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Douglas Stuart. Smith
*University of Windsor*

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# DENSITY AND VISCOSITY MEASUREMENTS OF ACETONE WATER SOLUTIONS UNDER HIGH PRESSURE AND CONTROLLED TEMPERATURES

BY

DOUGLAS STUART SMITH

A THESIS

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1972

In the beginning was the Word, and the Word was with God, and the Word was God.

And the Word was made flesh, and dwelt among us, (and we beheld his glory, the glory of the only begotten of the Father,) full of grace and truth.

And ye shall know the truth, and the truth shall make you free.

John 1:1,14
8:32

# ABSTRACT

Studies of the effect of pressure on the physical properties of acetone water solutions and the pure components from 0 to 40,000 psig. under controlled temperatures were made in an extensively modified (33) high pressure apparatus. The properties investigated were viscosity and specific volume.

The proposed equation of state is (6)

$$P = rB_{(v)}^{q}$$

where $$B_{(v)} = (v_o/v)^4 - (v_o/v)^2$$

and r and q are empirical constants and v and $v_o$ are the specific volumes at any pressure, and atmospheric pressure respectively.

The viscosity pressure correlation is

$$\eta = \eta_o \exp(mP)$$

where m is a function of composition.

$$m = \frac{\ln(N_1/0.0467)}{0.11} \times 10^{-6}$$

where $N_1$ is the mole fraction acetone in the solution.

The viscosity data are estimated to be correct to within ± 1.14% and the specific volume data correct to within ± 0.63%.

# ACKNOWLEDGEMENT

I would wish to take this opportunity to express my sincere gratitude to Dr. R.A. Stager and Dr. G.P. Mathur for their able guidance and constructive criticisms throughout this work.

Thanks are also expressed to Mr. George Ryan for his helpful suggestions and excellent workmanship during the equipment modification stage of the project.

Thanks are equally due to my wife, Anne, who's understanding and encouragement were most necessary.

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# I. INTRODUCTION

Since the development of the ideal gas law which predicts much of the P-V-T behaviour of gases, man has strived to duplicate this feat with a similar simple law for liquids. The kinetic molecular theory of gases led to the formulation of the ideal gas law, however, because of the complex nature of the liquid molecule and its associated forces, purely theoretical attempts at a liquid law have failed. Because of theoretical failures, the semi-empirical relationships have replaced these attempts and have met with varying degrees of success. It was a purpose of this project to measure the volume-pressure relationship of a liquid mixture system under controlled temperatures in order to increase the physical property data available today and consequently to increase the evidence supporting the semi-empirical equation of Chaudhuri et al (6). Mixtures as well as pure components were chosen as the subject of this study to test the general applicability of this equation of state.

Since viscosity is also an important physical property, equipment was designed to measure both liquid viscosity and density. It is this equipment developed initially by Chaudhuri (5), Rungta (33) and extensively modified by the author which has made possible the present study of viscosity and density as functions of pressure.

## II. LITERATURE SURVEY

Although P.W. Bridgman (2) is given the credit for being the father of high pressure research, some work was performed in the measurement of viscosity and compressibility of liquids under pressure in 1914. At this time O. Faust (15), drew from his measurements, the conclusion that at high pressures viscosity tends to a limiting behaviour, in that it is a linear function of volume only, so that viscosity is constant at a given volume and independent of temperature. Other early investigators who studied the behaviour of liquid viscosity as a function of temperature and pressure were R.B. Dow (11,12), R.H. Ewell and H. Eyring (13,14). An extensive survey on this subject was performed by Bridgman (2,3) including the early investigators through to the year 1958.

Since 1958 many investigators (19,21,26,29) have further increased man's knowledge of the behaviour of liquid viscosity, however, very little of their work has had to do with liquid mixtures and then only at atmospheric pressure (19,21,26).

When scientists turned their attention to the investigation of viscosity under pressures, most of their attention was devoted to the dense gas and liquid states of substances normally found as a gas. DeWitt and Thodos (9) investigated the viscosity of a methane-tetrafluoro-methane system up to 400 atmospheres at temperatures between 50 and 200 degrees centigrade. Their data were correlated and presented as a single relationship between $(\mu-\mu_0)\xi$ and the reduced density $\rho_R$. Their relationship was

$$(\mu-\mu_0)\,\xi = 17.0 \times 10^{-5}(e^{1.23\rho_R} - 1) \qquad 1$$

where $\mu_0$ is the viscosity at atmospheric pressure and $\xi$ is a viscosity parameter, equal to $T_c^{1/6}/M^{1/2}\,P_c^{2/3}$.

Previously, Jossi, Stiel, and Thodos (25) investigated $H_2$, Ar, $N_2$, $O_2$, $CO_2$, $SO_2$, $NH_3$, and many light hydrocarbons in their dense gas region and used a similar relationship of $(\mu-\mu_0)\,\xi$ and $\rho_R$.

Griest et al (18) used a rolling ball viscometer of the type originated by Flowers (16) to measure the viscosity of seven hydrocarbons having 25 or 26 carbon atoms, to a pressure of 3450 bars, and correlated their results with the equation

$$\log(\eta/\eta_0) = (K/T)\left[(v_0/v)^4 - (v_0/v)^2\right] \qquad 2$$

where $\eta_0$ was the viscosity at atmospheric pressure, $v_0$ was the specific volume at atmospheric pressure, T was the absolute temperature and K was an experimental constant.

Huang et al (23) used a falling cylinder viscometer to measure the viscosity of methane and propane from -170 °C to 0 °C at 5000 psia. Their results showed much the same trend as Thodos and co-workers (9,25) when they tabulated their data in a residual viscosity versus reduced density form.

Lee and Starling (28) also correlated the viscosity of light hydrocarbon systems with reduced density, using the equation

$$u/u_0 = \exp X_{(T)} P^{Y(T)} \qquad 3$$

where $X_{(T)} = C_1 + C_2/T$

and $Y_{(T)} = C_3 + C_4 X_{(T)}$

and $C_1$, $C_2$ , $C_3$, and $C_4$ are constants.

Reed and Taylor (32) studied mainly fluorocarbons and McAllister (31) studied the viscosity behaviour of mixtures of methanol-toluene, benzene-toluene, cyclohexane-heptane and acetone-water. However, in all cases the work was done only at atmospheric pressure.

More recently Chaudhuri (5), Rungta (33), and Chaudhuri et al (7,8) made measurements on the viscosity of liquids under extreme pressures. The work consisted of measuring the viscosity of aliphatic and aromatic aldehydes and correlating the data with the equation

$$\eta = \eta_0 \exp(mP) \qquad 4$$

where m is an experimental constant.

Early work in the field of compressibility of liquids was also covered extensively in Bridgman's book (2) and collected articles (3). Again since the time of Bridgman much work has taken place in measuring the change in density of substances with increasing pressure, however, much of this data centred on gases and the dense gas state (4).

Chaudhuri (5), Rungta (33), and Chaudhuri et al (6,7,8) made measurements on the P-V-T behaviour of liquids under extreme pressures. Their work, again on aliphatic and aromatic aldehydes gave rise to a new equation of state for liquids (6)

$$P = rB_{(v)}^{q} \qquad 5$$

where $B_{(v)} = (v_o/v)^4 - (v_o/v)^2$

and r and q were constants.

## III. THEORETICAL CONSIDERATIONS

There is little or no theory involved in the measurement of the compressibility of liquids. It suffices to say that a change of volume $\Delta V$ is measured and the compressibility is defined herein as $\frac{-\Delta V}{V_o}$ where $V_o$ was the volume of the system at atmospheric pressure.

There is, however, more theory to consider in the development of a falling body viscometer. Flowers (16) was the first to use the falling body viscometer, but Lawaczeck (27) and later Heinze (20) studied the theory behind the fall. From their work, three distinct resistances to the fall of the plummet through the liquid have been enumerated. They are:

1. the resistance which results from the liquid flowing in the annulus between the plummet and fall tube wall.
2. the viscous drag resulting from the relative movement of two cylindrical walls.
3. a head resistance caused by the formation of stream lines.

The head resistance is lowered by the relative size and shape of the plummet and fall tubes (5). By using a relatively long plummet 1.273 inches and a very small clearance 0.007 inches between the plummet and fall tube the effect of head resistance is minimized.

Lawaczeck's proposed equation for absolute viscosity is

$$\eta = \frac{t(\sigma-\rho)g}{s} \times \frac{\delta^3 d}{3(d+2\delta)^2 + 4\delta^2} \qquad 6$$

where $\sigma$ is the density of the plummet,

$\rho$ is the density of the test fluid,

t is the time of fall of the plummet,

$\delta$ is the clearance between the plummet and the wall of the fall tube, and

d, and s are the diameter of the plummet and the fall distance respectively. This equation is applicable if the fluid flows through the annulus in a laminar mode.

Jobling (24) modified this equation and measured viscosities up to 420 atmospheres, using a simpler form of the equation

$$\eta = \frac{(\sigma-\rho)(a-b)^3 gt}{6sb} \qquad 7$$

where a is the radius of the fall tube

b is the radius of the plummet

and g is the acceleration due to gravity.

Setting the instrument constant $k = \frac{(a-b)^3 g}{6sb}$ we are left with a rather easy equation to handle

$$\eta = kt(\sigma-\rho) \qquad 8$$

It is also encouraging to see that k was dependent here only on measurable quantities associated with the system. This same relationship was verified by the British Standards Institution and reported by Dinsdale and Moore (10) in 1962 and by Lohrenz, Swift, and Kurata (30) in 1960.

The above equation was found suitable, and used in this work because the flow in the annulus was laminar.

Additional theory that applies only to individual problems that arose during this project, and not with the overall mechanics of the equipment, will be dealt with as the individual components are described.

# IV. EQUIPMENT AND PROCEDURE

The high pressure equipment for measuring viscosity and compressibility consisted mainly of three distinct sections. These were the viscometer tube, the compressibility tube and the pressure system. Along with each of these three systems, of course, was the peripheral equipment necessary to precisely measure the physical properties.

## 1. VISCOMETER

The viscometer tube consisted of a 57.562 inch long stainless steel tube as shown in figure (1). The plummet was made of an Alnico magnet, highly polished with a length of 1.273 inches and a diameter of 0.173 inches. The ends of the magnet were rounded to produce more streamline flow.

The timing device consisted of two magnetic reed switches secured from I.B.M. of Windsor. They were mounted on a rod which enabled them to be swung into contact with the fall tube and also moved aside to allow the passage of an external magnet which was used to raise the plummet between readings. As the plummet passed the upper reed switch, a start signal was sent to a Hewlett Packard 522B electronic counter, and a stop signal was sent to the counter as the plummet passed the bottom switch. Details of the entire system can be seen in figures (2,3,4).

In operating the viscometer the plummet was raised by the

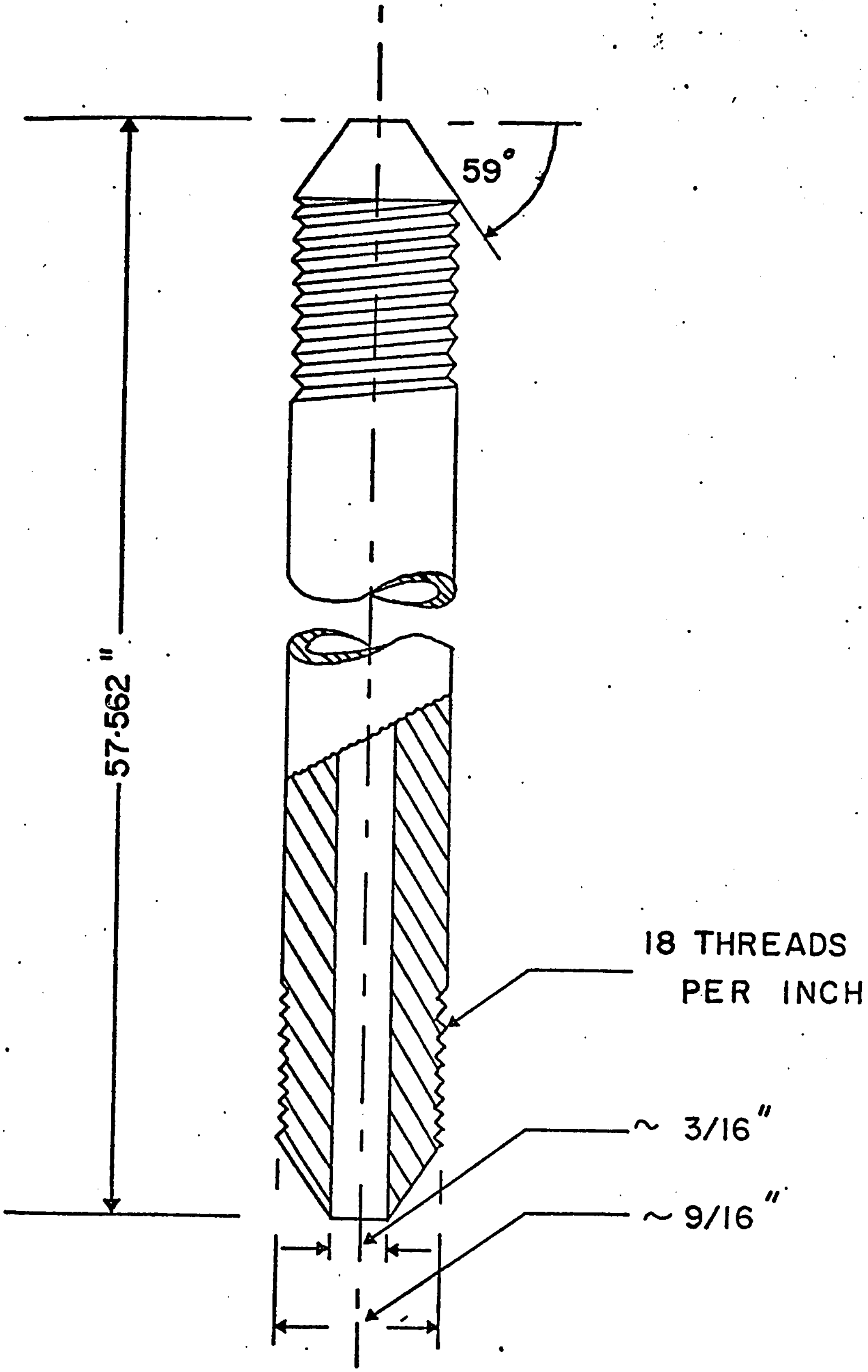


FIG.1 DETAILS OF THE FALL TUBE

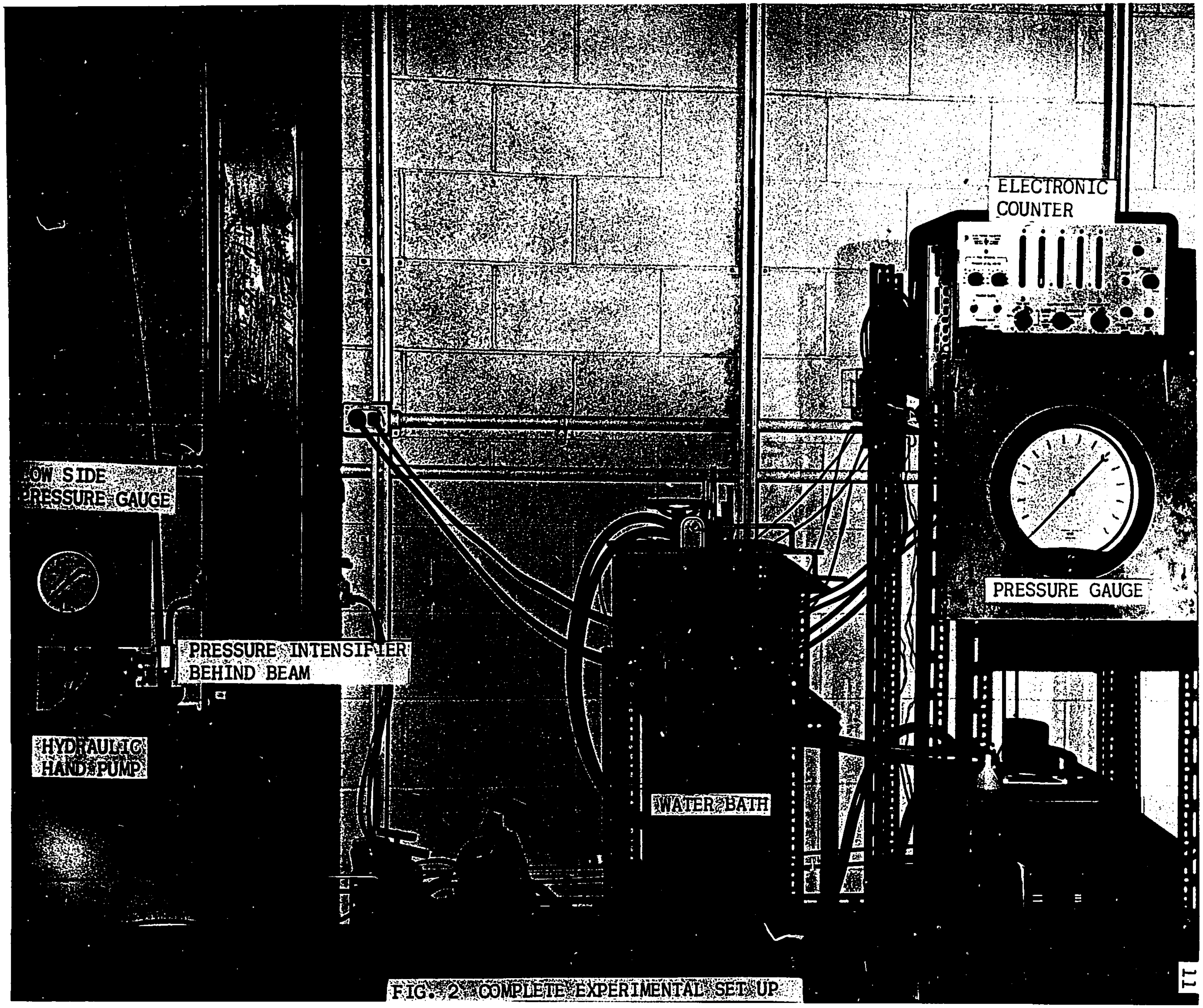


FIG. 2 COMPLETE EXPERIMENTAL SET UP

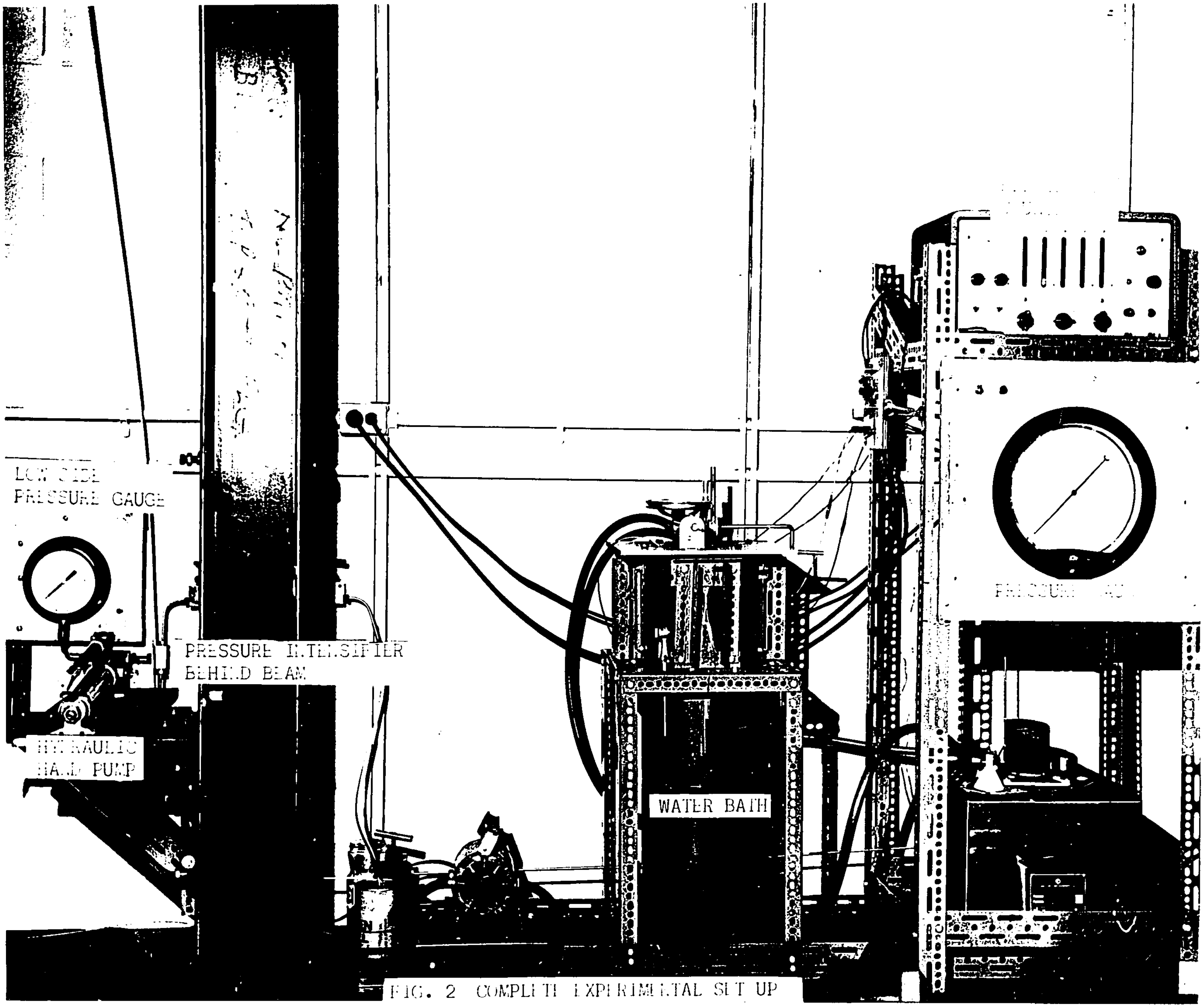


FIG. 2 COMPLETE EXPERIMENTAL SET UP

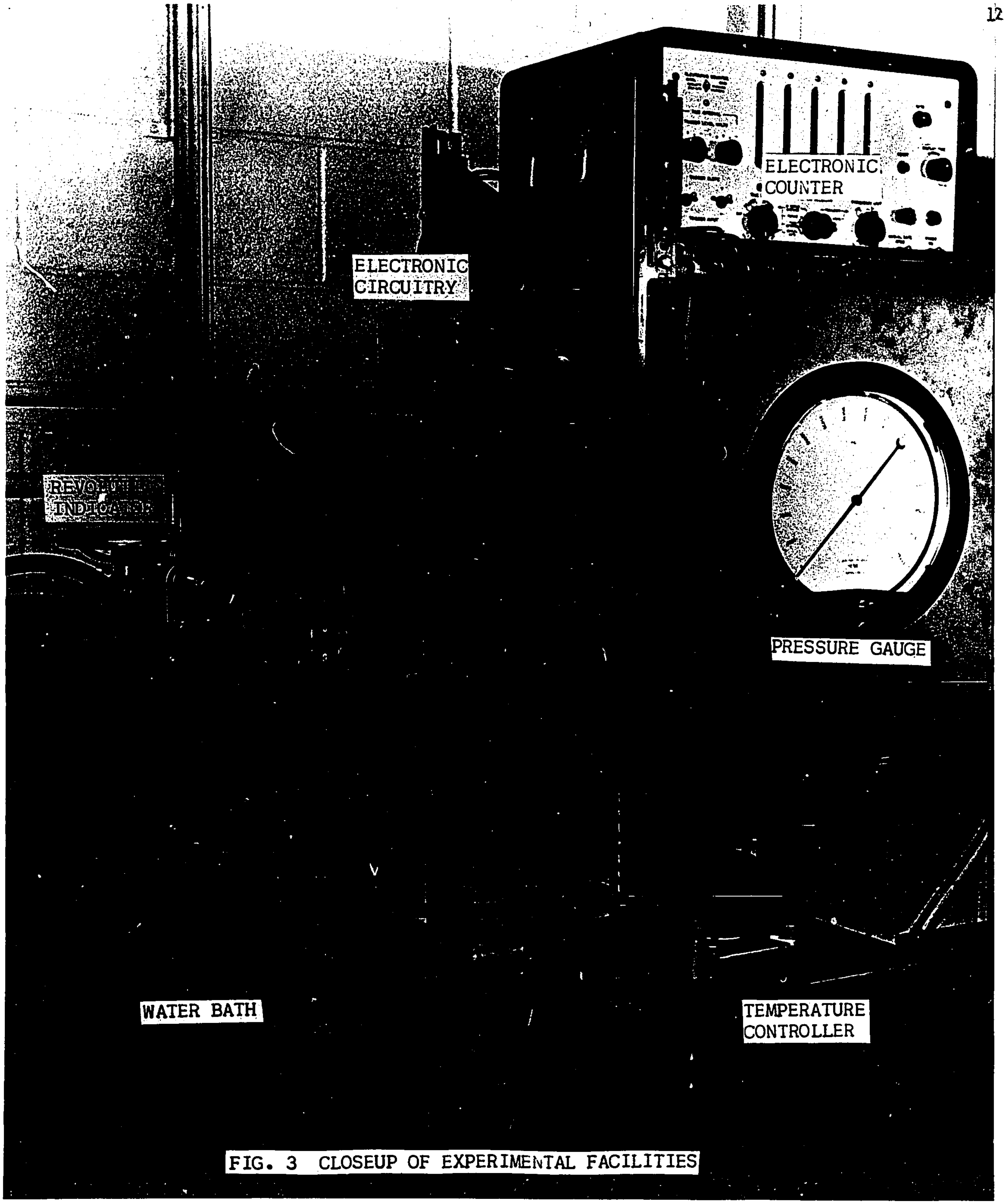


FIG. 3 CLOSEUP OF EXPERIMENTAL FACILITIES

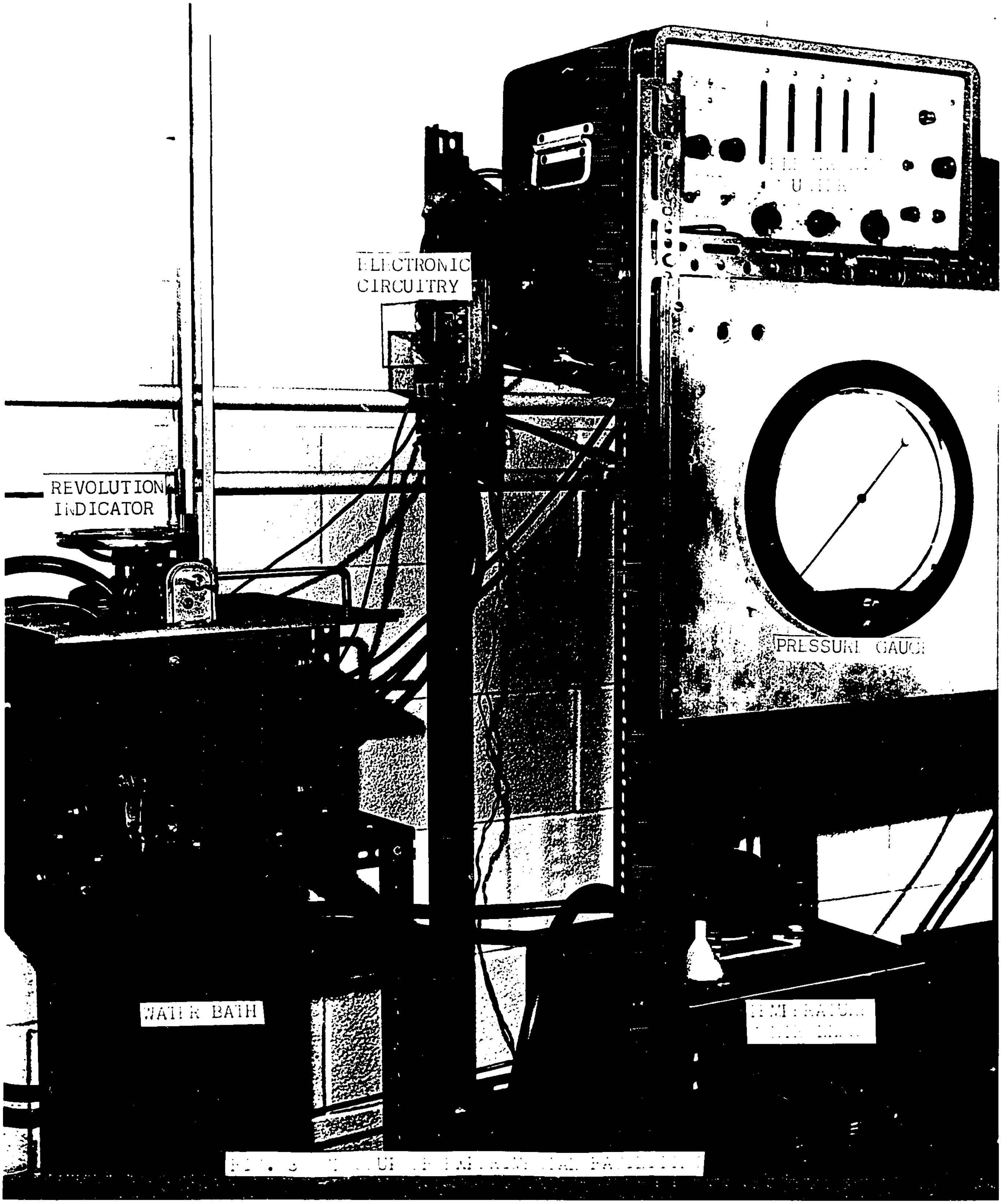


FIG. 3 [illegible] OF EXPERIMENTAL APPARATUS

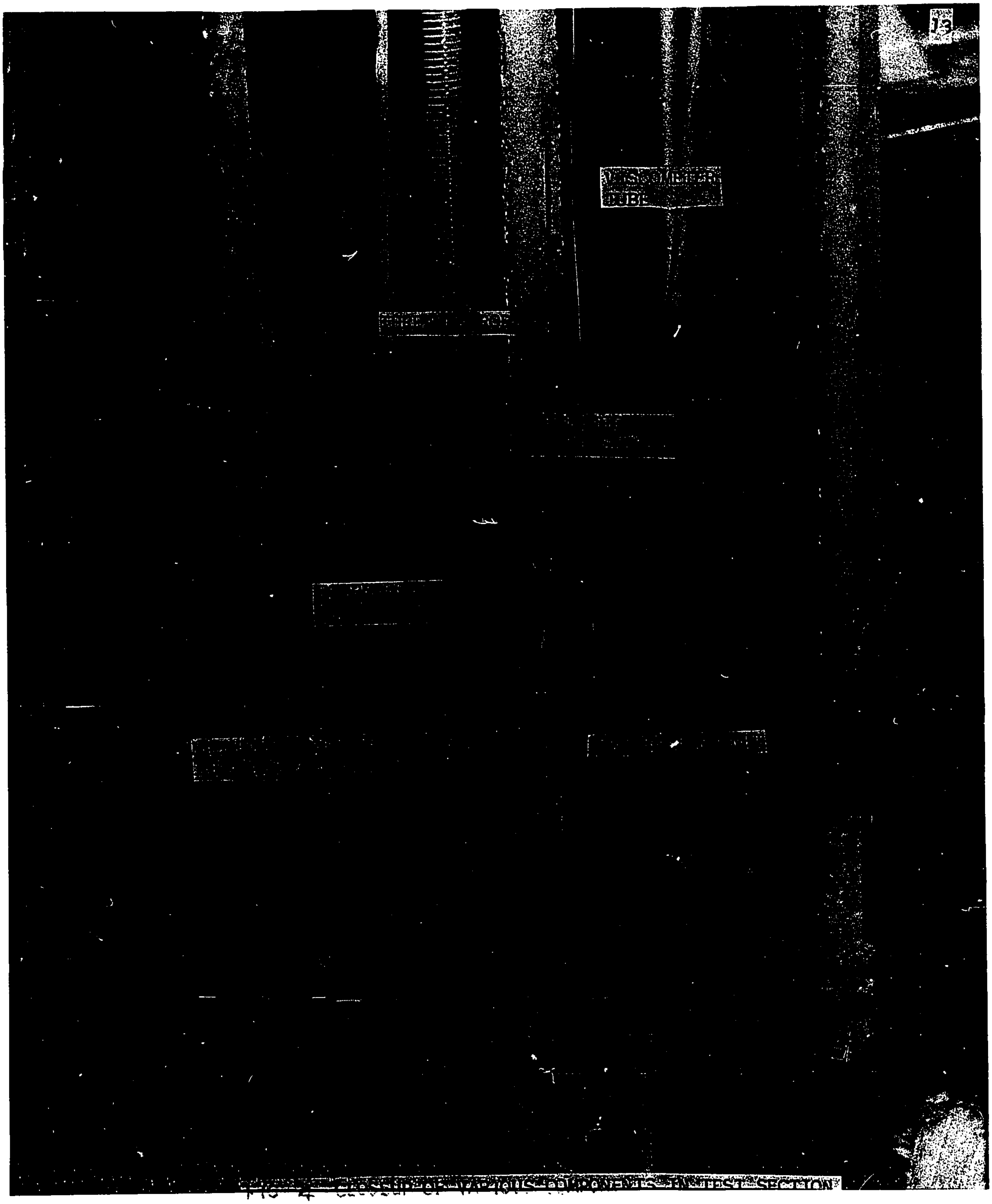
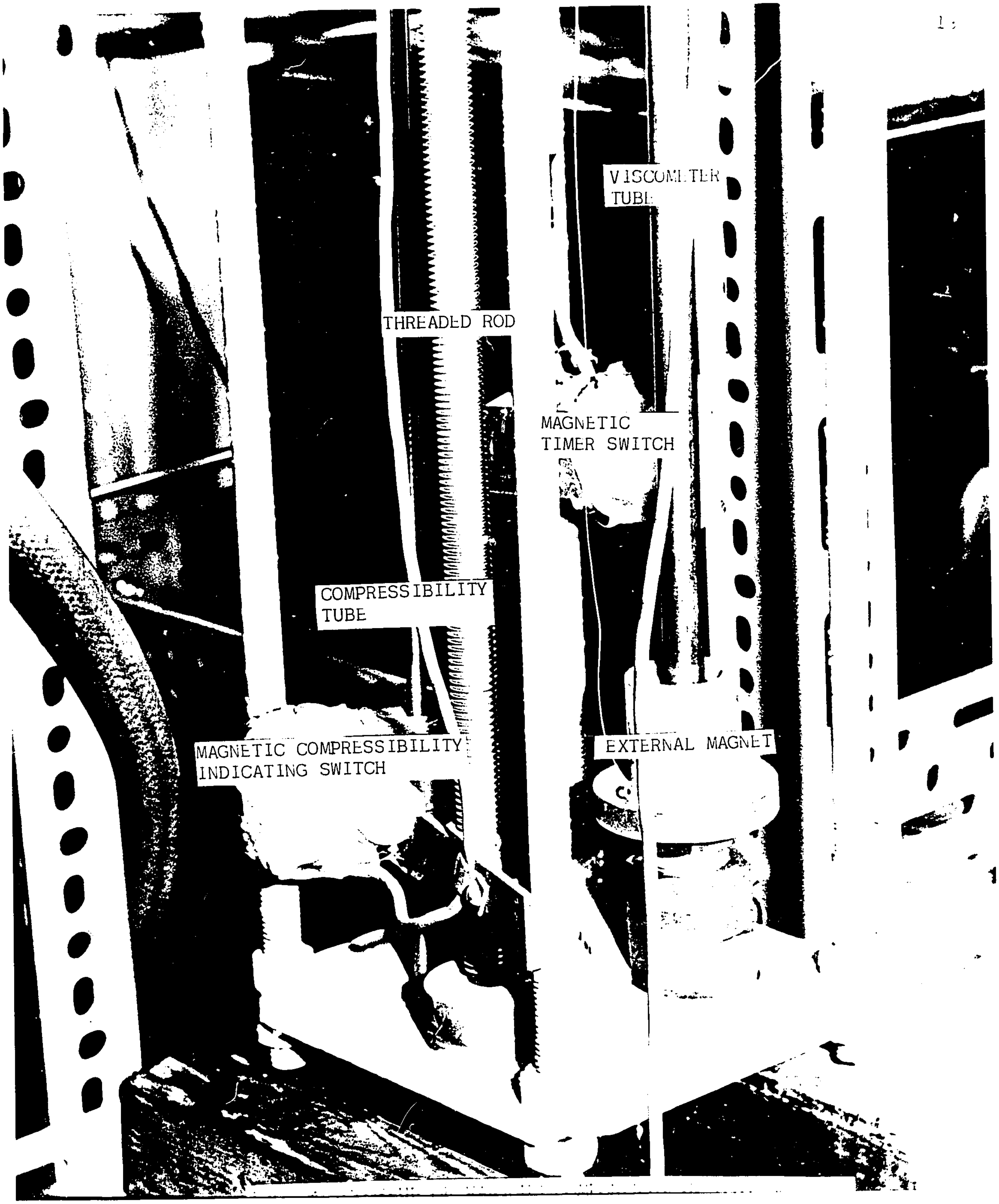


FIG 4 CLOSEUP OF VARIOUS COMPONENTS IN TEST SECTION


VISCOMETER
TUBE
THREADED ROD
MAGNETIC
TIMER SWITCH
COMPRESSIBILITY
TUBE
MAGNETIC COMPRESSIBILITY
INDICATING SWITCH
EXTERNAL MAGNET

external magnet, approximately five inches above the start switch, and the switches put in place. After waiting approximately fifteen to thirty seconds for the turbulence caused by raising the plummet to subside, the external magnet was raised higher and the plummet which was restricted by a plug in the fall tube was allowed to fall triggering the switches. After the time was recorded the procedure was repeated.

The estimated accuracy of the viscosity measurement was ± 1.14%. (refer to page 21 for error calculation)

## 2. COMPRESSIBILITY TUBE

The compressibility tube was joined to the fall tube at the top by means of high pressure tubing and fittings. The tube itself was 1/4 inch stainless steel high pressure tubing with an inside diameter of 0.083 inches and a length of 61.625 inches. A small tight fitting rubber piston was inserted into the compressibility tube to prevent the mixing of the hydraulic fluid and the test liquid, yet still to allow the transmission of pressure. A one inch long 1/16 inch diameter magnet was positioned on top of this rubber piston and by locating the position of this magnet the volume change with pressure could be calculated. The measurement of this position was made by an electronic circuit and another reed switch. The reed switch was mounted on a threaded rod which allowed the switch to travel up and down the length of the tube. When the switch came into proximity to the magnet the resulting electrical signal turned on a light on the control panel and the reading was recorded. The accuracy of the compressibility measurement was estimated to be within ± 0.61%.

### 3. PRESSURE SYSTEM

The pressure was applied for the system by means of an EnerPac hand operated hydraulic pump. This pump was capable of generating 10,000 psig. This pressure was applied to the low side of an Aminco 10:1 ratio pressure intensifier thus making the pressure system capable of delivering 100,000 psig. The pressure in the system was measured by a Heise Bourdon pressure gauge , with a 12 inch dial scaled from 0 to 75,000 psig and a precision of ± 50 psi.

Although these were the three main pieces of equipment, there were several other important accessories and techniques which should be noted here. The entire test section was maintained at constant temperature ± 0.5 °C for each run by means of a one foot diameter six foot long stainless steel water bath held at temperature by a Lab-line control unit and pump.

### 4. METHOD OF FILLING

The correct method of filling the test section was essential to reliable results. The section was filled from the top by the removal of two plugs, one for each tube. Long plastic spaghetti tubing was inserted through the openings, and pushed down to the bottom of the tubes. By using a hypodermic syringe the test liquid was slowly injected into the tubes through the spaghetti. After the level of the test fluid had reached the top of the test section and the spaghetti had been removed, the plummet was dropped several times to dislodge any bubbles that might have formed on the walls of the fall tube. The top plugs were then reinstalled and secured in position.

Before operation, the pressure system was also checked. Initial pressure was applied to the unit and the position of the compressibility magnet was determined after the release of this pressure. This procedure was repeated several times until no further movement in the position of this magnet could be detected.

## V. ERROR ANALYSIS

In the measurement of viscosity and compressibility there are various errors which must be taken into account. As the viscosity was calculated from the equation

$$\eta = k(\sigma - \rho)t \qquad 8$$

the error can be determined by analyzing the terms in this equation.

The instrument constant k was found for each individual run. By using the atmospheric viscosity and atmospheric density of the liquid and the fall time at zero gauge pressure, k was calculated. The error, then, in the determination of k would be due to the other variables in the formula and would be present in all subsequent portions of a particular run.

The first term to be considered is the viscosity at atmospheric pressure. This property was found experimentally by the use of Cannon-Ubbelohde viscometers in different ranges such that the efflux time was always greater than 200 seconds in accordance with American Society for Testing Materials procedures (1). The viscometers were calibrated using freshly distilled water at 20 °C as a reference, having a kinematic viscosity of 1.007 centistokes. With the viscometers calibrated and the instrument constants found, the error in finding the unknown kinematic viscosities were predicted. The error normally encountered in the time for the efflux bulb to empty was ± 0.8 seconds in 200 seconds. Therefore the error in kinematic viscosity was ± 0.8/200 x 100% = ± 0.40%.

The atmospheric density of the liquid mixtures was found experimentally by using a pycnometer with graduated limbs for use at various temperatures. The design of this pycnometer can be seen in figure (5) and a detailed report on it can be found in reference (36).

For the calibration of this instrument the volume A up to $B_1$ and $B_2$ was determined by using distilled water as the standard. This volume A was also found at the different temperatures of the experiment and thus the expansion of the glass was eliminated. The volume change with temperature and the weight were recorded, and hence density was found. The maximum deviation in the weight for any run between the start and finish was found to be

$$\frac{0.0164}{9.2989} \times 100\% = 0.176\%.$$

That is, the potential error due to evaporation was 0.176%. However, the error for evaporation was compensated for by the fact that it was assumed that the evaporation was uniform with time and the weights changed accordingly.

Each capillary tube was approximately 10 cm. in length and had a range of 0.5 ml. graduated in 0.01 ml. Each meniscus reading was made with the help of a lens to about 0.001 ml. If this

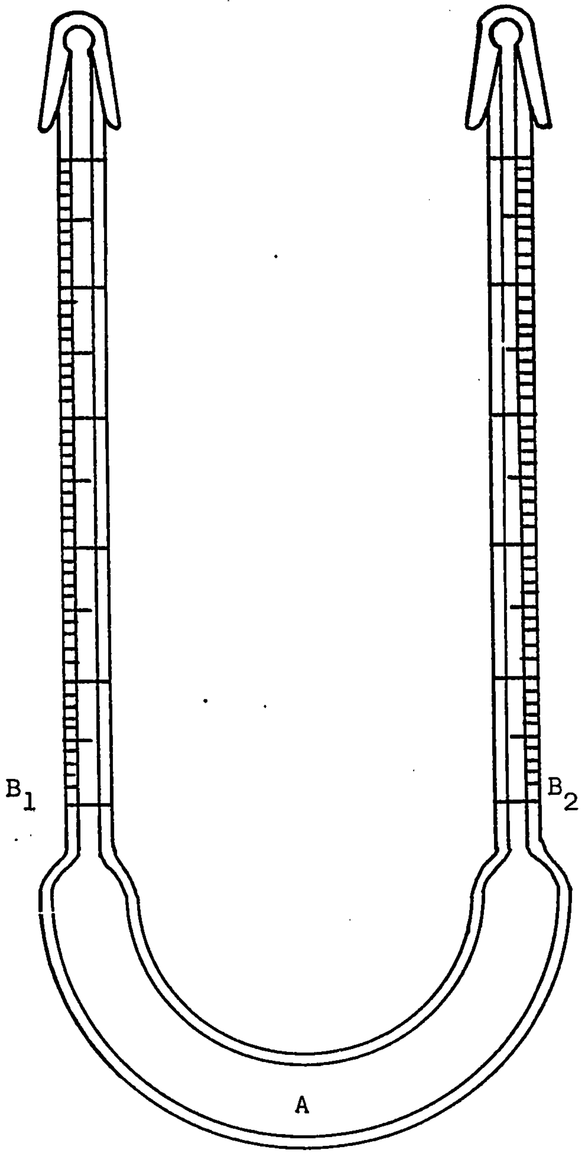


FIG. 5 PYCNOMETER FOR USE AT VARYING TEMPERATURES

figure was taken as the standard deviation of the reading in each arm, then the error of the combined observations in the two arms was $2 \times 0.001 = \pm 0.002$ ml. Now the total volume of A at 25 °C was 11.33148 ml. Therefore the % error in the volume

$$\text{was} \quad \frac{0.002}{11.33148} \times 100\% = \pm 0.0176\%$$

Thus the overall error in the absolute viscosity determination at atmospheric pressure was $\pm 0.40 + \pm 0.0176 = \pm 0.42\%$.

The second variable which affected the error in k was the combined term $(\sigma - \rho)$. Here the error in liquid density was negligible with respect to the error in the plummet density. The density of the plummet was determined by three methods. The first method consisted of physical weight and measurement techniques, assuming the rounded ends of the plummet to be half spheres with the radius 1/2 the diameter of the plummet. The other two methods were by volumetric and weight displacement in a pycnometer of 25 and 50 ml. capacity. The average density of the plummet for the three cases was found to be 7.2544 gm./cc. and the average deviation from the mean was 0.283%.

The last error in the determination of k was the fall time. The timing circuit measured the time of fall of the plummet to the nearest 0.01 seconds. As the time of fall for the least viscous fluid was approximately 12 seconds, the error involved in the measurement of fall time was at a maximum

$$\frac{0.01}{12} \times 100\% = 0.0833\%$$

Since $k = \frac{\eta}{(\sigma - \rho)t}$

the total error involved in determining the instrument constant was ± 0.08 + ± 0.28% + ± 0.42% = ± 0.78%.

Now that the error in k has been established the total error in the viscosity was found by seeing that the remaining terms that appear in the determination of absolute viscosity of the unknown mixtures were $(\sigma - \rho)$ and t. The errors in these terms as already shown were ± 0.28% and ± 0.08% respectively. Therefore the total error in the determination of absolute viscosity was ± 0.78 + ± 0.28 + ± 0.08 = ± 1.14%.

ERROR IN THE COMPRESSIBILITY MEASUREMENT

The compressibility $\frac{-\Delta V}{V_o}$ was a physically measured property as well as viscosity, and hence there were certain errors involved. One of these errors was in the measurement of $V_o$.

In obtaining $V_o$ there were many lengths of tubes and diameters that were measured. The length of the fall tube was measured to the nearest 1/16 of an inch and hence the error in the length was ± 0.03125 inches. The I.D. of the fall tube was ± 0.0005 in. The volume of the fall tube was $V = \frac{\pi D^2 l}{4}$. Therefore the error can be approximated by the relationship

$dV = \frac{\pi D^2 l}{4}\ dl + \frac{2\pi Dl}{4}\ dD$ where dl and dD were the errors in the length and diameter respectively. Therefore the error in the fall tube volume was $\pi/4(0.002897)$ in.$^3$ = ± 0.002276 in.$^3$

In a similar manner, the error in the volume of the compressibility tube was found to be ± 0.00475 in.$^3$ The error in the volume of connecting tubing was ± 0.0004053 in.$^3$ There were additional errors in the two tees and the error in the plummet itself however, these measurements had a tolerance of ± 0.0005 in. and the errors were negligible compared to those already mentioned. Therefore the total error in $V_o$ was ± ( 0.002276 + 0.00475 + 0.0004053) in.$^3$ Therefore the % error in $V_o$ was 0.0074313/1.88218 x100% = ± 0.395%.

The remaining term in the compressibility was the $\Delta V$. The compressibility indicator traveled along the compressibility tube by the advancement of a threaded rod at the rate of 1/11 of an inch per revolution. The control of this rod was such that 1 degree or 1/360 of a revolution could be indicated. However, the readings were only reproducible to ± 30 degrees, and hence the error in the length was $\frac{30}{360} \times \frac{1}{11}$ in. = 0.00758 in.

The error in the diameter of the compressibility tube has already been given as ± 0.0005 in. Therefore the error in the $\Delta V$ measurement was $\pi/4(0.083^2 \times 0.00758 + 2 \times 0.083 \times 0.0005 \times 61.625)$ = ± 0.004058 in.$^3$ Therefore the % error in $\Delta V$ was $\frac{0.004058}{1.88218} \times 100\%$

± 0.2156%. Therefore the total error in the compressibility measurement was ±( 0.395 + 0.2156) = ± 0.61%.

Since the density at high pressures was one property that was important, the error in this property will be discussed. For any experimental test run, the mass was a constant $\rho_o V_o$. At any elevated pressure the mass remained a constant $\rho V$.

That is $\rho_o V_o = \rho V$ or $\rho_o = \frac{\rho V}{V_o}$

But $V = V_o + \Delta V$

$$\rho_o = \frac{\rho(V_o + \Delta V)}{V_o}$$

$$\rho_o = \rho\left(1 + \frac{\Delta V}{V_o}\right)$$

$\rho_o = \rho(1 - \text{compressibility})$ Therefore the density at any pressure =(original density)/(1 - compressibility).

Here we have an error in the density at high pressures coming from the atmospheric density which was reported as ± 0.0176% and the error in compressibility of ± 0.61%. Therefore the estimated error in the density at high pressure was ± 0.63%.

There were also other uncertainties in the system but either no value could be placed on them or some means was applied to compensate for them. As was mentioned in the equipment section the run temperatures were kept within ± 0.5 °C and when the atmospheric runs were performed the temperatures were kept within ± 0.1 °C with a thermometer furnished by the National Bureau of Standards.

In making up the test solutions, freshly distilled water was used and acetone that was certified 99 mole% pure was supplied by Fisher Scientific. The solutions were prepared using pipettes, and the graduations on the pipettes were to the nearest 0.01 ml. This would make an error of 0.005 ml. for water and 0.005 ml. for the acetone, for a combined error of $\frac{0.01}{30.84343} \times 100\% = 0.0324\%$.

Therefore the solution mixtures were assumed to be the recorded percentages ± 0.0324%.

In order to minimize other errors, a temperature and a pressure correction was applied in analyzing the data. The runs were performed at essentially constant temperature, and as the major effect of temperature was on $V_o$ a correction was applied to this term. The $V_o$ at 35 °C would be greater than the $V_o$ at 25 °C by the following relationship

$$V_{o\ 25} = V_{o\ 35}\,(1 + B\Delta T) \qquad 9$$

where B was the coefficient of thermal volume expansion. The linear coefficient of thermal expansion for type 316 stainless steel was $8.9 \times 10^{-6}\ /^{o}F$. The coefficient of volume expansion B may be approximated by 3 times the coefficient of linear expansion.

$$\text{Therefore}\quad B = 3 \times 8.9 \times 10^{-6}\ /^{o}F$$

$$= 2.52 \times 10^{-5}\ /^{o}F$$

$$= 4.536 \times 10^{-5}\ /\ ^{o}C.$$

From this relationship new $V_o$'s were calculated for the test runs at 35 °C and 45 °C thus minimizing any errors due to expansion of the tubes because of temperature.

The largest correction, however, was the correction that must be made for the expansion of the tubes due to the increased pressure. The correction was made according to the principles laid down in the book Applied Elasticity (35). For this discussion the nomenclature used in that text will be used . According to figure (6) let us consider a thick cylinder, submitted to uniform pressure on the inner and outer surfaces. Let a and b be the inner and outer radii of the cylinder and $P_i$ and $P_o$ be the internal and external pressures respectively. Upon integration of the compatability equation we have:

$$Eu = 2C_2(1-\surd)r - C_3(1-\surd)1/r \qquad 10$$

where u is the increase in radius

E is Young's modulus of elasticity = 28 x $10^6$ for 316 stainless

$\surd$ is Poisson's ratio = 1/3 for stainless.

Also for a thick walled cylinder

$$2C_2 = \frac{P_i a^2 - P_o b^2}{b^2 - a^2} \qquad 11$$

and

$$C_3 = \frac{a^2 b^2 (P_o - P_i)}{b^2 - a^2} \qquad 12$$

Now, in this investigation $P_o$ = 0 psi., that is 0 psig.

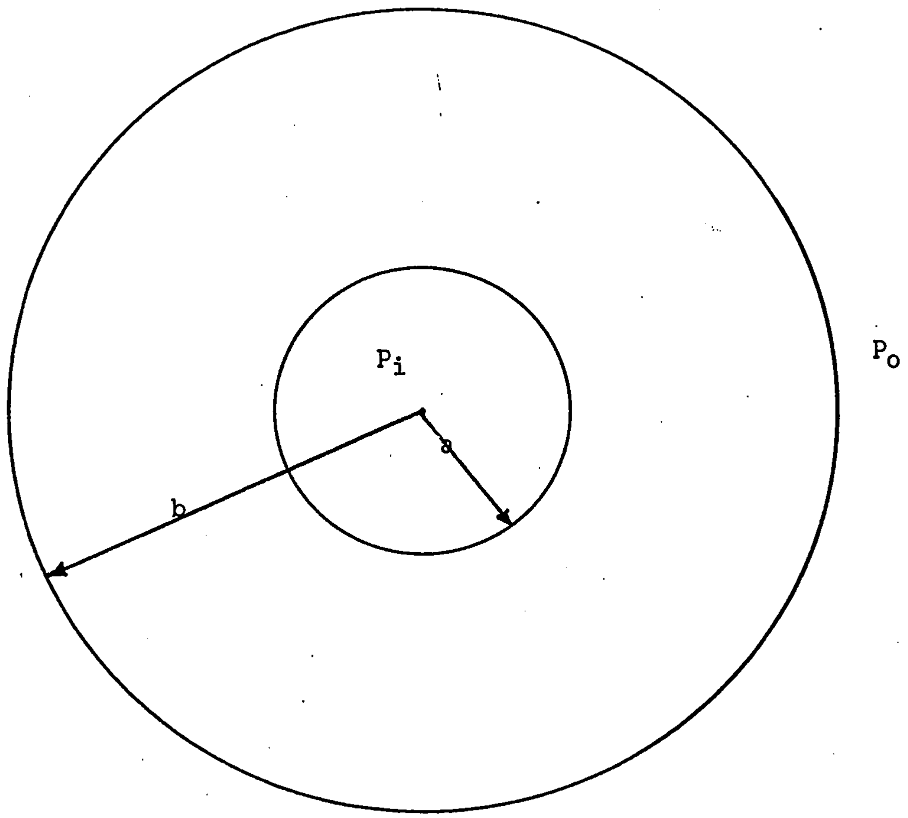


FIG. 6 THICK WALLED CYLINDER UNDER UNIFORM PRESSURE

Thus,

$$2C_2 = \frac{Pi}{\frac{b^2}{a^2} - 1} \qquad 13$$

and

$$C_3 = \frac{-b^2Pi}{\frac{b^2}{a^2} - 1} \qquad 14$$

Also for this experimental set up in both the fall tube and the compressibility tube b/a = 3. Therefore Eu at r = a was

$$Eu = \frac{Pi}{\frac{b^2}{a^2} - 1}(1-1/3)a + \frac{b^2Pi}{\frac{b^2}{a^2} - 1}(1 + 1/3)1/a \qquad 15$$

$$= \frac{Pi}{8}\left(\frac{2a}{3}\right) + \frac{b^2Pi}{8}(4/3a)$$

$$= Pia/12 + b^2Pi/6a$$

$$= \frac{a^2Pi + 2b^2Pi}{12a}$$

$$u = \frac{a^2Pi + 2b^2Pi}{12aE} \qquad 16$$

Also $(\sigma_r + \sigma_\theta) + E\epsilon_z = \sigma_z = 0$ (ends free to expand) 17

Therefore $(\sigma_r + \sigma_\theta) = -E\epsilon_z$

Now $$\sigma_r + \sigma_\theta = (2Pia^2)/(b^2-a^2) \qquad 18$$

Therefore $$\epsilon_z = \frac{-2Pia^2}{(b^2 - a^2_E)}$$

$$= \frac{-2Pi}{(\frac{b^2}{a^2} - 1)E}$$

$$= Pi/4E \qquad 19$$

Knowing the change in the radius and the length of the tubes with pressure, a correction was made in the computer program that handled the data and thus this error was minimized.

The expansion of the tubes with pressure will also give rise to an error in the viscosity measurements. This error is due to the increase in clearance between the plummet and tube walls and can be predicted mathematically and thus minimized using the same analysis as used in the density correction. However, the error was not discovered in time to incorporate a correction into the quoted data. Consequently a correction which will increase the quoted viscosity values by 1.3% at the maximum pressure (40,000 psig.) is suggested. The correction may be applied proportionately at intermediate pressures.

# VI. RESULTS AND DISCUSSION

## A. TREATMENT OF COMPRESSIBILITY DATA

One of the first concerns in the treatment of the compressibility data was the frictional effect of the rubber piston. Figure (7) showing a 45% acetone 55% water solution at 25, 35, and 45 °C, demonstrates adequately that the effect of friction on the rubber piston at increasing and decreasing pressures was indeed negligible. However, to establish that this was the usual case and not just a coincidence, data for increasing and decreasing pressure were taken for several other runs as well and the same result was obtained. Examples of this can be found in Appendix (1).

An additional test of the reliability of the compressibility data was to check the deviation between separate runs performed on separate days. Good agreement was again found to be the case as evidenced by the 20% acetone 80% water run at 35 °C figure (8).

An additional concern was eliminated when it was found that no apparent discrepancies resulted when a test run was started at high pressure and reduced as in the case of the pure acetone run at 25 °C, figure (9).

As shown in the error analysis, page (23), the compressibility or density data was found to be in error by ± 0.61% for compressibility and ± 0.63% for density. Since there was only a

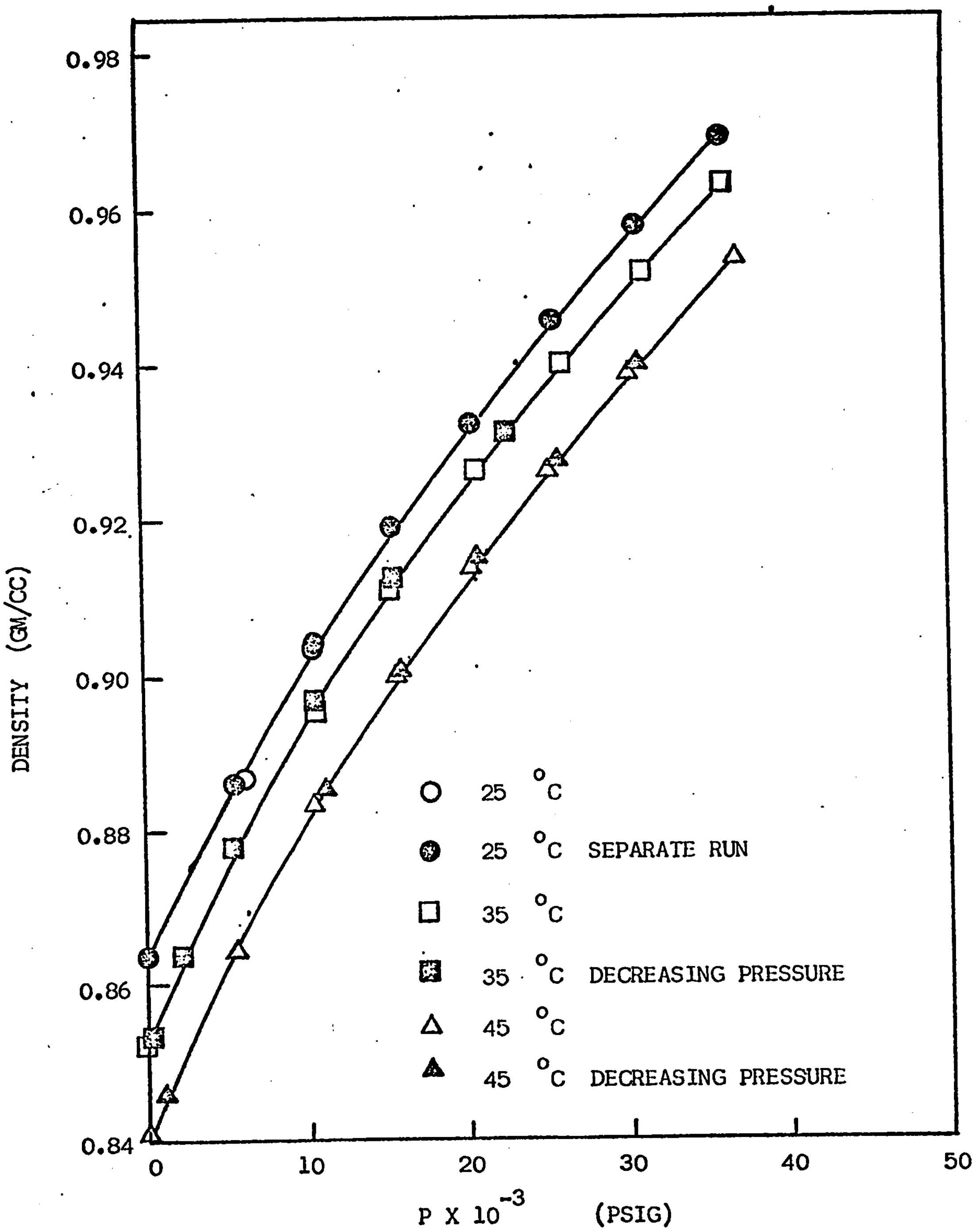


FIG. 7 EFFECT OF PRESSURE ON DENSITY OF 45% ACETONE 55% WATER SOLUTION

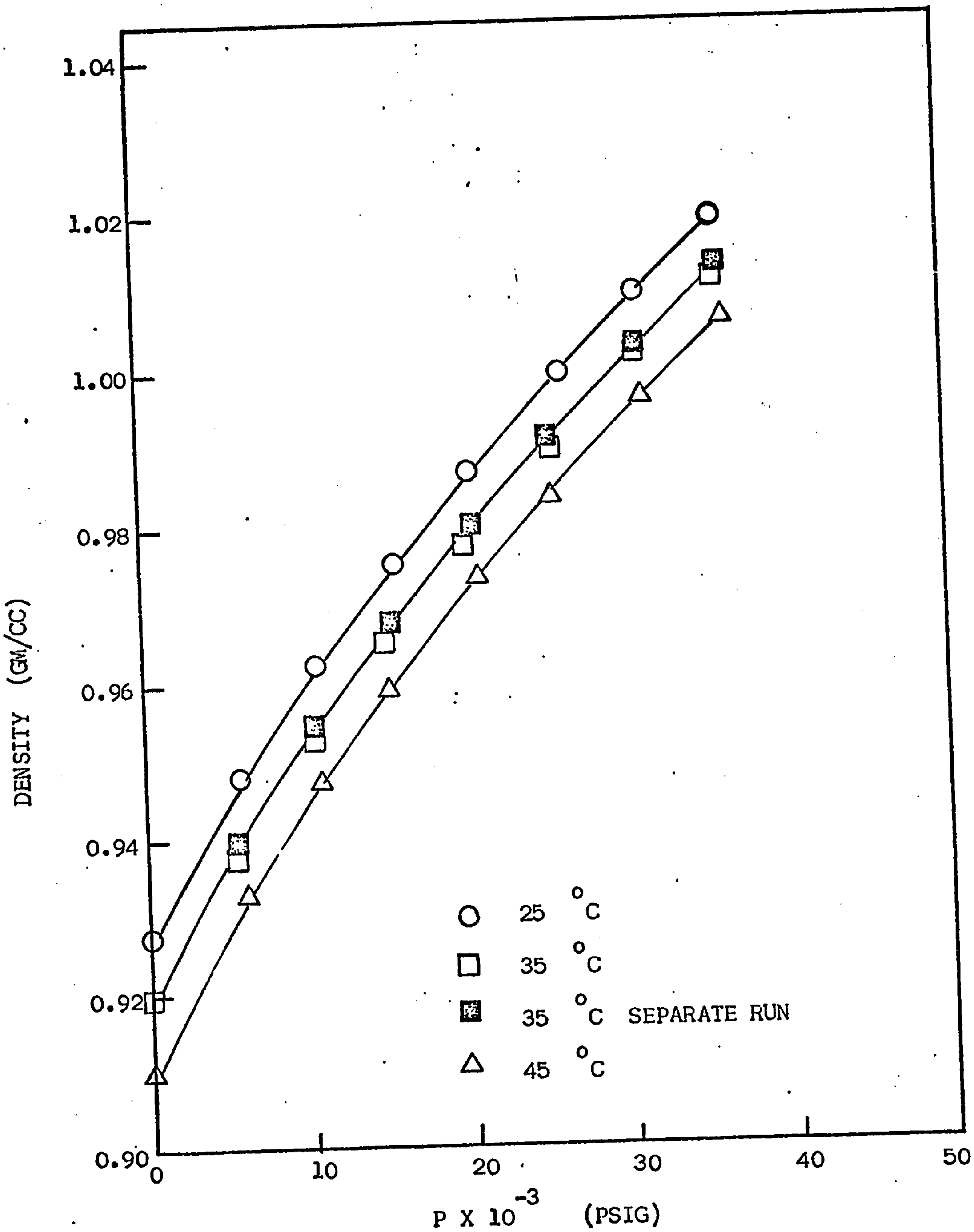


FIG. 8 EFFECT OF PRESSURE ON DENSITY OF 20% ACETONE 80% WATER SOLUTION

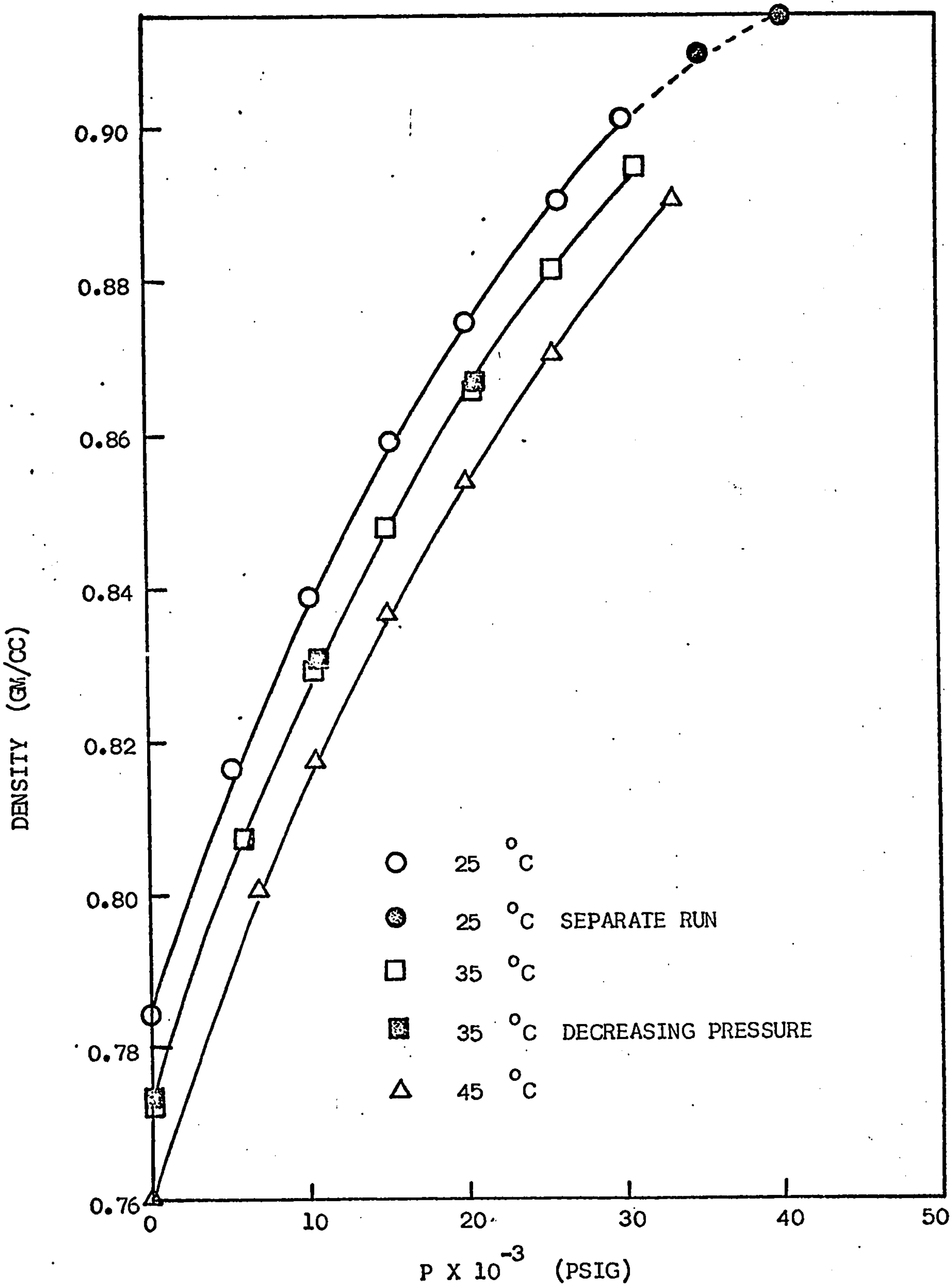


FIG. 9 EFFECT OF PRESSURE ON DENSITY OF PURE ACETONE

very limited amount of data in the literature for this particular mixture, only distilled water data could be used as a comparison of results under high pressure. In figure (10) the data of Whalley and Kell (37) at 25 °C was shown with the experimental data, and the maximum deviation was found to be approximately 0.55% which was within the error limits placed upon these results.

## B. TREATMENT OF VISCOSITY DATA

Upon examination of the viscosity data at atmospheric pressure and the test runs from the experimental equipment, the instrument constants were calculated. The results of these calculations are shown in table (1). It was seen that there was no apparent relationship between the liquid concentration and the constant. However, there was a temperature dependency. It was clearly seen in every case that as the temperature increased the instrument constant decreased. This dependency that was noted, added weight to the reason for finding an instrument constant for each run rather than an average instrument constant. For each test run pressure, between 5 and 10 fall times were recorded in order to insure reproducibility of the results and the error in the viscosity was predicted at ± 1.14% (page (21)).

As the entire viscosity measuring technique was based on the fact that terminal velocity had been essentially attained when the timer circuit was started, it was felt that this fact should be proved. R.A. Horne (22) suggested that the plummet

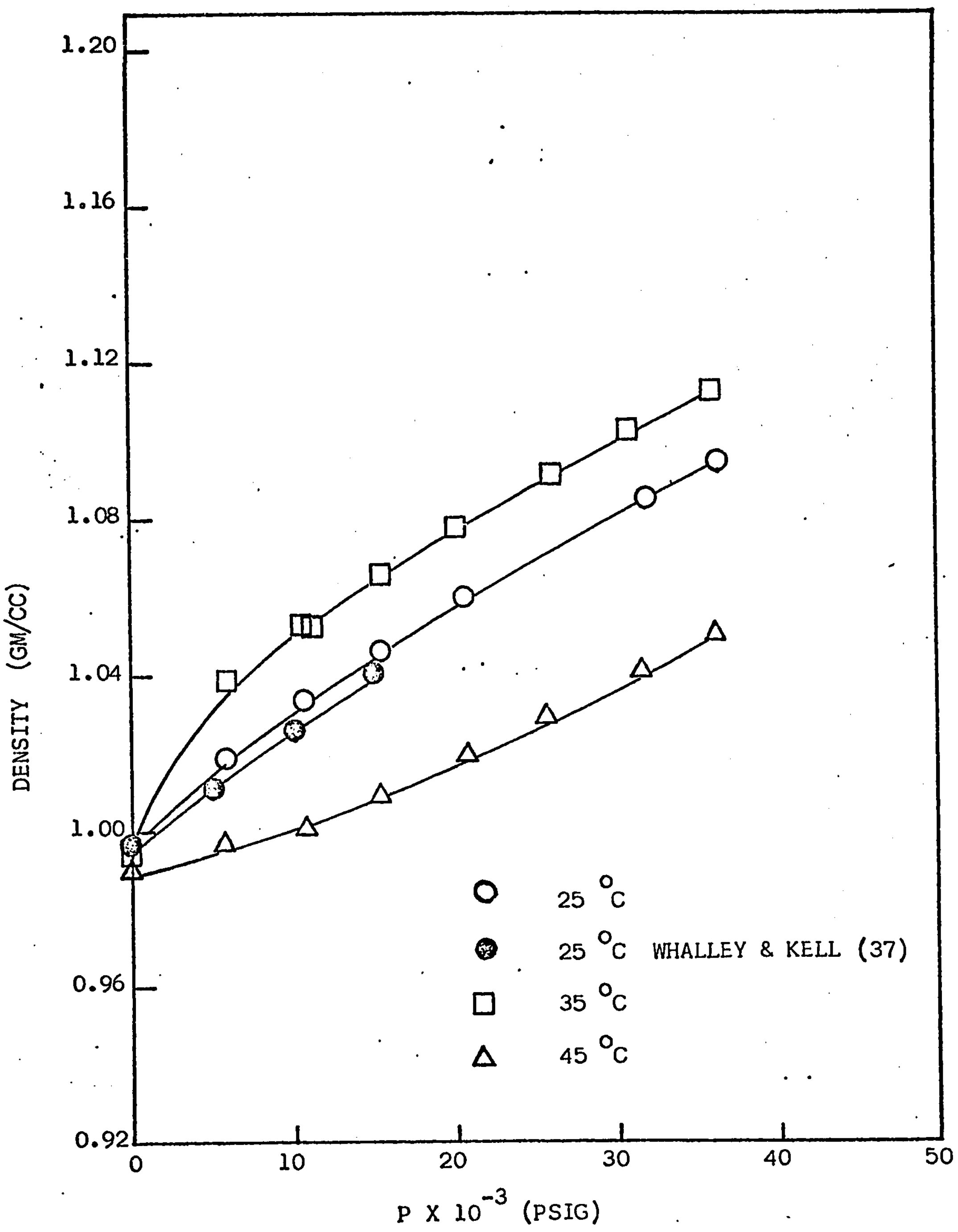


FIG. 10 EFFECT OF PRESSURE ON DENSITY OF PURE WATER

| MOLE % ACETONE | INSTRUMENT CONSTANT $k \times 10^3$ | | |
|---|---|---|---|
| | 25 °C | 35 °C | 45 °C |
| 0 | 3.556 | 3.478 | 3.425 |
| 5 | 3.651 | 3.435 | 3.318 |
| 10 | 3.608 | 3.451 | 3.383 |
| 15 | 3.686 | 3.515 | 3.484 |
| 20 | 3.630 | 3.511 | 3.432 |
| 25 | 3.527 | 3.459 | 3.381 |
| 45 | 3.461 | 3.417 | 3.321 |
| 75 | 3.301 | 3.242 | 3.225 |
| 100 | 3.371 | 3.322 | 3.276 |

TABLE 1 VARIATION OF INSTRUMENT CONSTANT WITH TEMPERATURE

be elevated 4 to 5 cm. above the start switch in order to achieve this state. However, to insure terminal velocity this system was designed to have 4 to 5 inches above the start signal to achieve the desired result. For the worst case the Reynold's number never exceeded ninety-three. Also experimental data taken over different fall distances resulted in velocities that were within 1% of each other. For a theoretical determination of fall time necessary to approach terminal velocity see Appendix (2). It was determined that to approach within 99.9% terminal velocity only 0.1 seconds of fall time was necessary. The actual total fall time always exceeded 12 seconds.

## C. PRESSURE VOLUME CORRELATION

The density of the solutions was plotted against pressure for the three temperatures, and these results are shown in Appendix (1). With the exception of pure water, figure (10) there was very little dependency of density change with temperature but the densities increased with pressure. Rather than correlate the density with pressure, the equation of state of Chaudhuri et al (6),

$$P = rB_{(v)}^{\;q} \qquad 5$$

was employed. In this correlation, $B_{(v)}$ was a volume function equal to

$$(v_o/v)^4 - (v_o/v)^2 .$$

and r and q were constants. As shown in table (2) and by figure (11) the degree of fit of this correlation was extremely

| MOLE % ACETONE | $r \times 10^{-5}$ (PSIG) | | | q | | | CORRELATION COEFFICIENT | | |
|---|---|---|---|---|---|---|---|---|---|
| | 25 °C | 35 °C | 45 °C | 25 °C | 35 °C | 45 °C | 25 °C | 35 °C | 45 °C |
| 0 | 1.857 | 2.411 | 1.506 | 1.155 | 1.610 | 0.729 | 0.9995 | 0.9956 | 0.9922 |
| 5 | 1.714 | 1.666 | 1.633 | 1.017 | 0.999 | 0.993 | 0.9999 | 0.9997 | 0.9997 |
| 10 | 1.928 | 3.288 | 2.370 | 1.121 | 1.702 | 1.563 | 0.9995 | 0.9894 | 0.9975 |
| 15 | 1.781 | 1.682 | 1.658 | 1.114 | 1.092 | 1.129 | 0.9994 | 0.9998 | 0.9997 |
| 20 | 1.555 | 1.590 | 1.520 | 1.059 | 1.106 | 1.104 | 0.9919 | 0.9999 | 0.9999 |
| 25 | 1.501 | 1.290 | 1.193 | 1.106 | 1.000 | 0.911 | 0.9995 | 0.9986 | 0.9973 |
| 45 | 1.163 | 0.957 | 1.108 | 1.081 | 1.020 | 1.106 | 0.9996 | 0.9984 | 0.9996 |
| 75 | 0.961 | 0.861 | 0.787 | 1.090 | 1.065 | 0.939 | 0.9994 | 0.9994 | 0.9978 |
| 100 | 0.785 | 0.729 | 0.688 | 1.143 | 1.128 | 1.116 | 0.9995 | 0.9998 | 0.9999 |

TABLE 2 r AND q AND DEGREE OF FIT OF RELATIONSHIP $P = rB_{(v)}^{q}$

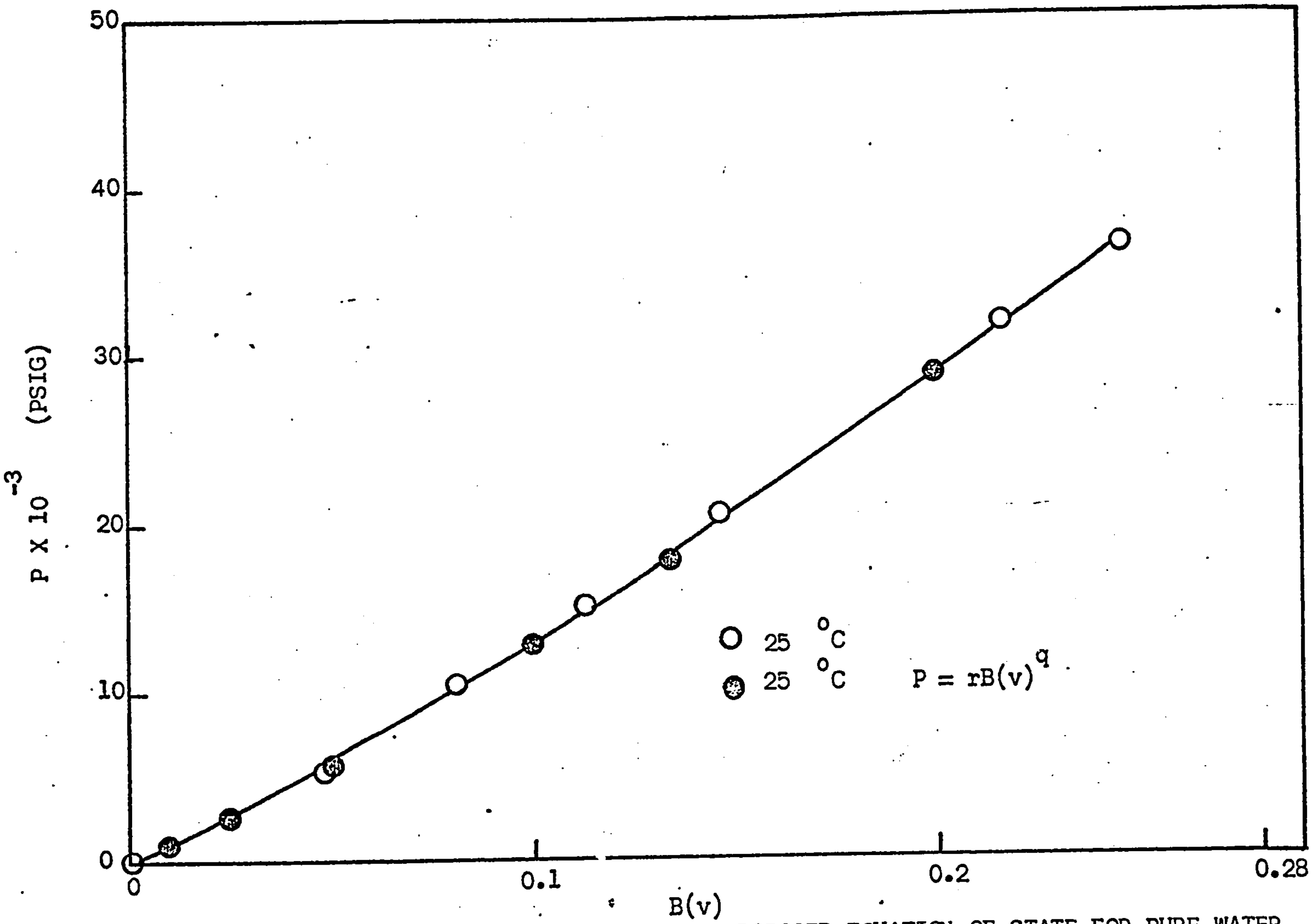


FIG. 11 COMPARISON OF DATA WITH PROPOSED EQUATION OF STATE FOR PURE WATER

good. In all cases the correlation coefficient indicated that there was less than a 0.001% chance of having rejected the null hypothesis of having no correlation and still being wrong.

From the compressibility data Appendix (3) it was noted that when another liquid was added to water, the compressibility was decreased as compared to water alone, regardless of the liquid added having a greater or lesser compressibility than that of pure water. This phenomenon was also noted by Bridgman (2). The data corresponded to this behaviour until the volume of added liquid became greater than the volume of water. This corresponded to a 20% acetone 80% water solution by moles. However, this was more than 50% acetone by volume. The above compressibility phenomenon was not noted, however, where the temperature was at 45 °C.

Attempts were made to correlate r and q with either composition and/or temperature, however, no satisfactory correlation could be found.

### D. VISCOSITY PRESSURE CORRELATION

The viscosity behaviour of the liquid systems studied, showed several interesting effects. The first interesting effect was the anomoly of water. As the pressure in the system increased the viscosity of water first decreased, unlike other liquids. This trend is shown in figure (12), and it was noted that this effect did not occur when the temperature was at 45 °C. This was in agreement with the works of Stanley and Batten (34), and

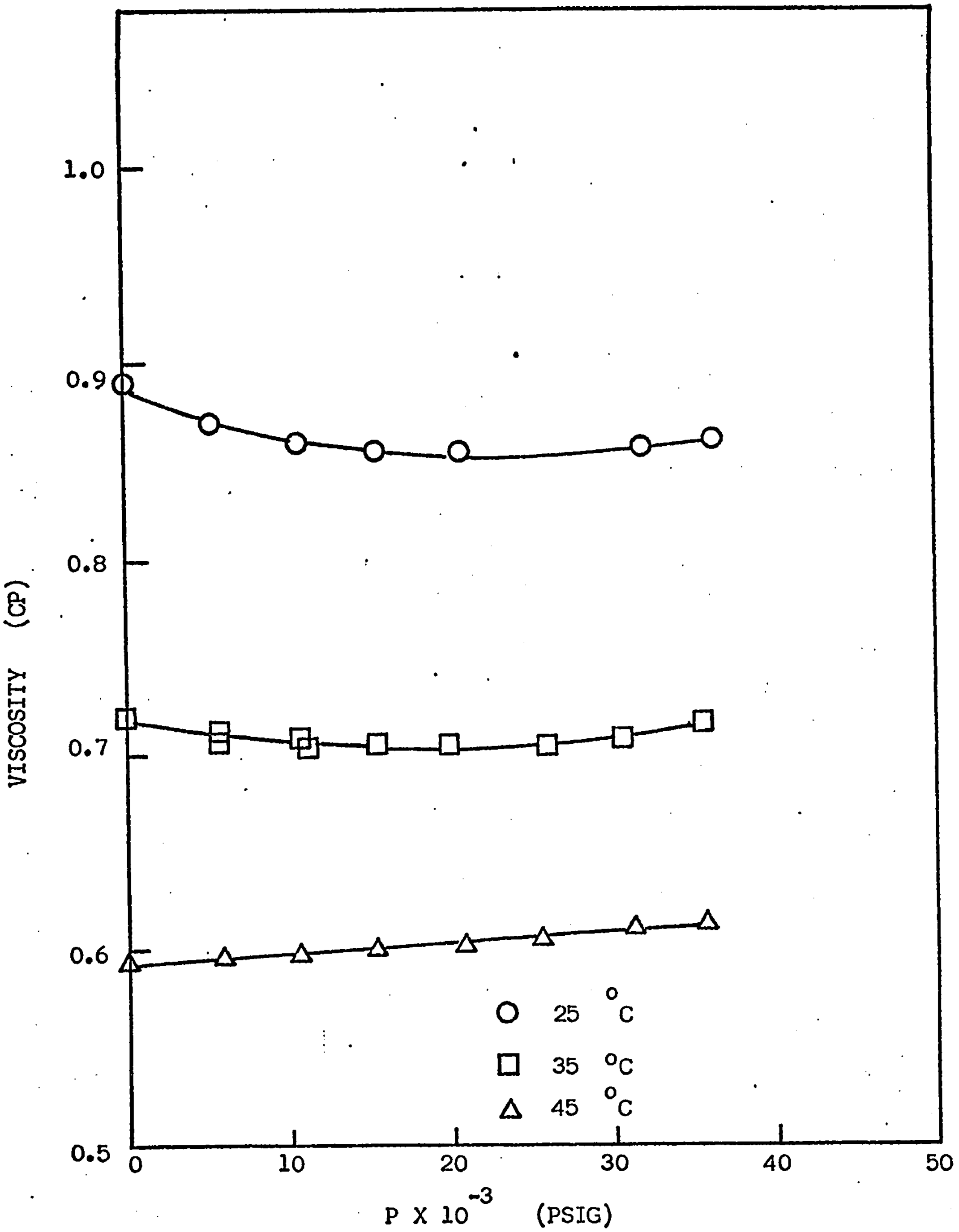


FIG. 12 EFFECT OF PRESSURE ON VISCOSITY OF PURE WATER

Horne and Johnson (22). The anomoly in water could be explained as a function of two simultaneously occuring processes. Under pressure, there would be a breakup of the hydrogen bonded water causing a decrease in viscosity, and there would also be a compaction of the associated and unassociated water molecules which would result in an increase in viscosity.

It has been postulated by Franks and Good (17) that at one atmosphere pressure and 36 °C water undergoes a change from a quasi-crystalline structure to a suspension of clusters. Hence at temperatures above 36 °C the decrease in viscosity with pressure would not be noted. This explained the absence of this phenomenon at 45 °C. It was also noted that as the pressure increased more and more, the viscosity of water eventually started to increase as well.

All the other liquid solutions increased in viscosity with an increase in pressure. The viscosity pressure relationship used was of the form:

$$\eta = \eta_o \exp(mP) \qquad 4$$

where m was a constant determined from the experimental data. The viscosity pressure relationship could be correlated to this form or it could be correlated in a linear fashion

$$\eta/\eta_o = m_o P + 1.0 \qquad 20$$

Both methods gave good correlation fits, tables (3,4), however, each method was a compromise. The viscosities seemed to be linear figure (13) at lower pressures and then exponential as the pressure

| MOLE % ACETONE | m x 10 $^{6}$ (PSIG$^{-1}$) | | | CORRELATION COEFFICIENT | | |
|---|---|---|---|---|---|---|
| | 25 °C | 35 °C | 45 °C | 25 °C | 35 °C | 45 °C |
| 0 | -1.392 | -0.591 | 0.745 | 0.4995 | 0.6318 | 0.9423 |
| 5 | 1.834 | 2.675 | 3.075 | 0.9927 | 0.9982 | 0.9984 |
| 10 | 5.566 | 6.123 | 6.170 | 0.9960 | 0.9947 | 0.9953 |
| 15 | 9.525 | 9.502 | 9.765 | 0.9950 | 0.9949 | 0.9925 |
| 20 | 13.179 | 12.506 | 11 965 | 0.9922 | 0.9952 | 0.9946 |
| 25 | 15.257 | 14.885 | 14.097 | 0.9938 | 0.9926 | 0.9921 |
| 45 | 23.813 | 21.837 | 20.292 | 0.9985 | 0.9964 | 0.9938 |
| 75 | 24.210 | 24.152 | 24.041 | 0.9911 | 0.9885 | 0.9835 |
| 100 | 28.293 | 28.237 | 27.264 | 0.9847 | 0.9798 | 0.9812 |

TABLE 3 VARIATION AND DEGREE OF FIT OF m WITH COMPOSITION

| MOLE % ACETONE | $m_o \times 10^6$ (PSIG$^{-1}$) | | | CORRELATION COEFFICIENT | | |
|---|---|---|---|---|---|---|
| | 25 °C | 35 °C | 45 °C | 25 °C | 35 °C | 45 °C |
| 0 | -0.669 | -0.195 | 0.930 | 0.6225 | 0.2917 | 0.9672 |
| 5 | 1.869 | 2.899 | 3.260 | 0.9922 | 0.9970 | 0.9981 |
| 10 | 5.887 | 6.444 | 6.548 | 0.9988 | 0.9986 | 0.9983 |
| 15 | 10.674 | 10.764 | 10.866 | 0.9997 | 0.9993 | 0.9991 |
| 20 | 15.569 | 14.865 | 14.043 | 0.9995 | 0.9998 | 0.9996 |
| 25 | 19.086 | 18.351 | 17.455 | 0.9998 | 0.9997 | 0.9971 |
| 45 | 36.047 | 30.798 | 27.759 | 0.9964 | 0.9991 | 0.9997 |
| 75 | 35.190 | 34.887 | 34.113 | 0.9996 | 0.9998 | 0.9998 |
| 100 | 39.614 | 38.937 | 39.449 | 0.9998 | 0.9997 | 0.9997 |

TABLE 4 VARIATION AND DEGREE OF FIT OF $m_o$ WITH COMPOSITION

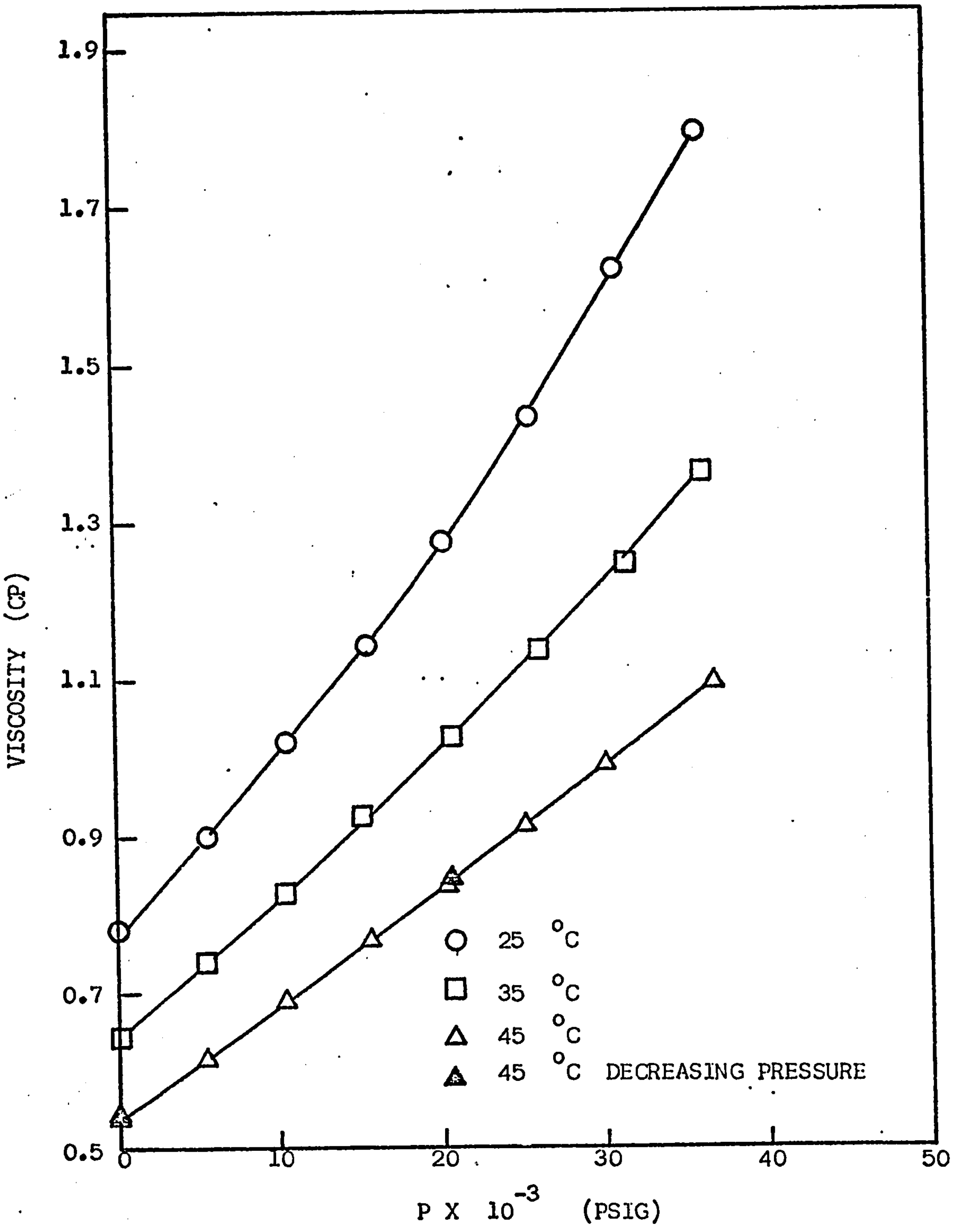


FIG. 13 EFFECT OF PRESSURE ON VISCOSITY OF 45% ACETONE 55% WATER SOLUTION

increased. The data was fitted to the linearized form of equation (4) and all the solutions gave good correlation coefficients with no better than a 0.001 chance of being incorrect. This was true for every liquid except pure water at 25 and 35 °C. The reason for this discrepancy has already been explained. It should be noted, however, that pure water at 45 °C was adequately fitted to this form. Thus it could be said that pure water above approximately 36 °C behaves as other liquids, Appendices (4,5).

The value of m in equation (4) was found not to be constant but rather to be a function of composition of the solution. Figure (14) shows the variation of m with composition. m could be correlated by the following expression,

$$m = \frac{\ln(N_1/0.0467)}{0.11} \times 10^{-6} \qquad 21$$

where $N_1$ was the mole fraction of acetone. The correlation coefficient of 0.9895 indicated a good fit and there was only a 0.001 chance of wrongly rejecting the null hypothesis. $m_o$ of equation (20) was also correlated to composition figure (15) and was found to be of the form

$$m_o = \frac{\ln(N_1/0.0605)}{0.717} \times 10^{-6} \qquad 22$$

with a correlation coefficient of 0.9691.

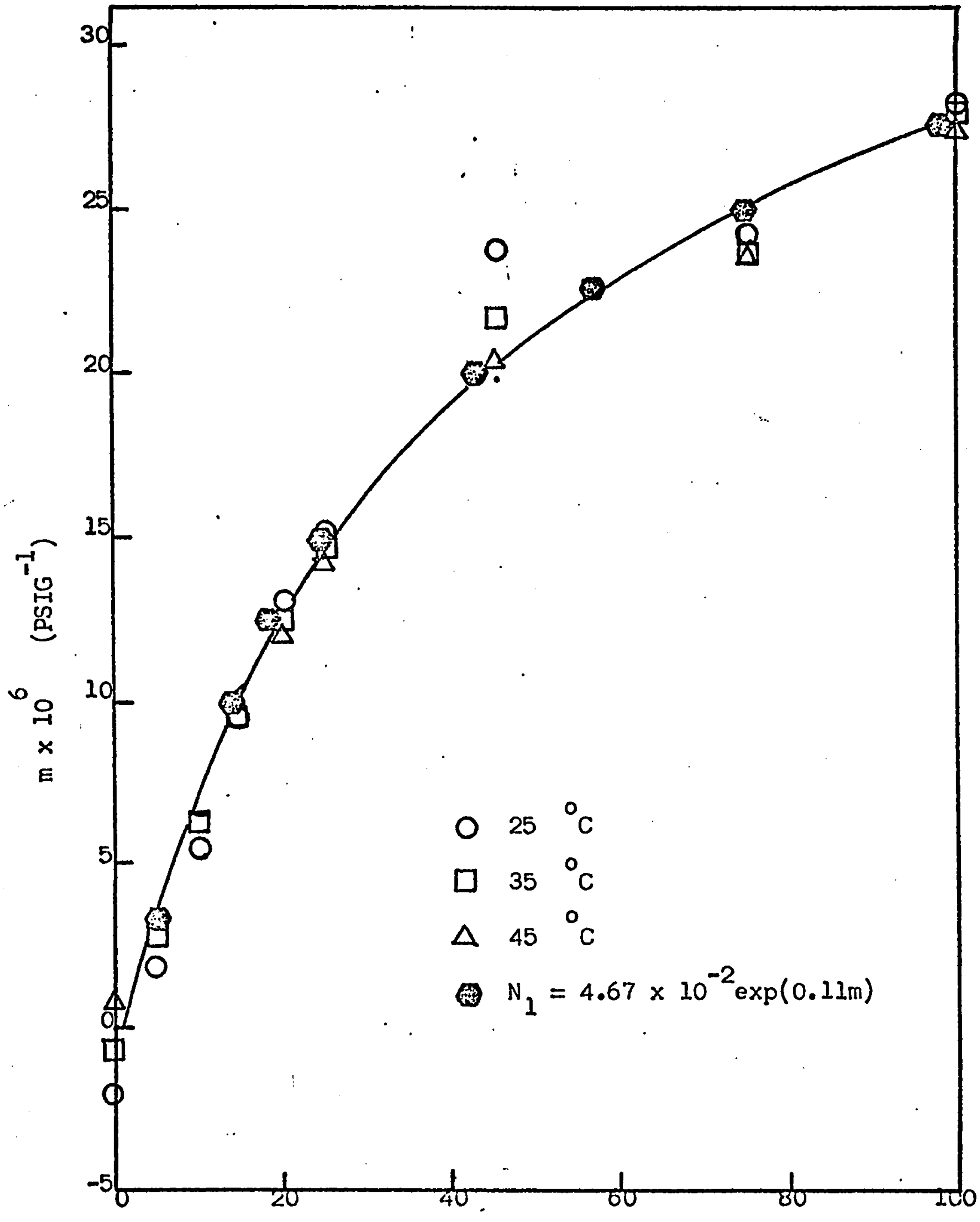


FIG. 14 COMPARISON OF DATA AND CORRELATION FOR m

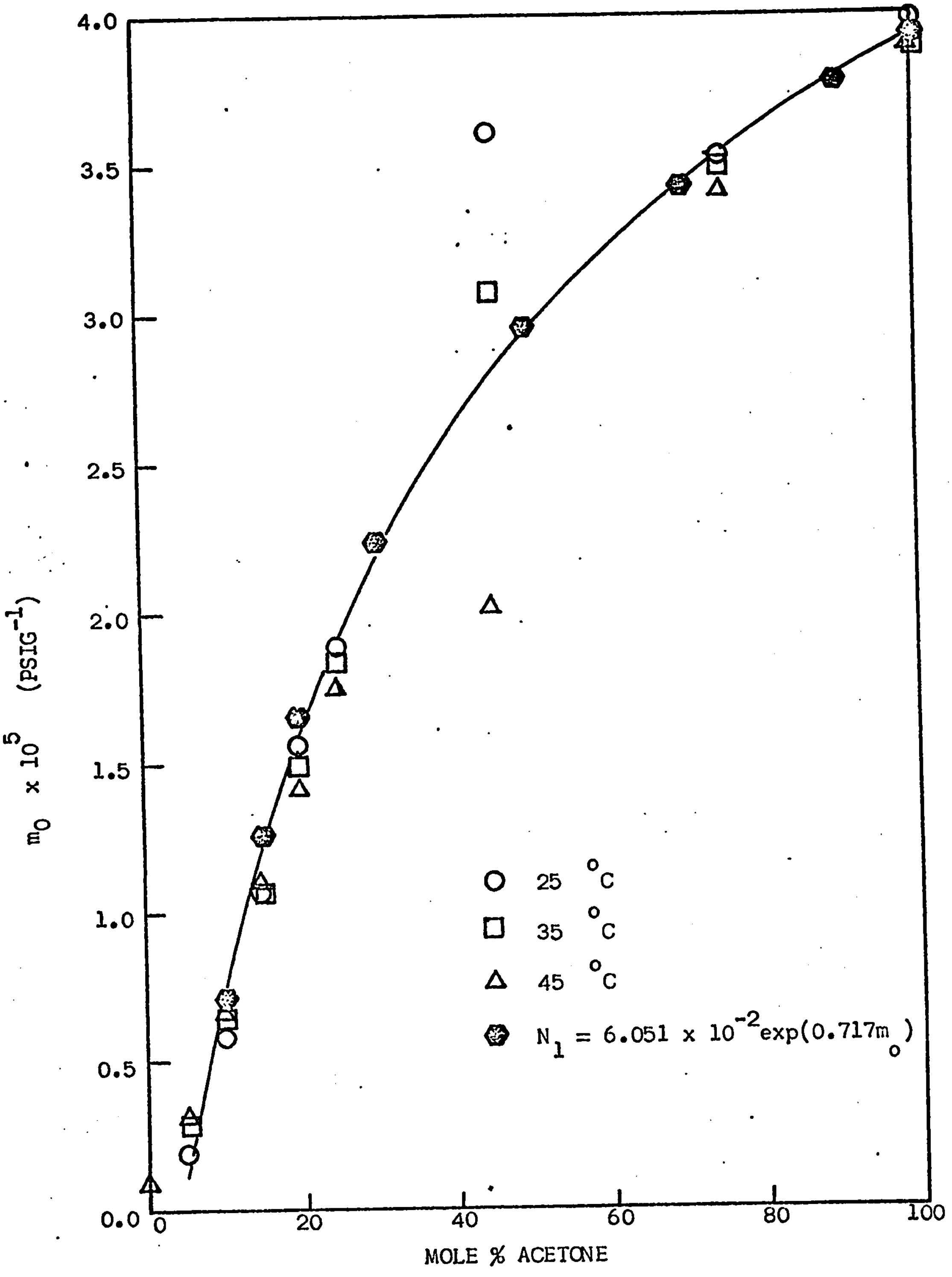


FIG. 15 COMPARISON OF DATA AND CORRELATION FOR $m_o$

## E. VISCOSITY COMPOSITION CORRELATION

The variation of viscosity with composition can be seen in figure (16). It was noted that as acetone was added to the pure water the viscosity increased to a maximum at about 15 mole % acetone and then decreased to the minimum at pure acetone. The atmospheric pressure data of Howard and McAllister (21) are shown also to be in good agreement with the present experimental results. The cubic and quartic models of McAllister were based on the two and three dimensional interactions of acetone and water molecules. Because there was a large size difference between the two types of molecules McAllister concluded that an eighth order system would be needed to adequately describe the results. This approach though explaining the situation seemed rather cumbersome for engineering and design purposes, and to use an eighth order system on approximately 8 data points is quite meaningless. From the pure theoretical point of view the work of McAllister was important.

It could also be noted that at increased pressures, the same general trend of viscosity with composition remained, and the temperature effect of higher temperature lower viscosity was evident for each mixture in addition to the pure substances involved, Appendix (6).

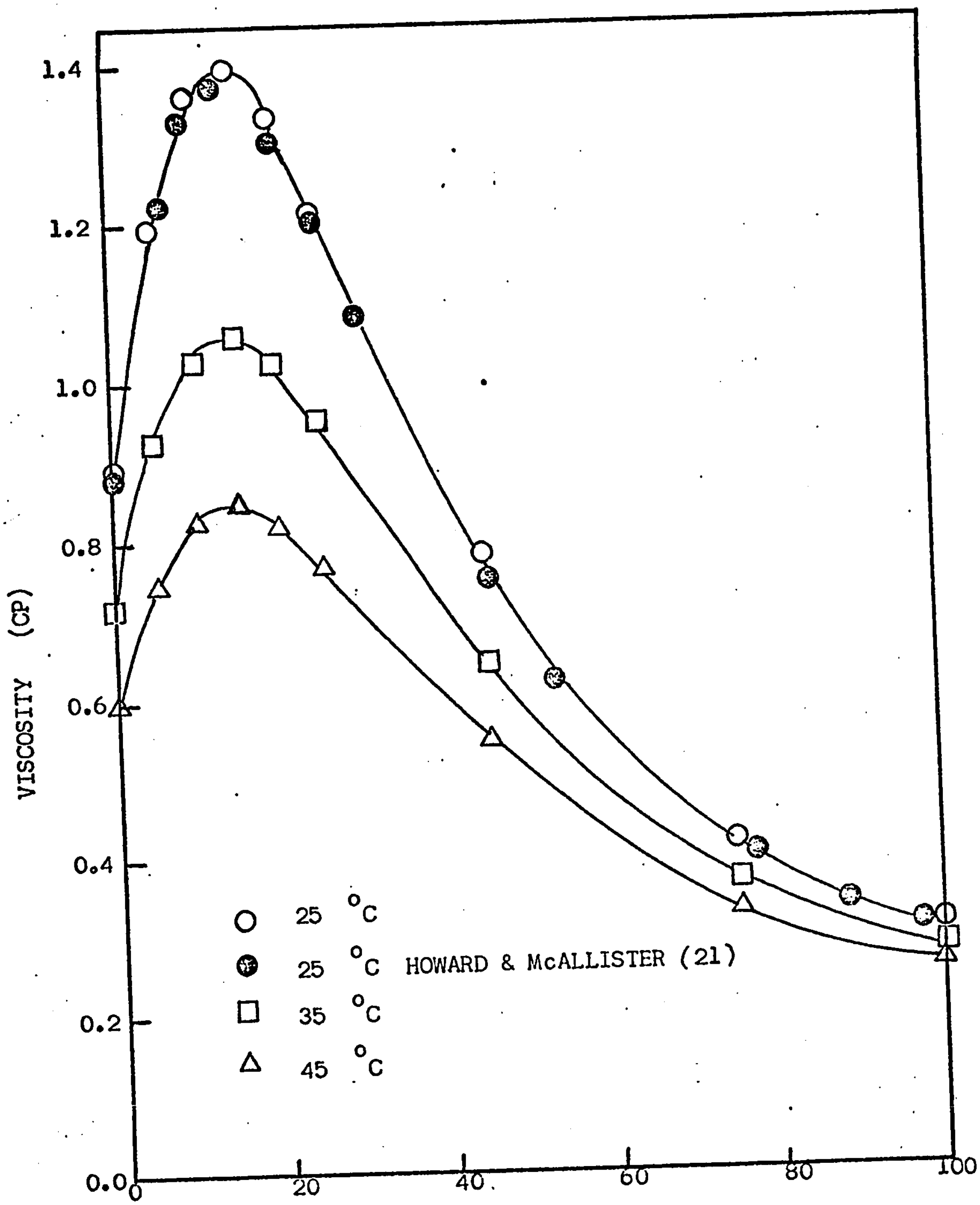


FIG. 16 VISCOSITY VERSUS COMPOSITION AT ATMOSPHERIC PRESSURE

# VII. CONCLUSIONS

The instrument used in this experiment is a reliable high pressure instrument capable of measuring liquid densities and viscosities almost simultaneously. This feature should make this type of instrument applicable to industry where high pressure absolute viscosity and density measurements might be necessary.

The measurements of viscosity and density made in this experiment were correct to within ± 1.14% and ± 0.63% respectively.

From this data a pressure volume correlation $P = rB_{(v)}{}^{q}$ and a viscosity pressure correlation $\eta = \eta_o \exp(mP)$ were checked and found to be very good correlations. This now lends needed support to the equation of state for liquids proposed by Chaudhuri et al (6). Until the present study this equation had not been supported by any liquid mixture data.

The constant m in the viscosity versus pressure correlation was found to be a function of the composition, thus expanding the knowledge of liquid mixtures.

This study has only begun the investigation into high pressure liquid mixture properties. However, with more and more research, man will no doubt gain the needed insight into understanding the complete liquid state.

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## IX NOMENCLATURE

| | |
|---|---|
| B | coefficient of volume expansion /°C |
| $B_{(v)}$ | volume function = $(v_o/v)^4 - (v_o/v)^2$ |
| $C_1, C_2, C_3, C_4$ | constants in equation (3) |
| E | Young's Modulus of Elasticity psi. |
| F | force lb.f. |
| K | constant in equation (2) °K |
| M | molecular weight |
| $N_1$ | mole fraction acetone |
| P | pressure psig. |
| T | absolute temperature °K |
| V | volume of system cc. |
| $\Delta V$ | change in volume of system cc. |
| X | function of temperature in equation (3) |
| Y | function of temperature in equation (3) |
| a | radius of fall tube in. |
| b | radius of plummet in. |
| d | diameter of plummet in. |
| g | acceleration due to gravity ft./sec.$^2$ |
| $g_c$ | constant for dimensional consistency (lbm./lbf.) ft./sec.$^2$ |
| k | instrument constant |

| | | |
|---|---|---|
| m | function of composition in equation (4) | |
| q | empirical constant in equation (5) | |
| r | empirical constant in equation (5) | |
| s | flight distance of plummet | in. |
| t | time of fall | sec. |
| u | increase in radius of tube with pressure | in. |
| v | specific volume | cc./gm. |

GREEK SYMBOLS

| | | |
|---|---|---|
| $\eta$ | absolute viscosity | cp. |
| $\mu$ | absolute viscosity | cp. |
| $\xi$ | viscosity parameter | |
| $\rho$ | density of test liquid | gm./cc. |
| $\sigma$ | density of plummet | gm./cc. |
| $\delta$ | clearance between plummet and fall tube | in. |
| $\sigma$ | stress on tube walls with pressure | psi. |
| $\epsilon$ | strain on tube walls with pressure | in./in. |
| $\nu$ | Poisson's ratio | |

SUBSCRIPTS

| | |
|---|---|
| o | at atmospheric pressure |
| R | reduced |
| c | critical |
| i | internal |
| r | direction in polar coordinates |

| | |
|---|---|
| $\theta$ | direction in polar coordinates |
| $z$ | direction in polar coordinates |
| $D$ | drag |
| $W$ | weight |
| $B$ | buoyant |
| $p$ | plummet |
| $l$ | liquid |
| $t$ | terminal |

# APPENDIX I

# EFFECT OF PRESSURE ON DENSITY OF ACETONE WATER SOLUTIONS

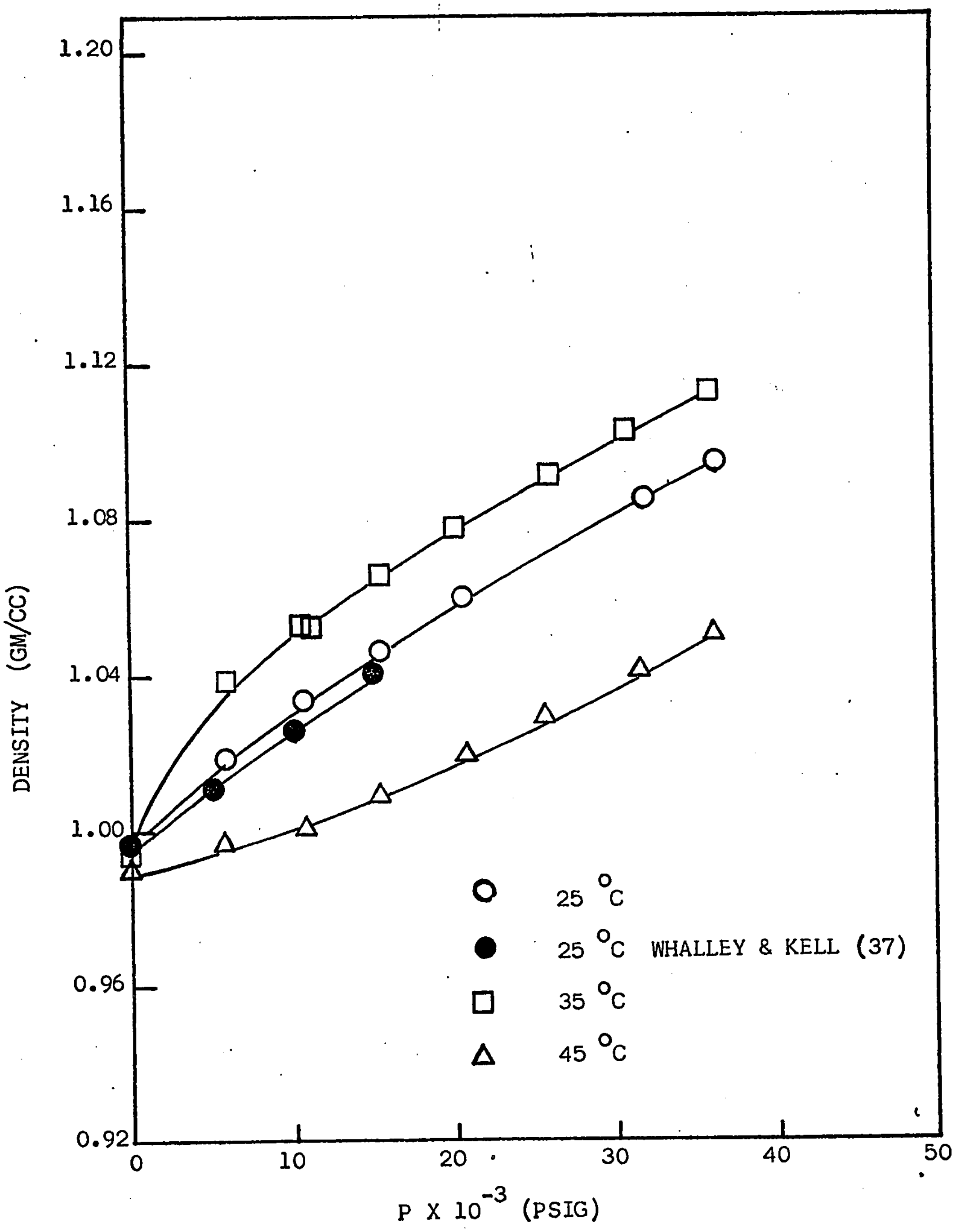

FIG. 17 EFFECT OF PRESSURE ON DENSITY OF PURE WATER

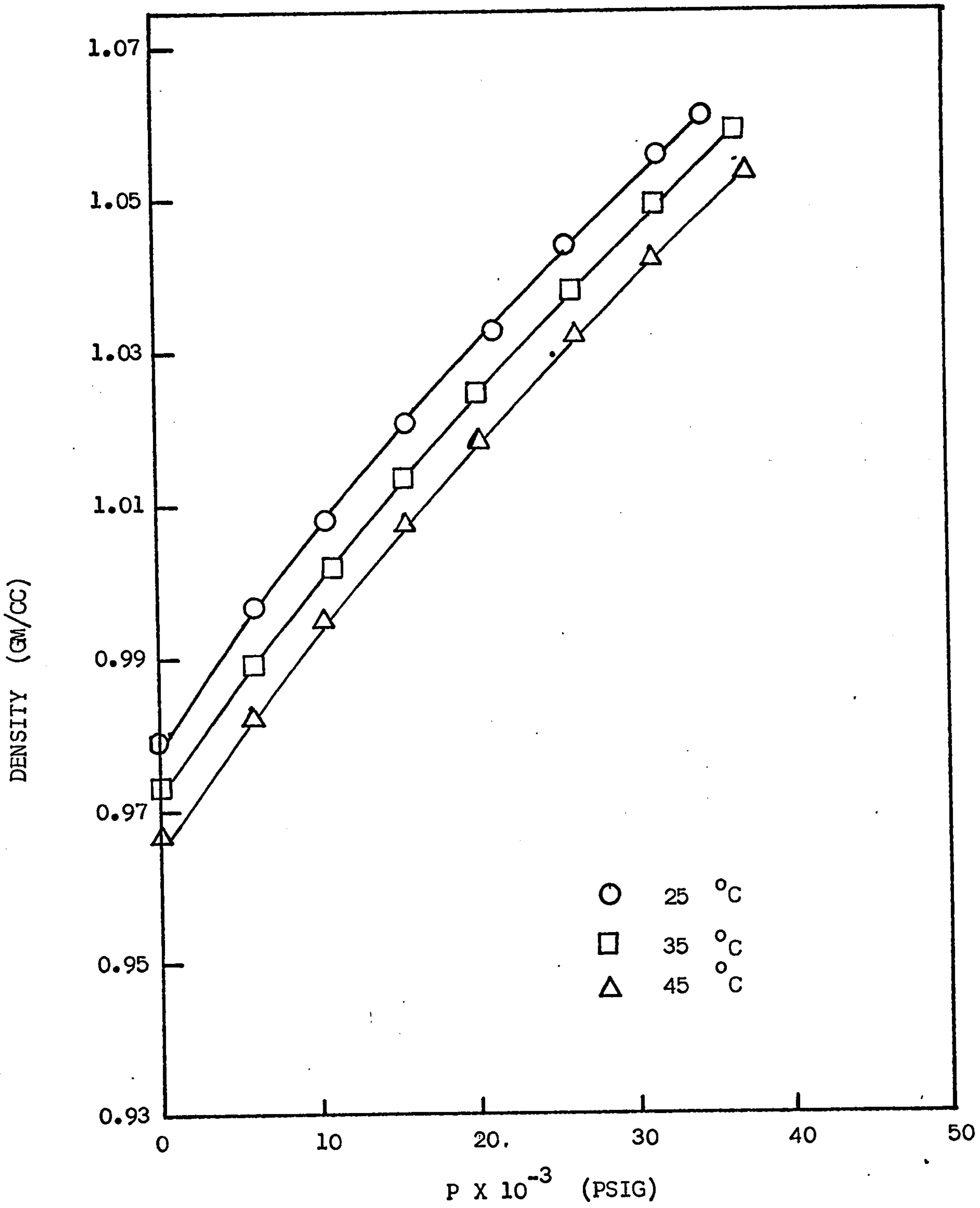

FIG. 18 EFFECT OF PRESSURE ON DENSITY OF 5% ACETONE 95% WATER SOLUTION

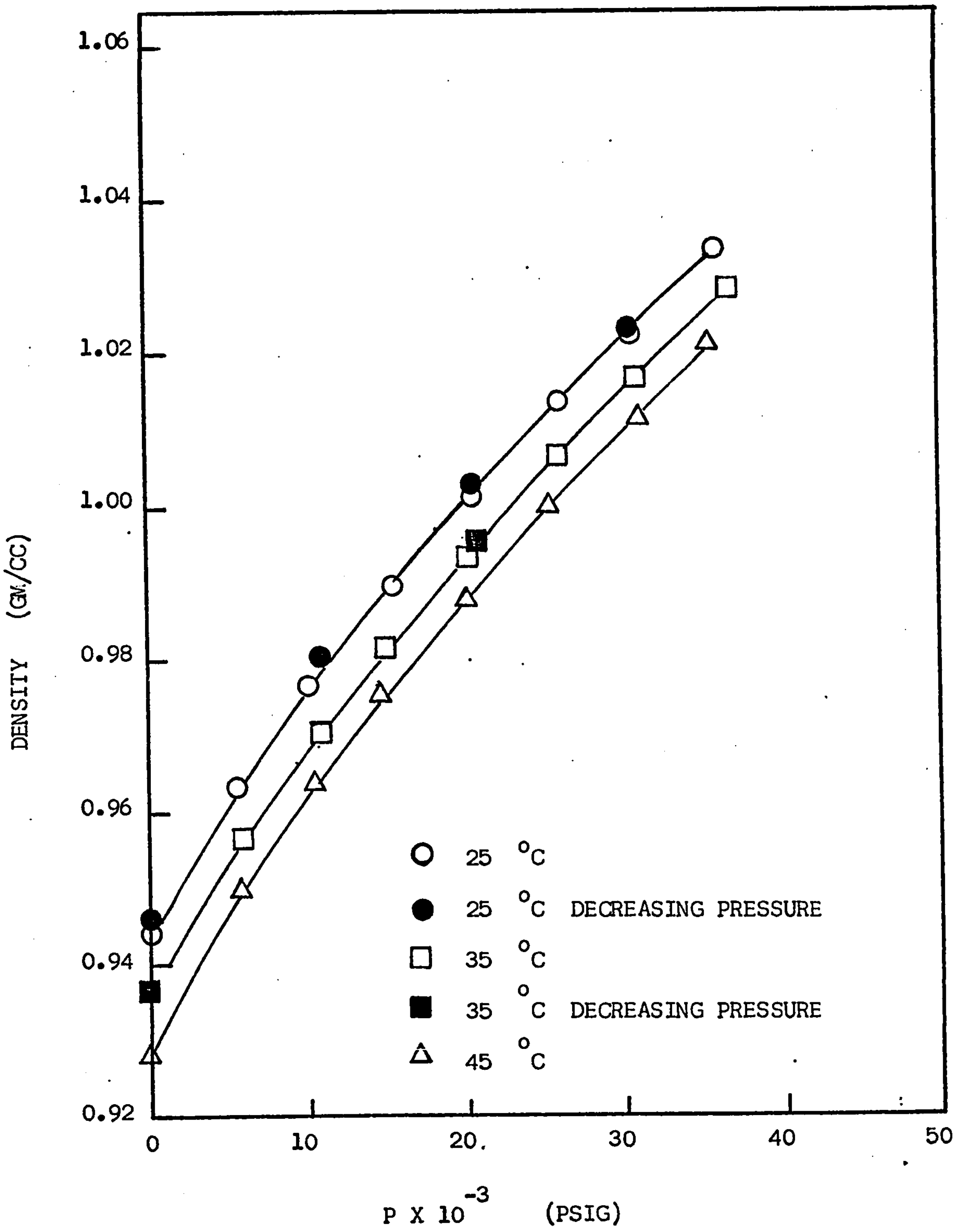

FIG. 19 EFFECT OF PRESSURE ON DENSITY OF 10% ACETONE 90% WATER SOLUTION

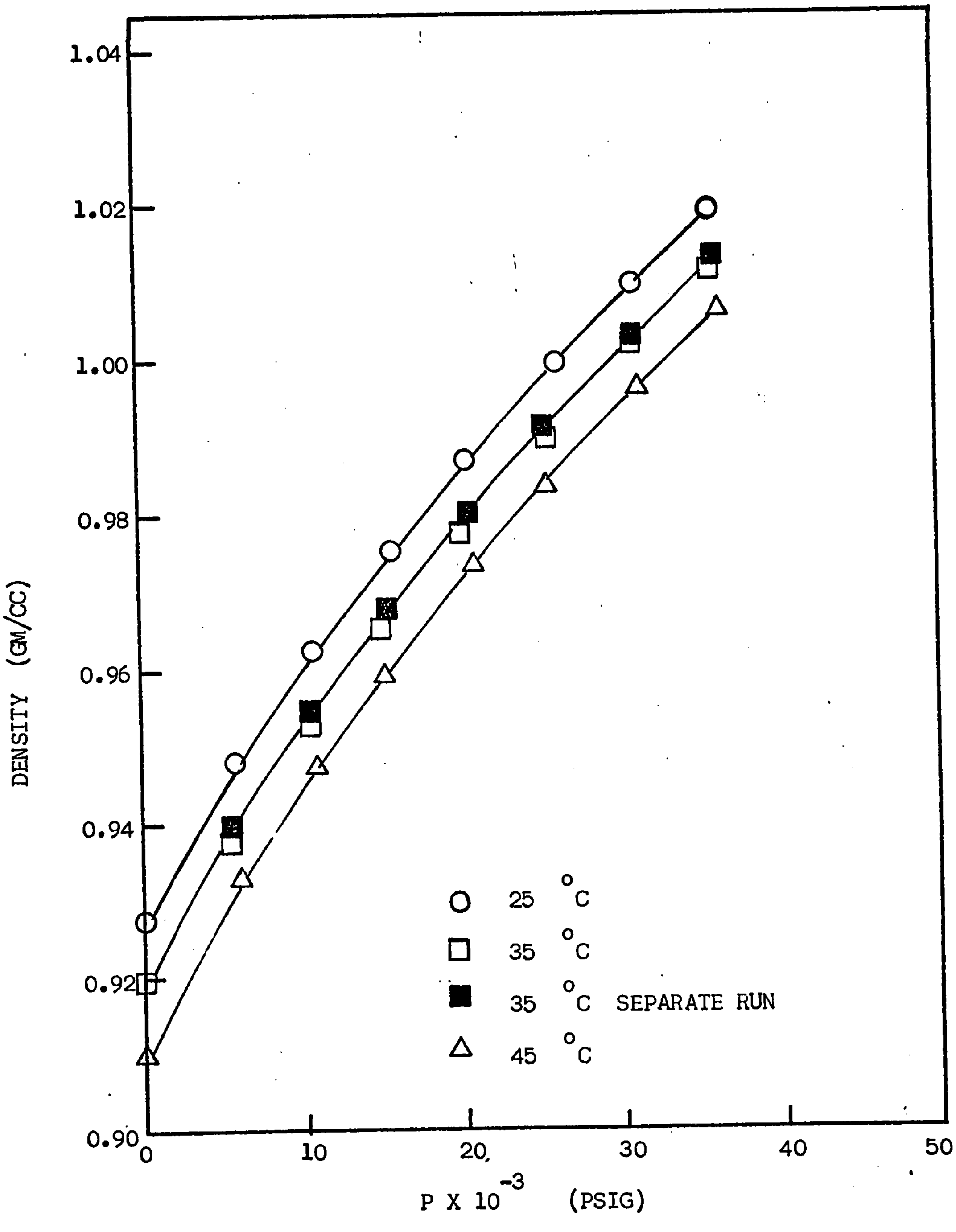

FIG. 20 EFFECT OF PRESSURE ON DENSITY OF 20% ACETONE 80% WATER SOLUTION

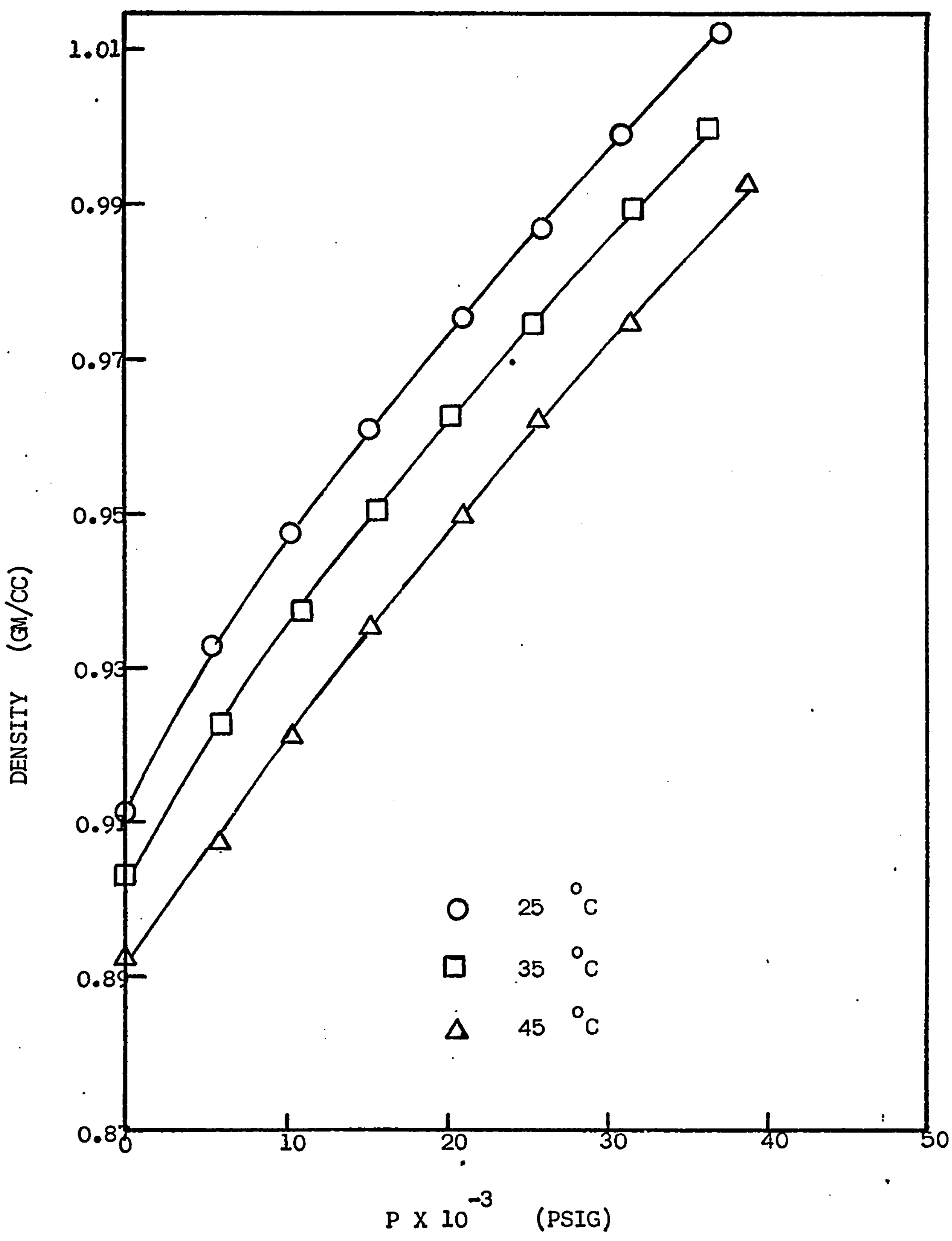

FIG. 21 EFFECT OF PRESSURE ON DENSITY OF 25% ACETONE 75% WATER SOLUTION

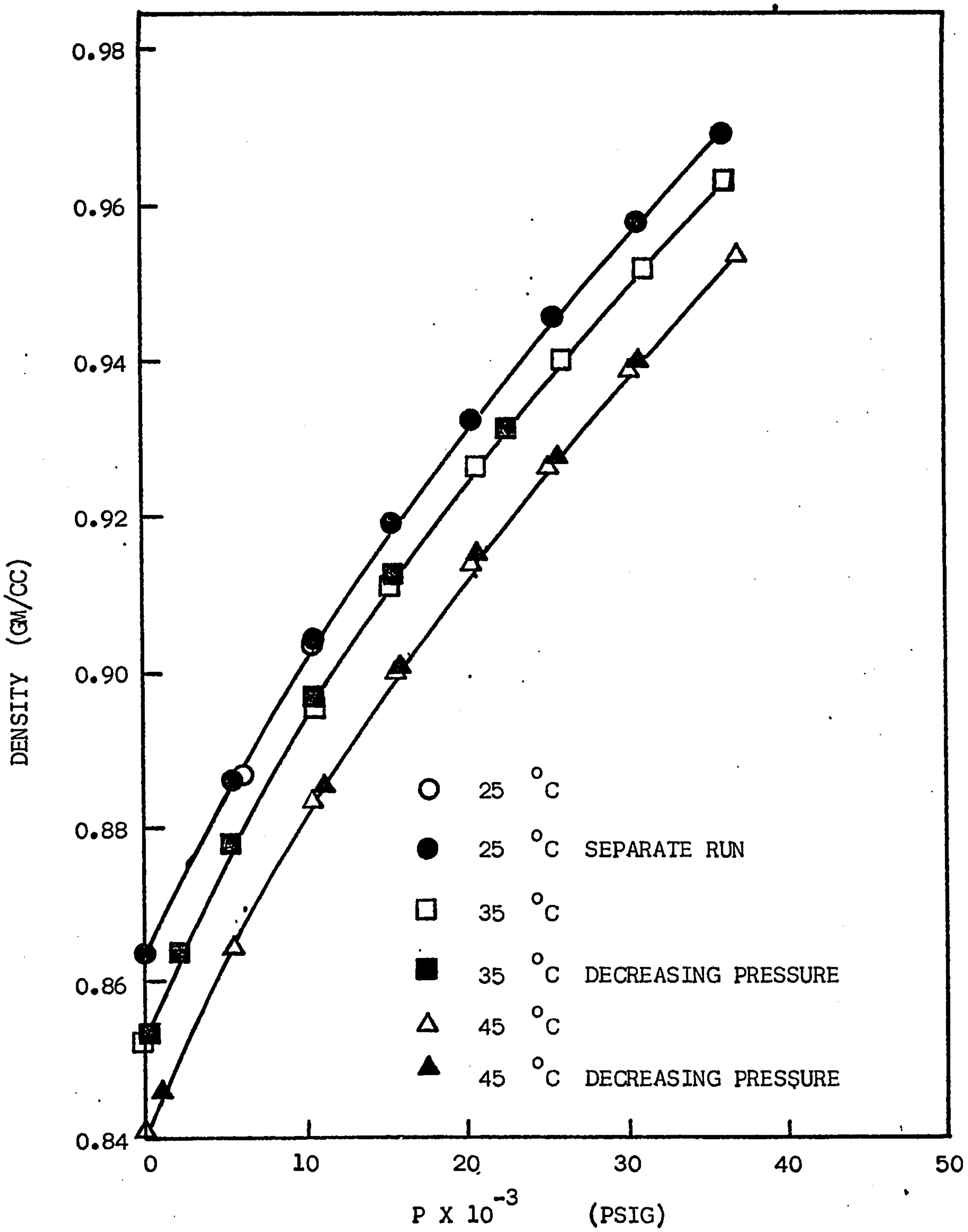

FIG. 22 EFFECT OF PRESSURE ON DENSITY OF 45% ACETONE 55% WATER SOLUTION

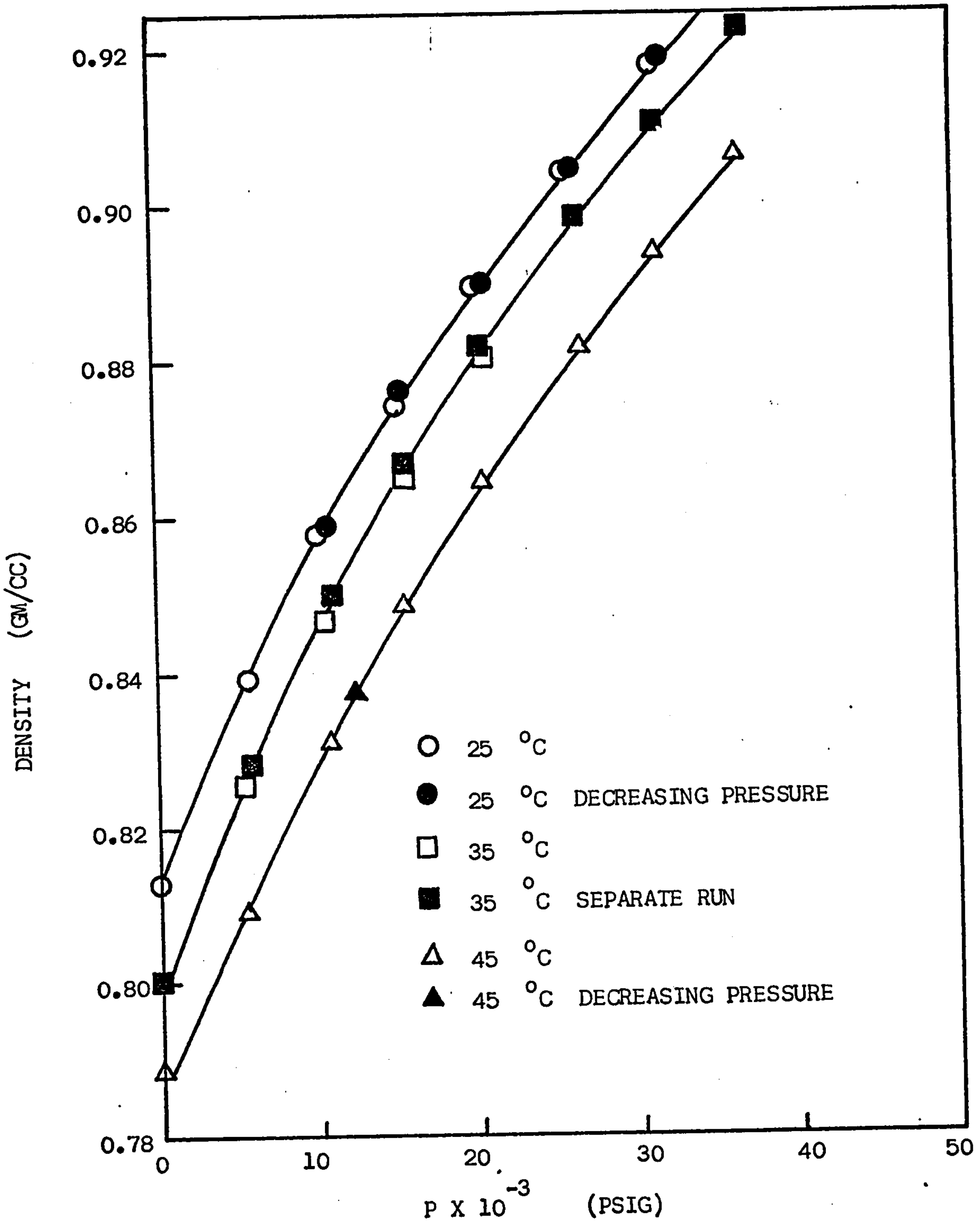

FIG. 23 EFFECT OF PRESSURE ON DENSITY OF 75% ACETONE 25% WATER SOLUTION

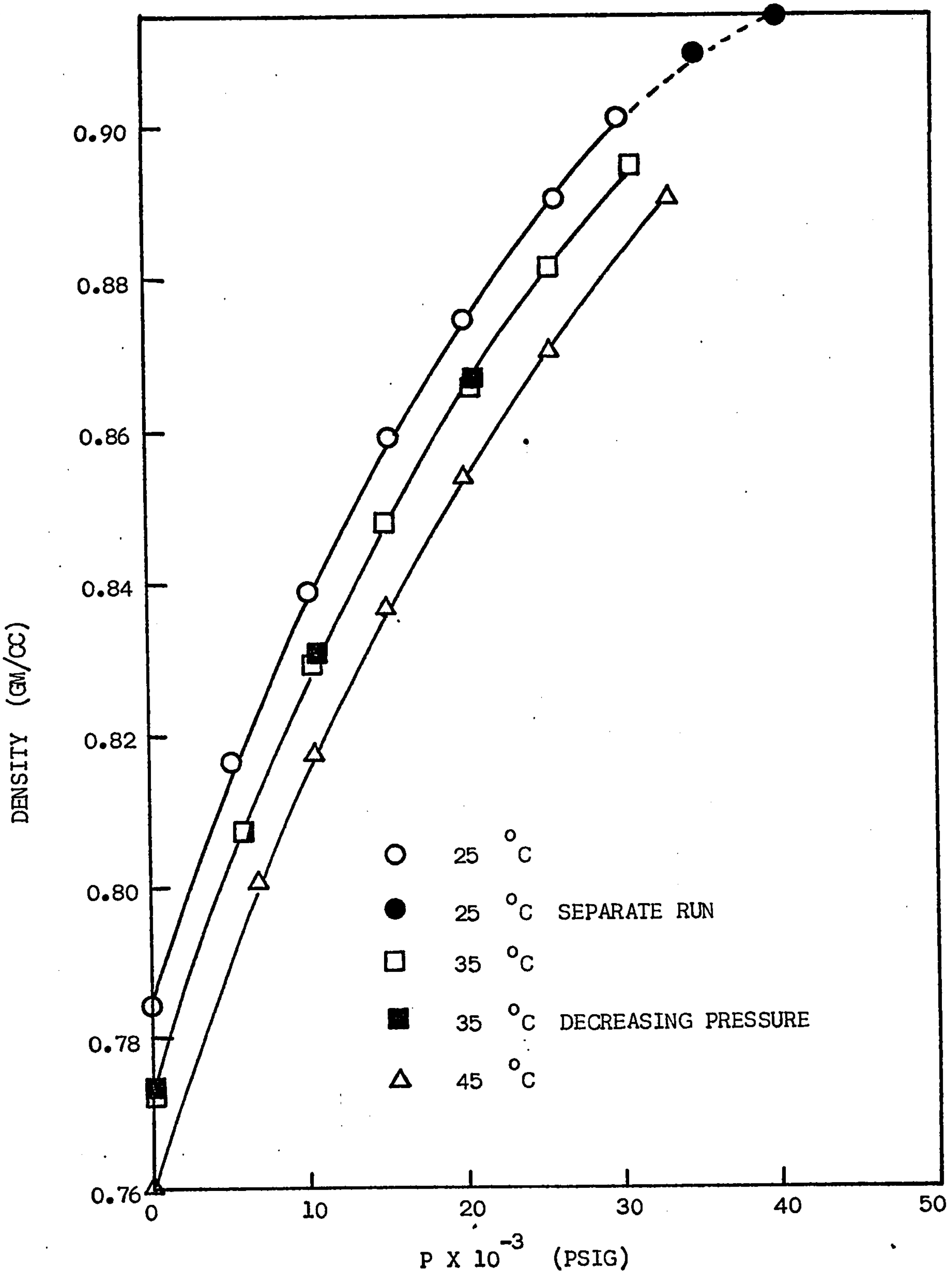

FIG. 24 EFFECT OF PRESSURE ON DENSITY OF PURE ACETONE

# APPENDIX II

# THEORETICAL DETERMINATION OF TIME TO REACH TERMINAL VELOCITY

With the positive direction downwards, let us assume that the plummet is falling with velocity v, acceleration a, and the downward direction is the z direction. Now, the drag force

$$F_D = -kv/g_c \qquad 23$$

where k is a constant and $g_c$ is a constant for dimensional consistency. The weight force of the plummet is

$$F_W = \text{Vol.}\rho_p g/g_c \qquad 24$$

and the buoyant force is

$$F_B = -\text{Vol.}\rho_l g/g_c \qquad 25$$

Now,

$$\Sigma F = ma/g_c \qquad 26$$

Therefore

$$\text{Vol.}(\rho_p-\rho_l)g/g_c - kv/g_c = \text{Vol.}\rho_p a/g_c$$

$$\frac{\rho_p-\rho_l}{\rho_p} g - (k/\text{Vol.}\rho_p)\frac{dz}{dt} = \frac{d^2z}{dt^2} \qquad 27$$

Let $\frac{dz}{dt} = v$ and $A = k/\text{Vol.}\rho_p$ and $B = (1-\rho_l/\rho_p)g$

Therefore

$$\frac{dv}{dt} + Av - B = 0 \qquad 28$$

Integrating and applying boundary conditions we have

$$v = \frac{B}{A}(1-e^{-At}) \qquad 29$$

At terminal velocity $\Sigma F=0$ and the acceleration $a = 0$.

Therefore

$$v_t = Vol.(\rho_p-\rho_l)g/k \tag{30}$$

or

$$k/Vol. = (\rho_p-\rho_l)g/v_t \tag{31}$$

Also

$$A = k/Vol.\rho_p \tag{32}$$

Combining equations 31 and 32 we get .

$$A = (1-\rho_l/\rho_p)g/v_t \tag{33}$$

Combining equations 29 and 33 we get

$$v = B/A(1-e^{-(1-\rho_l/\rho_p)gt/v_t}) \tag{34}$$

Now

$$B/A = \frac{\frac{\rho_p-\rho_l}{\rho_p}\ g}{k/Vol.\rho_p}$$

$$= (\rho_p-\rho_l)Vol.g/k \tag{35}$$

Notice here that equations 30 and 35 are identical. That is $v_t = B/A$.

Substituting this in equation 34 we have

$$v = v_t(1-e^{-(\frac{\rho_p-\rho_l}{\rho_p})\frac{gt}{v_t}}) \tag{36}$$

Assuming $(\rho p-\rho l)/\rho p$ is approximately 1, and g is 32.2 ft./sec.$^2$ and that the average velocity of 0.289 ft./sec. is the terminal velocity for a first approximation we get

$$v/v_t = (1 - e^{-111t}) \qquad 37$$

After 0.1 seconds $v/v_t = (1 - e^{-11.1})$

$$= (1 - 0.00005)$$

$$= 0.99995$$

Therefore after only 0.1 seconds we have reached better than 99.9% terminal velocity.

# APPENDIX III

## EXPERIMENTAL DATA

## PURE WATER

TEMPERATURE 25 °C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 0.89044 | 0.99708 | 0.00000 |
| 5450 | 0.86952 | 1.01979 | 0.02227 |
| 10500 | 0.85996 | 1.03410 | 0.03580 |
| 15350 | 0.85511 | 1.04715 | 0.04781 |
| 20550 | 0.85319 | 1.06009 | 0.05944 |
| 31800 | 0.85889 | 1.08496 | 0.08100 |
| 36225 | 0.86139 | 1.09440 | 0.08893 |

TEMPERATURE 35 °C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 0.71940 | 0.99406 | 0.00000 |
| 5600 | 0.71247 | 1.03947 | 0.04369 |
| 10500 | 0.70874 | 1.05344 | 0.05637 |
| 15350 | 0.70491 | 1.06642 | 0.06786 |
| 20000 | 0.70459 | 1.07782 | 0.07771 |
| 25825 | 0.70396 | 1.09151 | 0.08928 |
| 30550 | 0.70700 | 1.10200 | 0.09795 |
| 35525 | 0.71700 | 1.11248 | 0.10645 |

TEMPERATURE 45 °C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 0.59593 | 0.99024 | 0.00000 |
| 5850 | 0.59671 | 0.99693 | 0.00671 |
| 10850 | 0.59789 | 1.00111 | 0.01086 |
| 15200 | 0.60051 | 1.00905 | 0.01864 |
| 20600 | 0.60252 | 1.02098 | 0.03011 |
| 25500 | 0.60586 | 1.03062 | 0.03918 |
| 31350 | 0.61127 | 1.04193 | 0.04961 |
| 35950 | 0.61574 | 1.05070 | 0.05755 |
| 0 |  | 0.99120 | 0.00097 |

## 5% ACETONE 95% WATER SOLUTION

### TEMPERATURE 25 °C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 1.19594 | 0.97945 | 0.00000 |
| 5900 | 1.20936 | 0.99652 | 0.01713 |
| 10400 | 1.21981 | 1.00854 | 0.02885 |
| 15600 | 1.22688 | 1.02127 | 0.04094 |
| 20900 | 1.23810 | 1.03329 | 0.05211 |
| 25750 | 1.25245 | 1.04413 | 0.06195 |
| 31400 | 1.26750 | 1.05610 | 0.07258 |
| 34300 | 1.27789 | 1.06170 | 0.07747 |

### TEMPERATURE 35 °C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 0.92319 | 0.97332 | 0.00000 |
| 5750 | 0.93640 | 0.98935 | 0.01621 |
| 10750 | 0.94648 | 1.00252 | 0.02913 |
| 15200 | 0.96071 | 1.01359 | 0.03973 |
| 20100 | 0.97299 | 1.02482 | 0.05025 |
| 26150 | 0.98905 | 1.03826 | 0.06255 |
| 31450 | 1.00382 | 1.04933 | 0.07243 |
| 36475 | 1.02133 | 1.05912 | 0.08101 |

### TEMPERATURE 45 °C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 0.74345 | 0.96677 | 0.00000 |
| 5600 | 0.75505 | 0.98218 | 0.01569 |
| 10300 | 0.76944 | 0.99502 | 0.02839 |
| 15550 | 0.78170 | 1.00786 | 0.04077 |
| 20350 | 0.78950 | 1.01894 | 0.05120 |
| 26400 | 0.80367 | 1.03225 | 0.06344 |
| 31200 | 0.81918 | 1.04209 | 0.07228 |
| 37050 | 0.83432 | 1.05393 | 0.08270 |

## 10% ACETONE 90% WATER SOLUTION

### TEMPERATURE 25 $^{o}$C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 1.36012 | 0.96332 | 0.00000 |
| 5450 | 1.40962 | 0.98270 | 0.01972 |
| 10500 | 1.45550 | 0.99590 | 0.03272 |
| 15100 | 1.49454 | 1.00697 | 0.04335 |
| 21100 | 1.52821 | 1.02079 | 0.05630 |
| 26550 | 1.57616 | 1.03233 | 0.06685 |
| 31500 | 1.62058 | 1.04226 | 0.07574 |
| 37300 | 1.66290 | 1.05329 | 0.08541 |

### TEMPERATURE 35 $^{o}$C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 1.02852 | 0.95639 | 0.00000 |
| 6150 | 1.07730 | 0.99521 | 0.03901 |
| 10600 | 1.10893 | 1.00759 | 0.05081 |
| 15300 | 1.13981 | 1.01935 | 0.06177 |
| 20200 | 1.16892 | 1.03092 | 0.07229 |
| 26100 | 1.20414 | 1.04409 | 0.08399 |
| 31300 | 1.24461 | 1.05496 | 0.09344 |
| 36350 | 1.27370 | 1.06489 | 0.10189 |
| 24250 | 1.18812 | 1.03990 | 0.08031 |
| 20400 |  | 1.03333 | 0.07446 |
| 10400 | 1.10813 | 1.00962 | 0.05275 |
| 2100 | 1.04425 | 0.98304 | 0.02711 |

### TEMPERATURE 45 $^{o}$C

| PRESSURS (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 0.82238 | 0.94851 | 0.00000 |
| 5600 | 0.85444 | 0.98905 | 0.04099 |
| 10550 | 0.88139 | 1.00299 | 0.05432 |
| 15250 | 0.90906 | 1.01509 | 0.06559 |
| 20250 | 0.93725 | 1.02694 | 0.07638 |
| 25500 | 0.96415 | 1.03880 | 0.08692 |
| 30600 | 0.98089 | 1.04956 | 0.09628 |
| 36950 | 1.02656 | 1.06209 | 0.10694 |
| 30250 | 0.99070 | 1.04870 | 0.09554 |
| 25350 | 0.96233 | 1.03806 | 0.08627 |
| 20350 | 0.93898 | 1.02692 | 0.07635 |
| 10700 | 0.88726 | 1.00537 | 0.05656 |
| 5700 | 0.85783 | 0.98872 | 0.04067 |
| 0 | 0.83054 | 0.94812 | -0.00041 |

## 15% ACETONE 85% WATER SOLUTION

TEMPERATURE 25 °C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 1.39483 | 0.94396 | 0.00000 |
| 5500 | 1.48151 | 0.96365 | 0.02043 |
| 10200 | 1.55732 | 0.97660 | 0.03343 |
| 15400 | 1.63649 | 0.98977 | 0.04628 |
| 20500 | 1.71102 | 1.00160 | 0.05755 |
| 26150 | 1.79292 | 1.01384 | 0.06892 |
| 30500 | 1.85531 | 1.02279 | 0.07708 |
| 35800 | 1.92894 | 1.03335 | 0.08651 |
| 30500 | 1.85506 | 1.02347 | 0.07769 |
| 20450 | 1.70.39 | 1.00267 | 0.05856 |
| 10875 | 1.56614 | 0.98021 | 0.03698 |
| 0 | 1.39545 | 0.94890 | 0.00521 |

TEMPERATURE 35 °C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 1.06064 | 0.93616 | 0.00000 |
| 5875 | 1.12353 | 0.95686 | 0.02163 |
| 10650 | 1.18585 | 0.97009 | 0.03497 |
| 15150 | 1.24140 | 0.98180 | 0.04649 |
| 20175 | 1.29951 | 0.99372 | 0.05793 |
| 25975 | 1.36214 | 1.00668 | 0.07005 |
| 30900 | 1.41504 | 1.01682 | 0.07933 |
| 36675 | 1.47439 | 1.02822 | 0.08954 |
| 20950 | 1.30804 | 0.99587 | 0.05996 |
| 0 | 1.06264 | 0.93641 | 0.00027 |

TEMPERATURE 45 °C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 0.84462 | 0.92763 | 0.00000 |
| 5675 | 0.90452 | 0.94983 | 0.02338 |
| 10475 | 0.95920 | 0.96390 | 0.03762 |
| 14950 | 0.99566 | 0.97584 | 0.04941 |
| 20100 | 1.04035 | 0.98838 | 0.06147 |
| 25400 | 1.08749 | 1.00038 | 0.07272 |
| 30850 | 1.13492 | 1.01193 | 0.08330 |
| 35450 | 1.17074 | 1.02119 | 0.09162 |

## 20% ACETONE 80% WATER SOLUTION

### TEMPERATURE 25 °C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 1.33368 | 0.92766 | 0.00000 |
| 5675 | 1.45795 | 0.94825 | 0.02171 |
| 10600 | 1.56912 | 0.96271 | 0.03640 |
| 15500 | 1.67245 | 0.97538 | 0.04892 |
| 20400 | 1.76830 | 0.98705 | 0.06017 |
| 26050 | 1.86761 | 0.99938 | 0.07176 |
| 30950 | 1.98708 | 1.00977 | 0.08131 |
| 35650 | 2.08715 | 1.01913 | 0.08131 |
| 13100 | 1.61988 | 0.96214 | 0.03583 |
| 0 | 1.33732 | 0.93306 | 0.00579 |

### TEMPERATURE 35 °C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 1.02346 | 0.91945 | 0.00000 |
| 5300 | 1.10247 | 0.93774 | 0.01950 |
| 10300 | 1.17734 | 0.95251 | 0.03470 |
| 15100 | 1.25242 | 0.96542 | 0.04761 |
| 20050 | 1.32530 | 0.97754 | 0.05943 |
| 25500 | 1.40229 | 0.98981 | 0.07109 |
| 30750 | 1.48056 | 1.00109 | 0.08155 |
| 35700 | 1.56245 | 1.01186 | 0.09133 |

### TEMPERATURE 35 °C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 1.02349 | 0.91945 | 0.00000 |
| 5350 | 1.10764 | 0.93979 | 0.02164 |
| 10400 | 1.19003 | 0.95483 | 0.03705 |
| 15225 | 1.26250 | 0.96772 | 0.04988 |
| 20300 | 1.33449 | 0.98024 | 0.06201 |
| 25250 | 1.40540 | 0.99145 | 0.07262 |
| 30800 | 1.49618 | 1.00326 | 0.08353 |
| 35950 | 1.57464 | 1.01354 | 0.09283 |
| 0 | 1.01727 | 0.92273 | 0.00356 |

## 20% ACETONE 80% WATER SOLUTION

TEMPERATURE 45 °C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 0.81897 | 0.91015 | 0.00000 |
| 5950 | 0.89423 | 0.93299 | 0.02448 |
| 10600 | 0.94471 | 0.94705 | 0.03896 |
| 15100 | 1.00173 | 0.95926 | 0.05120 |
| 20850 | 1.06534 | 0.97366 | 0.06523 |
| 25300 | 1.10775 | 0.98386 | 0.07492 |
| 31100 | 1.17865 | 0.99633 | 0.08650 |
| 36025 | 1.23948 | 1.00661 | 0.09583 |

## 25% ACETONE 75% WATER SOLUTION

### TEMPERATURE 25 °C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 1.21710 | 0.91184 | 0.00000 |
| 5350 | 1.34293 | 0.93330 | 0.02299 |
| 10150 | 1.45796 | 0.94783 | 0.03797 |
| 15050 | 1.57189 | 0.96116 | 0.05131 |
| 20800 | 1.70638 | 0.97528 | 0.06505 |
| 25900 | 1.81976 | 0.98721 | 0.07635 |
| 30950 | 1.92678 | 0.99923 | 0.08746 |
| 37000 | 2.08567 | 1.01285 | 0.09973 |

### TEMPERATURE 35 °C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 0.95470 | 0.90301 | 0.00000 |
| 5850 | 1.05896 | 0.92226 | 0.02088 |
| 10700 | 1.14559 | 0.93724 | 0.03652 |
| 15500 | 1.23487 | 0.95049 | 0.04996 |
| 20150 | 1.31896 | 0.96231 | 0.06162 |
| 25400 | 1.40913 | 0.97493 | 0.07377 |
| 31500 | 1.50201 | 0.98930 | 0.08723 |
| 36200 | 1.59118 | 0.99997 | 0.09697 |
| 20200 |  | 0.96724 | 0.06641 |
| 0 |  | 0.90357 | 0.00063 |

### TEMPERATURE 45 °C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 0.76570 | 0.89230 | 0.00000 |
| 5900 | 0.84676 | 0.90742 | 0.01666 |
| 10200 | 0.91071 | 0.92129 | 0.03147 |
| 15200 | 0.97829 | 0.93576 | 0.04644 |
| 20800 | 1.05238 | 0.94996 | 0.06070 |
| 25850 | 1.11882 | 0.96205 | 0.07250 |
| 31350 | 1.18666 | 0.97494 | 0.08476 |
| 38900 | 1.30382 | 0.99314 | 0.10154 |
| 0 | 0.75989 | 0.89110 | -0.00135 |

## 45% ACETONE 55% WATER SOLUTION

TEMPERATURE 25 °C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 0.78202 | 0.86308 | 0.00000 |
| 5700 | 0.90275 | 0.88647 | 0.02639 |
| 10350 | 1.00305 | 0.90349 | 0.04472 |
| 15275 | 1.11649 | 0.91914 | 0.06099 |

TEMPERATURE 25 °C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 0.78209 | 0.86308 | 0.00000 |
| 5200 | 0.90067 | 0.88594 | 0.02580 |
| 10300 | 1.01976 | 0.90402 | 0.04529 |
| 15250 | 1.14521 | 0.91953 | 0.06139 |
| 20100 | 1.27462 | 0.93261 | 0.07455 |
| 25400 | 1.43470 | 0.94588 | 0.08754 |
| 30550 | 1.62004 | 0.95778 | 0.09887 |
| 35850 | 1.79397 | 0.96906 | 0.10937 |

TEMPERATURE 35 °C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 0.64170 | 0.85243 | 0.00000 |
| 5350 | 0.73808 | 0.87734 | 0.02840 |
| 10200 | 0.82861 | 0.89553 | 0.04813 |
| 15050 | 0.92128 | 0.91126 | 0.06456 |
| 20500 | 1.02712 | 0.92656 | 0.08000 |
| 25850 | 1.13505 | 0.94019 | 0.09334 |
| 31150 | 1.24760 | 0.95189 | 0.10449 |
| 35900 | 1.36323 | 0.96303 | 0.11485 |
| 22300 |  | 0.93196 | 0.08533 |
| 15375 |  | 0.91261 | 0.06595 |
| 10400 |  | 0.89674 | 0.04941 |
| 5250 |  | 0.87757 | 0.02865 |
| 2000 |  | 0.86356 | 0.01289 |
| 150 | 0.64679 | 0.85309 | 0.00078 |

## 45% ACETONE 55% WATER SOLUTION

TEMPERATURE 45 °C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 0.54355 | 0.84052 | 0.00000 |
| 5350 | 0.61564 | 0.86421 | 0.02741 |
| 10350 | 0.68786 | 0.88332 | 0.04845 |
| 15500 | 0.76582 | 0.90040 | 0.06651 |
| 20350 | 0.83774 | 0.91426 | 0.08065 |
| 25150 | 0.91314 | 0.92697 | 0.09326 |
| 30100 | 0.99080 | 0.93893 | 0.10481 |
| 36800 | 1.09634 | 0.95372 | 0.11869 |
| 30350 | | 0.93983 | 0.10567 |
| 25300 | | 0.92765 | 0.09393 |
| 20450 | 0.84653 | 0.91509 | 0.08149 |
| 15600 | | 0.90111 | 0.06724 |
| 11000 | | 0.88538 | 0.05067 |
| 875 | | 0.84592 | 0.00638 |
| 0 | 0.53679 | 0.84030 | -0.00026 |

## 75% ACETONE 25% WATER SOLUTION

### TEMPERATURE 25 °C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 0.41462 | 0.81245 | 0.00000 |
| 5500 | 0.49083 | 0.83923 | 0.03191 |
| 10100 | 0.55678 | 0.85758 | 0.05262 |
| 14900 | 0.62383 | 0.87413 | 0.07056 |
| 19900 | 0.69511 | 0.88913 | 0.08624 |
| 25600 | 0.77733 | 0.90440 | 0.10167 |
| 31200 | 0.86246 | 0.91803 | 0.11502 |
| 35700 | 0.94040 | 0.92788 | 0.12440 |
| 31450 |  | 0.91980 | 0.11671 |
| 25850 |  | 0.90493 | 0.10219 |
| 20200 |  | 0.88974 | 0.08686 |
| 15100 |  | 0.87653 | 0.07311 |
| 10650 |  | 0.85892 | 0.05411 |

### TEMPERATURE 35 °C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 0.36692 | 0.80046 | 0.00000 |
| 5350 | 0.43225 | 0.82527 | 0.03006 |
| 10400 | 0.48880 | 0.84699 | 0.05494 |
| 15500 | 0.55100 | 0.86511 | 0.07473 |
| 20500 | 0.61102 | 0.88053 | 0.09094 |

### TEMPERATURE 35 °C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 0.36692 | 0.80046 | 0.00000 |
| 5600 | 0.43869 | 0.82801 | 0.03328 |
| 10700 | 0.50222 | 0.84999 | 0.05827 |
| 15400 | 0.56120 | 0.86683 | 0.07657 |
| 20150 | 0.61991 | 0.88155 | 0.09198 |
| 26250 | 0.69857 | 0.89860 | 0.10921 |
| 31100 | 0.76051 | 0.91065 | 0.12100 |
| 36450 | 0.83808 | 0.92282 | 0.13259 |

## 75% ACETONE 25% WATER SOLUTION

TEMPERATURE 45 °C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 0.32700 | 0.78874 | 0.00000 |
| 5500 | 0.39596 | 0.80906 | 0.02511 |
| 10550 | 0.45048 | 0.83161 | 0.05155 |
| 15400 | 0.50269 | 0.84890 | 0.07087 |
| 20450 | 0.55457 | 0.86470 | 0.08784 |
| 26500 | 0.62536 | 0.88169 | 0.10543 |
| 31150 | 0.68082 | 0.89386 | 0.11760 |
| 36850 | 0.74080 | 0.90683 | 0.13022 |
| 12350 |  | 0.83731 | 0.05800 |

## PURE ACETONE

### TEMPERATURE 25 °C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 0.30714 | 0.78424 | 0.00000 |
| 5100 | 0.37264 | 0.81621 | 0.03917 |
| 10050 | 0.43506 | 0.83932 | 0.06562 |
| 15375 | 0.49907 | 0.85977 | 0.08785 |
| 20100 | 0.55178 | 0.87491 | 0.10364 |
| 25900 | 0.62404 | 0.89072 | 0.11954 |
| 29900 | 0.67484 | 0.90118 | 0.12976 |
| 24950 | 0.61215 | 0.88940 | 0.11823 |
| 15400 | 0.49921 | 0.86026 | 0.08837 |
| 0 | 0.30963 | 0.78596 | 0.00219 |

### TEMPERATURE 35 °C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 0.27990 | 0.77223 | 0.00000 |
| 5600 | 0.34528 | 0.80739 | 0.04355 |
| 10250 | 0.39858 | 0.82928 | 0.06879 |
| 14950 | 0.44917 | 0.84747 | 0.08879 |
| 20450 | 0.50488 | 0.86593 | 0.10821 |
| 25450 | 0.55779 | 0.88119 | 0.12365 |
| 30650 | 0.61944 | 0.89471 | 0.13689 |
| 20500 | 0.50631 | 0.86662 | 0.10892 |
| 10500 | 0.40141 | 0.83047 | 0.07013 |
| 0 | 0.27778 | 0.77230 | 0.00009 |

### TEMPERATURE 45 °C

| PRESSURE (PSIG) | VISCOSITY (CP) | DENSITY (GM/CC) | COMPRESSIBILITY |
|---|---|---|---|
| 0 | 0.25593 | 0.75944 | 0.00000 |
| 6750 | 0.32796 | 0.80075 | 0.05159 |
| 10400 | 0.36575 | 0.81733 | 0.07083 |
| 15075 | 0.41569 | 0.83677 | 0.09242 |
| 20150 | 0.46262 | 0.85409 | 0.11082 |
| 25550 | 0.51183 | 0.87016 | 0.12724 |
| 30550 | 0.56535 | 0.88399 | 0.14089 |
| 33100 | 0.59240 | 0.89044 | 0.14712 |

# APPENDIX IV

## EFFECT OF PRESSURE ON VISCOSITY OF ACETONE WATER SOLUTIONS

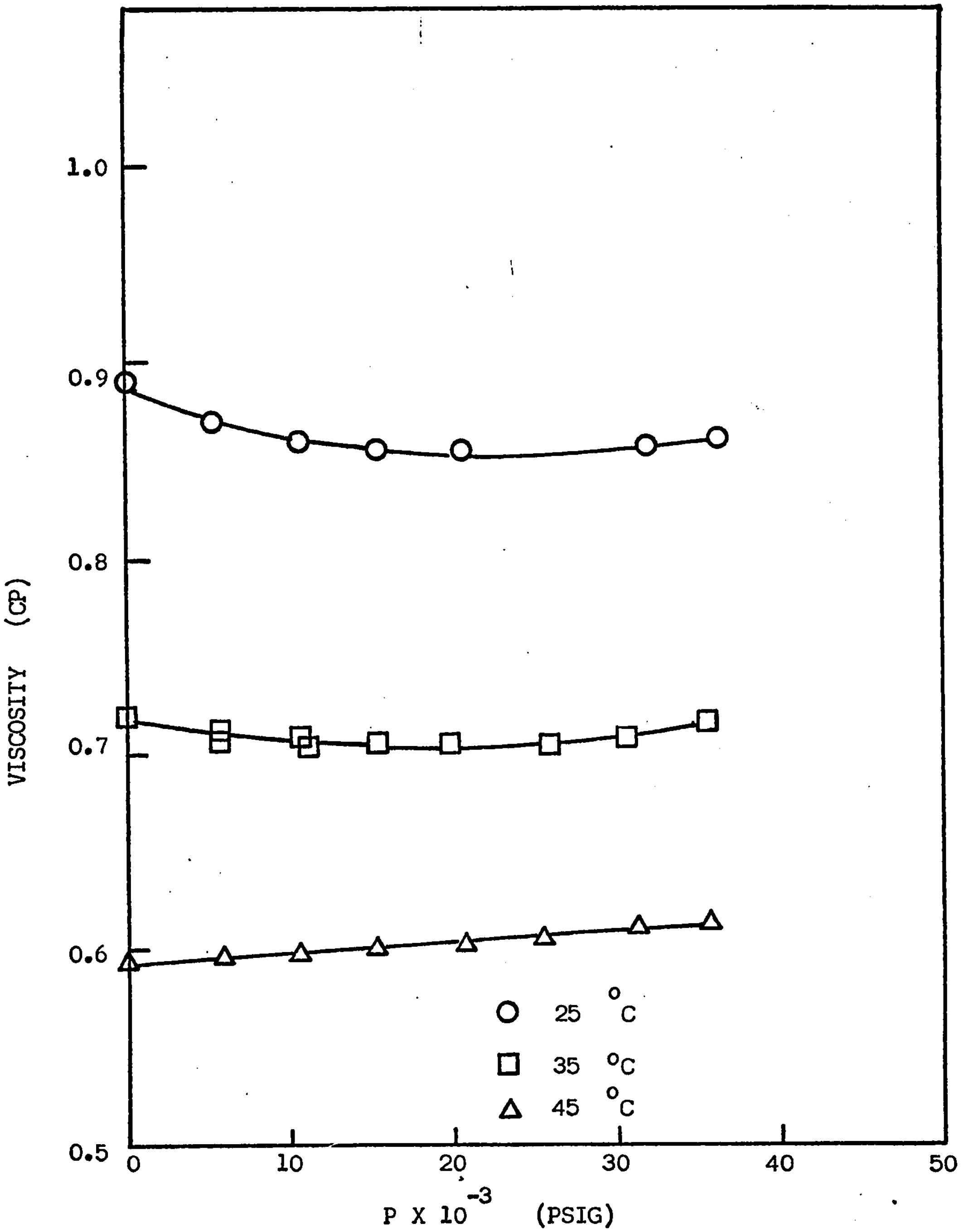

FIG. 25 EFFECT OF PRESSURE ON VISCOSITY OF PURE WATER

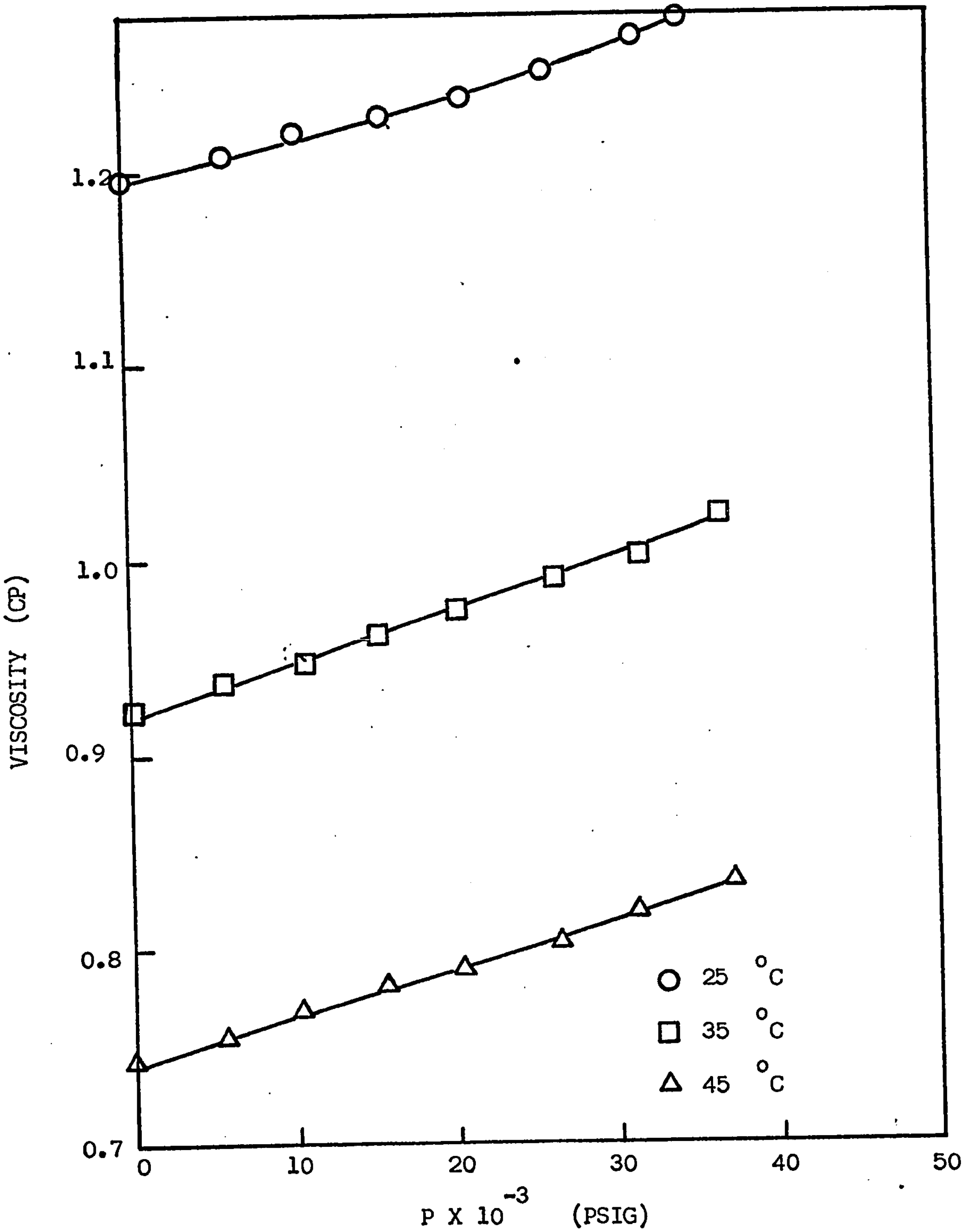

FIG. 26 EFFECT OF PRESSURE ON VISCOSITY OF 5% ACETONE 95% WATER SOLUTION

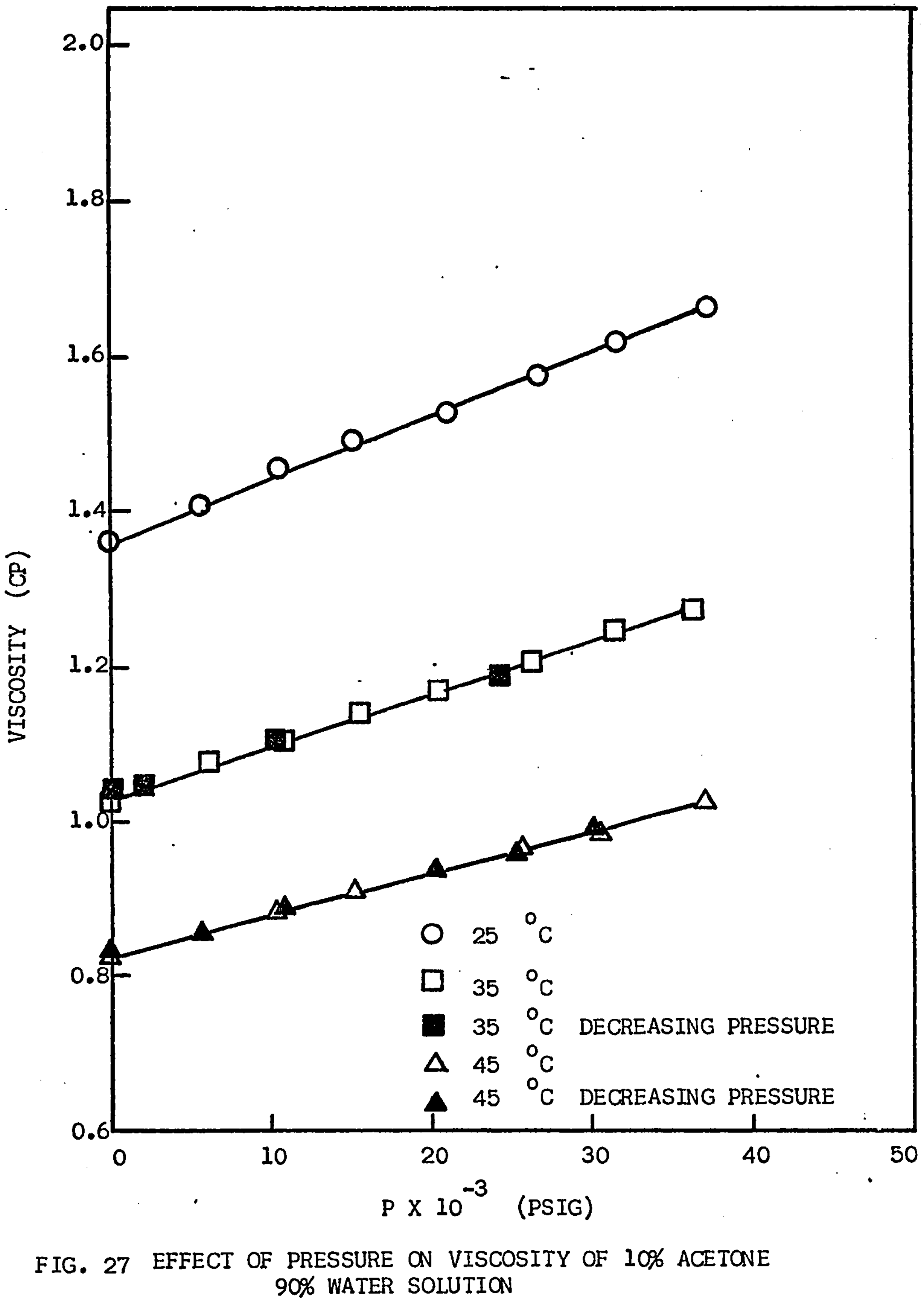

FIG. 27 EFFECT OF PRESSURE ON VISCOSITY OF 10% ACETONE 90% WATER SOLUTION

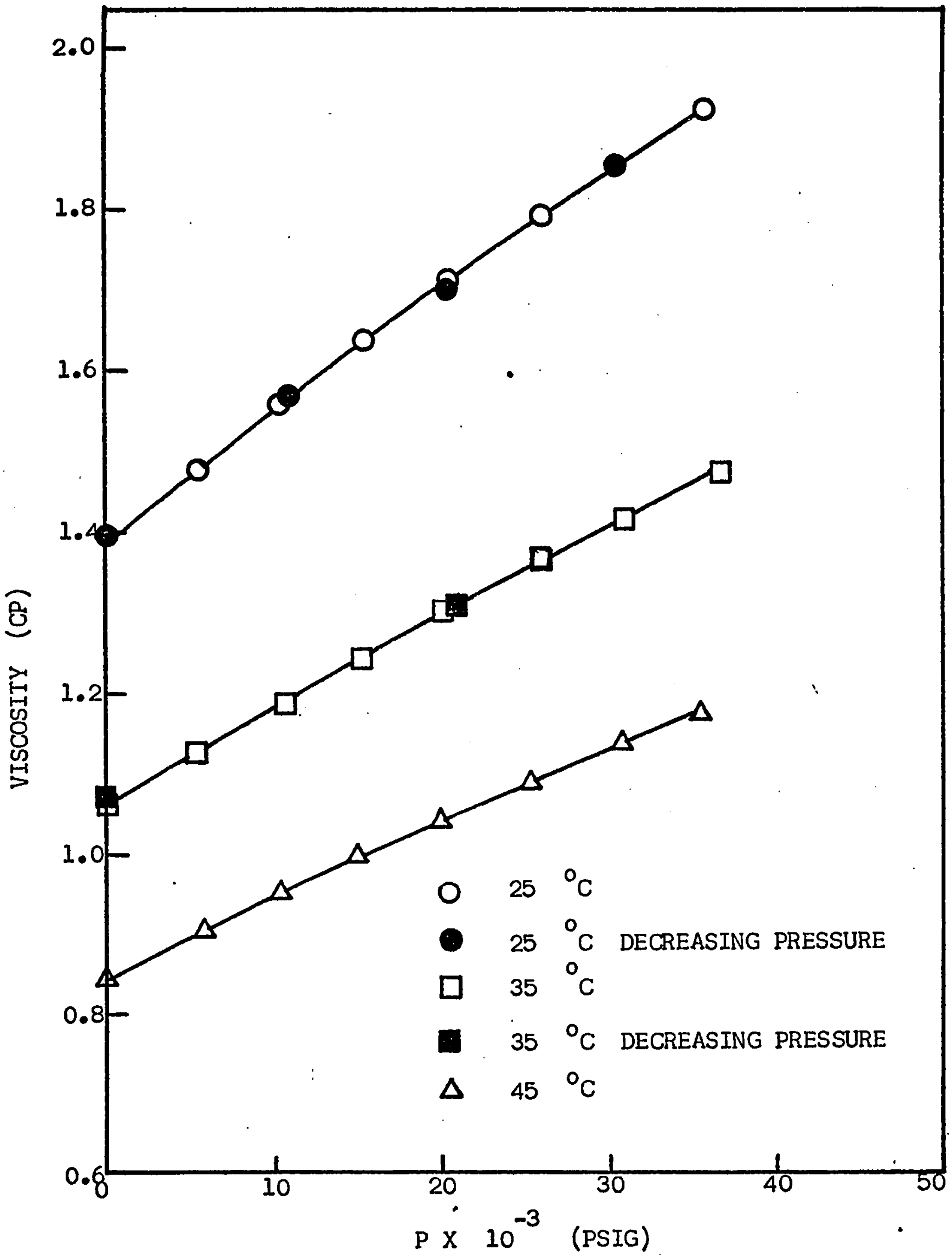

FIG. 28 EFFECT OF PRESSURE ON VISCOSITY OF 15% ACETONE 85% WATER SOLUTION

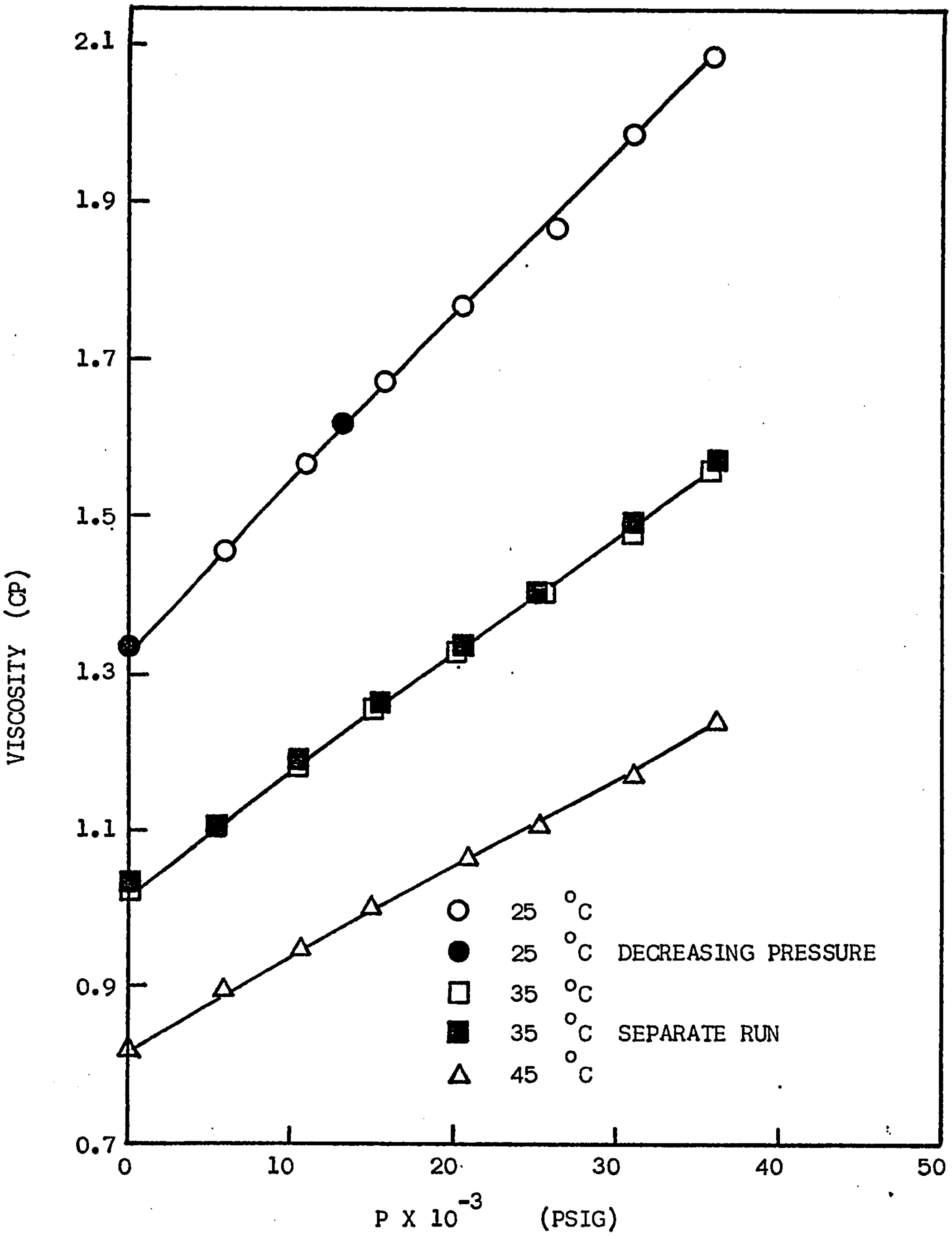

FIG. 29 EFFECT OF PRESSURE ON VISCOSITY OF 20% ACETONE 80% WATER SOLUTION

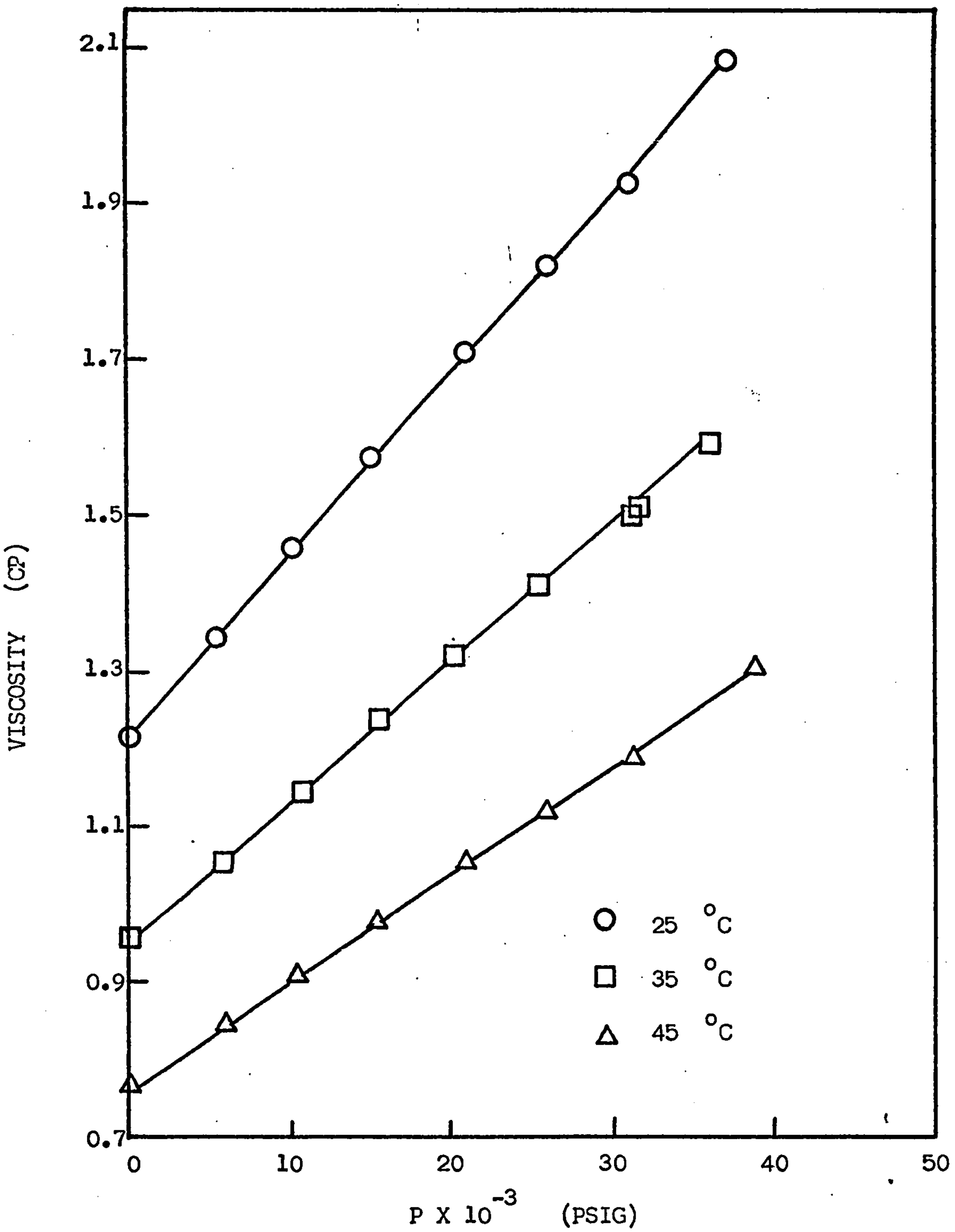

FIG. 30 EFFECT OF PRESSURE ON VISCOSITY OF 25% ACETONE 75% WATER SOLUTION

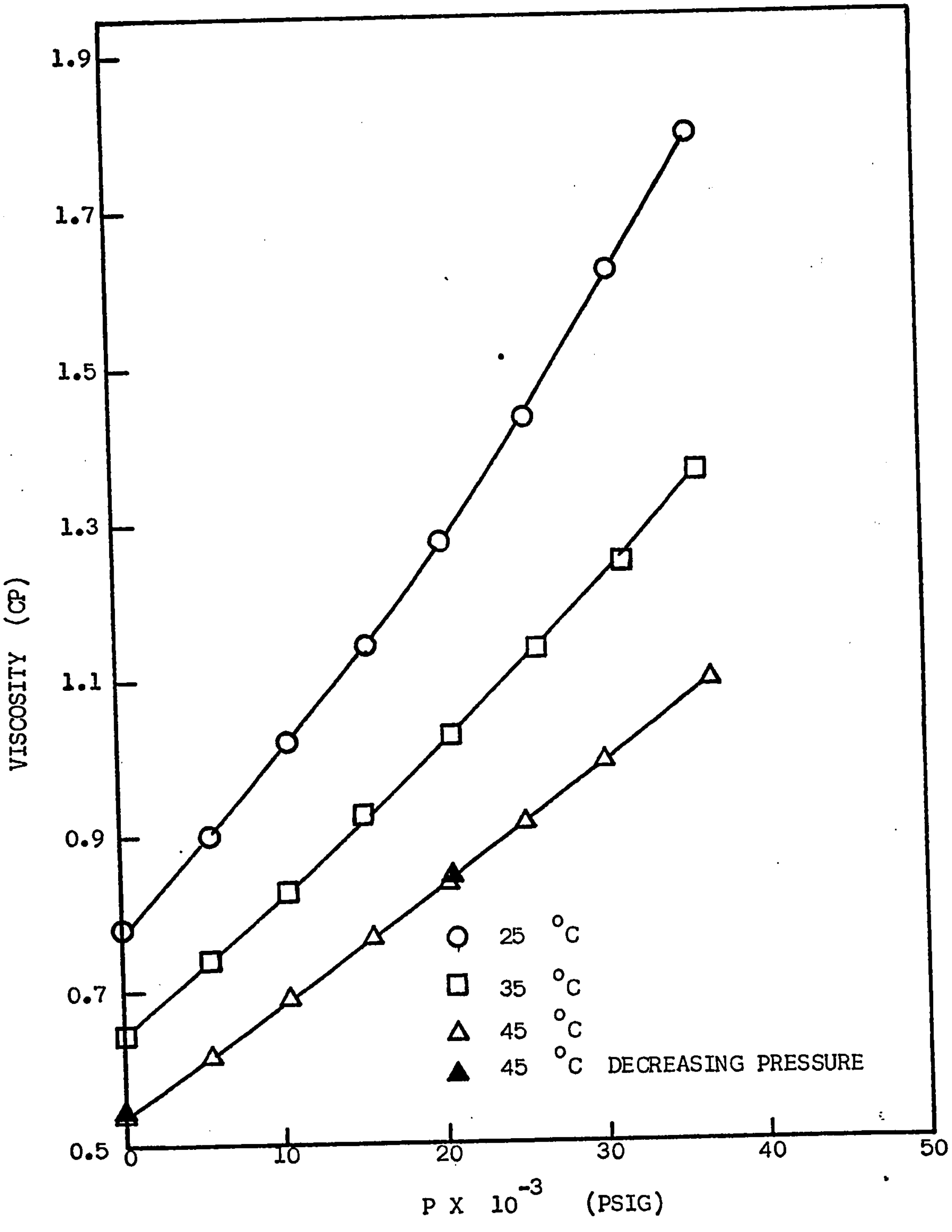

FIG. 31 EFFECT OF PRESSURE ON VISCOSITY OF 45% ACETONE 55% WATER SOLUTION

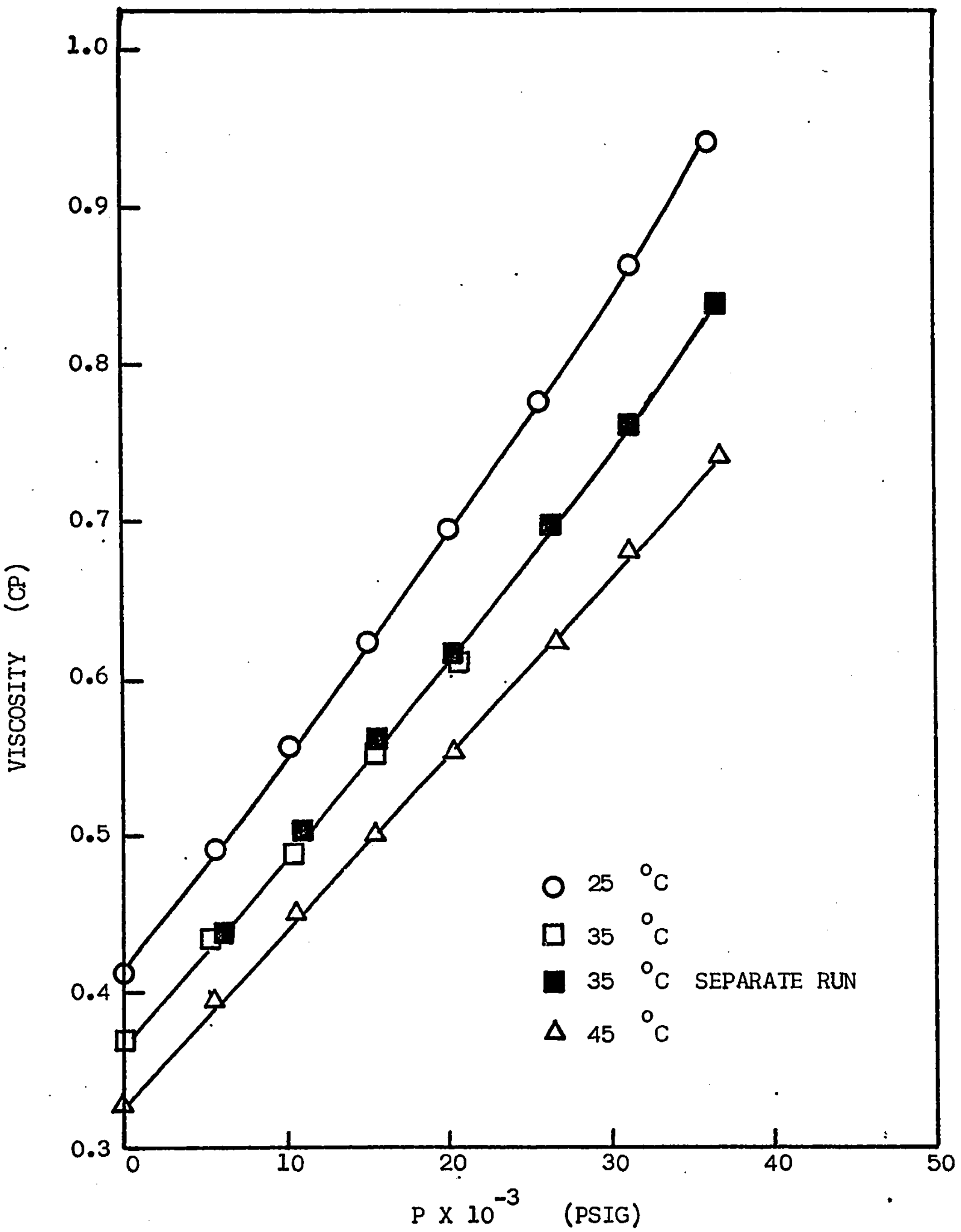

FIG. 32 EFFECT OF PRESSURE ON VISCOSITY OF 75% ACETONE 25% WATER SOLUTION

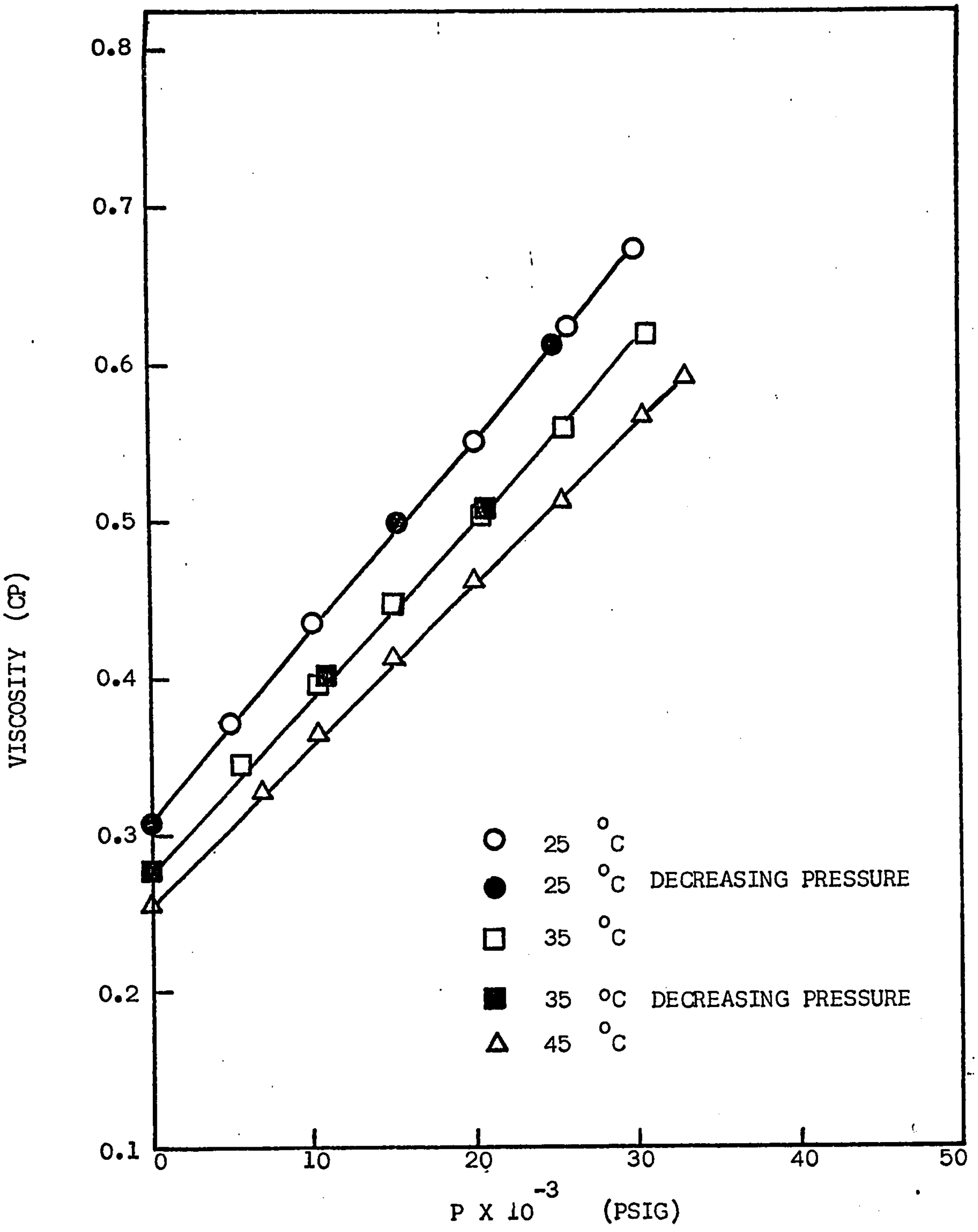

FIG. 33 EFFECT OF PRESSURE ON VISCOSITY OF PURE ACETONE

# APPENDIX V

## EFFECT OF PRESSURE ON VISCOSITY OF ACETONE WATER SOLUTIONS

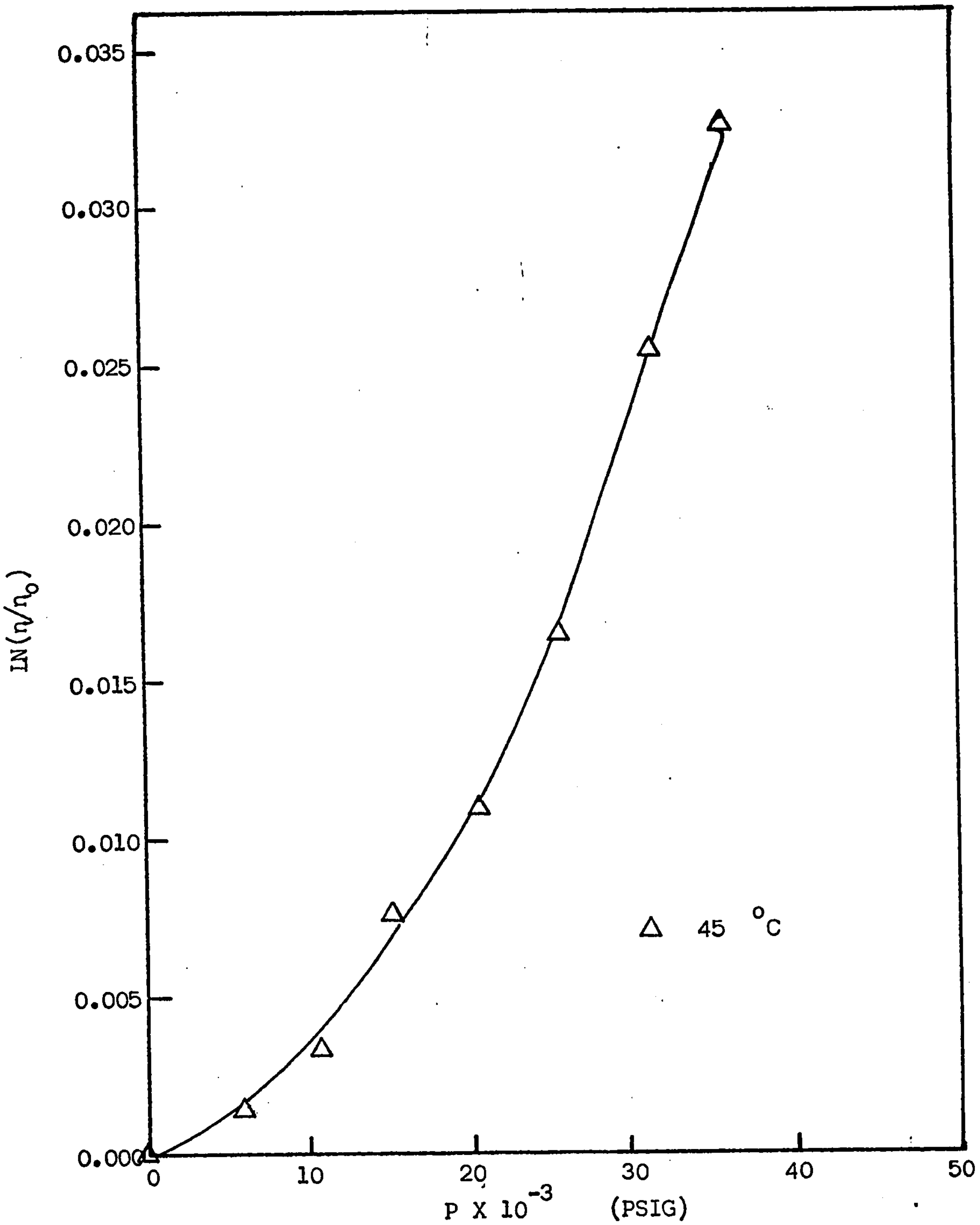

FIG. 34 EFFECT OF PRESSURE ON VISCOSITY OF PURE WATER

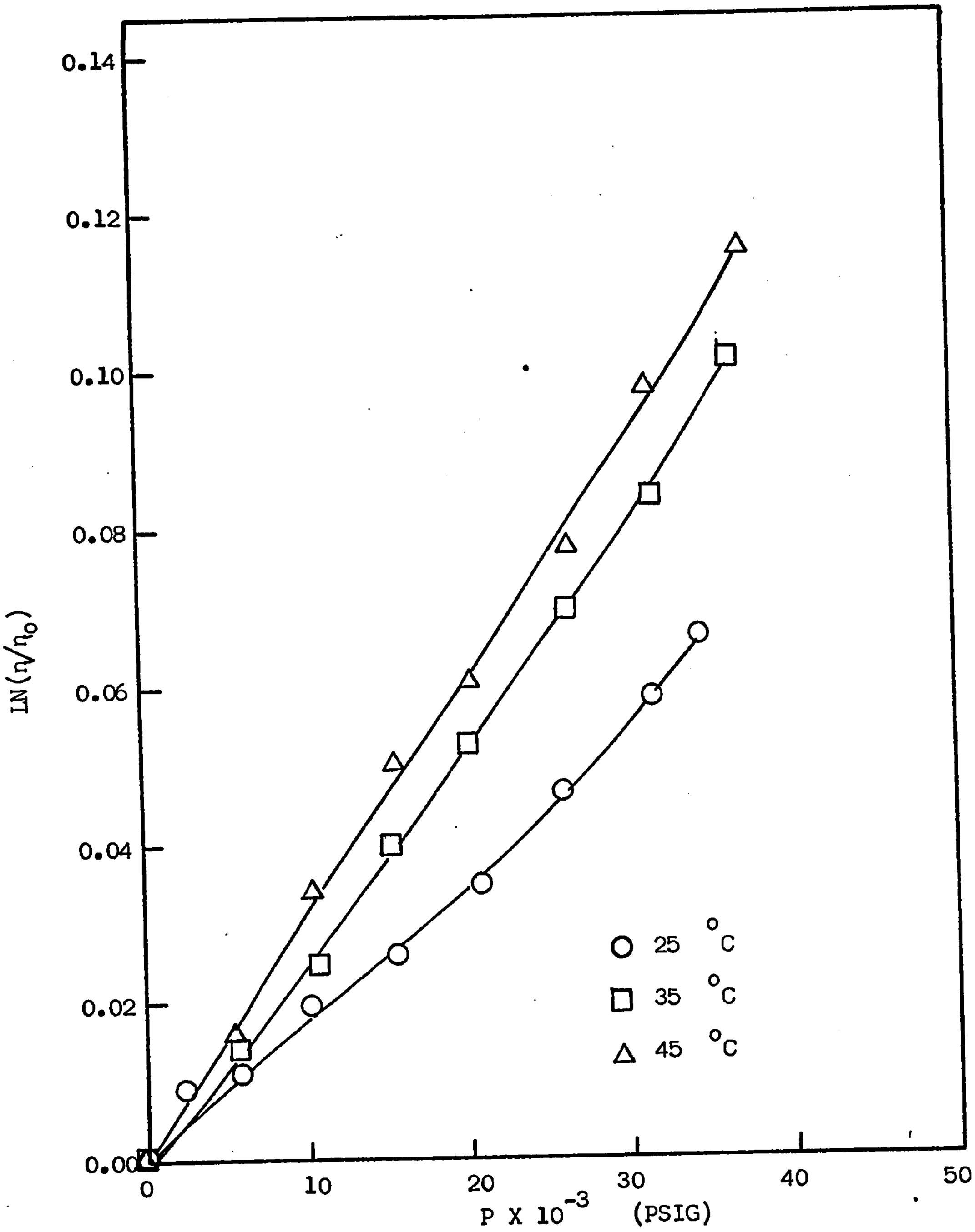

FIG. 35 EFFECT OF PRESSURE ON VISCOSITY OF 5% ACETONE 95% WATER SOLUTION

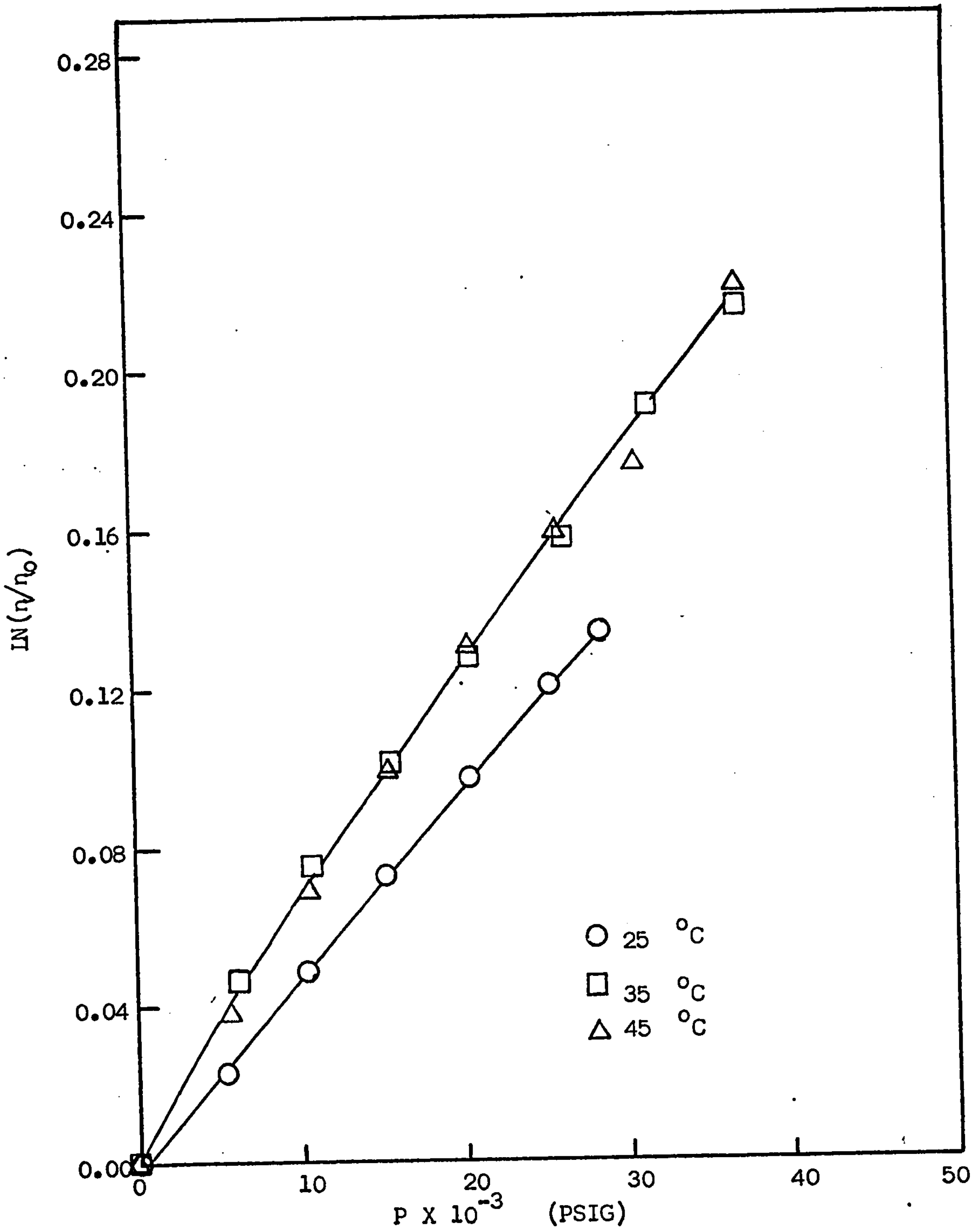

FIG. 36 EFFECT OF PRESSURE ON VISCOSITY OF 10% ACETONE 90% WATER SOLUTION

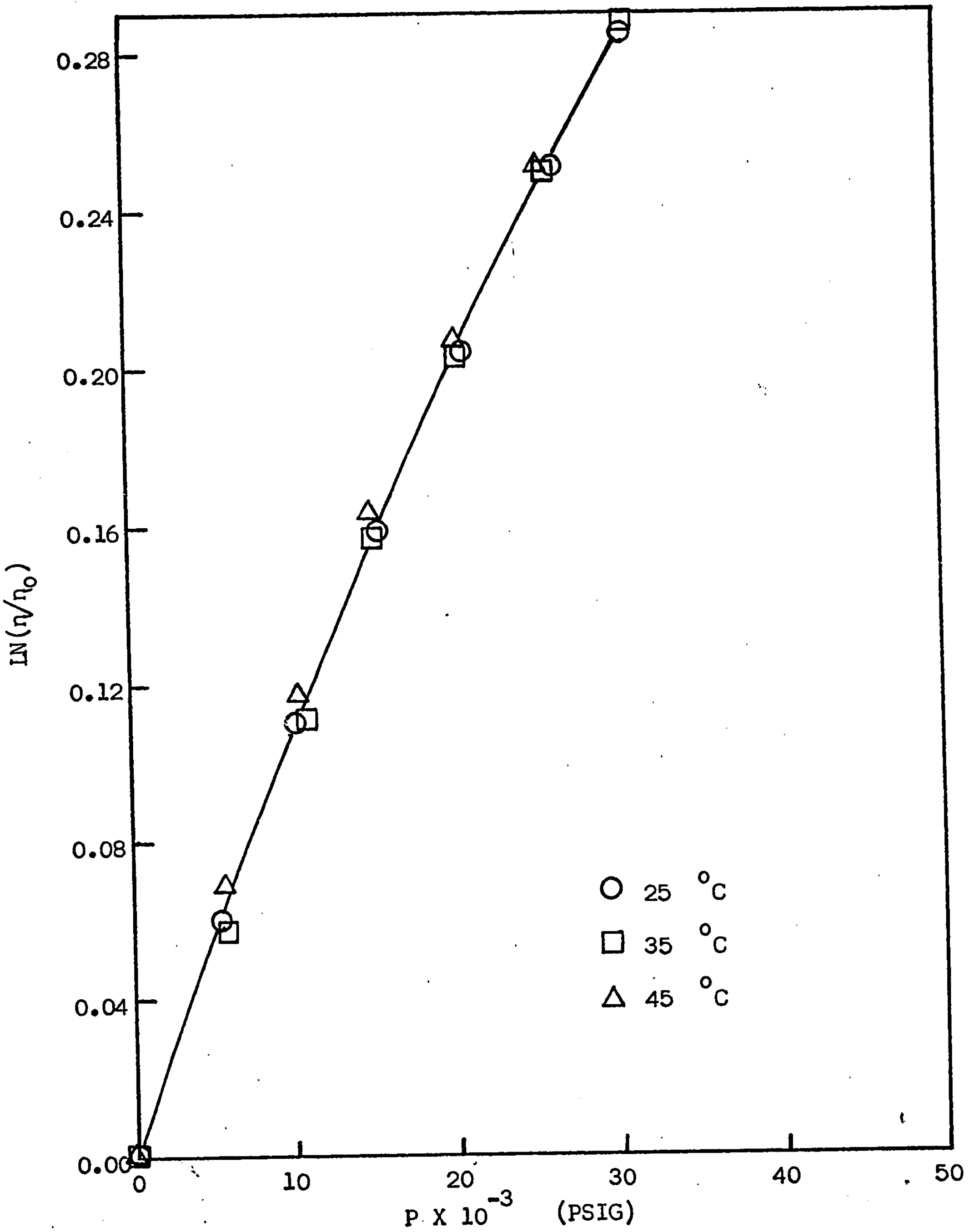

FIG. 37 EFFECT OF PRESSURE ON VISCOSITY OF 15% ACETONE 85% WATER SOLUTION

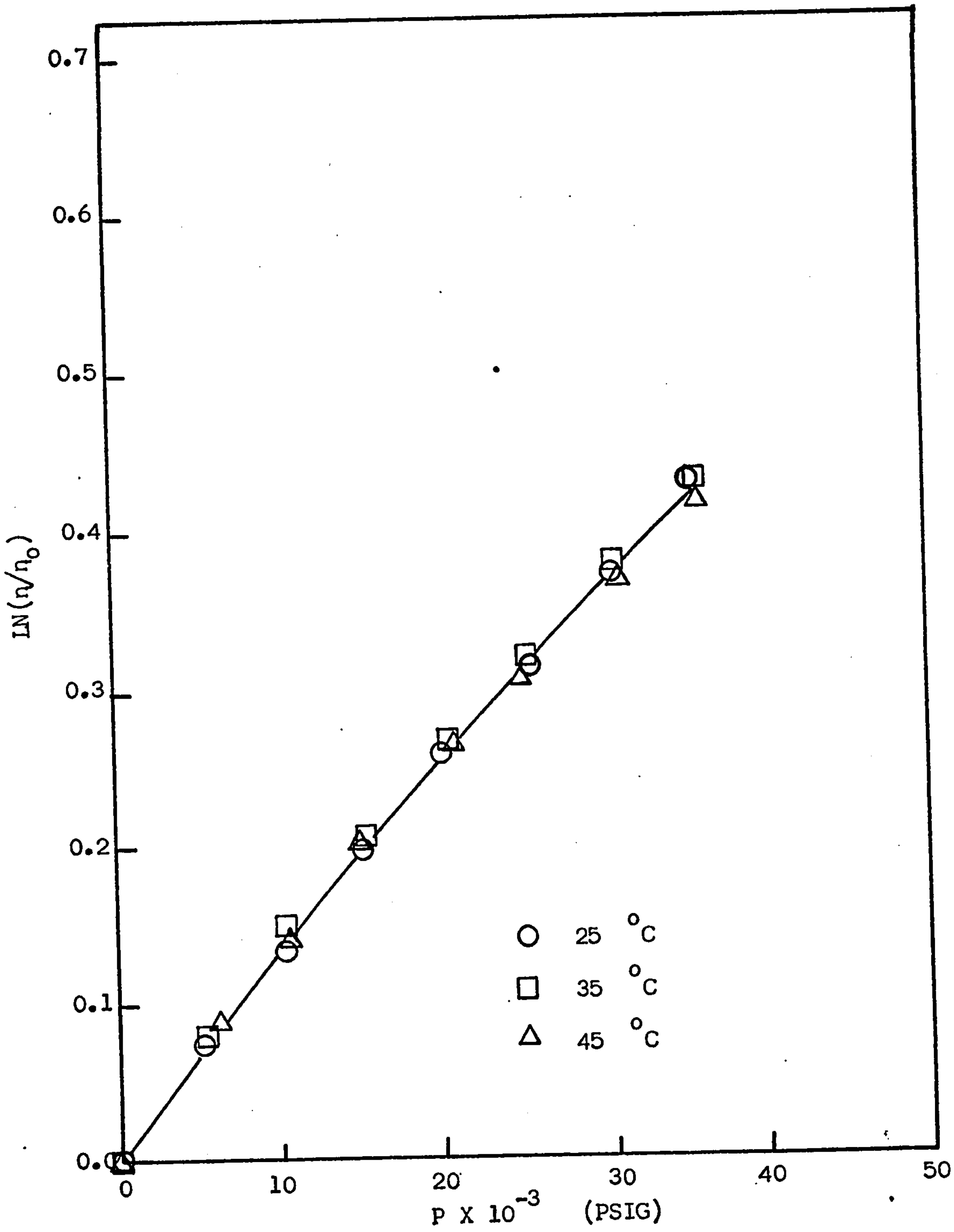

FIG. 38 EFFECT OF PRESSURE ON VISCOSITY OF 20% ACETONE 80% WATER SOLUTION

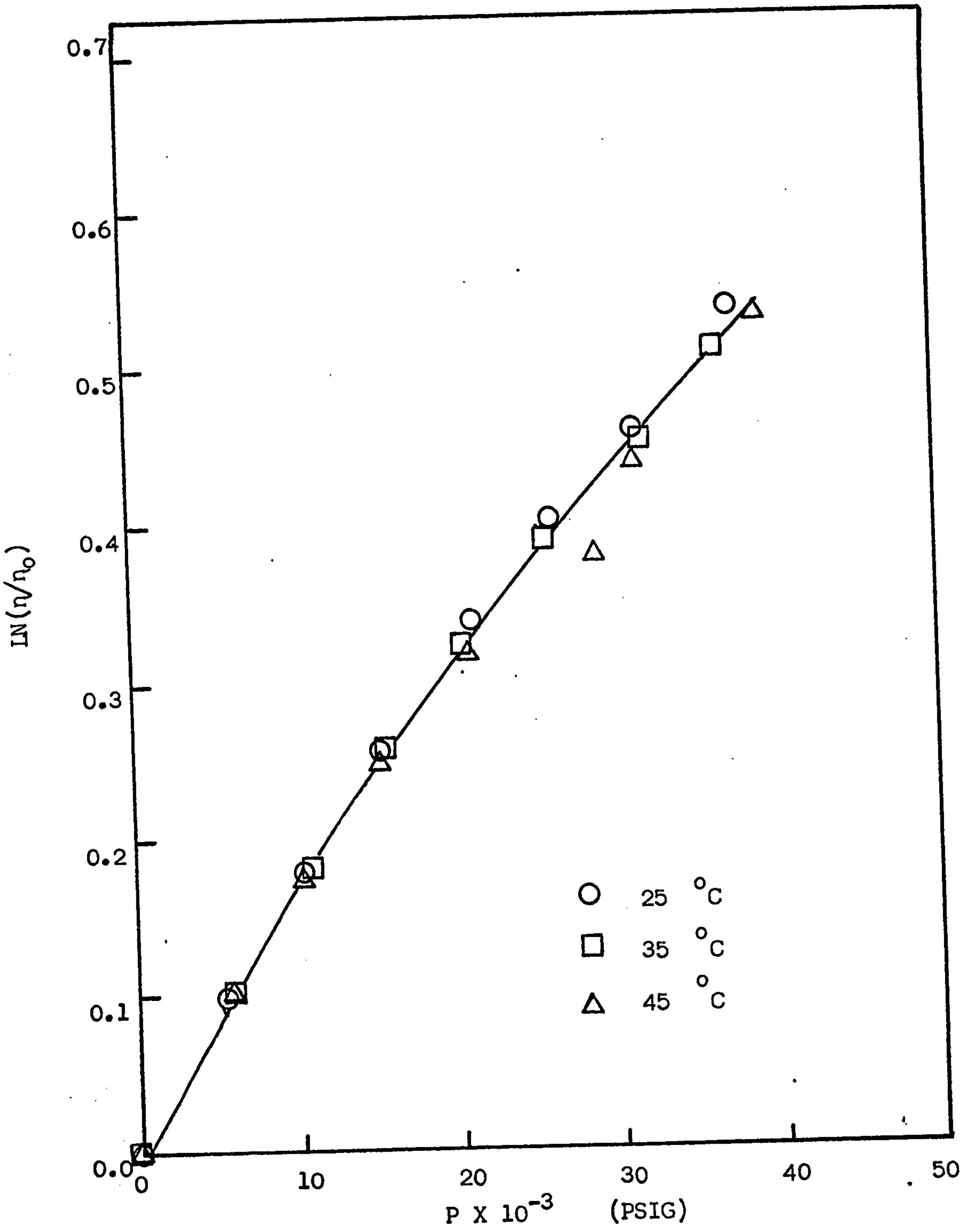

FIG. 39 EFFECT OF PRESSURE ON VISCOSITY OF 25% ACETONE 75% WATER SOLUTION

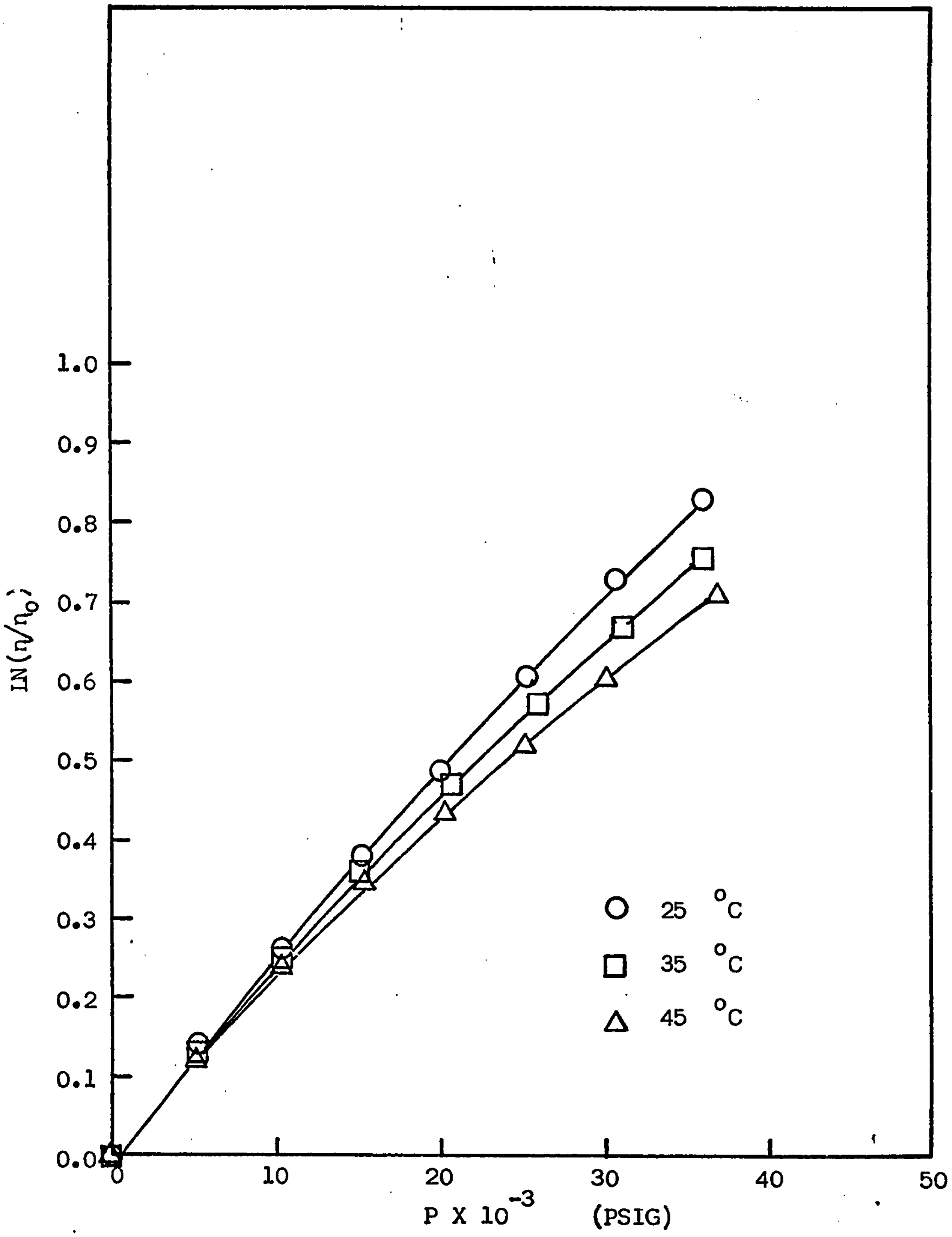

FIG. 40 EFFECT OF PRESSURE ON VISCOSITY OF 45% ACETONE 55% WATER SOLUTION

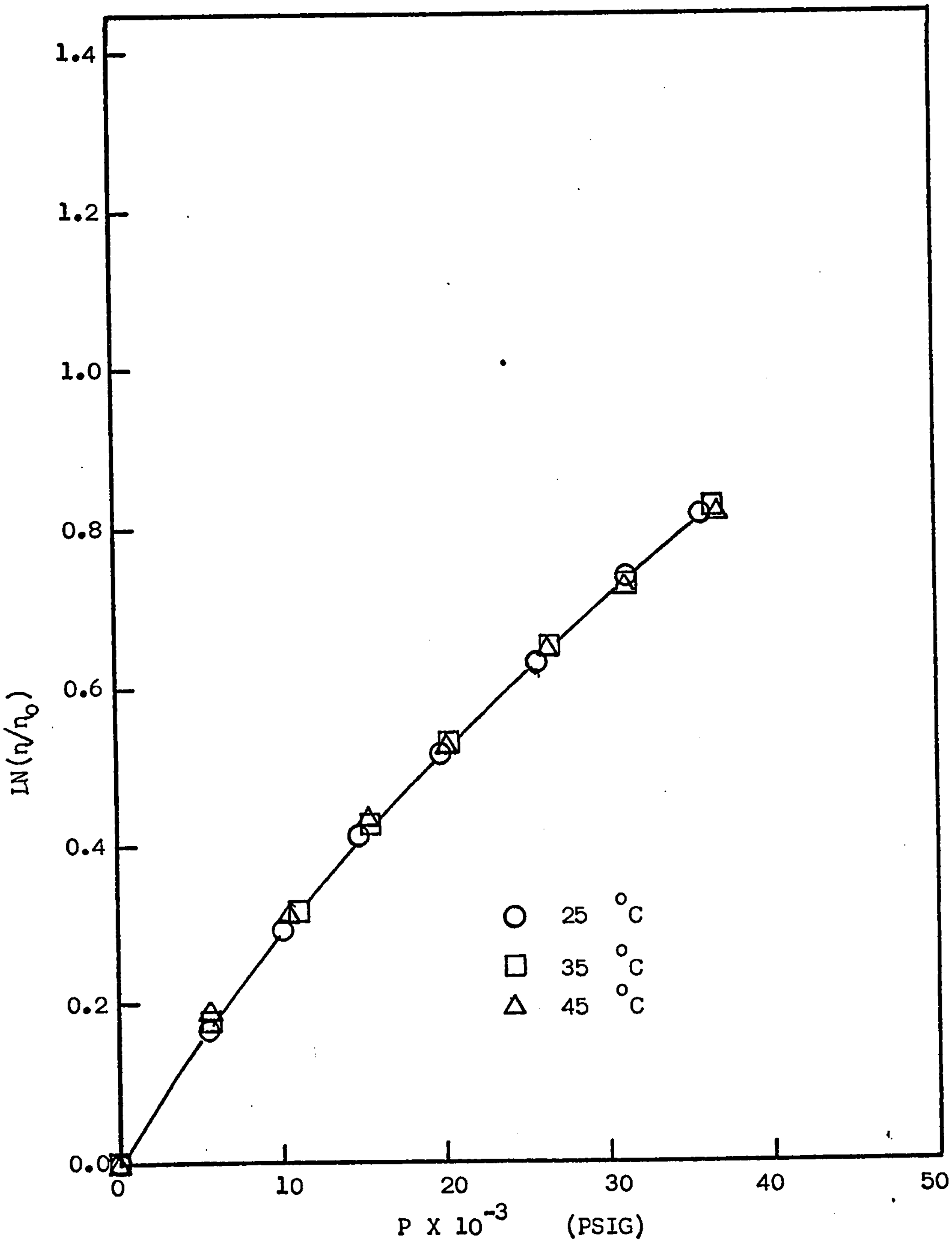

FIG. 41 EFFECT OF PRESSURE ON VISCOSITY OF 75% ACETONE 25% WATER SOLUTION

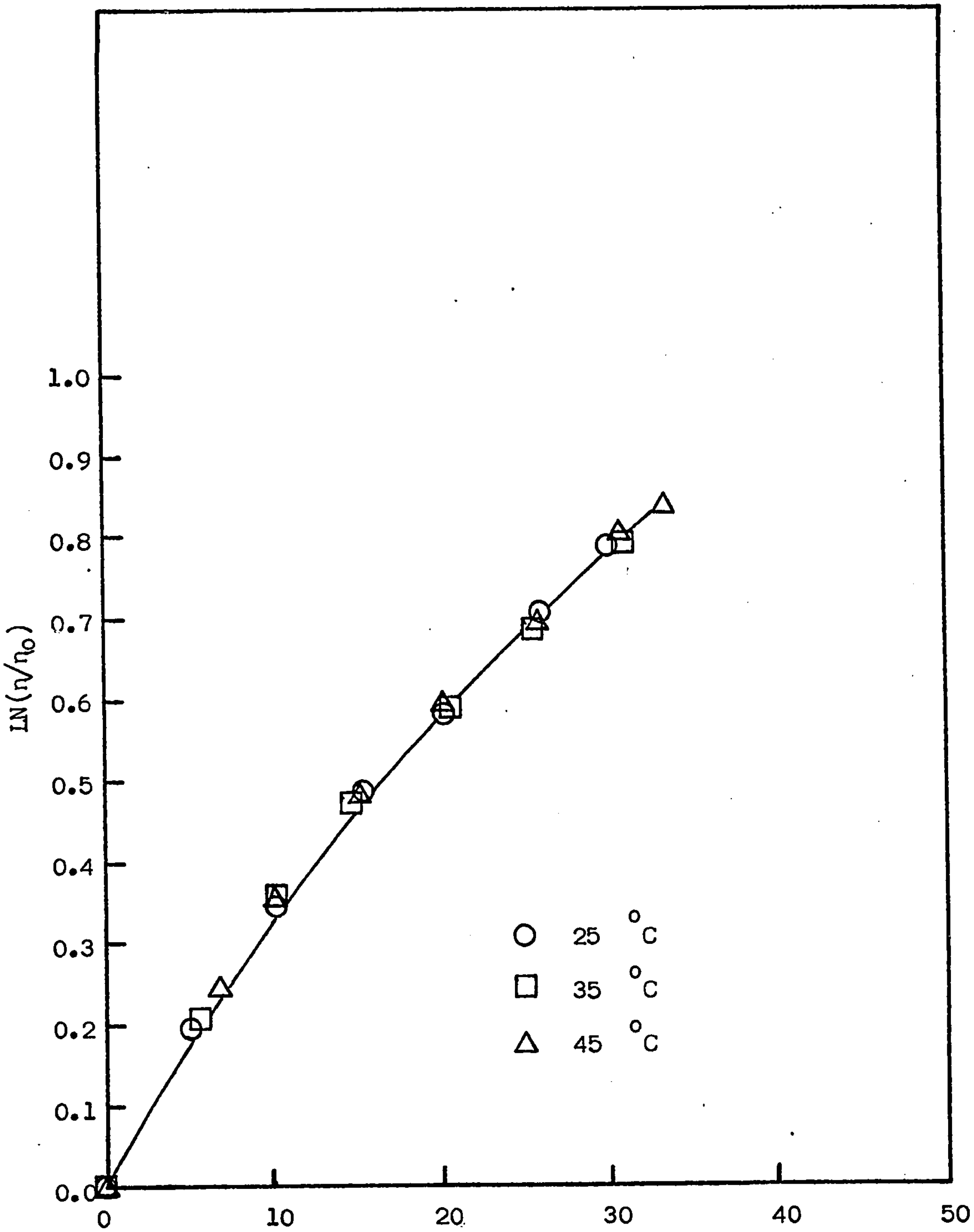

FIG. 42 EFFECT OF PRESSURE ON VISCOSITY OF PURE ACETONE

# APPENDIX VI

## VARIATION OF VISCOSITY WITH COMPOSITION OF ACETONE WATER SOLUTIONS

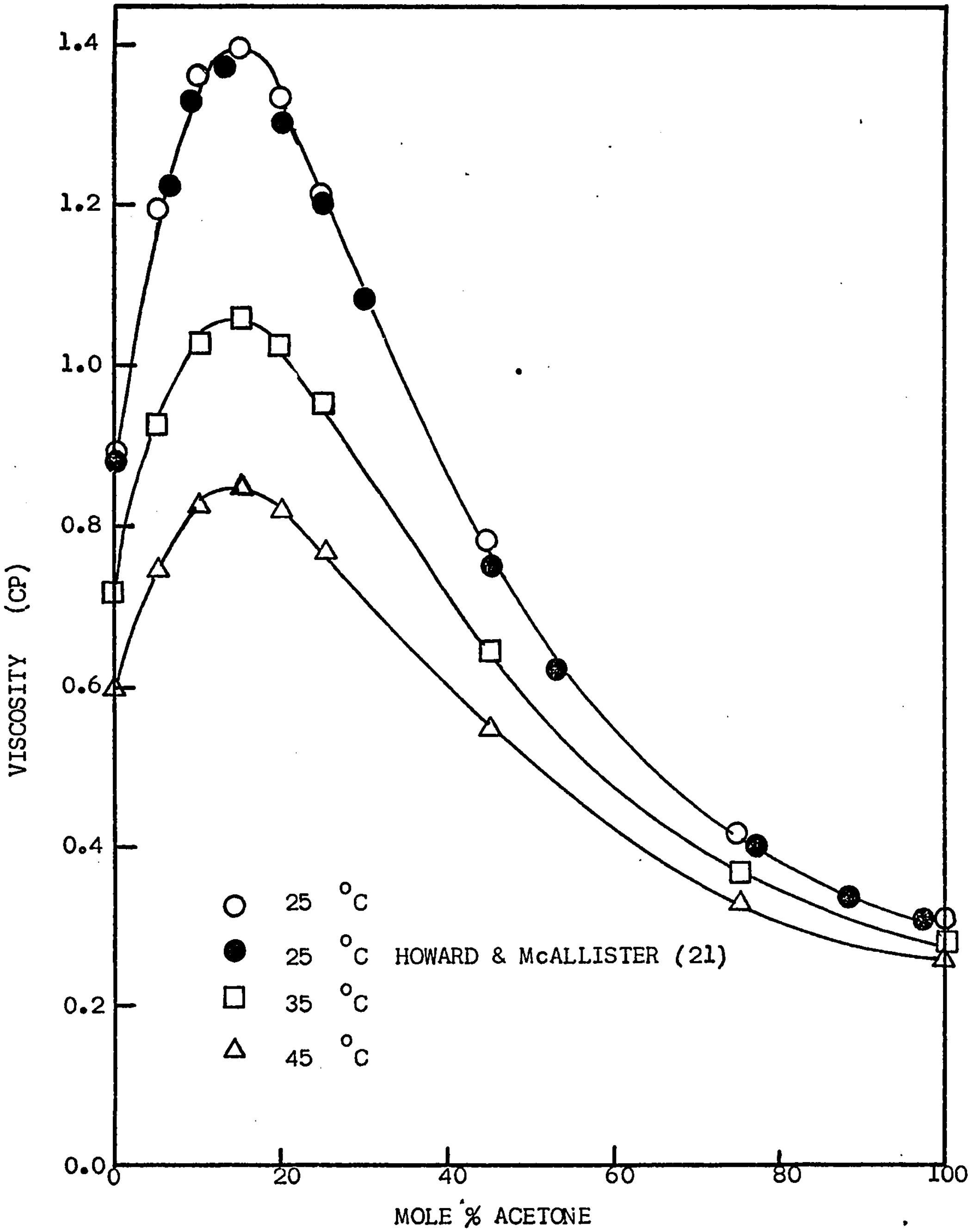

FIG. 43 VISCOSITY VERSUS COMPOSITION AT ATMOSPHERIC PRESSURE

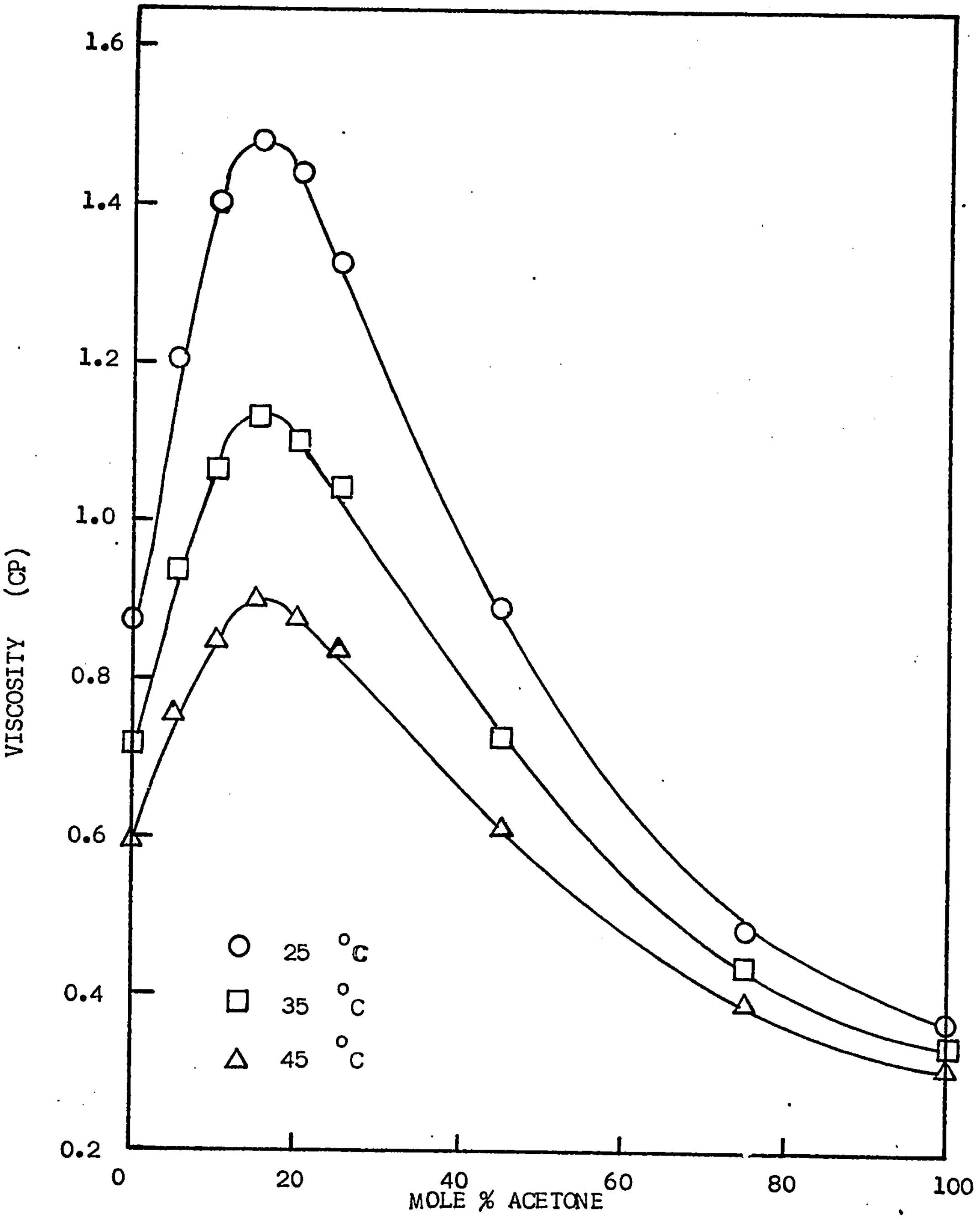

FIG. 44 VISCOSITY VERSUS COMPOSITION AT 5000 (PSIG)

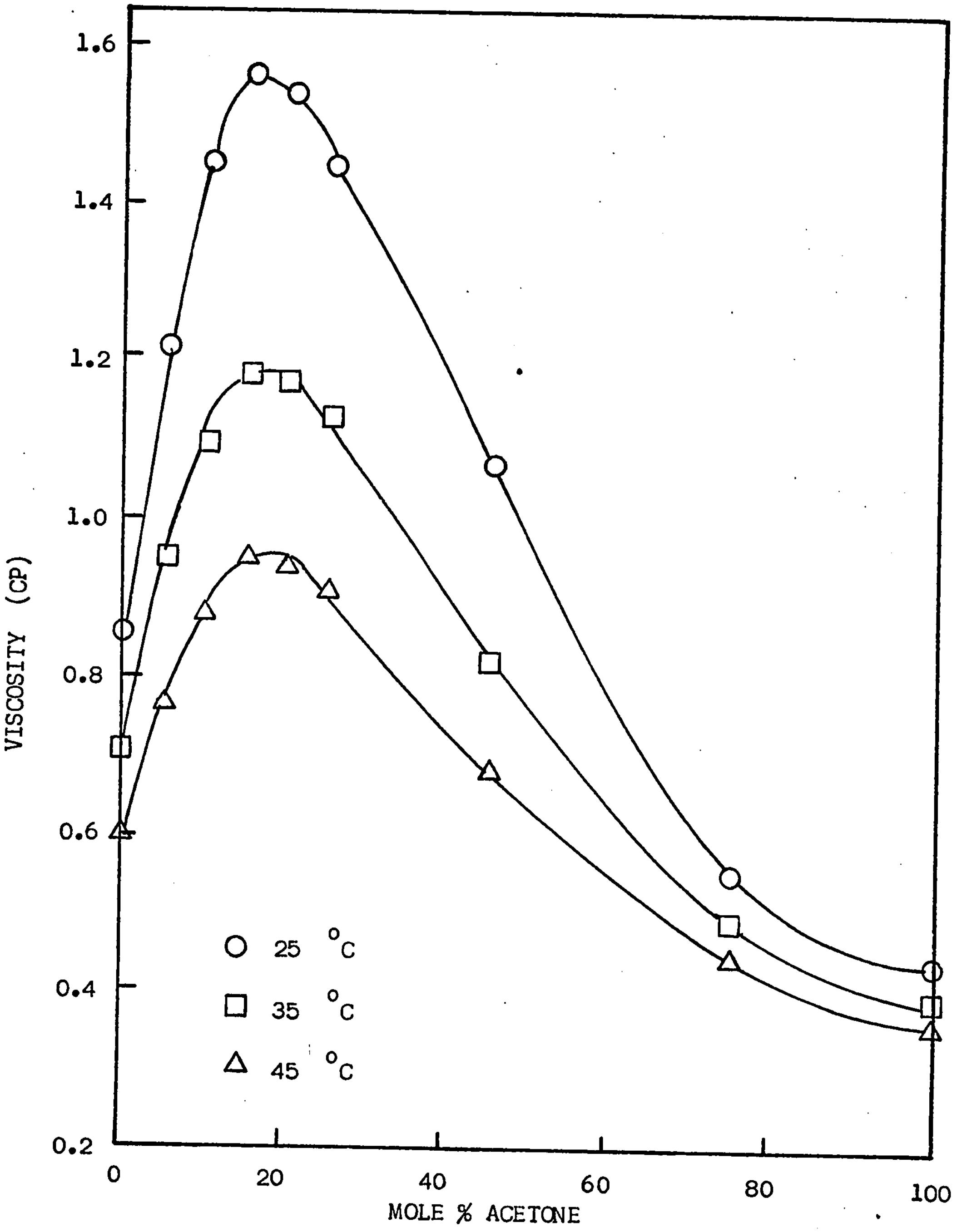

FIG. 45 VISCOSITY VERSUS COMPOSITION AT 10,000 (PSIG)

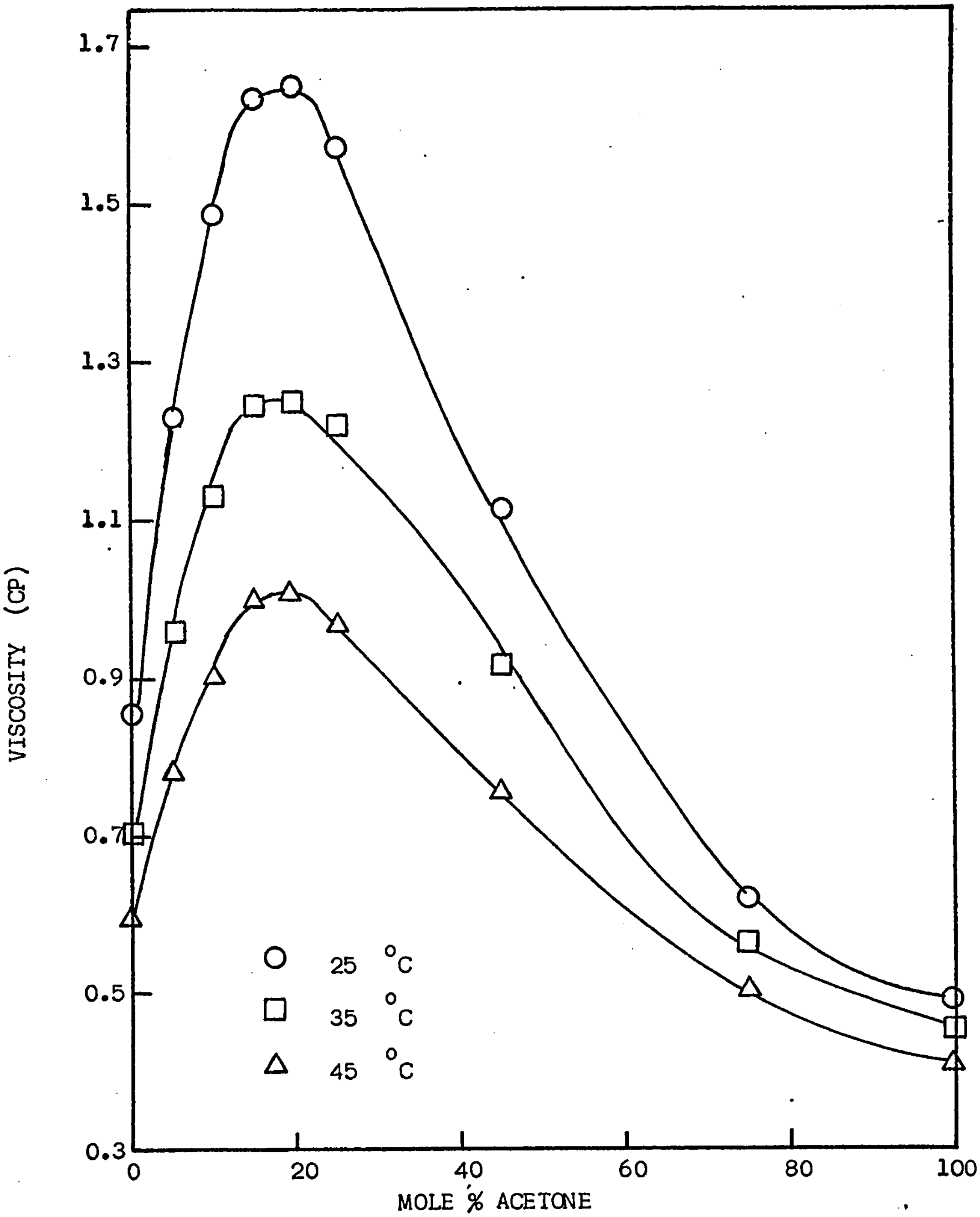

FIG. 46 VISCOSITY VERSUS COMPOSITION AT 15,000 (PSIG)

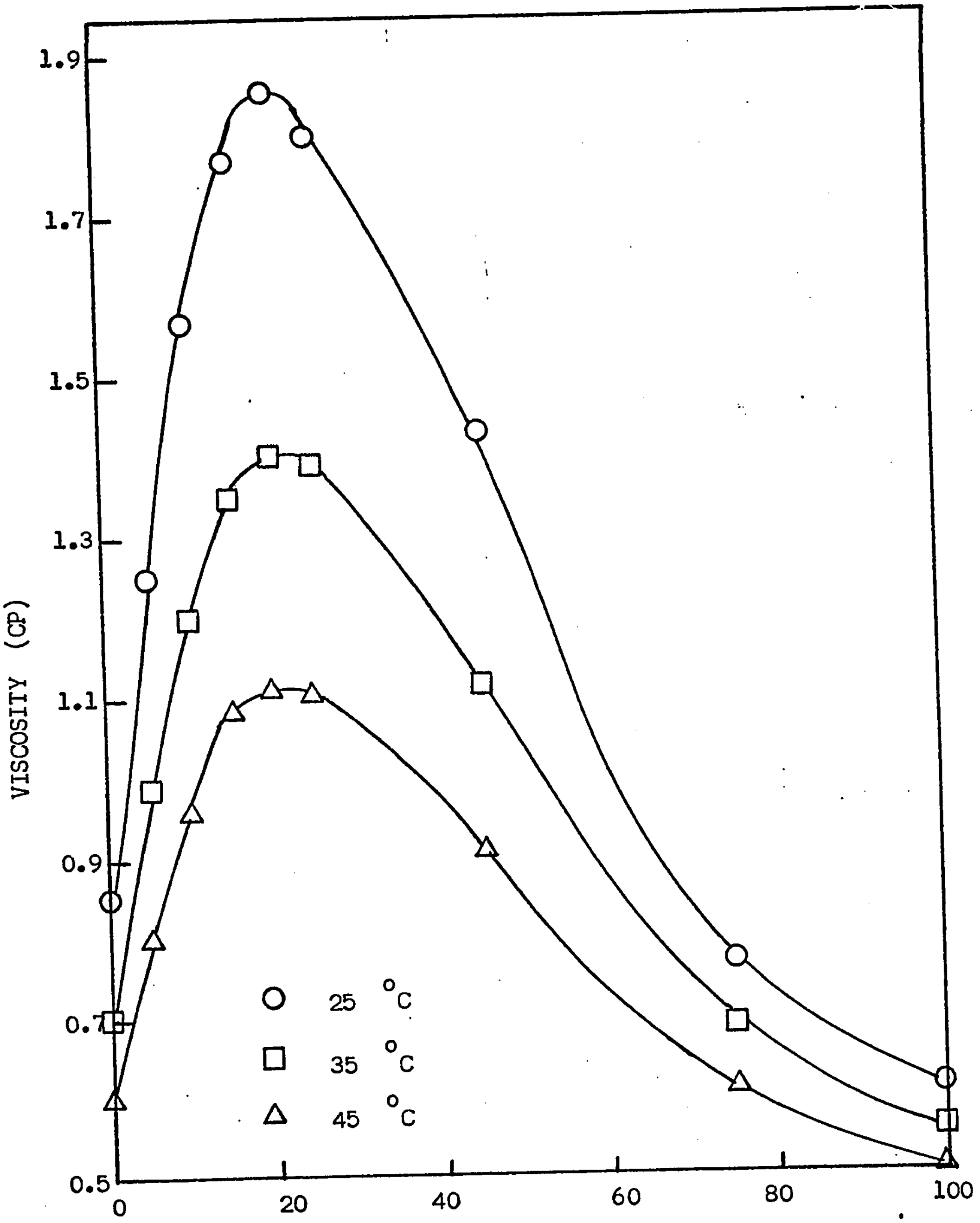

FIG. 47 VISCOSITY VERSUS COMPOSITION AT 25,000 (PSIG)

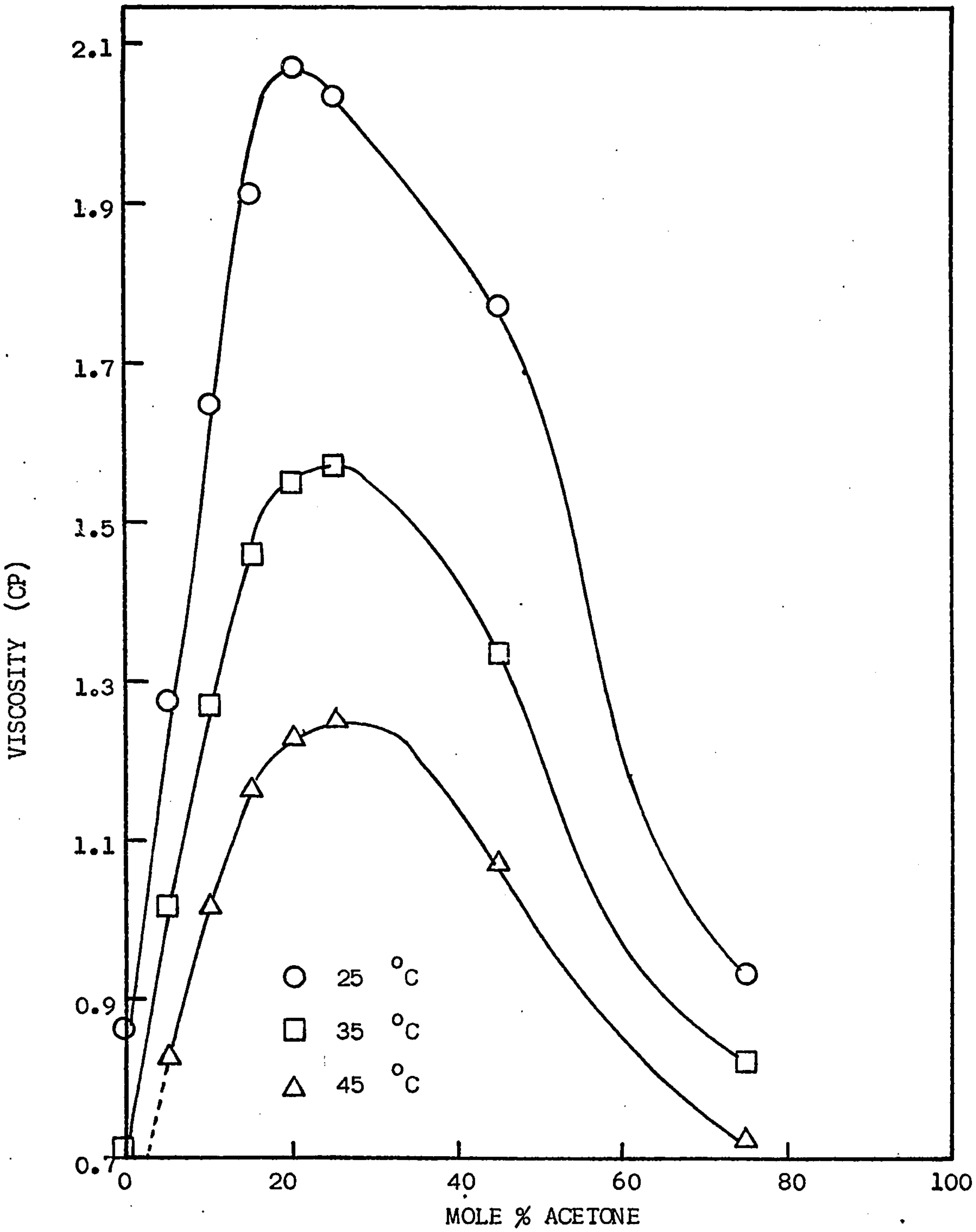

FIG. 48 VISCOSITY VERSUS COMPOSITION AT 35,000 (PSIG)

# VITA AUCTORIS

| | |
|---|---|
| 1947 | Born in Windsor, Ontario, Canada. |
| 1966 | Completed Secondary school in Welland, Ontario, Canada. |
| 1970 | Received the degree of Bachelor of Applied Science in Chemical Engineering at the University of Windsor, Windsor, Ontario, Canada. |
| 1972 | Presently a candidate for the degree of Master of Applied Science in Chemical Engineering at the University of Windsor, Windsor, Ontario, Canada. |