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CRUDE OIL STEAM DISTILLATION IN STEAM FLOODING

FINAL REPORT

Work Performed for the U.S. Department of Energy
Under Contract No. DE-AS03-78ET12357

Date Published—August 1980

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Final Report

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ABSTRACT

Steam distillation yields of sixteen crude oils from various parts of the United States have been determined at a saturated steam pressure of 200 psig. Study made to investigate the effect of steam pressure (200 to 500 psig) on steam distillation yields indicates that the maximum yields of a crude oil may be obtained at 200 psig. At a steam distillation correlation factor ($\frac{V_w}{V_{oi}}$) of 15, the determined steam distillation yields range from 12 to 56% of initial oil volume for the sixteen crude oils with gravity ranging from 12 to 40^o API.

Regression analysis of experimental steam distillation yields shows that the boiling temperature (simulated distillation temperature) at 20% simulated distillation yield can predict the steam distillation yields reasonably well: the standard error ranges from 2.8 to 3.5% (in yield) for $\frac{V_w}{V_{oi}} < 5$ and from 3.5 to 4.5% for $\frac{V_w}{V_{oi}} > 5$. The oil viscosity (cs) at 100^{o}F can predict the steam distillation yields with standard error from 3.1 to 4.3%. The API gravity can predict the steam distillation yields with standard error from 4.4 to 5.7%. Characterization factor is an unsatisfactory correlation independent variable for correlation purpose.

INTRODUCTION

Steam distillation is a process employing steam to vaporize and/or to strip the lighter fractions from a mixture. It has been used in chemical and other process industries for the separation of components that either have high normal boiling points or are likely to decompose at high distillation temperatures. The process can be a batch (or semi-batch) process or a continuous flow process.

Steam distillation has been recognized to take place in thermal oil recovery processes such as steamflooding and in-situ combustion processes. It is considered as one of the major mechanisms which effect high oil recovery by steam flooding. Willman, et al.(1) have experimentally estimated the oil recovery due to the steam distillation mechanism. For the crude oils tested, the oil recovery by steam distillation alone ranges from 5 to 19% of original oil in place at steam temperatures up to 520°F. Farouq Ali(2) has estimated that 5 to 10% of the heavy oil recovery and as much as 60% of light oil recovery by steamflooding may be attributed to steam distillation. Field tests reported by Volek and Proyer(3) and by Konopnicki, et al.(4) have indicated that the residual oil saturation after steam distillation drive is less than 8%.

Although the importance of steam distillation mechanism has been recognized in steamflood processes, its effects on heavy and light oil recovery by steamflooding are not well understood. Quantitative information on crude oil steam distillation remains scarce, while mathematical calculations suffer from insufficient basic steam distillation information. Due to shortage of energy, high cost of importing foreign oil, and inadequate discovery of new domestic oil fields, steamflooding is gaining importance in enhancing oil recovery from existing heavy and light oil reservoirs. Quantitative steam distillation information should be significantly useful in steamflood simulation and process design to further steamflood recovery efficiency. Therefore, the objectives of the investigation are (1) to determine the crude oil steam distillation yields of 12 to 35^{o} API crude oils from different parts of the United States, and (2) to develop a technique to estimate the crude oil steam distillation yields based on basic crude oil properties such as ^{o}API, oil viscosity, characterization factor, and simulated distillation yields.

LITERATURE SURVEY

Laboratory and Field Tests

Several papers have reported the effects of steam distillation on oil recovery observed in laboratory steam displacement tests. Willman, et al.[1] have reported that steamflooding results in significantly greater oil recovery than does hot water flooding at the same temperature, mainly due to steam distillation. Wu and Fulton[5] have reported that oils in the steam plateau of an in-situ combustion process are removed mainly by steam distillation. Johnson, et al.[6] have reported that the oil vaporization recovery by steam ranges from 54.7 to 94.0% of immobile oil volume for the oils used in their experiments. Volek and Proyer[3] have demonstrated the extent of steam distillation transition zone by analyzing the hydrocarbon composition distribution in the residual oil of a laboratory steamflood. In steam displacement tests, quantitative information on the effect of steam distillation is not obtainable.

In order to separate the effects of steam distillation on oil recovery from that of steam displacement, Quinones[7] and Wu and Brown[8] have conducted laboratory crude oil steam distillation tests. Quinones has reported that the steam distillation yield of Bradford crude oil at 75 psia is 59% of steam-contacted oil-in-place, and for Lagunillas crude oil at 40 psia is 20%. Wu and Brown have reported the steam distillation yields of six crude oils with gravity ranging from 9 to 36° API. The crude oil steam distillation yields obtained at 200 and 500 psig range from 7 to 57% of steam-contacted oil-in-place. These data are insufficient for developing predictive methods to estimate the steam distillation yields using basic crude oil properties.

Steam flooding has been commercially used to recover heavy oils(9),(10),(11), however, it is demonstrated to be effective in recovering light oils(3),(4), as well. Volek and Proyer(3) have reported a steam distillation drive test in Brea field, California. The Brea crude is 24° API with a viscosity of 6 centipoise. The Lower B Sands East has a 66° dip at an average depth of about 4,000 feet. Test results indicate a residual oil saturation of less than 8% in the steamed-out region. Konopnicki, et al.(4) have recently reported a pilot steam distillation drive test in the Shiells Canyon field, Ventura County, California. The Shiells Canyon crude is 34° API with a viscosity of 6 centipoise. The Shiells Canyon 203 Zone has a 35° dip at an average depth of 850 feet. Results indicate a residual oil saturation of less than 5% in the steamed-out region.

Mathematical Studies

Calculation methods for batch and continous steam distillation are available from published literature[(12),(13),(14),(15),(16),(17)]. These methods are limited to isothermal immiscible cases. Robinson and Gilliland[(13)] have presented steam distillation equations for batch and co-current steam distillation of binary systems. Holland and Welch[(14)] have developed a method of calculating steam batch distillation of multi-component systems. Van Winkle[(16)] has presented a good summary of steam distillation equations for batch and continuous processes. Moreno[(17)] has recommended to use Holland and Welch approach to calculate crude oil steam distillation. Rhee[(18)] has extended Holland and Welch approach to consider the condensation effect on steam distillation in steamflooding.

Approximate methods have been reported in the literature for calculating the amount of oil distilled during steamflooding. Sukkar[(19)] has presented a calculation method based on theoretical consideration using local mass and heat balances. Johnson, et al.[20] have reported a more realistic approach to calculate the amount of oil vaporized during steamflooding. However, the approach does not distinguish the amount of oil recovered by steam distillation and by steam displacement. Coats[21] has developed a compositional steamflood simulator using a finite difference approach. In the approach the oil phase is assumed to be comprised of three components with assumed equilibrium constants. Rhee[18] has developed a calculation method by combining Marx and Langenheim[22] and Holland and Welch approaches. All mathematical approaches have suffered from lack of supporting steam distillation data.

EXPERIMENTAL INVESTIGATION

Crude Oil Samples

Twenty-nine crude oil samples have been received from the Department of Energy in Wyoming and from 17 oil companies in the United States. Out of these twenty-nine crude oils, sixteen are used in the experiments. The basic properties of the sixteen crude oil samples are measured. Table 1 lists the properties of these crude oils. A Soxhlet type distillation is performed on each sample to determine the water content in volume percent. The API gravity is determined by weighing method and by correcting to a water-free basis. The kinematic viscosity of each oil is measured at three different temperatures using Cannon-Fenske viscometers. Plots of kinematic viscosity vs. temperature are shown in Figures A1 through A4 in Appendix A. Since simulated distillation of crude oil closely approximates the true boiling point distillation, it is performed instead of ASTM distillation. Simulated distillation are shown in Figures A5 through A20 in Appendix A. Simulated distillation procedure is described in Appendix B. The characterization factor of each crude oil is determined using the simulated distillation data[23].

Apparatus

The schematic diagram of the experimental apparatus appears in Figure 1. The apparatus consists of five major components: a positive displacement pump, a steam generator, a steam distillation cell, a back pressure regulator and a liquid-gas separator, and a temperature control and recording system.

A Ruska positive displacement pump is used to produce the required flow rates. The dual cylinders allow for the continuous operation of the pump; as one pumps the other draws distilled water from the water reservoir. The pump is used either to displace water into the steam generator as would be the case during a run, or to displace oil from the oil reservoir into the steam distillation cell during preparation for a run.

A diagram of the steam generator is presented in Figure 2. The generator is made of a 12 in. long, 1-5/8 in. ID 308 stainless steel. It is packed with 1/2 to 1 inch long 1/8 in. stainless steel tubings. The heat input is provided by three band heaters. The bottom two band heaters are arranged in parallel and controlled by an automatic proportional controller capable of maintaining a set temperature ($\pm 2^{o}F$). The set temperature is checked by the temperature monitored by a thermocouple on the outside of the generator. The top heater is regulated by a variable transformer set manually. The water is allowed to flow downwards through the generator to prevent water build-up. The steam leaving the generator travels through a 14 in. long 1/4 in. tubing and a check valve to the steam distillation cell. The 1/4 in. tubing is wrapped with 130-watt heating tape, insulated by asbestos, and controlled by a variable transformer.

The steam distillation cell which contains the oil for steam distillation is a stainless steel tube whose cross-section is shown in Figure 3. The 36 in. long and 3 in. ID cell has a 1/8 in. copper jacket welded inside to provide a uniform temperature distribution. On the outside 2500 watt strip heaters partially provides the required heat. The remaining heat input is provided by band heaters located on the top and bottom flanges (150 & 350 watt, respectively). To control the heat input, the 2500 watt strip and the 350 watt band heaters are wired to automatic proportioning controllers. The 150-watt band heater is connected to a variable transformer which is set manually. To monitor the temperature of the cell, seven other thermocouples are placed inside and outside the cell. To reduce heat losses the cell has 4 inch sodium silicate insulation.

The vapor leaving the steam distillation cell enters a 22" water cooled condenser which leads to an adjustable back pressure regulator. The produced fluid from the back pressure regulator enters a liquid-gas separator. Any produced gas travels to an erlenmeyer flask which lies in an ice bath to collect additional liquids. The gas continues to a wet test meter and finally to a vent. The liquid for the separator is allowed to settle until an adequate sample has been collected (20-500 ml). The liquid is then placed in either graduated cylinders (5-100 ml) or erlenmeyer flasks (500 ml).

The electric circuits for heat generation and temperature control are shown in Figure 4.

Procedure

A laboratory procedure has been developed to determine the crude oil steam distillation yields. In general, the procedure can be divided into two phases: the first phase involves cell preparation and the second phase involves the actual distillation test. The procedure for cell preparation is as follows:

1. Inject air from the top of steam distillation cell and produce any fluid present from the bottom.

2. Pull vacuum and close valves.
3. Introduce approximately 700 ml of toluene from the bottom.
4. Allow toluene to sit a minimum of 15 minutes.
5. Inject air again from top and produce toluene from bottom.
6. Repeat injection of toluene until produced toluene is clear (3-6 times).
7. Heat cell to 220°F.
8. Inject air through the cell for a minimum of 3 hours.
9. Close stem valve at the bottom of the cell.
10. Pump approximately 500 ml of water through steam generator (room temperature) and bottom tubing.
11. Close valve from steam generator to the cell.
12. Pull vacuum on the cell.
13. Close valve closest to cell (on the vent side).
14. Pump water into generator to a pressure of 125 psi.
15. Pump 160 ml of water under pressure into cell.

16. Clean and fill oil reservoir by separate operation.

17. Pump water into oil reservoir from bottom.

18. Produce approximately 100 ml of oil through a vent at the top of the oil reservoir.

18. Connect the oil reservoir to the cell and inject desired volume plus 6 ml of oil into the cell (at 100 psig).

20. Close stem valve at the cell and disconnect the oil reservoir; inject 150 cc of water through generator and bottom line to the vent.

21. Produce and measure the produced oil from the vent.

22. Set the two temperature controllers for the cell to the desired temperature.

23. Set the variable transformer for the cell to the desired temperature.

24. Allow the cell to warm-up (for T=387^{O}F, approximately 4 hours).

25. Set the other controllers and variable transformers.

26. Allow the generator to warm-up (approximately 1/2 hour.)

27. Pass water at desired rate through the steam generator and bottom tubing and valve assembly of cell.

28. Allow generator temperature to stabilize at the rate.

After the cell preparation is completed, the procedure for crude oil distillation is as follows:

1. Record initial pressure and temperature.

2. Mark the start of a run on the temperature recording chart.

3. Set back pressure valve to a pressure greater than the desired pressure for the run.

4. Open the valve between the cell and the separator.

5. Start water injection at desired rate.

6. Open valve at bottom of cell.

7. Slowly open back pressure valve to desired pressure.

8. Collect sample in the separator.

9. Drain sample from the separator to graduated cylinder and record: total production, oil production, water production, injection reading on pump, and pressure on cell.

10. Calculate incremental water injected, cummulative water injected, cummulative fluid produced, and accumulation of water in cell.
11. Make adjustment based on water volume balance and recorded temperatures.
12. Terminate the run after the produced oil-water ratio is approximately .004.

Results and Discussions

A series of 25 runs is made. A summary of runs is tabulated in Table 2. Eight of the runs are made on Shiells Canyon crude oil to determine the reproducibility of the experiments and the effect of steam pressure (with corresponding saturation temperature), steam injection rate and initial oil volume on the steam distillation yields. Results of these runs are tabulated in Table 3 through Table 24 and plotted on Figure 5 through Figure 26. The yield is defined as the ratio of oil volume distilled (V_o) and initial oil volume (V_{oi}). The ratio of steam throughput (as condensate, V_w) and initial oil volume is called the "steam distillation correlation parameter".

Figure 27 shows the reproducibility of the experiments. The reproducibility is good with a maximum error of approximately 5%. The results are comparable with that reported by Konopnicki, et al.(4).

Figure 28 shows the pressure effect on the steam distillation yields. The data indicate that in general, as the pressure increases the yield decreases; however, as $\frac{V_w}{V_{oi}}$ increases, the ultimate yields may approach the same value. The decreased yield at higher pressure may be attributed to increase in mutual solubility between oil and water. Due to time constraint, all runs for different crude oils are made at 200 psig which is considered to give maximum steam distillation yield at various steam distillation correlation parameters.

Figure 29 shows the effect of steam injection rate and initial oil volume on the steam distillation yields. The results indicate that the effect of these process parameters on the steam distillation yields is small(less than 6%).

Steam distillation data obtained from this investigation are tabulated in Table 25 and plotted on Figure 30. Plots in this figure show that the steam distillation yields may cross over at different values of correlation parameter. They also show that the maximum steam distillation yield is not dependent on the ^{o}API gravity. These results indicate that steam distillation yields may be a complex function of crude oil composition, mutual solubility of water and oil component, and system pressure.

REGRESSION ANALYSES

Regression Analysis Techniques

Both univariable and multivariable regression analysis techniques are employed to investigate the relationship of crude oil steam distillation yields and the basic crude oil properties, such as API gravity, oil viscosity, characterization factor, and simulated distillation yields. A linear polynomial regression computer program is used to correlate the steam distillation yield at the correlation parameter values of 1, 2, 3, 4, 5, 10, 15, and 20 with respect to an independent variable, such as API gravity, oil viscosity at 100°F, characterization factor, or selected simulated distillation yield. A multivariable regression analysis is used to correlate the steam distillation yields with respect to two independent variables of API gravity and oil viscosity or to three independent variables of API gravity, oil viscosity, and characterization factor.

Results and Discussions

Figure 31 shows plots of steam distillation yields versus the crude oil API gravity for the correlation parameter values of 1, 5, and 15. While the trend indicates increasing yields with respect to increasing API gravity, the data scatter is enormous and the trend reverses when the API gravity is greater than 33^{O} API. The reverse trend is considered to result from increasing solubility of oil in water for lighter oils. Figure 32, 33, and 34 show the expected values of linear and quadratic regression equations. Results of the analysis are tabulated on Table 26. Comparison of standard errors indicates the linear and quadratic regression equations give comparable results.

Figure 35 shows plots of steam distillation yields versus natural logorithm of crude oil viscosity at 100^{O}F. It is apparent the relationship is quadratic. Figure 36, 37, and 38 show the expected values of quadratic regression equations. Results of this analysis are tabulated on Table 27.

Figure 39 shows the expected values of linear regression equation for the correlation of steam distillation yields with the characterization factor. Results of this analysis are tabulated on Table 28.

Simulated distillation temperature at simulated distillation yields of 5, 10, 20, and 30% are tabulated in Table 29. Simulated distillation yields at boiling points 445, 485, 505, 525, 550, 580, 600, and 615^{O}F are tabulated in Table 30. These data are empirically selected for correlation with the steam distillation yields.

Figure 40 shows the expected values of linear regression equations for the correlation of steam distillation yields with the simulated distillation temperatures at 20% yields. Similar correlations are obtained for simulated distillation temperatures at 5, 10, and 30%, however, 20% shows the best overall correlation for steam distillation yields at various values of steam distillation correlation parameters. Results of this analysis are tabulated on Table 31.

Figure 41 shows the expected values of quadratic regression equations for the correlation of steam distillation yields and the simulated distillation yields at various boiling temperatures. Results of the analysis are tabulated in Table 32.

Figure 42, 43, 44, and 45 show the predicted steam distillation yields for South Belridge, Toborg, Plum Bush, and Shiells Canyon crude oil, respectively. Figure 42, 43, and 44 show the results over the whole range of crude oil API gravity. Figure 45 shows the worst case of the predictions. These data indicate that the correlation using simulated distillation temperatures at 20% yield gives the best overall result. In sequential order of good predictions, the rest of the independent variables are oil viscosity, simulated distillation yields, and API gravity. Characterization factor gives the worst prediction results.

Multivariate regression analysis results show no improvement over the correlations using oil viscosity and API gravity individually.

CONCLUSIONS

1. Steam distillation yields of sixteen crude oils obtained from various parts of the United States have been determined at a saturated steam pressure of 200 psig. The yields at $\frac{V_w}{V_{oi}} = 15$ range from 12 to 56% of V_{oi}.
2. The effect of pressure on the ultimate steam distillation yields (when $\frac{V_w}{V_{oi}} > 15$) appears to be small. However, its effect is significant for $\frac{V_w}{V_{oi}} < 15$.
3. Univariate regression analysis results indicate that:
   a. In general, the steam distillation yield increases linearly with respect to the API gravity up to 33° API. Above 33° API, the steam distillation yield decreases with increasing API gravity.
   b. In general, the steam distillation yield decreases logrithmically with respect to the oil viscosity (100°F). When the oil viscosity is less than 10 cs (at 100°F, the relationship is uncertain.
   c. In general, the steam distillation yield increases linearly with respect to the characterization factor of the crude oils. This is not a good parameter for correlation.

d. In general, the steam distillation yield increases linearly with respect to the simulation distillation temperature (^{o}F) at 20% simulated distillation yield.

e. In general, the steam distillation yield at $\frac{V_w}{V_{oi}}$ = 1, 2, 3, 4, 5, 10, 15, and 20 show second order polynomial relationships with respect to simulated distillation yields at 445, 485, 505, 525, 550, 585, 600, and 615^{o}F, respectively.

4. For first-hand approximation, crude oil viscosity at 100^{o}F can be used to estimate the steam distillation yields. If crude oil viscosity is not available, API gravity is the next choice.

5. In addition, if simulated distillation data are available, the boiling point at 20% yield will provide the best estimate of steam distillation yields.

RECOMMENDATIONS

1. Experimental data strongly suggest that crude oil steam distillation yields are closely related to the simulated distillation yields. A mathematical model may be developed to predict the crude oil steam distillation yields using simulated distillation data.
2. While some experimental data indicate the ultimate steam distillation yield may not be dependent on the system pressure, the effect of pressure on the steam distillation yields should be further investigated, especially for light oils (>25^{o}API).
3. Closely related to pressure effect is the effect of mutual solubility between oil and water on the crude oil steam distillation. Further investigation should explain and describe the decreasing steam distillation yields with pressure increase when the API gravity is greater than 33^{o}API.

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TABLE 1. PROPERTIES OF CRUDE OIL SAMPLES

No.	Field	Reservoir	County State	Water Content (Vol.%)	^{o}API	μ_o@ 100^{o}F(cp)	Characterization Factor	Company
1	South Belridge	Tulare	Kern Calif.	8.0	12.4	4085	9.7	Mobil
2	Winkle-man Dome	Nugget	Freemont WY	4.6	14.9	488	9.6	Amoco
3	White Castle	Central "V"	Iberville LA	9.8	16.0	308	9.7	Shell
4	Edison	Kern River	Kern Calif.	0.5	16.1	397	9.7	Exxon
5	Red Bank	---	Creek Okla.	0	17.1	300	9.9	Sun
6	Slocum	Carrizo	Anderson TX	0	18.8	395	10.0	Shell
7	Hidden Dome	Tensleep	Washakie WY	0.2	20.7	86	10.1	Marathon
8	Toborg	---	Pecos TX	0	22.2	36	10.1	Gulf
9	Brea	Lower B	Orange Calif.	1.9	23.5	39	10.0	Shell
10	Shannon	Shannon	Natrona WY	0	24.7	32	10.2	Amoco

TABLE 1. PROPERTIES OF CRUDE OIL SAMPLES (continued)

No.	Field	Reservoir	County State	Water Content (Vol.%)	^{o}API	μ_{o}@ 100^{o}F(cp)	Characterization Factor	Company
11	Robinson	Robinson	Crawford Illinois	0.8	26.0	29	10.3	Marathon
12	El Dorado	---	Butler Kansas	0	32.5	5	10.1	Cities Service
13	Shiells	203 Zone	Ventura Calif.	0	33.0	6	10.2	Texaco
14	Teapot Dome	Shannon	Natrona WY	0	34.5	6	10.4	DOE
15	Rock Creek	---	Roane West Virginia	0	38.2	5	10.4	Pennzoil
16	Plum Bush	J_1&J_2	Washington CO	0	39.9	6	10.5	Conoco

TABLE 2 SUMMARY OF RUNS

RUN NO.	CRUDE OIL	^{o}API	INITIAL VOLUME (ml)	P (PSIA)	T(^{o}F)	INJ. RATE (ml/hr)	YIELD ($\frac{V_w}{V_{oi}}$ =15)
1	SHIELLS CANYON	33.0	199	219	378	320	---
2	SHIELLS CANYON	33.0	100	215	373	320	---
3	SHIELLS CANYON	33.0	90	212	371	320	---
4	SHIELLS CANYON	33.0	203	489	460	320	0.49
5*	SHIELLS CANYON	33.0	206	509	460	320	0.49
6	SHIELLS CANYON	33.0	202	349	425	320	0.57
7	SHIELLS CANYON	33.0	400	219	378	640	---
8	SHIELLS CANYON	33.0	200	494	459	320	0.56
9	SHIELLS CANYON	33.0	100	224	385	320	0.56
10	SHIELLS CANYON	33.0	203	219	383	320	0.57
11	ROCK CREEK	38.2	207	204	377	320	0.47
12	TEAPOT DOME	34.9	203	216	383	320	0.54
13	PLUM BUSH	39.9	201	224	385	320	0.49
14	EL DORADO	32.5	201	223	379	320	0.48
15	TOBORG	22.2	200	226	386	320	0.35
16	ROBINSON	26.0	173.4	219	381	320	0.31

TABLE 2 SUMMARY OF RUNS (Con't)

RUN NO.	CRUDE OIL	°API	INITIAL VOLUME (ml)	P (PSIA)	T (°F)	INJ. RATE (ml/hr)	YIELD ($\frac{V_w}{V_{oi}}$ =15)
17	BELRIDGE	12.4	185.8	204	380	320	0.12
18	HIDDEN DOME	20.7	200.6	212	378	320	0.28
19	WHITE CASTLE	16.0	180.4	204	379	320	0.21
20	WINKLEMAN	14.9	190.8	234	390	320	0.18
21	SLOCUM	18.8	200	225	386	320	0.20
22	EDISON	16.1	200	224	385	320	0.20
23	SHANNON	24.7	200	226	385	320	0.33
24	BREA	23.5	200	234	390	320	0.34
25	RED BANK	17.1	200	231	388	320	0.24

*N_2 was initially in the cell at 100 psig

TABLE 3

CRUDE OIL STEAM DISTILLATION RESULTS: SHIELLS CANYON : RUN # 4

SAMPLE NUMBER	:	13
AVE. RUN TEMPERATURE	:	460. °F
AVE. RUN PRESSURE	:	489. PSIA
INITIAL TEMPERATURE	:	455. °F
INITIAL PRESSURE	:	524. PSIA
INJECTION RATE	:	320. CC/HR
INITIAL OIL VOLUME	:	203. CC

VW/VOI	FRAC.YIELD	DENSITY
0.010	.0394	...
0.094	.0788	...
0.153	.1106	...
0.256	.1478	...
0.379	.1897	...
0.527	.2192	...
0.680	.2436	...
0.862	.2685	...
1.167	.3030	...
1.665	.3424	...
2.158	.3816	...
3.232	.4261	...
8.493	.4606	...
10.507	.4704	...

TABLE 4

CRUDE OIL STEAM DISTILLATION RESULTS: SHIELLS CANYON : RUN # 5

SAMPLE NUMBER	:	13
AVE. RUN TEMPERATURE	:	460. °F
AVE. RUN PRESSURE	:	509. PSIA
INITIAL TEMPERATURE	:	547. °F
INITIAL PRESSURE	:	549. PSIA
INJECTION RATE	:	320. CC/HR
INITIAL OIL VOLUME	:	206. CC

VW/VOI	FRAC.YIELD	DENSITY
0.058	.0049	...
0.180	.0388	...
0.294	.1238	...
0.517	.1869	...
0.684	.2451	...
0.857	.2816	...
1.024	.3277	...
1.626	.3568	...
2.811	.4005	...
5.573	.4393	...
9.369	.4636	...

TABLE 5

CRUDE OIL STEAM DISTILLATION RESULTS: SHIELLS CANYON : RUN # 6

SAMPLE NUMBER	:	13
AVE. RUN TEMPERATURE	:	425. °F
AVE. RUN PRESSURE	:	349. PSIA
INITIAL TEMPERATURE	:	435. °F
INITIAL PRESSURE	:	419. PSIA
INJECTION RATE	:	320. CC/HR
INITIAL OIL VOLUME	:	202. CC

VW/VOI	FRAC.YIELD	DENSITY
0.153	.0520	...
0.248	.1015	...
0.436	.2154	...
0.554	.2649	...
0.738	.3045	...
1.020	.3243	...
1.396	.3639	...
1.817	.3837	...
2.203	.4035	...
2.653	.4282	...
3.149	.4431	...
4.386	.4728	...
5.451	.4926	...
6.272	.5124	...
8.970	.5322	...
10.569	.5421	...
11.955	.5520	...
12.960	.5569	...

TABLE 6

CRUDE OIL STEAM DISTILLATION RESULTS: SHIELLS CANYON : RUN # 7

SAMPLE NUMBER	:	13
AVE. RUN TEMPERATURE	:	378. °F
AVE. RUN PRESSURE	:	219. PSIA
INITIAL TEMPERATURE	:	387. °F
INITIAL PRESSURE	:	232. PSIA
INJECTION RATE	:	640. CC/HR
INITIAL OIL VOLUME	:	400. CC

VW/VOI	FRAC.YIELD	DENSITY
0.012	.0500	...
0.042	.1100	...
0.117	.1675	...
0.265	.2375	...
0.490	.2800	...
0.688	.3200	...
1.162	.3575	...
2.202	.4200	...

TABLE 7

CRUDE OIL STEAM DISTILLATION RESULTS: SHIELLS CANYON : RUN # 8

SAMPLE NUMBER	:	13
AVE. RUN TEMPERATURE	:	459. °F
AVE. RUN PRESSURE	:	494. PSIA
INITIAL TEMPERATURE	:	450. °F
INITIAL PRESSURE	:	594. PSIA
INJECTION RATE	:	320. CC/HR
INITIAL OIL VOLUME	:	200. CC

VW/VOI	FRAC.YIELD	DENSITY
0.070	.0350	...
0.135	.0550	...
0.300	.1000	...
0.545	.1500	...
0.837	.2025	...
1.138	.2475	...
1.662	.3075	...
2.083	.3325	...
2.477	.3525	...
2.952	.3675	...
3.438	.3825	...
3.977	.3925	...
4.478	.4025	...
5.012	.4075	...
7.183	.4375	...
8.862	.4525	...
10.872	.4675	...
13.447	.4825	...
15.923	.4975	...
18.447	.5125	...
19.713	.5225	...

TABLE 8

CRUDE OIL STEAM DISTILLATION RESULTS: SHIELLS CANYON : RUN # 9

SAMPLE NUMBER	:	13
AVE. RUN TEMPERATURE	:	385. °F
AVE. RUN PRESSURE	:	224. PSIA
INITIAL TEMPERATURE	:	387. °F
INITIAL PRESSURE	:	234. PSIA
INJECTION RATE	:	320. CC/HR
INITIAL OIL VOLUME	:	100. CC

VW/VOI	FRAC.YIELD	DENSITY
0.020	.1350	...
0.135	.2400	...
0.235	.3000	...
0.660	.4150	...
1.270	.4650	...
2.060	.4950	...
7.010	.5450	...
11.870	.5850	...
14.465	.5900	...

TABLE 9

CRUDE OIL STEAM DISTILLATION RESULTS: SHIELLS CANYON : RUN #10

SAMPLE NUMBER	:	13
AVE. RUN TEMPERATURE	:	383. °F
AVE. RUN PRESSURE	:	219. PSIA
INITIAL TEMPERATURE	:	380. °F
INITIAL PRESSURE	:	229. PSIA
INJECTION RATE	:	320. CC/HR
INITIAL OIL VOLUME	:	203. CC

VW/VOI	FRAC.YIELD	DENSITY
0.015	.0542	...
0.064	.1133	...
0.118	.1970	...
0.266	.2562	...
0.399	.2980	...
0.633	.3399	...
0.995	.3793	...
1.453	.4089	...
1.906	.4310	...
2.384	.4507	...
2.852	.4655	...
3.655	.4852	...
4.507	.5049	...
5.980	.5172	...
6.963	.5271	...
8.103	.5345	...
10.631	.5493	...
13.187	.5566	...

TABLE 10

CRUDE OIL STEAM DISTILLATION RESULTS: ROCK CREEK : RUN #11

SAMPLE NUMBER	:	15
AVE. RUN TEMPERATURE	:	377. °F
AVE. RUN PRESSURE	:	210. PSIA
INITIAL TEMPERATURE	:	385. °F
INITIAL PRESSURE	:	235. PSIA
INJECTION RATE	:	320. CC/HR
INITIAL OIL VOLUME	:	207. CC

VW/VOI	FRAC.YIELD	DENSITY
0.017	.0483	...
0.063	.1063	...
0.184	.1691	...
0.382	.2343	...
0.582	.2609	...
1.031	.2947	...
1.510	.3285	...
1.918	.3502	...
2.372	.3792	...
2.928	.4010	...
3.464	.4058	...
5.952	.4299	...
8.546	.4444	...
10.469	.4541	...
12.396	.4589	...

TABLE 11

CRUDE OIL STEAM DISTILLATION RESULTS: TEAPOT DOME : RUN #12

SAMPLE NUMBER	:	14
AVE. RUN TEMPERATURE	:	383. °F
AVE. RUN PRESSURE	:	222. PSIA
INITIAL TEMPERATURE	:	390. °F
INITIAL PRESSURE	:	255. PSIA
INJECTION RATE	:	320. CC/HR
INITIAL OIL VOLUME	:	203. CC

VW/VOI	FRAC.YIELD	DENSITY
0.025	...	.7646
0.049	.0443	...
0.117	...	.7716
0.123	.0813	...
0.185	.1133	...
0.389	.1749	...
0.400	...	.8084
0.616	.2143	...
1.022	.2463	...
1.273	...	.8460
1.453	.2833	...
1.931	.3202	...
3.461	...	.8649
3.596	.3793	...
4.990	.4286	...
7.640	...	.8712
7.650	.4778	...
10.291	.5074	...
12.736	.5246	...
13.841	...	.8789
15.382	.5394	...
17.392	.5493	...

TABLE 12

CRUDE OIL STEAM DISTILLATION RESULTS: PLUM BUSH : RUN #13

SAMPLE NUMBER	:	16
AVE. RUN TEMPERATURE	:	385. °F
AVE. RUN PRESSURE	:	230. PSIA
INITIAL TEMPERATURE	:	388. °F
INITIAL PRESSURE	:	285. PSIA
INJECTION RATE	:	320. CC/HR
INITIAL OIL VOLUME	:	201. CC

VW/VOI	FRAC.YIELD	DENSITY
0.021	...	.7566
0.042	.0497	...
0.075	...	.7527
0.107	.0995	...
0.152	...	.7574
0.197	.1493	...
0.356	.1965	...
0.396	...	.7798
0.595	.2363	...
1.060	.2836	...
1.475	.3134	...
1.570	...	.8161
1.938	.3383	...
2.545	.3532	...
5.092	.3930	...
5.189	...	.8427
7.833	.4378	...
11.650	...	.8614
12.813	.4826	...
15.468	.4900	...

TABLE 13

CRUDE OIL STEAM DISTILLATION RESULTS: EL DORADO : RUN #14

SAMPLE NUMBER	:	12
AVE. RUN TEMPERATURE	:	379. °F
AVE. RUN PRESSURE	:	229. PSIA
INITIAL TEMPERATURE	:	404. °F
INITIAL PRESSURE	:	290. PSIA
INJECTION RATE	:	320. CC/HR
INITIAL OIL VOLUME	:	201. CC

VW/VOI	FRAC.YIELD	DENSITY
0.025	...	.7679
0.050	.0895	...
0.091	...	.7749
0.132	.1716	...
0.209	...	.7950
0.286	.2313	...
0.398	...	.7999
0.510	.3060	...
0.836	.3356	...
0.888	...	.8378
1.266	.3632	...
1.741	.3856	...
2.359	...	.8591
3.453	.4403	...
4.808	.4527	...
7.535	.4677	...
9.774	.4702	...

TABLE 14

CRUDE OIL STEAM DISTILLATION RESULTS: TOBORG : RUN # 15

SAMPLE NUMBER	:	7
AVE. RUN TEMPERATURE	:	386. °F
AVE. RUN PRESSURE	:	232. PSIA
INITIAL TEMPERATURE	:	386. °F
INITIAL PRESSURE	:	231. PSIA
INJECTION RATE	:	320. CC/HR
INITIAL OIL VOLUME	:	200. CC

VW/VOI	FRAC.YIELD	DENSITY
0.040	...	.7843
0.080	.0550	...
0.165	.0900	...
0.190	...	.8174
0.300	.1225	...
0.505	.1525	...
0.531	...	.8528
0.763	.1800	...
1.231	...	.8787
1.250	.2150	...
1.700	.2275	...
2.200	.2425	...
2.685	.2575	...
3.505	...	.9088
5.310	.3075	...
7.905	...	.9327
7.960	.3300	...
10.500	.3425	...

TABLE 15

CRUDE OIL STEAM DISTILLATION RESULTS: ROBINSON : RUN #16

SAMPLE NUMBER	:	11 .
AVE. RUN TEMPERATURE	:	381. °F
AVE. RUN PRESSURE	:	225. PSIA
INITIAL TEMPERATURE	:	390. °F
INITIAL PRESSURE	:	241. PSIA
INJECTION RATE	:	320. CC/HR
INITIAL OIL VOLUME	:	173. CC

VW/VOI	FRAC.YIELD	DENSITY
0.092	.0404	...
0.231	.0634	...
0.372	.0836	...
0.591	.1096	...
0.937	.1240	...
1.485	.1528	...
2.062	.1759	...
5.124	.2566	...
8.273	.2797	...
11.427	.3028	...

TABLE 16

CRUDE OIL STEAM DISTILLATION RESULTS: BELRIDGE : RUN #17

SAMPLE NUMBER : 1
AVE. RUN TEMPERATURE : 380. °F
AVE. RUN PRESSURE : 210. PSIA
INITIAL TEMPERATURE : 380. °F
INITIAL PRESSURE : 210. PSIA
INJECTION RATE : 320. CC/HR
INITIAL OIL VOLUME : 186. CC

VW/VOI	FRAC.YIELD	DENSITY
0.344	.0134	...
1.447	.0430	...
4.375	.0726	...
7.318	.0886	...
10.267	.1022	...
13.054	.1130	...
15.476	.1211	...

TABLE 17

CRUDE OIL STEAM DISTILLATION RESULTS: HIDDEN DOME : RUN #18

SAMPLE NUMBER	:	7
AVE. RUN TEMPERATURE	:	378. °F
AVE. RUN PRESSURE	:	218. PSIA
INITIAL TEMPERATURE	:	378. °F
INITIAL PRESSURE	:	231. PSIA
INJECTION RATE	:	320. CC/HR
INITIAL OIL VOLUME	:	201. CC

VW/VOI	FRAC.YIELD	DENSITY
0.035	.0249	...
0.150	.0573	...
0.327	.0822	...
0.875	.1147	...
3.597	.1770	...
6.169	.2218	...
8.781	.2468	...
11.408	.2617	...
15.521	.2842	...

TABLE 18

CRUDE OIL STEAM DISTILLATION RESULTS: WHITE CASTLE : RUN #19

SAMPLE NUMBER	:	3
AVE. RUN TEMPERATURE	:	379. F
AVE. RUN PRESSURE	:	210. PSIA
INITIAL TEMPERATURE	:	385. F
INITIAL PRESSURE	:	231. PSIA
INJECTION RATE	:	320. CC/HR
INITIAL OIL VOLUME	:	180. CC

VW/VOI	FRAC.YIELD	DENSITY
0.152	.0139	...
0.302	.0333	...
3.623	.1219	...
6.472	.1552	...
9.327	.1829	...
11.860	.1968	...
15.280	.2134	...
18.157	.2190	...

TABLE 19

CRUDE OIL STEAM DISTILLATION RESULTS: WINKLEMAN DOME : RUN #20

SAMPLE NUMBER	:	2
AVE. RUN TEMPERATURE	:	390. °F
AVE. RUN PRESSURE	:	240. PSIA
INITIAL TEMPERATURE	:	396. °F
INITIAL PRESSURE	:	260. PSIA
INJECTION RATE	:	320. CC/HR
INITIAL OIL VOLUME	:	191. CC

VW/VOI	FRAC.YIELD	DENSITY
0.115	.0341	...
0.493	.0707	...
3.239	.1284	...
5.912	.1520	...
9.172	.1703	...
14.869	.1834	...

TABLE 20

CRUDE OIL STEAM DISTILLATION RESULTS: SLOCUM : RUN #21

SAMPLE NUMBER	:	6
AVE. RUN TEMPERATURE	:	386. °F
AVE. RUN PRESSURE	:	231. PSIA
INITIAL TEMPERATURE	:	389. °F
INITIAL PRESSURE	:	232. PSIA
INJECTION RATE	:	320. CC/HR
INITIAL OIL VOLUME	:	200. CC

VW/VOI	FRAC.YIELD	DENSITY
0.235	.0050	...
0.645	.0350	...
1.095	.0650	...
3.670	.0925	...
6.230	.1325	...
8.770	.1650	...
11.250	.1850	...
13.780	.1900	...

TABLE 21

CRUDE OIL STEAM DISTILLATION RESULTS: EDISON : RUN #22

SAMPLE NUMBER	:	4
AVE. RUN TEMPERATURE	:	385. °F
AVE. RUN PRESSURE	:	230. PSIA
INITIAL TEMPERATURE	:	387. °F
INITIAL PRESSURE	:	232. PSIA
INJECTION RATE	:	320. CC/HR
INITIAL OIL VOLUME	:	200. CC

Vw/VOI	FRAC.YIELD	DENSITY
0.093	.0226	...
0.334	.0653	...
2.887	.1508	...
5.575	.1734	...
10.827	.1910	...
13.887	.1960	...

TABLE 22

CRUDE OIL STEAM DISTILLATION RESULTS: SHANNON : RUN #23

SAMPLE NUMBER	:	10
AVE. RUN TEMPERATURE	:	385. °F
AVE. RUN PRESSURE	:	232. PSIA
INITIAL TEMPERATURE	:	386. °F
INITIAL PRESSURE	:	239. PSIA
INJECTION RATE	:	320. CC/HR
INITIAL OIL VOLUME	:	200. CC

VW/VOI	FRAC.YIELD	DENSITY
0.255	.0500	...
0.473	.1125	...
1.897	.1925	...
3.623	.2250	...
6.188	.2875	...
7.923	.3025	...
10.138	.3150	...

TABLE 23

CRUDE OIL STEAM DISTILLATION RESULTS: BREA : RUN #24

SAMPLE NUMBER	:	9 .
AVE. RUN TEMPERATURE	:	390. °F
AVE. RUN PRESSURE	:	240. PSIA
INITIAL TEMPERATURE	:	394. °F
INITIAL PRESSURE	:	252. PSIA
INJECTION RATE	:	320. CC/HR
INITIAL OIL VOLUME	:	200. CC

VW/VOI	FRAC.YIELD	DENSITY
0.148	.0503	...
0.319	.1056	...
0.704	.1559	...
1.205	.2088	...
2.860	.2641	...
5.490	.2993	...
9.917	.3295	...
11.718	.3395	...

TABLE 24

CRUDE OIL STEAM DISTILLATION RESULTS: RED BANK : RUN #25

SAMPLE NUMBER	:	5
AVE. RUN TEMPERATURE	:	388. °F
AVE. RUN PRESSURE	:	237. PSIA
INITIAL TEMPERATURE	:	390. °F
INITIAL PRESSURE	:	240. PSIA
INJECTION RATE	:	320. CC/HR
INITIAL OIL VOLUME	:	200. CC

VW/VOI	FRAC.YIELD	DENSITY
0.242	.0650	...
0.580	.1050	...
1.052	.1325	...
2.752	.1825	...
5.252	.2125	...
11.003	.2400	...

TABLE 25

SUMMARY OF SMOOTHED STEAM DISTILLATION YIELD

NO.	FIELD	API	VISCO.* (CS)	CHAR. FAC.	VW/VOI 1	2	3	4	5	10	15	20
1	S. BELRIDGE	12.4	4085.	9.7	.031	.046	.060	.069	.075	.100	.119	.130
2	WINKLEMAN DOME	14.9	488.	9.6	.089	.111	.125	.136	.142	.170	.182	.195
3	WHITE CASTLE	16.0	308.	9.7	.070	.095	.110	.122	.137	.185	.210	.230
4	EDISON	16.1	397.	9.7	.092	.120	.140	.151	.164	.190	.198	.209
5	RED BANK	17.1	300.	9.9	.128	.162	.180	.195	.205	.231	.241	.250
6	SLOCUM	18.9	395.	10.0	.032	.080	.097	.110	.122	.172	.195	.200
7	HIDDEN DOME	20.7	86.	10.1	.119	.148	.169	.190	.205	.250	.280	.295
8	TOBORG	22.2	36.	10.0	.196	.239	.267	.285	.300	.339	.349	.360
9	BREA	23.5	39.	10.0	.210	.240	.265	.283	.296	.330	.340	.354
10	SHANNON	24.5	32.	10.2	.140	.192	.220	.240	.260	.307	.328	.331
11	ROBINSON	26.0	29.	10.3	.128	.176	.208	.228	.245	.295	.312	.320
12	EL DORADO	32.5	5.	10.1	.345	.400	.430	.441	.450	.470	.475	.480
13	SHIELLS CANYON	33.0	6.	10.2	.378	.438	.470	.490	.508	.541	.558	.570
14	TEAPOT DOME	34.5	6.	10.4	.240	.320	.360	.396	.425	.503	.534	.570
15	ROCK CREEK	38.2	5.	10.4	.295	.360	.400	.412	.420	.447	.465	.480
16	PLUM BUSH	39.9	6.	10.5	.280	.338	.360	.380	.400	.460	.489	.530

*At 100°F.

TABLE 26 REGRESSION ANALYSIS RESULTS FOR STEAM DISTILLATION YIELDS VERSUS API GRAVITY

$y = a+bx$:

	$\frac{V_w}{V_{oi}}$							
	1	2	3	4	5	10	15	20
a	-0.089	-0.089	-0.083	-0.076	-0.089	-0.044	-0.032	-0.026
b	0.012	0.013	0.013	0.014	0.014	0.015	0.015	0.015
SE*	0.056	0.055	0.056	0.056	0.056	0.051	0.049	0.050

*SE = standard error = $(\text{Sum of Squares due to Errors})^{1/2}/14$

$y = a+bx+cx^2$:

	$\frac{V_w}{V_{oi}}$							
	1	2	3	4	5	10	15	20
a	-0.207	-0.238	-0.261	-0.276	-0.289	-0.283	-0.255	-0.225
b	0.021	0.025	0.029	0.031	0.033	0.035	0.033	0.032
c	-0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SE*	0.057	0.054	0.055	0.054	0.052	0.046	0.044	0.048

*SE = $(\text{Sum of Squares due to Errors})^{1/2}/13$

TABLE 27 REGRESSION ANALYSIS RESULTS FOR STEAM DISTILLATION YIELDS VERSUS OIL VISCOSITY AT 100°F

$y = a + b\ln x + c(\ln x)^2$:

	V_w/V_{oi}							
	1	2	3	4	5	10	15	20
a	0.461	0.544	0.586	0.606	0.621	0.660	0.683	0.720
b	-0.102	-0.115	-0.121	-0.120	-0.119	-0.116	-0.118	-0.127
c	0.006	0.006	0.007	0.007	0.007	0.006	0.006	0.007
SE*	0.043	0.038	0.038	0.036	0.035	0.031	0.032	0.039

*SE = $(\text{Sum of Squares due to Errors})^{1/2}/13$

TABLE 28 REGRESSION ANALYSIS RESULTS FOR STEAM DISTILLATION YIELDS VERSUS CHARACTERIZED FACTOR

$y = a+bx$:

	V_w/V_{oi}							
	1	2	3	4	5	10	15	20
a	-2.465	-2.997	-3.218	-3.356	-3.473	-3.736	-3.850	-4.001
b	0.262	0.320	0.344	0.360	0.373	0.463	0.416	0.432
SE*	0.084	0.088	0.091	0.090	0.090	0.085	0.082	0.087

*SE = (Sum of Squares due to Errors)$^{1/2}$/14

$y = a+bx + cx^2$:

	V_w/V_{oi}							
	1	2	3	4	5	10	15	20
a	-13.774	-14.479	-16.150	-16.719	-16.528	-12.577	-9.194	0.437
b	0.251	0.261	0.292	0.302	0.297	0.216	0.148	-0.277
c	-0.112	-0.114	-0.128	-0.132	-0.129	-0.088	-0.053	0.035
SE*	0.087	0.091	0.094	0.093	0.093	0.088	0.085	0.091

*SE = (Sum of Squares due to Errors) /13

TABLE 29

SUMMARY OF SIMULATED DISTILLATION TEMPERATURES SELECTED FOR CORRELATION

NO.	FIELD	API	VISCO.* (CS)	CHAR. FAC.	TEMPERATURES (°F) V5 **	V10	V20	V30
1	S. BELRIDGE	12.4	4085.	9.7	521.	590.	680.	762.
2	WINKLEMAN DOME	14.9	488.	9.6	430.	500.	600.	685.
3	WHITE CASTLE	16.0	308.	9.7	432.	490.	580.	640.
4	EDISON	16.1	397.	9.7	455.	520.	610.	682.
5	RED BANK	17.1	300.	9.9	350.	460.	592.	0.
6	SLOCUM	18.9	395.	10.0	512.	580.	650.	715.
7	HIDDEN DOME	20.7	86.	10.1	350.	430.	560.	650.
8	TOBORG	22.2	36.	10.0	310.	390.	500.	590.
9	BREA	23.5	39.	10.0	270.	340.	450.	548.
10	SHANNON	24.5	32.	10.2	410.	470.	560.	620.
11	ROBINSON	26.0	29.	10.3	360.	420.	500.	569.
12	EL DORADO	32.5	5.	10.1	225.	270.	320.	380.
13	SHIELLS CANYON	33.0	6.	10.2	200.	230.	300.	375.
14	TEAPOT DOME	34.5	6.	10.4	220.	290.	390.	470.
15	ROCK CREEK	38.2	5.	10.4	215.	250.	310.	375.
16	PLUM BUSH	39.9	6.	10.5	205.	240.	320.	395.

*At 100°F.

**V5,V10,V20,V30 = 5%,10%,20%,and 30% simulated distillation yield.

TABLE 30

SUMMARY OF SIMULATED DISTILLATION YIELD
SELECTED FOR CORRELATION

NO.	FIELD	API	VISCO* (CS)	CHAR. FAC.	Simulated Distillation Yields 445°F	485	505	525	550	580	600	615
1	S. BELRIDGE	12.4	4085.	9.7	.011	.022	.032	.048	.070	.095	.110	.125
2	WINKLEMAN DOME	14.9	488.	9.6	.060	.088	.105	.124	.150	.184	.195	.215
3	WHITE CASTLE	16.0	308.	9.7	.060	.095	.110	.140	.170	.210	.235	.260
4	EDISON	16.1	397.	9.7	.041	.070	.085	.180	.130	.160	.181	.200
5	RED BANK	17.1	300.	9.9	.090	.112	.128	.142	.161	.185	.205	.220
6	SLOCUM	18.9	395.	10.0	.022	.031	.045	.060	.080	.110	.120	.145
7	HIDDEN DOME	20.7	86.	10.1	.110	.136	.155	.168	.195	.225	.240	.260
8	TOBORG	22.2	36.	10.0	.150	.190	.210	.230	.255	.290	.305	.325
9	BREA	23.5	39.	10.0	.192	.232	.258	.275	.305	.331	.350	.370
10	SHANNON	24.5	32.	10.2	.082	.111	.135	.160	.190	.235	.260	.285
11	ROBINSON	26.0	29.	10.3	.130	.175	.205	.235	.270	.325	.345	.375
12	EL DORADO	32.5	5.	10.1	.415	.480	.512	.545	.575	.625	.650	.675
13	SHIELLS CANYON	33.0	6.	10.2	.392	.450	.470	.500	.525	.570	.595	.610
14	TEAPOT DOME	34.5	6.	10.4	.270	.320	.355	.380	.415	.475	.500	.530
15	ROCK CREEK	38.2	5.	10.4	.412	.475	.510	.530	.570	.620	.635	.660
16	PLUM BUSH	39.9	6.	10.5	.360	.425	.455	.480	.515	.560	.585	.610

*At 100°F.

TABLE 31 REGRESSION ANALYSIS RESULTS FOR STEAM DISTILLATION YIELD VERSUS SIMULATED DISTILLATION TEMPERATURE AT 20% YIELD

$y = a+bx$:

	V_w/V_{oi}							
	1	2	3	4	5	10	15	20
a	0.488	0.570	0.615	0.641	0.663	0.710	0.729	0.763
b	-0.001	-0.001	0.001	-0.001	-0.001	-0.001	-0.001	-0.001
SE*	0.028	0.029	0.031	0.032	0.035	0.040	0.043	0.045

SE* = (Sum of Squares due to Errors)$^{1/2}$/14

$y = a+bx + cx^2$:

	V_w/V_{oi}							
	1	2	3	4	5	10	15	20
a	0.691	0.823	0.869	0.885	0.901	0.950	0.989	0.067
b	-0.002	-0.003	-0.003	-0.003	-0.003	-0.003	-0.003	-0.003
c	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SE*	0.029	0.030	0.032	0.034	0.035	0.040	0.043	0.046

*SE = (Sum of Squares due to Errors)$^{1/2}$/13

TABLE 32 REGRESSION ANALYSIS RESULTS FOR STEAM DISTILLATION YIELD VERSUS SIMULATED DISTILLATION YIELD AT VARIOUS BOILING TEMPERATURES

$y = a+bx + cx^2$:

	$\frac{Vw}{Voi}=1$ vs Y445°F	2 vs Y485	3 vs Y505	4 vs Y525	5 vs Y550	10 vs Y580	15 vs Y600	20 vs Y615
a	0.026	0.0341	0.032	0.017	-0.007	-0.025	-0.023	-0.050
b	1.085	1.087	1.143	1.247	1.334	1.484	1.453	1.542
c	-0.836	-0.698	-0.727	-0.847	-0.925	-1.058	-0.976	-1.026
SE*	0.027	0.030	0.030	0.035	0.038	0.048	0.045	0.046

*SE = (Sum of Squares due to Errors)$^{1/2}$/13

FIGURE 1 STEAM DISTILLATION APPARATUS

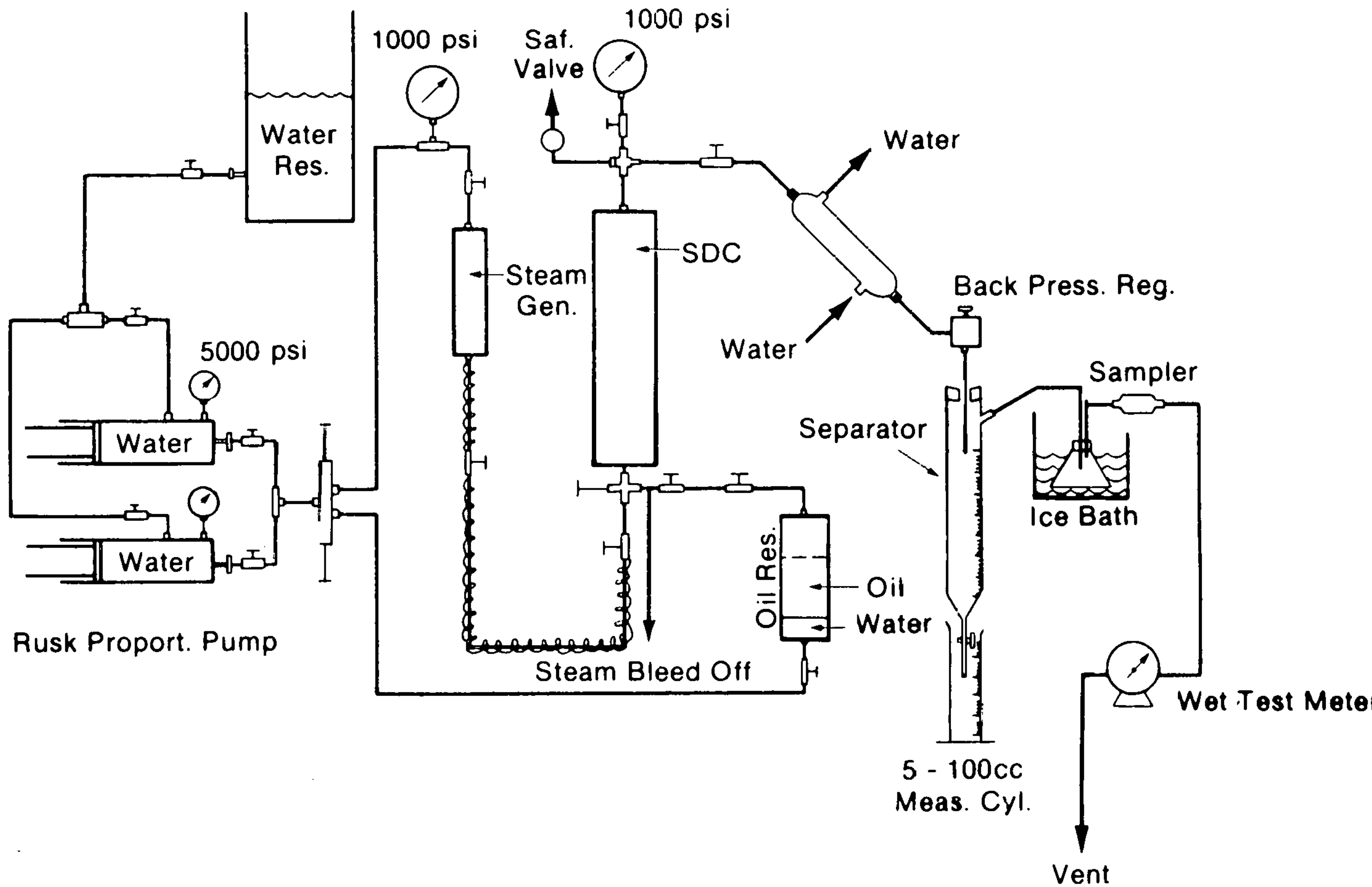


FIGURE 2 STEAM GENERATOR

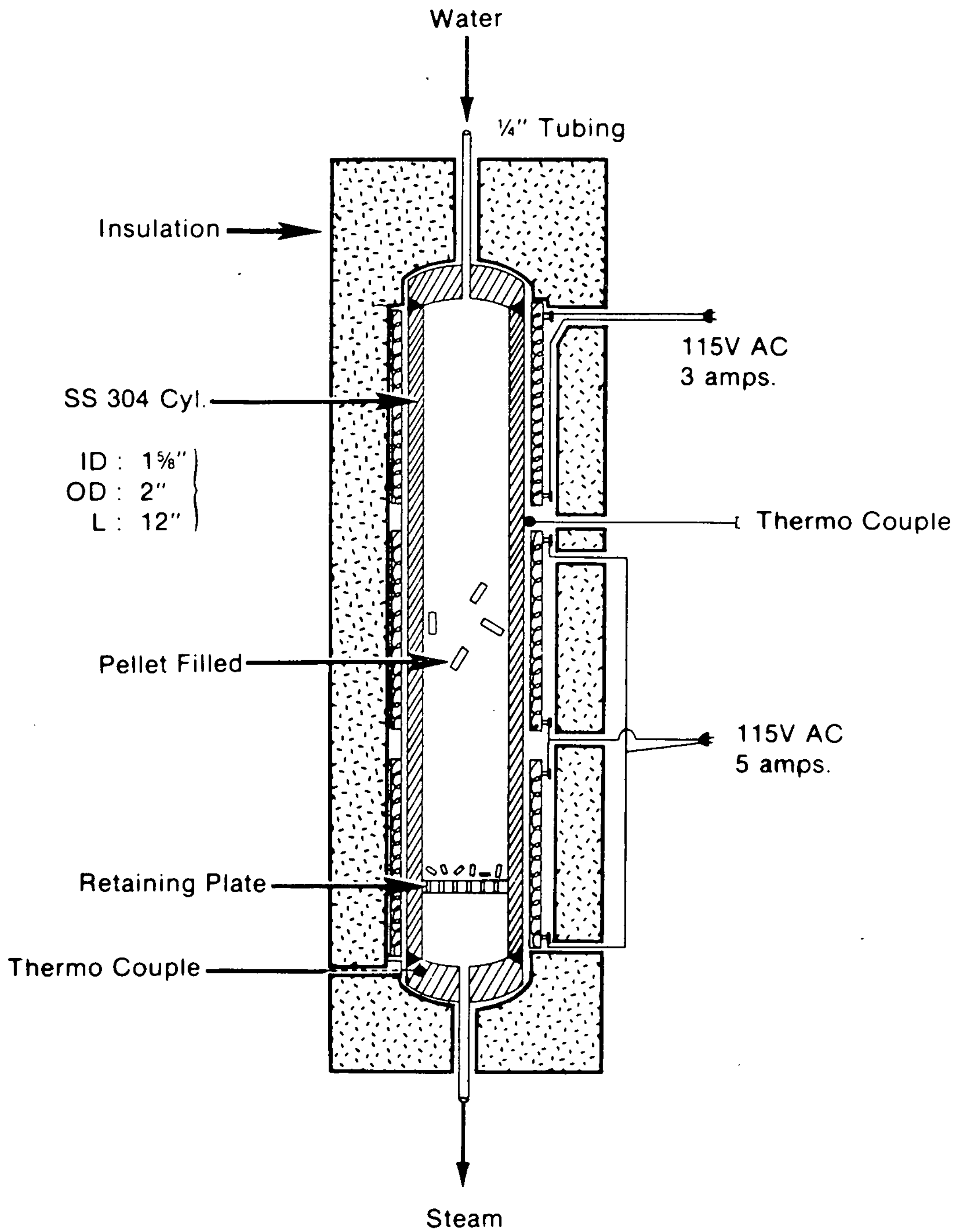
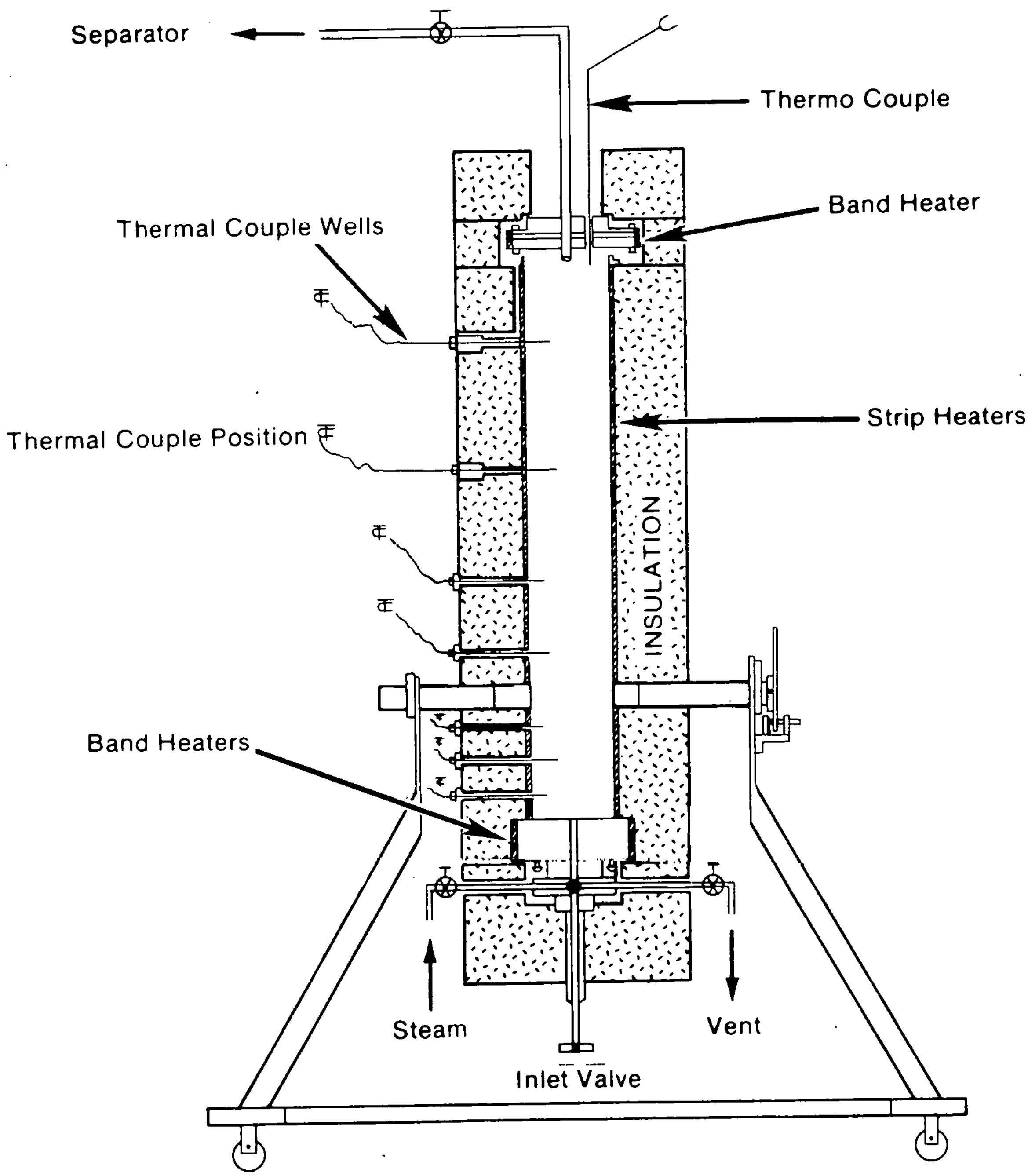


FIGURE 3 STEAM DISTILLATION CELL AND SUPPORT



Legend for Electric Circuits

1. Ruska's 2-1000 cc volumetric displacement pump
2. Band heater for steam generator — 41Ω
3. Band heater for steam generator — 41Ω
4. Temperature controller for 2 and 3 with thermocouple to steam generator
5. Power reostat for 6
6. Band heat for steam generator — 41Ω
7. Temperature controller for 8 with thermocouple to steam cell
8. Band heat for steam cell — 17Ω
9. Power reostat for 10
10. Bottom tubing heater — 62 Ω
11. Power reostat for 12
12. Top tubing heater — 62 Ω
13. Temperature controller for 14 with thermocouple to steam cell
14. Band heater for steam cell — 31 Ω
15. Power reostat for 16
16. Band heater for steam cell — 89Ω

FIGURE 4 ELECTRIC CIRCUITS

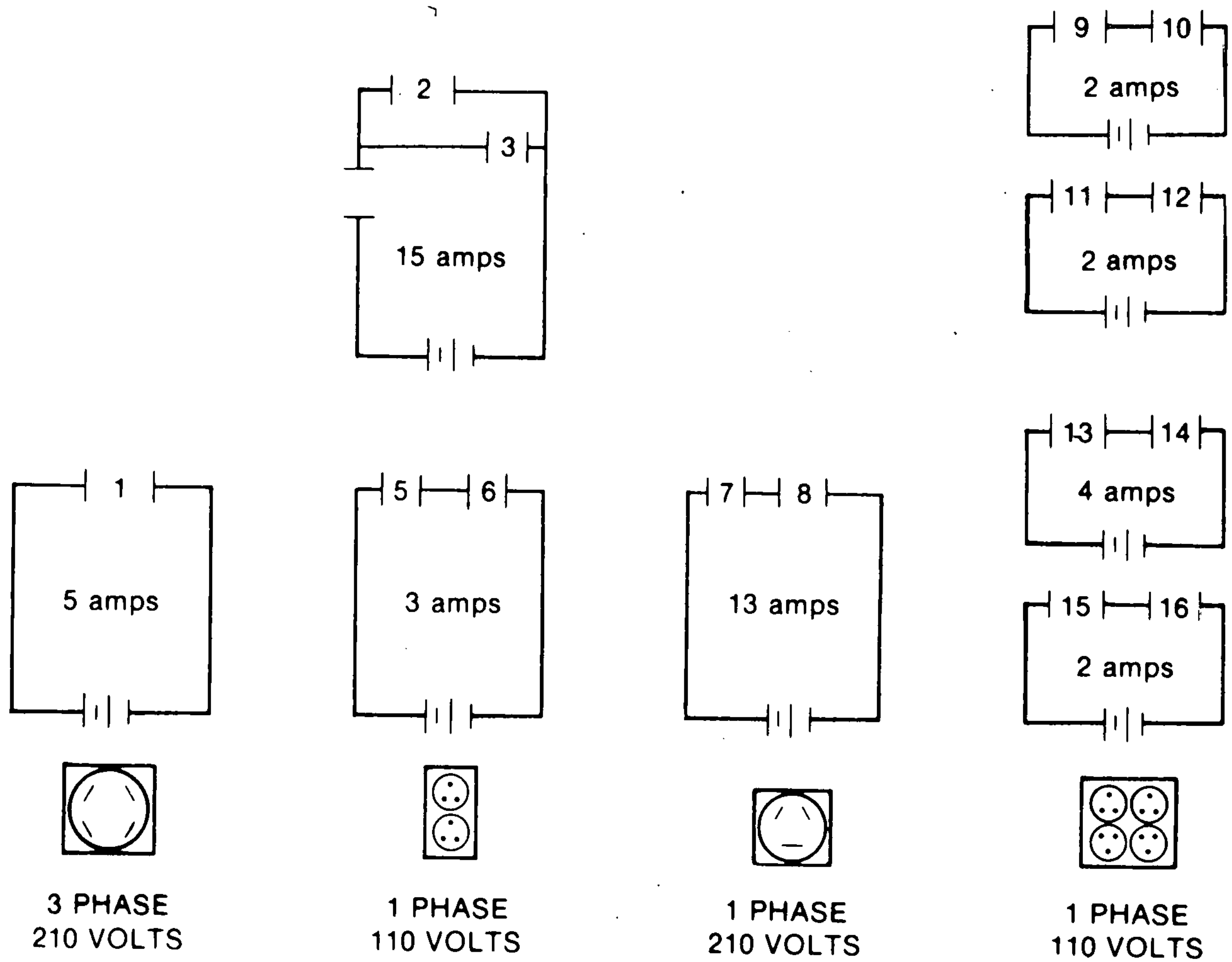


FIGURE 5

CRUDE OIL STEAM DISTILLATION YIELD
SHIELLS CANYON; RUN NO. 4

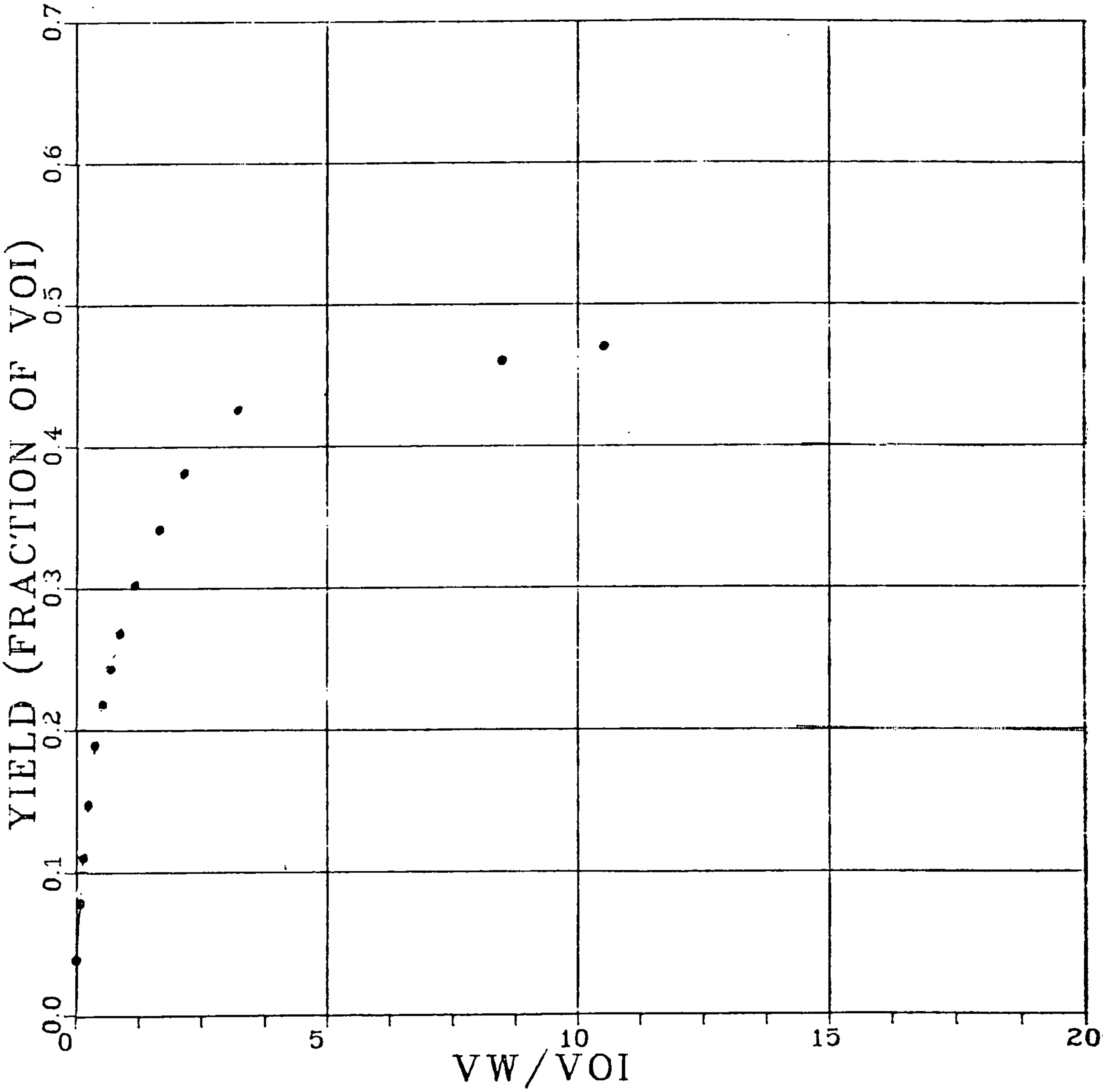


FIGURE 6

CRUDE OIL STEAM DISTILLATION YIELD
SHIELLS CANYON: RUN NO. 5

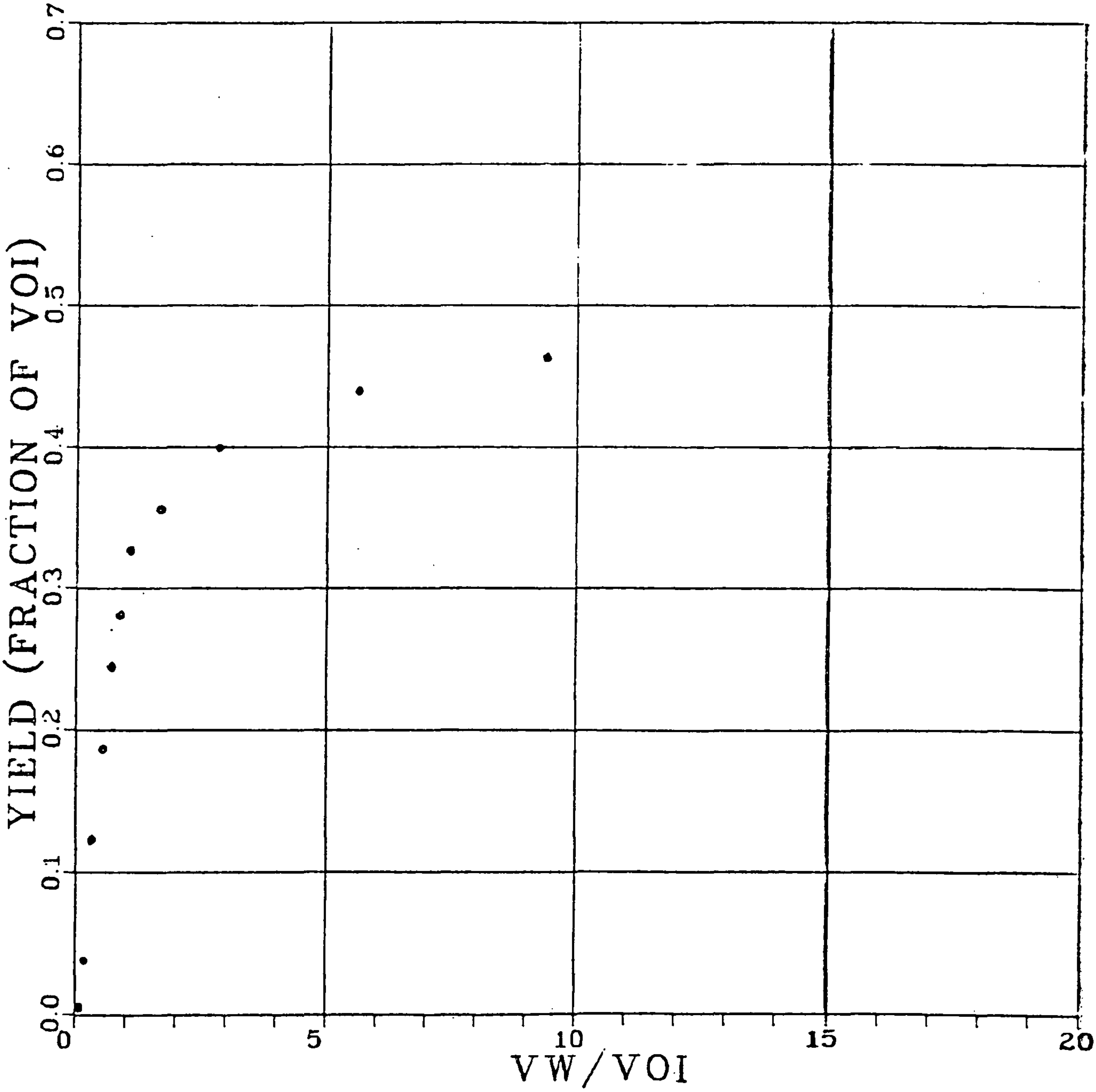


FIGURE 7

CRUDE OIL STEAM DISTILLATION YIELD
SHIELLS CANYON; RUN NO. 6

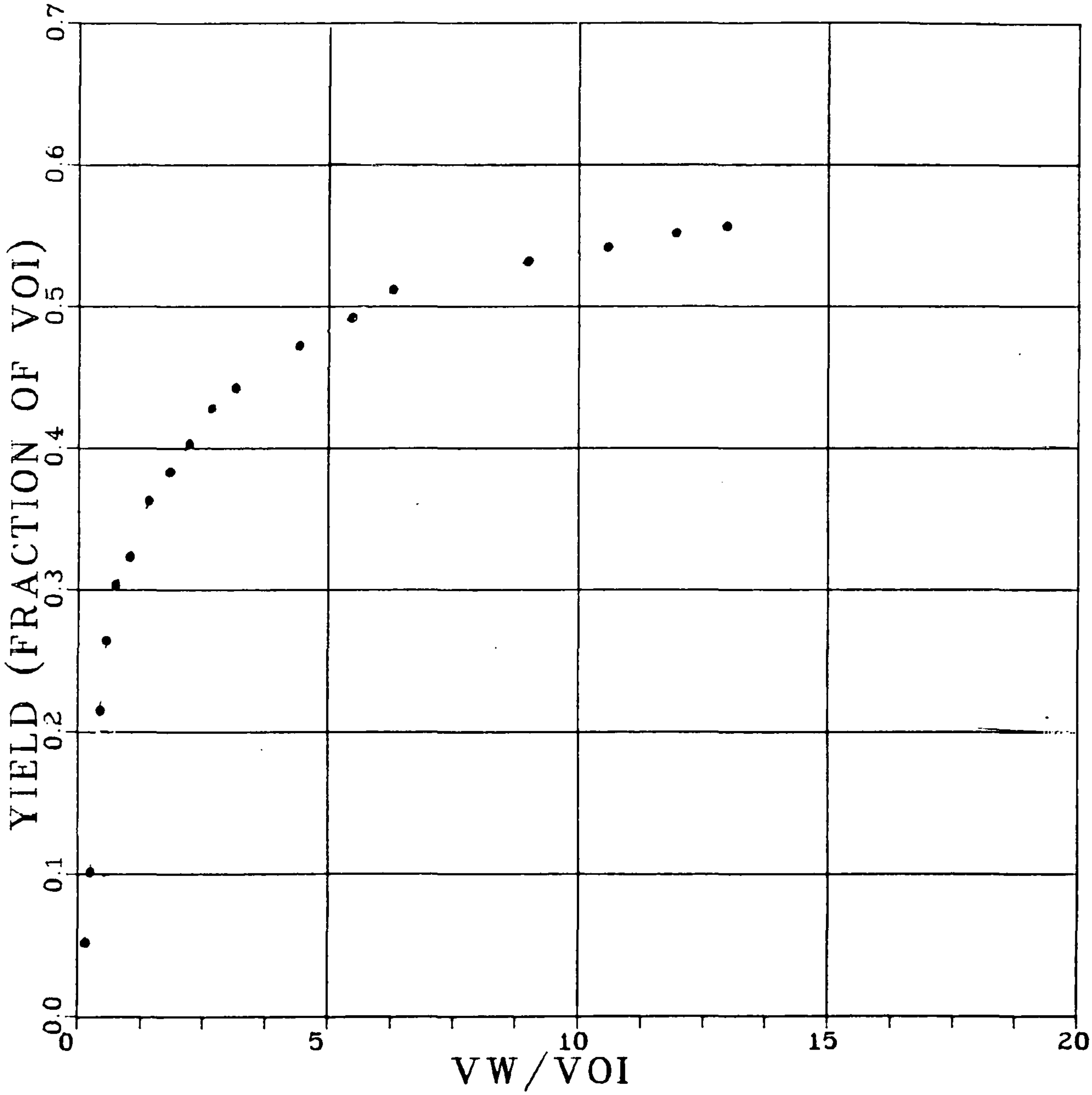


FIGURE 8

CRUDE OIL STEAM DISTILLATION YIELD
SHIELLS CANYON, RUN NO. 7

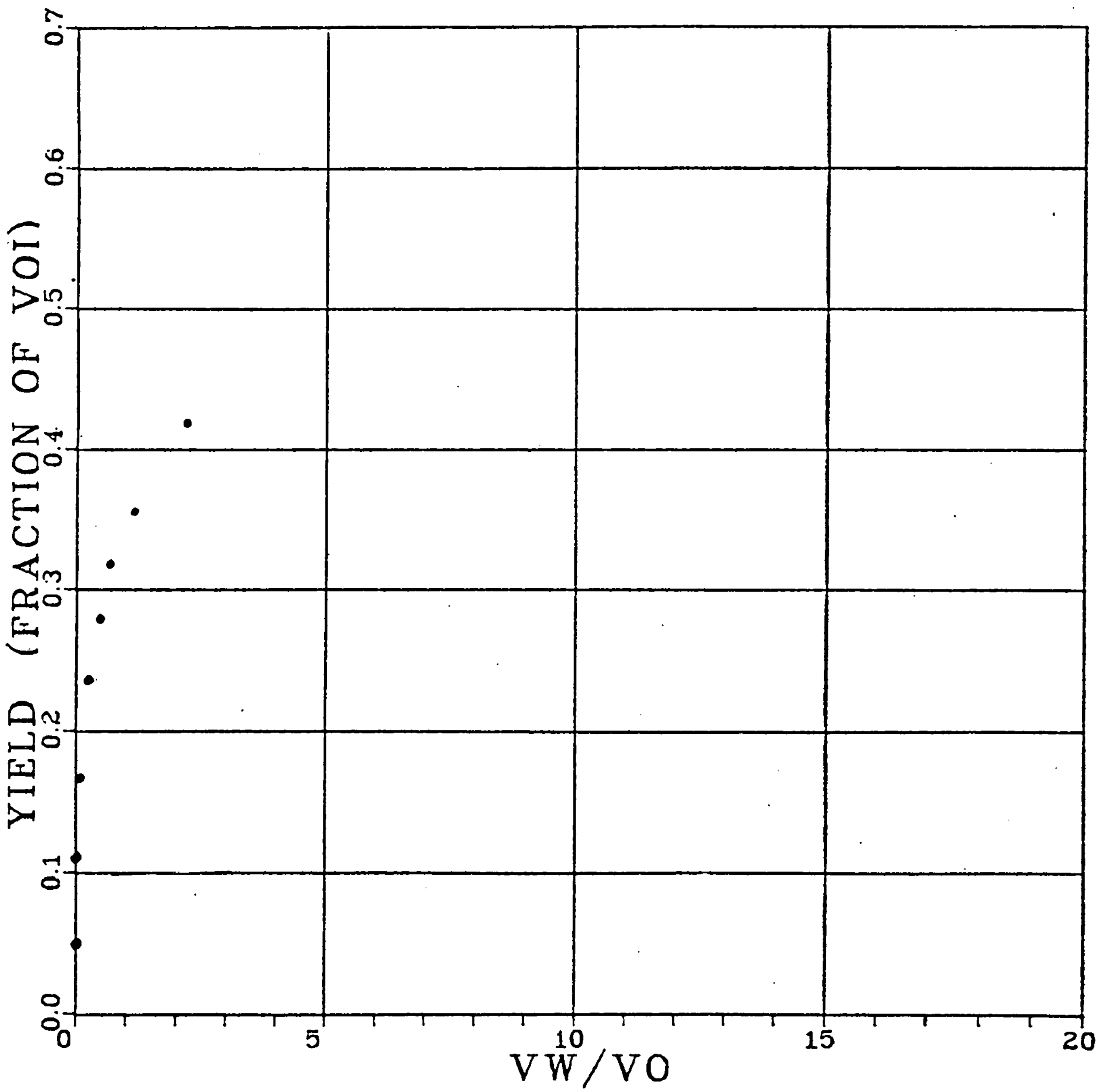


FIGURE 9

CRUDE OIL STEAM DISTILLATION YIELD
SHIELLS CANYON, RUN NO.8

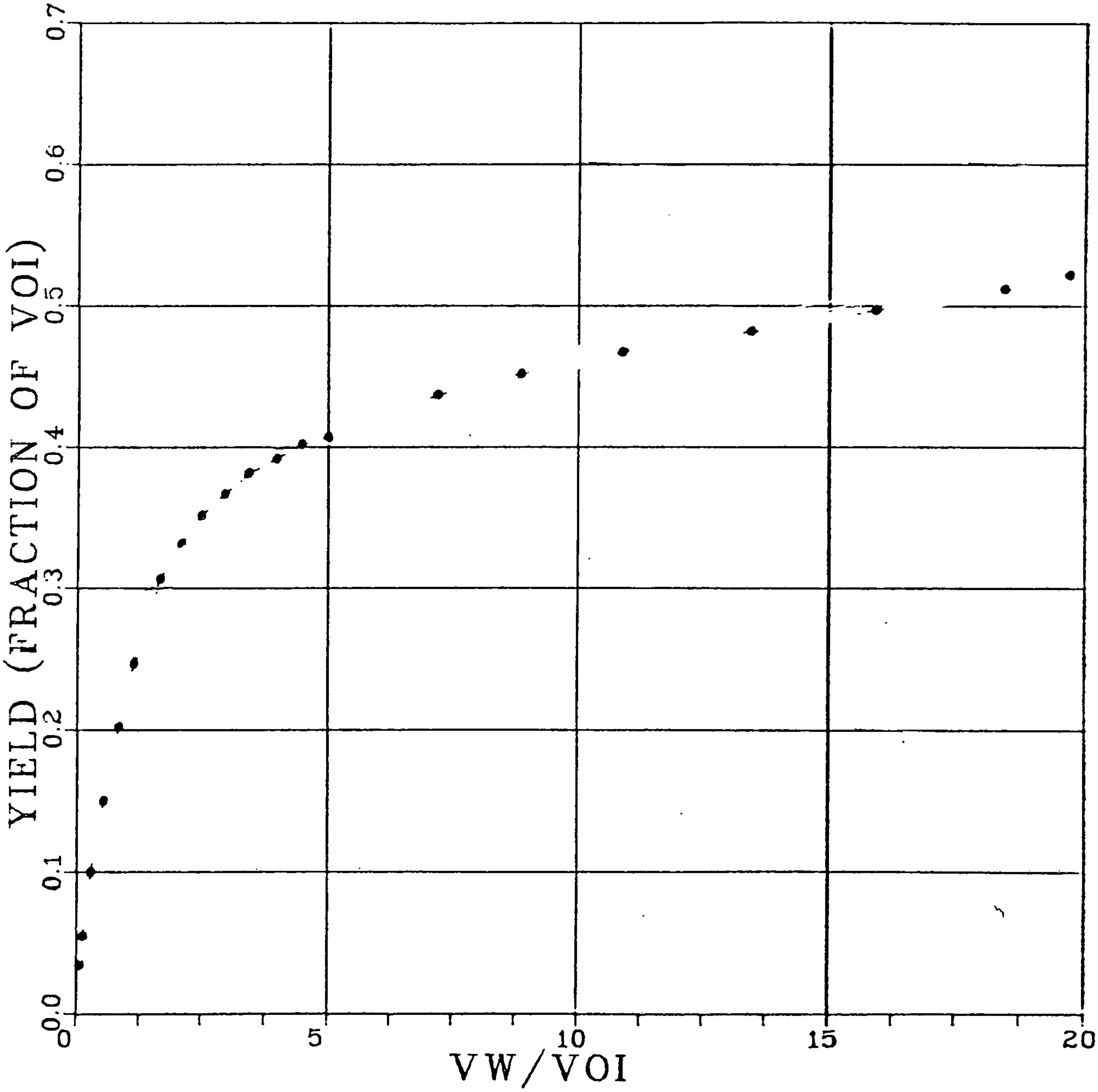


FIGURE 10

CRUDE OIL STEAM DISTILLATION YIELD
SHIELLS CANYON; RUN NO. 9

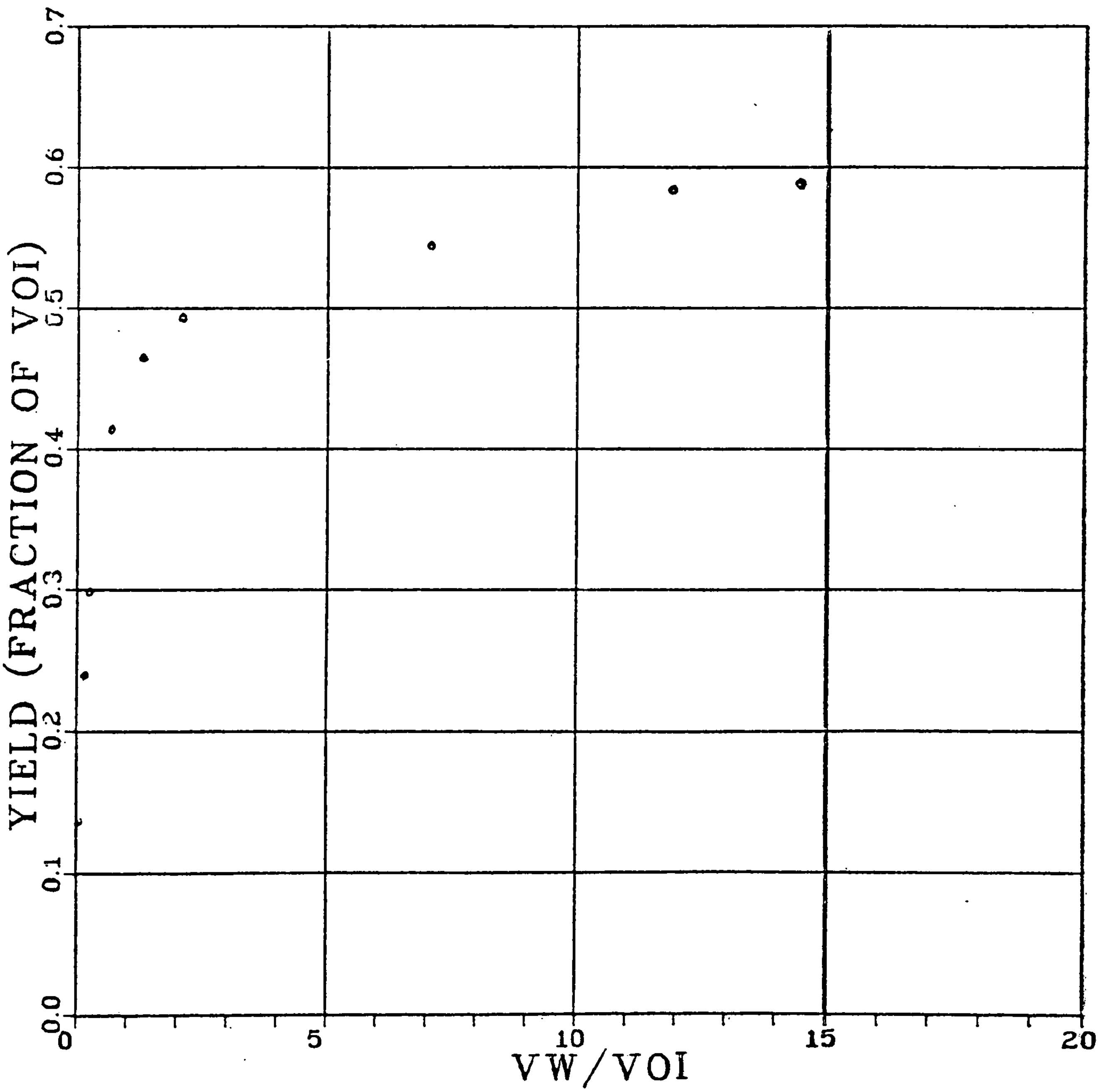
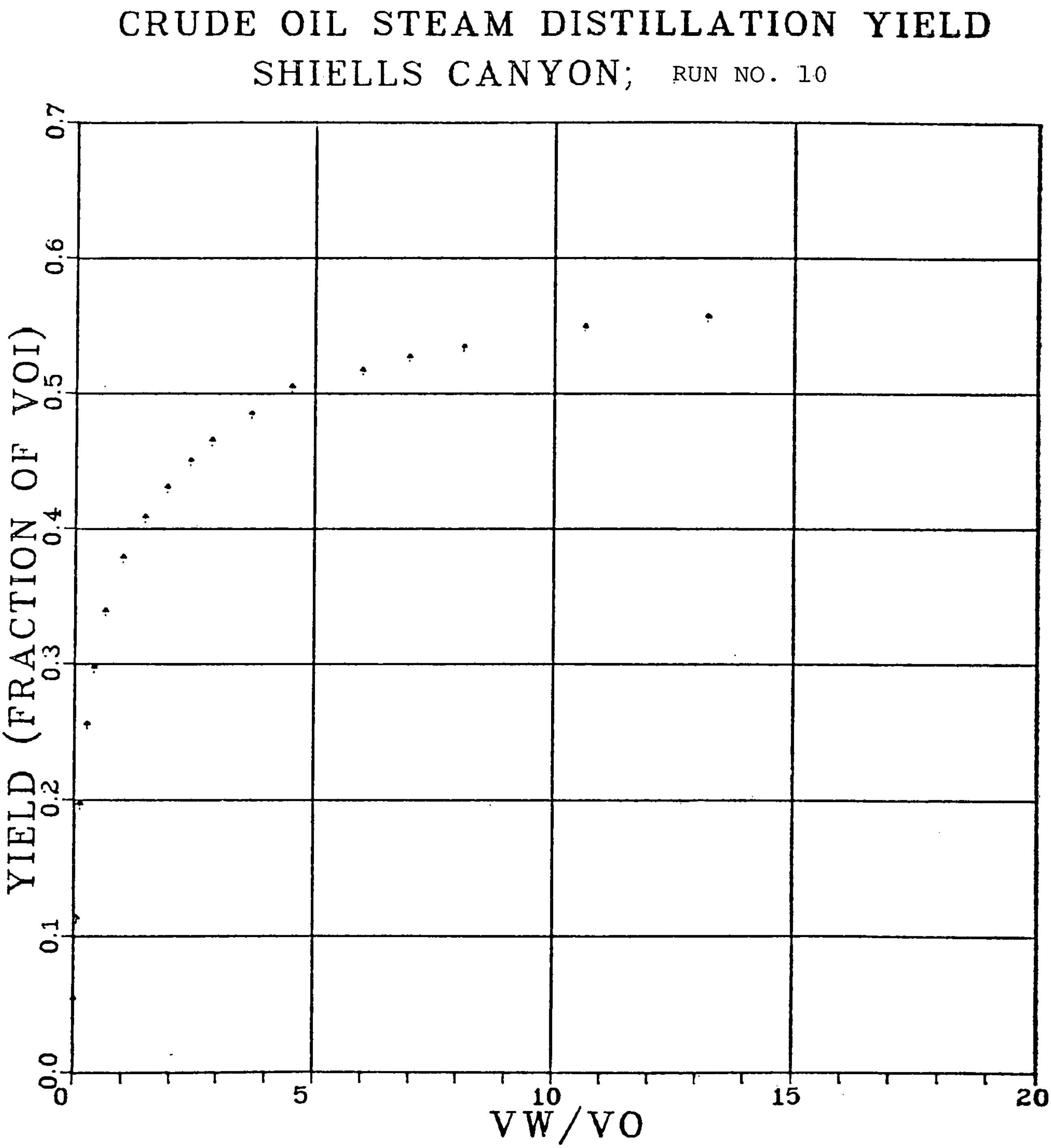


FIGURE 11



CRUDE OIL STEAM DISTILLATION YIELD
SHIELLS CANYON; RUN NO. 10
YIELD (FRACTION OF VOI)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
5
10
15
20
VW/VO

FIGURE 12

CRUDE OIL STEAM DISTILLATION YIELD
ROCK CREEK — RUN NO. 11

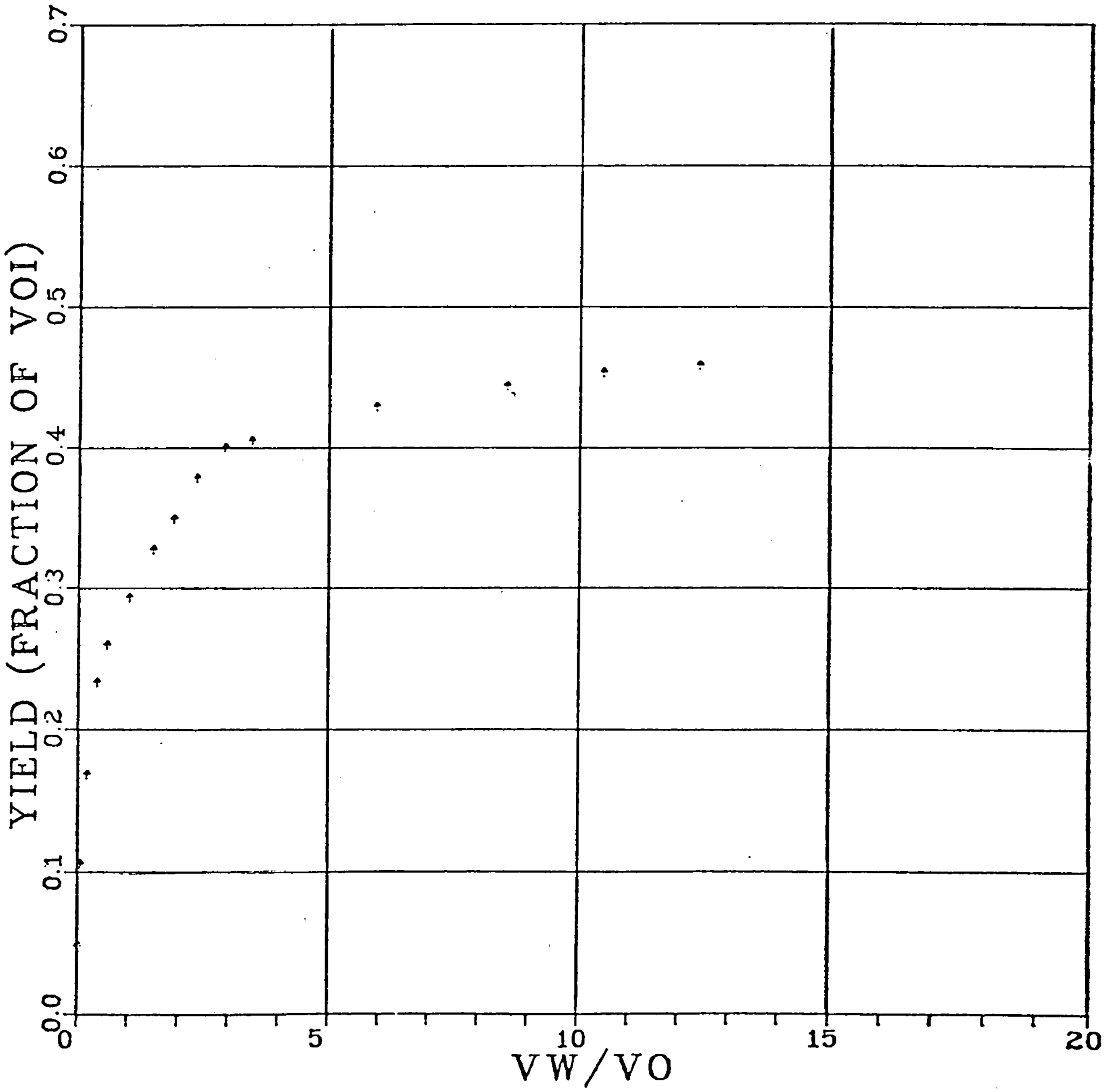


FIGURE 13

CRUDE OIL STEAM DISTILLATION YIELD
TEAPOT DOME — RUN NO. 12

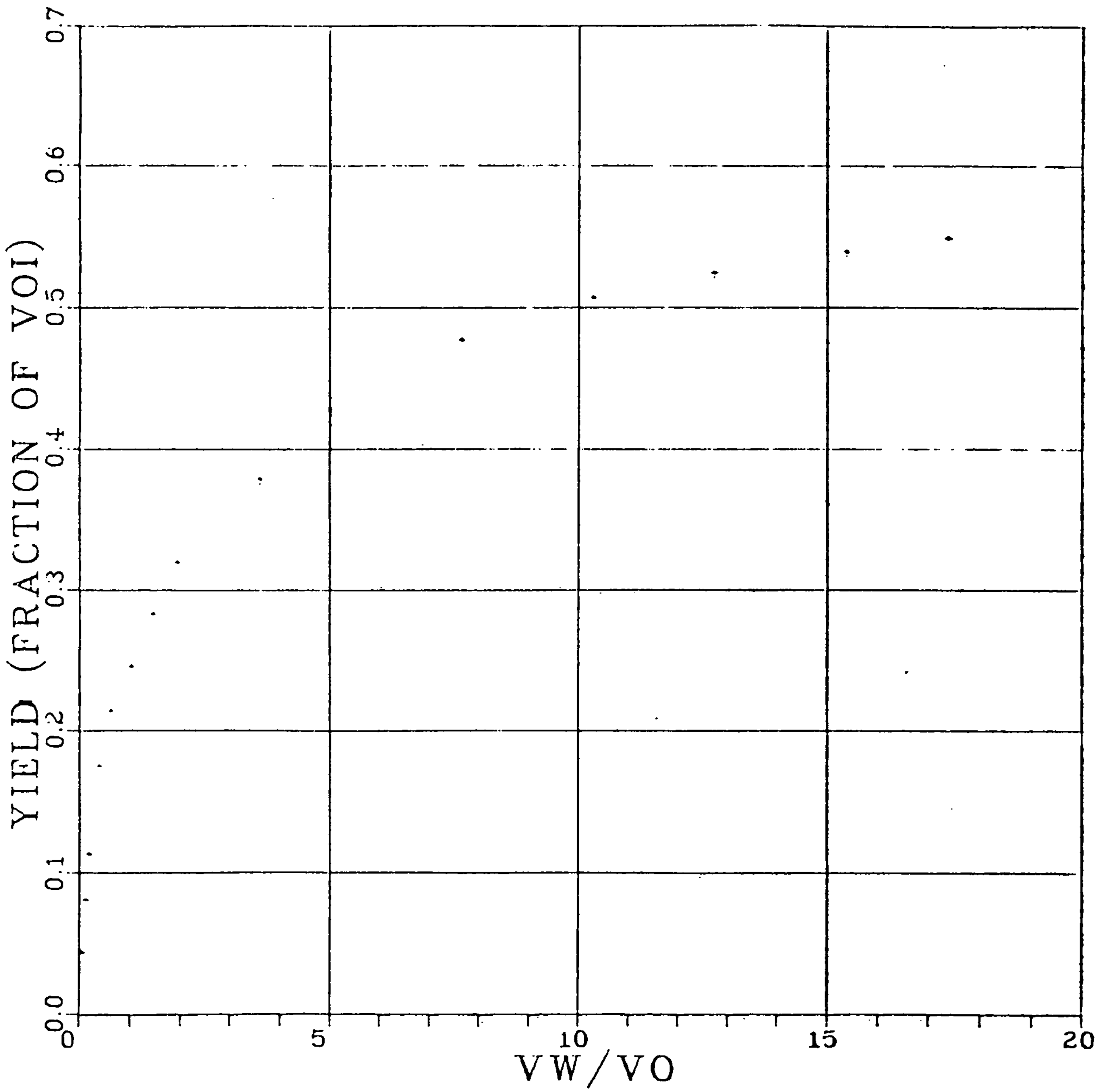


FIGURE 14

CRUDE OIL STEAM DISTILLATION YIELD
PLUM BUSH – RUN NO. 13

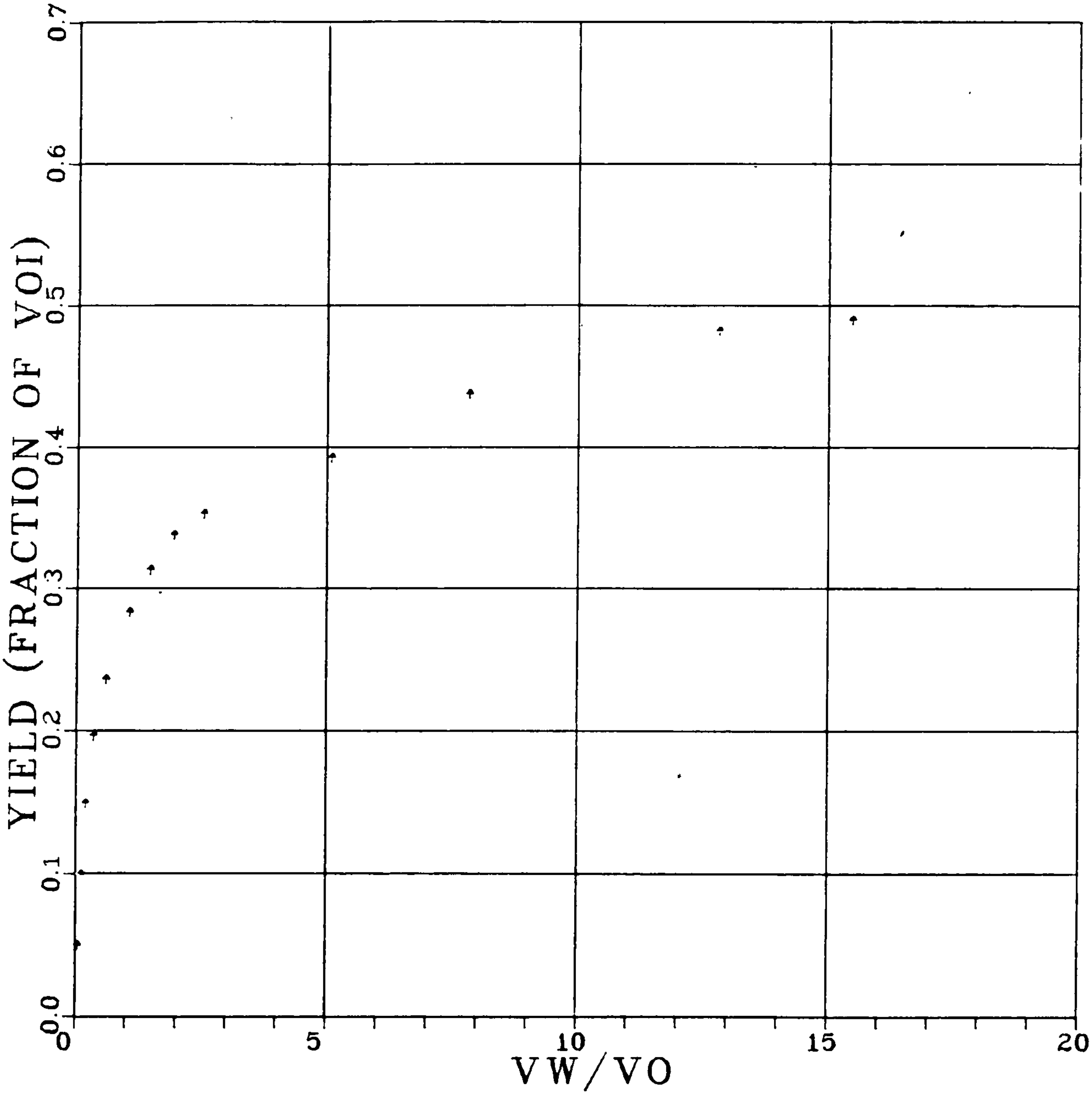


FIGURE 15

CRUDE OIL STEAM DISTILLATION YIELD
EL DORADO — RUN NO. 14

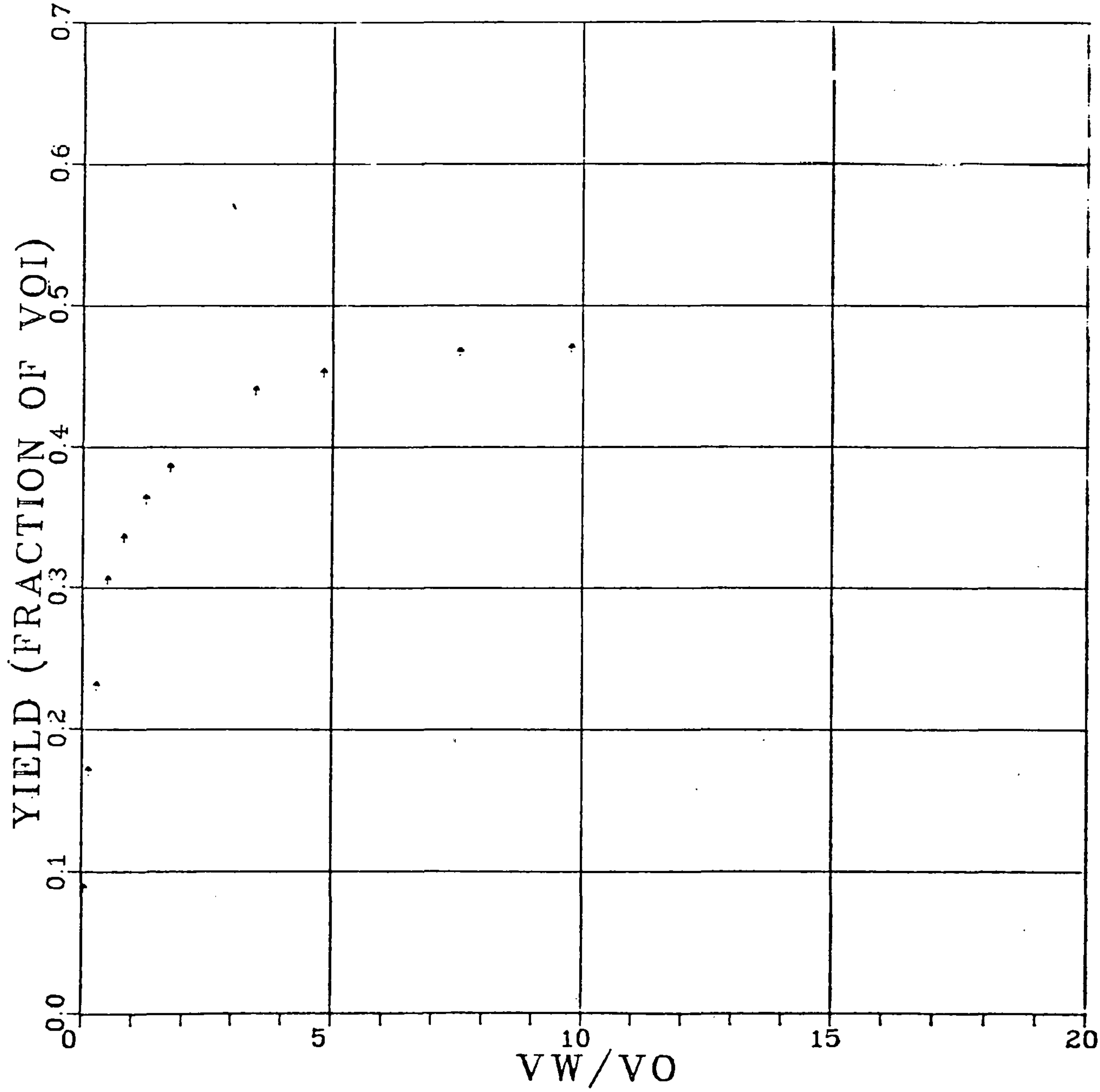


FIGURE 16

CRUDE OIL STEAM DISTILLATION YIELD
TOBORG — RUN NO. 15

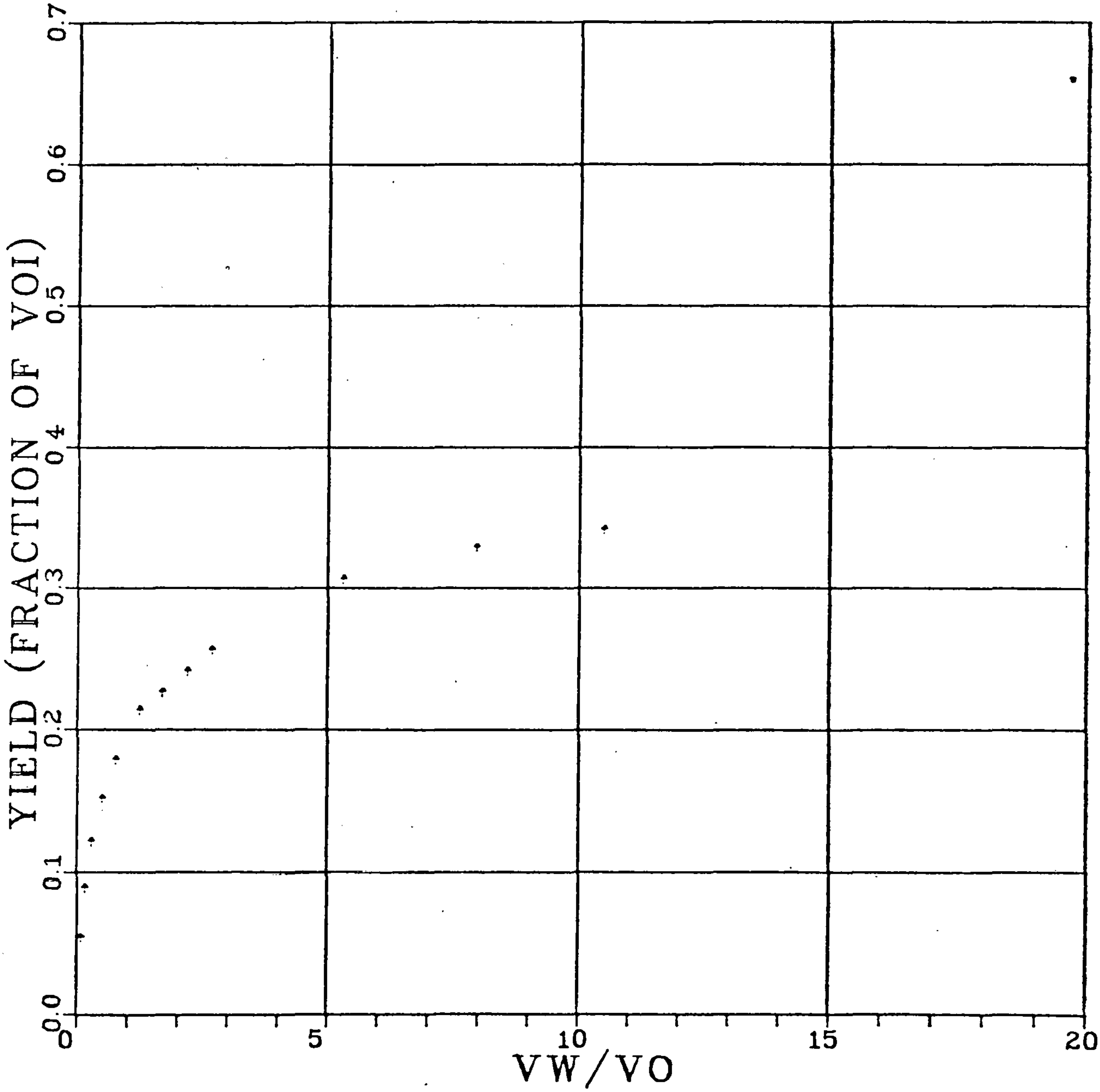


FIGURE 17

CRUDE OIL STEAM DISTILLATION YIELD

ROBINSON — RUN NO. 16

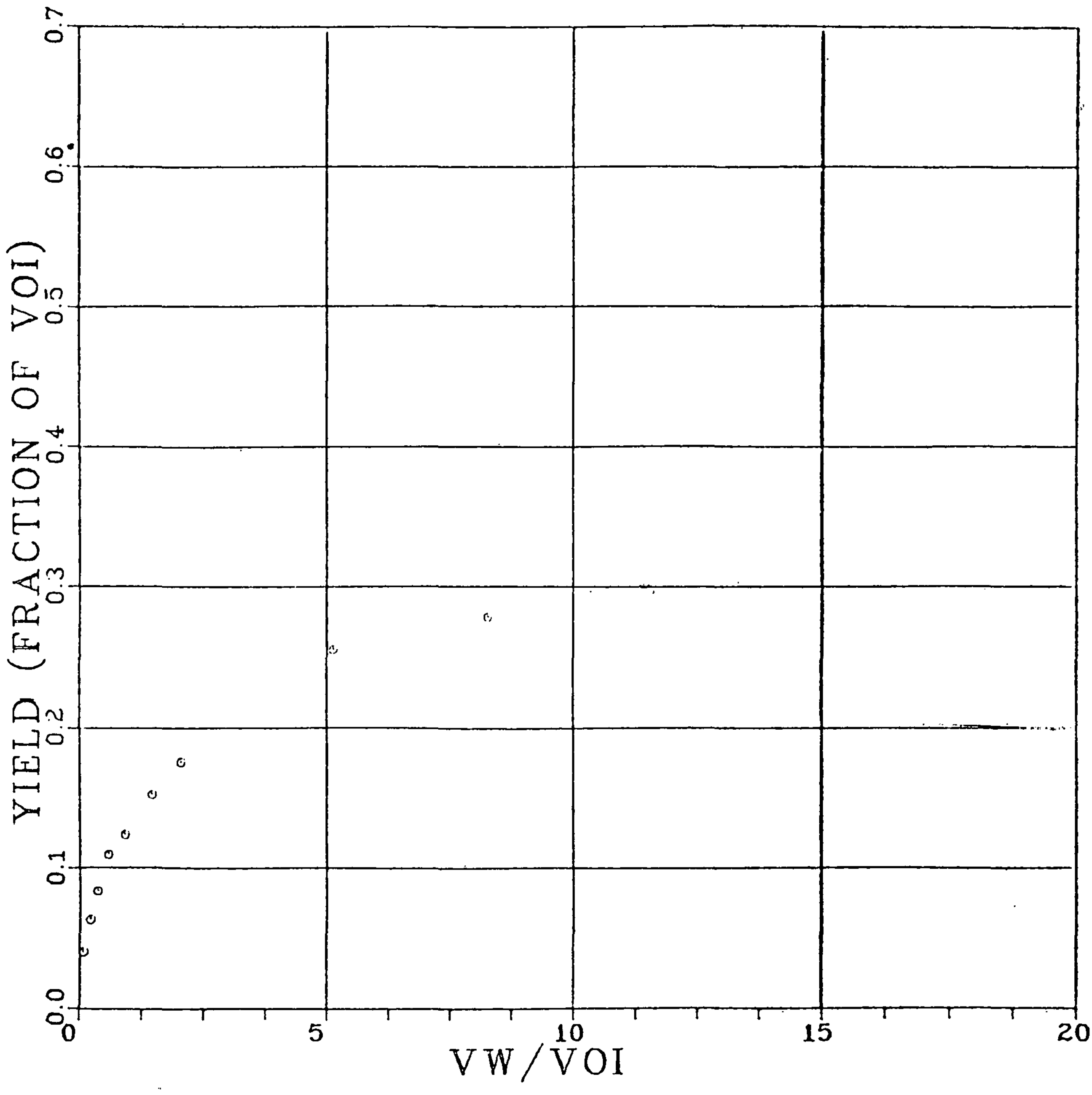


FIGURE 18

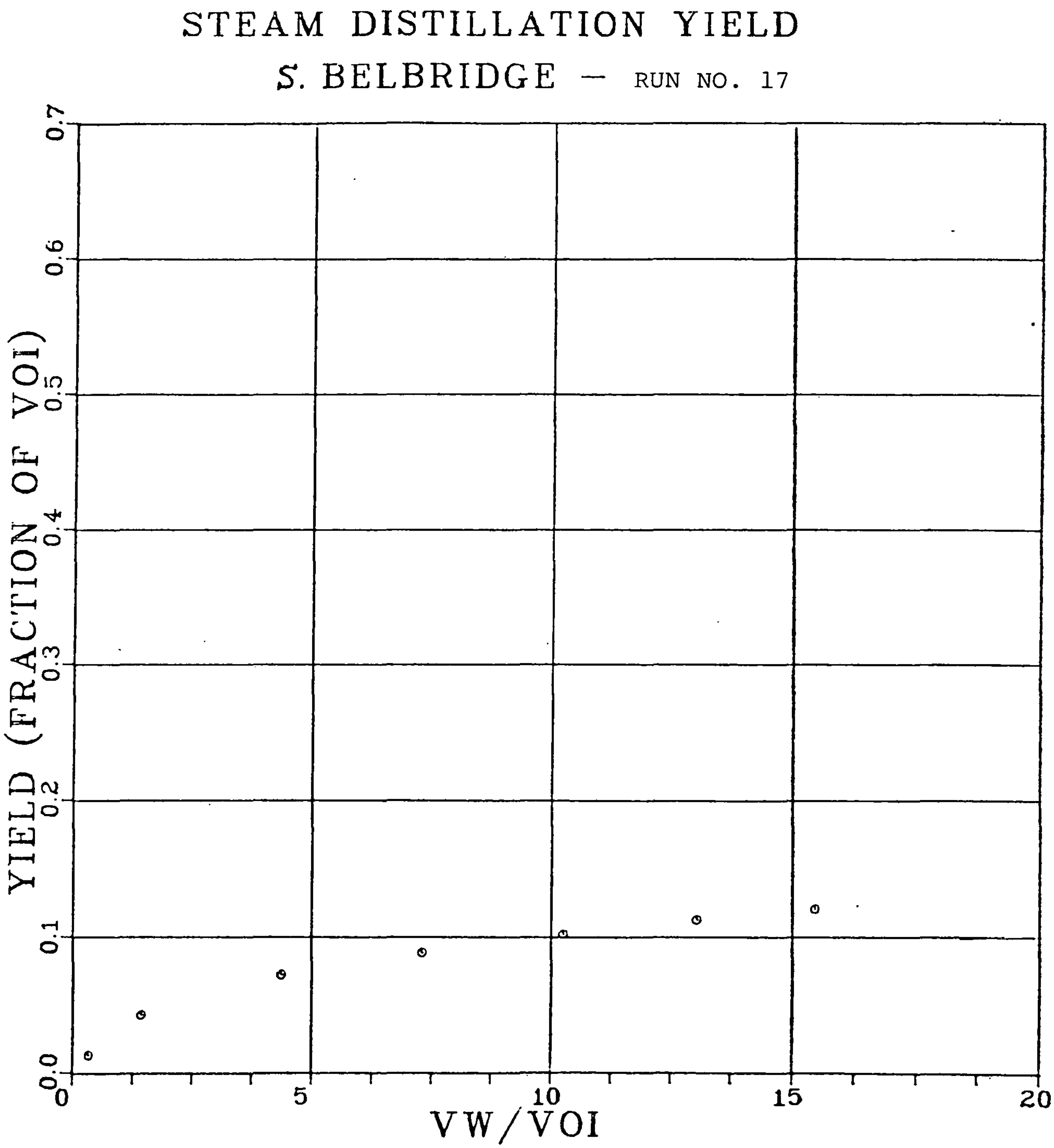

STEAM DISTILLATION YIELD
S. BELBRIDGE — RUN NO. 17
YIELD (FRACTION OF VOI)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
5
10
15
20
VW/VOI

FIGURE 19

CRUDE OIL STEAM DISTILLATION YIELD
HIDDEN DOME — RUN NO. 18

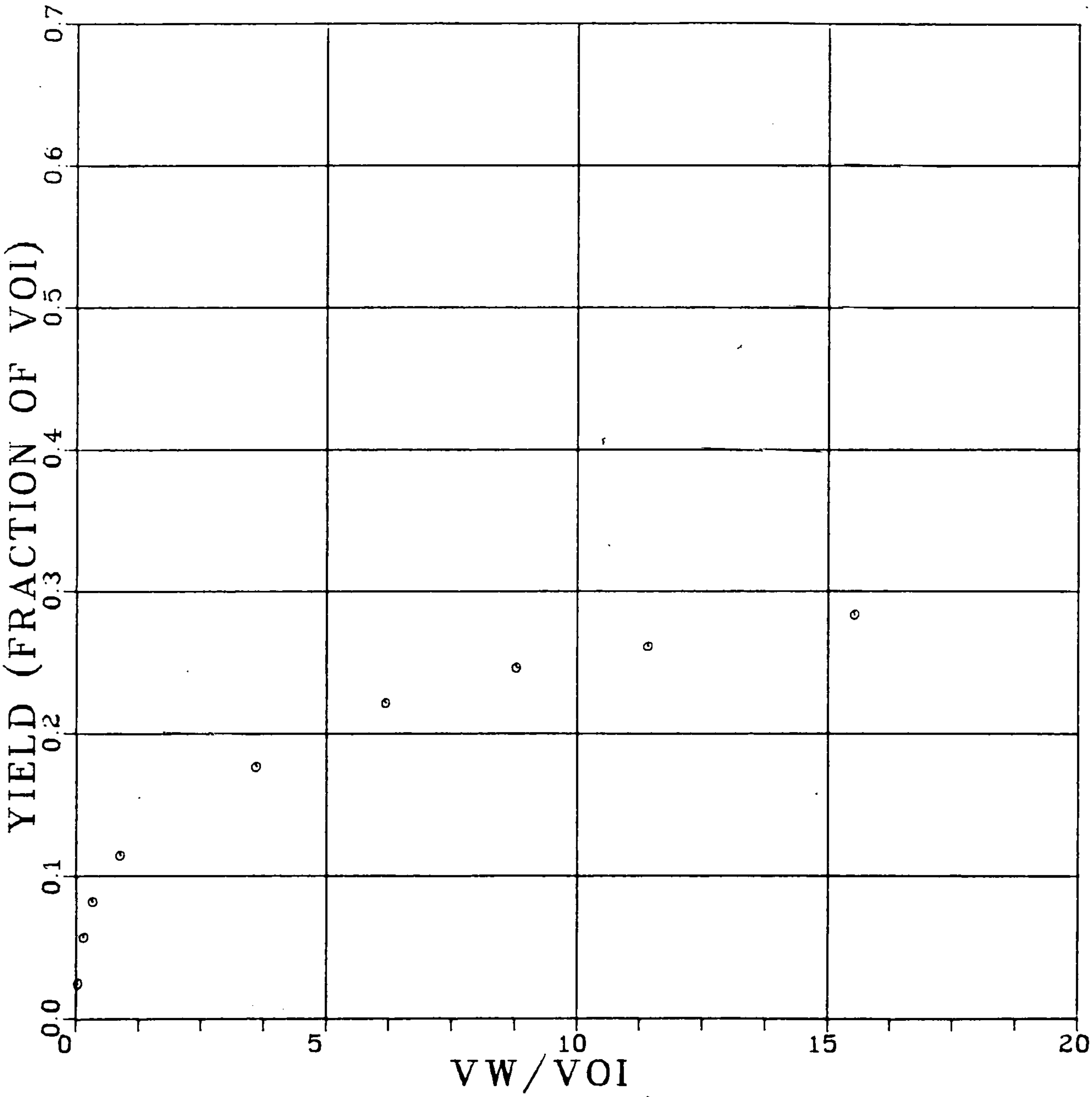


FIGURE 20

CRUDE OIL STEAM DISTILLATION YIELD
WHITE CASTLE — RUN NO. 19

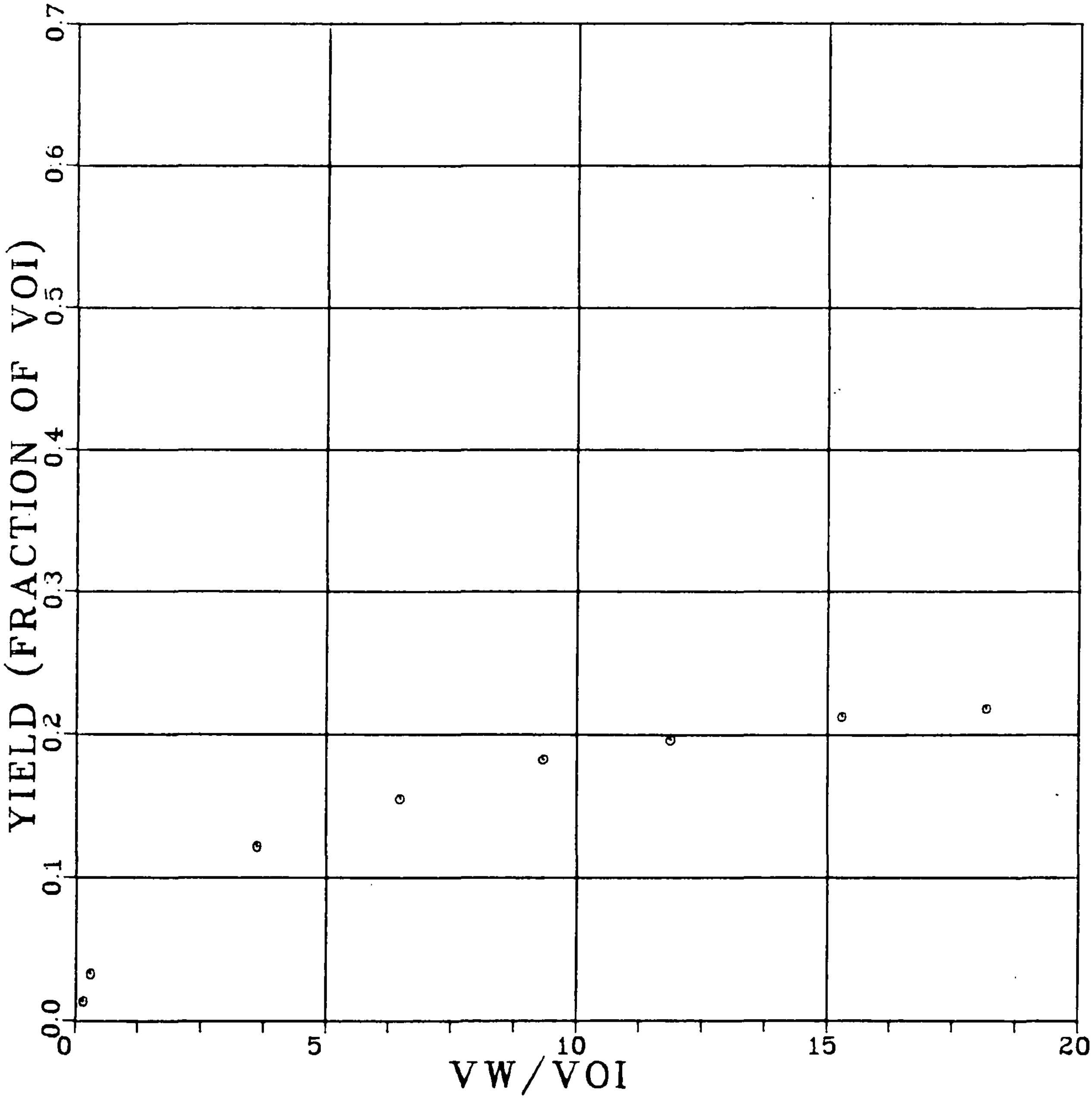


FIGURE 21

CRUDE OIL STEAM DISTILLATION YIELD
WINKLEMAN DOME — RUN NO. 20

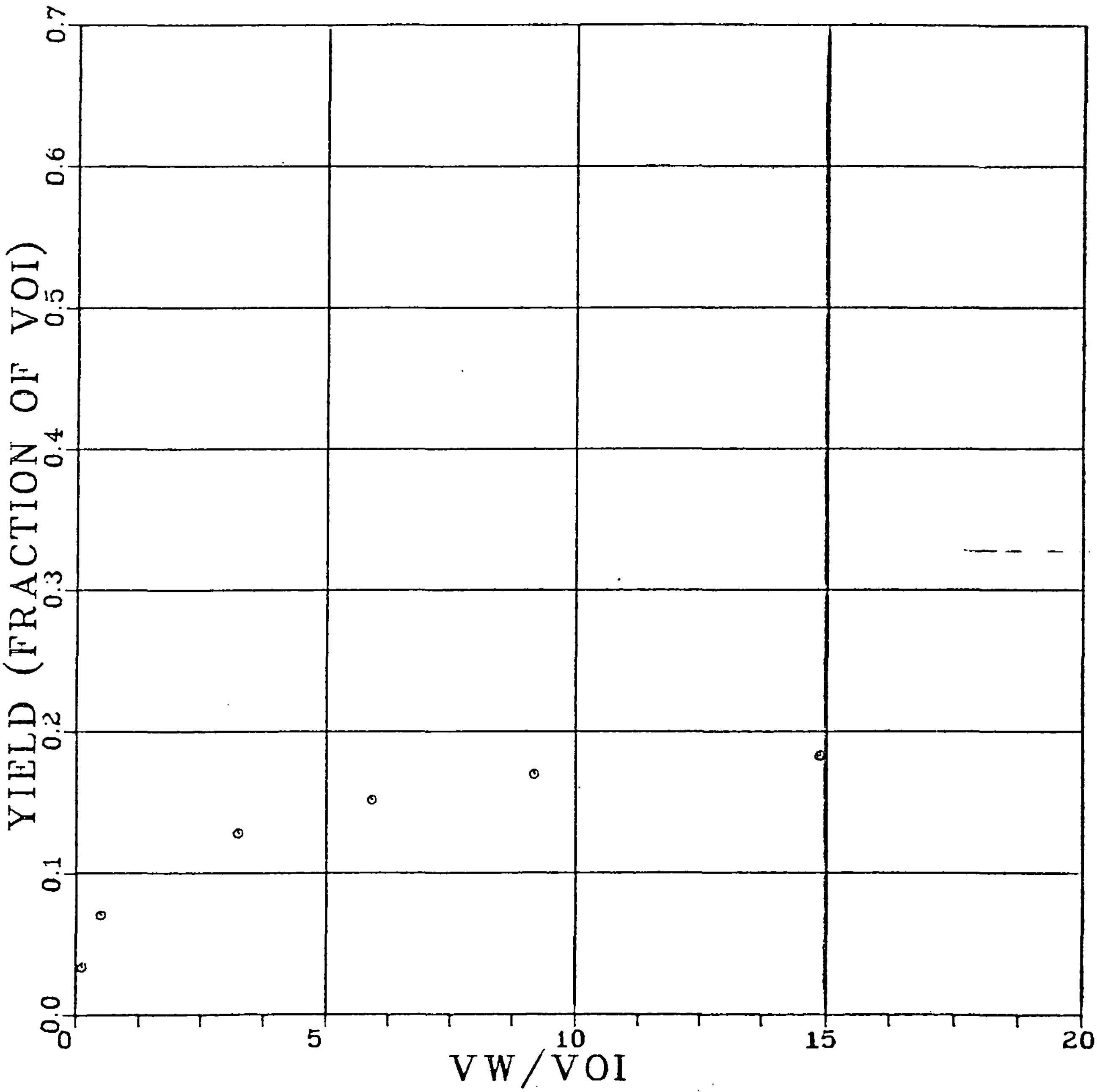


FIGURE 22

CRUDE OIL STEAM DISTILLATION YIELD
SLOCUM — RUN NO. 21

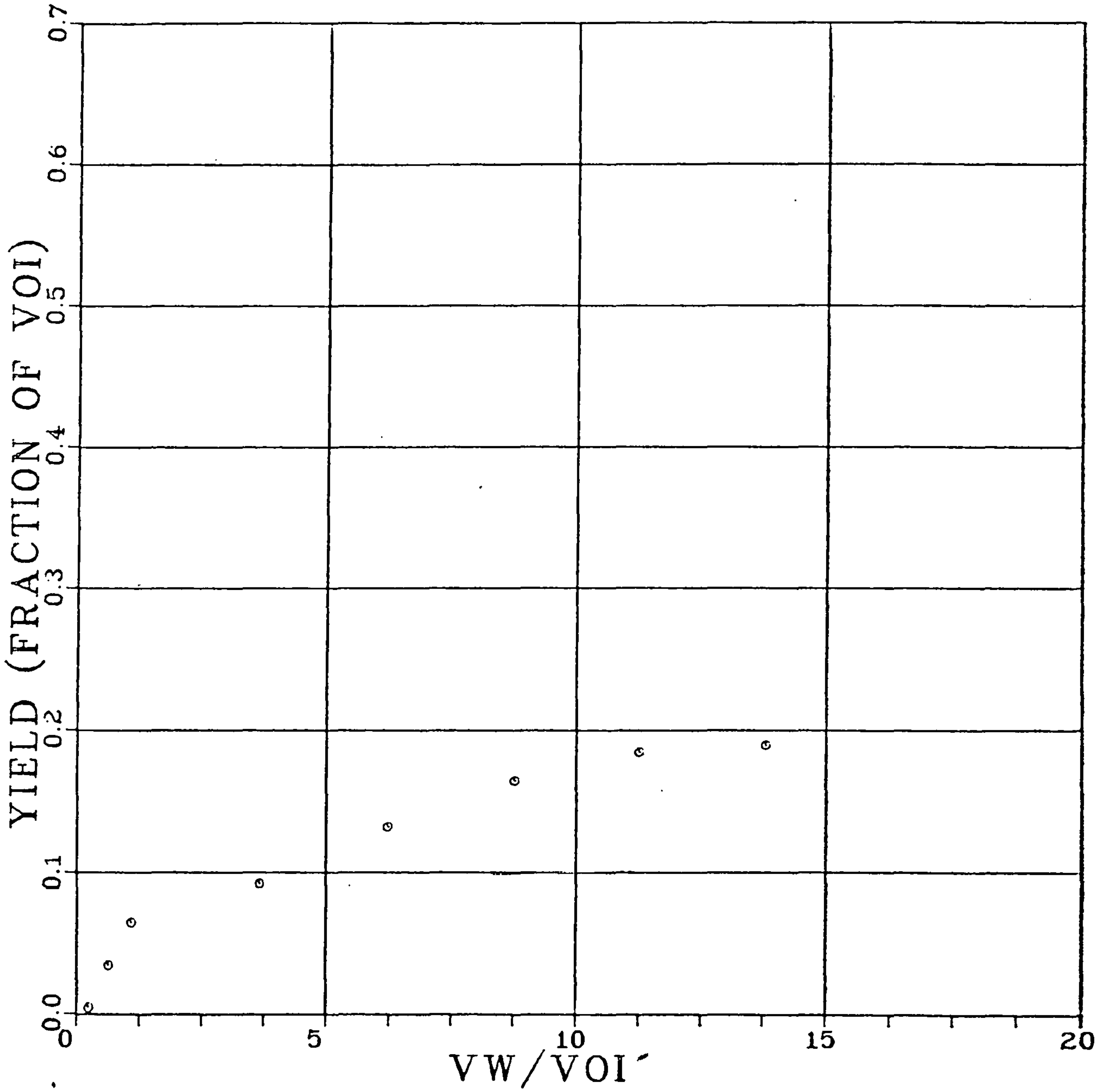


FIGURE 23

CRUDE OIL STEAM DISTILLATION
EDISON — RUN NO. 22

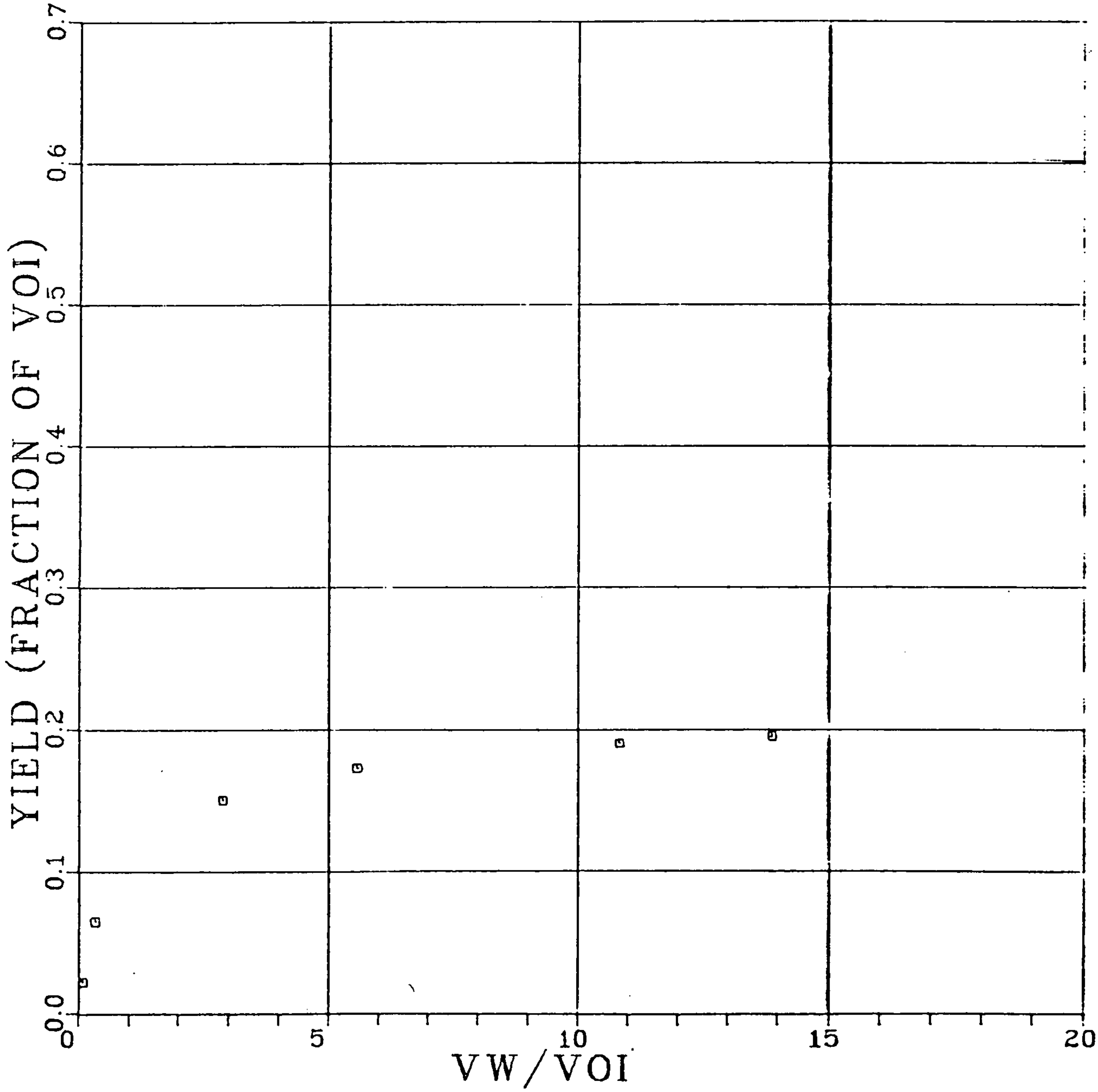


FIGURE 24

CRUDE OIL STEAM DISTILLATION
SHANNON — RUN NO. 23

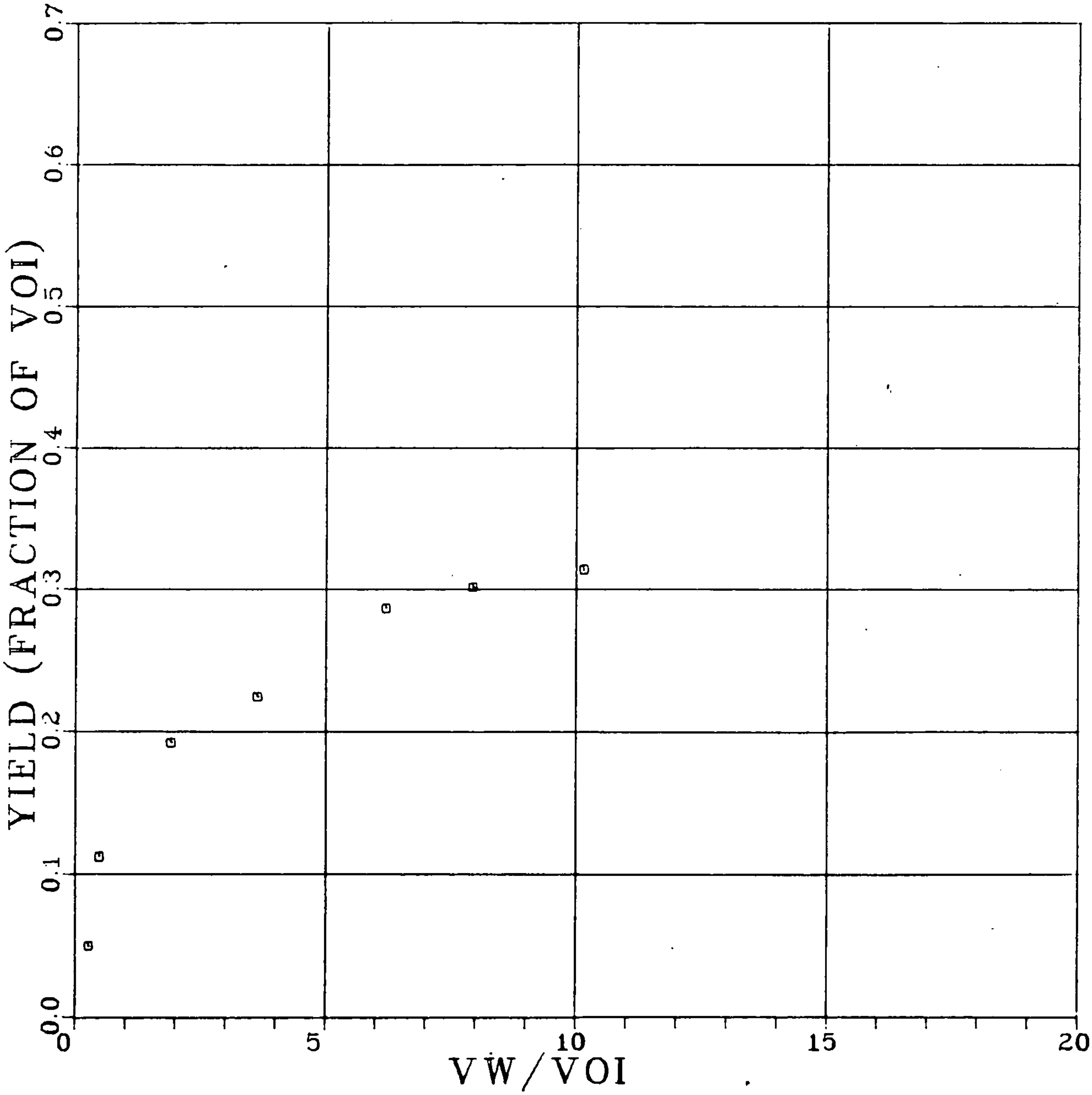
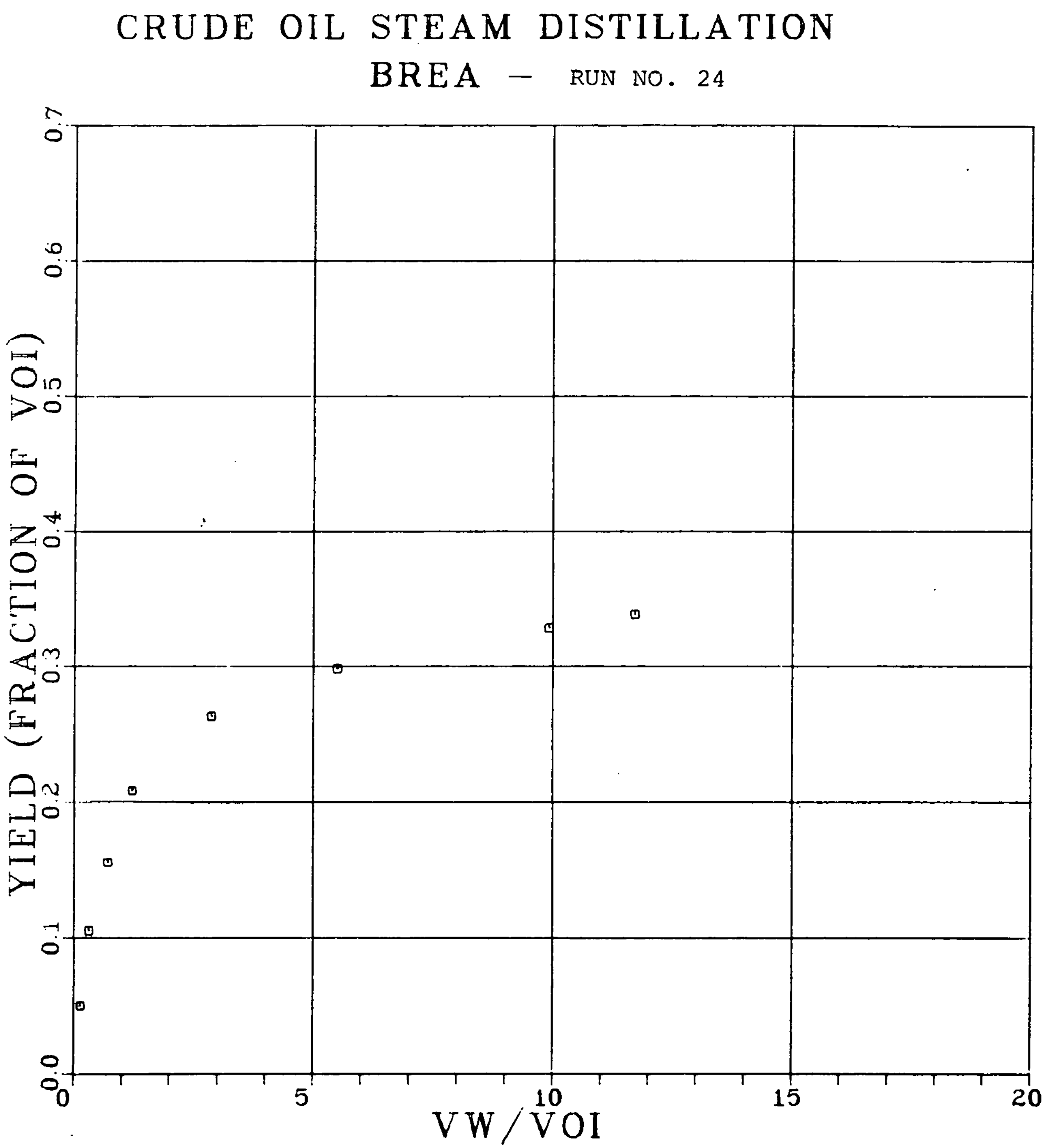


FIGURE 25



CRUDE OIL STEAM DISTILLATION
BREA — RUN NO. 24
YIELD (FRACTION OF VOI)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
5
10
15
20
VW/VOI

FIGURE 26

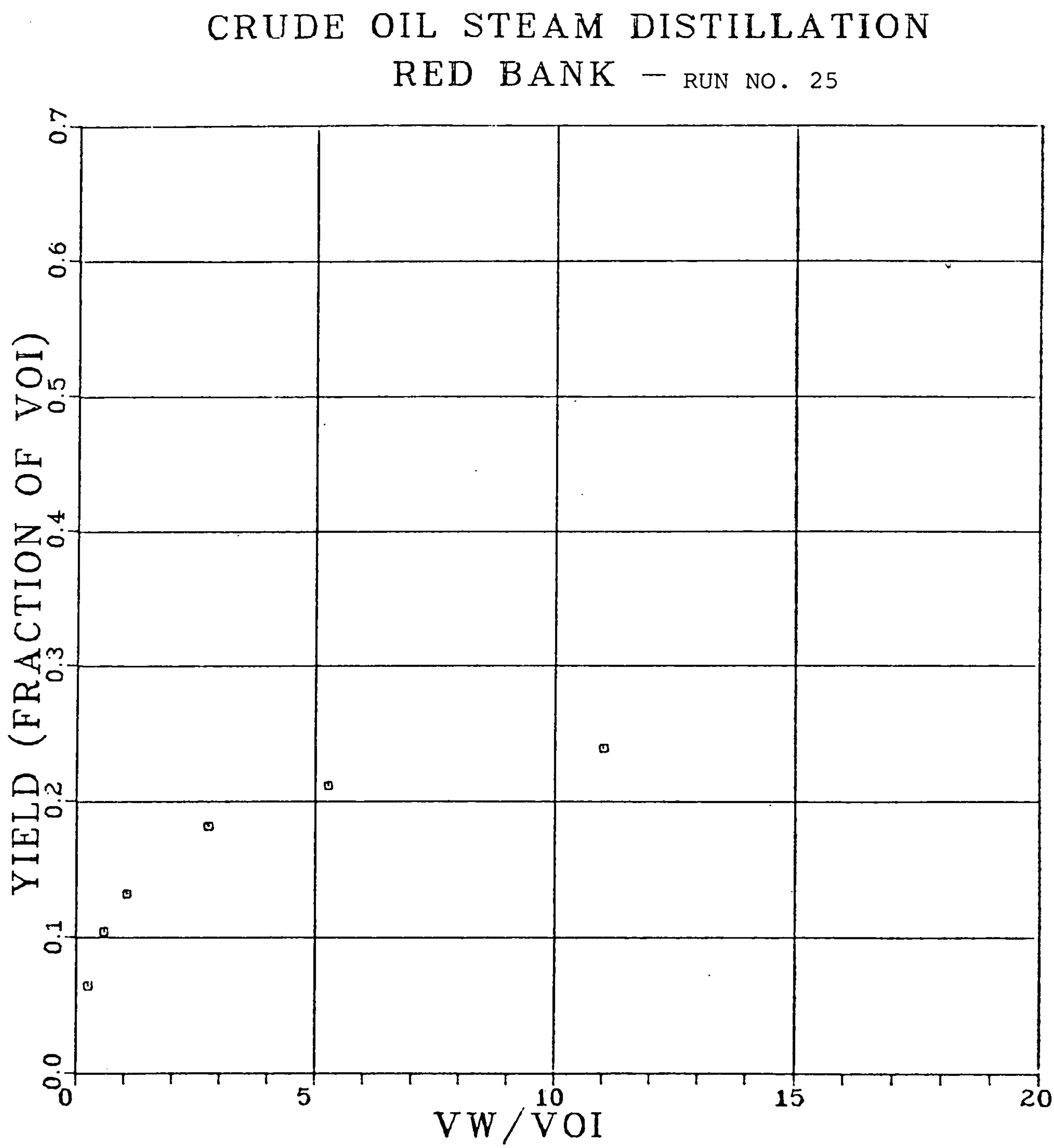

CRUDE OIL STEAM DISTILLATION
RED BANK — RUN NO. 25
YIELD (FRACTION OF VOI)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
5
10
15
20
VW/VOI

FIGURE 27

CRUDE OIL STEAM DISTILLATION YIELD REPEATABILITY TEST

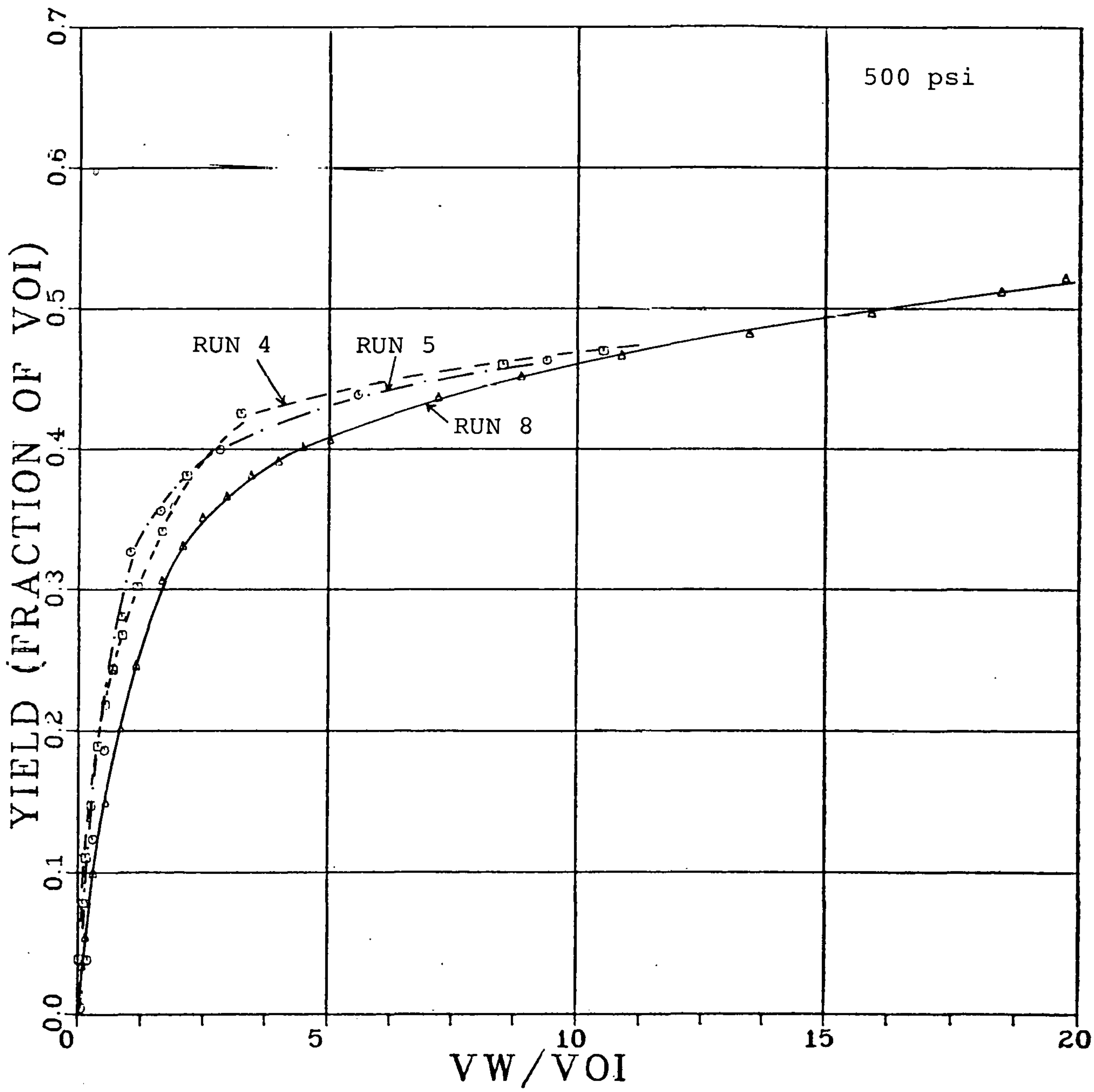
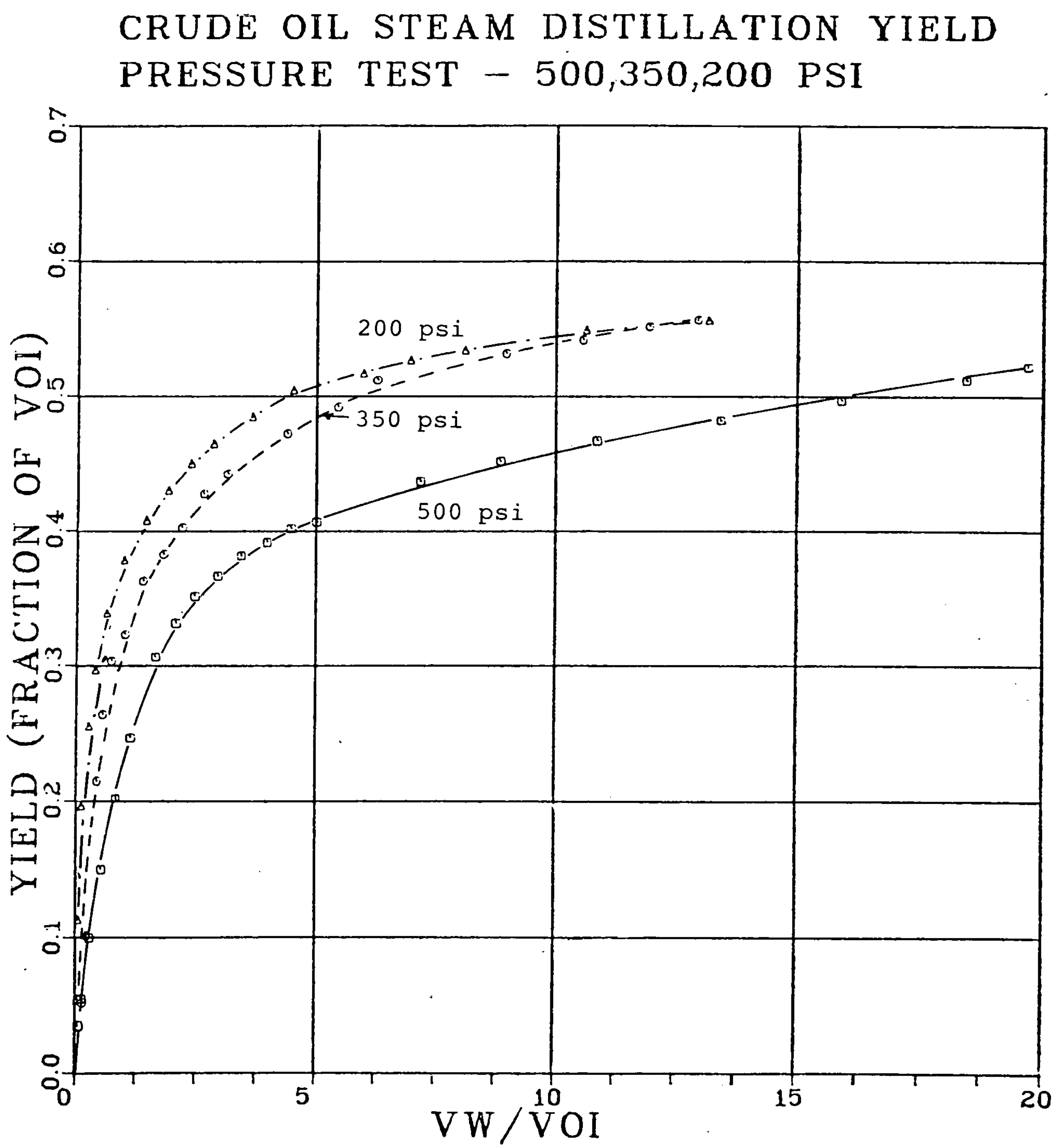


FIGURE 28



CRUDE OIL STEAM DISTILLATION YIELD
PRESSURE TEST – 500,350,200 PSI
200 psi
350 psi
500 psi
YIELD (FRACTION OF VOI)
VW/VOI
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
5
10
15
20

FIGURE 29

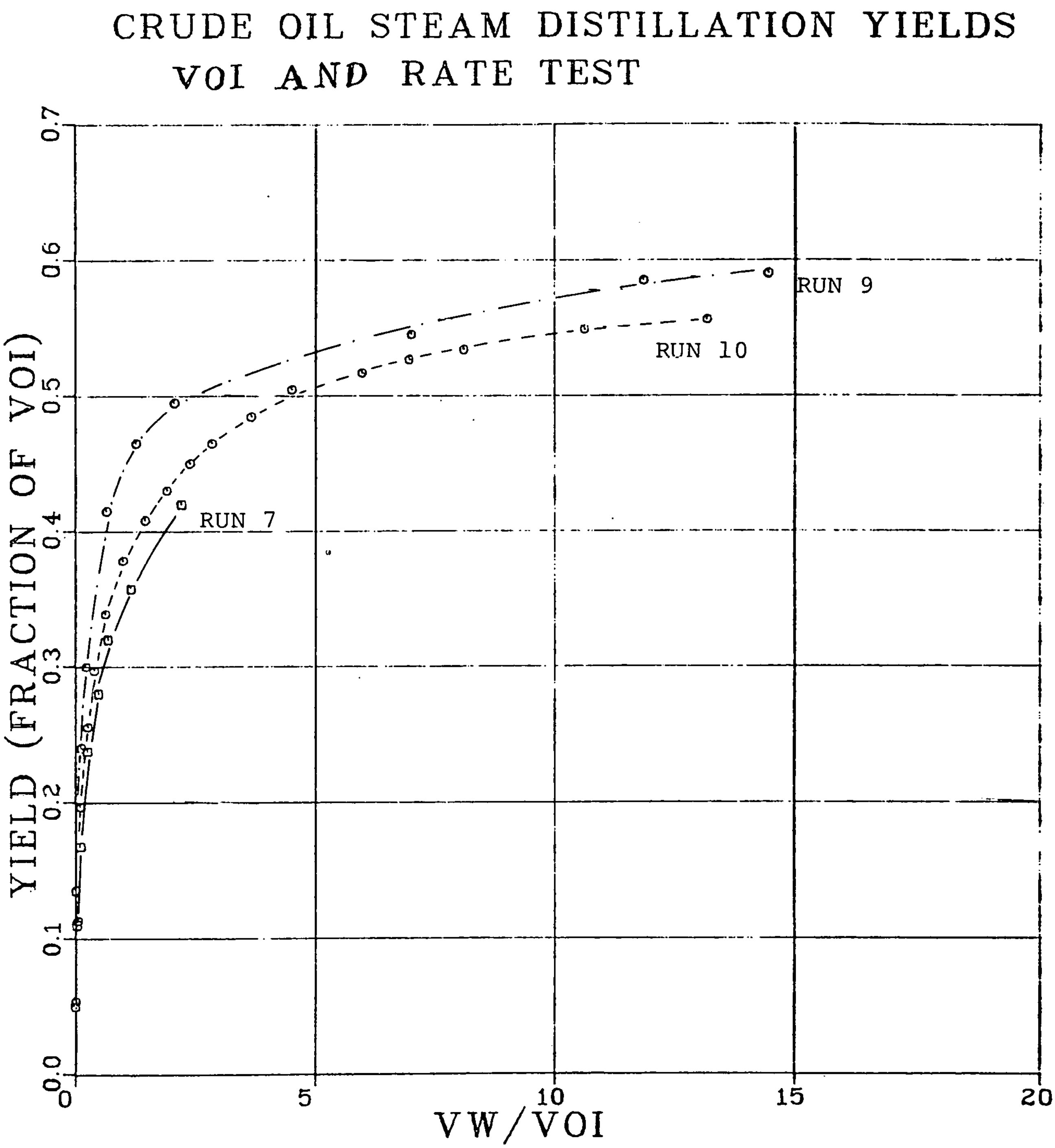

CRUDE OIL STEAM DISTILLATION YIELDS
VOI AND RATE TEST
YIELD (FRACTION OF VOI)
VW/VOI
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
5
10
15
20
RUN 9
RUN 10
RUN 7

FIGURE 30

COMPARISON OF

CRUDE OIL STEAM DISTILLATION YIELDS
NUMBERS 1–16

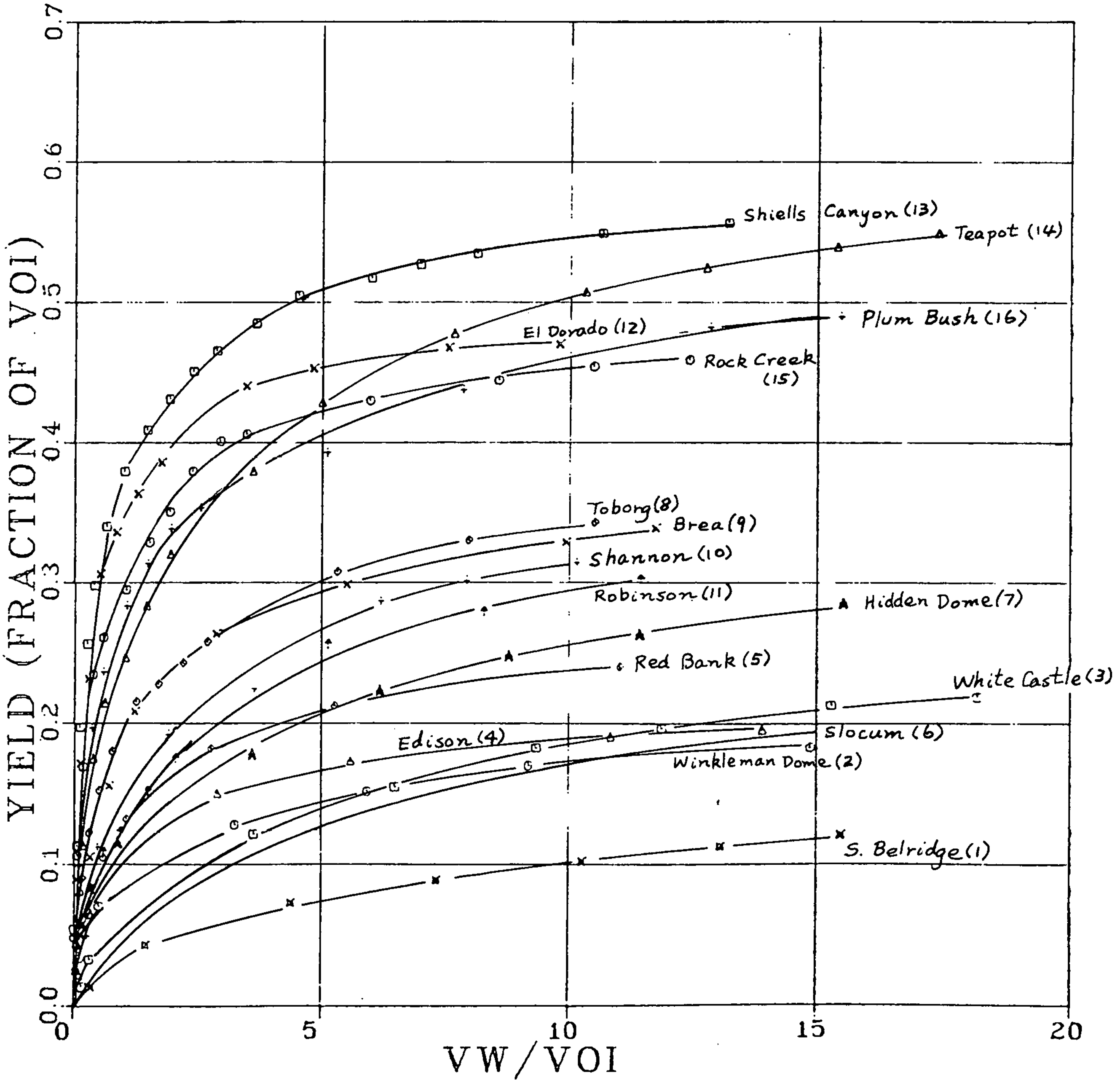


FIGURE 31 CORRELATION OF STEAM DISTILLATION YIELDS WITH CRUDE OIL API GRAVITY

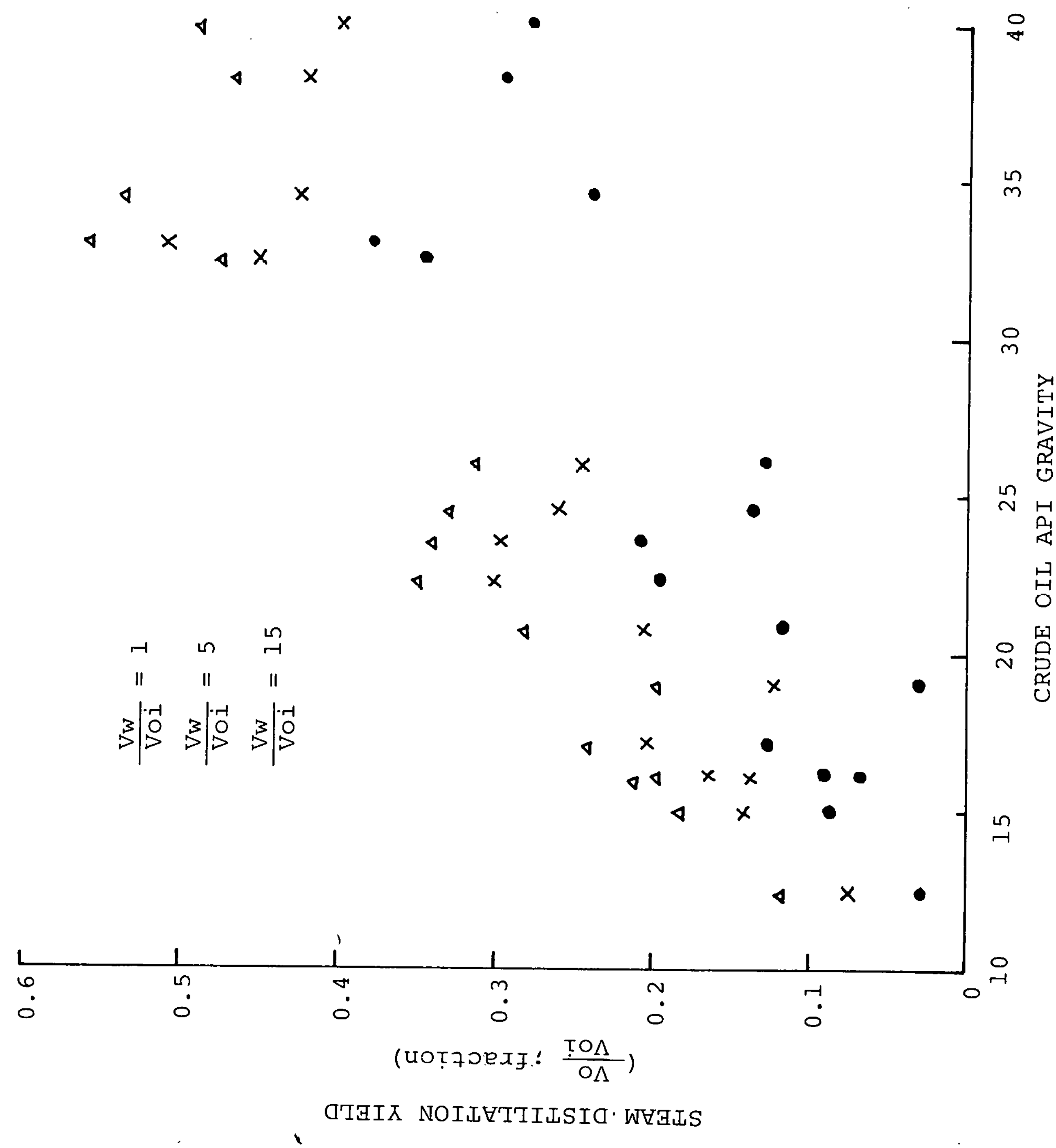


FIGURE 32 REGRESSION ANALYSIS OF STEAMS DISTILLATION YIELDS $(\frac{V_w}{V_{oi}} = 1)$ VERSUS CRUDE OIL API GRAVITY

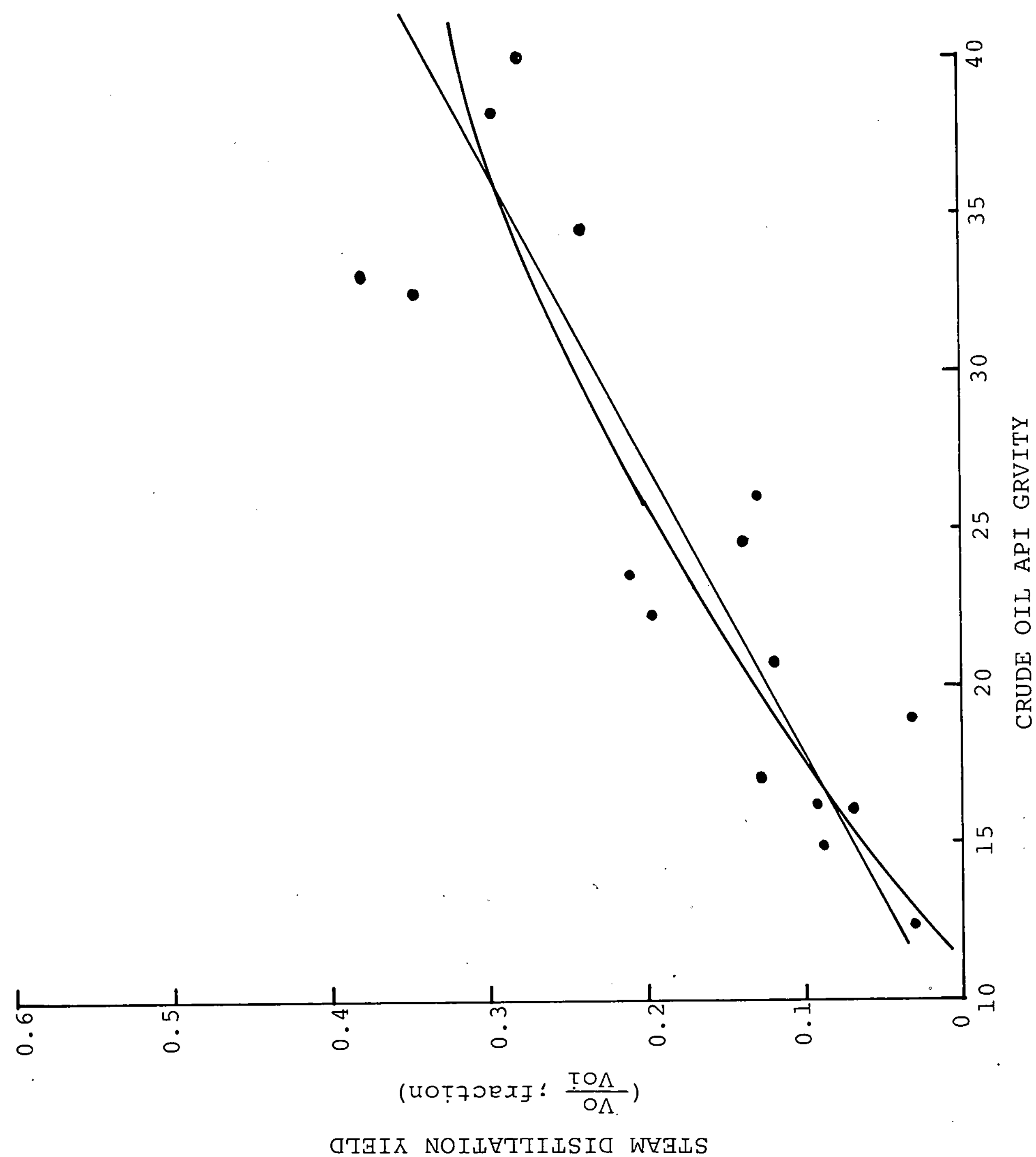
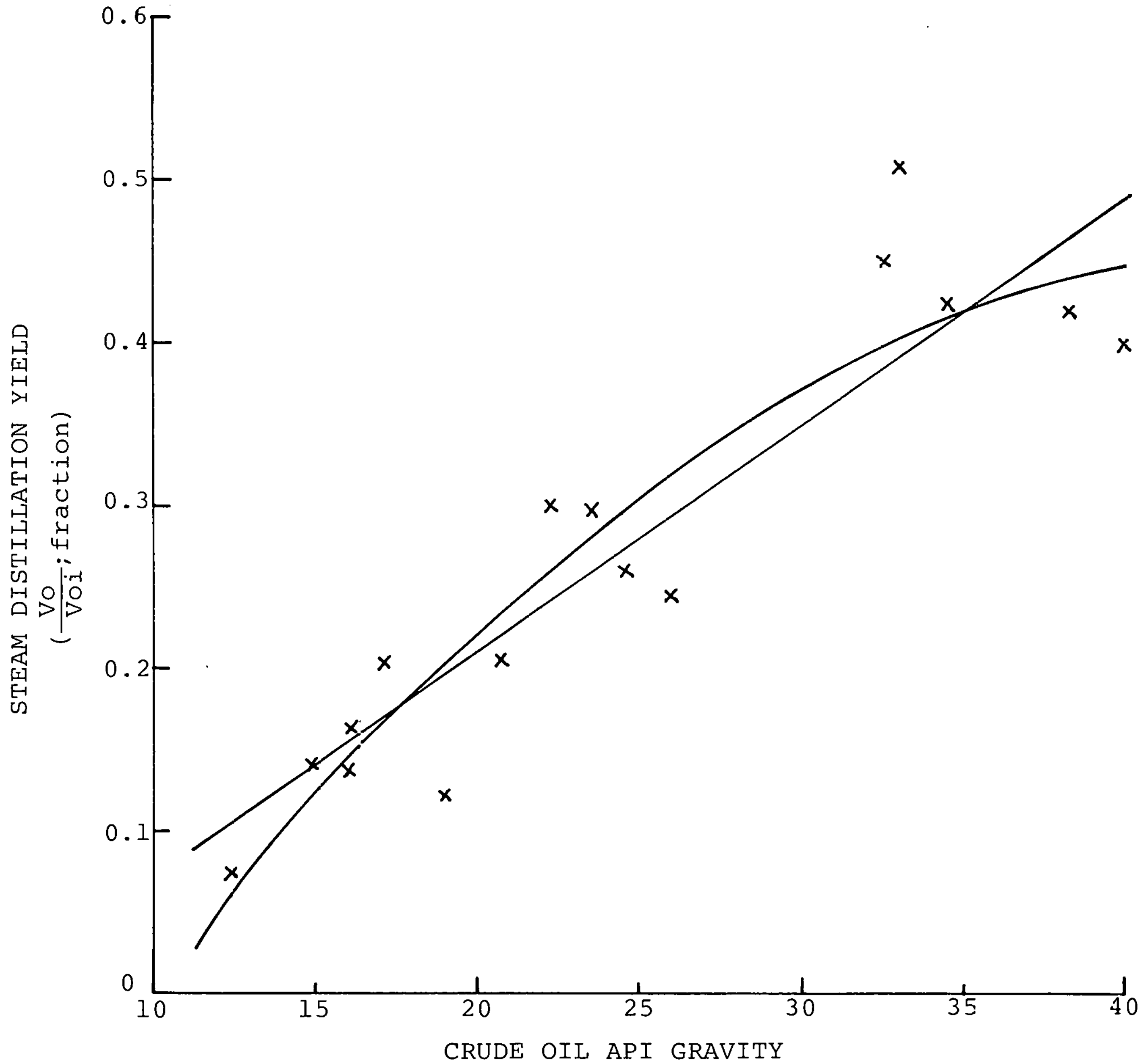


FIGURE 33 REGRESSION ANALYSIS OF STEAM DISTILLATION YIELDS ($\frac{V_w}{V_{oi}}$ = 5) VERSUS CRUDE OIL API GRAVITY



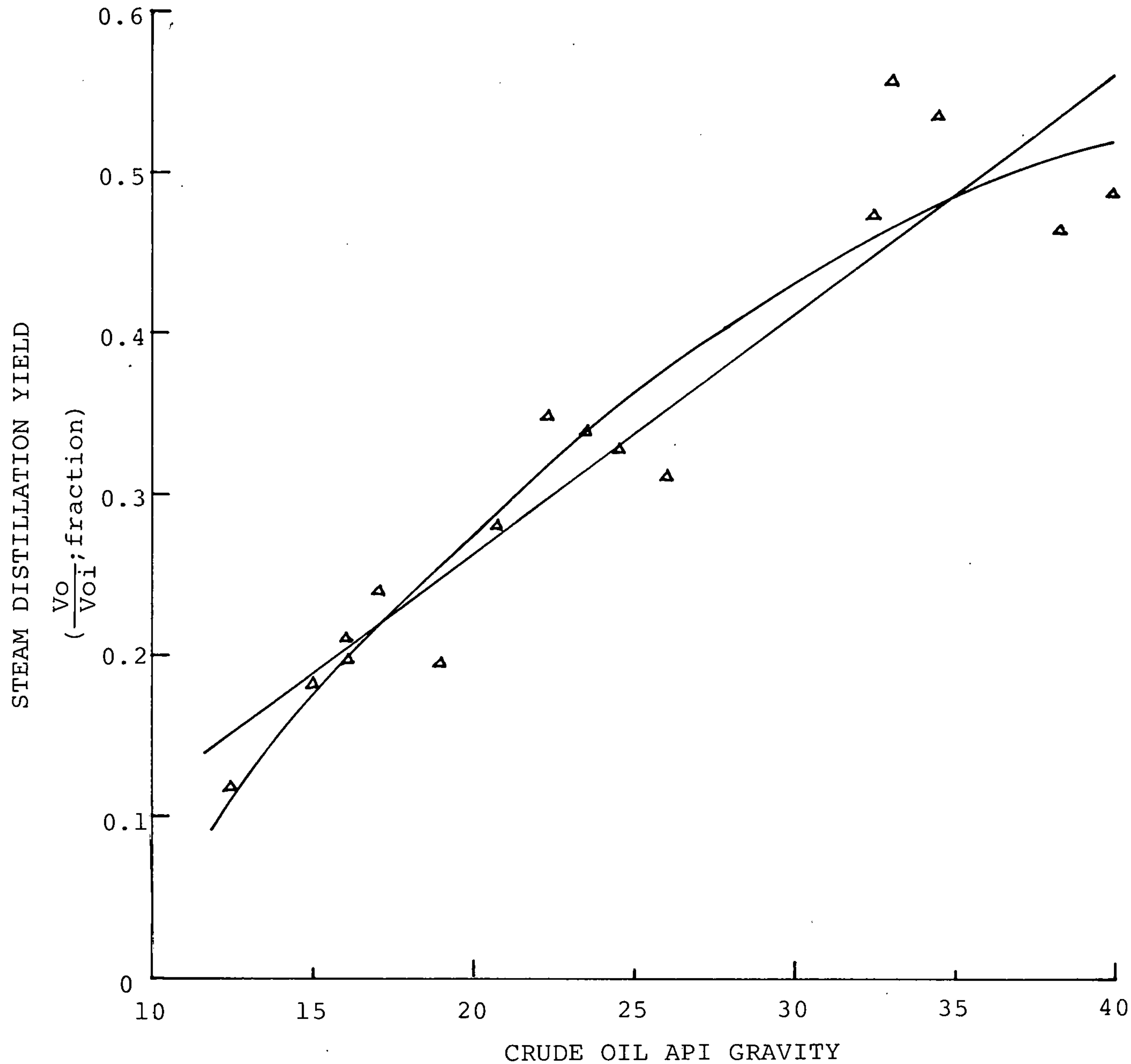
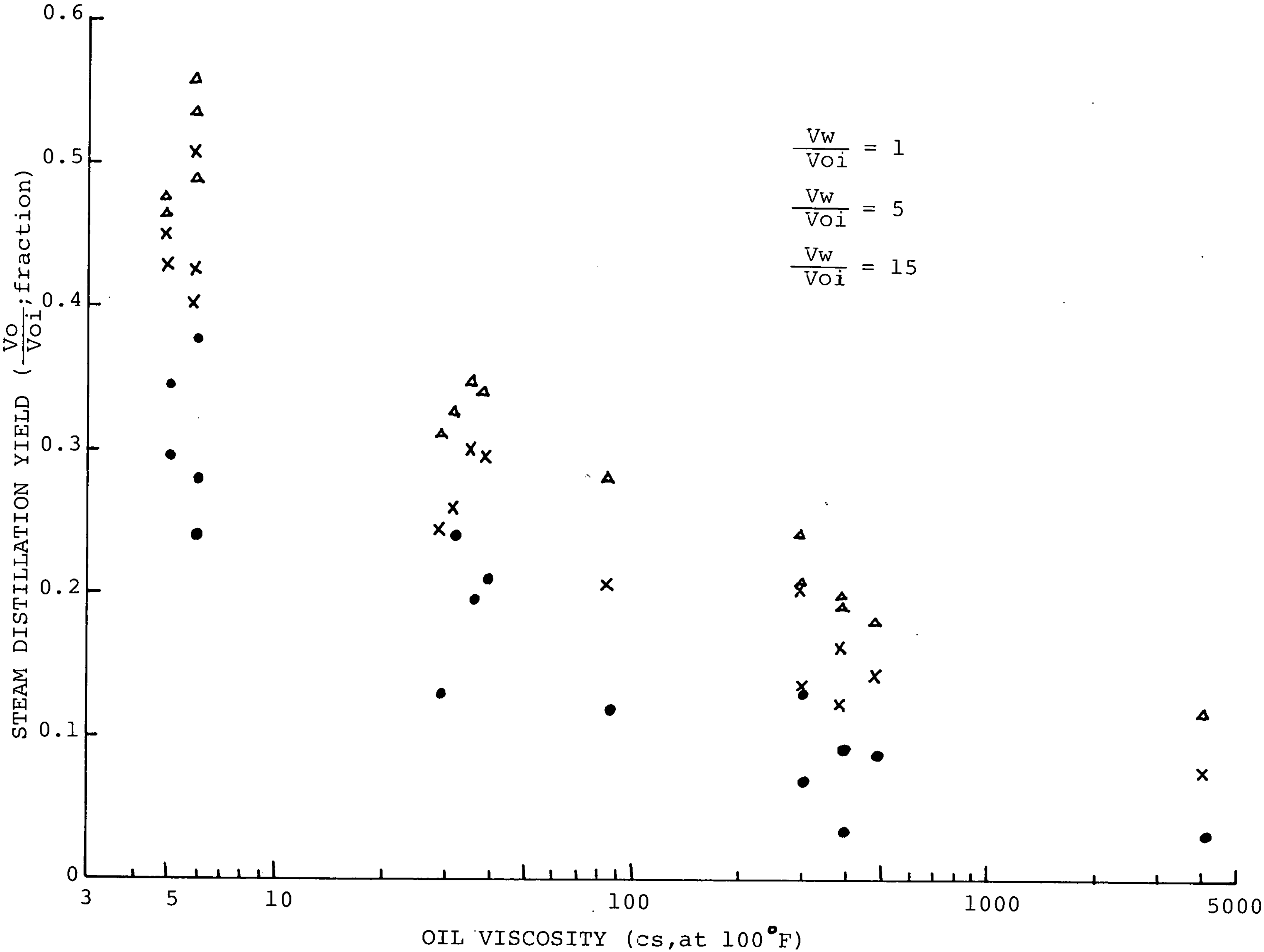


FIGURE 34 REGRESSION ANALYSIS OF STEAM DISTILLATION YIELDS ($\frac{V_w}{V_{oi}} = 15$) VERSUS CRUDE OIL API GRAVITY

FIGURE 35 CORRELATION OF STEAM DISTILLATION YIELDS WITH CRUDE OIL VISCSITY AT 100°F



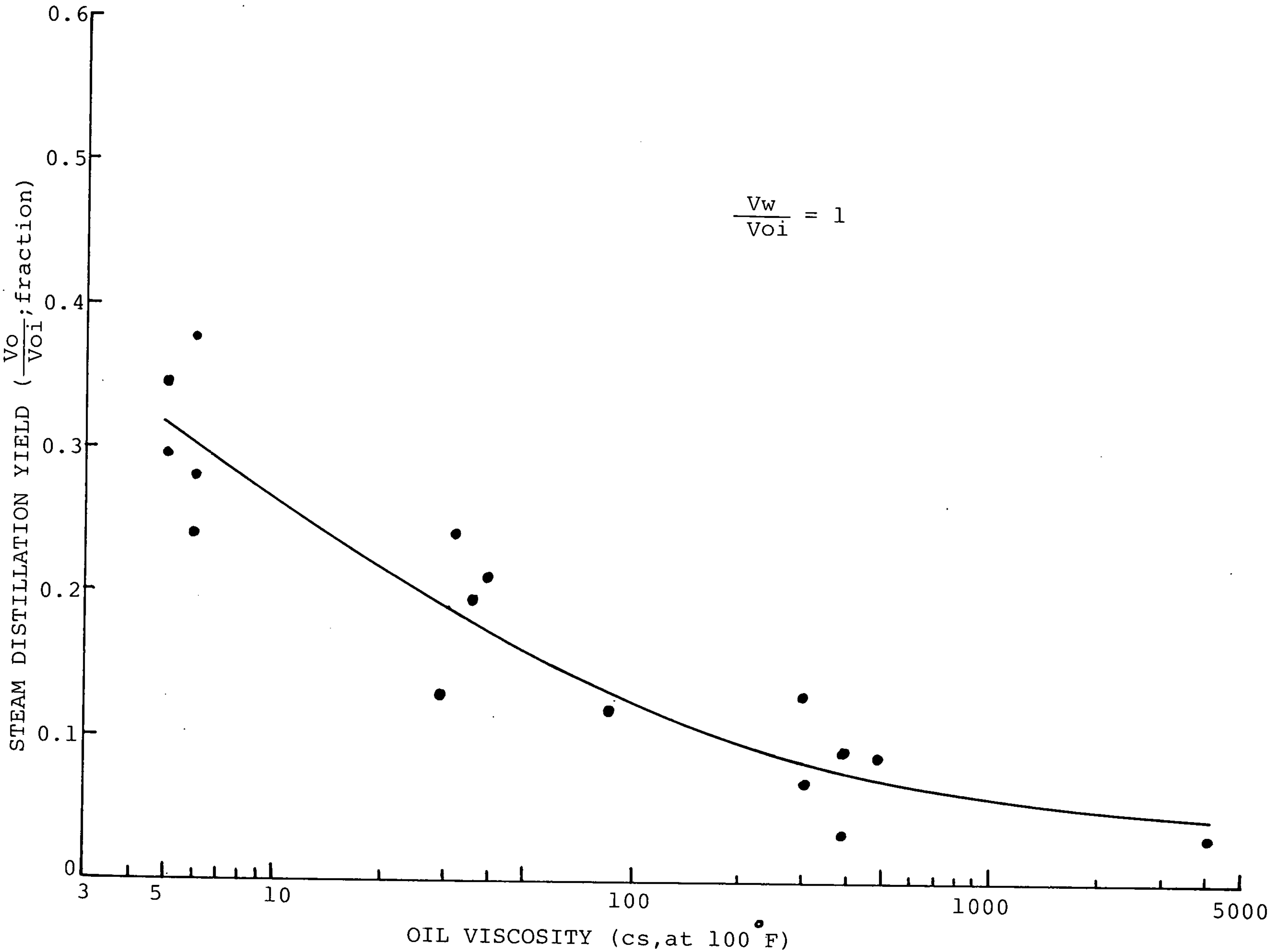
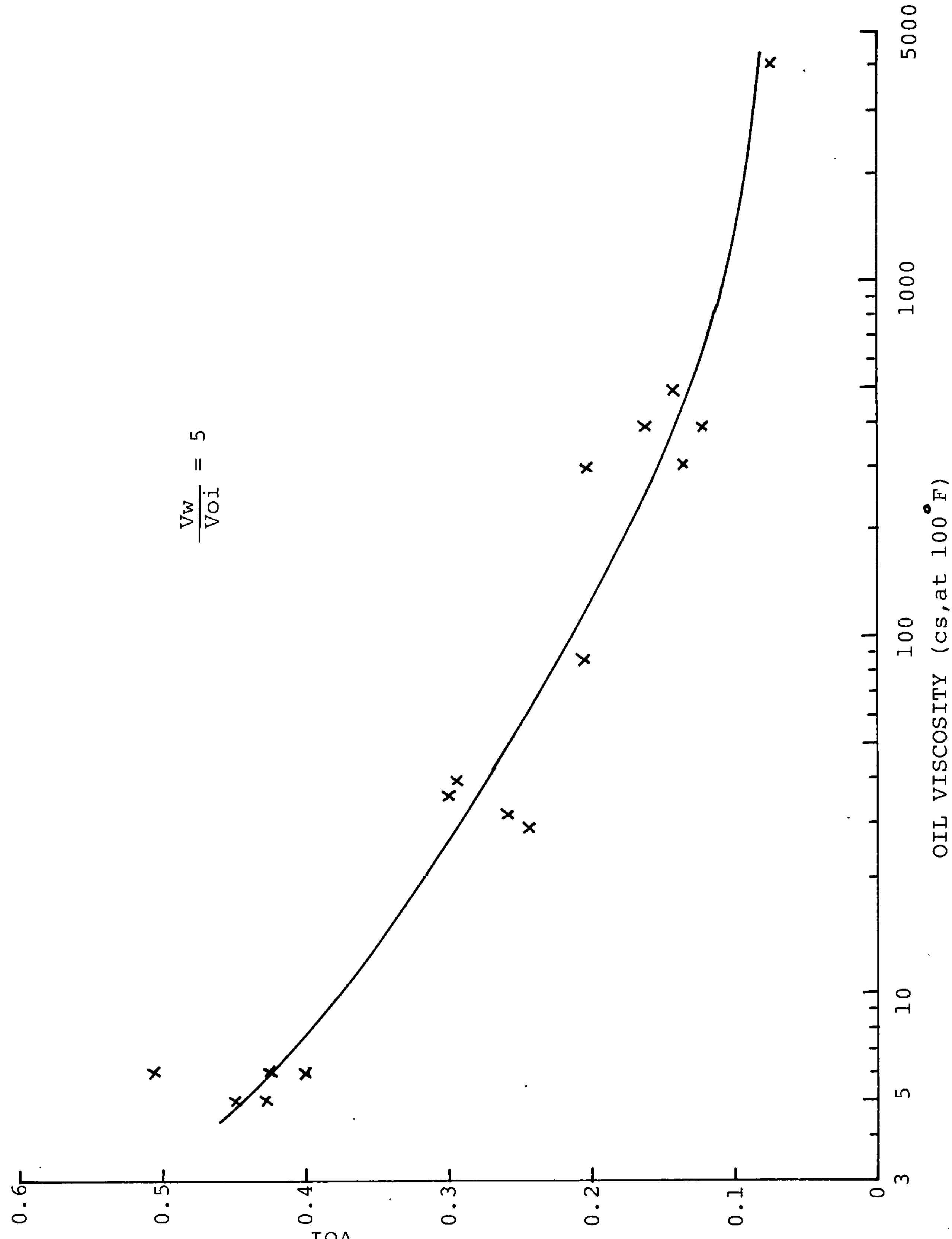


FIGURE 36 REGRESSION ANALYSIS OF STEAM DISTILLATION YIELDS ($\frac{V_w}{V_{oi}} = 1$) VERSUS CRUDE OIL VISCOSITY AT 100°F

FIGURE 37 REGRESSION ANALYSIS OF STEAM DISTILLATION YIELDS $(\frac{V_w}{V_{oi}} = 5)$ VERSUS CRUDE OIL VISCOSITY AT 100°F



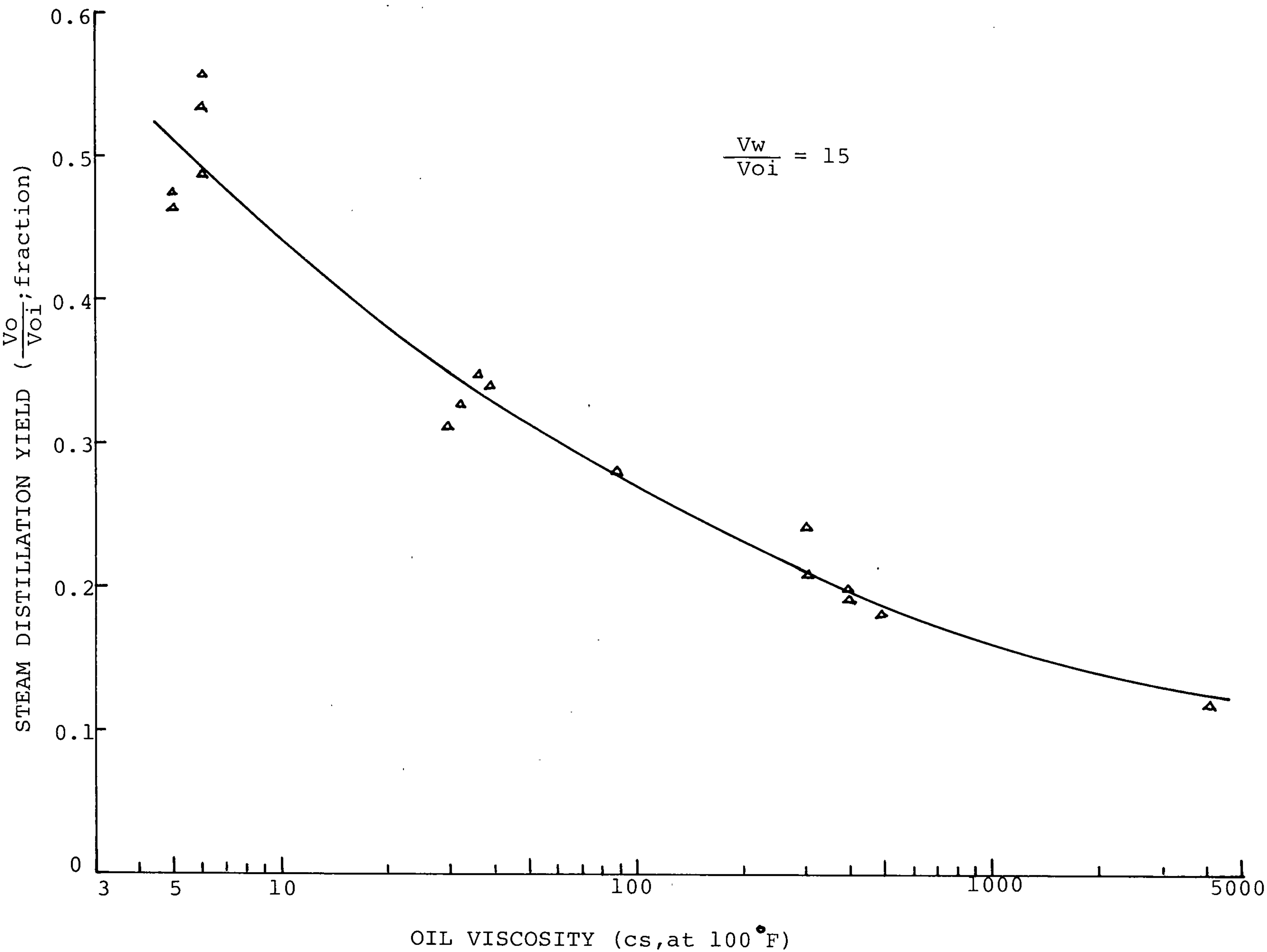


FIGURE 38 REGRESSION ANALYSIS OF STEAM DISTILLATION YIELDS ($\frac{V_w}{V_{oi}}$ = 15) VERSUS CRUDE OIL VISCOSITY AT 100°F

FIGURE 39 REGRESSION ANALYSIS OF STEAM DISTILLATION YIELDS VERSUS CHARACTERIZATION FACTOR

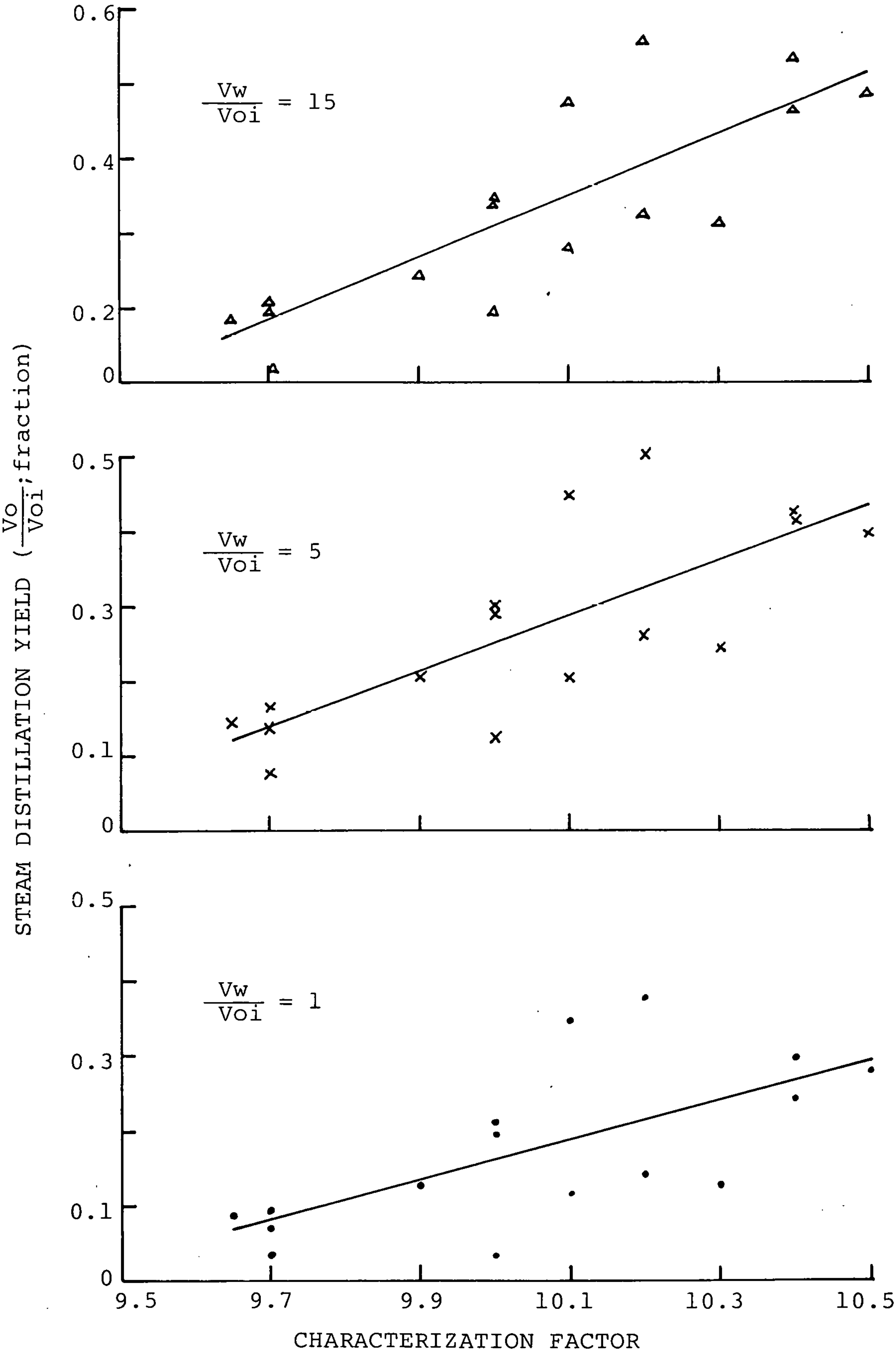


FIGURE 40 REGRESSION ANALYSIS OF STEAM DISTILLATION YIELDS ($\frac{V_w}{V_{oi}}$ = 1, 5 and 15) VERSUS SIMULATED DISTILLATION TEMPERATURES AT 20% YIELD

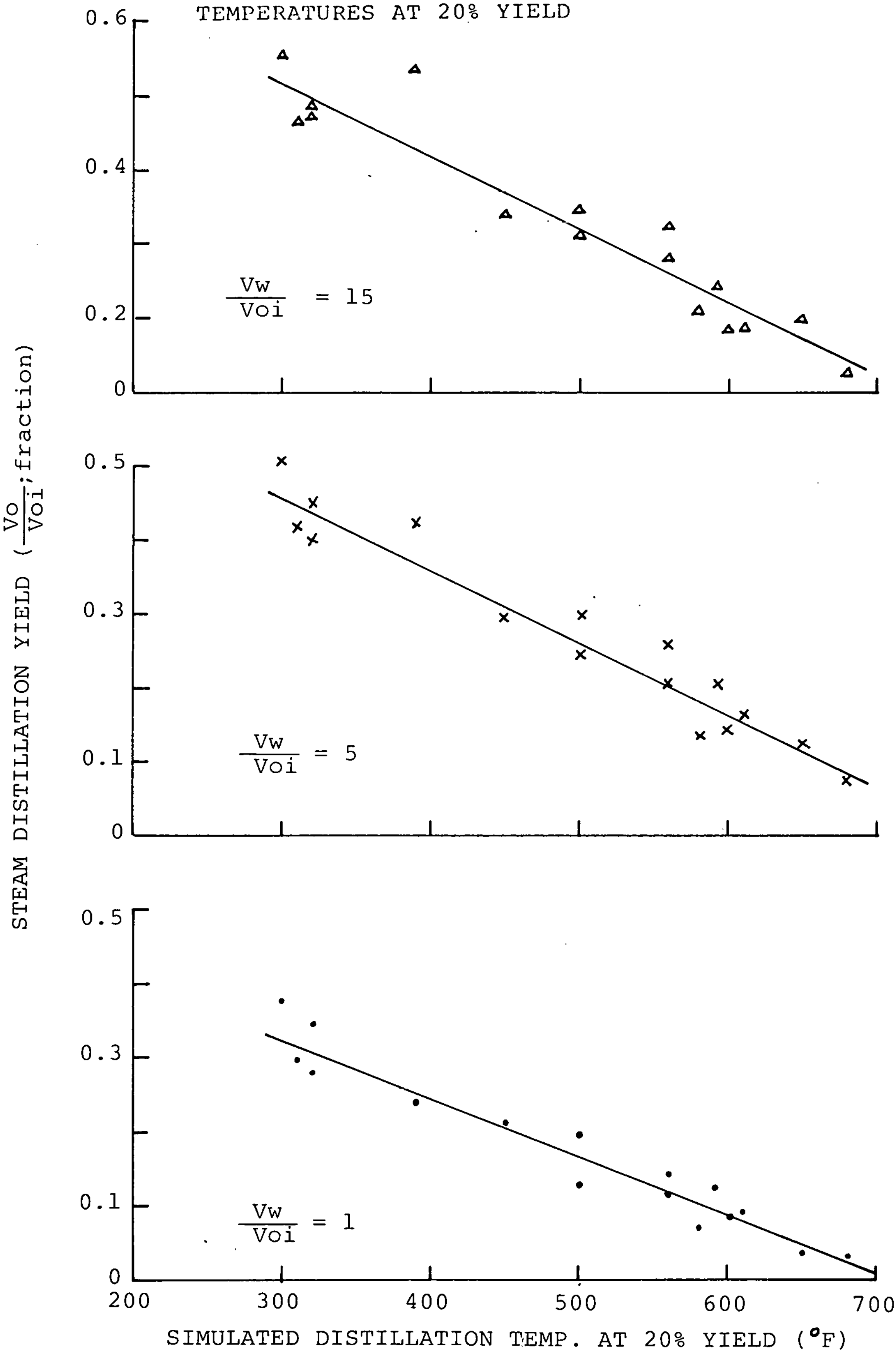


FIGURE 41 REGRESSION ANALYSIS OF STEAM DISTILLATION YIELDS ($\frac{V_w}{V_{oi}}$ = 1, 3, 5, and 15) VERSUS SIMULATED DISTILLATION YIELDS (445, 505, 550, and 600°F)

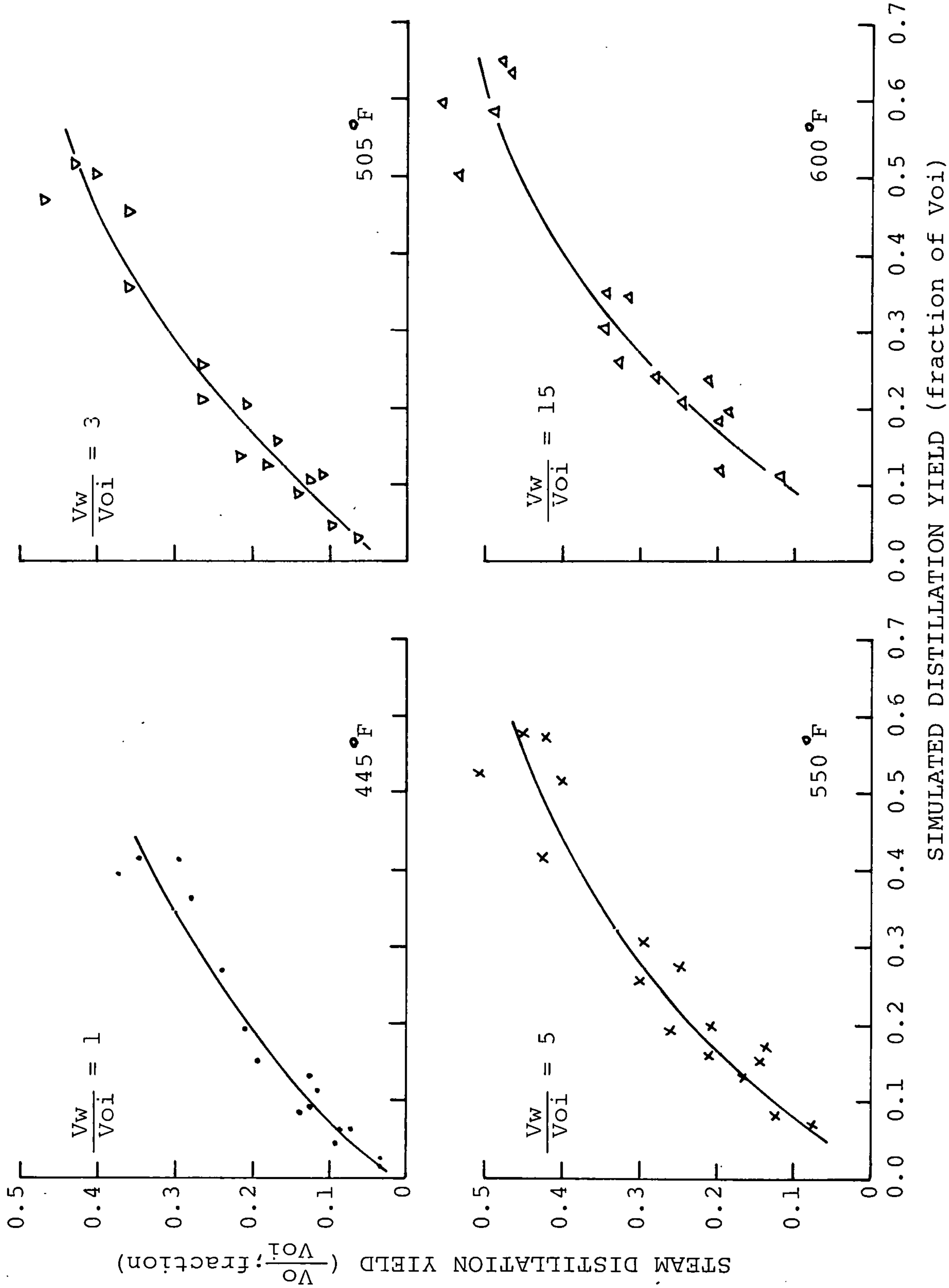


FIGURE 42 PREDICTED STEAM DISTILLATION YIELDS FOR SOUTH BELRIDGE CRUDE OIL

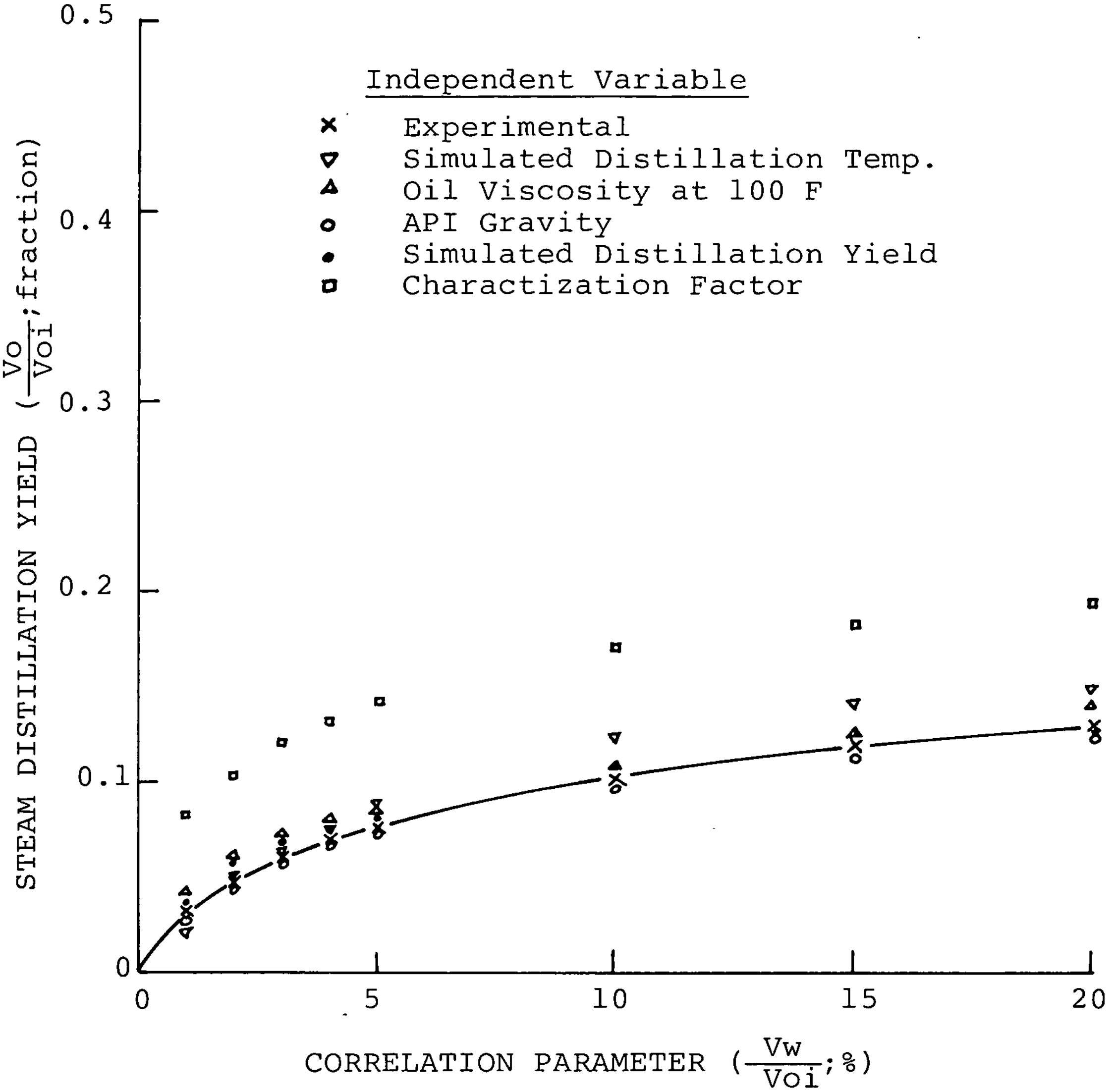


FIGURE 43 PREDICTED STEAM DISTILLATION YIELDS FOR TOBORG CRUDE OIL

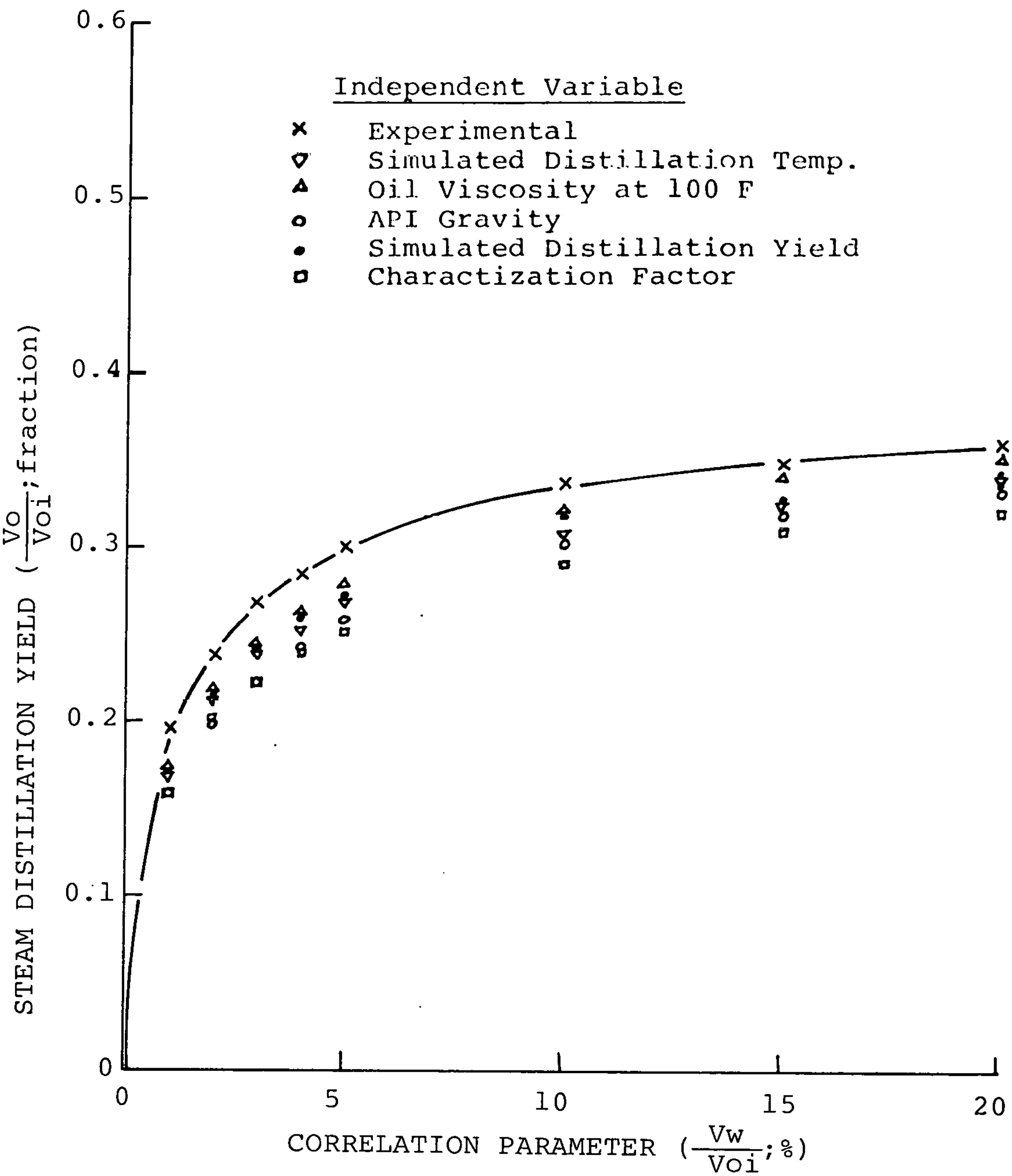


FIGURE 44 PREDICTED STEAM DISTILLATION YIELDS FOR PLUM BUSH CRUDE OIL

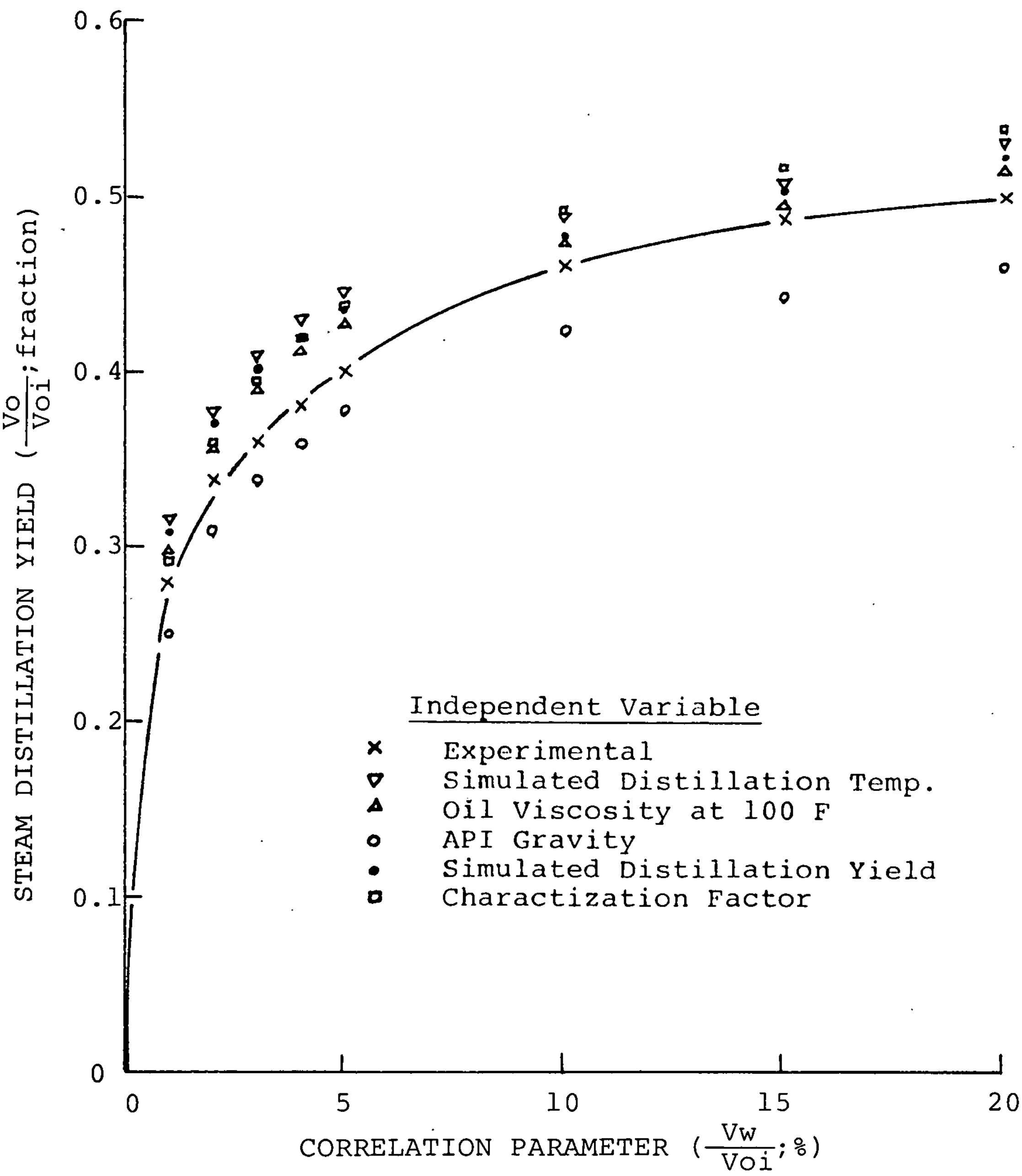
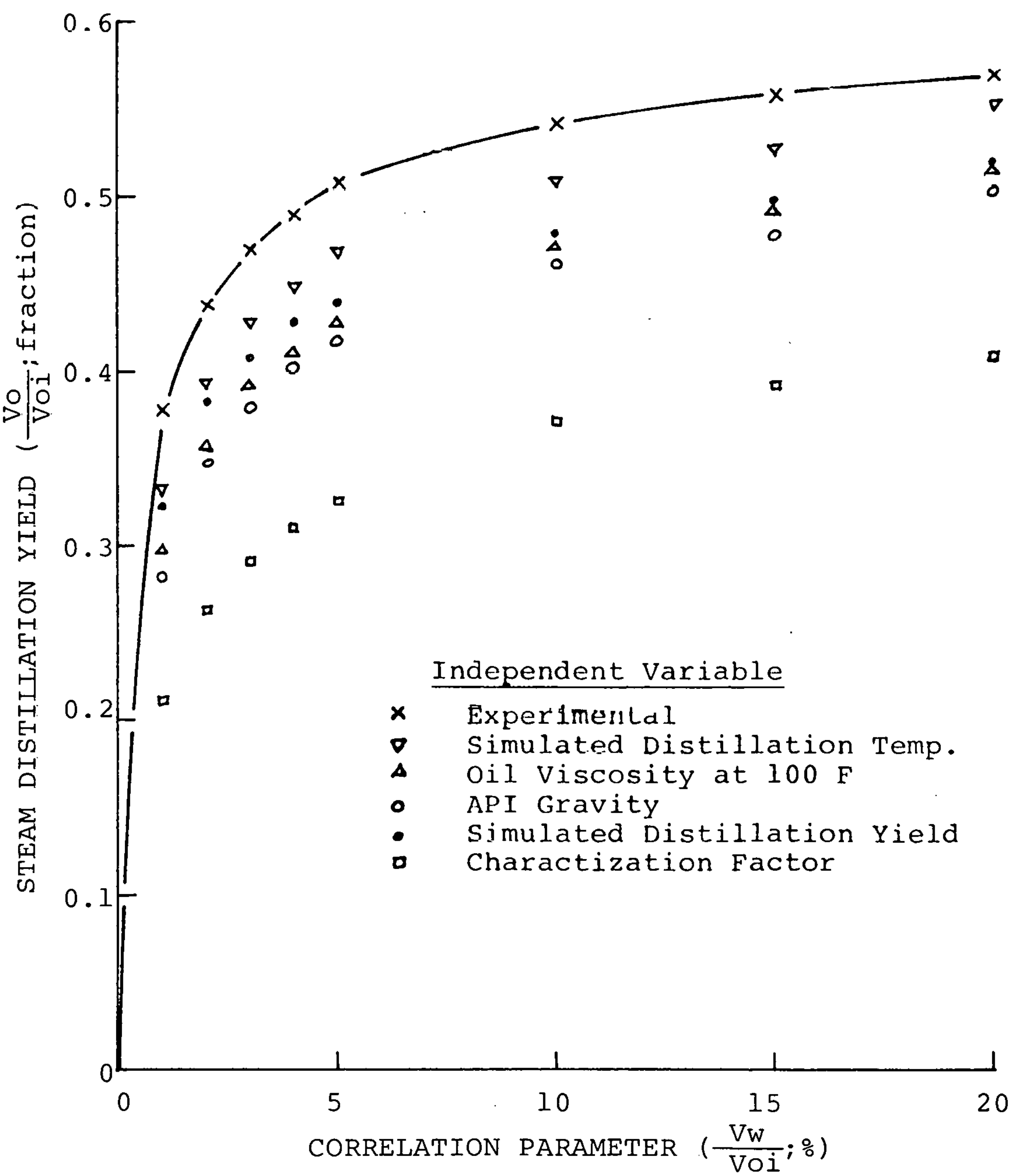


FIGURE 45 PREDICTED STEAM DISTILLATION YIELDS FOR SHIELLS CANYON CRUDE OIL



APPENDIX A CRUDE OIL VISCOSITIES AND SIMULATED DISTILLATION YIELDS

FIGURE A1-A4 CRUDE OIL VISCOSITIES

FIGURE A5-A20 SIMULATED DISTILLATION YIELDS

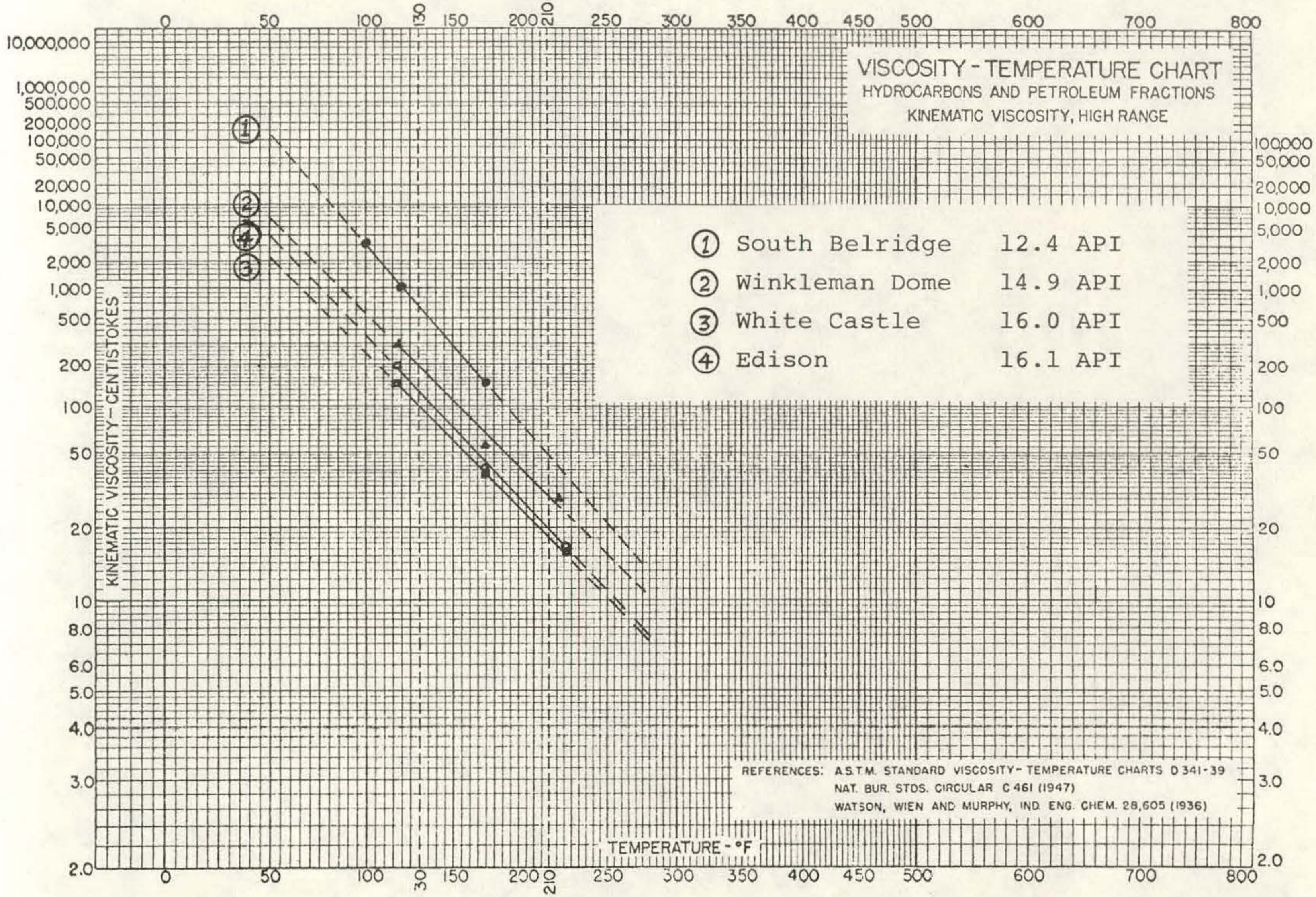


FIGURE A1 KINEMATIC VISCOSITY:12.4-16.1 API

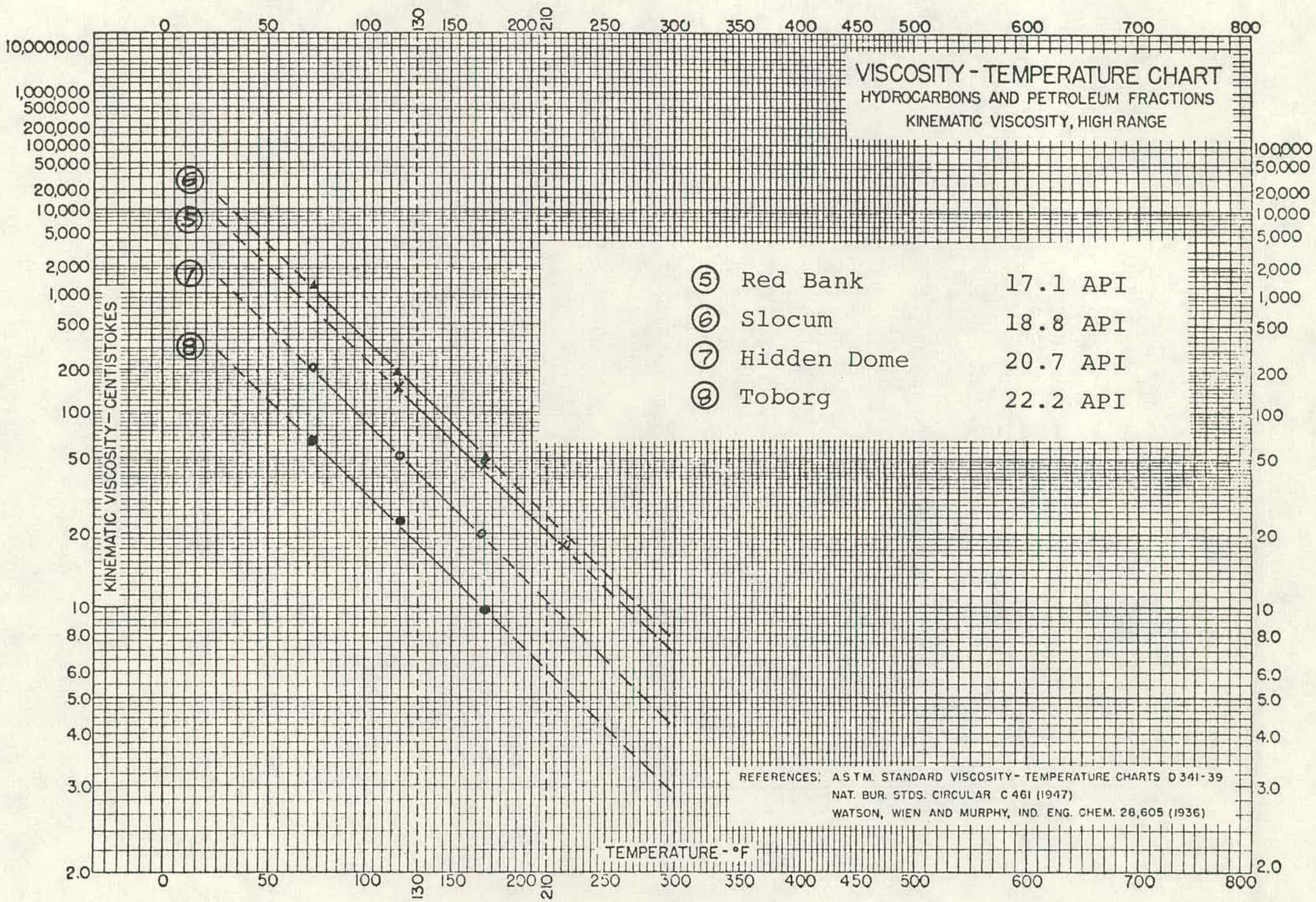


FIGURE A2 KINEMATIC VISCOSITY:17.1-22.2 API

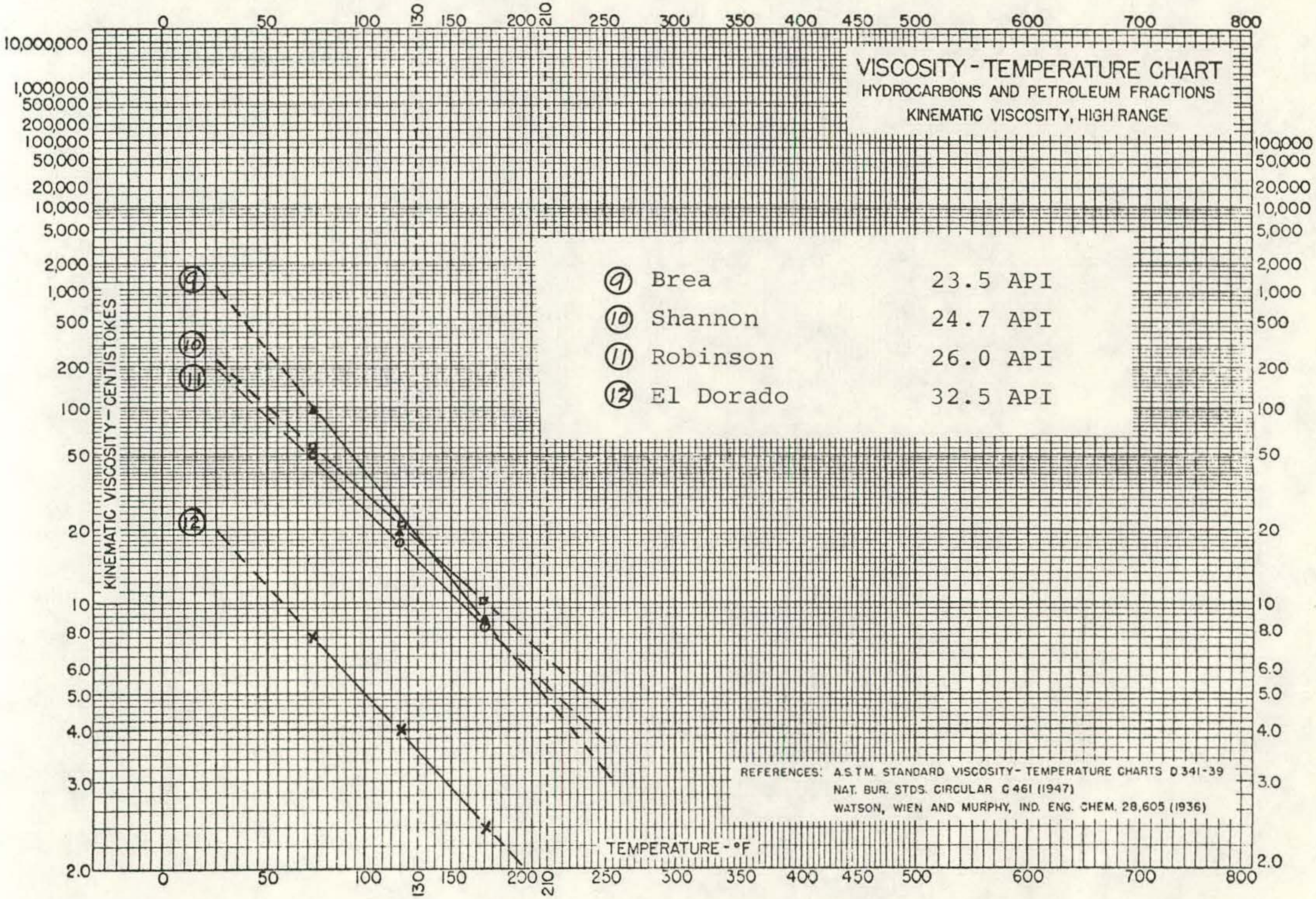


FIGURE A3 KINEMATIC VISCOSITY:23.5-32.5 API

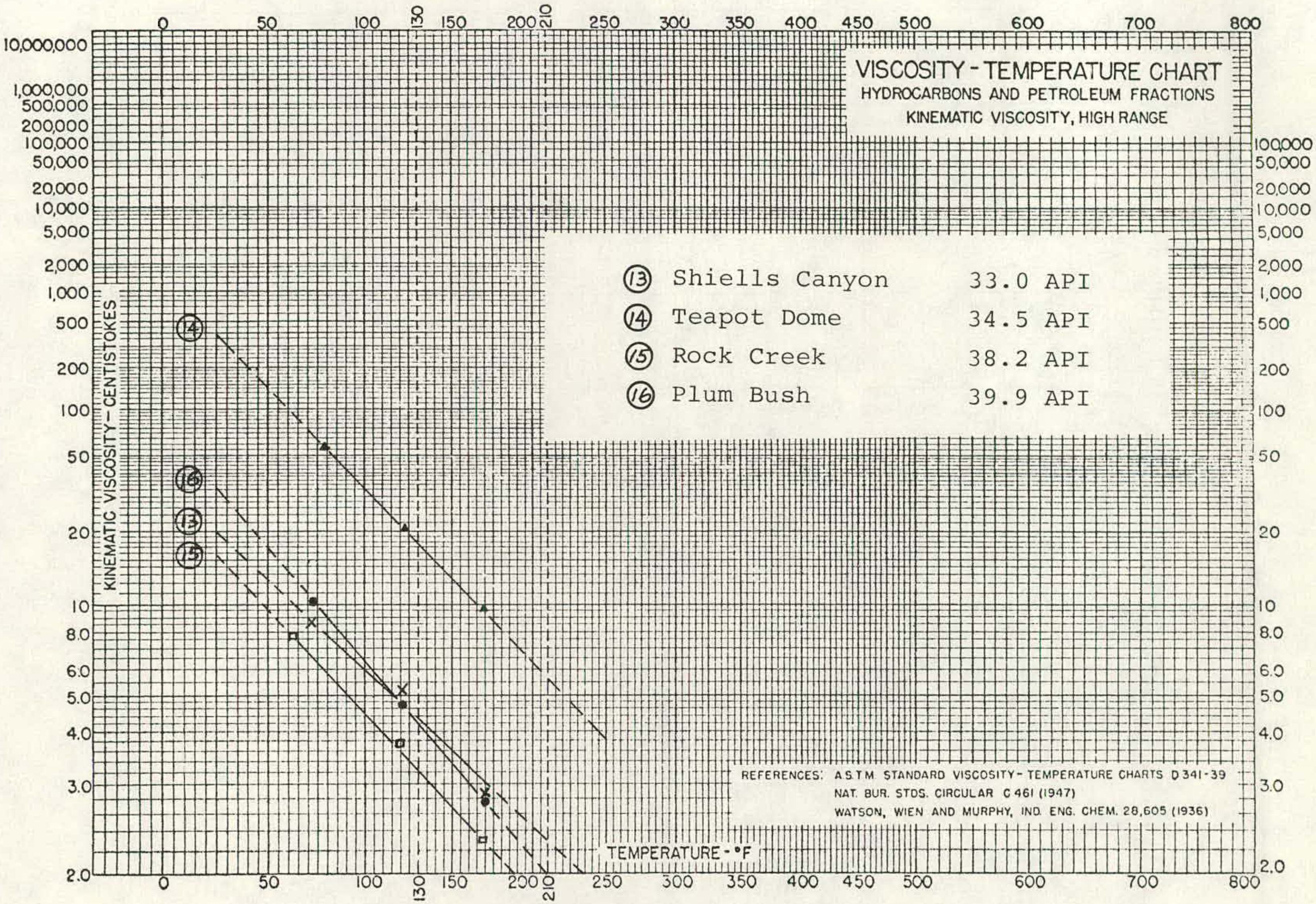


FIGURE A4 KINEMATIC VISCOSITY:33.0-39.9 API

FIGURE A5

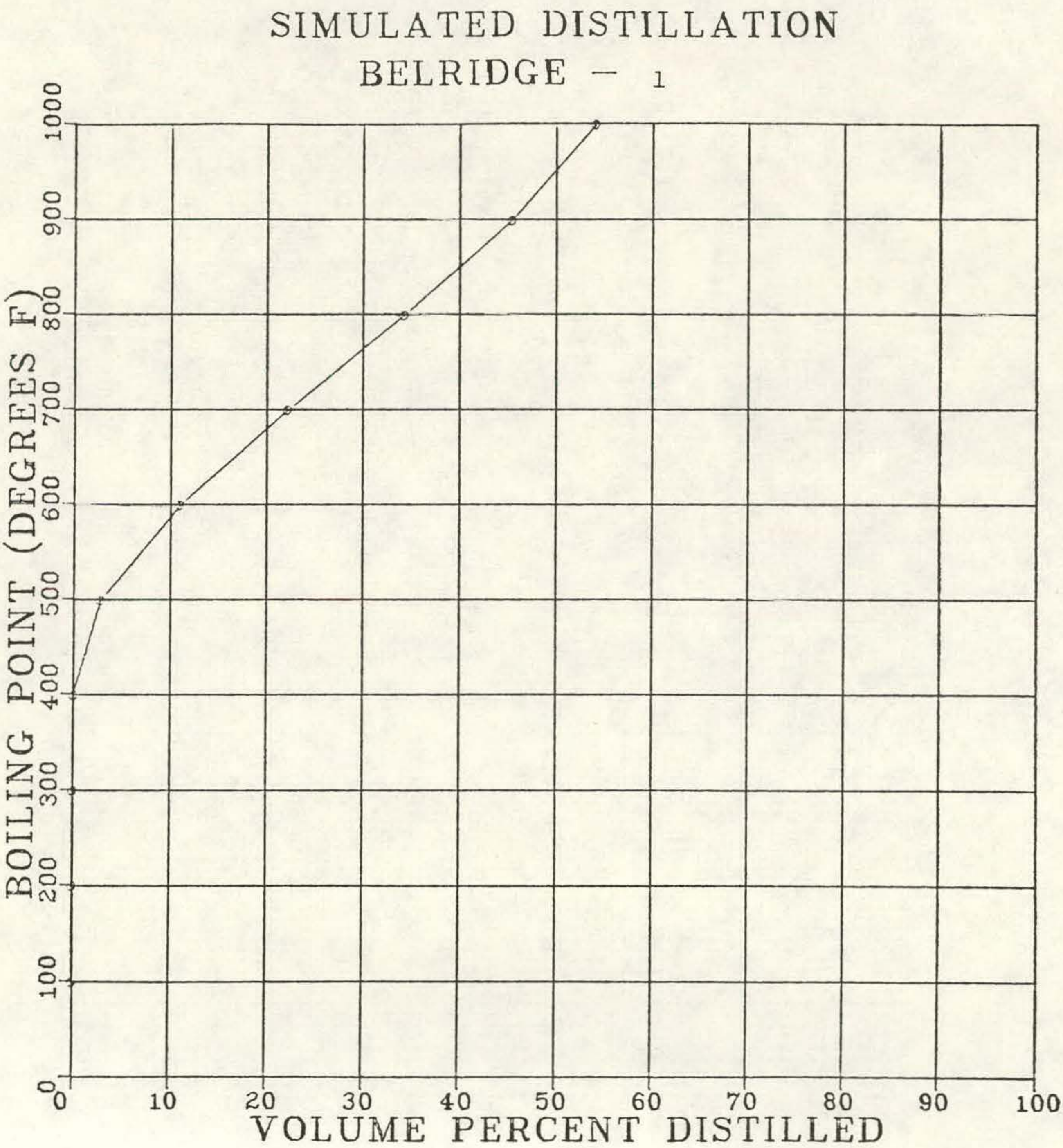

SIMULATED DISTILLATION
BELRIDGE - 1
BOILING POINT (DEGREES F)
0
100
200
300
400
500
600
700
800
900
1000
0
10
20
30
40
50
60
70
80
90
100
VOLUME PERCENT DISTILLED

FIGURE A6

SIMULATED DISTILLATION
WINKLEMAN DOME — 2

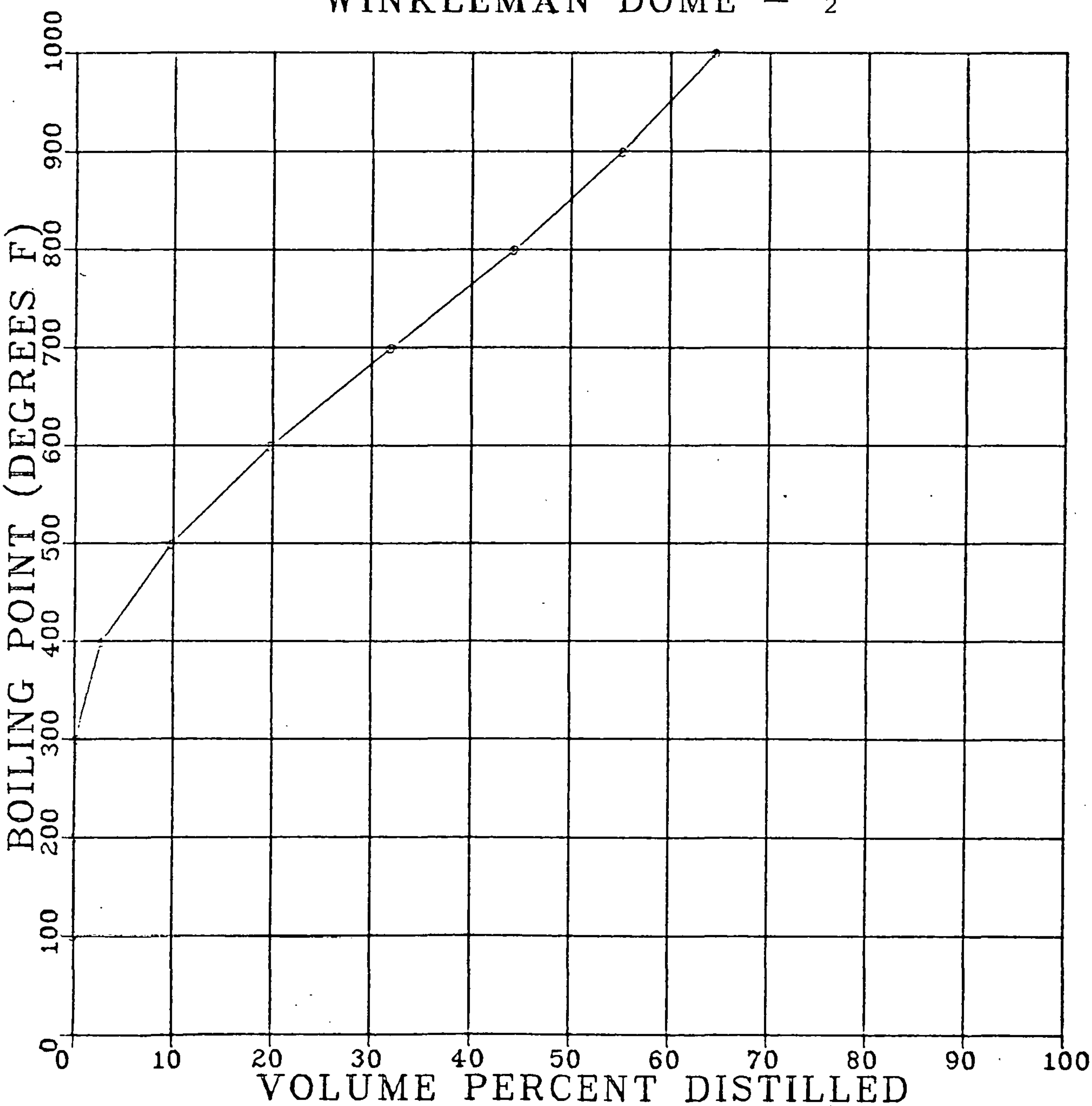


FIGURE A7

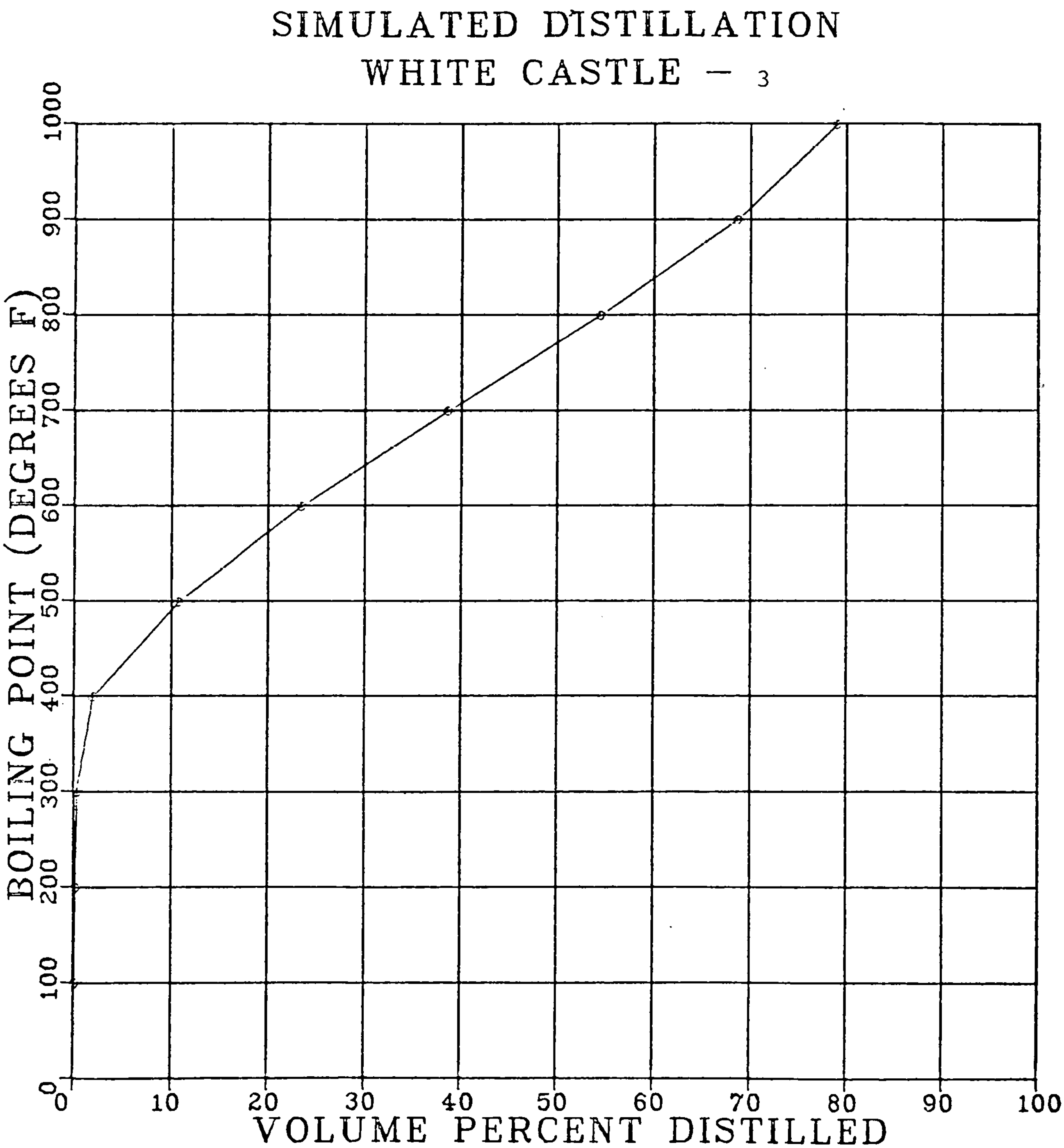

SIMULATED DISTILLATION
WHITE CASTLE - 3
BOILING POINT (DEGREES F)
0
100
200
300
400
500
600
700
800
900
1000
0
10
20
30
40
50
60
70
80
90
100
VOLUME PERCENT DISTILLED

FIGURE A8

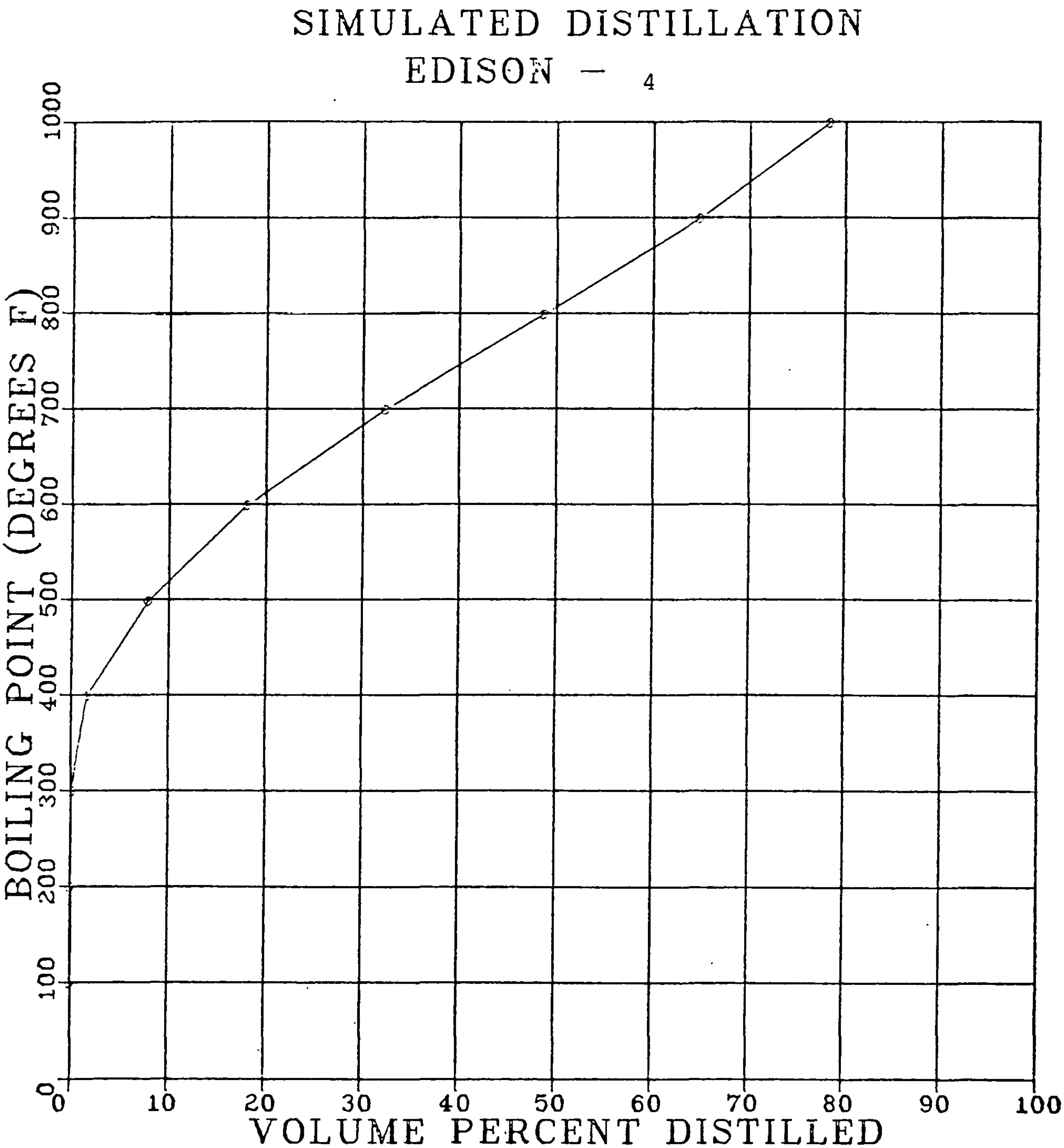

SIMULATED DISTILLATION
EDISON — 4
BOILING POINT (DEGREES F)
0
100
200
300
400
500
600
700
800
900
1000
0
10
20
30
40
50
60
70
80
90
100
VOLUME PERCENT DISTILLED

FIGURE A9

SIMULATED DISTILLATION
RED BANK — 5

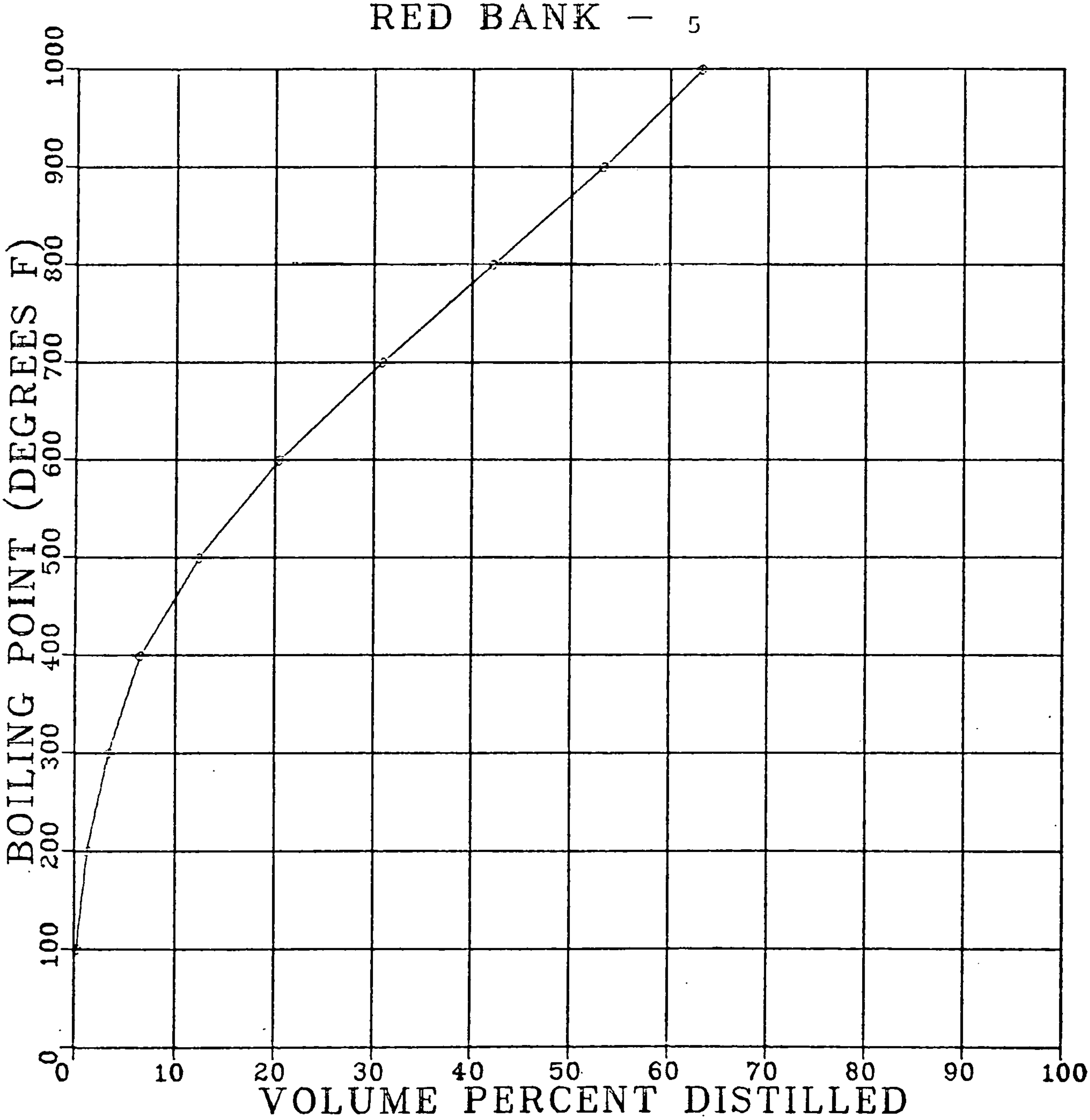
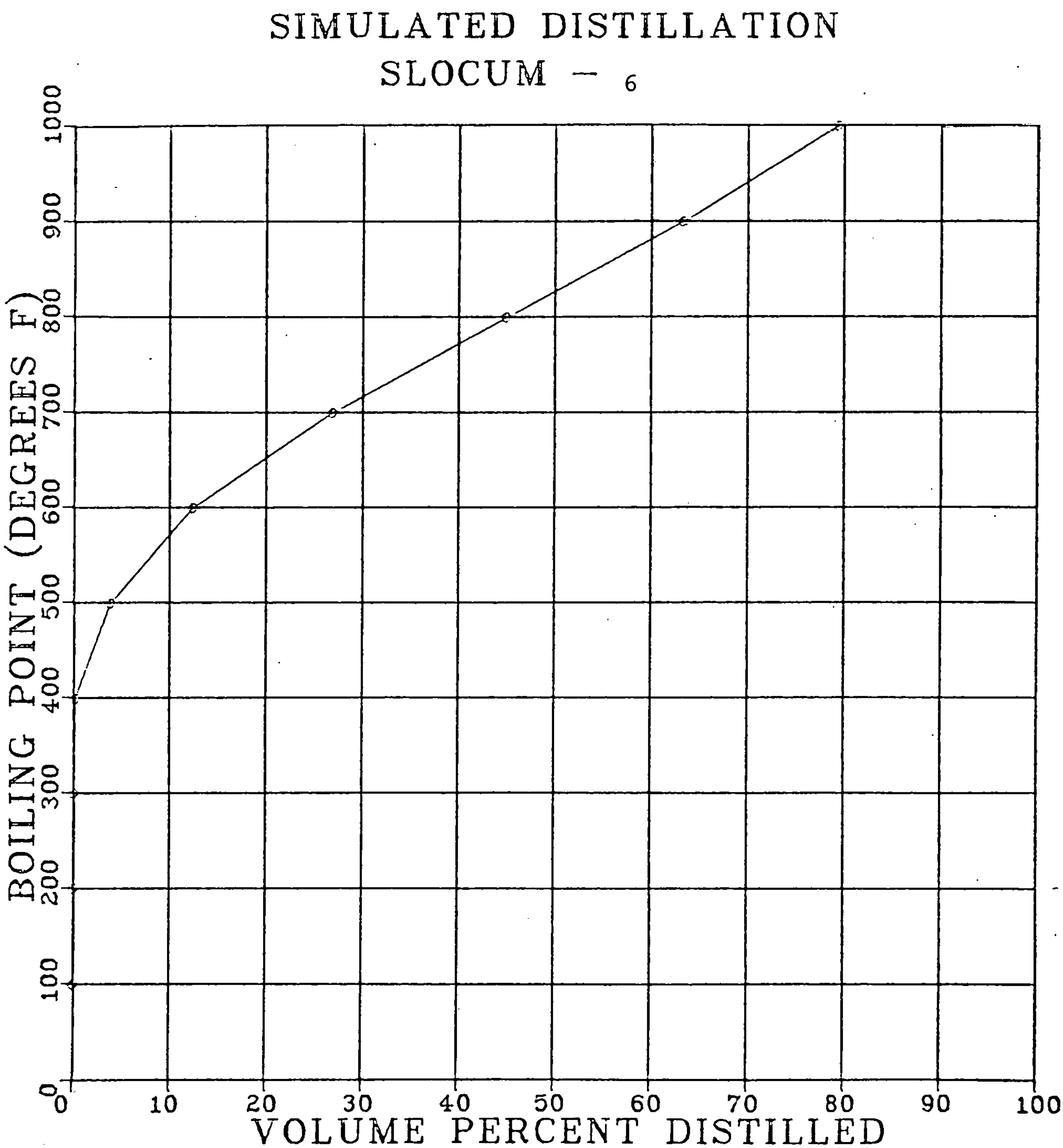


FIGURE A10



SIMULATED DISTILLATION
SLOCUM - 6
BOILING POINT (DEGREES F)
0
100
200
300
400
500
600
700
800
900
1000
0
10
20
30
40
50
60
70
80
90
100
VOLUME PERCENT DISTILLED

FIGURE A11

SIMULATED DISTILLATION
HIDDEN DOME — 7

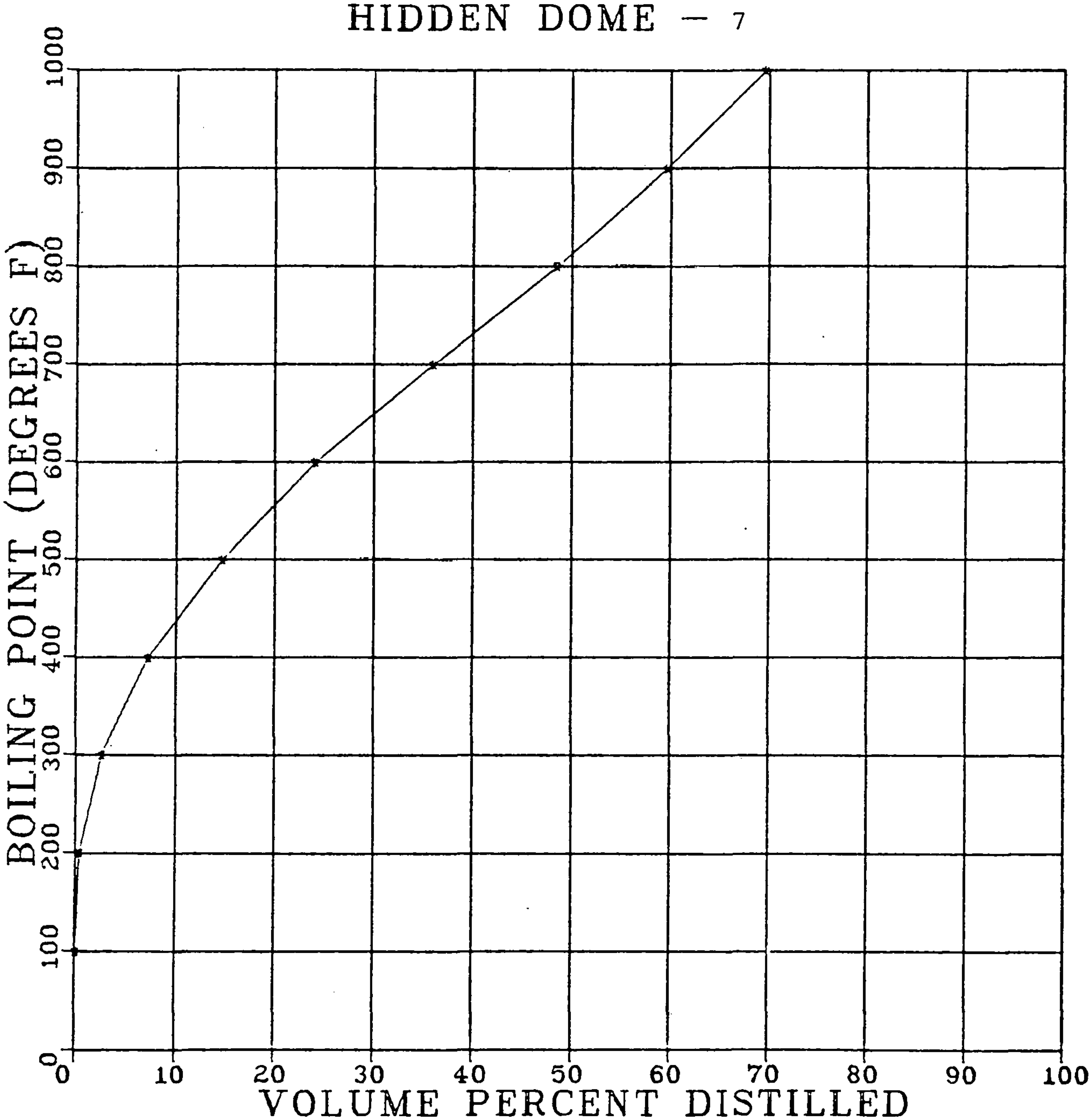


FIGURE A12

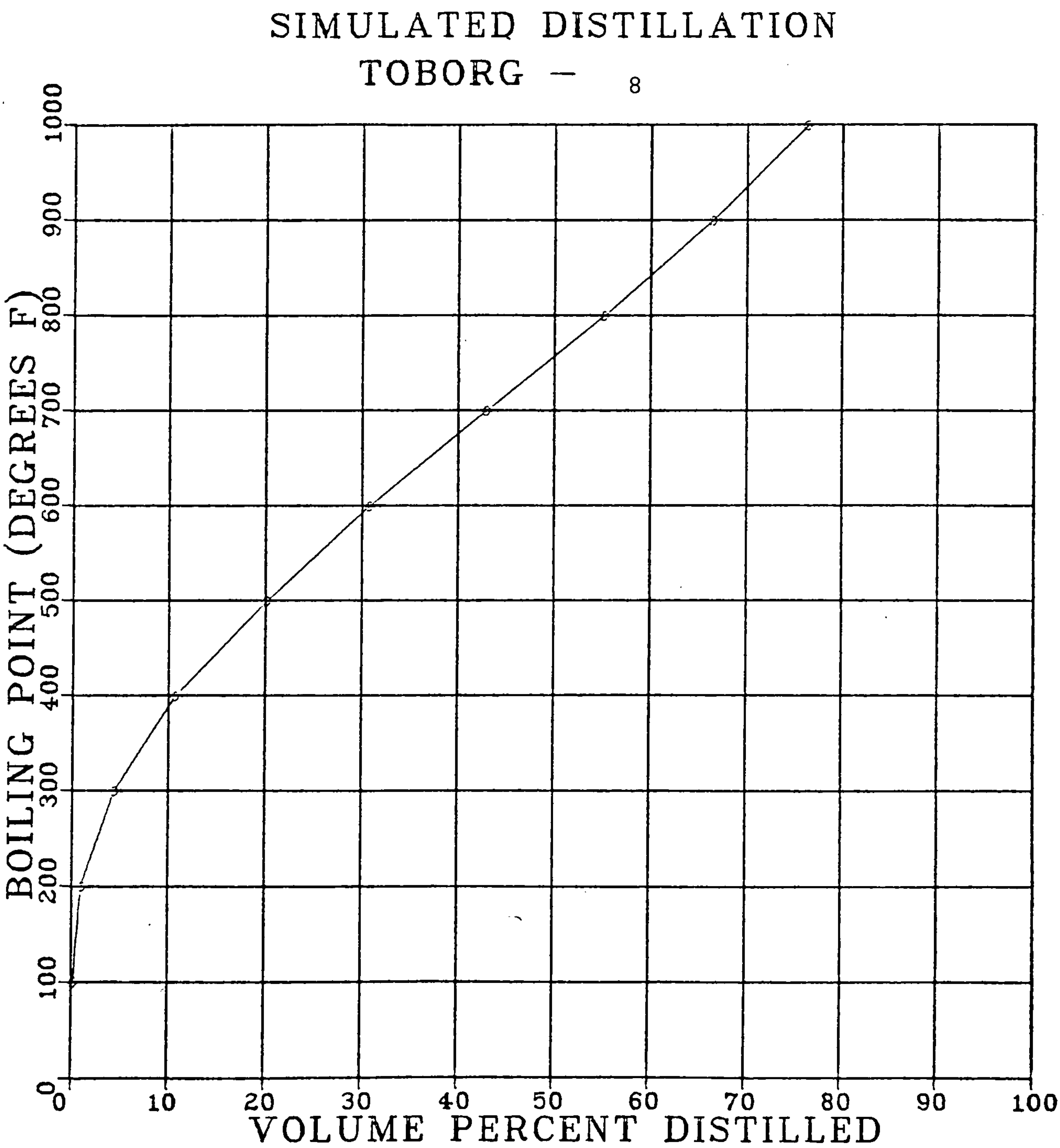

SIMULATED DISTILLATION
TOBORG — 8
BOILING POINT (DEGREES F)
0
100
200
300
400
500
600
700
800
900
1000
0
10
20
30
40
50
60
70
80
90
100
VOLUME PERCENT DISTILLED

FIGURE A13

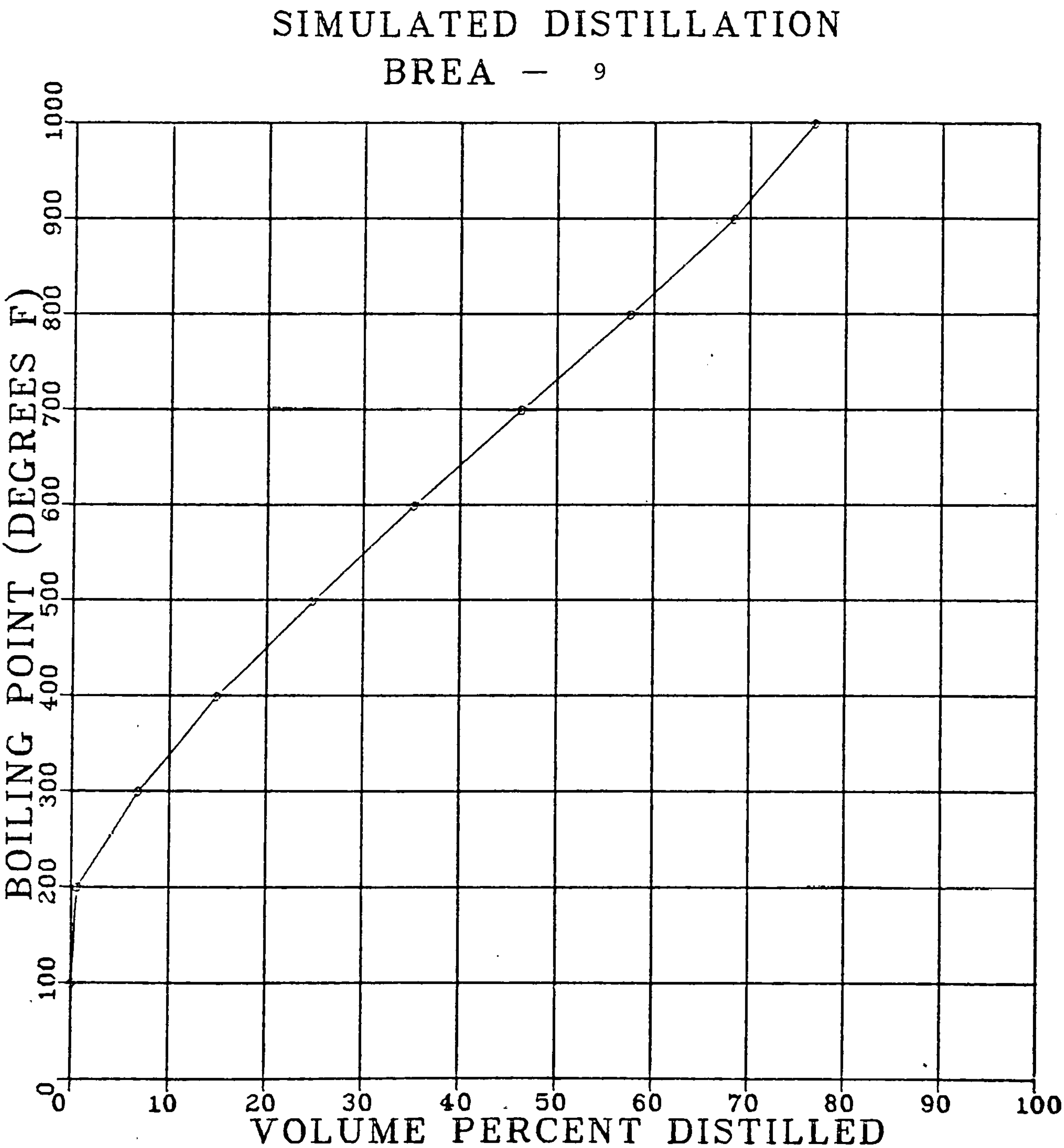

SIMULATED DISTILLATION
BREA — 9
BOILING POINT (DEGREES F)
0
100
200
300
400
500
600
700
800
900
1000
0
10
20
30
40
50
60
70
80
90
100
VOLUME PERCENT DISTILLED

FIGURE A14

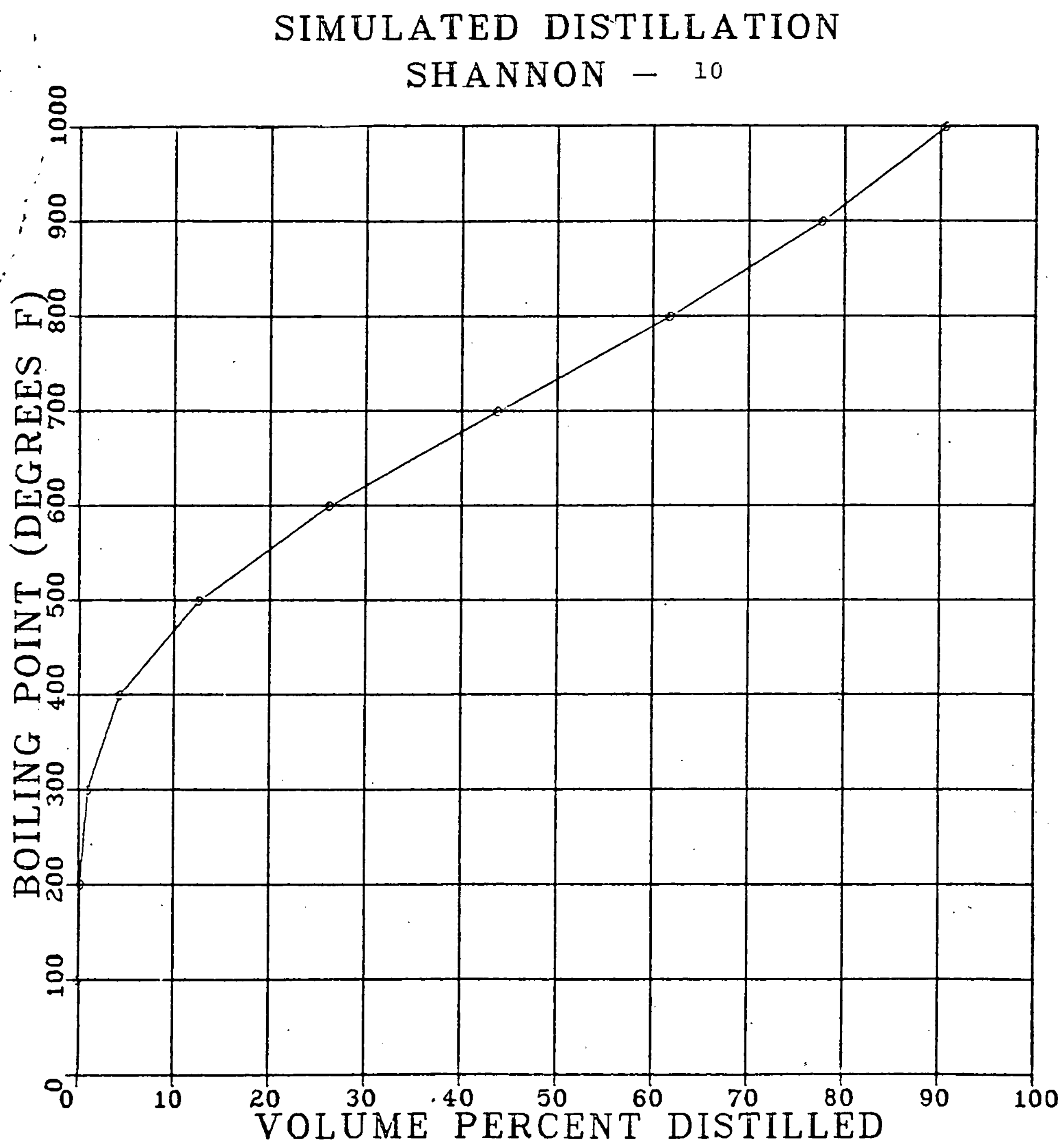

SIMULATED DISTILLATION
SHANNON — 10
BOILING POINT (DEGREES F)
0
100
200
300
400
500
600
700
800
900
1000
0
10
20
30
40
50
60
70
80
90
100
VOLUME PERCENT DISTILLED

FIGURE A15

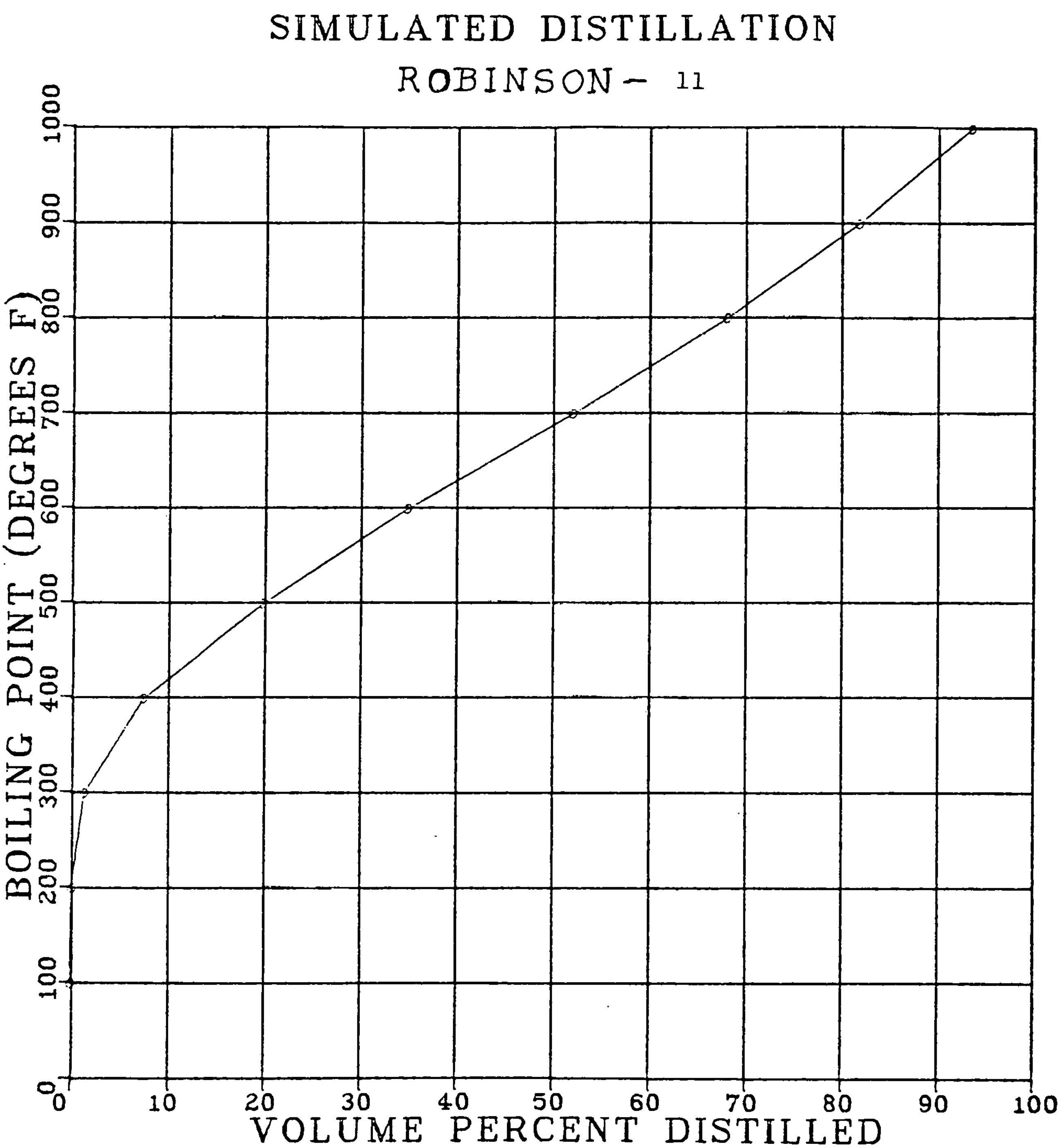

SIMULATED DISTILLATION
ROBINSON- 11
BOILING POINT (DEGREES F)
0
100
200
300
400
500
600
700
800
900
1000
0
10
20
30
40
50
60
70
80
90
100
VOLUME PERCENT DISTILLED

FIGURE A16

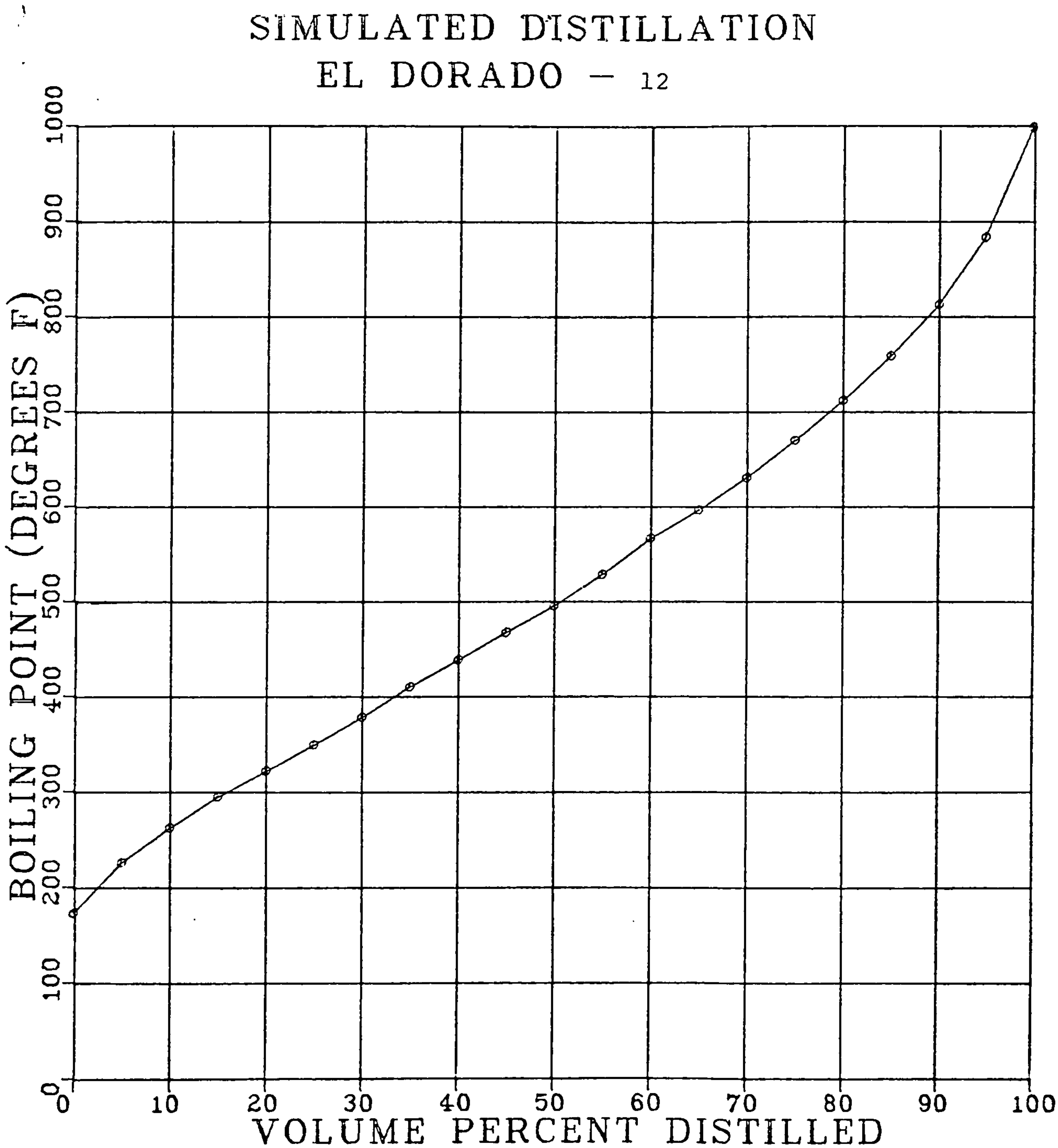

SIMULATED DISTILLATION
EL DORADO - 12
BOILING POINT (DEGREES F)
0
100
200
300
400
500
600
700
800
900
1000
0
10
20
30
40
50
60
70
80
90
100
VOLUME PERCENT DISTILLED

FIGURE A17

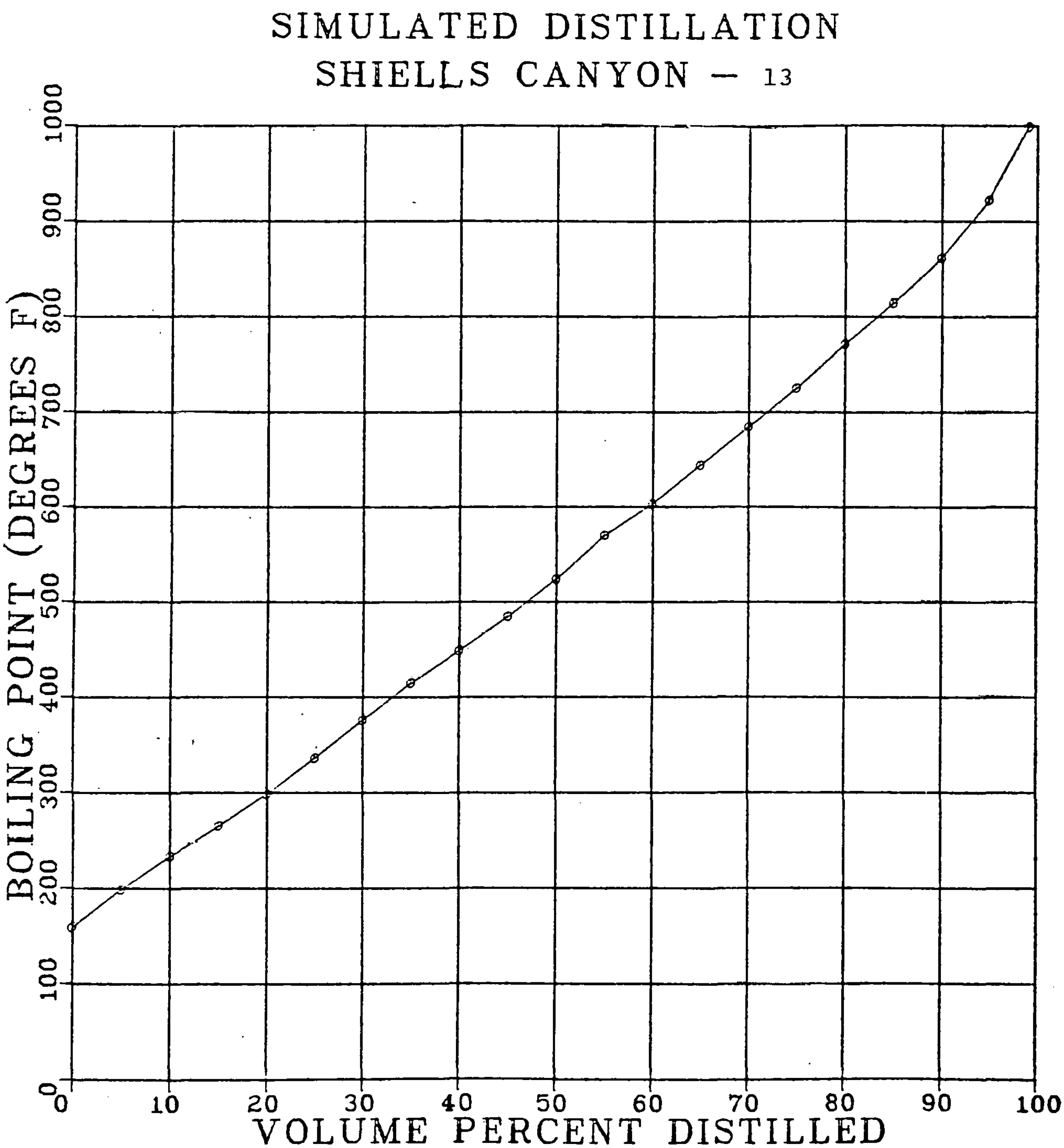

SIMULATED DISTILLATION
SHIELLS CANYON — 13
BOILING POINT (DEGREES F)
0
100
200
300
400
500
600
700
800
900
1000
0
10
20
30
40
50
60
70
80
90
100
VOLUME PERCENT DISTILLED

FIGURE A18

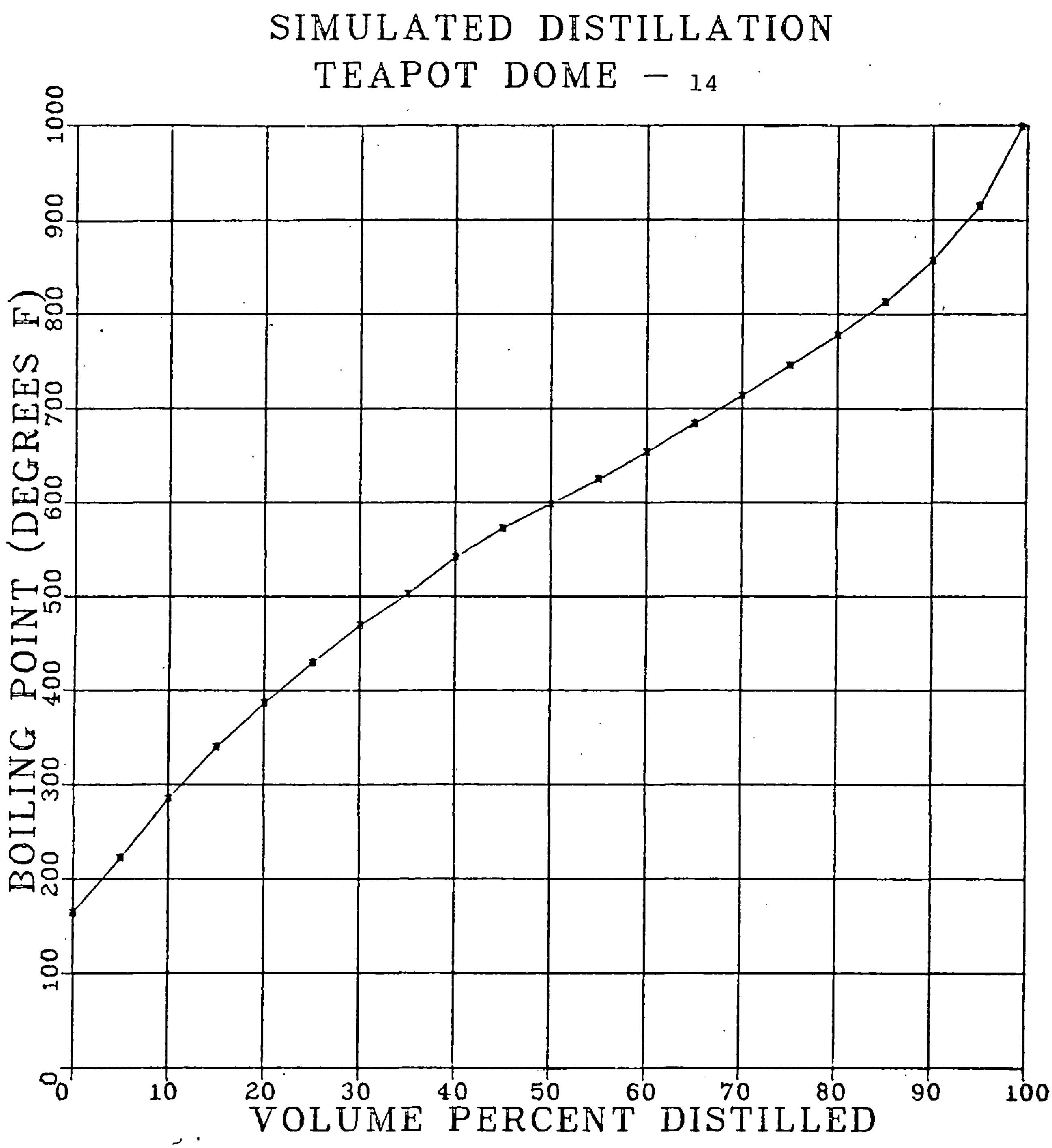
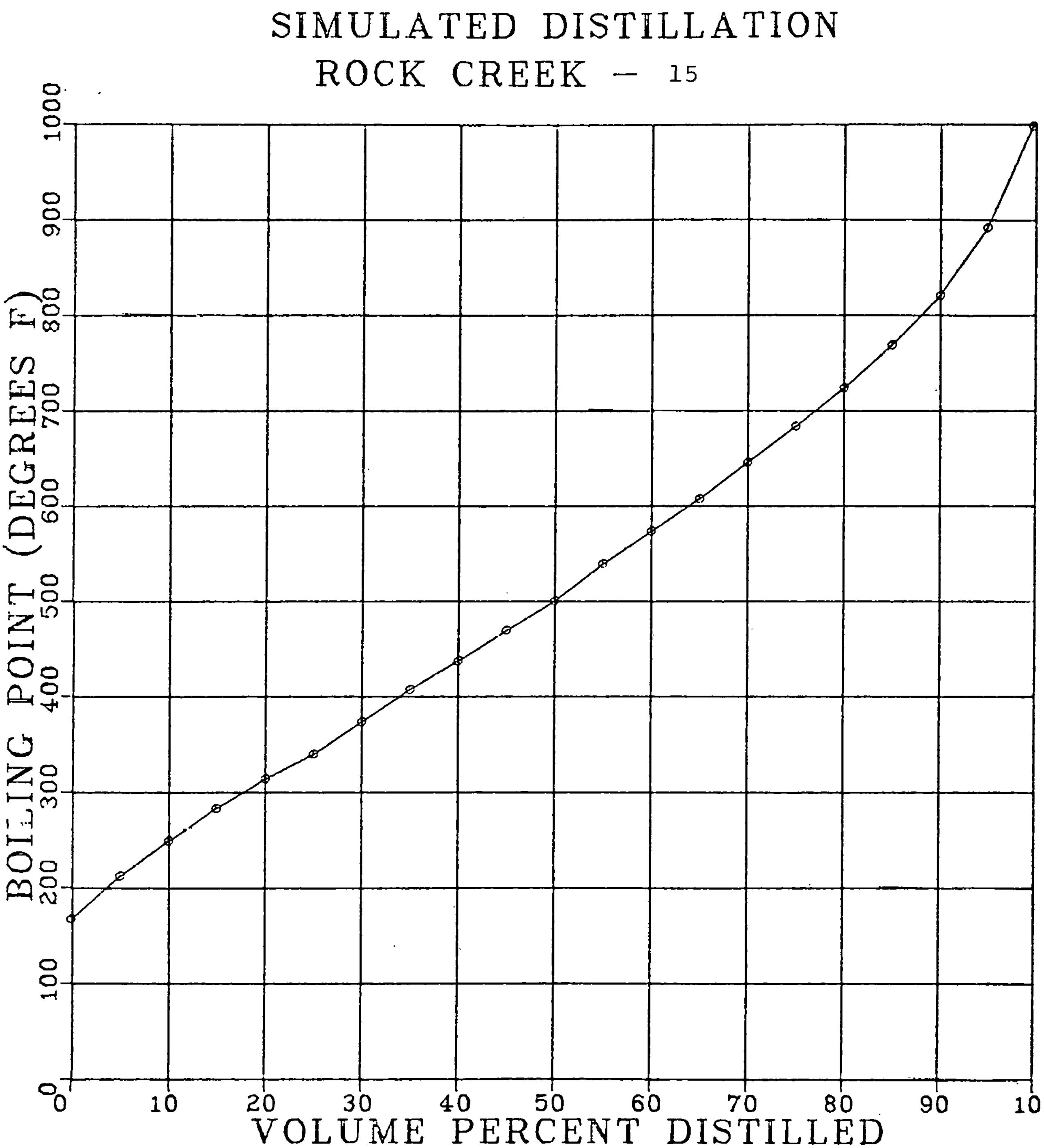
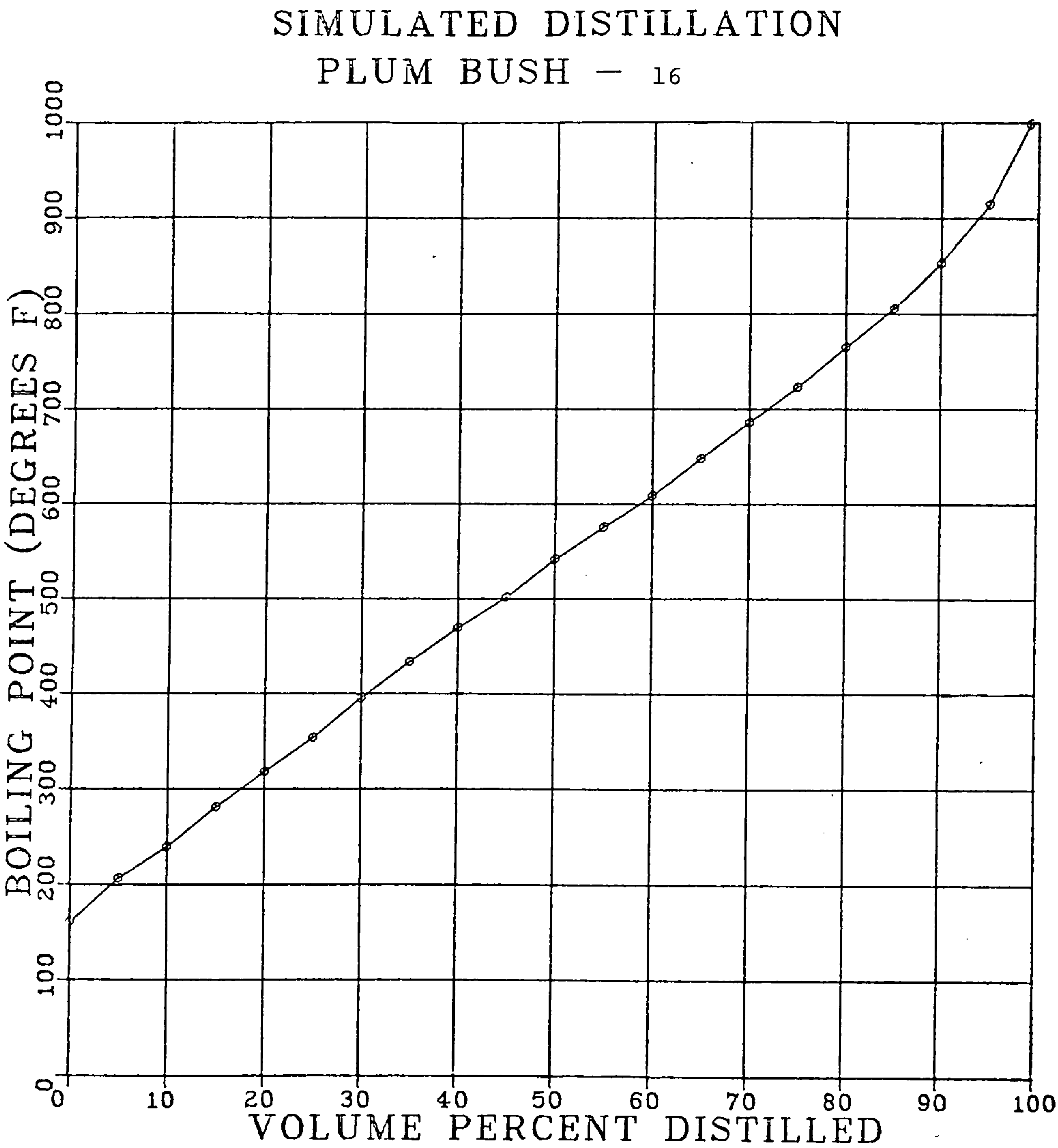

SIMULATED DISTILLATION
TEAPOT DOME – 14
BOILING POINT (DEGREES F)
0
100
200
300
400
500
600
700
800
900
1000
0
10
20
30
40
50
60
70
80
90
100
VOLUME PERCENT DISTILLED

FIGURE A19



SIMULATED DISTILLATION
ROCK CREEK — 15
BOILING POINT (DEGREES F)
0
100
200
300
400
500
600
700
800
900
1000
0
10
20
30
40
50
60
70
80
90
100
VOLUME PERCENT DISTILLED

FIGURE A20


SIMULATED DISTILLATION
PLUM BUSH — 16
BOILING POINT (DEGREES F)
0
100
200
300
400
500
600
700
800
900
1000
0
10
20
30
40
50
60
70
80
90
100
VOLUME PERCENT DISTILLED

APPENDIX B SIMULATED DISTILLATION PROCEDURE

To further characterize the oil samples, simulated distillation is performed on all samples. The simulated distillation is done on a gas chromatograph to simulate true boiling point distillation. Results of the simulated distillation appear in Figure A5 to A20 in Appendix A.

The method by which the samples are treated is different depending on the distillability of the sample. The samples are categorized according to its total distillability at 1,000°F. Preparation of samples and analysis of results are outlined below.

Samples Not Totally Distillable at 1,000°F

The sample is first prepared in a solution of carbon disulfide (approximately 0.1 gm of oil per ml of solution). This is done by weighing and recording approximately 0.1 gm of oil, then adding some carbon disulfide and allowing the solvent to dissolve the oil for about 10 minutes. The remaining solvent is then added to make up a solution of 1 ml. The solution is tranferred to a vial which can be sealed air tight. The same procedure is repeated for other samples.

The samples are placed in a Hewlett-Packard 7671A automatic sampler. The samples are spaced by blank samples which are pure solvents for checking baseline drift.

A Hewlett-Packard 571 A Gas Chromatograph is then set at the conditions given in Table B1. The system is now ready for automatic injection. The injector first washes the syringe five times and also pumps out the samples five times before injecting the sample. The response of the gas chromatograph is sent to both a Beckman 10" Recorder and an HP 2100A mini-computer in conjunction with an HP 3354-C Auto-lab system.

Since not all oil volume injected passes through the column and detected, a method is used to determine the amount of residuum. This method involves an external standard run whose sample is totally distillable. By comparing the sample run and external standard run the residuum is determined. The simulated distillation yield is calculated as a function of simulated distillation temperature (boiling temperature).

Samples Totally Distillable at 1,000^{O}F

The sample is prepared in approximately a 1 to 1 ratio between oil sample and carbon disulfide to a total of about 1 ml. Since all oil is distillable no weight measurement is required, and no external standard run is needed. However, one calibration is required to determine the retention times for the desired boiling points. Otherwise, the procedure and data calculation are similar to that for samples not totally distillable at 1,000°F.

TABLE B1 SIMULATED DISTILLATION CONDITIONS

Detector Temperature	350°C
Injection Temperature	350°C
Oven Temperature Range	-20°C to 350°C
Temperature Program	10.6°C/min
Carrier Gas and Rate	He - 60 ml/min
Column	18" long,¼"dia. 6% SE-30
Mesh Size	100-120
Detector	FID
Detector Gas	H_2
Recorder	Beckman 10" (one pen)
Mode	Differential (Dual Col.)
Time @ Max. Temp.	8 Min.
HP 18652A A/D Converter	
HP 18653A Sampler Control Module	

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