

THE EFFECT OF NITROGEN ON THE
VARIOUS COMPOSITIONAL MATERIAL BALANCE
METHODS FOR A GAS-CONDENSATE RESERVOIR

by

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A Thesis submitted to the Faculty and the Board
of Trustees of the Colorado School of Mines in partial
fulfillment of the requirements for the degree of
Masters of Science in Petroleum Engineering.

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ABSTRACT

This thesis explores the effects of nitrogen concentration upon three compositional material balance methods of treating the non-hydrocarbon fraction for a gas-condensate reservoir. The three methods are as follows:

1. The non-hydrocarbon fraction may be considered as it actually occurs in both the liquid and vapor phase of the reservoir fluid.
2. The non-hydrocarbon fraction may be considered as existing only in the vapor phase of the reservoir fluid.
3. The non-hydrocarbon fraction may be treated as part of a hydrocarbon fraction. In the case of nitrogen, the non-hydrocarbon fraction is added to the methane fraction.

Recoveries of reservoir fluids are calculated using

each of the above methods at nitrogen concentrations ranging from 1 to 18 mole per cent. These recoveries are compared on the basis of the percentage recovery of the reservoir material initially in place. Recovery trends with nitrogen concentration and pressure are shown for each of these compositional material balance methods.

Original vapor volumes of the reservoir are calculated and compared using each of the compositional material balance methods presented above. The deviations of the original vapor volumes as calculated by methods two and three from the original vapor volumes calculated by method one, are presented as a function of nitrogen concentration which ranges from 1 to 18 mole per cent. The effect of pressure upon these original vapor volume calculations is also presented.

ACKNOWLEDGMENTS

The author wishes to express his gratitude to Mr. W. C. Sheldon for the patience and aid given in his capacity as thesis advisor.

Sincere appreciation is extended to Dr. D. Marsh and Prof. D. M. Bass for the time spent as committee members.

Special thanks are given to the Marathon Oil Co., Denver Research Center, for the use of their computer and library facilities.

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INTRODUCTION

It is customary in the practice of petroleum engineering to characterize crude oils and natural gases as simple mixtures of paraffinic hydrocarbons. These mixtures are broken into components ranging from methane through hexane and a pseudo-component known as the heptanes-plus fraction. This heptanes-plus fraction contains all the hydrocarbon fractions heavier than hexane and is characterized by an apparent molecular weight and specific gravity.

Crude oils and natural gases may also contain materials other than hydrocarbons. The non-hydrocarbon components most commonly found are nitrogen, carbon dioxide and hydrogen sulfide. Proper treatment of these non-hydrocarbon fractions is crucial when dealing with a compositional material balance for a hydrocarbon reservoir. The success of the compositional balance rests upon accurate representation of the phase

behavior of the reservoir fluid. However, many of the routines and correlations used in compositional material balances already consider the presence of small amounts of nitrogen and carbon dioxide. This is true because the hydrocarbon mixtures used in the preparation of the correlations contained small amounts of these non-hydrocarbon compounds. These same correlations and procedures are for the most part generated empirically or by making use of simplifying assumptions in otherwise rigorous scientific relationships. In either case, the precision of these routines and correlations are limited by their nature. Also, the use of measured field and PVT data are necessary and the precision of these input data are also limited by their nature. Since the whole is but the sum of its parts, the precision of the balance is limited by the nature of its internal workings. Therefore, it behooves the engineer to study well the choices available to him and to select that which will represent the non-hydrocarbon fraction of the reservoir fluid within the degree of precision of which the balance is capable. The choices most often available are as follows:

1. The non-hydrocarbon fraction may be treated as it actually occurs in both the liquid and vapor phases

of the reservoir fluid. This necessitates determination of equilibrium ratios for the non-hydrocarbon components.

2. The non-hydrocarbon components may be considered as existing only in the vapor phase of the mixture. While this approach is not as rigorous as that just discussed, it does allow the non-hydrocarbon fraction to exert influence on the balance without using equilibrium ratios.
3. The non-hydrocarbon components may be considered as part of a hydrocarbon fraction. In the case of nitrogen, the non-hydrocarbon fraction is added to the methane fraction. This approach disregards any direct influence the non-hydrocarbons may have on the balance but yields satisfactory results when concentrations of non-hydrocarbons are low.

It is obvious that the engineer's choice will depend upon the concentration of the non-hydrocarbon fraction in the reservoir fluid. This thesis presents a study of the effect of nitrogen concentration upon the three compositional material balance methods for treating the non-hydrocarbon fraction mentioned above. In addition, it presents the balance itself which is a phase behavior model of a gas-condensate reservoir.

REVIEW OF LITERATURE

Conventional depletion drive calculation methods, such as described by Turner (1944) are essentially material balance calculations coupled with relative permeability concepts for recovery predictions. These methods have a number of assumptions in common--the most serious of which ignores the liquid recovered from the gaseous phase of the reservoir fluid. This assumption yields satisfactory results as long as a black oil or dry gas reservoir is under consideration. When the gaseous phase of the reservoir fluid begins to contribute significantly to liquid production, as is the case for volatile oil or condensate reservoirs, this assumption invalidates the conventional approach.

The compositional material balance was developed to take into account the liquid produced at the surface

from the vapor phase in the reservoir.

Allen and Roe (1950) presented one of the first compositional material balances available in the literature. Their study was limited to a constant volume gas-condensate reservoir, assuming an immobile liquid phase. The theoretical performance of the reservoir was calculated under the two separate assumption of flash and differential vaporization.

Brinkman (1954) developed a component-type material-balance method for application to a solution-gas drive black oil reservoir. Woods (1955) presented a case history of a volatile oil reservoir and stressed the importance of the subsurface sample analysis of the original reservoir fluid. Jacoby and Berry (1957) modified Brinkman's method and applied it to a constant volume, depletion drive, volatile oil reservoir. Their paper illustrates the importance of considering the vapor phase as a major contributor to liquid production. The predicted liquid recovery using the component balance was more than twice that predicted by conventional methods. Jacoby and Berry (1958) subsequently extended their procedure to include pressure maintenance by injection of dry gas at a constant reservoir pressure.

Ridings (1958) was the first to consider a depletion

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mechanism other than a simple solution-gas drive when using a compositional material balance. His method allowed for the effects of water encroachment upon a volatile oil reservoir. Lohrenz, Clark and Francis (1963) presented a sophisticated component-type material balance which in its most comprehensive case could handle a solution gas-gas cap-water drive reservoir with water production, water influx, separate or commingled production from the oil and gas zones, any surface processing arrangement and gas injection into the gas and/or oil zones.

In the studies of the component-type material balances mentioned above, no great emphasis was placed upon the presence of non-hydrocarbon fractions in the reservoir fluid. Allen and Roe (1950) did use the presence of small amounts of nitrogen, which were not included in their calculations, as one explanation for variation between observed and theoretical reservoir performance. Brinkman (1954) used a completely hydrocarbon system. Jacoby and Berry (1957) used, as an example, a reservoir fluid containing small amounts of nitrogen and carbon dioxide. They made no mention of any special procedures to consider the non-hydrocarbon fractions. Lohrenz, Clark and Francis (1963) presented the most detailed procedure for treating non-

hydrocarbon fractions. Special equations were set up to fit the equilibrium ratio values from the NGPSA Engineering Data Book for low concentrations of hydrogen sulfide, nitrogen and carbon dioxide. Van der Waal's simple constants were used for the non-hydrocarbons in the procedure of Alani and Kennedy (1960) for calculating liquid densities. In the remainder of the empirical procedures used, the non-hydrocarbons were treated in the same manner as the hydrocarbons.

This seeming disregard for the non-hydrocarbon fraction of a reservoir fluid is not hard to understand for there is not a wealth of useful literature available on the actions of non-hydrocarbon matter in a natural hydrocarbon environment. However, Eilerts, Carlson and Mullens (1948) did explore the effect of nitrogen content upon the volumetric behavior of natural gases. They presented a procedure for calculating the effect of nitrogen on the compressibility factors of nitrogen-natural gas mixtures. The effect of carbon dioxide on compressibility factors of hydrocarbon mixtures has not been explored in as much detail. Reamer, Olds, Sage and Lacey (1943 and 1945) presented data on the binary systems of methane-carbon dioxide and ethane-

carbon dioxide which were used to develop a compressibility-factor chart. Reamer, Sage and Lacey (1950) presented compressibility factors for hydrogen sulfide.

A few papers have appeared covering the effects of non-hydrocarbons on the phase behavior of reservoir fluids. Poettman and Katz (1946) presented equilibrium ratios for carbon dioxide in a natural gas-condensate system exploring a range of 1 to 10 mole per cent carbon dioxide. Jacoby and Rzasa (1952) presented experimental equilibrium ratios for nitrogen, carbon dioxide and hydrogen sulfide in two natural gas-absorber oil mixtures. Jacoby (1953) presented equilibrium ratio data pertaining to nitrogen, carbon dioxide and hydrogen sulfide in a natural gas-condensate system. Vagtborg (1954) obtained equilibrium data for light hydrocarbons, nitrogen, carbon dioxide and hydrogen sulfide in a reservoir fluid containing 35 mole percent hydrogen sulfide.

A good correlation for determining equilibrium ratios for carbon dioxide and hydrogen sulfide is not available in the literature. It appears that the equilibrium ratios for these two non-hydrocarbon components may, unlike hydrocarbons, depend strongly on concentration level. This invalidates extrapolation of work done with binary systems to multi-component natural systems.

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Equilibrium ratios for nitrogen do not seem to be as affected by concentration. In fact, recent binary and ternary data obtained at the University of Texas are largely the basis of the equilibrium ratio charts for nitrogen in the 1966 NGPSA Engineering Data Book.

THE COMPOSITIONAL MATERIAL BALANCE

The compositional material balance used in this study is similar to that presented by Allen and Roe (1950). This balance is divided into two main computational branches--Past Performance and Future Performance. The past performance routine utilizes known production data to calculate the original vapor pore volume of the reservoir. Future performance calculations predict the production behavior of a reservoir knowing certain past and present data. Both procedures are presented below along with the assumptions imposed on the balance by either its nature or the limitations of this study. A discussion of the internal subroutines peculiar to this balance is also presented.

PAST PERFORMANCE

Calculation of the original vapor pore space using the compositional material balance involves a trial and error approach. It is necessary to know the composition

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of the original reservoir fluid, pressure and production history, analyses of the produced material and suitable equilibrium ratios for the reservoir fluid at existing reservoir conditions.

An initial vapor volume is assumed and converted into moles of reservoir fluid. The number of moles of reservoir fluid produced to date is determined from the production data. Knowing these values, the composition of the existing fluid in the reservoir is calculated. The vapor-liquid make-up of this fluid is determined by flashing the fluid at existing reservoir conditions using the appropriate equilibrium ratios. Knowing this vapor-liquid equilibria, the volumes occupied by each phase under reservoir conditions are calculated. The sum of these volumes is compared to the initial assumed vapor volume. If they do not agree within the limits imposed on the balance, another value for initial vapor volume is assumed and the procedure is repeated. Figure 1 is a flow diagram of this procedure showing the equations used. The appendix contains the nomenclature used in these equations.

FUTURE PERFORMANCE

The prediction of production behavior by a compositional material balance is an explicit procedure when

there is single phase flow in the reservoir. When considering a condensate reservoir, this means only the gas phase is flowing. It is necessary to know the composition of the original reservoir fluid, the original vapor pore space of the reservoir and appropriate equilibrium ratios at reservoir conditions. Presuming the reservoir fluid initially exists as a single phase, a pressure decrement is selected which will bring the fluid below the dew point. The vapor-liquid equilibria at this lower pressure is determined by flashing the fluid at reservoir conditions. The volumes occupied by each phase are calculated and summed. The difference between this volume and the original vapor pore space is presumed to be the production for the pressure decrement. This production has the composition of the vapor phase and is deducted from the reservoir fluid leaving a new reservoir fluid occupying a volume equal to the original vapor pore volume. The composition of this new reservoir fluid is calculated by means of a component balance. A new pressure decrement is selected and the process repeated until the reservoir pressure is depleted. A cumulative count is kept of the moles of each component produced to give ultimate production in moles. Figure 2

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is a flow diagram of this procedure showing the equations used. Again the appendix contains the pertinent nomenclature.

ASSUMPTIONS

The simplifying assumptions that are either inherent or superimposed on the balance by limiting this study to a gas-condensate reservoir are:

1. The natural gas in the reservoir is initially above its dew point.
2. Any liquid formed by retrograde condensation in the reservoir is immobile.
3. The reservoir pore volume occupied by reservoir fluid is constant.
4. There exists no recovery mechanism except depletion drive from fluid expansion.
5. There is complete equilibrium between liquid and gas phases throughout the reservoir.

INTERNAL SUBROUTINES

Much of the validity of the compositional material balance rests upon the internal subroutines and procedures used to calculate or correlate properties of the reservoir fluid. A discussion of the significant internal workings of this compositional material balance is presented below.

Density of Oil

Determination of oil density is accomplished by the method of Alani and Kennedy (1960). This method is an empirical adaptation of Van der Waal's equation of state and is applicable to both pure liquid hydrocarbons and to normal reservoir systems. Common non-hydrocarbon fractions may be treated in the same manner as the hydrocarbon fractions by using the applicable empirical constants.

Density of Gas

The density of the vapor fraction is determined by application of the perfect gas law corrected by use of the compressibility factor Z. The relationship is as follows:

$$\rho_g = \frac{pM_g}{ZRT}$$

Z is an empirical correction factor to the perfect gas law and is a function of pressure, temperature and gas composition. Brown, Katz, Oberfell and Allen (1948) presented the correlation most often used to determine the Z factor for methane-rich natural gases. The

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correlation incorporates the compositional parameter into the pressure and temperature parameters by utilizing pseudo-reduced properties for correlating purposes. An adaptation of this correlation is utilized in this study to form a 20 x 25 matrix of Z values versus pseudo-reduced temperature and pseudo-reduced pressure respectively. A table look-up routine using linear interpolation is used to contact the matrix.

An option is included to correct the compressibility factor for nitrogen concentration. The method used is that presented by Eilerts, Carlson and Mullens (1948). They defined an additive compressibility factor Z_a as follows:

$$Z_a = \left(Z_n \cdot y_n \right) + \left(Z_g \cdot (1-y_n) \right)$$

The true compressibility factor Z is then expressed by the relationship:

$$Z = CZ_a$$

Eilerts and co-workers presented the correction factor C as a function of pressure and temperature for two nitrogen concentrations--7.907 and 18.280 mole per cent. The

values of C at reservoir pressure, temperature and these nitrogen concentrations are read into the compositional material balance and linear interpolation used to adjust for actual nitrogen concentration in the reservoir vapor phase.

Molecular Weight

The molecular weights of the reservoir liquid and gaseous phases are determined in the same manner. The property is actually the average molecular weight of a mixture and is defined mathematically as the summation of the products of the individual mole fractions of the mixture times their respective molecular weights.

Flash Calculations

The flash calculation is used to determine the vapor-liquid make-up of a hydrocarbon mixture. It entails the use of equilibrium ratios which may be defined as the ratio of the mole fraction of a constituent in the vapor phase to the mole fraction of the constituent in the liquid phase. The equilibrium ratios used in this study are input data. The procedure of solution in a flash calculation is as follows:

1. Knowing the appropriate equilibrium ratios for each component in the mixture, a value for V

is selected. This fixes the value of L since

$$L + V = 1.$$

2. The following equation is solved

$$\sum_{i=1}^m x_i = \sum_{i=1}^m \frac{z_i}{L + VK_i} = 1.$$

3. If $\sum_{i=1}^m x_i = 1$, the problem is solved and

the value assumed for V is correct. The values calculated for the x_i 's represent the analysis of the liquid. The analysis of the vapor is calculated by the relationship:

$$y_i = K_i x_i$$

4. If $\sum_{i=1}^m x_i \neq 1$, then a new value is assumed

for V and the process is repeated.

COMPUTATIONAL PROCEDURE

The purpose of this study is to explore the effect of nitrogen concentration upon three compositional material balance methods of treating the non-hydrocarbon fraction for a gas-condensate reservoir. The three methods are presented in the introduction of this thesis and are reiterated below:

1. The non-hydrocarbon fraction may be considered as it actually occurs in both the liquid and vapor phase of the reservoir fluid.
2. The non-hydrocarbon fraction may be considered as existing only in the vapor phase of the reservoir fluid.
3. The non-hydrocarbon fraction may be treated as part of a hydrocarbon fraction. In the case of nitrogen, the non-hydrocarbon fraction is added to the methane fraction.

CALCULATION ROUTINE

The procedure used to generate comparative data in the computation of the original vapor volume of the reservoir for methods one, two and three utilizes both the Future Performance and Past Performance routines of the compositional material balance. An initial reservoir fluid composition containing a given amount of nitrogen is selected. Using the Future Performance routine of the compositional material balance and considering the nitrogen as existing in both the vapor and liquid phases, production data is generated for a given pressure decrement. Then using the Past Performance routine, and applying each of the three methods of treating the nitrogen fraction to the production data from the prediction routine, an original reservoir vapor volume is calculated for each of the three methods. In other words, the production data from the prediction routine reflects or is altered to reflect the following:

1. The nitrogen fraction existing in both the vapor and liquid phases of the reservoir fluid.
2. The nitrogen fraction existing in only the vapor phase of the reservoir fluid.
3. The nitrogen fraction being added to the methane fraction of the reservoir fluid.

The original vapor volumes that are calculated are those that would have to have existed before production commenced in order to yield the above versions of the production data. Another pressure decrement is selected and the routine continued until the reservoir pressure is considered depleted. At this point, the initial reservoir fluid composition is adjusted to reflect a different nitrogen concentration and the entire procedure is repeated. Figure 3 is a flow chart of this computation procedure.

Comparative data for reservoir fluid recoveries by methods one, two and three are generated using the Future Performance routine of the compositional material balance. Recovery data, using method one, were calculated as part of the computation procedure for the original vapor volume of the reservoir. Recovery data using methods two and three are computed in a like manner treating the nitrogen fraction as prescribed in the definitions of methods two and three.

Seven different nitrogen levels ranging from 1 to 18 mole per cent are considered in this study. An average of 28 equal pressure decrements are considered for each nitrogen concentration.

RESERVOIR DATA

The data used in this thesis are from an artificially

conceived condensate reservoir. The pore space occupied by the reservoir fluid is arbitrarily taken to be 100 cu ft. The composition of the nitrogen-free reservoir fluid is taken from a classical paper on condensate fluids by Roland, Smith and Kaveler (1941) and describes a fluid with a convergence pressure of 4000 psia, existing at 4000 psia and 200° F. The dew point of this fluid is 3360 psia. This paper also provides the necessary heptanes-plus data and equilibrium ratios for the hydrocarbon constituents. Equilibrium ratios for nitrogen are taken from a modified Winn nomograph as presented by Hadden and Grayson (1961). Table 1 presents the nitrogen-free compositional data and Figure 4 illustrates the equilibrium ratios used in this study.

It was assumed that the presence of nitrogen would have no effect upon the equilibrium ratios of the hydrocarbons. This assumption was made on the bases of the insensitivity of these equilibrium ratios to hydrocarbon composition. The methane concentrations of the fluids used by Roland, Smith and Kaveler (1941) to determine these equilibrium ratios, varied from 50 to 90 per cent of the total fluid with little effect on the equilibrium ratios. Since nitrogen is not much more volatile than methane, it was assumed that a varying nitrogen fraction would

not affect the equilibrium ratios of the hydrocarbons.

As mentioned previously, seven nitrogen levels were explored in this study. The compositions of the reservoir fluids containing these nitrogen levels were derived from the nitrogen-free reservoir fluid by subtracting a proportionate share of the given nitrogen fraction from each hydrocarbon fraction. The compositions of these artificial reservoir fluids containing the various nitrogen levels are presented in Table 2. It should be noted that for the nitrogen-free fluid, Roland, Smith and Kaveler (1941) did not separate the butanes and pentanes into the normal and isomeric fractions. This was done, for the purposes of this thesis, by arbitrarily assigning one-half of each fraction to each category. The critical properties of each component, excepting the heptanes-plus fraction, along with values for molecular weight were taken from Eilerts (1957). The critical properties of the heptanes-plus fraction were taken from a correlation by Matthews, Roland and Katz (1942) and were assumed to remain constant and not vary with pressure.

RESULTS

Calculations for this study were made using a Burroughs B5500 digital computer. The compositional material balance was written in FORTRAN II and translated by the machine into ALGOL 60 for actual running. All reservoir calculations were stopped at a reservoir pressure of 500 psia because this pressure includes the economic limit of most condensate reservoirs.

Any evaluation of the Future Performance portion of the compositional material balance is necessarily an evaluation of the recoveries predicted by this routine. Recoveries are expressed as a percentage of the moles of material, calculated by the particular compositional material balance method under study, to be originally in place in the reservoir. Table 3 and Figure 5 present the recovery at 500 psia of total reservoir fluid versus nitrogen concentration in the original reservoir fluid

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for methods one, two and three. Table 4 and Figures 6 through 13 present the same data for the individual components of the reservoir fluid. Figure 14 illustrates the effect of pressure upon the cumulative total liquid recovery at the 18 per cent nitrogen levels in the original reservoir fluid for compositional material balance methods one, two and three. Tables 3 and 4 and Figures 5 through 14 are designed to show the effect of pressure and/or nitrogen concentration upon the three compositional material balance methods of treating the nitrogen fraction in the Future Performance routine of the compositional material balances.

The Past Performance routine of the compositional material balance is concerned with calculating the original vapor volume of the reservoir that existed before production commenced. Since method one is the most rigorous approach to calculating the original vapor volume of the reservoir, methods two and three are compared on the basis of the average absolute relative deviation of the original vapor volume, calculated using methods two and three, from the original vapor volume computed using method one. The average absolute relative deviation, hereafter referred to as the deviation,

is defined mathematically as .

$$D = \frac{\sum_{i=1}^{i=m} \left| \frac{V_1 - V_x}{V_1} \right| \cdot 100}{m}$$

where V_1 is the value of the original vapor volume of the reservoir as calculated by method one and V_x the value of the original vapor volume as calculated by either method two or three. The parameter m is the number of pressure decrements considered for the particular initial nitrogen concentration under study. D is the deviation of the original vapor volume of the reservoir, as calculated by the particular compositional material balance method under study, from the original vapor volume of the reservoir as calculated by method one. These deviations are a function of nitrogen concentration in the initial reservoir fluid and are presented as such in Figure 15.

The differences in the original vapor volumes of the reservoir as calculated by methods one, two and three are also a function of reservoir pressure. Figures 16 and 17 depict this behavior at nitrogen concentrations of 5 and 18 mole per cent in the initial reservoir fluid.

The differences in the original vapor volumes, calculated by methods two and three are high lighted by comparing the volumes on the basis of what fraction they are of the original vapor volume calculated by using method one.

Figures 15, 16 and 17 are designed to show the effect of pressure and/or nitrogen concentration upon the three compositional material balance methods of treating the nitrogen fraction in the Past Performance routine of the compositional material balance.

DISCUSSION OF RESULTS

The three compositional material balance methods of treating the non-hydrocarbon fraction presented in this study are reiterated below:

1. The non-hydrocarbon fraction may be considered as it actually occurs in both the liquid and vapor phase of the reservoir fluid.
2. The non-hydrocarbon fraction may be considered as existing only in the vapor phase of the reservoir fluid.
3. The non-hydrocarbon fraction may be treated as part of a hydrocarbon fraction. In the case of nitrogen, the non-hydrocarbon fraction is added to the methane fraction.

For ease of notation these compositional material balance

methods are often referred to in this study as methods one, two and three taking their numerical designation from the order in which they are presented above.

The recoveries of total reservoir fluid predicted by the three compositional material balance methods of treating the nitrogen fraction are very similar. This is readily illustrated by Table 3 and Figure 5. Figure 14 expresses cumulative recovery calculated by methods one, two and three as a function of pressure at the 18% nitrogen level. It is evident that the recoveries calculated by each method are also very similar throughout the entire pressure spectrum. While the differences in the recoveries of total reservoir fluid predicted by the three methods are small, very definite trends are apparent. Recoveries of total reservoir fluid predicted by methods one and two are nearly identical and show a decreasing recovery with an increasing nitrogen fraction. Recoveries of total reservoir fluid predicted by method three show an increasing recovery with an increasing nitrogen fraction.

The nearly identical results produced by methods one and two are indicative of the volatile nature of nitrogen. In other words, at the reservoir conditions

specified in this study, nitrogen exists almost entirely in the vapor phase, so little difference in recovery is noted by considering the small fraction of nitrogen that exists in the liquid phase. The decreasing recovery of total reservoir fluid with increasing nitrogen content of the initial reservoir fluid, shown by methods one and two, can be explained by examining the recoveries of the individual components of the reservoir fluid. Figures 6 through 13 and Table 4 illustrate the effect of nitrogen concentration upon the recoveries of the individual components of the reservoir fluid as calculated by methods one, two and three. It is immediately apparent for methods one and two that the recoveries of methane, ethane and nitrogen follow the same trend of decreasing recovery with increasing nitrogen concentration as is followed by the recoveries of total reservoir fluid for methods one and two. Since the methane and nitrogen fraction make up over 85% of the reservoir fluid, it is the influence of these components that most affect the total reservoir fluid concentrations. Seemingly, increasing the nitrogen fraction forces more methane, ethane and nitrogen into the liquid phase thus lowering the recoveries of the total reservoir fluid along with

the recoveries of these individual components.

The recovery of propane, as calculated by method one, does not seem to have a definite trend with an increasing nitrogen concentration. However, the recovery of propane calculated by method two and the recoveries of the components, butane through heptanes-plus, calculated by both methods one and two show a definite trend of increasing recovery with an increasing nitrogen fraction.

By definition, method three does not consider the recovery of nitrogen. The recovery of methane calculated by method three decreases very slightly with increasing nitrogen concentration in the initial reservoir fluid. However, the remainder of the components, ethane through heptanes-plus, show increasing recovery with an increasing nitrogen fraction when calculated by method three. This accounts for the increasing recovery of total reservoir fluid with an increasing nitrogen fraction shown by method three.

The effect of an increasing nitrogen concentration for methods one and two is seemingly to decrease the recoveries of the more volatile components such as nitrogen, methane and ethane while increasing the

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recoveries of the intermediate and heavy components. In the case of the compositional material balance under study, this is comparable to saying that an increasing nitrogen fraction drives an increasing amount of the more volatile components into the liquid phase of the reservoir fluid. Conversely, the intermediate and heavy components are driven toward the vapor phase of the reservoir fluid. Actually, similar behavior is observed for method three. However, since the nitrogen fraction is added to the methane fraction in the execution of method three, what really is observed is the effects of a slightly increasing methane fraction. Since the increase in methane concentration is slight and the volatility of methane less than that of nitrogen, the effect on the system is much less than is observed when using methods one and two.

Although recoveries of reservoir fluid predicted by methods one, two and three are very similar, such is not the case for the calculation of the original vapor volume of the reservoir. Differences are small in the original vapor volumes calculated by methods one and two but significant differences exist between these values and those calculated by method three. At the 18% nitrogen

levels, the deviation from the value calculated by method one of the original reservoir vapor volume calculated by method two is 0.506% as compared to 17.818% for method three. Figure 15 illustrates these differences over the full range of nitrogen concentrations.

Figure 15 utilizes the average absolute relative deviation values defined in the preceding section to represent the differences in the original reservoir vapor volumes calculated by methods one, two and three. Figures 16 and 17 show the average absolute relative deviation to be a slightly biased statistical parameter in that the values show definite trends with pressure variation.

All three compositional material balance methods seem to be acceptable for predicting recoveries for a condensate reservoir whose non-hydrocarbon fraction is limited to nitrogen. The difference in the total reservoir fluid recovery at 500 psia as calculated by methods one and three is only 1.68% at a nitrogen concentration of 13% in the initial reservoir fluid. Therefore, it would seem that due to ease of use, method two which treats the nitrogen fraction as always existing in the vapor phase, is the best possible choice for predicting reservoir fluid recoveries even at relatively high

nitrogen concentrations.

Unfortunately, the same cannot be said for determination of the original vapor volume of the reservoir. In this case method three produces a lack of precision in the compositional material balance that is approximately equal to the level of nitrogen in the reservoir fluid. For example, a nitrogen level of 15 mole per cent in the initial reservoir fluid will yield an initial reservoir vapor volume deviating 15.575% from a like value calculated by method one. Measured field and PVT data are seldom more accurate than $\pm 3\%$. The average deviation of the Alani and Kennedy (1960) method for determining oil density is given as 1.6%. The correlation for determining the compressibility factor has an average absolute deviation of 1%. Thus, it would seem that method three would seldom be acceptable for determining the original vapor volume of the reservoir at nitrogen concentrations of more than 3 mole per cent in the initial reservoir fluid. Method two, however, even at a concentration of 18 mole per cent in the initial reservoir fluid, deviates only 0.506% from a like value calculated by method one. Therefore, method two, which considers the nitrogen fraction as being in the vapor

state at all times, and which is easier to apply than method one, seems to be the best possible method of determining the original vapor volume of the reservoir at nitrogen concentrations of 3 mole per cent or more in the initial reservoir fluid.

In summation, it should be remembered that the recoveries of reservoir fluid predicted using methods one, two and three are compared on the relative basis of percentage recovery. Therefore, in order to predict actual quantities of produced material, it is necessary to know the original vapor volume of the reservoir. If the determination of the original vapor volume of the reservoir is accomplished by a means independent of the compositional material balance, any one of the three compositional material balance methods for treating the nitrogen fraction can be used to estimate quantities of produced material. However, only methods one and two are acceptable compositional material balance methods for computing the original vapor volume of the reservoir at nitrogen concentrations of 3% or more.

CONCLUSIONS

The purpose of this thesis was to examine the effect of nitrogen concentration upon three compositional material balance methods of treating the non-hydrocarbon fraction for a gas-condensate reservoir. These three methods are presented below:

1. The non-hydrocarbon fraction may be considered as it actually occurs in both the liquid and vapor phase of the reservoir fluid.
2. The non-hydrocarbon fraction may be considered as existing only in the vapor phase of the reservoir fluid.
3. The non-hydrocarbon fraction may be treated as part of a hydrocarbon fraction. In the case of nitrogen, the non-hydrocarbon fraction is added to the methane fraction.

All three compositional material methods were found to be acceptable for calculating reservoir fluid recoveries at nitrogen concentrations of up to 18 mole per cent in the initial reservoir fluid. However, method two is recommended for routine use because of its ease of application.

Only methods one and two were found satisfactory for computing the original vapor volume of the reservoir at nitrogen concentrations of 3 mole per cent or more in the initial reservoir fluid. The lack of precision shown by method three, in calculating the original vapor volume, is approximately equal to the nitrogen concentration in the initial reservoir fluid. Method two is again recommended for routine use because it is nearly as precise as method one and is easier to apply since equilibrium ratios for nitrogen are not needed.

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APPENDIX

NOMENCLATURE

Symbol	Description	Units
L	Fraction of reservoir fluid in liquid phase	
V	Fraction of reservoir fluid in vapor phase	
ρ_L	Density of reservoir fluid in liquid phase	lb per cu ft
ρ_g	Density of reservoir fluid in vapor phase	lb per cu ft
M_L	Molecular weight of reservoir fluid in liquid phase	
M_g	Molecular weight of reservoir fluid in vapor phase	
ρ_I	Initial density of reservoir fluid	lb per cu ft
M_I	Initial molecular weight of reservoir fluid	
V_M	Composite molal volume	cu ft
V_I	Initial hydrocarbon volume of the reservoir	cu ft
V_A	Assumed initial hydrocarbon volume of the reservoir	cu ft
V_C	Calculated initial hydrocarbon volume of the reservoir	cu ft

Symbol	Description	Units
n_I	Initial number of moles of reservoir fluid	moles
n_p	Cumulative produced moles of reservoir fluid	moles
n_{pi}	Number of moles of component "i" produced to date	moles
ΔV	Increment of reservoir fluid expansion during pressure decrement	cu ft
Δn_p	Incremental moles produced during pressure decrement	moles
P	Reservoir pressure	psia
T	Reservoir temperature	$^{\circ}R$
R	Universal gas constant	cu ft-lb <hr/> (mole) (sq in.) ($^{\circ}R$)
Z	Gas compressibility factor	
Z_a	Additive compressibility factor	
Z_n	Compressibility factor for nitrogen	
Z_g	Compressibility factor for hydrocarbon fraction of reservoir fluid	
C	Additive correction factor for the compressibility factor of a natural gas containing nitrogen	
z_{Ii}	Fraction of component "i" in the initial reservoir fluid	
K_i	Equilibrium ratio for component "i"	

Symbol	Description	Units
z_i	Fraction of component "i" in the reservoir fluid	
x_i	Fraction of component "i" in the liquid phase of the reservoir fluid	
y_i	Fraction of component "i" in the vapor phase of the reservoir fluid	
D	Average absolute relative deviation	

Table 1

COMPOSITION OF NITROGEN FREE RESERVOIR FLUID

4000 psia -- 200° F

<u>Component</u>	<u>Mole Fraction</u>
Methane	0.86270
Ethane	0.03380
Propane	0.02330
Iso-Butane	0.01035
N-Butane	0.01035
Iso-Pentane	0.00345
N-Pentane	0.00345
Hexane	0.00900
Heptanes +	<u>0.04360</u>
	1.00000

Heptanes-Plus Properties

Specific Gravity	0.766
Molecular Weight	119.5
Critical Temperature	1060 °R
Critical Pressure	405 psia

Table 2

Initial Compositions of Reservoir Fluids Containing Nitrogen

Component	Mole Fraction									
Nitrogen	0.01000	0.03000	0.05000	0.07000	0.10000	0.15000	0.18000			
Methane	0.85407	0.83681	0.81955	0.80229	0.77640	0.73325	0.70736			
Ethane	0.03346	0.03278	0.03210	0.03140	0.03040	0.02870	0.02768			
Propane	0.02306	0.02258	0.02210	0.02162	0.02090	0.01970	0.01898			
Iso-Butane	0.01025	0.01005	0.00985	0.00965	0.00935	0.00885	0.00855			
N-Butane	0.01025	0.01005	0.00985	0.00965	0.00935	0.00885	0.00855			
Iso-Pentane	0.00342	0.00336	0.00330	0.00324	0.00315	0.00300	0.00291			
N-Pentane	0.00342	0.00336	0.00330	0.00324	0.00315	0.00300	0.00291			
Hexane	0.00891	0.00873	0.00855	0.00937	0.00810	0.00765	0.00738			
Heptanes +	<u>0.04316</u>	<u>0.04228</u>	<u>0.04140</u>	<u>0.04052</u>	<u>0.03920</u>	<u>0.03700</u>	<u>0.03568</u>			
	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000			

Table 3

Recoveries of Total Reservoir Fluid

N ₂ Conc%	Recoveries%		
	Method 1	Method 2	Method 3
1	84.99	84.77	84.85
3	84.95	84.74	84.96
5	84.75	84.70	85.07
7	84.67	84.65	85.18
10	84.56	84.59	85.35
15	84.40	84.52	85.62
18	84.36	84.48	85.78

Table 4

Recoveries of Individual Components of the Reservoir Fluid

N ₂ Conc%	Recoveries%											
	Nitrogen			Methane			Ethane			Propane		
	Method	1	2	3	Method	1	2	3	Method	1	2	3
1	88.42	89.20	-	88.00	88.02	88.15	86.18	86.01	86.10	83.49	83.10	83.14
3	88.17	88.85	-	87.79	87.77	88.15	86.07	85.91	86.17	83.54	83.19	83.32
5	87.93	88.52	-	87.55	87.54	88.13	85.85	85.80	86.25	83.37	83.30	83.50
7	87.67	88.18	-	87.23	87.29	88.11	85.72	85.70	86.31	83.37	83.36	83.69
10	87.31	87.73	-	86.98	86.94	88.08	85.52	85.54	86.41	83.39	83.47	83.96
15	86.68	87.11	-	86.56	86.51	88.04	85.27	85.35	86.57	83.36	83.74	84.39
18	86.57	86.82	-	86.30	86.27	88.04	85.15	85.23	86.66	83.44	83.68	84.66

Table 4

(Continued)

N ₂ Conc%	Recoveries%											
	Butane Method			Pentane Method			Hexane Method			Heptanes + Method		
	1	2	3	1	2	3	1	2	3	1	2	3
1	79.35	78.51	78.50	71.47	70.14	69.96	59.37	57.20	56.92	34.47	29.97	29.53
3	79.42	79.00	78.90	71.93	70.99	70.58	60.33	58.54	57.73	35.81	32.68	30.34
5	79.49	79.37	79.27	72.08	71.83	71.18	60.21	59.83	58.52	34.82	33.44	31.19
7	79.71	79.71	79.60	72.56	72.56	71.75	61.08	61.08	59.35	35.99	35.20	32.07
10	80.04	80.21	80.10	73.35	73.69	72.61	62.36	62.93	60.60	37.82	37.94	33.47
15	80.35	81.06	80.96	74.12	75.60	74.12	63.86	66.13	62.77	39.15	43.15	36.04
18	80.68	81.21	81.45	75.13	76.04	75.06	65.28	66.91	64.14	41.35	43.63	37.74

FIGURE NO. I PAST PERFORMANCE

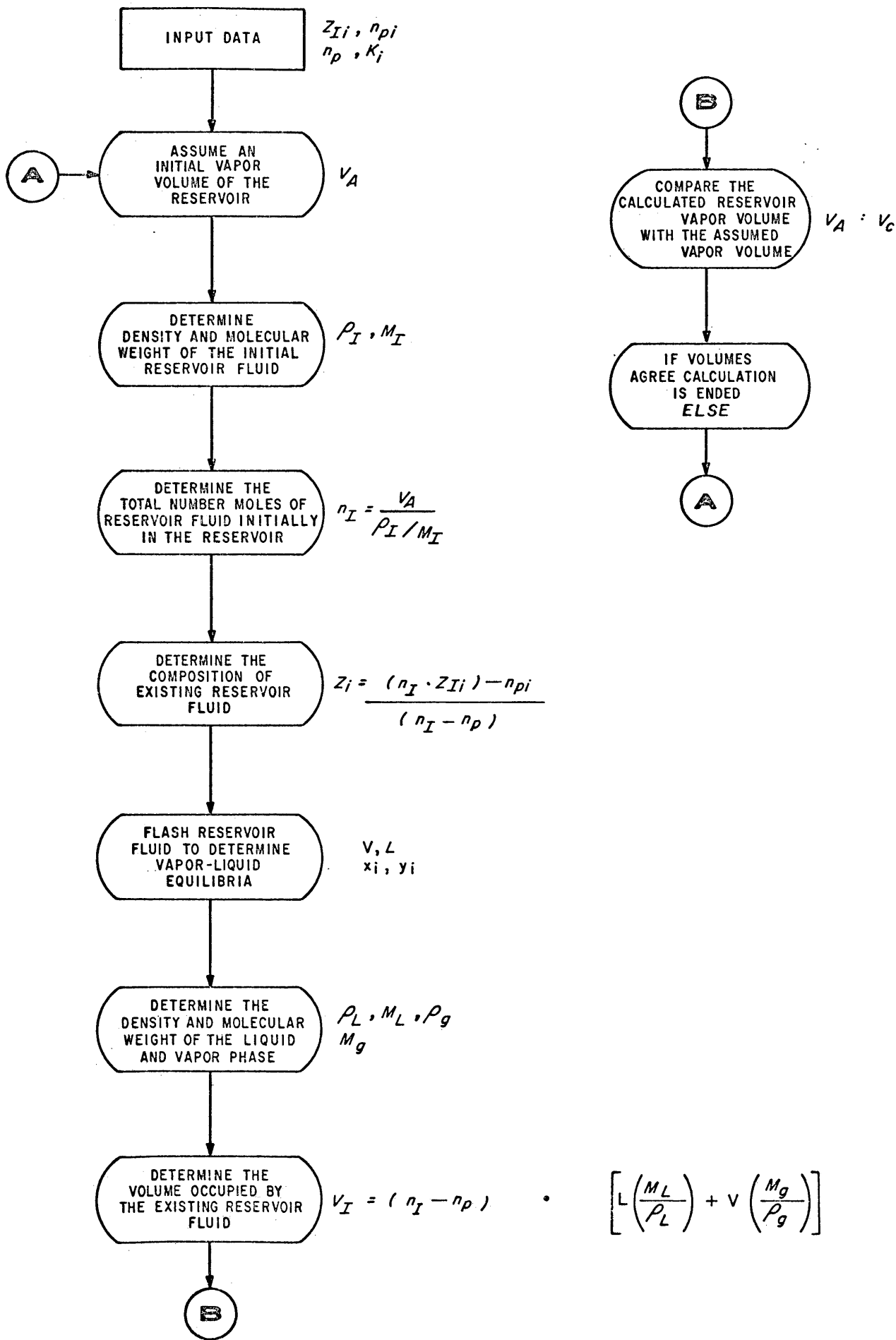


FIGURE NO.2 FUTURE PERFORMANCE

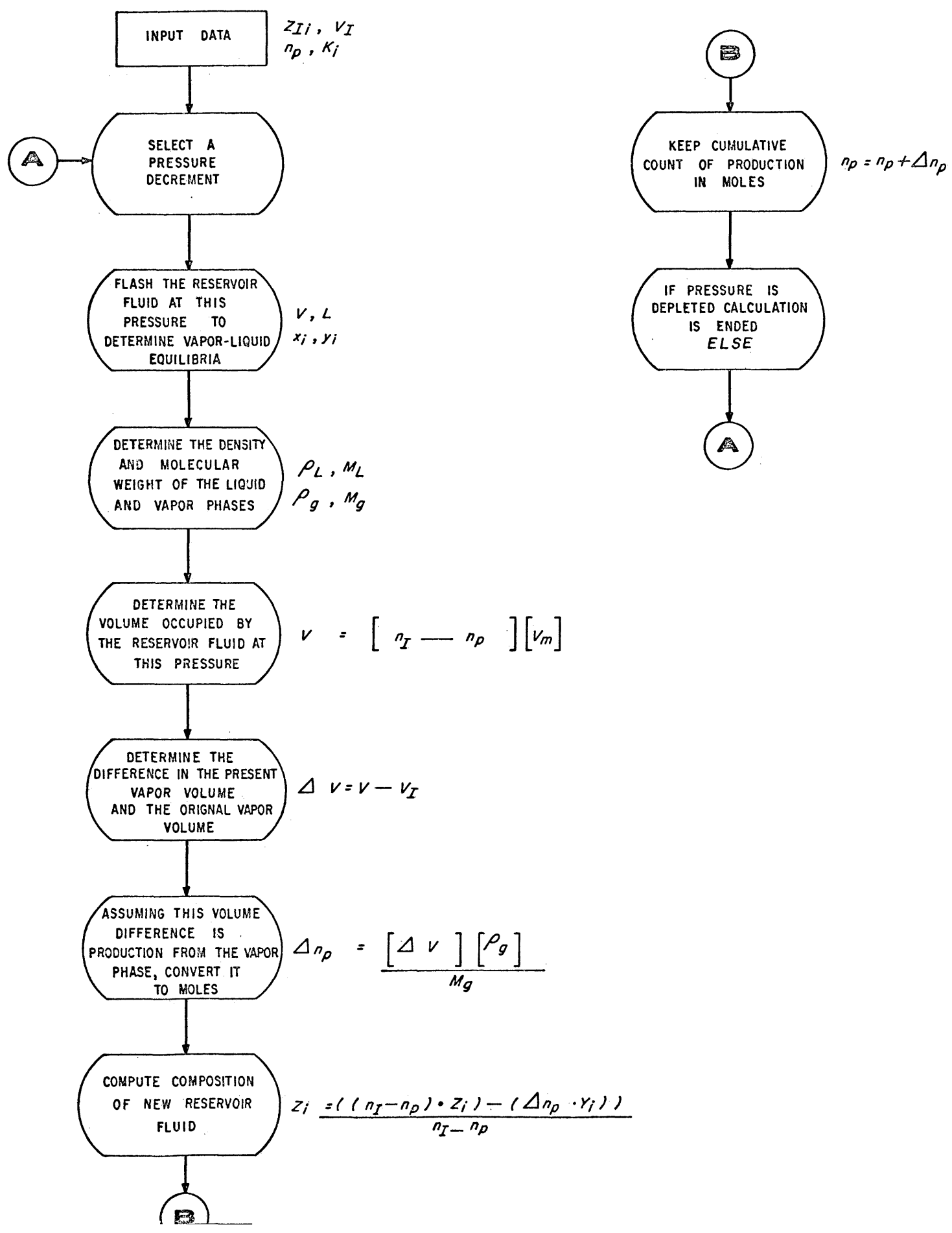


FIGURE NO. 3 CALCULATION ROUTINE

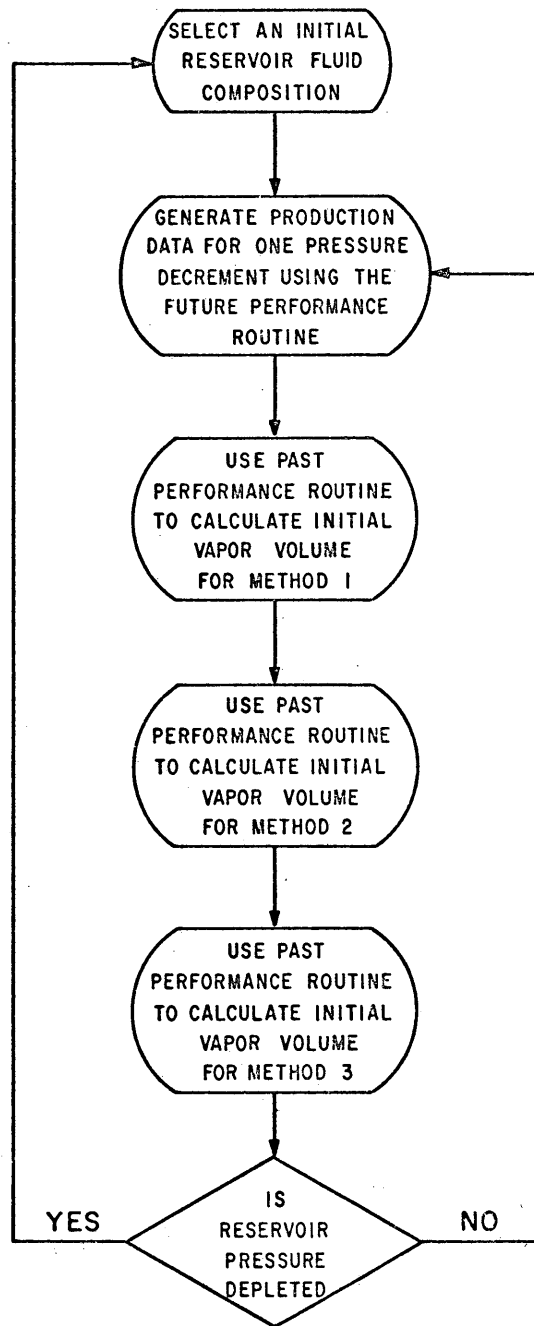


FIGURE 5 RECOVERY OF TOTAL RESERVOIR FLUID

Δ = METHOD NO. 1
O = METHOD NO. 2
□ = METHOD NO. 3

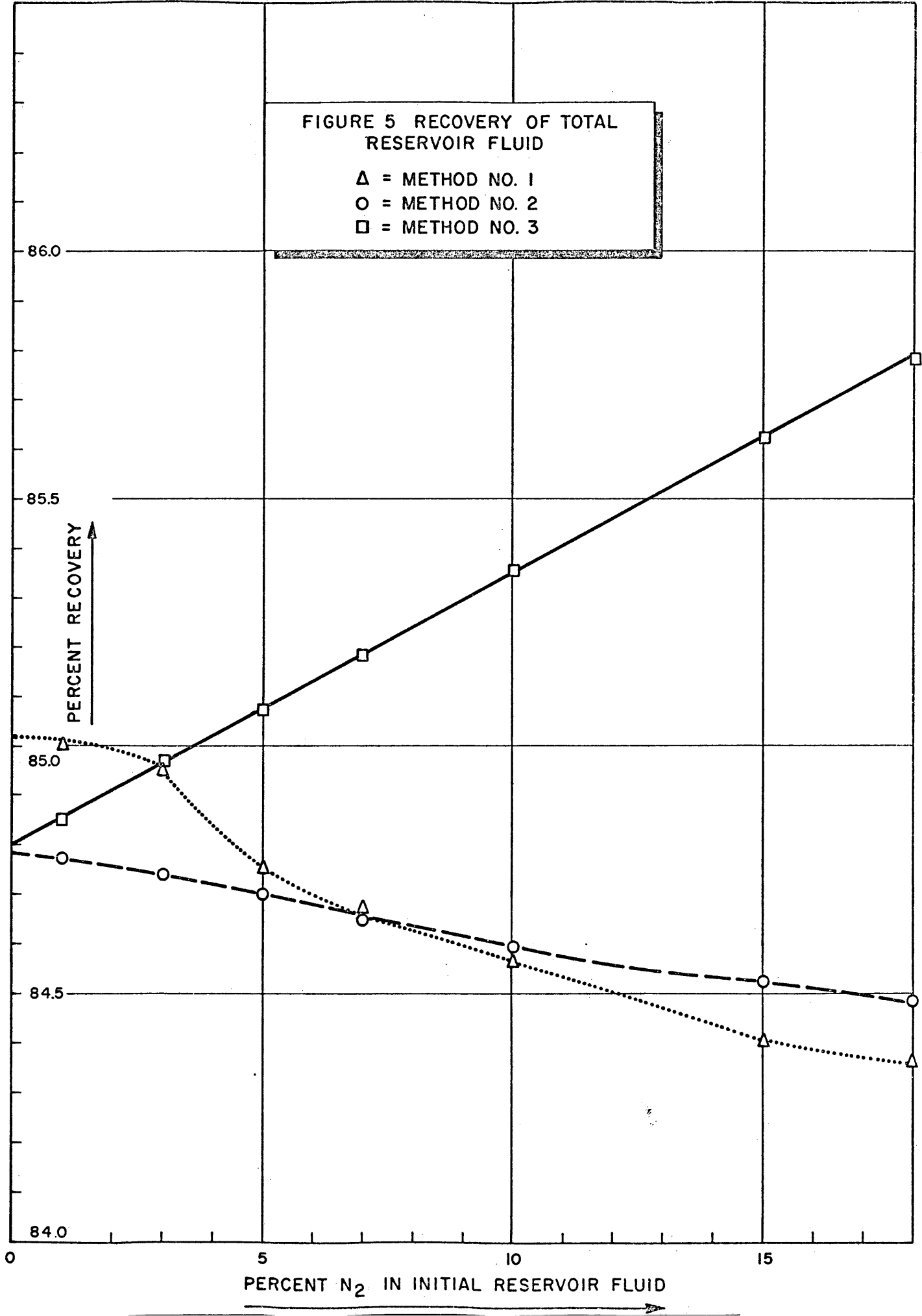


FIGURE 6 RECOVERY OF NITROGEN
△ = METHOD NO. 1
○ = METHOD NO. 2

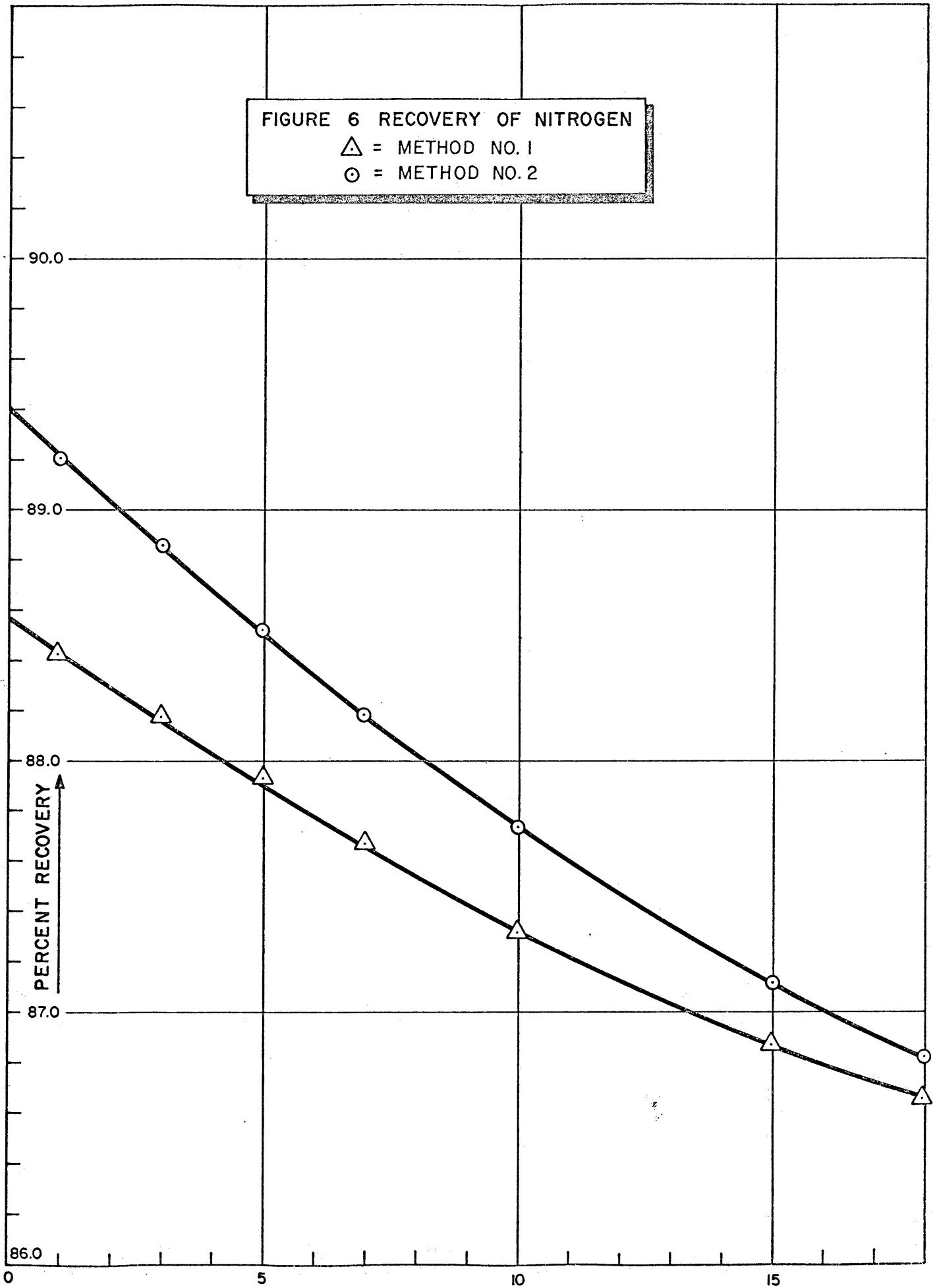


FIGURE 7 RECOVERY OF METHANE
△ = METHOD NO. 1
○ = METHOD NO. 2
□ = METHOD NO. 3

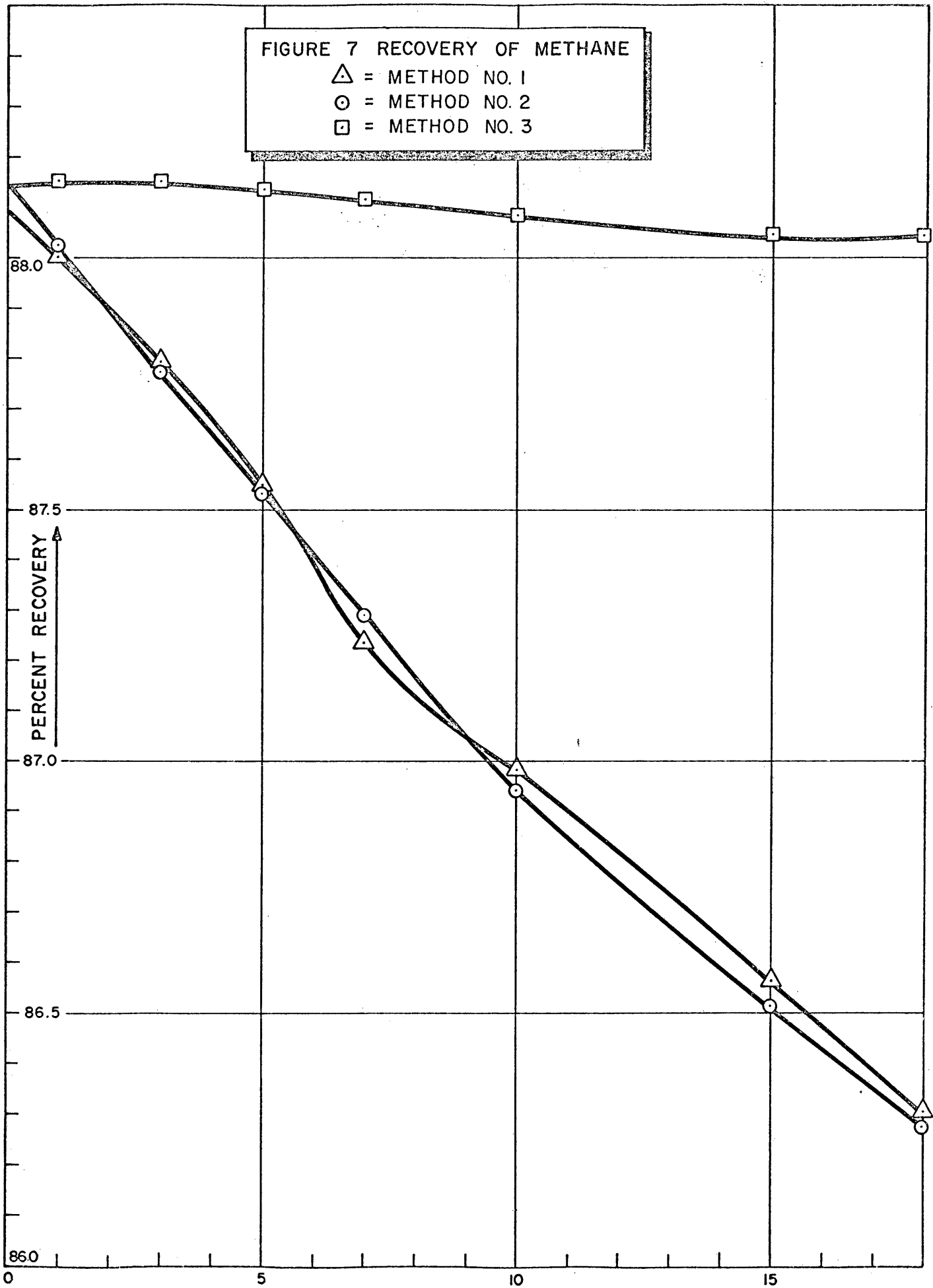
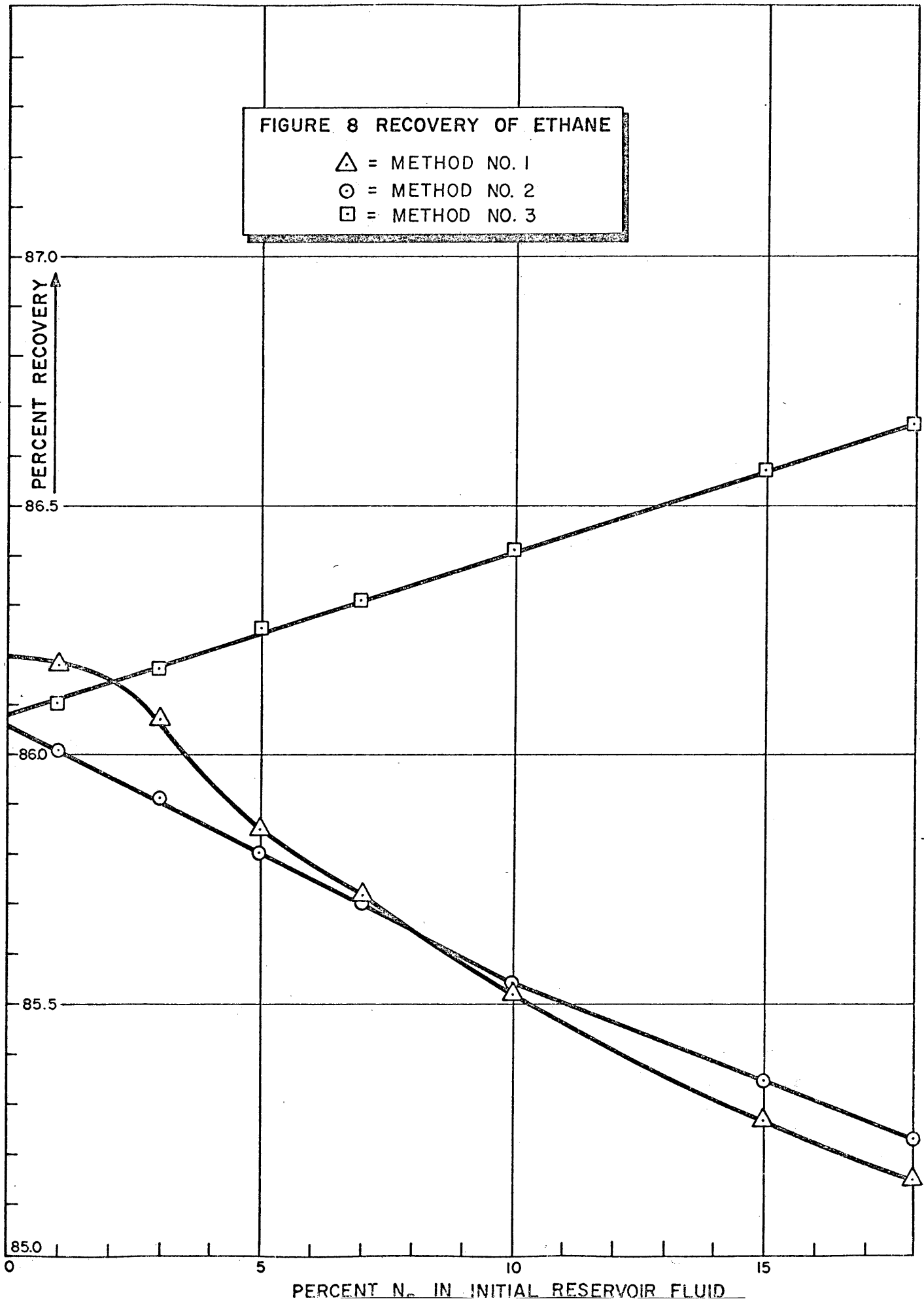
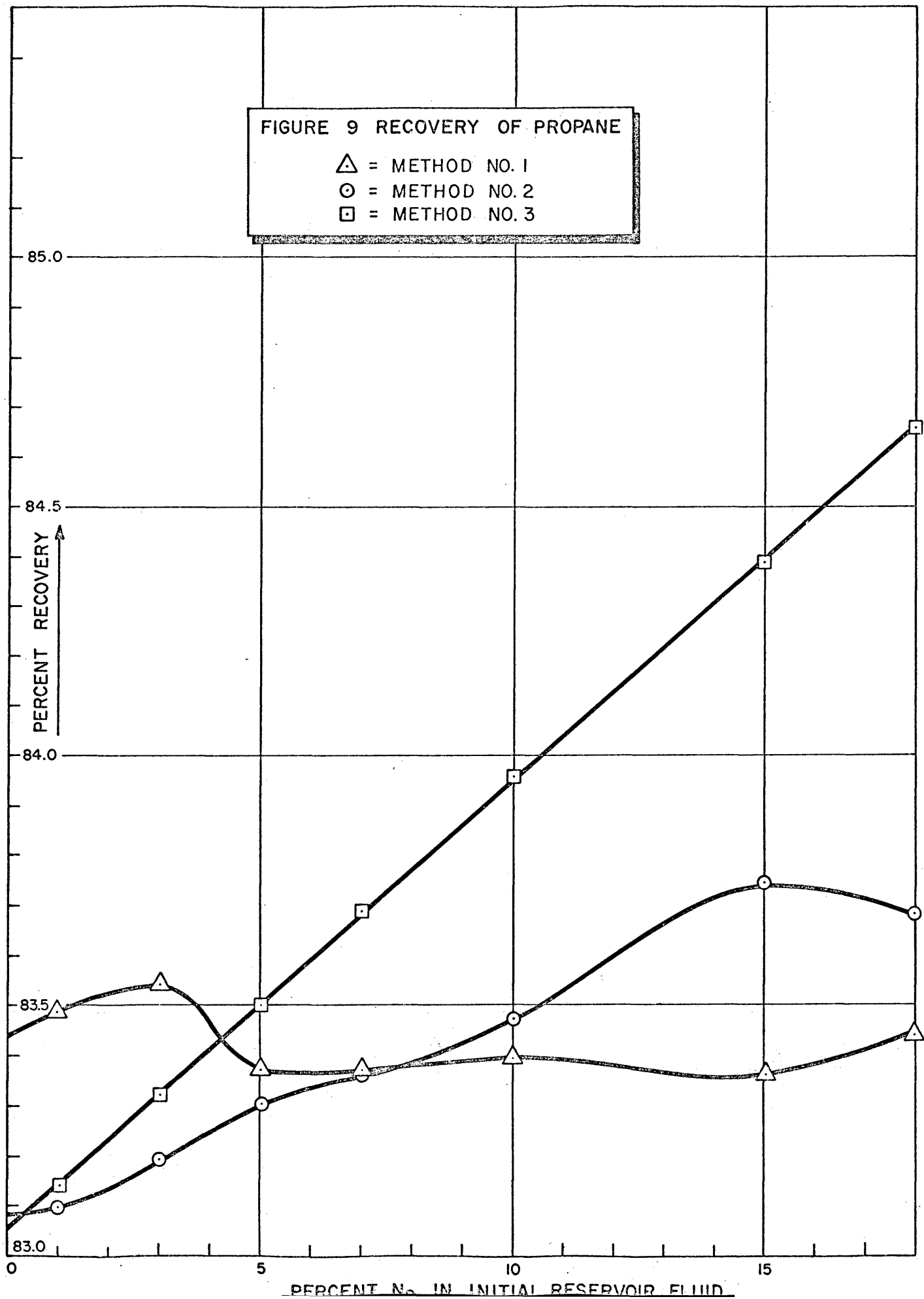


FIGURE 8 RECOVERY OF ETHANE
△ = METHOD NO. 1
○ = METHOD NO. 2
□ = METHOD NO. 3





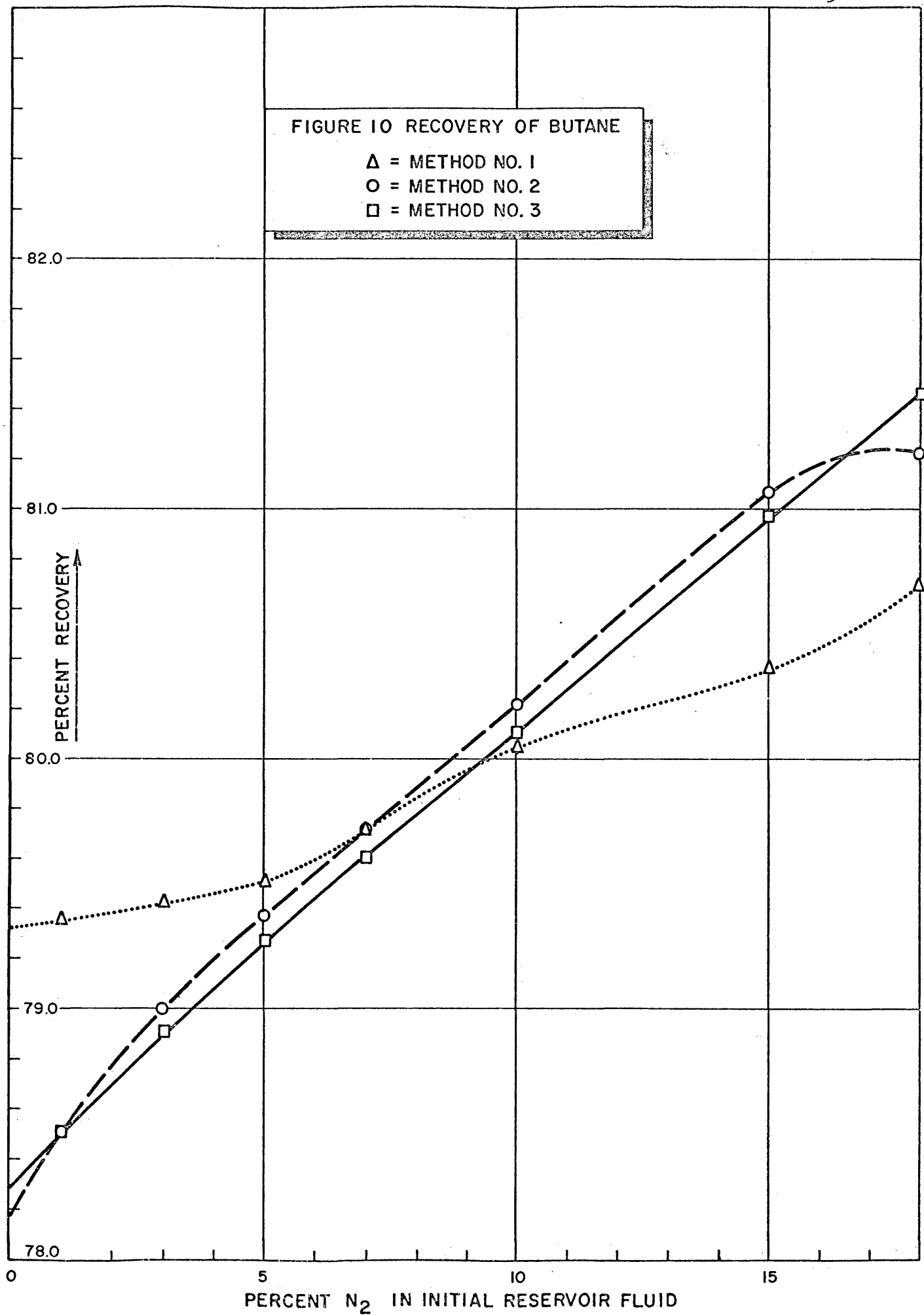


FIGURE II RECOVERY OF PENTANE
Δ = METHOD NO. 1
O = METHOD NO. 2
□ = METHOD NO. 3

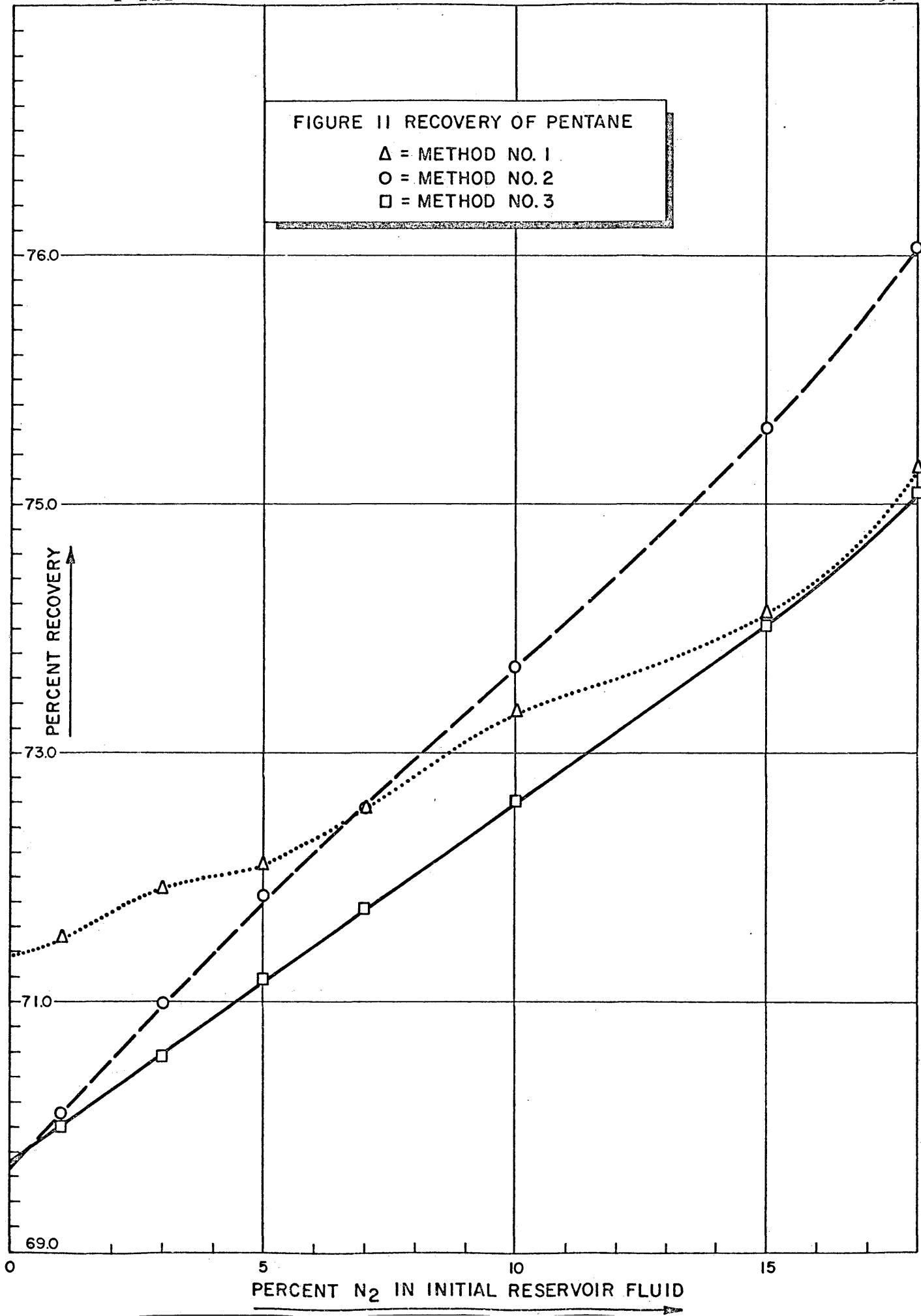
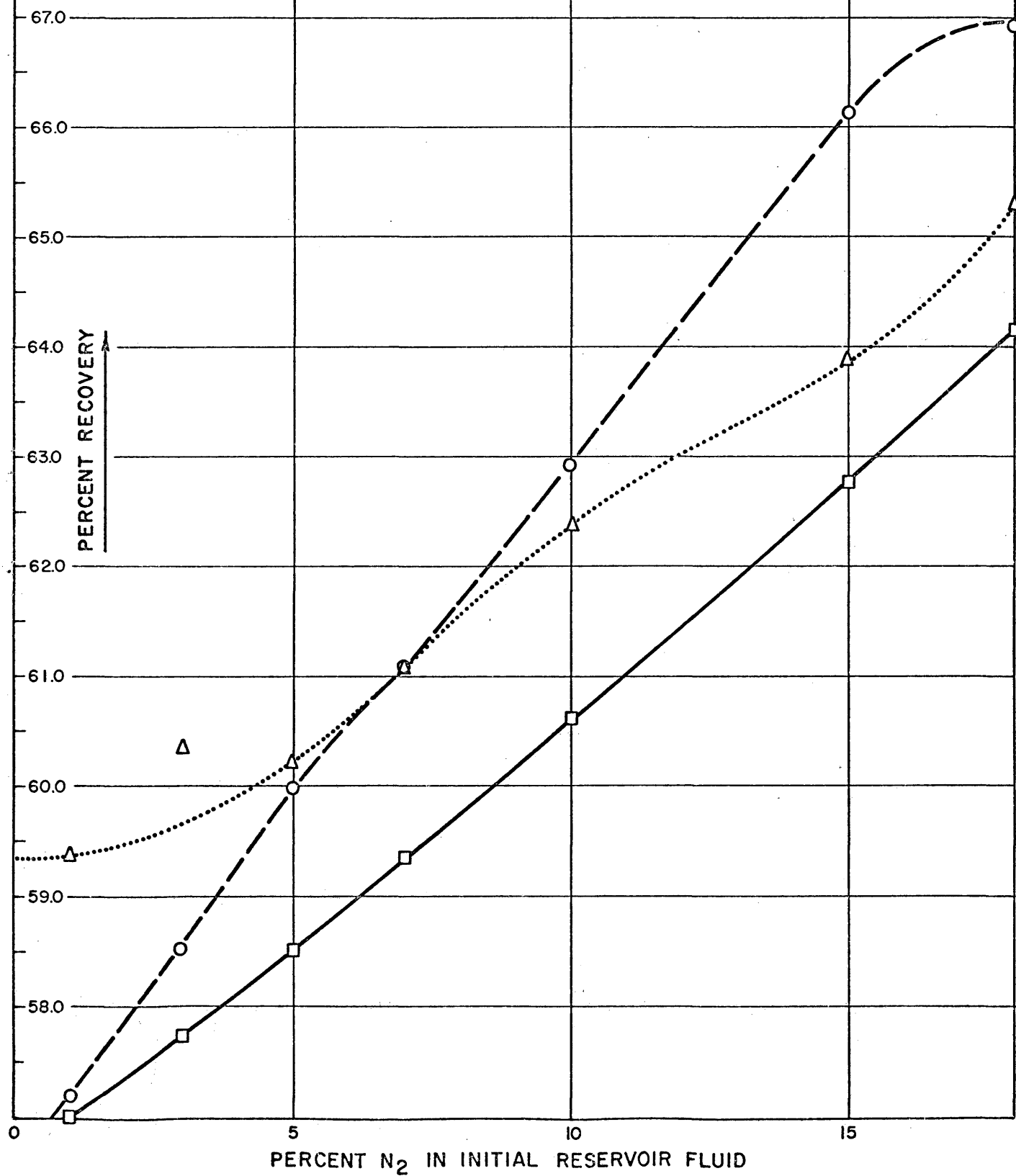


FIGURE 12 RECOVERY OF HEXANE

Δ = METHOD NO. 1
O = METHOD NO. 2
 \square = METHOD NO. 3



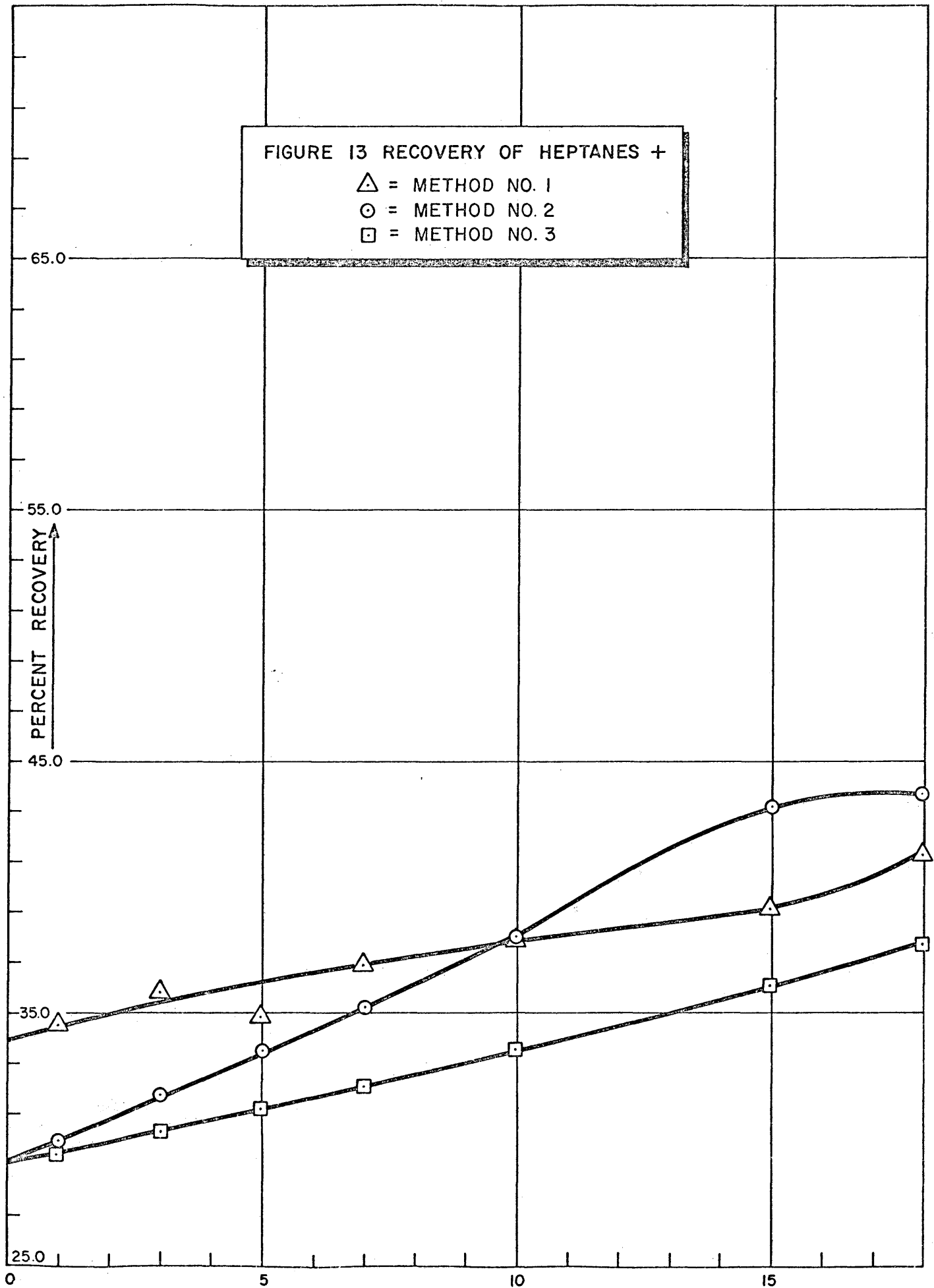


FIGURE 14 CUMULATIVE TOTAL LIQUID RECOVERY AS A FUNCTION OF PRESSURE AT 18 MOLE % NITROGEN CONCENTRATION
△ = METHOD NO. 1
○ = METHOD NO. 2
□ = METHOD NO. 3

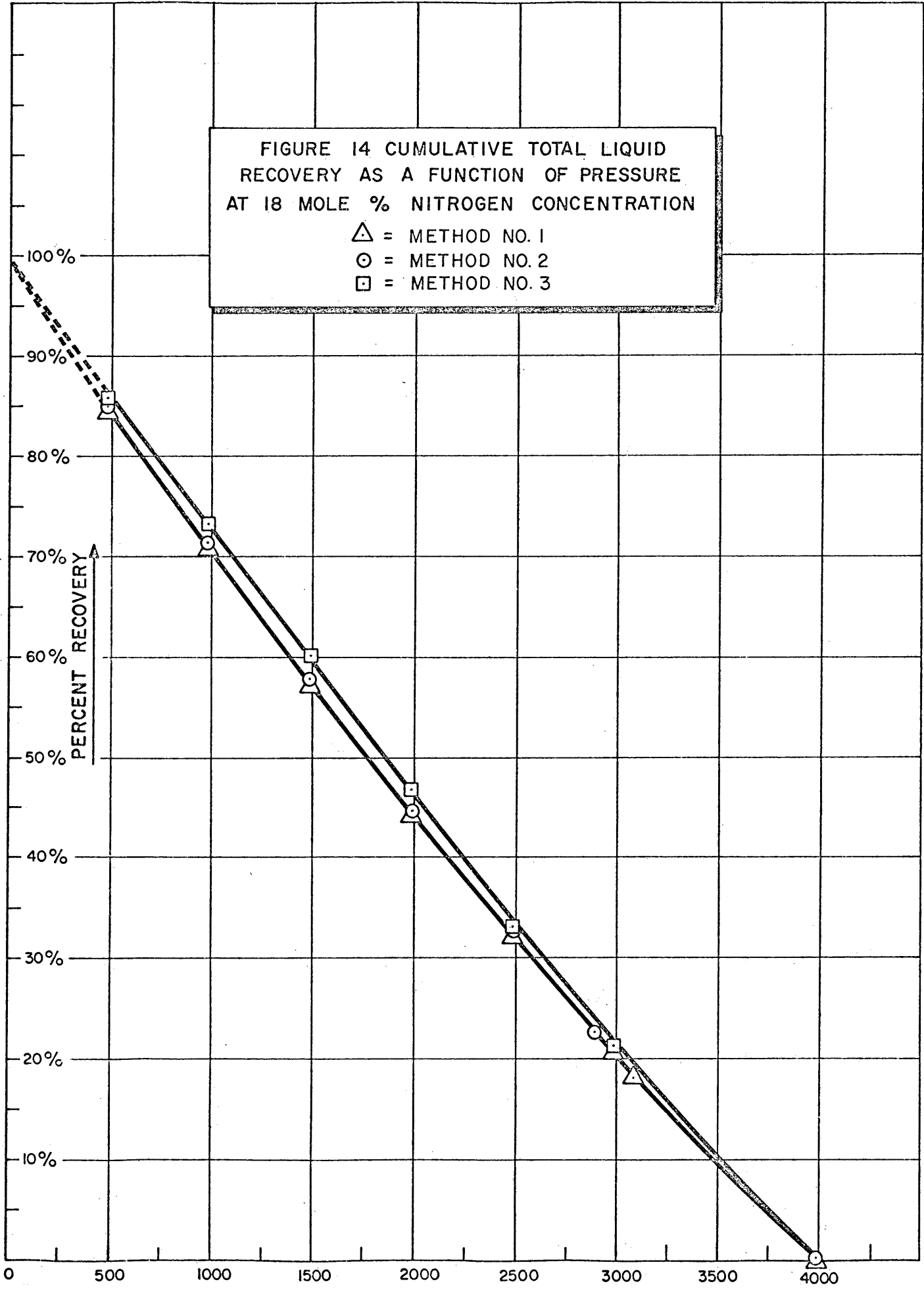


FIGURE 15 DEVIATION OF V_I
○ = METHOD NO.2
□ = METHOD NO.3

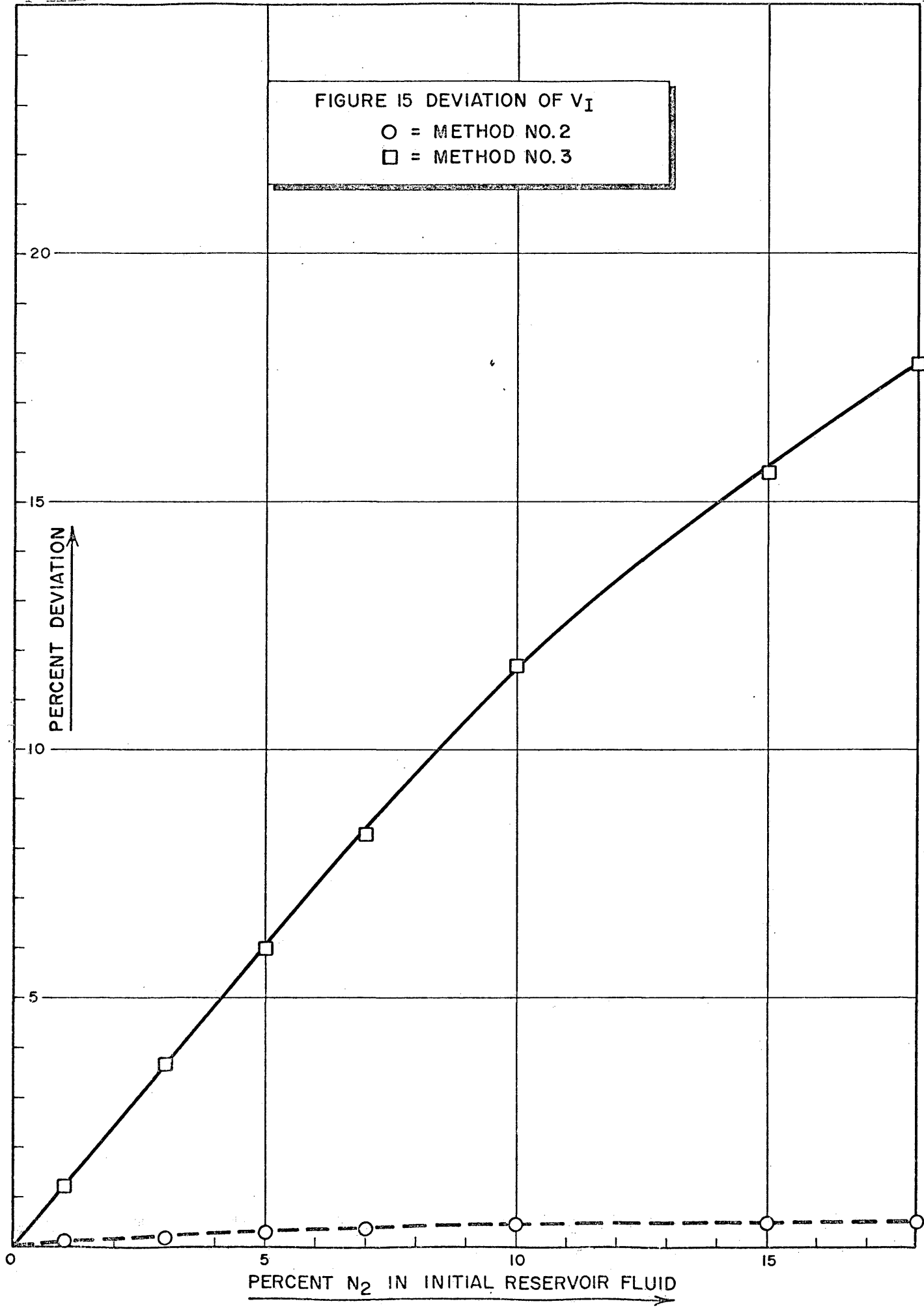


FIGURE 16 FRACTION OF ORIGINAL VAPOR VOLUME AS A FUNCTION OF PRESSURE AT A NITROGEN CONCENTRATION OF 5 MOLE PERCENT
○ = METHOD NO. 2
□ = METHOD NO. 3

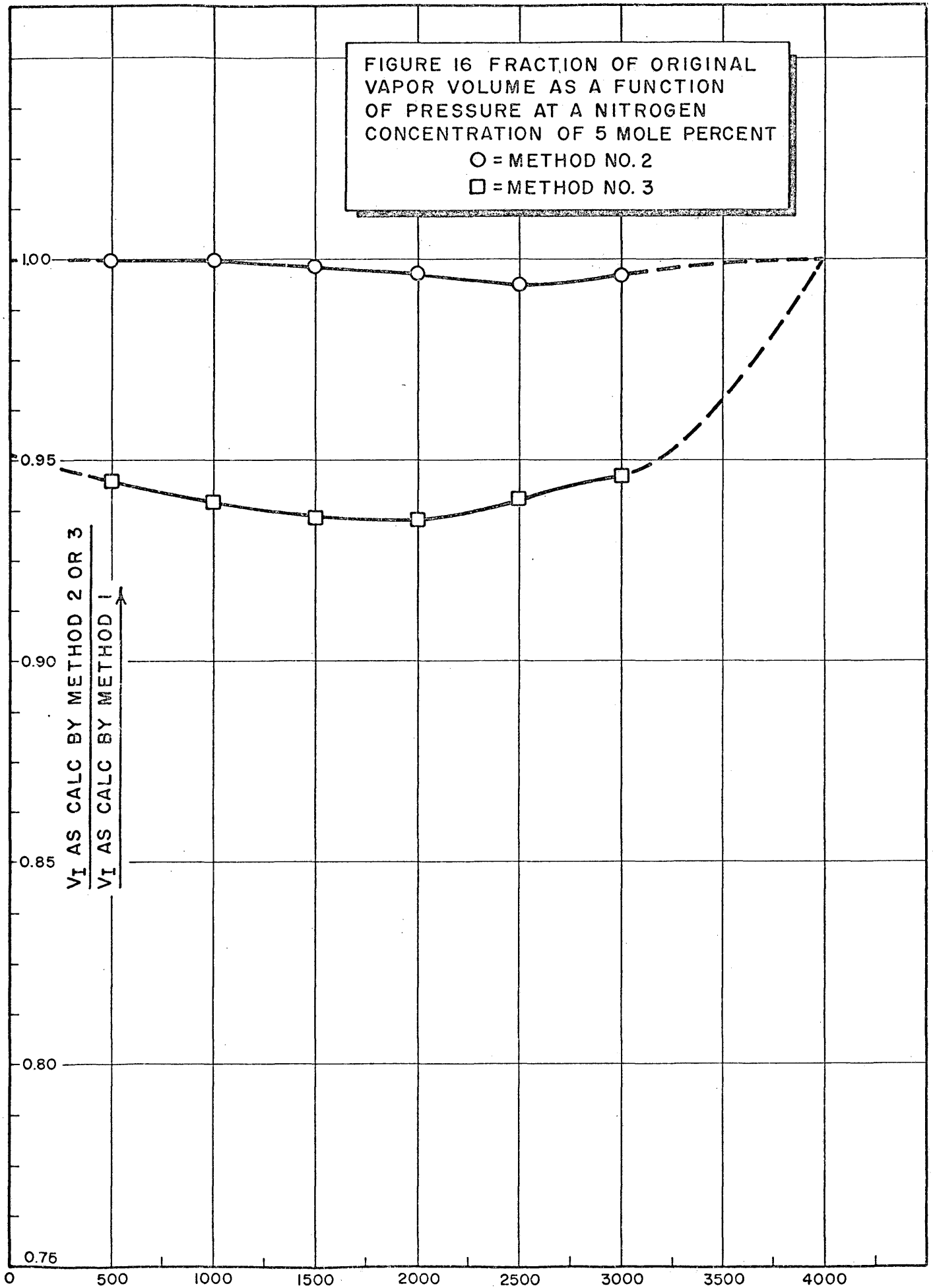


FIGURE 17 FRACTION OF ORIGINAL VAPOR VOLUME AS A FUNCTION OF PRESSURE AT A NITROGEN CONCENTRATION OF 18 MOLE PERCENT
 ○ = METHOD NO. 2
 □ = METHOD NO. 3

