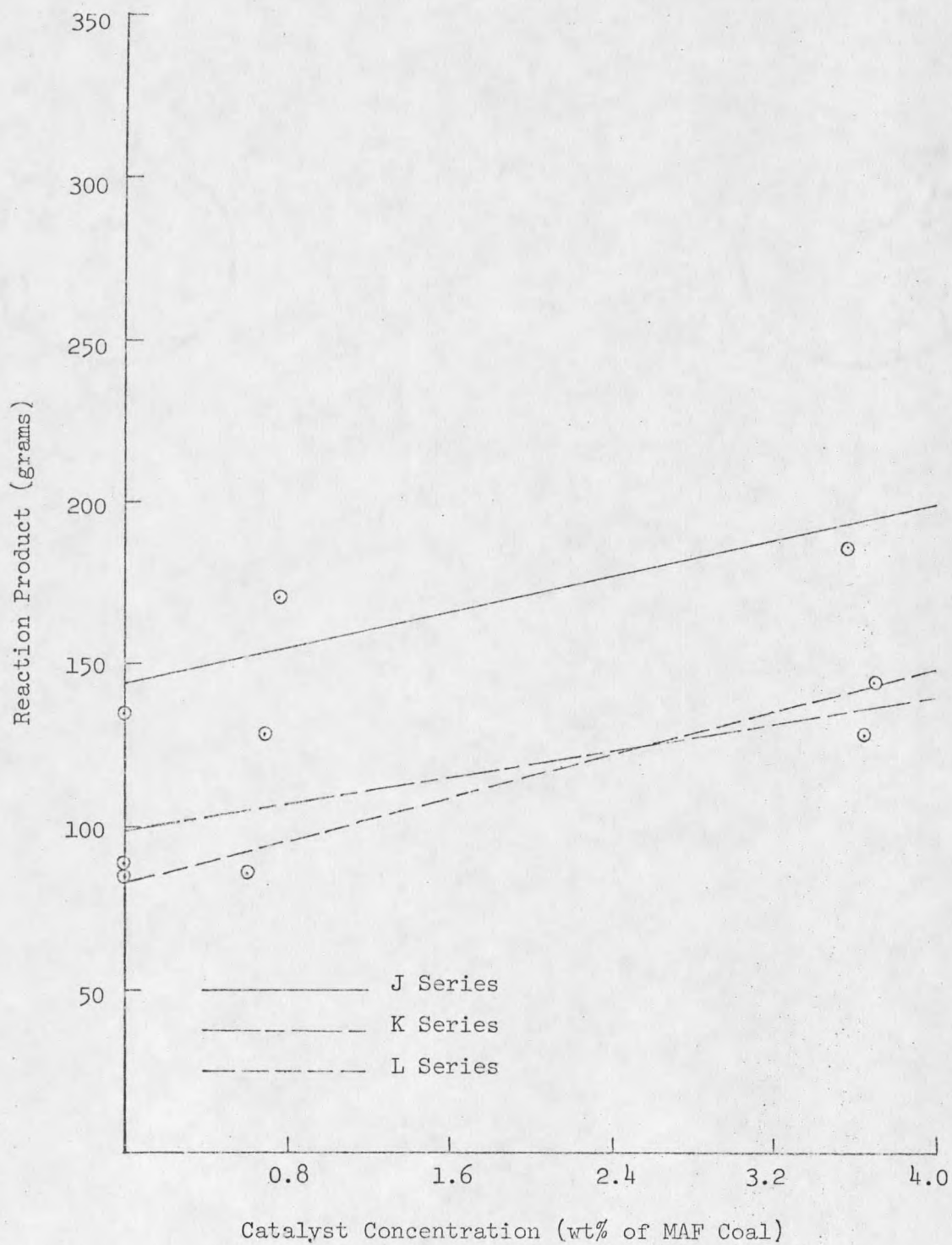


Figure 3. Effect of Catalyst Concentration on Reaction Product at 425°C.

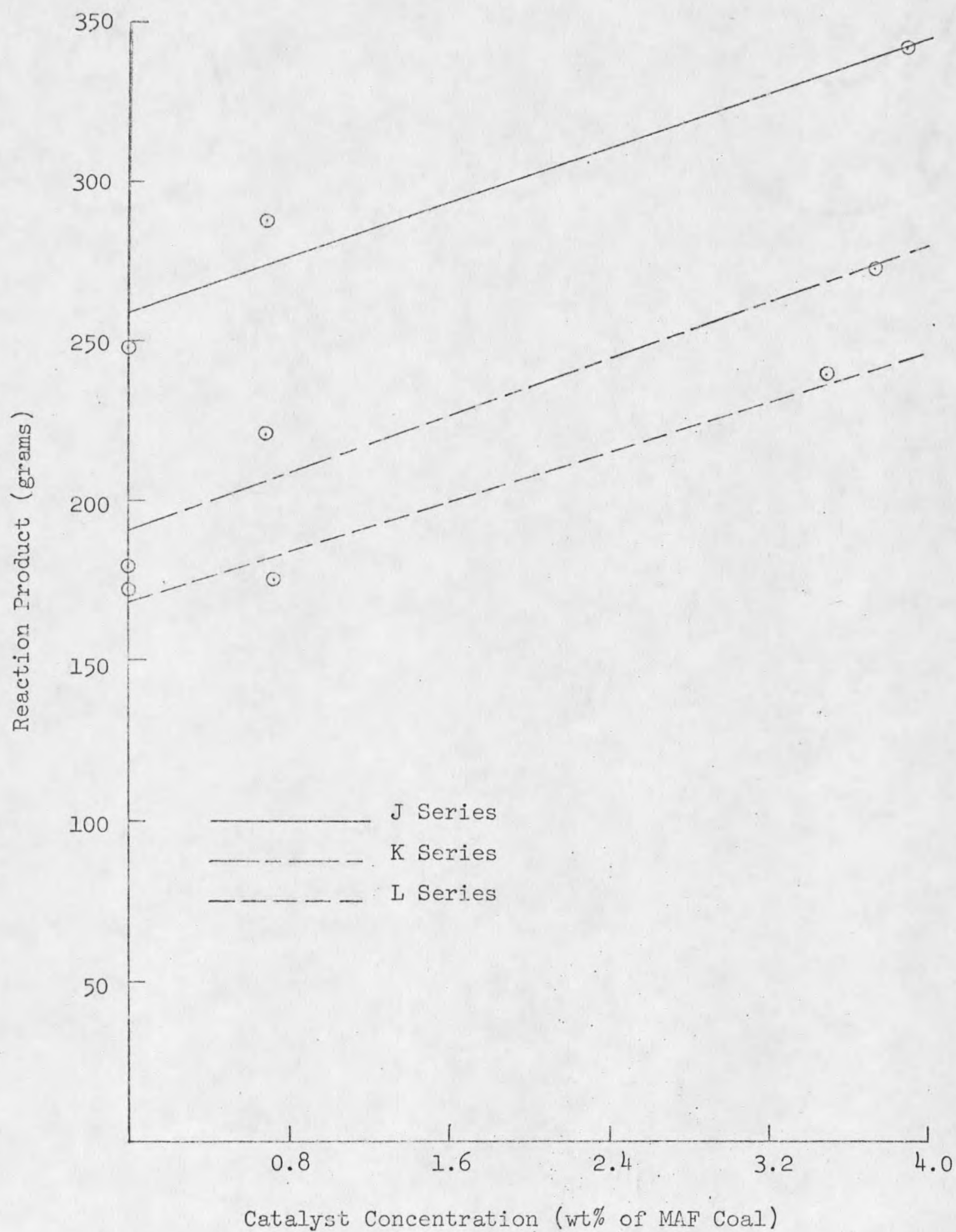


Figure 4. Effect of Catalyst Concentration on Reaction Product at 475°C

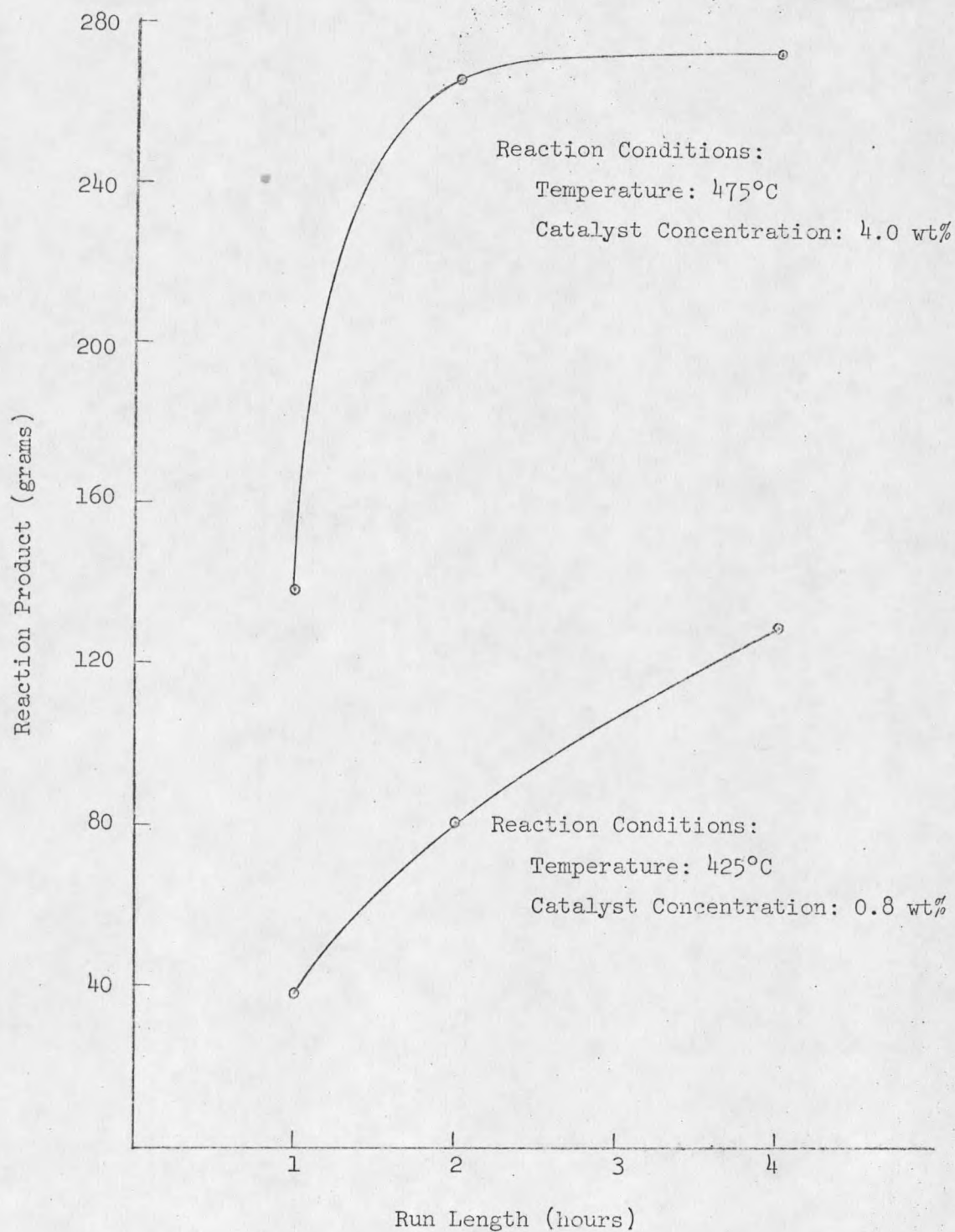


Figure 5. Effect of Run Length on Reaction Product

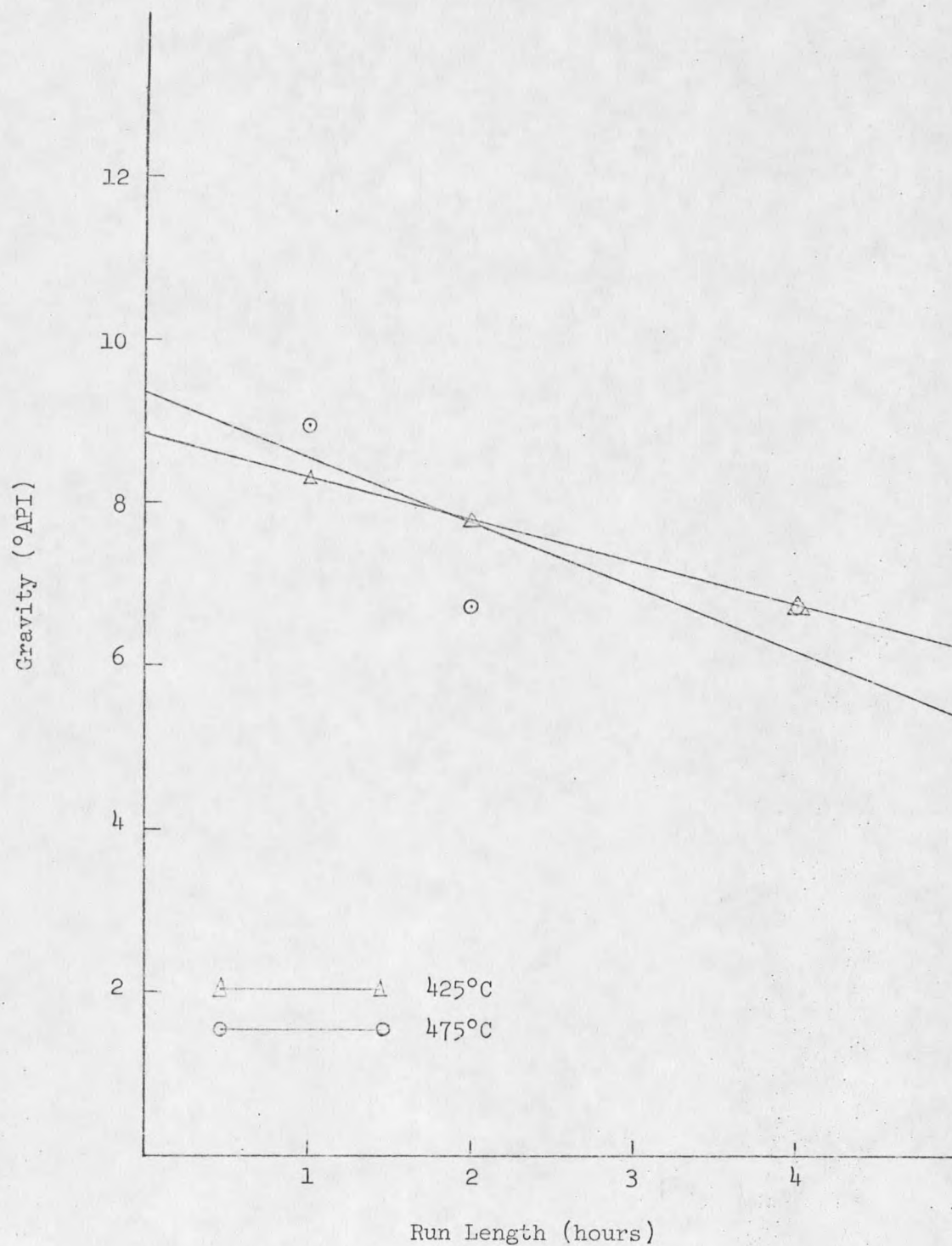


Figure 6. Effect of Run Length on API Gravity of Reaction Product.

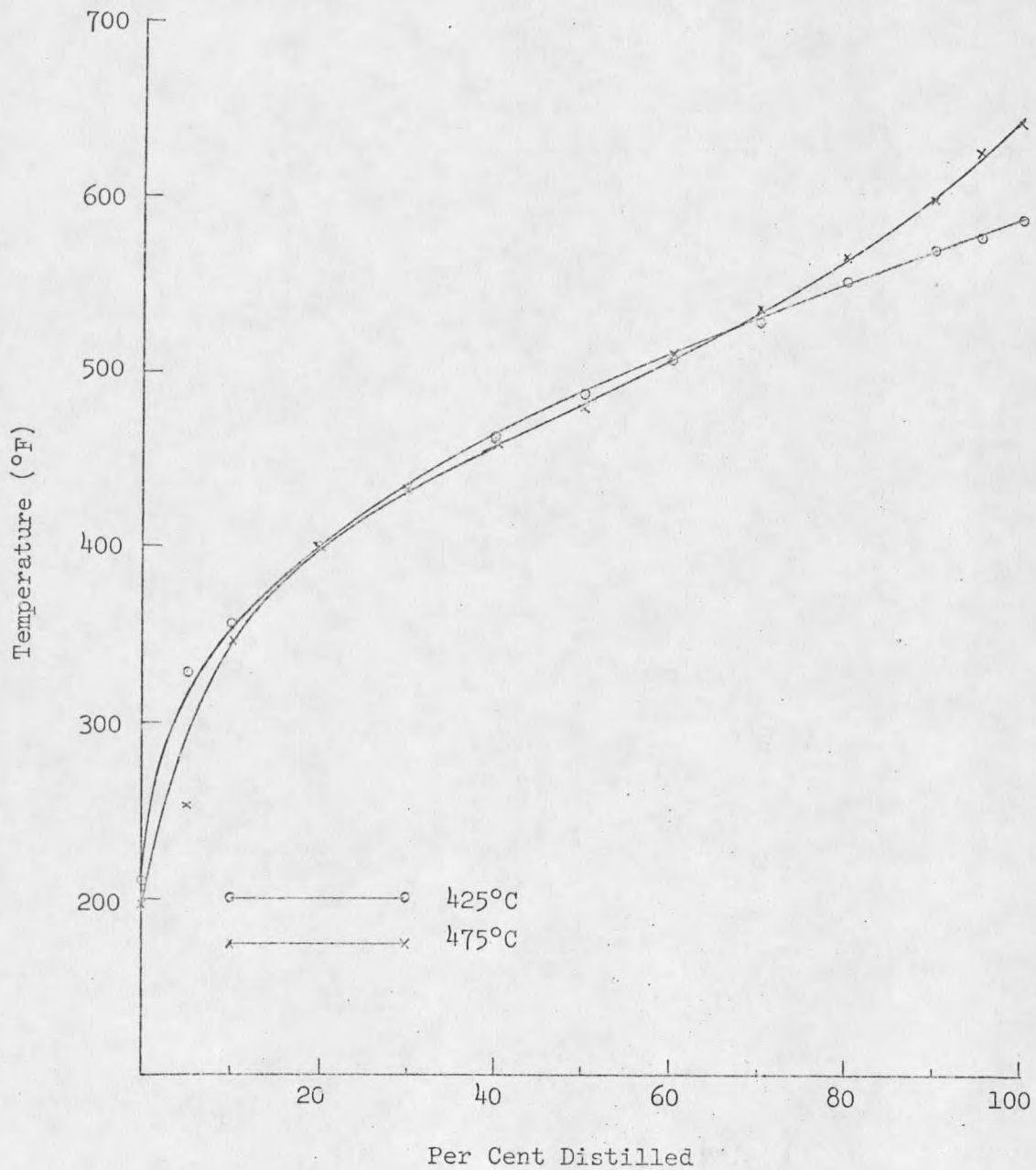


Figure 7. ASTM Distillations for J Series Products at 0 Catalyst Concentration.

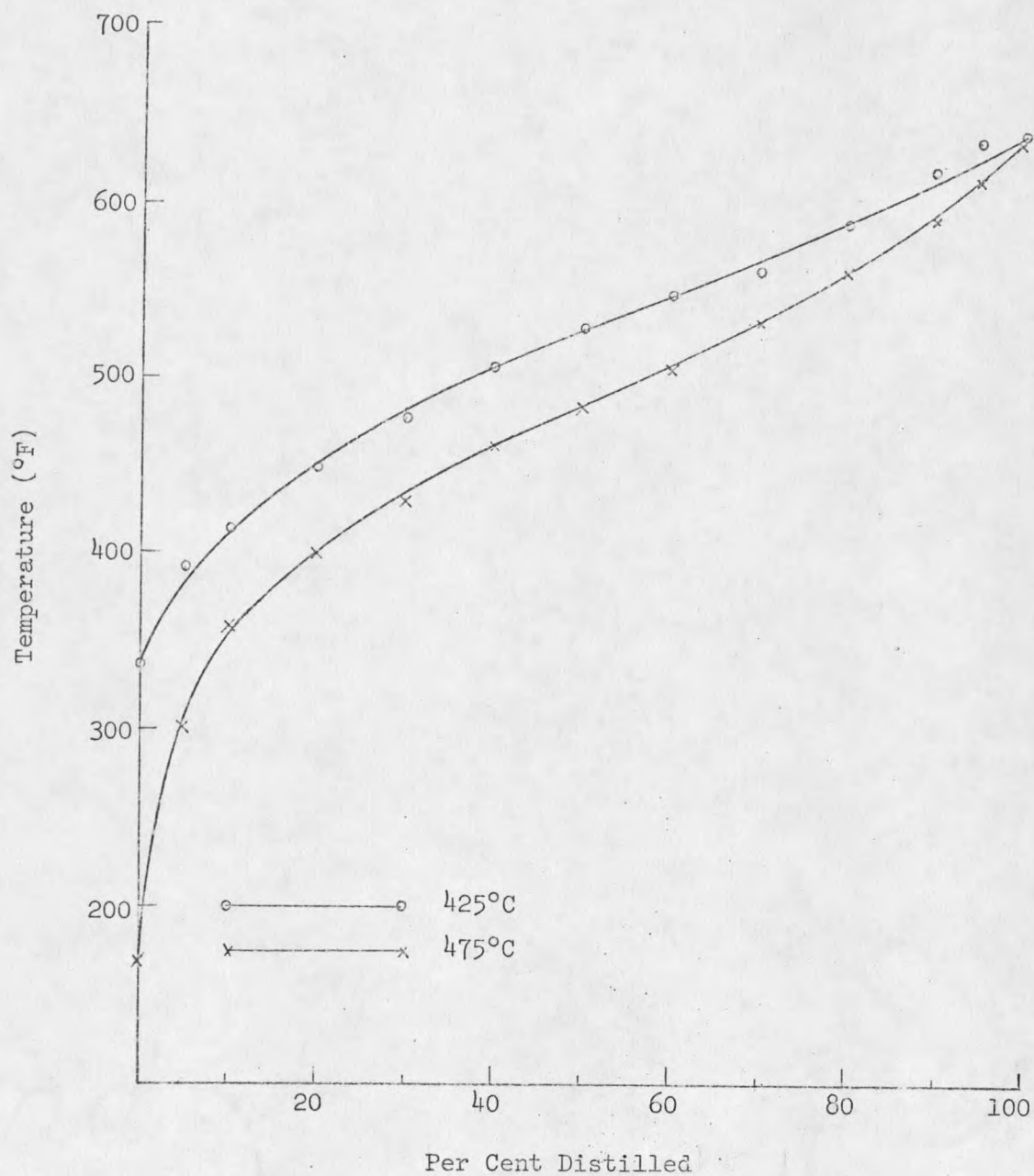


Figure 8. ASTM Distillations for J Series Products at 3.6 wt% Catalyst Concentration.

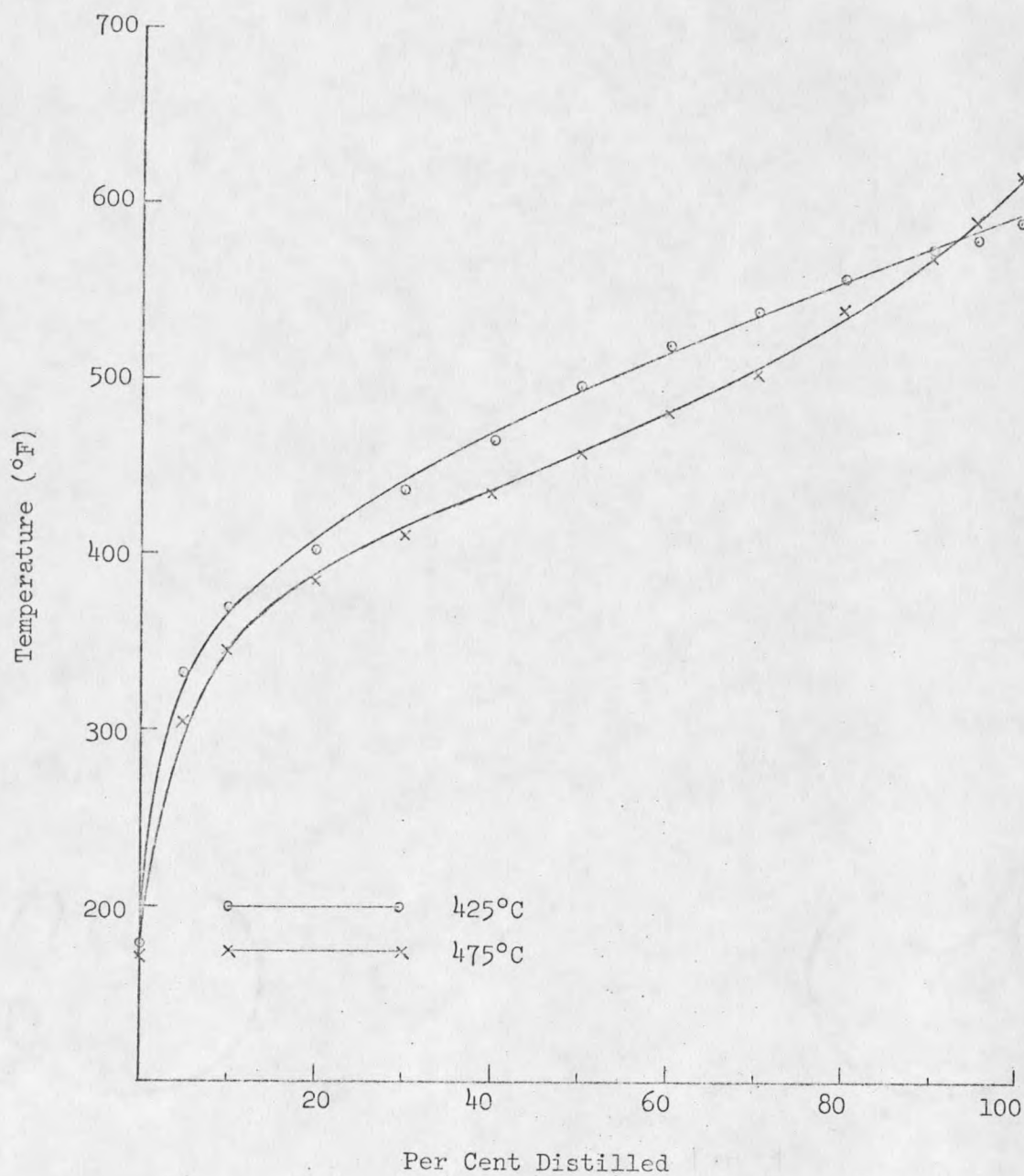


Figure 9. ASTM Distillations for K Series Products at 0 Catalyst Concentration.

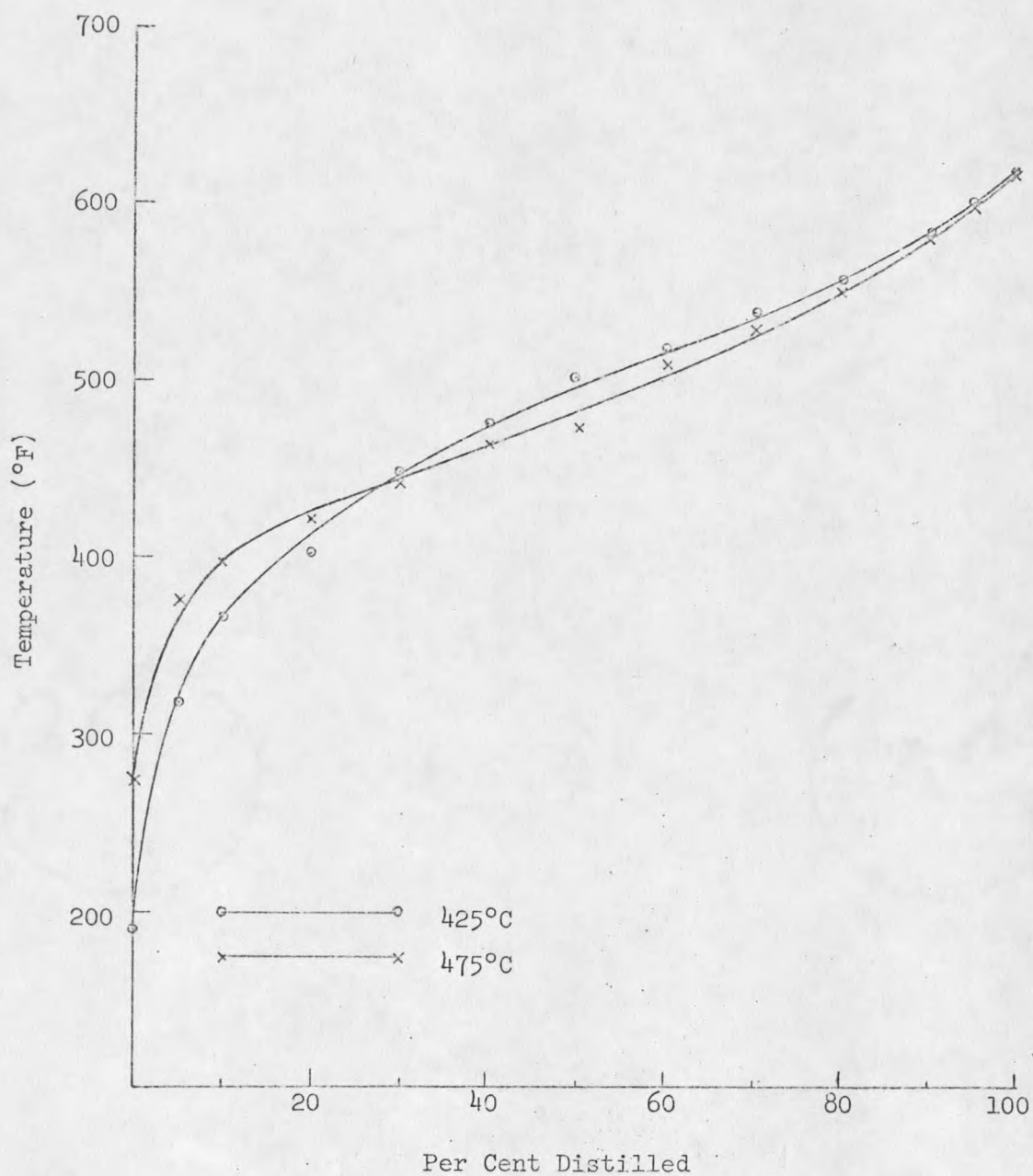


Figure 10. ASTM Distillations for K Series Products at 3.6 wt% Catalyst Concentration.

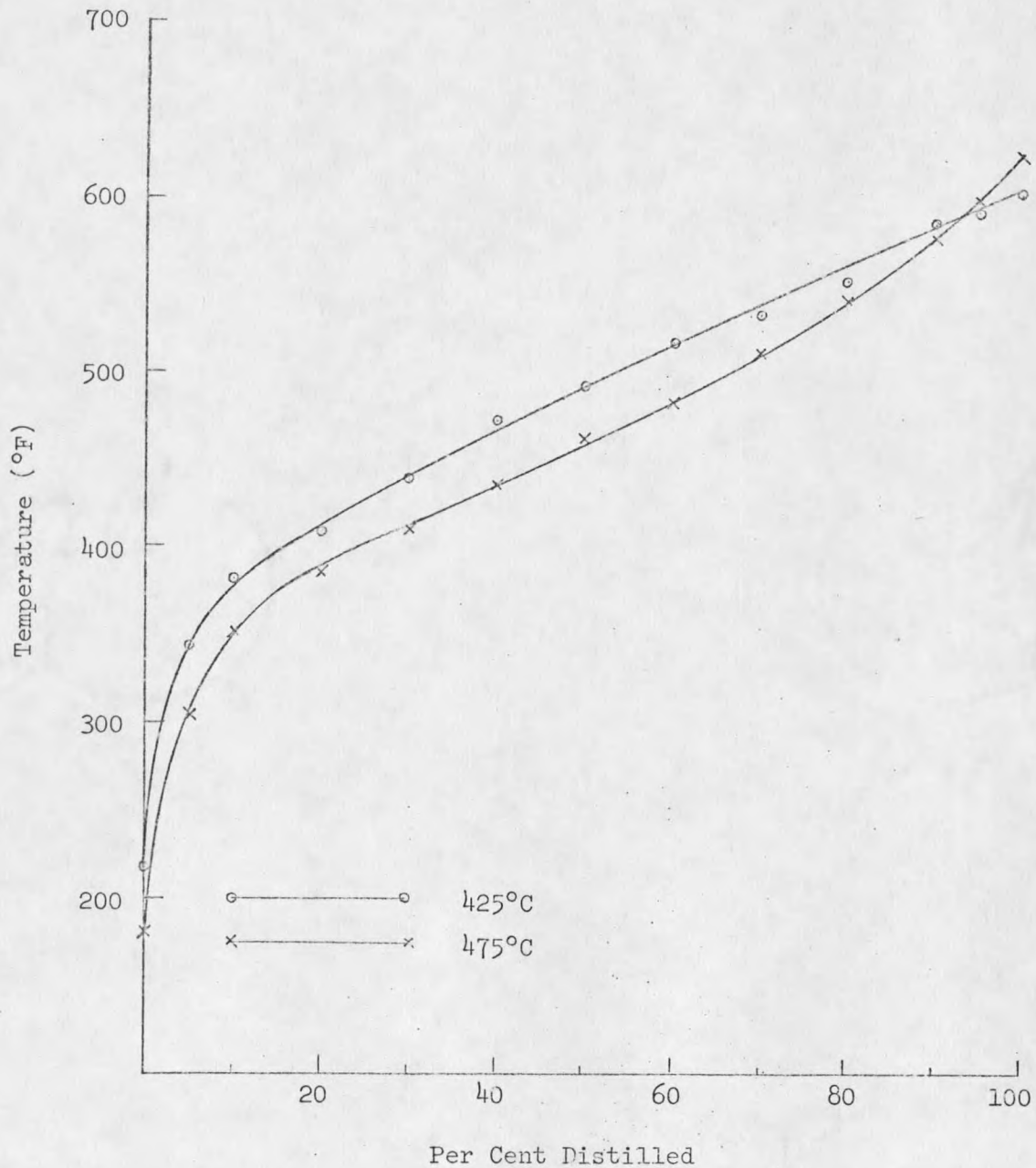


Figure 11. ASTM Distillations for L Series Products at 0 Catalyst Concentration.

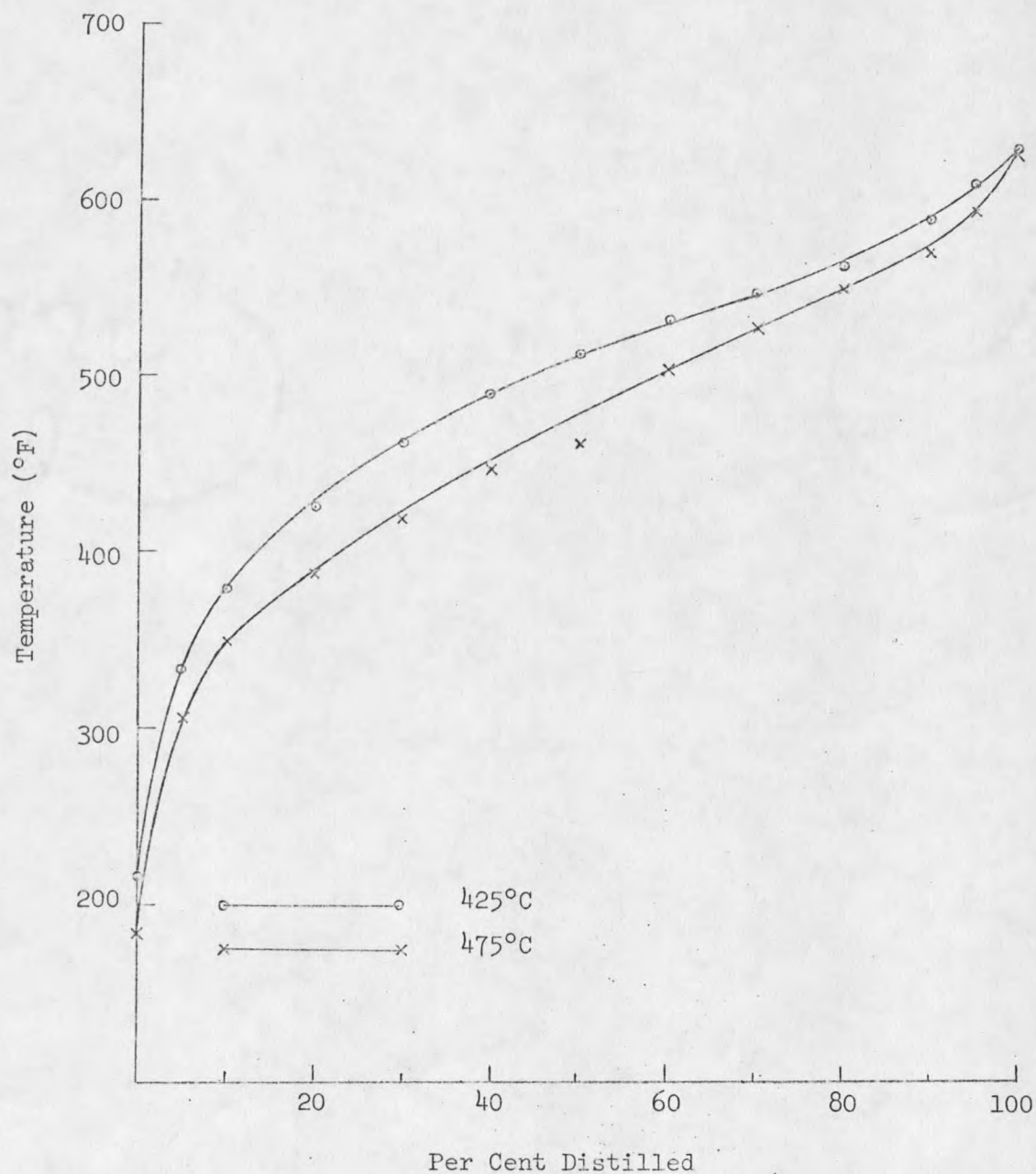


Figure 12. ASTM Distillations for L Series Products at 3.6 wt% Catalyst Concentration.

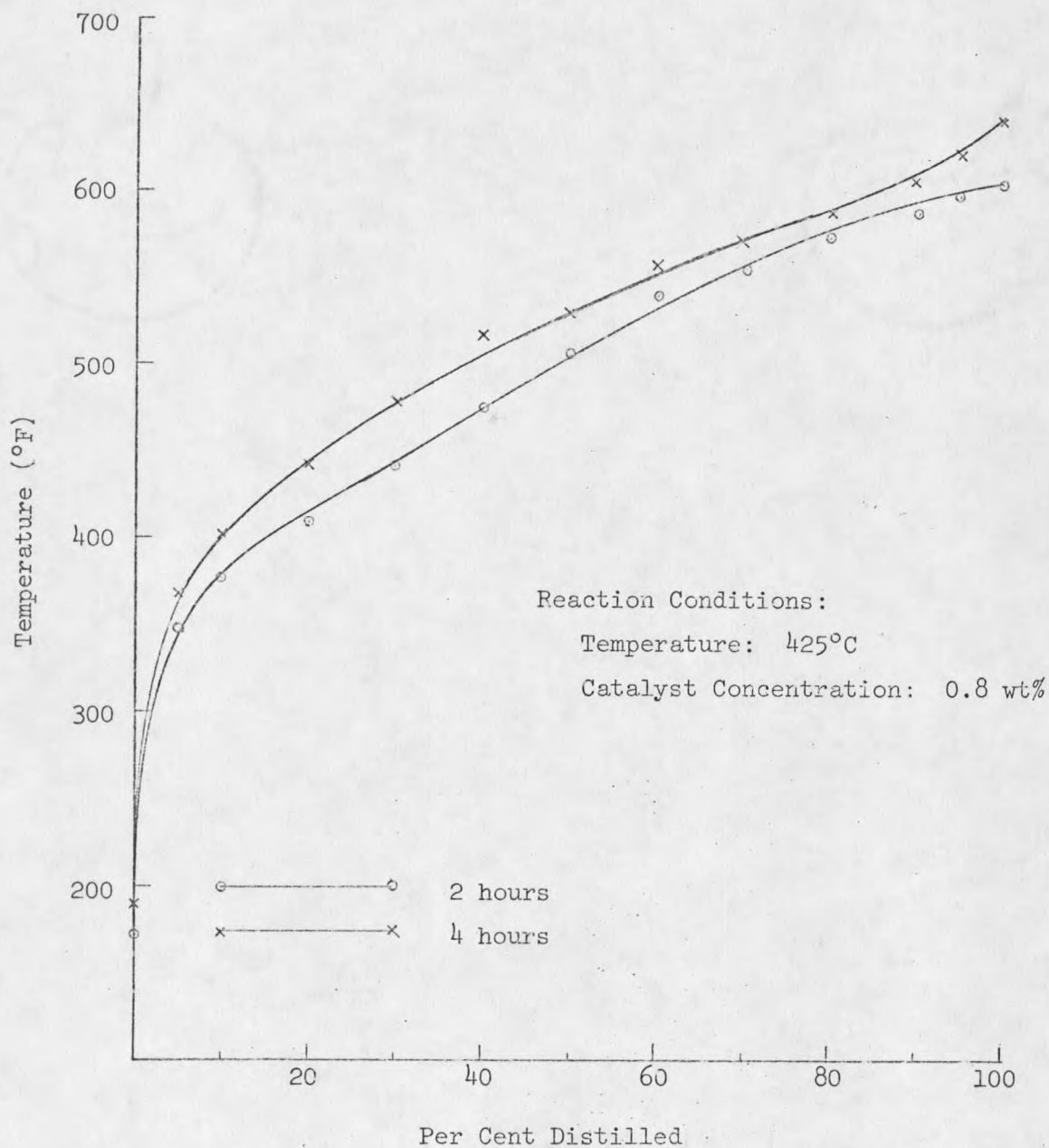


Figure 13. Effect of Run Length on ASTM Distillations of Reaction Products

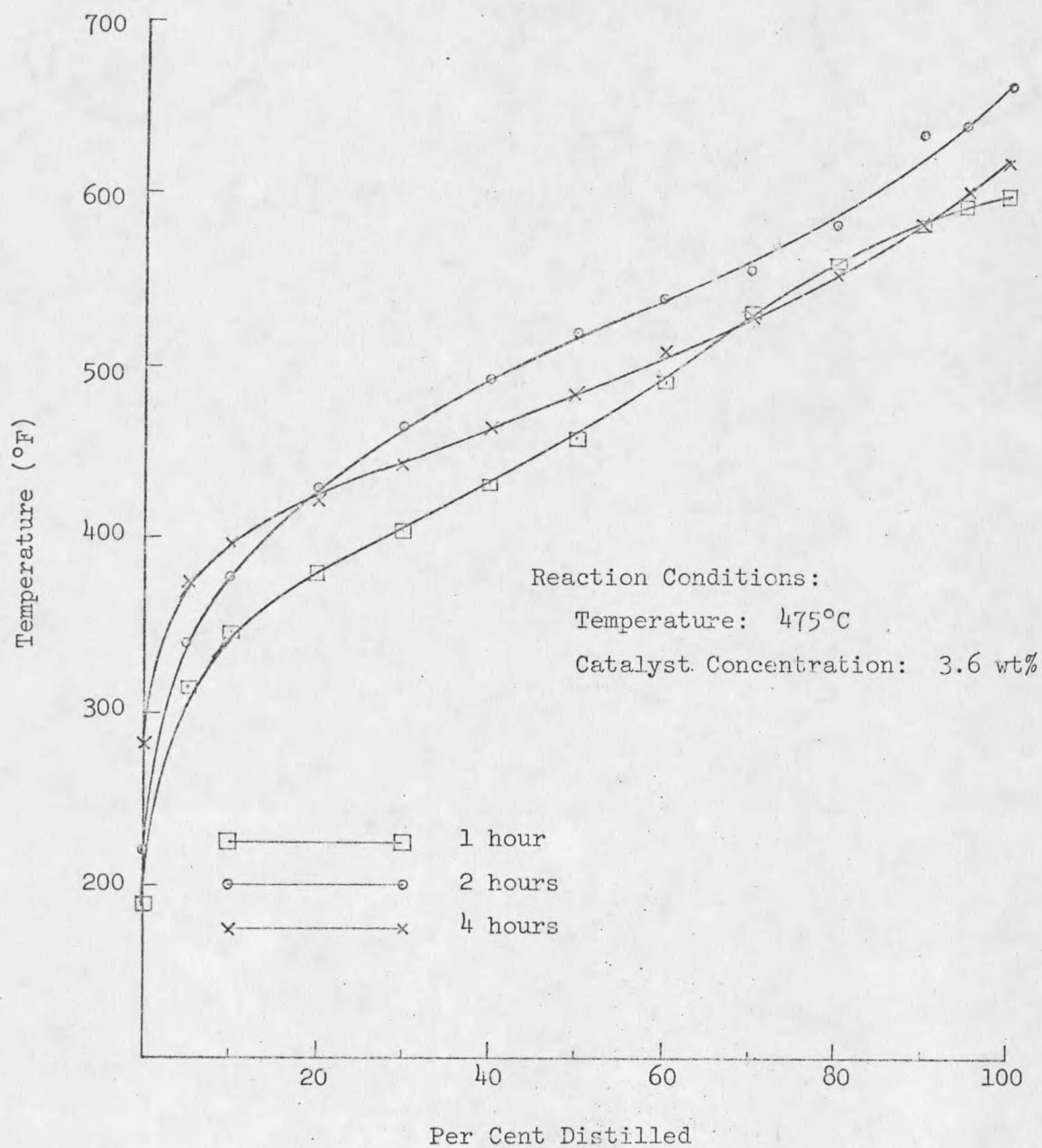


Figure 14. Effect of Run Length on ASTM Distillation of Reaction Products.

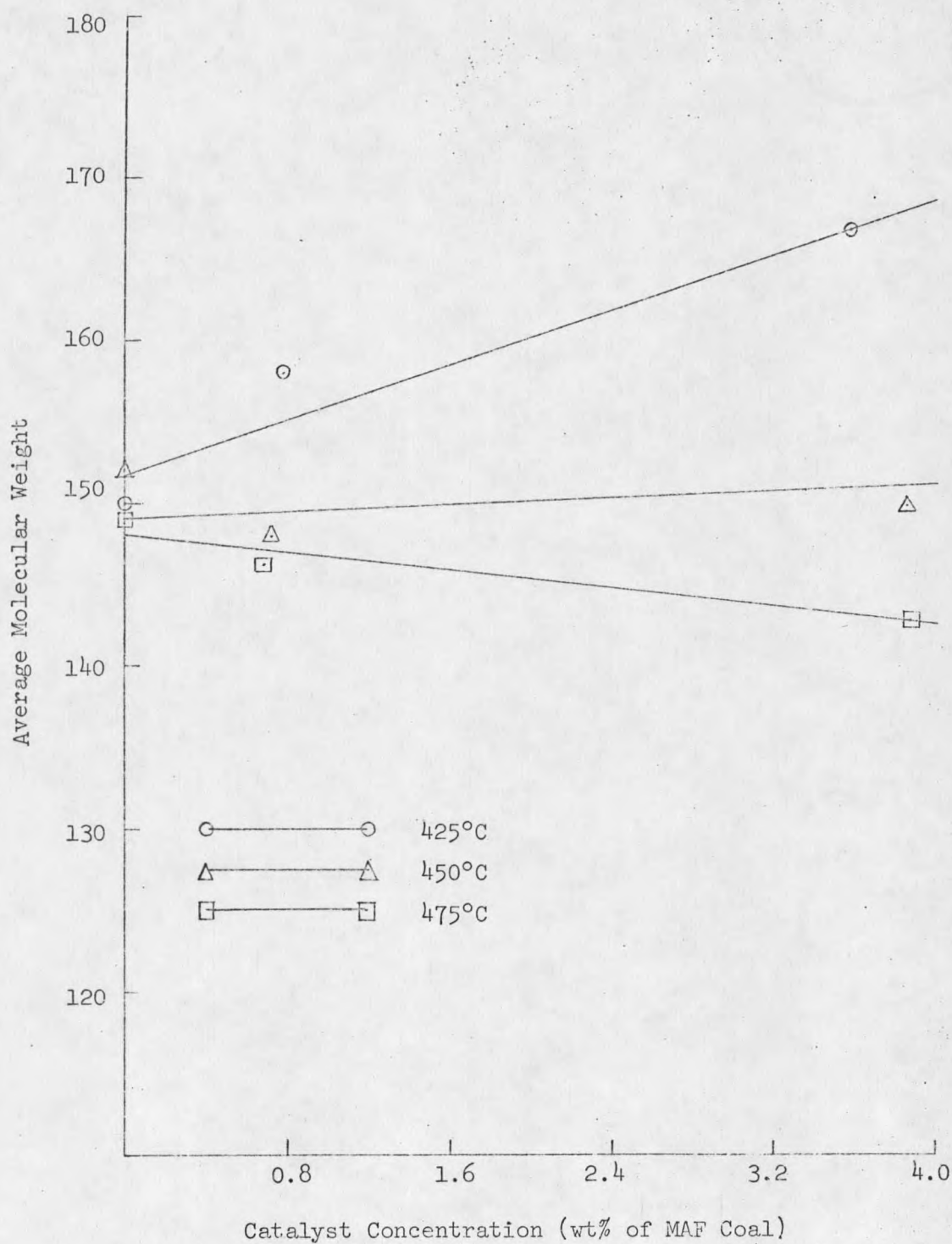


Figure 15. Effects of Temperature and Catalyst Concentration on Average Molecular Weight of Reaction Products for J Series Runs.

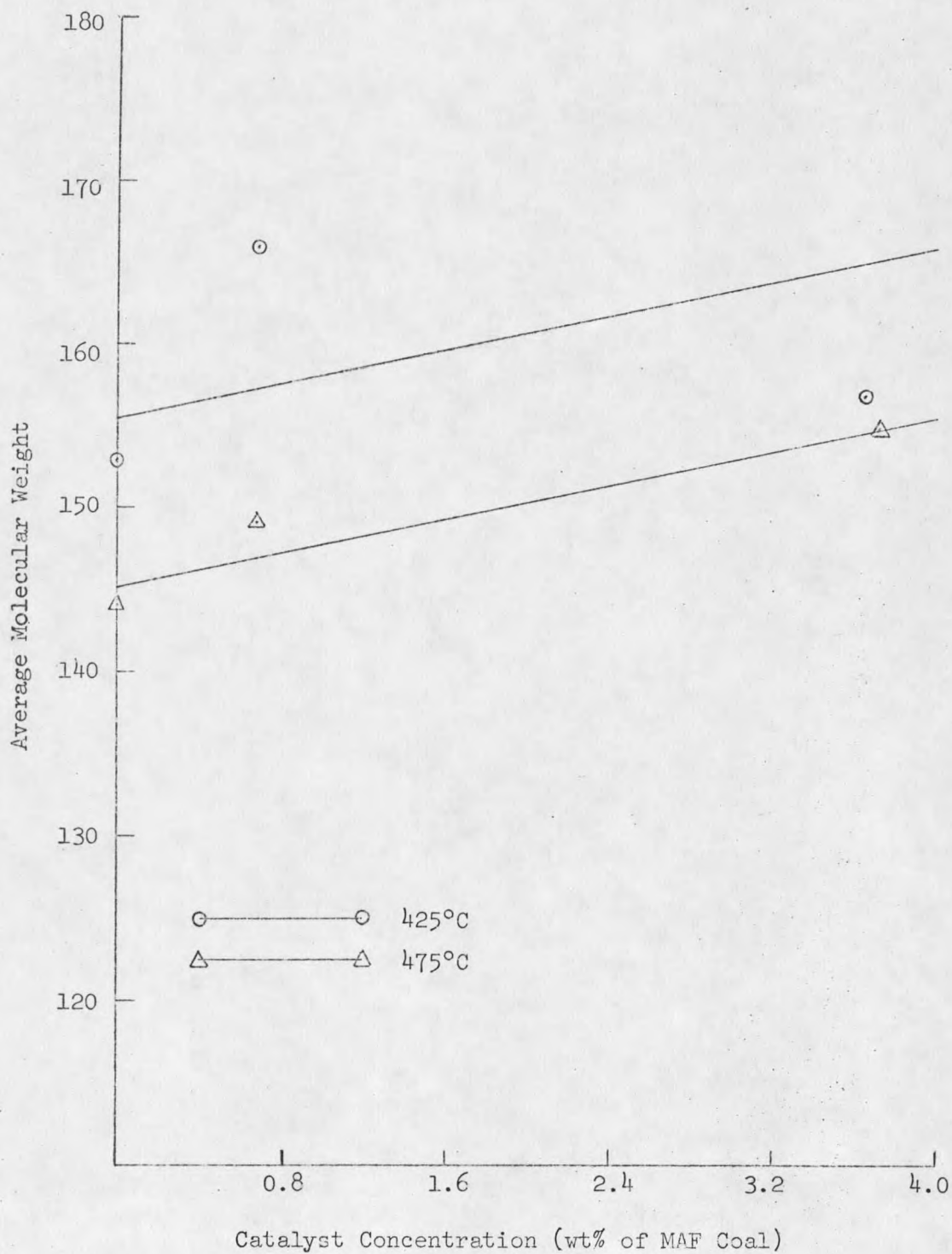


Figure 16. Effects of Temperature and Catalyst Concentration on Average Molecular Weight of Reaction Products for K Series Runs.

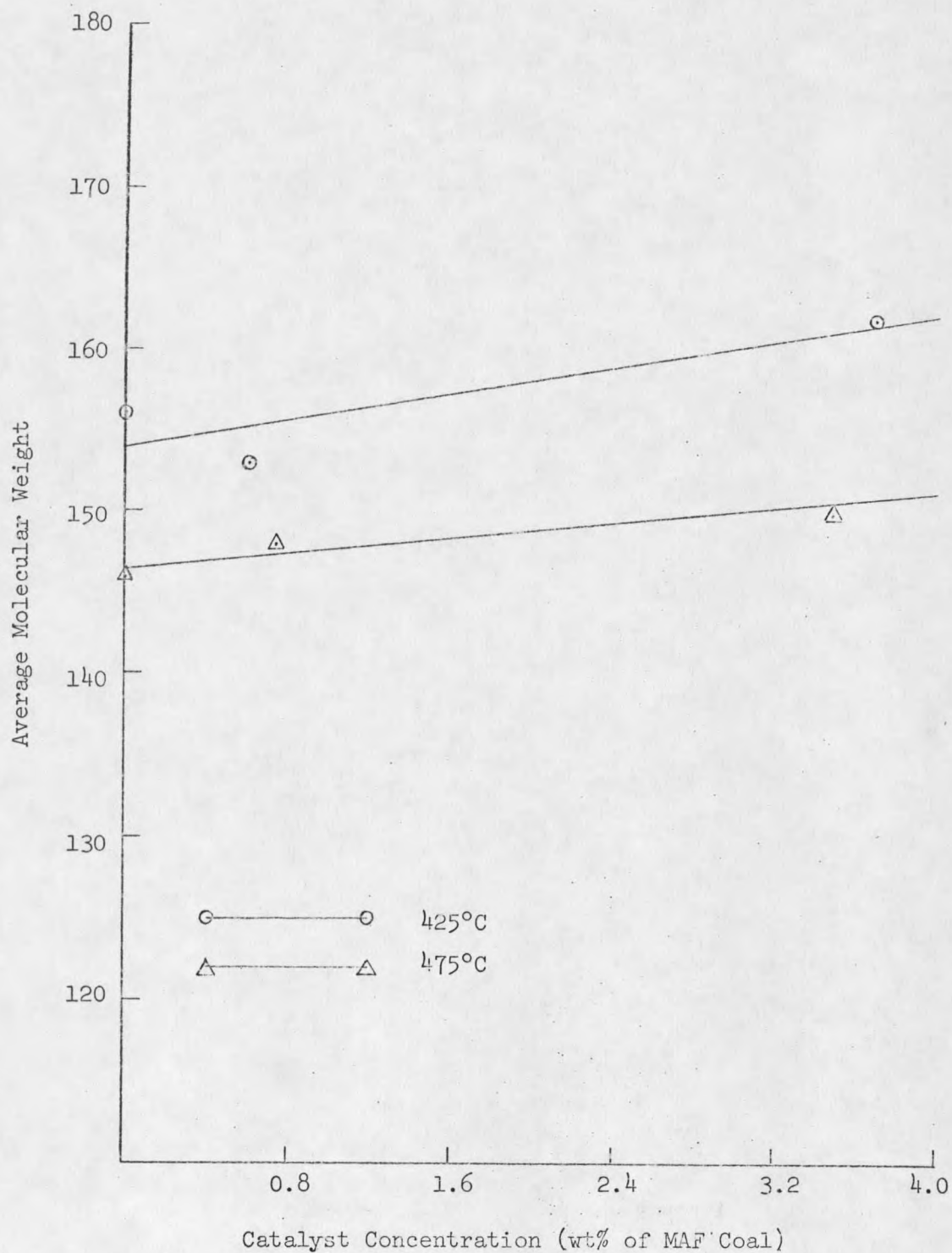


Figure 17. Effects of Temperature and Catalyst Concentration on Average Molecular Weight of Reaction Products for L Series Runs.

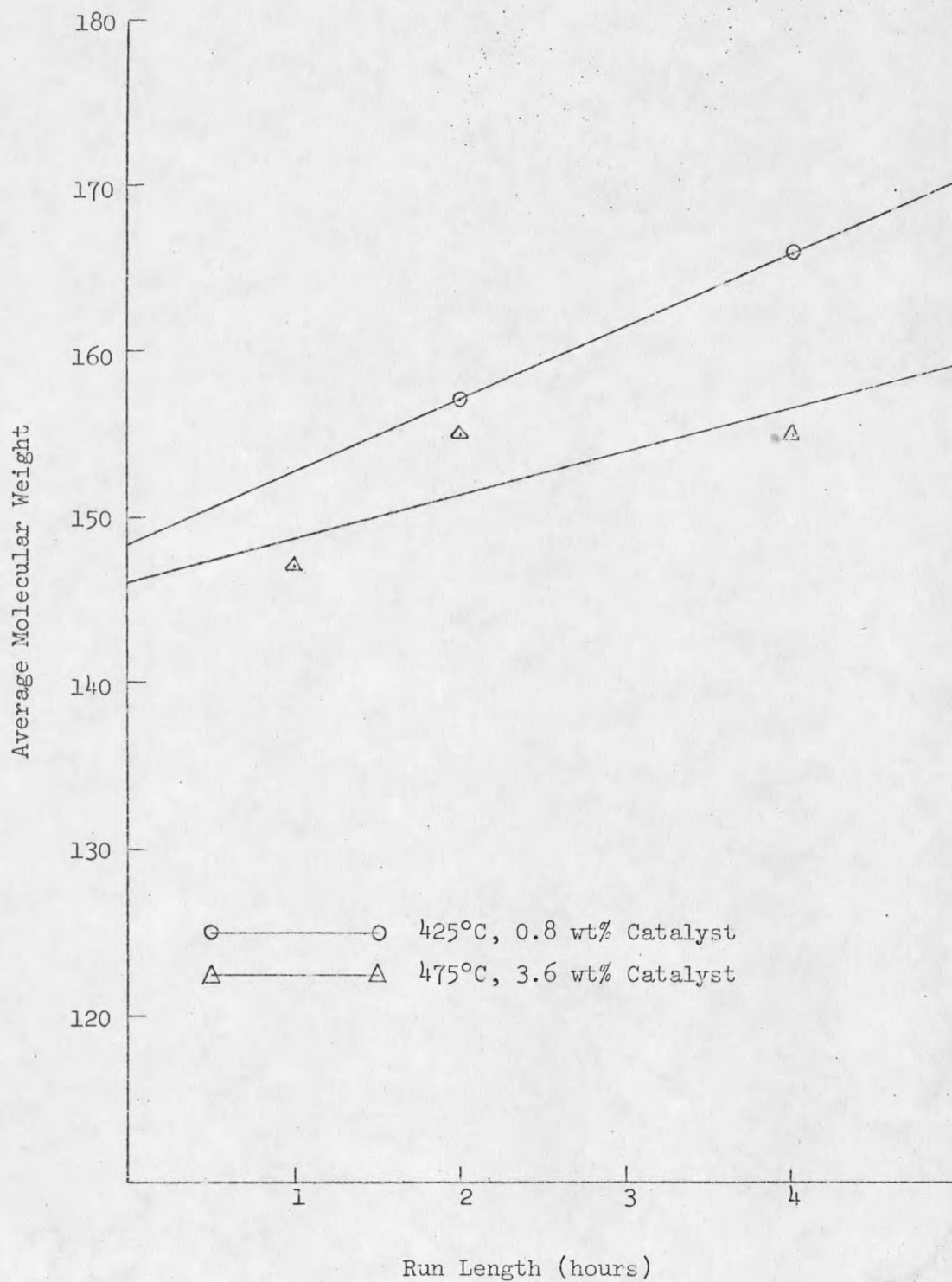


Figure 18. Effect of Run Length on Average Molecular Weight of Reaction Products.

VIII LITERATURE CITED

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