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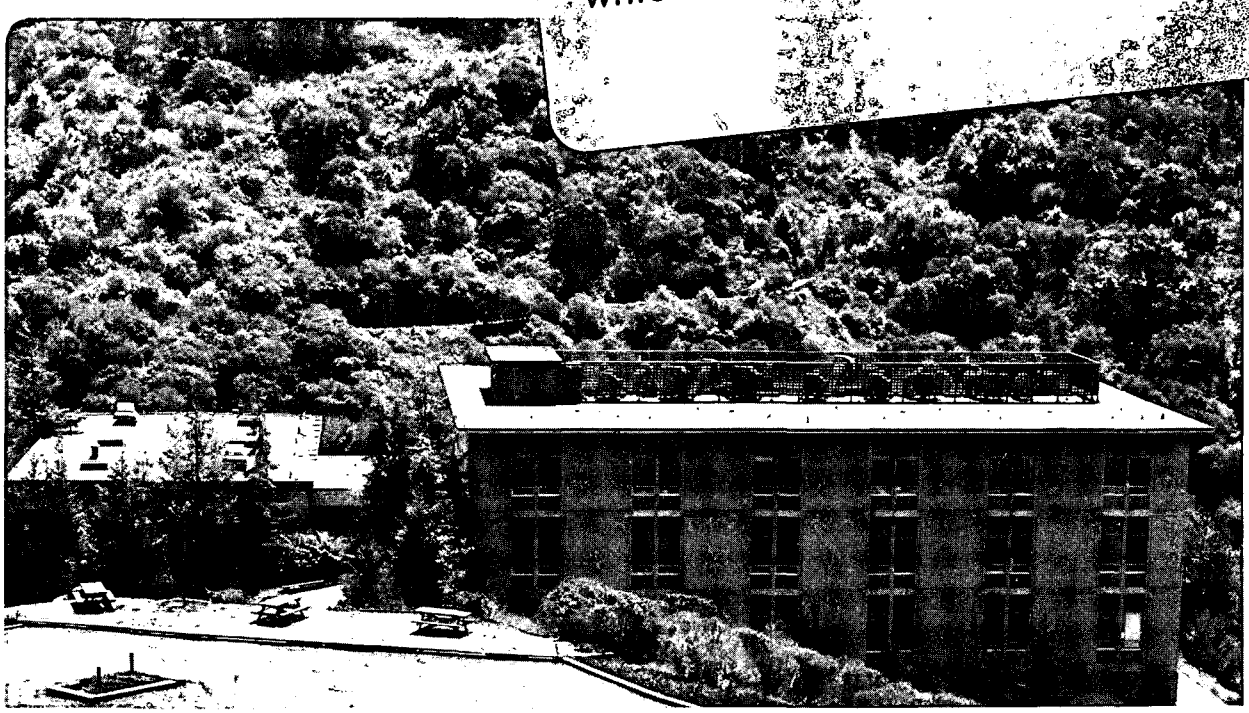

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VAPOR PRESSURES AND SATURATED-LIQUID DENSITIES OF HEAVY FOSSIL-FUEL FRACTIONS

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ABSTRACT

Measurements are reported for vapor pressures and saturated liquid densities of characterized fossil-fuel fractions. Vapor pressures were measured for twelve fractions and densities for thirty fractions. The fractions originated from crude oils, coal liquid, and tar sands. Initial atmospheric boiling points of the fractions range from 492 to 700 K. Vapor pressures to 575 K were measured using an ebulliometer; between one and seven percent of the sample was vaporized during these measurements. Saturated liquid densities were measured between 292 and 578 K using sealed glass cells heated in an air bath. For most samples, the measured properties showed only small observable effects of cracking. The data reported may be useful for testing correlations used in process-design calculations.

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INTRODUCTION

As the supply of high-quality light crude oil is depleted, heavier and more varied hydrocarbon feeds must be used by refiners to meet the world's fuel needs. Heavy fossil fuels may come from a number of sources including low-quality crude oil; heavy, previously unused, ends of crude oil; coal liquids; tar sands; and shale oil. Such fuels contain larger, more aromatic molecules than those found in light fuels. and these molecules often contain more heteroatoms (oxygen, nitrogen, and sulfur) than those found in traditional liquid fuels. Because of these differences, conventional correlations to predict thermodynamic properties of light crudes often cannot be used to predict properties of heavy fossil fuels (1,2). However, reliable estimates of thermodynamic properties are necessary to design equipment for processing heavy fossil fuels. Property estimates needed for process design must be provided by new correlations developed for heavy fossil fuels. This work presents a contribution to the data base to establish the new correlations.

In recent years, several authors have reported experimental studies of vapor pressures and densities of heavy fossil fuels (1,3-6). However, characterization data for fuels show large qualitative variation, depending on the authors preference for different characterization methods.

This work reports subatmospheric vapor pressures and saturated liquid densities of fossil-fuel fractions under conditions where the extent of vaporization is small. These fractions include crude oils obtained from Belridge, California and Hendrick Station, Texas, two other crudes obtained from proprietary locations (Exxon A and B), Exxon Donor Solvent process product (EDSPP), Wilsonville (Alabama) coal liquifaction product (WCLP), and a tar-sands product from Syncrude Canada. Table I shows a list of samples. The atmospheric boiling points (except for WCLP 4) shown in Table I are estimated from vacuum distillations.

Vapor pressures are given here for the first twelve samples in Table I. Density data are given for all of the samples. The samples studied here, except for the Syncrude sample, have

been characterized by Alexander et al (7) and Rodgers et al (8). These characteriztion measurements include elemental analysis, molecular weight, hydrogen distribution, and concentration of groups containing heteroatoms.

VAPOR-PRESSURE MEASUREMENTS

Vapor pressures of twelve heavy fossil-fuel samples were measured over a temperature range extending from the boiling point at 0.001 bar to 575 K. Between one and seven weight percent of the sample was vaporized during these measurements. A simple ebulliometer, shown in Figure 1, was used to collect vapor-pressure data. All connections are made by latex rubber hose. This ebulliometer allows the use of small samples, 25 to 30 ml, and does not allow light gases produced by cracking to contribute significantly to the measured vapor pressures. Dissolved gases and gases produced by cracking are removed by the pressure control system.

For each datum, the pressure was set using the pressure controller. The sample was heated and stirred until it reached a steady boiling temperature; the lowest pressure studied was about 0.001 bar. Extension of this method to lower pressures is limited by the need for the sample to nucleate and boil smoothly.

The pressure was measured using a mercury manometer and a cathetometer. The temperature was measured using a copper-constantan thermocouple in the equilibrium cell. Measurements were repeated at increasing pressures until the boiling temperature was approximately 573 K or the pressure was roughly 0.74 bar. To test for any effect of decomposition, boiling points of several samples were measured again after the sample had been heated to approximately 573 K. With the exception of WCLP cut 9, no hysteresis was observed. A sequence of increasing pressures was preferred because it minimized the sample's time at high temperature. The total heated time for a sample was between three and five hours.

The equilibrium cell, shown in Figure 2, consists of three glass sections: a 50-ml round-bottom flask, a 11-cm long condenser, and a T-shaped piece. The three glass pieces were

connected by 14/20 ground-glass joints sealed with Dow-Corning high-vacuum grease. The round-bottom flask was loaded with 25 to 30 ml of sample, approximately twenty boiling stones (approximately 4-mm in diameter), and a 1-inch teflon-coated magnetic stir bar. The flask was placed in a heating mantle on top of a magnetic stirrer. A 1/8-inch-diameter stainless-steel, sheathed copper-constantan thermocouple was fed through the septum at the top of the cell. The thermocouple was calibrated using NBS traceable standard thermometers. The tip of the thermocouple was placed as close as possible to the center of the spinning stir bar. As the sample boiled, foaming liquid engulfed the thermocouple eliminating the possibility of reading the temperature of superheated liquid. Cold water was fed into the top of the condenser to prevent solidification of the condensate at the water inlet. Valves at the cooling-water inlet and outlet controlled the water flow rate and level. The water level was maintained well above any visible condensate. A 120-V variable transformer was used to control the heating mantle. The equilibrium cell was connected to the pressure controller through one arm of the T-shaped piece.

Pressure was controlled by a Perkin-Elmer vacuum controller. A float valve in the controller regulated suction. The height of the float was determined by the pressure difference between a set-point reservoir and the system. For these experiments, the valve floated on silicone vacuum oil. The suction worked against a nitrogen leak. Nitrogen bubbled through traps filled with mineral oil to prevent the leak pressure from going above atmospheric and to prevent air from entering the system. The nitrogen then passed through a cold trap before entering the system. The air leak was used to prevent the float valve from sticking and to reduce pressure oscillations due to very low vacuum pressures at the float valve. The maximum pressure oscillation was 0.0001 bar. For most of the measurements, pressure oscillation was not measurable.

Mercury-manometer readings were corrected to 45° latitude and 0° C. Each side of the manometer could be read to within 0.03 mm. A Gilmont swivel-type McCleod gauge was used to measure the reference pressure of the manometer to within 20 mtorr.

The estimated accuracy of the pressure measurements is 0.0001 bar. Uncertainty in the temperature measurement is 0.2 K. To test the ebulliometer, the vapor pressure of n-hexadecane was also measured; these measurements agree with published values (9) with an average absolute deviation of 0.0004 bar.

VAPOR-PRESSURE RESULTS

Tables II to V show the vapor-pressure data. Normal boiling points of the samples were estimated by extrapolation of linear semilogarithmic plots giving the pressure as a function of inverse temperature. Figures 3 shows plots of vapor pressure as a function of temperature for W CLP cut 8, Exxon A cut 5, and the Syncrude resid. W CLP cut 9 was the only sample that exhibited any noticeable effects of cracking.

Estimated boiling point from distillations do not always agree with those from vapor-pressure measurements. For Exxon A, the least aromatic samples, the estimated boiling point is within a few degrees of the initial boiling point of the sample as estimated from distillation. The estimated boiling points for the Exxon B samples are approximately thirty degrees Kelvin lower than those estimated from distillation. Estimated normal boiling points fall in the center of the boiling range for the heavy W CLP cuts. The boiling points fall at either end of the boiling range for the light W CLP cuts.

Several reasons account for discrepancies between extrapolated boiling points and those from distillation data. The temperature measured in a condenser is essentialy a dew-point temperature, which is not necessarily equal to the near bubble-point temperature. The method used to extapolate from a subatmospheric distillation to atmospheric presssures may be in error. Simple extrapolations of vapor-pressure data may also cause error, although it is unlikely that these errors are large as those occuring from conversion of distillation data to atmosphric pressure. Different estimates of the boiling points of these samples illustrate the danger of using an estimated normal boiling point as a characterization parameter for heavy crudes.

DENSITY MEASUREMENTS

Liquid-density measurements were performed using glass cells shown in Figure 4. The cells are made of four sections: the bottom bulb has a volume between 1.6 and 2.6 ml; the scale is from a 2-ml pipette; a bubble-breaker bulb is of approximately the same size as that of the bottom bulb; and a capillary is at the top. The volume of the liquid in the cell is determined from the level read on the pipette scale. Volume calibrations were performed at room temperature by measuring the weight of n-heptane deposited in the cell and reading the level at the bottom of the meniscus on the pipette scale. The volume of the cell up to the liquid level was then determined by dividing the measured weight of heptane by its apparent density. The apparent density of heptane (the density observed without correcting for the buoyancy of heptane in air) was obtained by subtracting the density of air (0.0012 g/ml) from tabulated values of the density of heptane (10). At least four calibration points were used to determine a linear relation between volume and scale reading. The total volume of the cell up to the bottom of the capillary was determined in the same manner. If the cell was reused, the capillary was replaced and the total volume calibration was repeated using distilled water after each run. The density of distilled water was obtained from Perry (11).

Prior to each run, the cell was tared and a sample was deposited in the bottom of the cell up to a level approximately 3 cm above the lower bulb. A syringe with a 12-inch needle was used to deliver the sample through the capillary to the bottom of the cell. For viscous samples, the syringe and cell were warmed. If the sample was extremely viscous (e.g. the Syncrude resid and WCLP cut 9), the sample was loaded using the piston device shown in Figure 5; that device is similar to a stainless-steel syringe. The sample was loaded in the top and the piston was screwed down until enough sample was loaded. Sample sizes ranged between 1.5 and 2.8 grams.

After loading, the sample was degassed. Degassing was performed by connecting the cell's capillary to a vacuum manifold through a latex-rubber hose. The vacuum system

attained pressures as low as 50 mtorr. During degassing, the sample was either frozen and thawed or the bottom bulb of the cell was placed in an ultrasonic water bath to produce nucleation of gas bubbles. The degassing method and the temperature of the ultrasonic bath depend on the volatility of the sample. If the bath was heated, an infrared lamp was used to heat the scale of the cell. Samples were degassed about eight hours except the two heaviest samples which were degassed twenty-four hours. Degassing loses were negligible for samples with a normal boiling point over 500 K and were as high as 13 weight percent for the lightest samples.

Following degassing, the capillary was fused about 1.5 cm from its bottom while the cell was still connected to the vacuum manifold. The sample and cell were then weighed. The total volume of the sealed cell was determined from the previously measured cell volume plus the added volume due to the length of the unsealed capillary. Sample mass was determined by weighing with a buoyancy correction equal to the weight of air removed from the cell during degassing and filling. The mass of air removed was determined by multiplying the total volume of the cell by the density of air (0.0012 g/ml).

A rack, capable of holding three cells simultaneously, held the cells vertically in an air bath equipped with a window to allow viewing of the cells. To prevent condensation in the top of the cell, heating tape was wrapped around the top bulb of the cells to keep the top roughly one degree Celsius warmer than the bottom. The bath, controlled by an Omega model-167 controller, provided a steady temperature to ±0.1 °C. The temperature at the bottom of the cell was measured with a copper-constantan thermocouple held in place by aluminum foil wrapped around the cell bottom. The thermocouples and display were calibrated against an NBS traceable platinum thermometer. Temperature measurements are accurate to within ±0.2 °C. Liquid-level measurements were made with the aid of a cathetometer, giving liquid volumes accurate to within 0.002 ml.

In most cases, data were collected by letting the liquid equilibrate at room temperature and measuring the temperature and level of the liquid relative to the tick marks on the scale.

The sample was then heated 20 or 30 °C and the measurement was repeated once the temperature was steady. For each datum, about one hour was required to allow the temperature to stabilize. For the Syncrude resid and W CLP 9, the samples were heated for 40 hours at 125 °C, prior to initial measurement at 101 °C, to allow oil stuck to the wall of the cell to flow to the bottom. Measurements were started at the higher temperatures to insure that the samples were in a liquid state. Data were collected to approximately 575 K or the samples normal boiling point, whichever is lower. For some cases, the sample was cooled from the high temperature to room temperature. Measurements were repeated to estimate the effect of cracking.

DENSITY-DATA REDUCTION

The measurements consisted of the cell temperature, the liquid level along the scale of the cell, the mass of sample in the cell and the total volume of the cell at room temperature. To determine the density, it is necessary to divide the measured volume of liquid by its mass. Since the cell is calibrated at room temperature, the volume of the liquid must be corrected for expansion of the cell. Liquid volume was determined from the scale reading of the cell and the calibration curve, corrected according to

$$v = v^c + \Delta v \qquad (1)$$
$$\Delta v = v^c \, \alpha \, (T^m - T^c)$$

where v^c is the volume from the calibration curve and α is the cubic expansion coefficient of Corning-8800 glass, 1.8×10^{-5} per degree Celsius (12). The mass of sample in the liquid must be corrected for vaporization loses. The mass of sample vaporized is determined by the volume of gas above the liquid, the vapor pressure of the sample, the molecular weight of the sample, and the ideal-gas law. The vapor volume is determined by calculating a corrected total volume from the room temperature total volume using Equation 1. The corrected liquid volume is then subtracted from the corrected total volume to obtain gas volume, v^g.

The vaporization loss, Δm, is

$$\Delta m = \frac{MW \ P^{sat} \ v^g}{R \ T} \tag{3}$$

where MW is the average molecular weight of the sample, P^{sat} is the vapor pressure of the sample and T is the cell temperature.

The density is determined by dividing the corrected mass by the corrected liquid volume.

Average molecular weights were those given by Alexander et al (7) and Rodgers et al (8) except for W CLP cut 9 and the Syncrude Resid. The molecular weight of W CLP cut 9 was 360, determined by Tewari (13), using vapor-pressure osmometry with tetrahydrofuran as the solvent. The molecular weight of the Syncrude sample was estimated to be 600, using Rodgers' et al (8) gel-permeation chromatography method. Vapor pressures were determined using data presented here and those given by Alexander (14) for the Belridge and Hendreick Station samples. Correlations presented by Alexander et al (15) were used for the ED SPP samples.

The density of n-hexadecane was measured and compared to literature values (16). Between 299 and 553 K, the measured densities average 0.0006 g/cm^3 higher than those published. The largest measured difference is 0.0015 g/cm^3; the average deviation is 0.09%

DENSITY RESULTS

Tables VI to XIII show measured and estimated densities at 289 K (60 °F). Densities at 289 K were estimated by extrapolating a polynomial fit of the data as a function of temperature. Linear or qudaratic fits were used depending on the sample. Figure 8 shows density vs. temperature for Exxon A cut 3, W CLP cut 8, and the Syncrude resid. Duplicate runs with fresh samples indicate that the data are reproducible to ±0.0005 g/cm^3, except those for W CLP cut 9 and the Syncrude resid.. A number of points were duplicated after samples had been heated to their maximum temperature. These indicate that the effect of cracking on the measurements was smaller than the experimental precision. For the Syncrude resid and W CLP cut 9, the precision was approximately 0.001 g/cm^3; this somewhat larger error is probably due to the tendency of these samples to stick to the cell walls.

The density results follow the expected pattern. At a fixed temperature, densities increase with rising boiling point except those for W CLP cuts 4 and 5, and ED SPP cuts 1 and 2. These exceptions are probably due to the high oxygen content of these cuts. The oxygen atoms cause the samples to be more polar then pure hydrocarbons, producing larger intermolecular attractive forces, and closer packing of the molecules. Exxon A is significantly less dense than Exxon B because of its lower aromaticity. Belridge samples are signifcantly denser than comparable Hendrick-Station samples even though they have similar aromaticities. The H/C ratio indicates that Belridge-sample molecules are more condensed, allowing tighter packing.

CONCLUSIONS

Density and vapor-pressure data were obtained for a number of heavey fossil fuels. Coupled with available characterization data, these data should be useful for testing correlations for properties of crude oils. The vapor-pressure data indicate the difficulties in predicting vapor pressures from distillation data. The density data show how molecular structure can effect density.

ACKNOWLEGEMENTS

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Table I. Samples Studied and Estimated Ranges of Normal Boiling Points. Estimates Based on Distillation Data.

sample		normal boiling range (K)	source
Exxon A	cut 1	644 to 658	crude oil
	cut 3	672 to 686	
	cut 5	700 to 714	
Exxon B	cut 1	616 to 644	crude oil
	cut 3	672 to 700	
	cut 4	700 to 728	
WCLP	cut 4	492 to 505	coal liquid
	cut 5	505 to 533	
	cut 7	589 to 617	
	cut 8	617 to 644	
	cut 9	655+	
Syncrude	resid	514+ at 0.026 bar	tar sands
Belridge	cut 1	422 to 478	crude oil
	cut 2	478 to 533	
	cut 3	533 to 617	
	cut 4	617 to 705	
	cut 5	705 to 811	
Hendrick Station	cut 1	422 to 478	crude oil
	cut 2	478 to 533	
	cut 3	533 to 617	
	cut 4	617 to 714	
	cut 5	714 to 811	
ED SPP	cut 1	379 to 399 at 0.068 bar	coal liquid
	cut 2	399 to 415 at 0.069 bar	
	cut 3	415 to 433 at 0.069 bar	
	cut 4	433 to 456 at 0.069 bar	
	cut 5	456 to 474 at 0.068 bar	
	cut 6	474 to 497 at 0.069 bar	
	cut 7	497 to 517 at 0.071 bar	
	cut 8	517+ at 0.069 bar	

Table II. Vapor Pressures of Exxon A Samples

cut 1		cut 3		cut 5	
T (K)	P (bar)	T (K)	P (bar)	T(K)	P (bar)
502.8	0.0204	512.1	0.0130	541.4	0.0135
513.9	0.0305	524.0	0.0206	550.0	0.0187
521.8	0.0394	533.4	0.0283	558.4	0.0247
534.0	0.0581	539.0	0.0342	565.0	0.0304
542.0	0.0738	545.5	0.0424	570.8	0.0365
552.3	0.0997	553.2	0.0547	573.8	0.0399
561.5	0.1281	561.8	0.0691	[697.	1.0133]
568.8	0.1565	574.2	0.0990		
571.4	0.1672	[667.	1.0133]		
[647.	1.0133]				

Brackets indicate estimated normal boiling points.

Table III. Vapor Pressures of Exxon B Samples

cut 1		cut 3		cut 4	
T (K)	P (bar)	T (K)	P (bar)	T(K)	P (bar)
431.6	0.0140	482.4	0.0156	505.6	0.0149
443.6	0.0220	487.2	0.0270	514.6	0.0208
452.4	0.0303	497.2	0.0267	523.0	0.0285
460.0	0.0393	515.0	0.0484	536.0	0.0425
470.6	0.0558	520.2	0.0564	543.8	0.0528
479.0	0.0724	522.0	0.0602	555.4	0.0728
493.0	0.1062	531.0	0.0780	561.4	0.0853
505.4	0.1510	548.0	0.1221	573.0	0.1163
515.8	0.2002	556.6	0.1524	[667.	1.0133]
529.4	0.2780	565.4	0.1911		
537.8	0.3407	575.2	0.2413		
551.4	0.4650	[639.	1.0133]		
564.2	0.6163				
[587.	1.0133]				

Brackets indicate estimated normal boiling points.

Table IV. Vapor Pressures of W CLP Samples

cut 4		cut 5		cut 7		cut 8		cut 9	
T (K)	P (bar)	T (K)	P (bar)	T (K)	P (bar)	T (K)	P (bar)	T (K)	P (bar)
363.1	0.0200	367.9	0.0097	475.6	0.0292	479.6	0.0153	529.3	0.0138
373.5	0.0324	379.3	0.0170	487.6	0.0445	489.4	0.0218	540.0	0.0201
383.7	0.0506	388.7	0.0267	494.8	0.0572	499.2	0.0305	551.4	0.0304
393.4	0.0681	399.9	0.0432	506.1	0.0802	507.4	0.0401	560.1	0.0406
404.5	0.1151	415.7	0.0798	514.0	0.1040	519.0	0.0584	[678.	1.0133]
415.1	0.1719	426.5	0.1169	518.4	0.1178	529.4	0.0809		
425.1	0.2402	438.7	0.1754	522.8	0.1341	542.6	0.1169		
434.9	0.3283	453.5	0.2781	528.4	0.1560	552.2	0.1522		
449.9	0.5159	462.9	0.3650	536.0	0.1938	562.8	0.2010		
463.1	0.7363	471.7	0.4684	544.8	0.2449	573.6	0.2636		
[473.	1.0133]	483.5	0.6338	552.4	0.2958	[631.	1.0133]		
		[499.	1.0133]	558.4	0.3420				
				564.8	0.3980				
				569.4	0.4427				
				[605.	1.0133]				

Cut 9 cracked at temperatures higher than 560.1 K.
Brackets indicate estimated normal boiling points.

Table V. Vapor Pressures of Syncrude Resid

T (K)	P (bar)
509.7	0.0182
522.8	0.0268
527.1	0.0309
533.8	0.0374
542.4	0.0469
549.2	0.0579
560.5	0.0780
570.8	0.1022
[679.	1.0133]

Brackets indicate estimated normal boiling point.

Table VI. Saturated Liquid Densities of Exxon A Samples

cut 1		cut 3		cut 5	
T (K)	ρ (g/cm^3)	T (K)	ρ (g/cm^3)	T (K)	ρ (g/cm^3)
[289.	0.903]	[289.	0.922]	[289.	0.930]
298.8	0.897	298.8	0.910	330.7	0.904
330.5	0.876	330.5	0.888	362.0	0.882
361.8	0.856	361.8	0.867	391.3	0.863
391.1	0.836	391.1	0.848	419.8	0.845
419.8	0.816	419.8	0.828	449.1	0.826
448.9	0.797	448.9	0.809	478.9	0.807
478.9	0.776	478.7	0.789	513.4	0.784
513.1	0.752	513.1	0.766	542.5	0.764
542.0	0.730	542.0	0.745	572.6	0.743
571.8	0.708	572.2	0.724		

Brackets indicate estimated density at 60 °F (289 K).

Table VII. Saturated Liquid Densities of Exxon B Samples

cut 1		cut 3		cut 4	
T (K)	ρ (g/cm^3)	T (K)	ρ (g/cm^3)	T (K)	ρ (g/cm^3)
[289.	0.917]	[289.	0.943]	[289.	0.960]
293.4	0.914	294.2	0.940	294.0	0.957
299.6	0.910	326.7	0.919	326.5	0.935
326.5	0.892	356.2	0.899	356.2	0.916
330.3	0.890	385.9	0.879	385.7	0.897
356.2	0.872	416.9	0.859	416.8	0.877
360.5	0.870	450.1	0.838	450.2	0.856
385.9	0.851	483.9	0.815	483.9	0.833
390.9	0.849	515.7	0.793	515.5	0.811
416.7	0.830	544.4	0.772	544.2	0.791
422.0	0.827	570.0	0.753	569.4	0.773
450.2	0.806				
452.7	0.806				
483.3	0.783				
483.9	0.782				
513.4	0.760				
515.3	0.758				
542.8	0.738				
544.0	0.735				
569.0	0.715				
572.6	0.713				

Brackets indicate estimated density at 60 °F (289 K).

Table VIII. Saturated Liquid Densities of W CLP Samples

cut 4		cut 5		cut 7		cut 8		cut 9	
T (K)	ρ (g/cm^3)	T (K)	ρ (g/cm^3)	T (K)	ρ (g/cm^3)	T (K)	ρ (g/cm^3)	T (K)	ρ (g/cm^3)
[289.	0.942]	[289.	0.936]	[289.	0.961]	[289.	0.984]	[289.	1.055]
300.4	0.933	300.6	0.928	299.7	0.954	299.6	0.978	373.7	1.001
320.1	0.918	320.1	0.913	330.3	0.933	330.3	0.956	392.3	0.989
338.9	0.903	338.9	0.898	360.4	0.912	360.4	0.936	413.4	0.975
357.4	0.888	357.2	0.884	390.9	0.891	390.9	0.915	432.3	0.962
375.5	0.873	375.4	0.869	422.2	0.868	422.0	0.895	452.1	0.949
394.5	0.857	394.5	0.854	453.1	0.846	453.0	0.873	473.0	0.935
414.2	0.839	414.2	0.838	483.7	0.825	483.3	0.851	492.9	0.921
433.9	0.822	433.5	0.822	543.2	0.780	513.7	0.829	533.4	0.893
452.0	0.805	451.5	0.807	573.2	0.756	542.6	0.807	551.5	0.880
472.2	0.785	471.7	0.789			572.6	0.785	572.9	0.865
		494.7	0.768						

Brackets indicate estimated density at 60 °F (289 K).

Table IX. Saturated Liquid Densities of Syncrude Resid

T (K)	ρ(g/cm^3)
[289.	1.019]
373.7	0.970
392.1	0.958
413.2	0.946
432.3	0.934
452.2	0.922
513.7	0.884
533.2	0.871
551.5	0.859
572.9	0.845

Brackets indicate estimated density at 60 °F (289 K).

Table X. Saturated Liquid Densities of Belridge Samples

cut 1		cut 2		cut 3		cut 4		cut 5	
T (K)	ρ (g/cm^3)	T (K)	ρ (g/cm^3)	T (K)	ρ (g/cm^3)	T (K)	ρ (g/cm^3)	T (K)	ρ (g/cm^3)
[289.	0.828]	[289.	0.848]	[289.	0.891]	[289.	0.943]	[289.	0.958]
297.8	0.822	297.8	0.842	299.8	0.884	297.8	0.937	297.8	0.953
329.2	0.795	299.8	0.840	332.0	0.862	329.2	0.915	329.2	0.933
335.8	0.791	329.2	0.819	368.0	0.836	335.8	0.912	335.8	0.929
370.6	0.762	332.0	0.818	403.6	0.811	370.6	0.887	370.6	0.905
375.4	0.759	335.8	0.814	429.8	0.793	375.4	0.885	375.4	0.904
413.4	0.728	368.0	0.791	459.0	0.772	413.4	0.859	414.4	0.878
414.4	0.727	370.6	0.789	478.2	0.758	414.4	0.858	441.0	0.861
441.0	0.705	375.4	0.785	504.4	0.738	441.0	0.840	460.6	0.848
460.6	0.684	403.6	0.764	506.4	0.737	460.6	0.826	487.2	0.832
		413.4	0.758	526.8	0.721	487.2	0.808	508.6	0.819
		414.4	0.756	546.2	0.705	508.6	0.794	510.0	0.818
		429.6	0.745	559.0	0.695	510.0	0.793	528.0	0.806
		441.0	0.736	573.6	0.682	528.0	0.780	549.0	0.793
		459.0	0.722			549.0	0.764	549.8	0.793
		460.6	0.719			549.8	0.765	564.4	0.783
		487.2	0.697			564.4	0.754	574.6	0.775
		508.6	0.679			574.6	0.747		
		510.0	0.678						

Brackets indicate estimated density at 60 °F (289 K).

Table XI. Saturated Liquid Densities of Hendrick-Station Samples

cut 1		cut 2		cut 3		cut 4		cut 5	
T (K)	ρ (g/cm^3)	T (K)	ρ (g/cm^3)	T (K)	ρ (g/cm^3)	T (K)	ρ (g/cm^3)	T (K)	ρ (g/cm^3)
[289.	0.795]	[289.	0.825]	[289.	0.868]	[289.	0.903]	[289.	0.933]
297.0	0.789	297.0	0.819	292.2	0.866	302.4	0.894	302.4	0.925
340.2	0.755	340.2	0.787	327.1	0.841	332.8	0.875	384.6	0.869
377.2	0.725	377.2	0.761	385.4	0.800	384.6	0.841	429.0	0.841
414.0	0.695	414.0	0.732	395.8	0.794	429.0	0.811	473.8	0.812
452.0	0.662	452.0	0.702	396.0	0.794	473.8	0.781	474.6	0.811
464.0	0.652	464.0	0.693	428.8	0.769	474.6	0.780	501.6	0.794
476.0	0.642	476.0	0.683	469.4	0.739	501.6	0.761	536.0	0.771
				496.2	0.717	536.0	0.737	558.8	0.756
				523.8	0.697	558.8	0.720	577.4	0.743
				545.4	0.680	577.4	0.706	578.0	0.743
				564.6	0.664	578.0	0.705		
				572.8	0.658				

Brackets indicate estimated density at 60 °F (289 K).

Table XII. Saturated Liquid Densities of ED SPP Cuts 1 through 4

cut 1		cut 2		cut 3		cut 4	
T (K)	ρ (g/cm^3)	T (K)	ρ (g/cm^3)	T (K)	ρ (g/cm^3)	T (K)	ρ (g/cm^3)
[289.	0.926]	[289.	0.907]	[289.	0.927]	[289.	0.939]
297.0	0.920	295.2	0.902	295.2	0.922	292.2	0.937
340.2	0.885	334.4	0.879	334.4	0.893	327.1	0.911
377.2	0.857	351.4	0.867	351.4	0.881	385.4	0.866
414.0	0.827	384.6	0.841	384.6	0.854	395.8	0.859
452.0	0.794	427.6	0.807	427.6	0.821	396.0	0.860
464.0	0.782	456.6	0.783	456.6	0.798	428.8	0.834
476.0	0.772	485.4	0.758	485.4	0.773	469.4	0.802
		499.0	0.746	499.0	0.763	496.2	0.779
		512.0	0.734	512.0	0.751	523.8	0.756
						545.4	0.737

Brackets indicate estimated density at 60 °F (289 K).

Table XIII. Saturated Liquid Densities of ED SPP Cuts 5 through 8

cut 5		cut 6		cut 7		cut 8	
T (K)	ρ (g/cm^3)	T (K)	ρ (g/cm^3)	T (K)	ρ (g/cm^3)	T (K)	ρ (g/cm^3)
[289.	0.962]	[289.	0.983]	[289.	0.986]	[289.	1.049]
292.2	0.960	292.2	0.981	302.4	0.976	332.8	1.020
327.1	0.934	327.1	0.956	332.8	0.954	384.6	0.985
385.4	0.890	385.4	0.914	384.6	0.917	429.0	0.954
395.8	0.883	395.8	0.906	429.0	0.885	473.8	0.924
396.0	0.883	396.0	0.906	473.8	0.851	474.6	0.923
428.8	0.858	428.8	0.880	474.6	0.850	501.6	0.904
469.4	0.827	469.4	0.852	501.6	0.830	536.0	0.878
496.2	0.805	496.2	0.831	536.0	0.804	558.8	0.862
523.8	0.783	523.8	0.811	558.8	0.785	577.4	0.848
545.4	0.765	545.4	0.793	577.4	0.770	578.0	0.848
564.6	0.748	564.6	0.778	578.0	0.770		
572.8	0.743	572.8	0.771				

Brackets indicate estimated density at 60 °F (289 K).

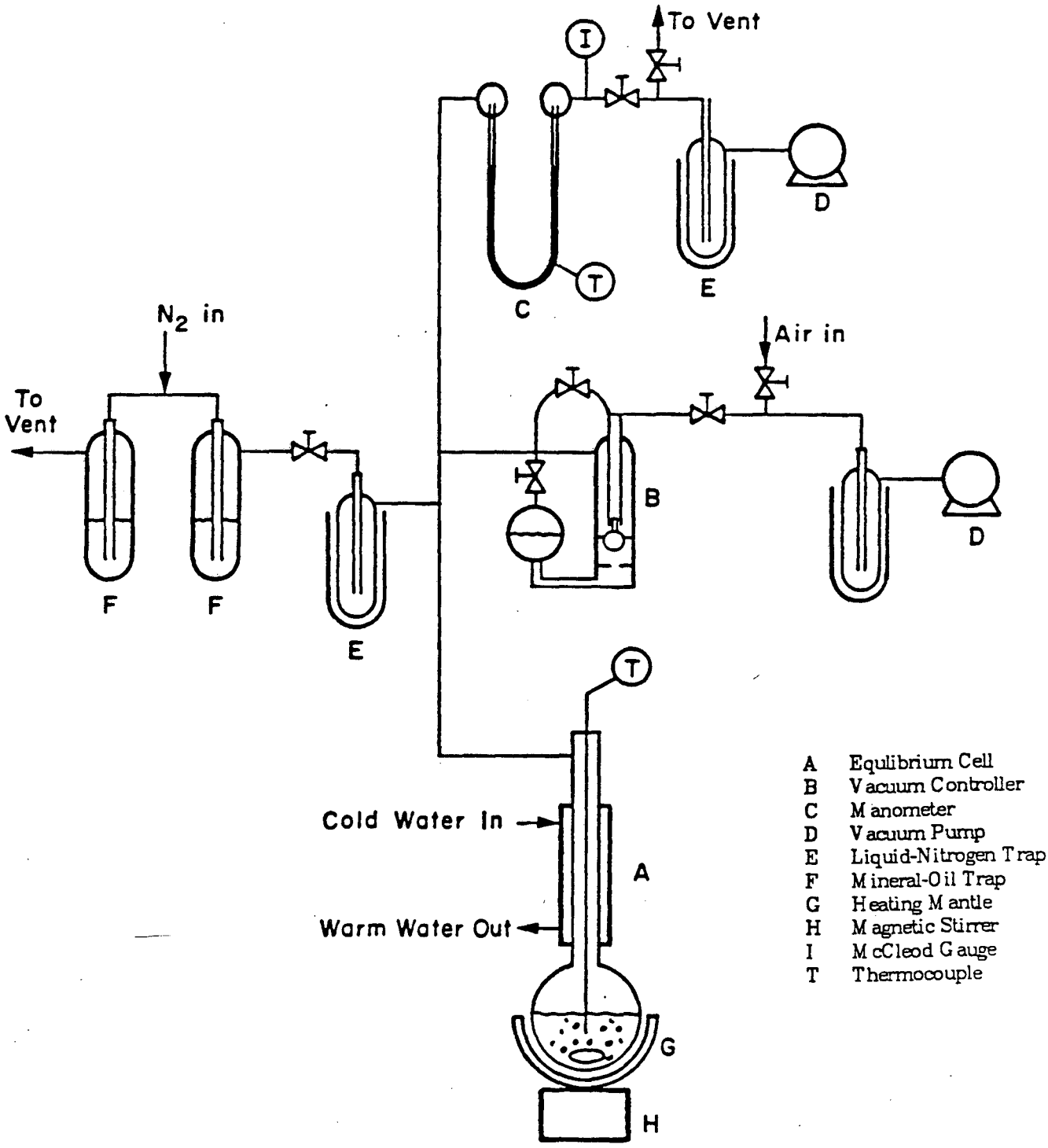

Figure 1. Schematic of Vapor-Pressure Apparatus

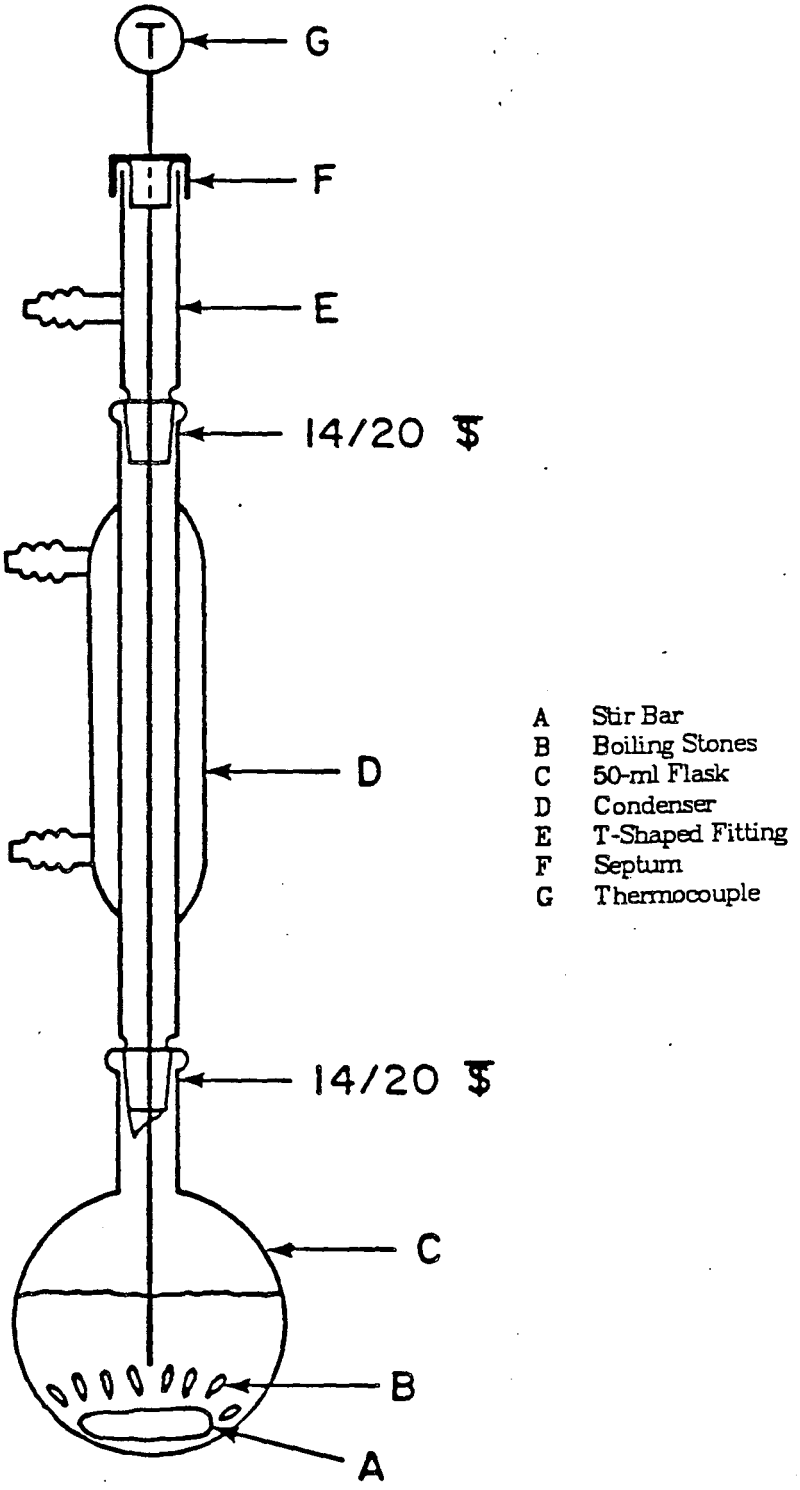

Figure 2. Bubble-Point Cell Diagram

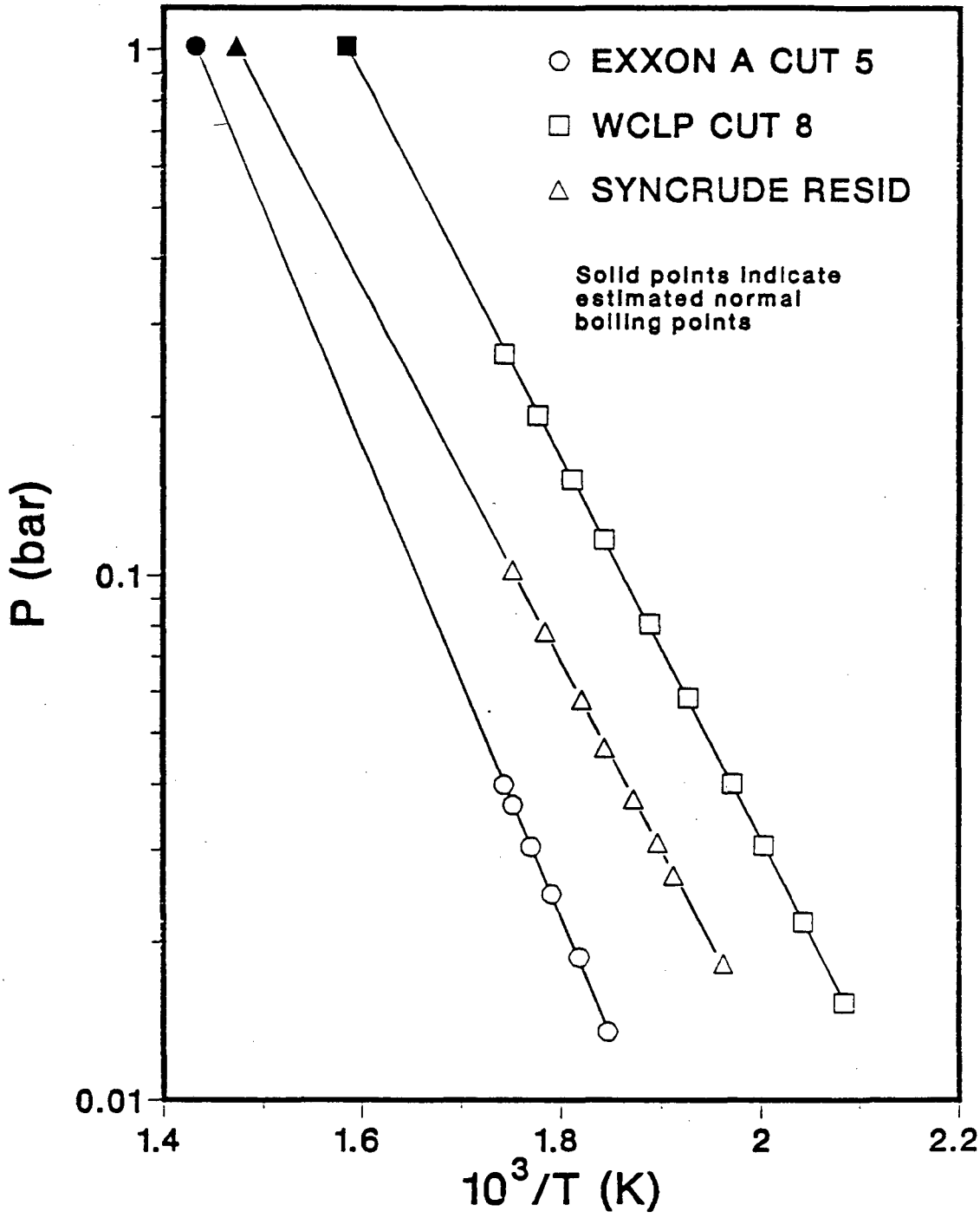

Figure 3. Vapor Pressures of Three Fractions

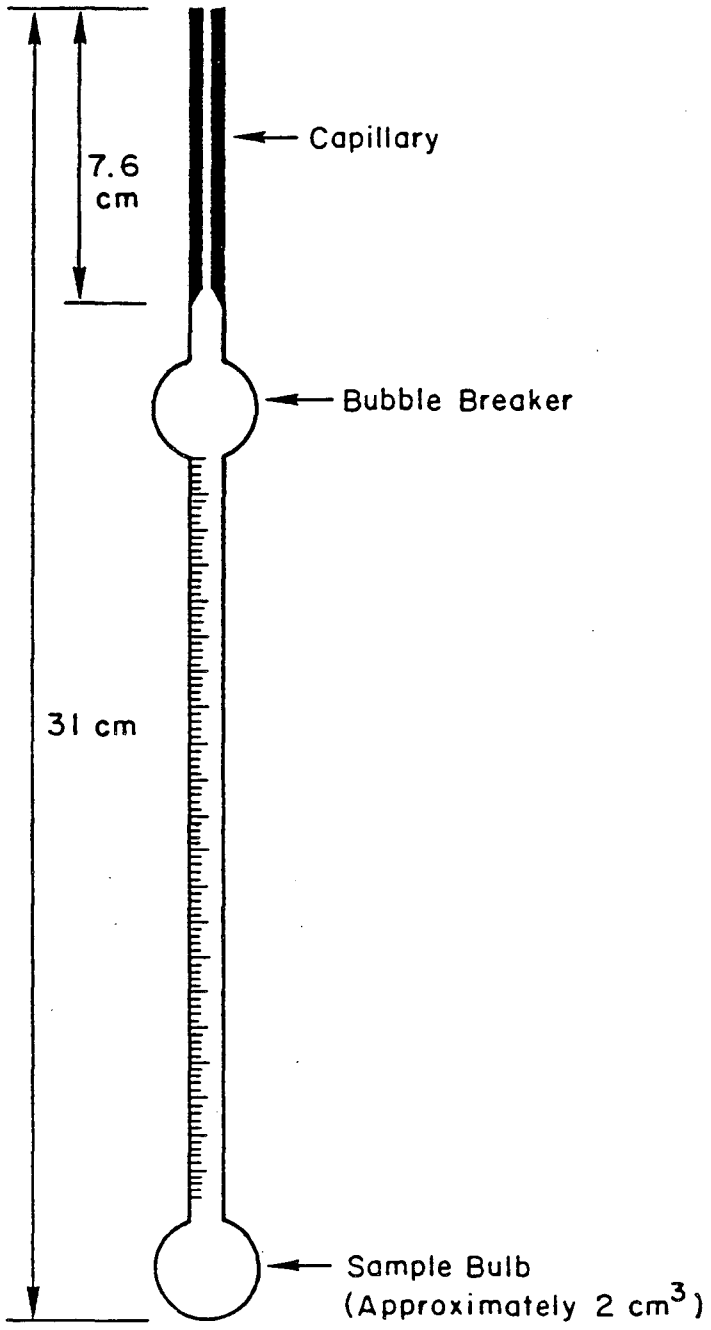

Figure 4. Density Cell

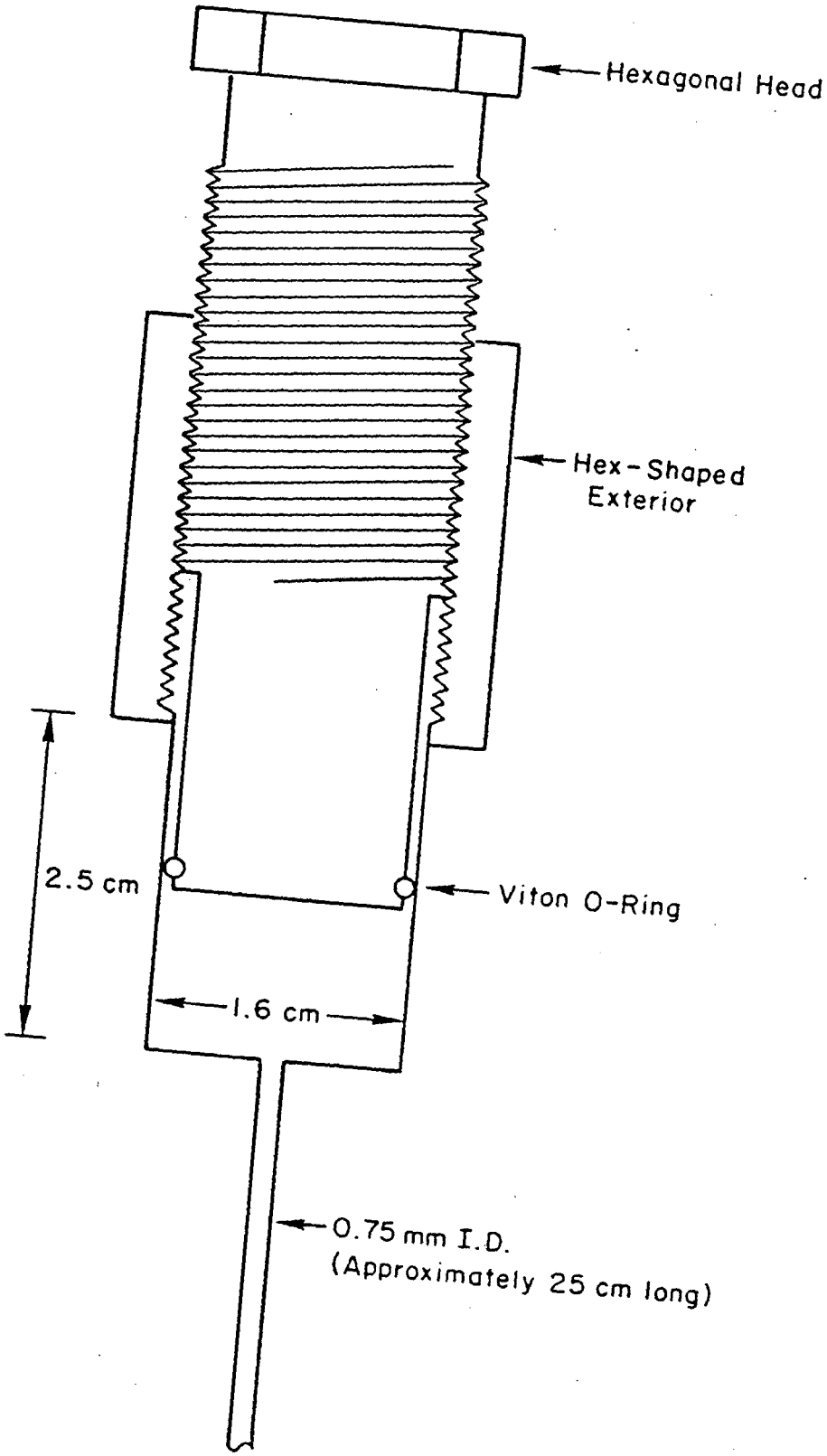

Figure 5. Sample Injector

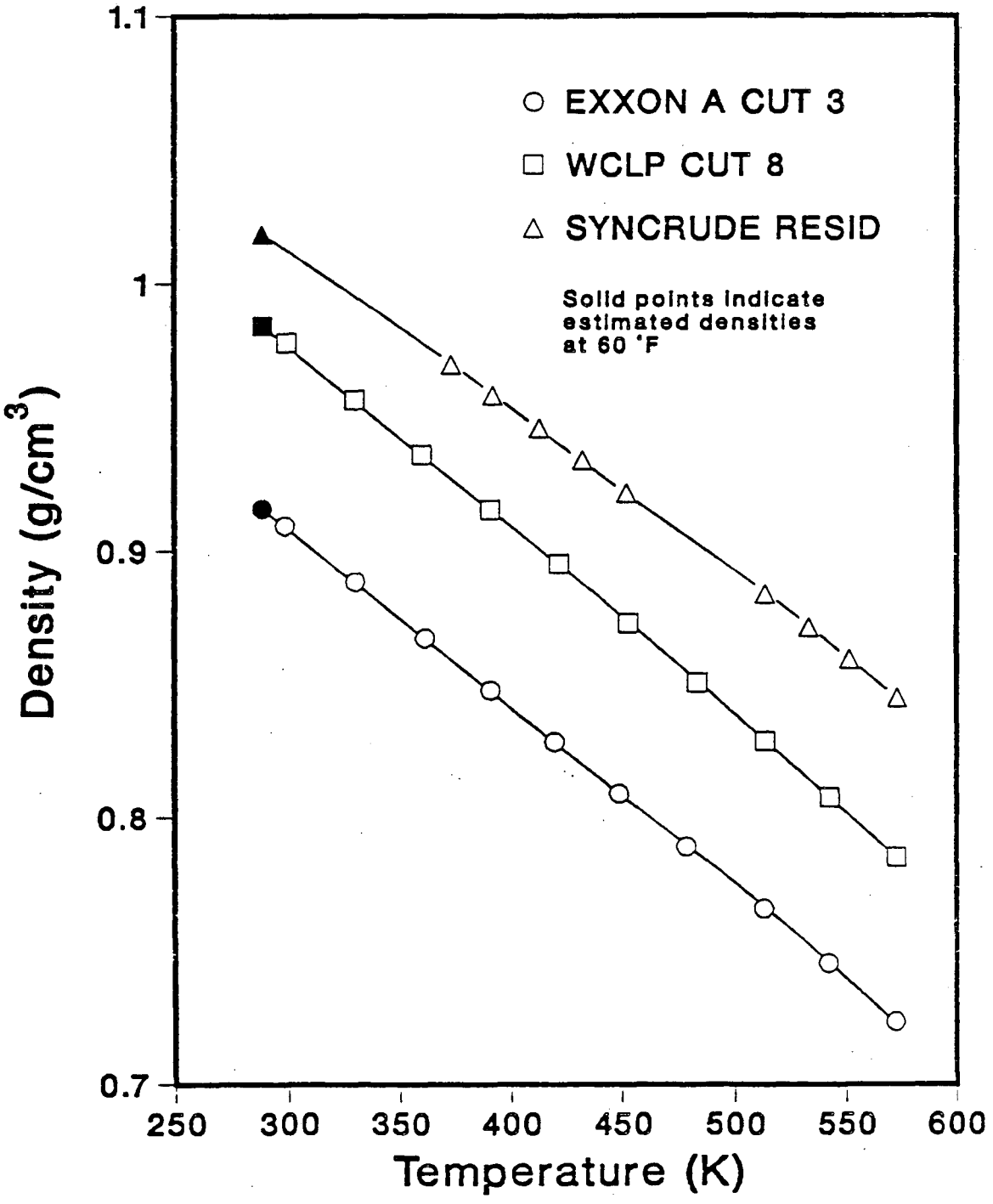

Figure 6. Densities of Three Fractions

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