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16. Abstract

This report summarizes the fundamental aspects in the development and application of a methodology for predicting pavement performance in terms of three indices: (a) present serviceability index, (b) distress area index, and (c) distress severity index. A statistical procedure used for estimating the parameters of the performance relationships guarantees that the goodness of fit between predicted and observed data is maximized. The most salient feature of the proposed methodology is the use of an S-shaped curve that recognizes a change in the rate of deterioration of a pavement as the traffic level accumulates until rehabilitation is needed. Serviceability ratings, based on data obtained from 164 pavement test sections, are used to predict the performance of black base, hot mix, and overlay pavements. Pavement performance can also be ascertained in terms of area and severity distress ratings for the following types of pavement distress: rutting, alligator cracking, longitudinal cracking, and transverse cracking. In addition to the development of pavement performance relationships, a methodology is provided to generate survivor curves for different critical performance levels.

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DEVELOPMENT OF PERFORMANCE EQUATIONS AND SURVIVOR CURVES FOR FLEXIBLE PAVEMENTS

by

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Research Report No. 284-5

Flexible Pavement Data Base and Design
Study No. 2-8-80-284

Conducted for the
Texas State Department of Highways and Public Transportation

by the

Texas Transportation Institute
Texas A&M University System
College Station, TX

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IMPLEMENTATION STATEMENT

All results developed in this project report have been computerized and are being implemented in the most recent version of the FPS program. The performance and survivor curves have been validated and can be immediately used to produce estimates of rehabilitation times and percent of mileage in need of rehabilitation for any representative pavement section of the Texas flexible pavement network. The performance and survivor curves can also be incorporated in the RENU2 program to assess the impact of traffic loadings on rehabilitation and maintenance (routine and preventive) costs for a specified planning period.

DISCLAIMER

LIST OF REPORTS

Report No. 284-1, "An Investigation of Vehicle Speed and Pavement Roughness Relationships for Texas Highways," by N. F. Rhodes, Jr., J. P. Mahoney, and R. L. Lytton, September 1979, unpublished.

Report No. 284-2, "Pavement Roughness on Expansive Clays," by Manuel O. Velasco and R. L. Lytton, October 1980.

Report No. 284-3, "Layer Equivalency Factors and Deformation Characteristics of Flexible Pavements," by J. T. Hung, J-L. Briaud, and R. L. Lytton, January 1982.

Report No. 284-3a, "Layer Equivalency Factors and Deformation Characteristics of Flexible Pavements Test Data," by J. T. Hung, J-L. Briaud, and R. L. Lytton, January 1982.

Report No. 284-4, "Design of Asphalt Pavements for Thermal Fatigue Cracking," by R. L. Lytton, U. Shanmugham, and B. D. Garrett, January 1983.

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1. INTRODUCTION

The purpose of this report is to summarize recent developments and actual applications of a pavement performance equation that predicts the loss of serviceability or deterioration due to various types of distress. The proposed model represents an improvement over the form of the original AASHO Road Test performance equation in that it predicts more realistic long term behavior. This is achieved through the use of a sigmoidal or "S-shaped" curve that recognizes the ability of a pavement to reduce its rate of deterioration as the traffic level approaches the service life of the pavement. This behavior, for example, is typical of pavements that have received adequate routine maintenance in the past. To evaluate the parameters in the performance model a least squares curve fit technique is employed using field measurements from the data base for flexible pavements available at the Texas Transportation Institute. The types of pavements considered along with number of test sections evaluated is as follows:

(a) Hot mix asphaltic concrete on bituminous base (Black Base) (51)

(b) Hot mix asphaltic concrete on flexible or unbound base course (Hot Mix) (36)

(c) Overlays (77)

The data for each test section consisted of values of the present serviceability index as a function of the number of 18-kip equivalent axle loads. In addition, the structural performance of the pavement was evaluated in terms of distress severity and area for the following distress types (in each case the primary variable correlated with the distress type is shown in parentheses):

(a) Rutting (N-18)

(b) Alligator Cracking (N-18)

(c) Patching (N-18)

(d) Flushing (ADT)

(e) Raveling (ADT)

(f) Longitudinal Cracks (Time)

(g) Transverse Cracks (Time)

In the above list, N-18 and ADT represent the number of 18-kip single-axle loads and the average daily traffic, respectively; additionally, Time represents the number of months since initial construction or major rehabilitation or reconstruction.

The first part of this report presents background information pertaining to the development of the AASHTO pavement performance equation. The next section describes the development and characteristics of the proposed sigmoidal or S-shaped curve. The procedure for determining the design constants for the curve using present serviceability index data is presented in Section 3. Section 4 deals with the prediction of pavement distress using the proposed methodology. A method for determining survivor curves based on the performance data is presented in Section 5. The last section deals with an actual application of the methods to predict the functional and structural performance of Texas pavements. A preliminary form of the multiple regression models for predicting the design parameters in terms of commonly measured variables is presented. The original data, curves and design parameters are given in the Appendices.

2. GENERAL BACKGROUND ON PERFORMANCE EQUATIONS

2.1 Types of Performance

In the twenty years since the AASHO Road Test began, the idea of performance has been accepted and broadened to accord with the measures of service that the pavement provides. Because of this, it is now possible to define roughly three types of performance: functional, structural, and survival.

1. Functional performance. This is the measure that was adopted by the AASHO Road Test: the present serviceability index which measures the quality of riding conditions from the point of view of the traveling public.
2. Structural performance. The deterioration of structural performance is measured by the appearance of various forms of distress and their relative importance in triggering decisions to maintain or to rehabilitate a pavement. These measures include roughness, cracking (several types), rutting, flushing, raveling, failures (potholes), and patches in flexible pavements. The measures for rigid pavements include spalling, cracking, and joint problems such as pumping, failures, and faulting. Because structural performance is visible or measurable, whereas functional performance is primarily subjective, there have been several attempts to relate the two.
3. Survival. The survival of a pavement is determined by the amount of time that it lasts before major maintenance or

rehabilitation must be performed. Survival is measured by the probability that a given pavement is still in service a number of years after its construction. Historical records may be used to develop such "survivor curves" which are important in projecting budget levels for maintenance and rehabilitation work.

Each of these kinds of performance has its own use in serving the public. The latter two are of principal importance to the agency that is charged with the responsibility of keeping a roadway network in good operating condition.

The form of the AASHTO pavement functional performance equation is

$$g = \left(\frac{W}{\rho}\right)^{\beta} \tag{1}$$

in which

g = the damage function. This is a normalized variable that ranges from 0 to 1 as distress increases or as functional performance or survival probability decrease.

W = the quantity of normalized load or climatic cycles, or the total elapsed time to reach a given level of g.

ρ = the quantity of normalized load or climatic cycles, or the total elapsed time until g reaches a value of 1. It is usually assumed to be a function of the structural variables.

β = a power which dictates the degree of curvature of the curve relating g to the ratio of W/ρ. A high value of β (greater than 1) indicates that g remains low over the majority of the life of the pavement. A low value of β (less than 1) indicates a high value of g over the life of the pavement.

The damage function in the AASHTO pavement function performance equation is defined as a serviceability index ratio.

$$g = \frac{P_o - P}{P_o - P_f} \qquad (2)$$

where

P_o = initial serviceability index

P_f = minimum serviceability index (in the AASHTO functional performance equation this value is equal to 1.5)

Combining Equations (1) and (2) the AASHO design equation can be rewritten as

$$P = P_o - (P_o - P_f)\left(\frac{W}{\rho}\right)^{\beta} \qquad (3)$$

A graphical representation of Equation (3) is given in Figure 1.

2.2 Alternative Forms of Functional Performance Equations

The shape that a functional performance curve should take can be deduced from the boundary conditions placed on the serviceability index scale as well as from long-term observations of field data. The serviceability rating scale ranges between 0 and 5 and, as it is defined, can be neither greater than 5 nor less than 0. As the pavement roughness increases, the serviceability rating will decrease and will approach, but not drop below, a serviceability rating of 0 no matter how much traffic passes over the pavement. Thus, the performance curve starts out horizontally bounded from above by a rating of 5. As load repetitions increase, the curve is bounded from

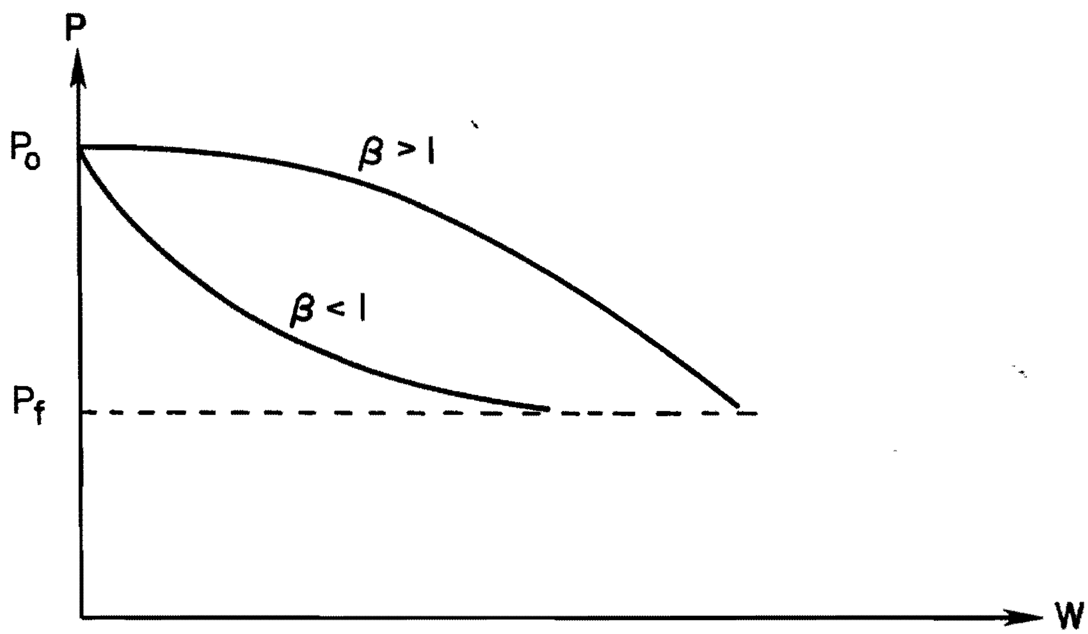

FIGURE 1. The AASHO Performance Curve

below by a rating of 0, a value which it approaches as an asymptote. These boundary conditions imply that a functional performance curve should be S-shaped.

The form of the AASHTO functional performance equation, Equation (1), assumed that the serviceability index-versus-traffic curve never reverses its curvature, as illustrated in Figure 1. By way of contrast to this assumed form of equation, a number of observed serviceability index-versus-traffic relations have shown a reversal of curvature as illustrated schematically in Figure 2. Appendix 2 contains a number of examples of these.

The S-shaped feature of the curve shown in Figure 2 requires an equation of the form

$$\frac{P_o - P}{P_o - P_f} = e^{-\left(\frac{\rho}{W}\right)^{\beta}} \tag{4}$$

which can be rewritten as

$$P = P_o - (P_o - P_f)e^{-\left(\frac{\rho}{W}\right)^{\beta}} \tag{5}$$

This equation has been investigated and validated using an extensive data base for flexible pavements available at the Texas Transportation Institute. Previous studies have also shown the validity of Equation (5) in predicting pavement performance (1,2,4,5,6).

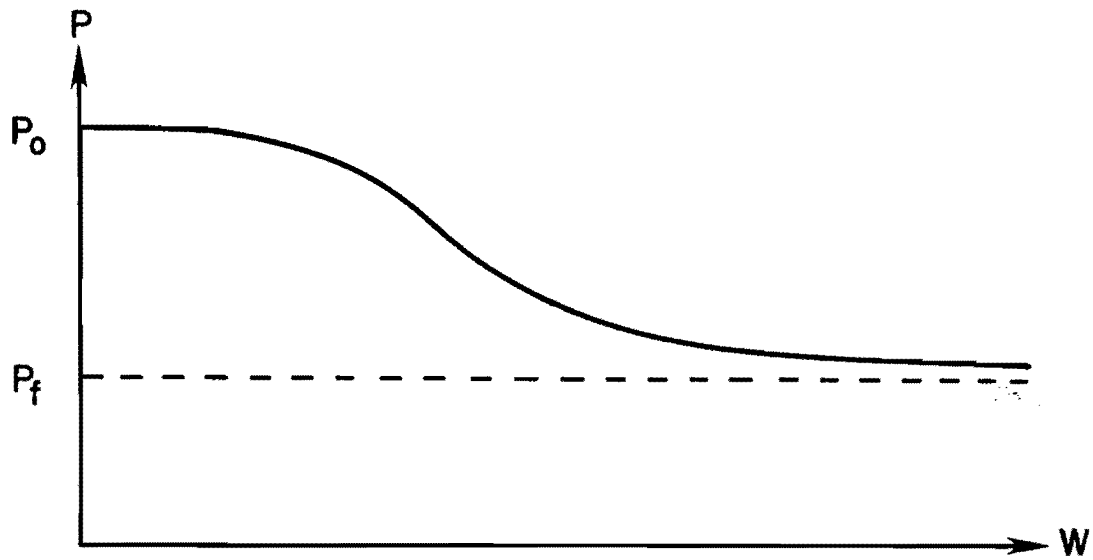

FIGURE 2. The S-shaped Performance Curve

3. PROCEDURE FOR DETERMINING DESIGN CONSTANTS

Assuming that P_o is known, the purpose of this section is to develop a statistical procedure to determine the constants P_f, ρ, and β on the basis of observed performance data for a given type of pavement.

The performance relationship, Equation (5), can be expressed as

$$P_o - P = \alpha\, e^{-\left(\frac{\rho}{W}\right)^{\beta}} \tag{6}$$

where

$$\alpha = P_o - P_f \tag{6a}$$

Taking the natural logarithm of Equation (6) yields

$$Ln(P_o - P) = Ln(\alpha) - \left(\frac{\rho}{W}\right)^{\beta} \tag{7}$$

which can also be written as,

$$Ln(P_o - P) = Ln(\alpha) - \rho^{\beta}\left(\frac{1}{W}\right)^{\beta} \tag{8}$$

Using the transformation $e^{\tau} = \frac{1}{W}$, Equation (9) becomes

$$Ln(P_o - P) = Ln(\alpha) - \rho^{\beta}(e^{\beta})^{\tau} \tag{9}$$

which is equivalent to

$$z = a - bc^{\tau} \tag{10}$$

where the variables of substitution are:

$$z = Ln(P_o - P) \tag{10a}$$

$$a = Ln(\alpha) \tag{10b}$$

$$b = \rho^{\beta} \tag{10c}$$

$$c = e^{\beta} \tag{10d}$$

Given a collection of m data points (P_i, W_i), where P_i is the serviceability index corresponding to a traffic level

W_i, and $i = 1,2,\ldots,m$, the remaining portion of this section will deal with the development of a statistical procedure to find a, b, and c on the basis of observed data.

Specifically, the data can be computed as follows:

(a) find $z_i = \text{Ln}(P_0 - P_i)$ for $i = 1,2,\ldots,m$

(b) find $\tau_i = \text{Ln}(\frac{1}{W_i})$ for $i = 1,2,\ldots,m$

Therefore, the observed values of P_i and W_i are transformed into values of z_i and τ_i, respectively. The statistical model to be used is defined as

$$z_i = a - bc^{\tau_i} + \varepsilon_i \tag{11}$$

where ε_i is the random error corresponding to the value z_i associated with τ_i.

The basic procedure to estimate the parameters a, b, and c is the well-known "least squares" method. This method computes a, b, and c in such a way that the quantity $\sum_{i=1}^{m} \varepsilon_i^2$ is minimized. This quantity can be obtained from Equation (11) as

$$\sum_{i=1}^{m} \varepsilon_i^2 = \sum_{i=1}^{m} (z_i - a + bc^{\tau_i})^2 \tag{12}$$

The necessary (and in this case sufficient) conditions for a minimum are given by

$$\frac{\partial(\sum_{i=1}^{m} \varepsilon_i^2)}{\partial a} = 0 \tag{13a}$$

$$\frac{\partial(\sum_{i=1}^{m} \varepsilon_i^2)}{\partial b} = 0 \tag{13b}$$

$$\frac{\partial\left(\sum_{i=1}^{m} \varepsilon_i^2\right)}{\partial c} = 0 \qquad (13c)$$

The above conditions can be shown to be equivalent to

$$\sum_{i=1}^{m} (z_i - a + bc^{\tau_i}) = 0 \qquad (14)$$

$$\sum_{i=1}^{m} (z_i - a + bc^{\tau_i})c^{\tau_i} = 0 \qquad (15)$$

$$\sum_{i=1}^{m} (z_i - a + bc^{\tau_i})\tau_i c^{\tau_i - 1} = 0 \qquad (16)$$

It is noted that Equations (14) and (15) are linear in a and b; therefore both parameters can be obtained in terms of z_i, τ_i, and c. The corresponding results are:

$$a = \frac{\left(\sum_{i=1}^{m} C^{2\tau_i}\right)\left(\sum_{i=1}^{m} Z_i\right) - \left(\sum_{i=1}^{m} C^{\tau_i}\right)\left(\sum_{i=1}^{m} Z_i C^{\tau_i}\right)}{m \cdot \left(\sum_{i=1}^{m} C^{2\tau_i}\right) - \left(\sum_{i=1}^{m} C^{\tau_i}\right)\left(\sum_{i=1}^{m} C^{\tau_i}\right)} \qquad (17)$$

$$b = \frac{-m \cdot \left(\sum_{i=1}^{m} Z_i C^{\tau_i}\right) + \left(\sum_{i=1}^{m} C^{\tau_i}\right)\left(\sum_{i=1}^{m} Z_i\right)}{m \cdot \left(\sum_{i=1}^{m} C^{2\tau_i}\right) - \left(\sum_{i=1}^{m} C^{\tau_i}\right)\left(\sum_{i=1}^{m} C^{\tau_i}\right)} \qquad (18)$$

The values of a and b given by Equations (17) and (18) can be substituted into Equation (16) to obtain the following final result:

$$\sum_{i=1}^{m} Z_i \tau_i C^{\tau_i} - \frac{\left(\sum_{i=1}^{m} C^{2\tau_i}\right)\left(\sum_{i=1}^{m} Z_i\right) - \left(\sum_{i=1}^{m} C^{\tau_i}\right)\left(\sum_{i=1}^{m} Z_i C^{\tau_i}\right)}{m \cdot \left(\sum_{i=1}^{m} C^{2\tau_i}\right) - \left(\sum_{i=1}^{m} C^{\tau_i}\right)\left(\sum_{i=1}^{m} C^{\tau_i}\right)} \cdot \left(\sum_{i=1}^{m} \tau_i C^{\tau_i}\right)$$

$$+ \frac{-m \cdot \left(\sum_{i=1}^{m} Z_i C^{\tau_i}\right) + \left(\sum_{i=1}^{m} C^{\tau_i}\right)\left(\sum_{i=1}^{m} Z_i\right)}{m \cdot \left(\sum_{i=1}^{m} C^{2\tau_i}\right) - \left(\sum_{i=1}^{m} C^{\tau_i}\right)\left(\sum_{i=1}^{m} C^{\tau_i}\right)} \cdot \left(\sum_{i=1}^{m} \tau_i C^{2\tau_i}\right) = 0 \tag{19}$$

Equation (19) can be solved for c using trial-and-error or a simple numerical analysis method. Once c is determined, a and b can be computed from Equations (17) and (18), respectively, and their corresponding values can be used to estimate α (and thus P_f), ρ, and β from Equations (10b), (10c), and (10d)

4. PREDICTION OF PAVEMENT DISTRESS

Pavement distress is best represented in two separate components: density and severity. Density may be expressed either as the percent of the total pavement surface area that is covered by the distress, or total crack length per unit area, or crack spacing, or similar measures. Severity may be expressed as either an objective or subjective measure. Examples of objective measures are crack width, crack depth, and relative displacement at a joint. Subjective measures may be assessed reliably by comparing the observed distress with photographs of different levels of severity which may be described as none, slight, moderate, or severe and may be given numerical ratings such as 0, 1, 2, and 3, respectively, or be assigned numbers that are proportional to these in a range between 0 and 1. The change of either area or severity of distress can be evaluated using the previously discussed equations.

In order to study the behavior of the area covered by a given type of distress, and the corresponding level of severity, two indices will be introduced: (a) the distress area index, and (b) the distress severity index. Each of these indices represents a number between 1 and 0 which decreases as the level of traffic is increased. Note that the present serviceability index (PSI) has a similar behavior, with the exception that it decreases from P_0 to P_f.

Specifically, the distress area index decreases from a value A_0 ($A_0 \leq 1$) to a value A_f ($0 \leq A_f \leq A_0$) as the traffic increases; similarly, the distress severity index decreases from a value of S

($S_0 \leq 1$) to a value S_f ($0 \leq S_f \leq S_0$) as the traffic level increases. Note that both the area and severity indices are reduced as traffic increases; that is, a recently rehabilitated pavement will have indices close to one, as opposed to pavements in need of rehabilitation which will have indices close to zero.

The distress area index, A, is expressed by a relationship similar to that of Equation (3), namely,

$$A = A_0 - (A_0 - A_f)e^{-\left(\frac{\rho}{W}\right)^{\beta}} \tag{20}$$

Similarly the distress severity index, S, is expressed as

$$S = S_0 - (S_0 - S_f)e^{-\left(\frac{\rho}{W}\right)^{\beta}} \tag{21}$$

Using the A, S, and W data from the Texas Transportation Institute data base it is possible to estimate A_f, S_f, ρ, and β following the procedure described by Equations (5) through (19) for each of the following types of distress:

(a) Rutting,

(b) Raveling,

(c) Flushing,

(d) Alligator cracking,

(e) Longitudinal cracking,

(f) Transverse cracking,

(g) Patching.

5. DEVELOPMENT OF SURVIVOR CURVES

5.1 Introduction

A survivor curve is a functional relationship that predicts the percentage of mileage in a given pavement category that does not require immediate rehabilitation at a specified time. This specified time can be considered as the time at which the pavement has reached a given traffic load level, or the time since last rehabilitation. Evidently, to decide if a pavement requires or does not require some kind of rehabilitation, it is first necessary to define a measure of pavement performance. This measure of performance has been defined in terms of PSI or distress as shown in the previous sections. The fundamental idea behind the development of a survivor curve is the concept that since the performance relationship is deterministic, it would be meaningful to determine a second relationship that estimates the percent of pavement mileage that actually survives when the performance function reaches a critical value.

Survival times are data that measure the time to failure. These times are subject to random variations, and like any random variables, form a distribution; the two-parameter Weibull distribution (3) is assumed as the survival distribution for predicting the survival or failure rate of pavements. The Weibull distribution is one of the well-known survival distributions; its applicability to various failure situations, such as electron tube failure, the fatigue life of deep-groove ball bearings, etc., has been extensively investigated and recommended.

The Weibull distribution is characterized by two non-negative parameters λ and γ; its probability density function, f(w), and the cumulative distribution function, F(w), are defined as follows:

$$f(w) = \lambda\gamma(\lambda w)^{r-1} e^{-(\lambda w)^{\gamma}} \tag{22}$$

$$F(w) = 1 - e^{-(\lambda w)^{\gamma}} \tag{23}$$

In the specific application of the Weibull distribution to the study of pavement survivability, w represents the traffic load (N-18 for PSI, Time for distress) at which the pavement reaches a critical performance level. The parameters λ and γ are referred to as a "scale parameter" and a "shape parameter," respectively.

The survival function, denoted by s(w), is defined as the probability that an individual mile of pavement of a given type survives a traffic load larger than w. From the definition of the cumulative distribution function F(w), it can be concluded that s(w) = 1-F(w). That is,

$$s(w) = e^{-(\lambda w)^{\gamma}} \tag{24}$$

As explained here, s(w) is the survival rate of a given type of pavement structure under w traffic loads.

5.2 Parameter Estimation Method

As already mentioned, the parameters λ and γ determine the position and shape of the survival distribution. The maximum likelihood estimation method (3) can be applied to obtain estimates $\hat{\lambda}$ and $\hat{\gamma}$ on the basis of a random sample of survival times or traffic loads w_1, w_2, ..., w_n. The corresponding estimates are the solution to the following non-linear system of Equations:

$$\frac{\sum_{i=1}^{n} W_i^{\hat{\gamma}} \, Ln(W_i)}{\sum_{i=1}^{n} W_i^{\hat{\gamma}}} - \frac{1}{\hat{\gamma}} - \frac{1}{n} \sum_{i=1}^{n} Ln(W_i) = 0 \qquad (25)$$

$$\frac{1}{\hat{\lambda}^{\hat{\gamma}}} - \frac{1}{n} \sum_{i=1}^{n} W_i^{\hat{\gamma}} = 0 \qquad (26)$$

Equation (25) can be approximately solved using the Newton-Raphson method (7) to find $\hat{\gamma}$, which in turn is used in Equation (26) to find $\hat{\lambda}$.

5.3 Data Generation Procedure

For a specified critical level of performance measured in terms of PSI or distress area/severity indices corresponding to a given type of distress (rutting, alligator cracking, longitudinal cracking, transverse cracking), the sample w_1, w_2, ..., w_n can be generated as follows. Equations (5), (20), and (21) can be generally formulated as

$$g = e^{-\left(\frac{\rho}{w}\right)^{\beta}} \qquad (27)$$

Solving Equation (27) for w, we obtain

$$w = \left(-\frac{\rho^{\beta}}{Ln(g_c)}\right)^{1/\beta} \tag{28}$$

where g_c represents the specified critical level of performance.

If the performance data correspond to measurements of the present serviceability index (PSI), the critical performance index is calculated as

$$g_c = \frac{P_o - P_c}{P_o - P_f} \tag{29}$$

For Equation (29) to yield a valid value of g_c it is necessary that $P_c \geq P_f$. Therefore, when considering test sections of a given type of pavement, Equation (28) can be used only in the case of sections having a P_f value less than or equal to the specified value P_c. All other sections violating this condition cannot be used to generate w values for the maximum likelihood estimation procedure. In the case of pavement distress analysis, the critical value g_c is directly specified as an input parameter. This is due to the assumption that A_o=1 and A_f=0 in Equation (20), and S_o=1 and S_f=0 in Equation (21). Under this assumption, critical values of w can be obtained by solving the following equation:

$$e^{-\left(\frac{\rho}{w}\right)^{\beta}} = \begin{cases} 1 - A_c = g_c \text{ (area)} \\ \\ 1 - S_c = g_c \text{ (severity)} \end{cases} \tag{30}$$

6. APPLICATIONS OF THE METHODOLOGY

6.1 Performance Curves for PSI and Distress

The S-shaped performance curve was found to adequately describe the performance of flexible pavements in Texas as a result of increased traffic levels. This behavior has been analyzed primarily in terms of the decrease in the present serviceability index as a function of the number of 18-kip equivalent axle loads. The proposed performance curve was developed on the basis of observed data (see Appendix 1) for pavements in each of the following categories: (a) black base, (b) hot mix, and (c) overlays. The performance curves and design parameters for each test section in the three pavement categories are given in Appendices 2 and 3, respectively. Table 1 gives the number of test sections in each category along with mean value and minimum and maximum observed values of the design parameters. The mean values of the curve fit parameters were obtained from the statistical procedure described earlier in this paper. Figure 3 shows the average performance curves obtained using these design parameters for each of the three pavement types.

The analysis of the data showed four possible cases for the curve fit. Typical test sections for each case are shown in Figure 4 and a description for each case is as follows:

TABLE 1. Serviceability Performance Curve Parameters by Pavement Type

Pavement Type	Black Base	Hot Mix Asphalt concrete	Overlays
Number of Test Sections	51	36	77
ρ (mean)	2.321	1.960	1.974
ρ (min)	0.005	0.100	0.013
ρ (max)	17.239	11.098	9.188
β (mean)	1.337	1.952	1.196
β (min)	0.300	0.095	0.095
β (max)	6.277	7.259	2.893
P_o (mean)	4.15	3.87	3.92
P_o (min)	2.79	2.86	2.07
P_o (max)	4.77	4.78	4.88
P_f (mean)	1.962	1.661	2.121
P_f (min)	0.000	0.000	0.004
P_f (max)	4.295	4.305	4.391

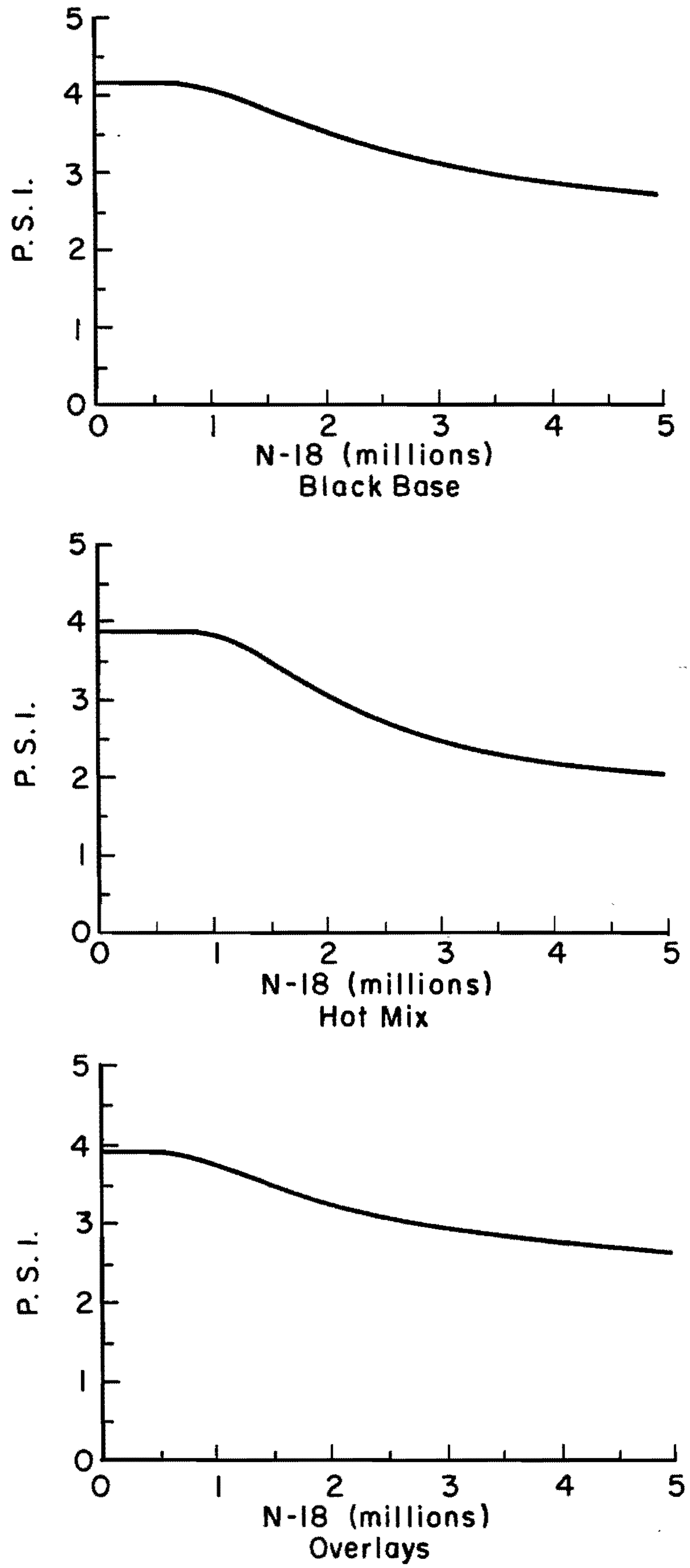

FIGURE 3. Performance Curves from the Mean Design Parameters

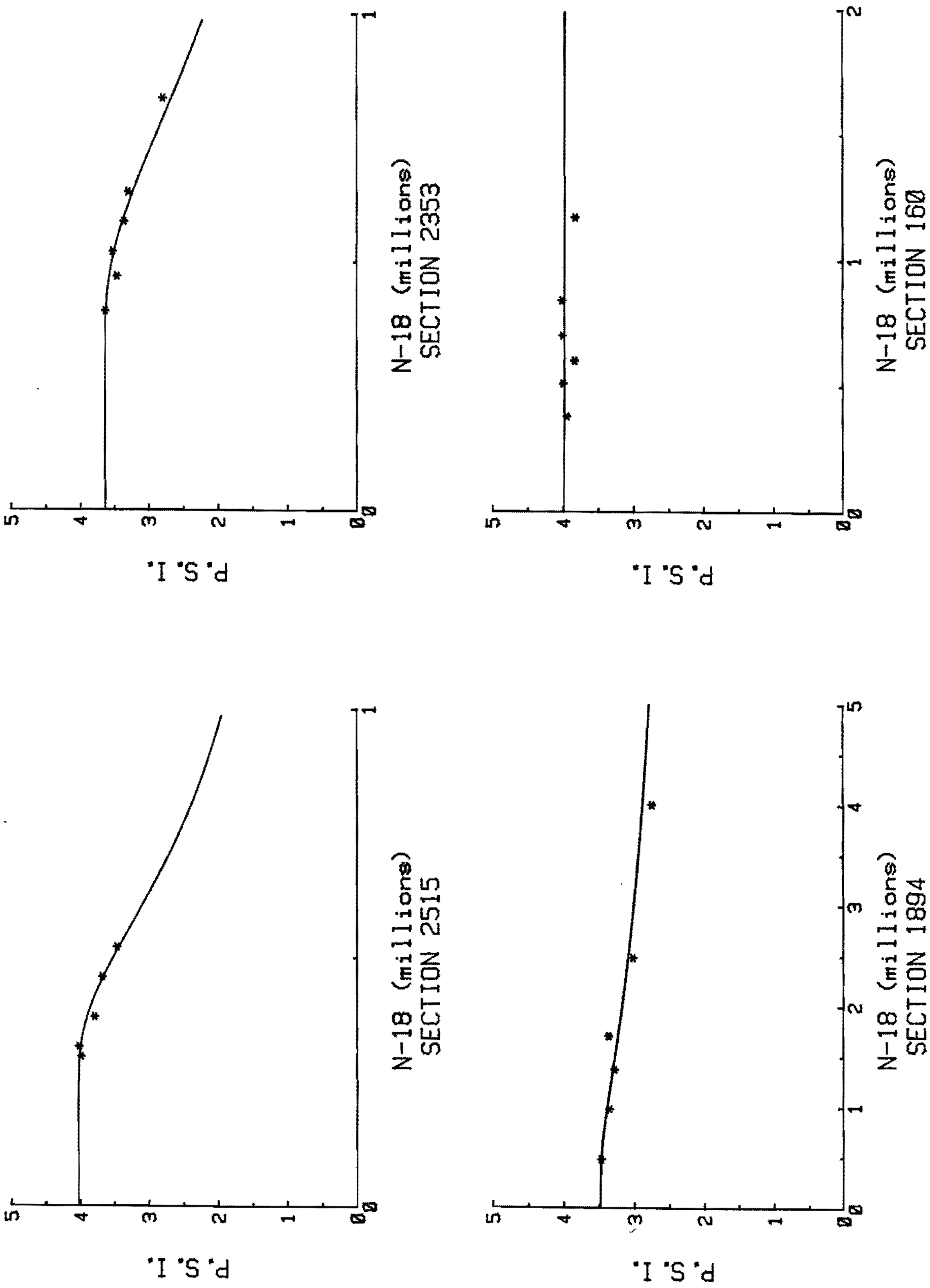

FIGURE 4. Typical Sections for the Four Cases of Serviceability Performance

(a) Case I (Figure 4a)

$\rho > 1$

$\beta > 1$

$P_o > P_f$

Comments: The complete S-shaped pattern can be distinguished.

Percent pavements of this type: 26.9

Example: Black Base, Test Section Number 2515

(b) Case II (Figure 4b)

$\rho \gg 1$

$\beta > 1$

$P_o > P_f$

Comments: The upper half of the S-shaped curve is observed.

Percent pavements of this type: 28.6

Example: Overlay, Test Section Number 2353

(c) Case III (Figure 4c)

$\rho > 0$

$\beta < 1$

$P_o > P_f$

Comments: The lower half of the S-shaped curve is observed

Percent pavements of this type: 21.3

Example: Overlay, Test Section Number 1894

(d) Case IV (Figure 4d)

$\rho > 0$

$\beta = 0$

$P_o = P_f$

Comments: No noticeable curve is observed

Percent pavements of this type: 21.3

Example: Overlay, Test Section Number 160

The S-shaped performance curve is also applicable in the analysis of distress data. For this case the assumptions that $A_o = S_o = 1$ and $A_f = S_f = 0$ will simplify the analysis, since only the parameters ρ and β remain to be estimated. These values can then be used to develop a performance curve for each of the two distress indices (area and severity). Work has also been performed to evaluate these quantities for each of the seven distress types discussed earlier in this report. Results of this analysis for distress types found to be critical (using the method of discriminant analysis as discussed by Allison et al. (1)) are shown in Table 2. Detailed results are given in the next section of this report.

6.2 Performance Models Generated Using Regression Analysis

An arithmetic and logarithmic multiple regression analysis has been performed for the PSI design parameters. In the analysis, the categories of primary importance are (a) pavement environment, (b) pavement structure, and (c) pavement history. The most important variables in each category are given in Table 3. The arithmetic and

TABLE 2. Primary Distress Type and Curve Fit Parameters by Pavement Type

Pavement Type	Black Base	Hot Mix Asphalt concrete	Overlays
Type of Distress	Alligator Cracking Severity	Alligator Cracking Area	Transverse Cracking Severity(*)
ρ (mean)	1.19	0.93	85.57
ρ (min)	0.14	0.07	24.13
ρ (max)	3.01	3.63	194.83
β (mean)	2.54	3.43	1.47
β (min)	0.89	0.50	0.50
β (max)	8.78	18.21	5.52

(*) The ρ and β terms for this case are determined in terms of the number of months the pavement has been in service.

TABLE 3. Variables Used in the Regression Models

Environmental	Structural	Pavement History
Thornthwaite Index (TI)	Plasticity Index (PI)	
Freeze/Thaw (F/T)	Equivalent Thickness (H')[1]	N-18/month (N-18)[6]
Average Temperature (T_{AVG})	Percent Asphalt Binder (Binder)[2]	
	Overlay Thickness (OVTH)[3]	
	Total Asphalt Thickness (ASPH)[4]	
	Surfacing Thickness (HMAC)[5]	

1. Equivalent thickness is the transformed pavement thickness based on the following expression:

$$H' = \sum_{i=1}^{m} (E_i/E_s)^n \, t_i$$

where

m = number of pavement layers under consideration
E_i = elastic modulus for the i-th layer
t_i = thickness of the i-th layer
E_s = elastic modulus of the subgrade as determined from Dynaflect measurements.
n = Odemark's constant (0.33) or can be obtained from field data.

In the regression models this variable is transformed as follows:

$$HPR2 = H'*E_s/10^5$$

The HPR3 term appearing in the regression equations is defined as follows:

$$HPR3 = \frac{10^{10}}{E_s * (H')^3}$$

2. This term is for black base and hot mix asphalt concrete pavements.
3. This term is for overlay pavements.
4. This term is for black base pavements. It is the total asphalt thickness of black base + surfacing course.
5. This term is for Hot Mix pavements.
6. The N-18/month value represents the observed value during the first performance period.

logarithmic design models were obtained using a stepwise regression procedure and shown in Tables 4 and 5, respectively. The regression equation for area and severity of distress for Black Base, Hot Mix and Overlaid pavements are shown in Tables 6, 7 and 8, respectively.

6.3 Survivor Curves for PSI and Distress

The performance curve developed for each test section was used to generate survivor curves using the method outlined in Section 5. For each pavement type, i.e. black base, hot mix and overlay, the parameters λ and γ of the Weibull distribution were estimated for three different critical levels of PSI. The results of this analysis are given in Table 9, and the survivor curves for each of the three pavement types are shown in Figures 5, 6, and 7.

A similar analysis was carried out for pavement distress using a critical performance index fixed at 0.25 and 0.50. Both distress area and severity were evaluated for the following types of distress:

(a) Rutting

(b) Alligator cracking

(c) Longitudinal cracking

(d) Transverse cracking

The resulting λ and γ values are shown in Table 10. It should be noted from this table that the survivor curve parameters are highly dependent upon the value specified for g_c. The Weibull distribution parameters given in Table 10 are used to plot the survivor curves shown in Appendix 4.

The computer programs used to determine the performance and survivor curve design parameters are given in Appendix 5.

TABLE 4. Arithmetic Regression Models for the Design Parameters (PSI)

Black Base

$$\rho = -0.02182(F/T) - 0.00831(PI) + 0.04499(Binder) + 0.15019(HPR2)$$

$$\beta = 0.01201(TI) + 0.03166(F/T) + 0.13775(T_{AVG}) + 0.00114(PI) - 0.31331(Binder) - 0.03234(HPR2)$$

$$P_f = -0.00637(F/T) - 0.01550(T_{AVG}) - 0.00658(PI) + 0.27714(Binder) + 0.05097(HPR2)$$

Hot Mix

$$\rho = -0.02000(TI) - 0.02481(F/T) - 0.03078(PI) + 0.60781(Binder) + 0.06424(HPR2)$$

$$\beta = 0.04045(F/T) + 0.22931(T_{AVG}) - 0.53010(Binder)$$

$$P_f = -0.00665(F/T) - 0.07017(T_{AVG}) - 0.02472(PI) + 0.57235(Binder) + 0.00722(HPR2)$$

Overlays

$$\rho = 0.26503(OVTH) + 0.07180(HPR2)$$

$$\beta = 0.00413(TI) + 0.01036(F/T) + 0.04769(T_{AVG}) + 0.01707(N\text{-}18) - 0.09144(OVTH) - 0.01066(HPR2)$$

$$P_f = 0.33037(OVTH) + 0.07627(HPR2)$$

TABLE 5. Logarithmic Regression Models for the Design Parameters (PSI)

Black Base

$$\rho = (F/T)^{-0.46679} * (T_{AVG})^{-0.86233} * (PI)^{-0.26711} * (HPR2)^{1.65694}$$

$$\beta = (F/T)^{0.60949} * (T_{AVG})^{0.93499} * (Binder)^{-1.37608} * (HPR2)^{-0.72725}$$

$$P_f = (F/T)^{-1.50634} * (T_{AVG})^{-2.69460} * (Binder)^{4.17755} * (HPR2)^{1.60919}$$

Hot Mix

$$\rho = (TI)^{-0.31419} * (F/T)^{-0.69942} * (T_{AVG})^{-0.96204} * (Binder)^{0.44492} * (HPR2)^{1.85110}$$

$$\beta = (F/T)^{0.40391} * (T_{AVG})^{0.44517} * (N\text{-}18)^{0.04576} * (Binder)^{-1.50340}$$

$$P_f = (F/T)^{-0.89516} * (T_{AVG})^{-3.14575} * (Binder)^{5.31210} * (HPR2)^{0.44486}$$

Overlays

$$\rho = (F/T)^{-0.24351} * (Binder)^{0.71372} * (HPR2)^{0.18059}$$

$$\beta = (F/T)^{0.09767} * (N\text{-}18)^{0.17402} * (Binder)^{-0.30623} * (HPR2)^{-0.22623}$$

$$P_f = (F/T)^{-0.14525} * (T_{AVG})^{-0.25053} * (N\text{-}18)^{-0.24283} * (Binder)^{0.32304} * (HPR2)^{0.62508}$$

TABLE 6. Regression Equations for Black Base Pavements

Rutting

Area

$\rho = 0.00175\ F/T - 0.0141\ T_{AVG} + 0.257\ ASPH$

$\beta = -0.00493\ F/T + 0.0262\ T_{AVG} + 0.0387\ PI - 0.0433\ ASPH$

Severity

$\rho = 0.00263 - 0.0137\ T_{AVG} + 0.253\ ASPH$

$\beta = 0.00337\ TI - 0.00928\ F/T + 0.0341\ T_{AVG} + 0.0242\ PI - 0.071\ ASPH$

Alligator

Area

$\rho = 0.134\ HPR2 - 0.067\ HPR3$

$\beta = 0.856\ HPR3$

Severity

$\rho = -0.00986\ PI + 0.0422\ ASPH + 0.0554\ HPR2$

$\beta = 1.37\ HPR3$

Longitudinal

Area

$\rho = 5.33\ ASPH + 29.44\ BINDER - 6.88\ HPR3$

$\beta = 0.0181\ T_{AVG} + 0.421\ HPR3$

Severity

$\rho = -0.425\ F/T - 0.0943\ PI + 2.915\ ASPH + 22.16\ BINDER - 11.59\ HPR3$

$\beta = 0.118\ TI + 0.0389\ F/T - 0.701\ BINDER + 0.553\ HPR3$

Transverse

Area

$\rho = -1.739\ PI + 0.428\ ASPH + 48.88\ BINDER - 46.7\ HPR3$

$\beta = 0.0153\ F/T + 0.625\ HPR3$

Severity

$\rho = -0.502\ PI + 26.75\ BINDER - 29.96\ HPR3$

$\beta = 0.165\ TI + 0.0362\ F/T - 1.047\ BINDER + 1.1488\ HPR3$

TABLE 7. Regression Equations for Hot Mix Pavements

Rutting

Area $\rho = 0.2776\ HMAC + 0.0151\ HPR2$

$\beta = 0.0128\ TI + 0.0326\ T_{AVG} - 0.0331\ HMAC - 0.00382\ HPR2$

Severity $\rho = -0.00770\ PI + 0.386\ HMAC$

$\beta = -0.000720\ F/T + 0.0273\ T_{AVG} - 0.00267\ HMAC - 0.000418\ HPR2$

Alligator

Area $\rho = 0.372\ HMAC$

$\beta = 2.198\ HPR3$

Severity $\rho = -0.0000749\ PI + 0.291\ HMAC$

$\beta = 3.145\ HPR3$

Longitudinal

Area $\rho = -0.988\ F/T + 4.38\ T_{AVG} - 2.99\ PI + 7.21\ HMAC$

$\beta = 0.0422\ F/T + 0.359\ HPR3$

Severity $\rho = -0.144\ TI + 3.018\ T_{AVG} - 3.155\ PI + 8.331\ HMAC$

$\beta = 0.0343\ TI + 0.0502\ F/T$

Transverse

Area $\rho = -1.97\ TI - 0.826\ F/T + 5.193\ T_{AVG} - 1.768\ PI - 26.3\ HPR3$

$\beta = 0.017\ TI + 0.0433\ F/T - 0.115\ HMAC - 0.0159\ HPR2 + 0.259\ HPR3$

Severity $\rho = -0.196\ TI + 2.90\ T_{AVG} - 2.690\ PI + 5.475\ HMAC$

$\beta = 0.0519\ F/T + 0.537\ HPR3$

TABLE 8. Regression Equations for Overlaid Pavements

Rutting

Area

$$\rho = -0.00119\ PI + 0.369\ OVTH + 0.0485\ HPR2$$

$$\beta = 0.0059\ TI - 0.00217\ F/T + 0.0206\ T_{AVG} - 0.122\ OVTH + 0.0789\ HPR3$$

Severity

$$\rho = -0.00507\ PI + 0.233\ OVTH + 0.0705\ HPR2 - 0.000779\ HPR3$$

$$\beta = 0.00900\ TI + 0.0146\ T_{AVG} + 0.0024\ PI - 0.0789\ OVTH + 0.0840\ HPR3$$

Alligator

Area

$$\rho = -0.0159\ F/T + 0.00820\ T_{AVG} - 0.0121\ PI + 0.0162\ OVTH + 0.145\ HPR2 - 0.0135\ HPR3$$

$$\beta = 0.0185\ TI + 0.171\ HPR3$$

Severity

$$\rho = -0.00975\ F/T + 0.0152\ T_{AVG} - 0.0106\ PI + 0.0568\ HPR2 - 0.0315\ HPR3$$

$$\beta = 0.0301\ TI + 0.2267\ HPR3$$

Longitudinal

Area

$$\rho = -0.0168\ TI - 0.0870\ F/T + 1.63\ T_{AVG} - 0.179\ PI + 2.68\ OVTH + 0.840\ HPR2$$

$$\beta = 0.0331\ TI + 0.00433\ F/T - 0.00713\ T_{AVG} - 0.0589\ OVTH + 0.399\ HPR3$$

Severity

$$\rho = -0.214\ F/T + 1.55\ T_{AVG}$$

$$\beta = 0.0218\ TI + 0.0134\ F/T - 0.0156\ HPR2 + 0.073\ HPR3$$

Transverse

Area

$$\rho = -0.794\ F/T + 1.922\ T_{AVG} + 22.81\ OVTH$$

$$\beta = -0.0097\ TI + 0.0149\ F/T - 0.0229\ T_{AVG} + 0.0441\ PI - 0.129\ OVTH + 0.480\ HPR3$$

TABLE 8. Regression Equations for Overlaid Pavements (cont'd)

Transverse (cont'd)

Severity $\rho = -0.0627\ F/T + 1.23\ T_{AVG} + 5.273\ OVTH$

$\beta = 0.0187\ TI + 0.0117\ F/T + 0.0109\ PI - 0.0305\ HPR2 + 0.108\ HPR3$

TABLE 9. Design Parameters for PSI survivor curves

Black Base		
P_c	λ	γ
1.0	0.276	2.111
2.0	0.417	1.549
3.0	0.607	1.497
Hot Mix		
P_c	λ	γ
1.0	0.423	1.363
2.0	0.687	1.365
3.0	0.787	1.012
Overlays		
P_c	λ	γ
1.0	0.327	1.524
2.0	0.555	1.163
3.0	0.818	1.088

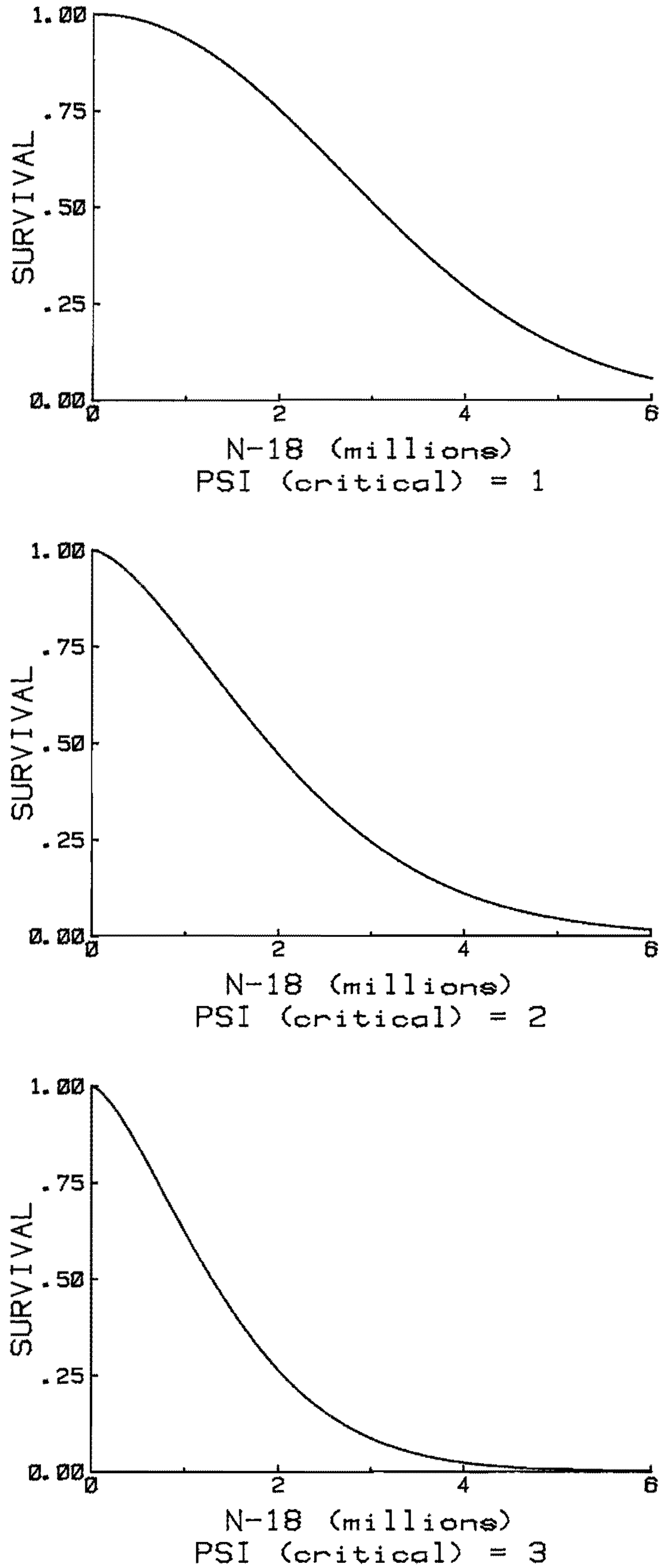

FIGURE 5. Black Base Survivor Curves as a Function of Critical PSI

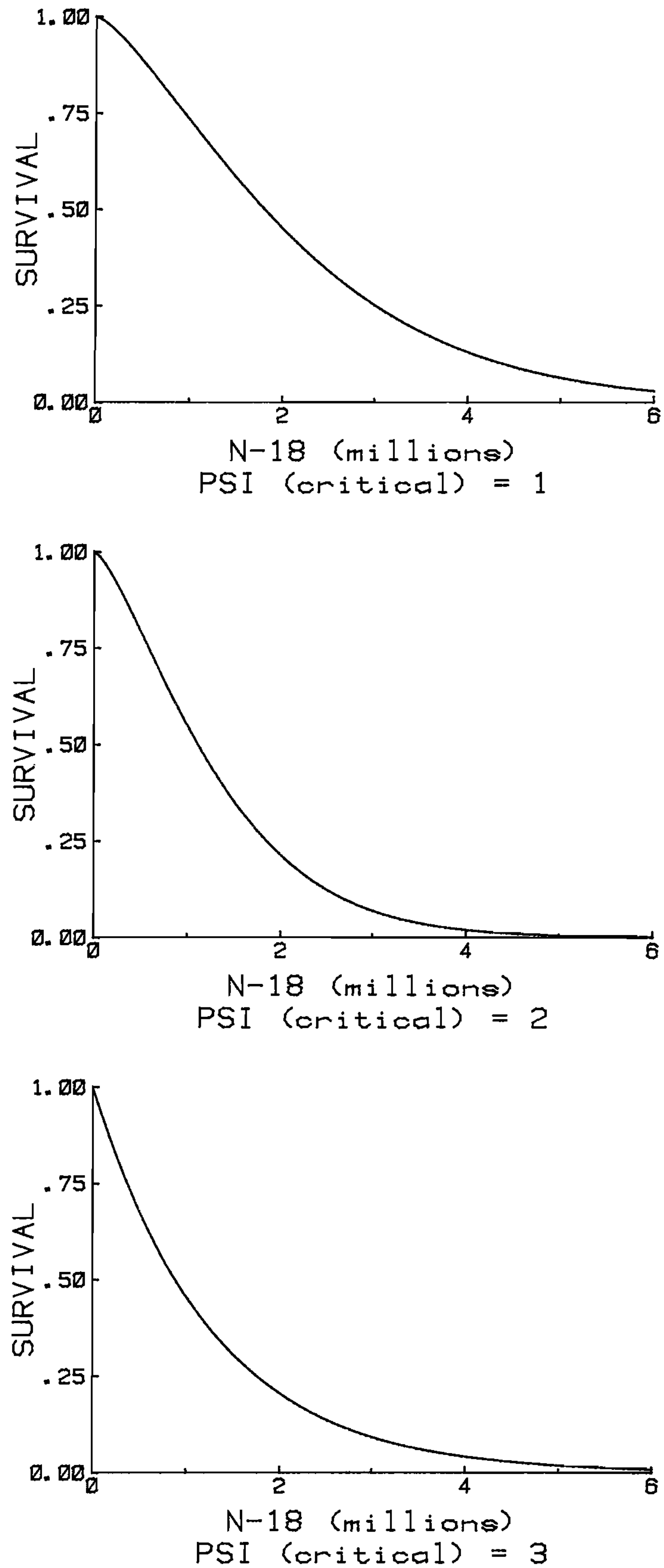

FIGURE 6. Hot Mix Survivor Curves as a Function of Critical PSI

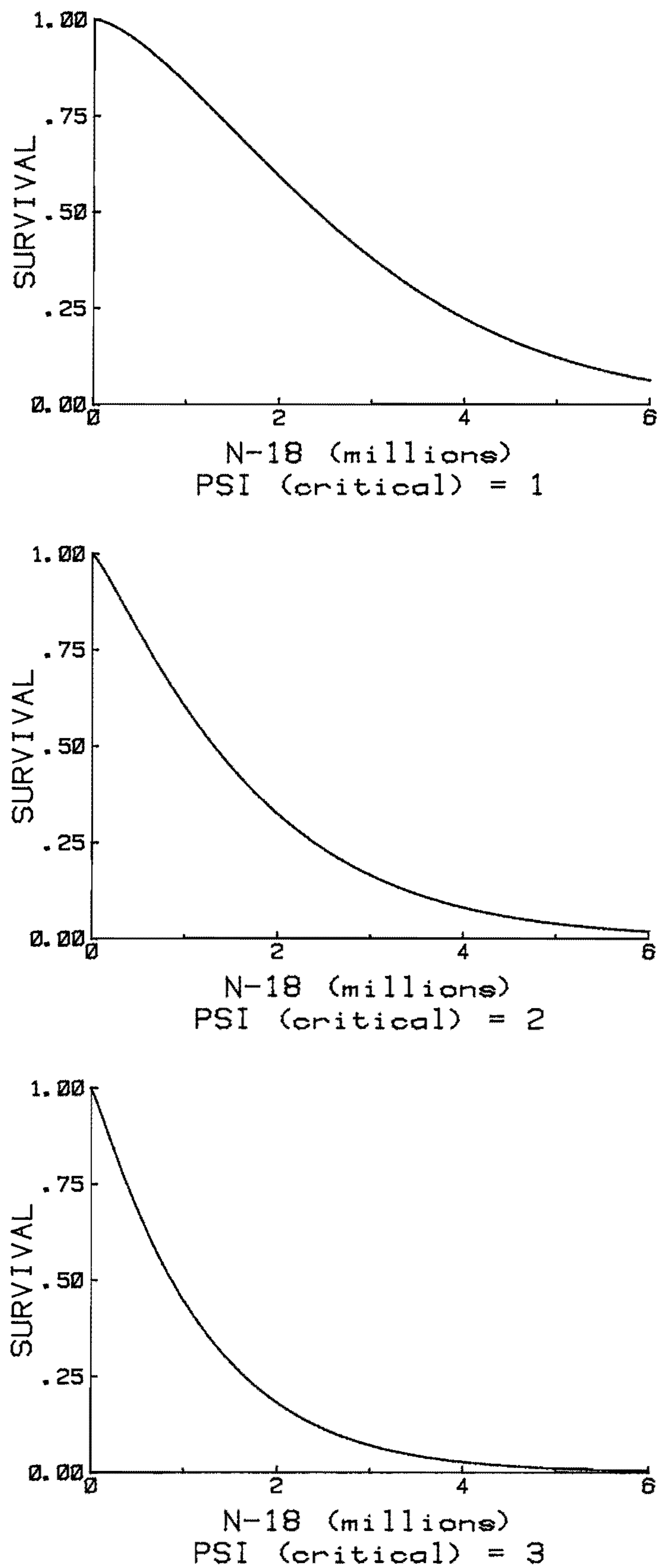

FIGURE 7. Overlay Survivor Curves as a Function of Critical PSI

TABLE 10. Design Parameters for Distress Survivor Curves

Black Base				
	g_c = 0.25		g_c = 0.50	
	λ	γ	λ	γ
Rutting				
Area	0.010	2.801	0.006	2.133
Severity	0.010	3.143	0.006	2.782
Alligator Cracking				
Area	0.006	3.065	0.003	2.129
Severity	0.007	4.380	0.004	2.681
Longitudinal Cracking				
Area	0.006	2.815	0.003	2.068
Severity	0.008	3.285	0.005	2.279
Transverse Cracking				
Area	0.006	2.760	0.003	1.878
Severity	0.008	3.382	0.004	2.443

TABLE 10. Design Parameters for Distress Survivor Curves (Cont'd)

	Hot Mix			
	$g_c = 0.25$		$g_c = 0.50$	
	λ	γ	λ	γ
Rutting				
Area	0.007	2.617	0.004	2.696
Severity	0.007	2.039	0.004	1.781
Alligator Cracking				
Area	0.006	3.304	0.004	3.343
Severity	0.007	3.227	0.005	2.610
Longitudinal Cracking				
Area	0.006	2.819	0.003	1.836
Severity	0.007	3.059	0.005	2.182
Transverse Cracking				
Area	0.006	2.111	0.004	1.696
Severity	0.008	2.551	0.005	2.129

TABLE 10. Design Parameters for Distress Survivor Curves (Cont'd)

Overlays				
	g_c = 0.25		g_c = 0.50	
	λ	γ	λ	γ
Rutting				
Area	0.009	1.604	0.004	1.219
Severity	0.010	1.819	0.005	1.804
Alligator Cracking				
Area	0.007	2.575	0.003	2.080
Severity	0.009	2.280	0.005	2.056
Longitudinal Cracking				
Area	0.008	1.519	0.004	1.197
Severity	0.011	1.919	0.006	1.693
Transverse Cracking				
Area	0.008	1.792	0.004	1.397
Severity	0.011	1.916	0.006	1.797

7. SENSITIVITY ANALYSIS

7.1 Introduction

The purpose of this section is to investigate the behavior of the performance equations after considering typical values of the design variables given in Table 3, section 6.2, and the effects of these variables on the design parameters, as determined by the regression models shown in Tables 4 through 8. This analysis was conducted using the modified version of the FPS subroutine "Time." This subroutine incorporates both the arithmetic and logarithmic regression models for PSI and distress (area and severity); in addition, it includes subroutine "Russian" for the calculation of H' (see Table 3, section 6.2).

7.2 Sensitivity Analysis for PSI and Distress Models

The effect of Thornthwaite Index (TI), number of freeze/thaw cycles (F/T), and average annual temperature (T_{AVG}), were considered for four scenarios. These scenarios correspond to District 1, District 4, District 17 and District 21. The values of the design variables under consideration are given below:

District 1:

Thornthwaite Index	44
Freeze/thaw cycles	35
Average annual temperature	63

District 4:

Thornthwaite Index	-20

Freeze/thaw cycles	82
Average annual temperature	58

District 17:

Thornthwaite Index	2
Freeze/thaw cycles	30
Average annual temperature	67

District 21:

Thornthwaite Index	-35
Freeze/thaw cycles	10
Average annual temperature	70

For all of the four Districts, the following variables were set at the values shown below:

Plasticity index (PI)	20.0
Percent Asphalt binder (Binder)	5.0
Traffic per month (N-18)	12,500

The pavement structure for each of the three pavement types is shown in Figure 8. The following layer elastic moduli were used in the analysis:

HMAC	- 500,000 psi
Overlay	- 500,000 psi
Black Base	- 400,000 psi
Flexible Base	- 70,000 psi
Lime Stabilized Subbase	- 50,000 psi
Subgrade	- 20,000 psi

The equivalent pavement thickness (H') is essentially the same

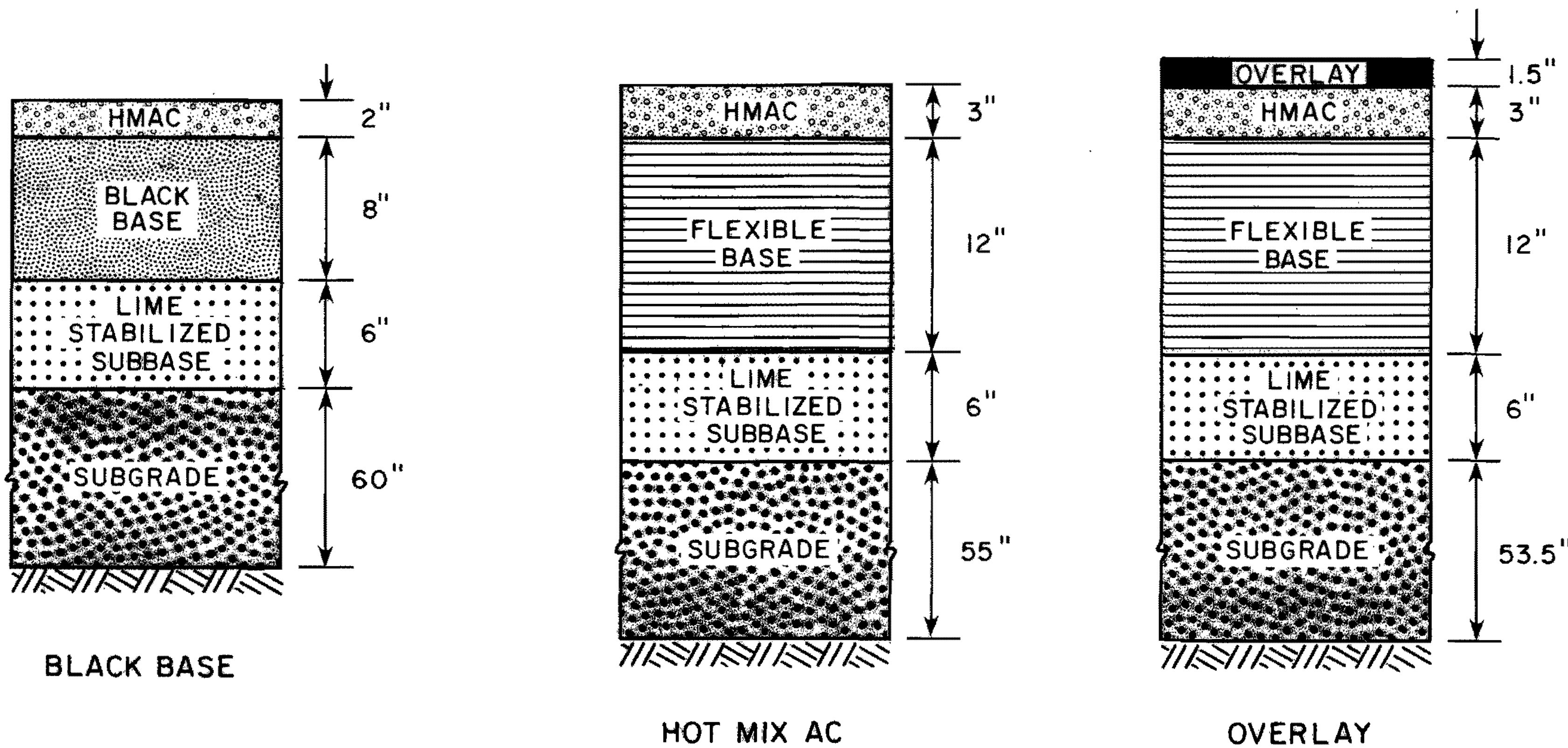

FIGURE 8. Pavement Types Used for Sensitivity Analysis

for each pavement type, with an average value of 102 in. The predicted functional performance as determined by district for the Black Base, Hot Mix, and Overlaid pavements are shown in Figures 9, 10, and 11, respectively.

A complete listing of pavement performance by district for both PSI and distress (area and severity) are given in Appendix 5. The climate associated with each district can be described as follows:

District 1 - Wet, some freeze/thaw

District 4 - Dry, many freeze/thaw

District 17 - Wet, few freeze/thaw

District 21 - Dry, no freeze/thaw

It should be noted that the figures in Appendix 5 primarily represent arithmetic models, as these had the higher correlation coefficient (r^2); however, under certain combinations of the design variable, it is possible to obtain negative design parameters. Should this occur, the program defaults to the logarithmic models which assure positive coefficients.

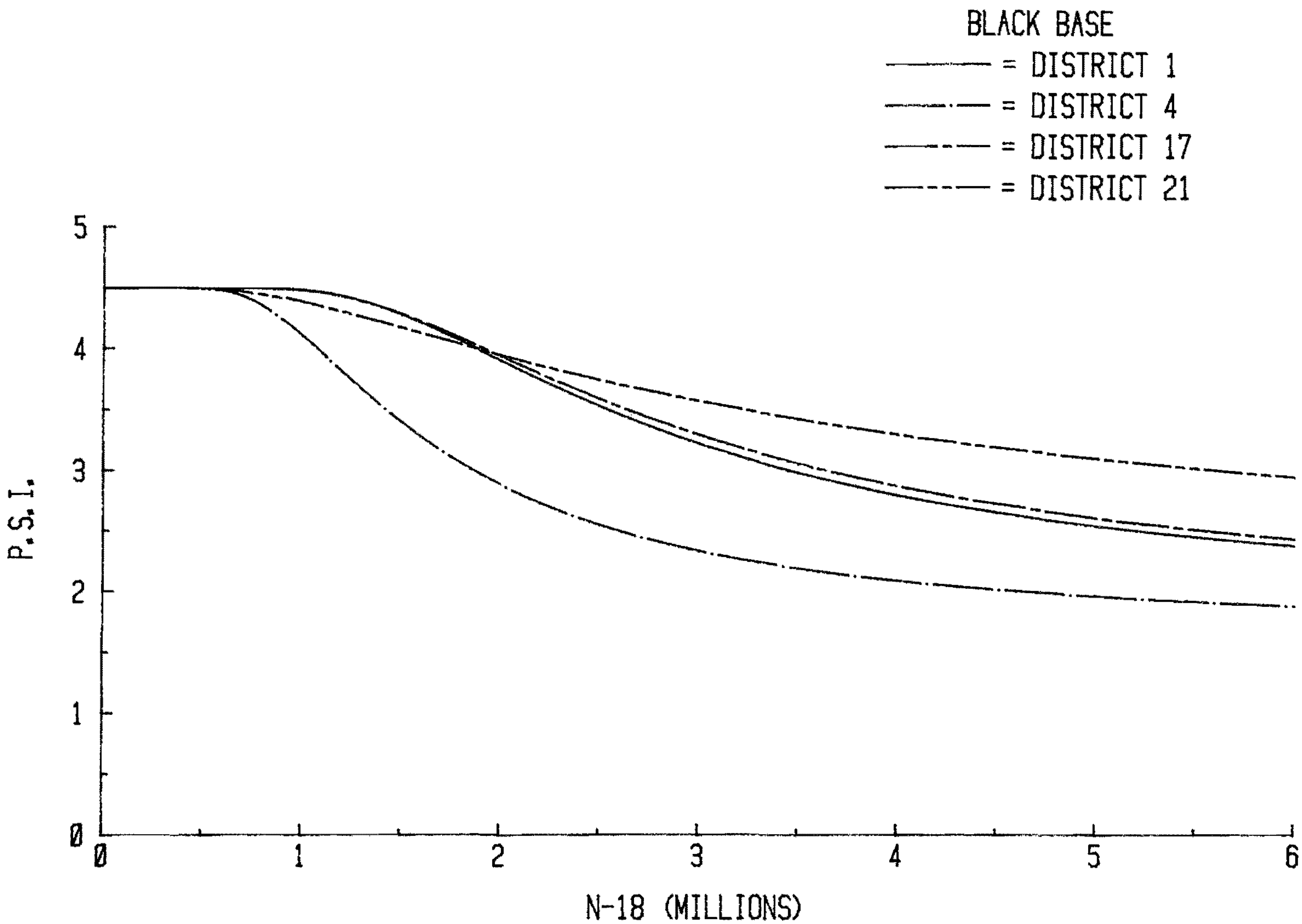

FIGURE 9. PSI Sensitivity Results for Black Base Pavements

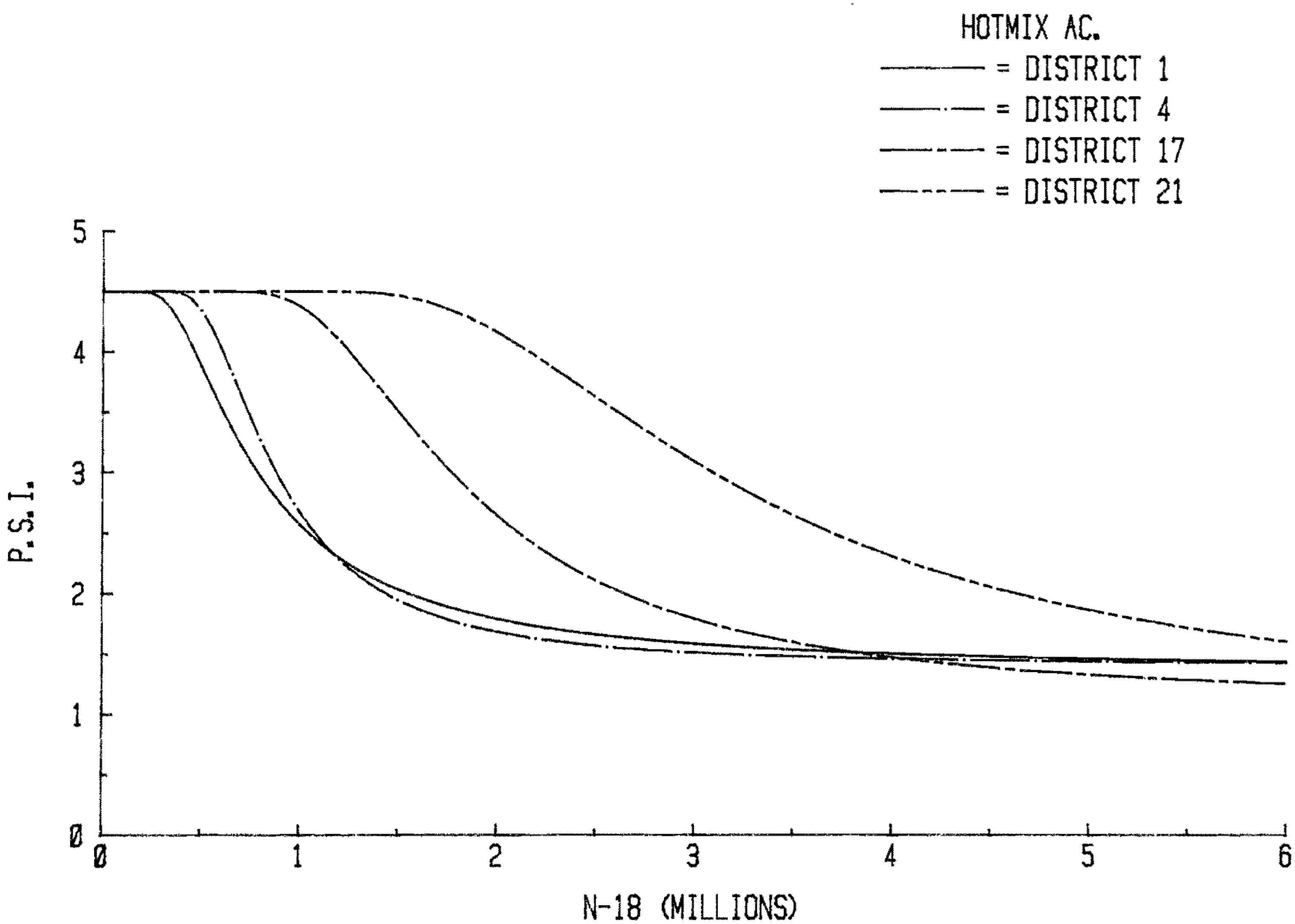

FIGURE 10. PSI Sensitivity Results for Hot Mix AC Pavements

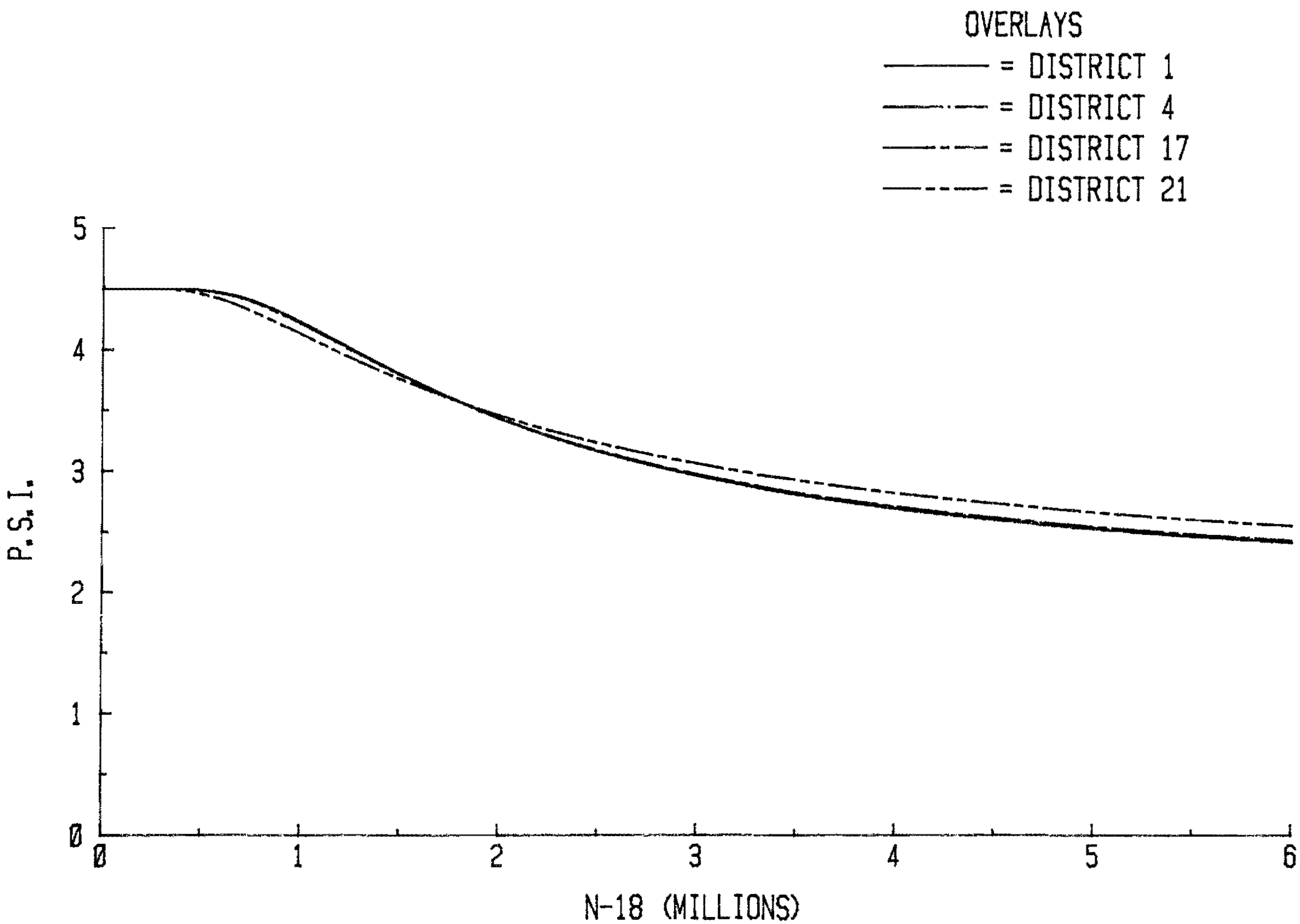

FIGURE 11. PSI Sensitivity Results for Overlay Pavements

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APPENDIX 1

DATA FOR PERFORMANCE ANALYSIS

Test Section Number	YEAR 73		74		75		76		77		80	
	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}
306	4.32	.56	4.52	.89	4.24	1.17	4.50	1.47	4.06	1.82	4.16	3.06
1556	3.83	.49	3.61	.92	3.24	1.21	3.51	1.44	3.36	1.74	3.57	2.64
1572	--	--	3.92	.95	4.01	1.31	4.03	1.68	3.99	2.11	3.84	4.12
1603	--	--	--	--	3.01	.79	2.99	.90	3.57	1.05	3.58	1.53
1690	3.79	.02	3.79	.25	3.56	.45	3.83	.59	3.87	.78	3.70	1.57
2251	4.02	.33	4.28	.86	4.31	1.31	4.54	1.85	4.39	2.47	3.85	4.04
2455	--	--	4.73	.05	--	--	4.82	.55	4.35	.91	4.39	2.10
2515	3.99	.30	4.02	.32	3.79	.38	3.68	.46	3.46	.52	--	--
2528	4.15	.37	4.26	.40	4.07	.49	--	--	3.84	.74	3.05	1.09
2531	4.26	.29	4.32	.30	4.34	.39	4.55	.52	4.43	.61	4.08	.96
2544	4.24	.59	4.49	.61	4.27	.77	4.48	1.02	--	--	3.66	1.92
2560	4.11	.85	3.89	.88	3.89	1.07	4.09	1.36	3.83	1.59	3.51	2.36
2573	4.56	.03	4.50	.05	4.41	.12	--	--	4.41	.30	4.30	.51
2586	4.54	.08	4.50	.11	4.50	.20	--	--	4.03	.47	3.99	.90
2599	4.16	.13	4.23	.15	4.07	.20	4.30	.29	4.25	.36	3.64	.56
2604	4.47	.46	4.46	.50	4.26	.77	4.56	1.25	4.25	1.59	4.47	3.07
2617	4.48	.08	--	--	4.44	.21	--	--	3.97	.49	3.74	.92
2633	4.35	.27	--	--	4.30	.56	4.40	.92	4.05	1.20	3.92	2.20
2646	3.98	.34	--	--	3.72	.50	3.78	.69	3.70	.83	--	--
2662	4.04	.71	--	--	4.23	.89	--	--	4.13	1.24	3.72	1.77
2824	--	--	4.21	.02	4.08	.03	4.12	.04	3.88	.05	3.46	.08
2837	4.21	.01	--	--	4.30	.01	4.49	.03	4.21	.04	3.76	.06
2840	3.45	.36	3.07	.37	3.25	.42	2.86	.49	3.03	.55	2.45	.70
2853	4.10	.19	4.25	.20	4.22	.27	2.38	.36	2.76	.43	3.34	.63

Test Section Number	YEAR 73 PSI	73 N_{18}	74 PSI	74 N_{18}	75 PSI	75 N_{18}	76 PSI	76 N_{18}	77 PSI	77 N_{18}	80 PSI	80 N_{18}
2866	4.47	.44	4.36	.46	4.31	.60	4.55	.83	4.19	1.01	2.70	1.60
2879	2.74	1.29	--	--	--	--	.87	1.74	1.13	1.95	--	--
2882	4.43	.37	4.40	.40	4.29	.54	--	--	3.85	.99	3.09	1.65
2895	4.31	.01	4.29	.01	--	--	--	--	4.19	.03	4.01	.06
2913	--	--	--	--	3.94	1.10	3.91	1.34	3.51	1.55	1.99	2.21
2926	--	--	--	--	--	--	4.52	1.06	4.33	1.26	3.69	1.86
2939	4.25	.74	4.29	.83	4.22	.95	--	--	3.57	1.28	--	--
2942	--	--	4.52	.80	4.52	.95	4.23	1.19	3.67	1.38	2.90	2.05
2955	--	--	4.62	.61	4.74	.75	4.71	.98	4.31	1.17	3.23	1.74
2968	--	--	--	--	--	--	4.47	1.77	3.89	1.98	3.37	2.57
3176	--	--	--	--	4.51	.54	4.48	.58	4.40	.68	3.73	.99
3189	--	--	3.57	.26	3.31	.37	3.24	.40	--	--	3.18	.66
3192	--	--	3.86	.30	3.83	.44	3.80	.48	--	--	3.51	.92
3207	--	--	3.81	.35	3.88	.46	3.80	.50	4.06	.58	--	--
3210	--	--	4.76	.16	4.70	.27	--	--	4.60	.39	4.08	.66
3223	--	--	--	--	3.92	.23	3.88	.26	--	--	3.38	.47
3236	--	--	3.53	.19	3.35	.27	--	--	--	.37	3.09	.50
3249	--	--	3.95	.57	--	--	3.89	.79	--	--	3.50	1.25
3281	--	--	--	--	4.41	.27	4.13	.31	4.40	.38	4.32	.66
3294	3.80	.16	--	--	3.93	.28	--	--	3.75	.35	3.66	.54
3309	3.79	.32	--	--	3.89	.57	4.00	.64	4.04	.74	3.76	1.17
3312	3.56	.14	--	--	--	--	--	--	3.32	1.20	2.65	2.28
3325	4.04	.42	--	--	3.99	1.42	3.94	1.73	3.84	2.17	3.43	4.20
3338	4.06	.42	--	--	--	--	3.86	1.68	3.82	2.12	3.59	3.86

YEAR

Test Section Number	73		74		75		76		77		80	
	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}
3341	--	--	--	--	3.52	.80	3.45	.91	3.46	1.06	3.49	1.54
3354	4.16	.86	--	--	4.21	1.32	4.57	1.44	4.33	1.65	4.60	2.41
3367	3.94	.79	--	--	4.12	1.28	4.35	1.41	4.06	1.65	4.35	2.42

YEAR

Test Section Number	73		74		75		76		77		80	
	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}
102	3.64	.35	3.55	.43	3.65	.49	3.68	.55	3.83	.67	3.25	.87
217	3.12	.67	3.06	.81	--	--	--	--	--	--	--	--
408	4.12	.65	4.33	.73	4.21	.79	4.46	.85	4.32	.93	4.09	1.20
437	3.80	1.95	--	--	--	--	--	--	3.80	2.69	--	--
479	3.31	.50	3.64	.56	3.12	.61	2.89	.66	3.05	.72	2.97	.91
500	--	--	--	--	--	--	3.93	2.27	3.69	2.53	--	--
513	3.06	1.41	3.07	1.62	2.64	1.71	--	--	2.99	2.15	--	--
615	--	--	4.77	.37	4.60	.48	4.80	.60	4.73	.72	4.49	1.18
673	3.79	.26	3.76	.28	3.84	.29	3.82	.31	--	--	3.58	.38
775	--	--	--	--	--	--	--	--	--	--	--	--
791	--	--	--	--	--	--	4.06	1.20	3.87	1.30	3.61	1.58
1145	3.72	.53	--	--	2.59	.83	2.23	.97	2.74	1.14	2.52	1.68
1276	--	--	3.66	.61	--	--	3.63	.73	3.68	.80	3.29	1.06
1292	--	--	4.27	.16	4.00	.24	4.25	.30	4.25	.39	2.86	.83
1687	3.79	1.44	--	--	3.53	2.11	--	--	4.13	2.62	3.71	3.86
1747	3.58	.06	3.31	.09	2.86	.11	2.76	.13	3.16	.15	2.33	.23
1878	3.44	.04	3.26	.05	3.14	.06	--	--	--	--	2.67	.11
1909	3.30	.34	3.17	.45	--	--	3.01	.60	--	--	2.85	1.11
1925	3.36	.43	--	--	3.39	.69	4.06	.82	3.61	1.00	2.71	1.56
2099	3.68	.15	3.39	.19	--	--	3.58	.28	3.50	.33	3.62	.51
2191	--	--	--	--	--	--	--	--	--	--	--	--
2206	3.74	.11	3.44	.14	3.66	.17	3.85	.19	3.61	.21	3.88	.32
2219	3.80	.17	3.83	.20	3.36	.25	3.77	.28	3.50	.33	3.80	.50
2675	--	--	2.85	1.10	2.63	1.29	--	--	2.59	1.79	1.75	2.67

Test Section Number	YEAR 73		74		75		76		77		80	
	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}
2691	--	--	4.13	1.13	4.27	1.32	4.54	1.61	4.19	1.84	3.70	2.57
2719	--	--	--	--	--	--	--	--	--	--	--	--
2722	--	--	--	--	--	--	--	--	--	--	--	--
2735	--	--	--	--	--	--	--	--	--	--	--	--
2748	--	--	4.61	.89	4.51	1.03	4.54	1.20	--	--	4.06	1.78
2751	--	--	4.71	.68	4.63	.79	4.69	.95	4.58	1.07	4.47	1.50
2764	--	--	4.54	.68	4.64	.79	4.29	.95	3.87	1.07	3.50	1.50
2777	--	--	4.16	1.08	4.23	1.26	4.63	1.54	4.24	1.76	3.72	2.51
2793	--	--	4.21	1.55	4.24	1.71	4.20	1.97	4.17	2.15	--	--
2971	--	--	3.37	.75	3.26	.80	2.51	.89	2.76	.96	2.29	1.15
2997	--	--	3.50	.62	3.02	.67	2.62	.75	2.95	.80	2.40	.96
3003	--	--	--	--	3.56	.17	2.96	.20	3.01	.23	2.29	.31
3016	--	--	4.43	.10	4.22	.12	4.39	.16	4.16	.18	4.06	.26
3029	--	--	--	--	4.22	1.19	4.10	1.29	3.89	1.36	2.10	1.56
3087	--	--	3.48	.73	3.72	.85	3.56	1.06	3.52	1.21	3.38	1.77
3090	--	--	--	--	--	--	--	--	--	--	--	--
3105	--	--	3.22	.33	3.34	.35	3.05	.39	3.44	.40	3.07	.48
3121	--	--	4.22	.01	4.31	.02	--	--	4.04	.04	3.93	.06

YEAR

Test Section Number	73		74		75		76		77		80	
	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}
13	3.35	1.36	3.38	1.52	3.42	1.65	3.36	1.78	3.50	1.93	3.18	2.35
39	--	--	3.44	2.26	--	--	3.45	2.91	3.30	3.35	2.66	4.60
71	3.56	.38	3.58	.60	3.60	.82	3.59	1.04	3.62	1.30	3.07	2.10
160	3.95	.38	4.00	.51	3.84	.60	4.01	.70	4.02	.84	3.83	1.17
186	--	--	--	--	--	--	4.06	1.53	4.27	1.95	3.20	2.75
199	--	--	--	--	--	--	4.20	.09	4.07	.41	4.12	1.02
220	4.05	.87	4.01	.93	3.97	.97	3.96	1.01	--	--	--	--
233	--	--	2.78	.20	2.79	.21	2.16	.23	2.80	.25	2.90	.29
246	3.98	.24	4.03	.38	4.05	.50	4.09	.60	3.87	.77	3.92	1.19
259	3.48	.04	3.30	.05	3.14	.06	3.32	.07	3.54	.09	3.31	.13
288	--	--	3.14	.59	2.91	.62	3.00	.65	3.24	.69	3.03	.82
291	--	--	3.84	.03	3.74	.04	--	--	3.66	.05	3.59	.06
319	--	--	4.48	.26	--	--	4.64	.56	4.26	.75	4.06	1.46
335	--	--	--	--	--	--	4.61	.04	4.29	.23	4.07	.81
351	--	--	--	--	4.06	.02	4.36	.06	3.99	.10	4.00	.27
393	--	--	4.23	.26	4.02	.52	3.96	.79	3.79	1.12	--	--
424	4.36	.07	4.57	.17	--	--	4.50	.35	4.23	.46	4.31	.81
555	2.33	1.71	2.48	1.81	2.48	1.98	2.26	2.17	2.94	2.36	2.76	3.05
602	4.40	.12	4.38	1.00	4.05	1.70	4.22	2.43	--	--	--	--
657	--	--	4.26	.04	4.18	.09	4.48	.13	4.30	.18	4.03	.35
660	4.50	.17	4.58	.21	4.60	.25	4.79	.28	4.49	.32	4.57	.46
759	3.23	.39	--	--	3.29	.46	3.35	.51	3.45	.54	3.12	.69
848	--	--	4.50	.47	4.40	1.00	4.81	1.57	4.34	2.22	3.76	4.12
877	--	--	3.40	.32	3.31	.37	3.66	.42	3.63	.48	2.97	.65

Test Section Number	YEAR 73		74		75		76		77		80	
	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}
893	--	--	4.60	.40	4.32	.83	4.47	1.29	3.94	1.78	2.74	3.52
924	4.11	2.34	4.39	2.96	4.06	3.40	4.12	3.91	4.23	4.74	3.70	6.16
937	4.21	.08	4.42	.25	4.26	.36	4.51	.47	4.35	.66	3.87	1-03
953	3.85	.13	4.06	.22	3.83	.28	3.95	.34	4.19	.45	2.59	.62
966	--	--	4.53	.04	4.58	.12	4.31	.18	4.46	.31	3.60	.51
995	--	--	--	--	4.87	.59	4.66	.76	4.62	1.41	4.08	2.71
1001	3.65	.37	3.84	.46	3.45	.53	3.39	.59	3.54	.70	--	--
1043	3.41	2.11	--	--	3.19	2.72	3.29	3.01	3.14	3.39	2.54	4.42
1072	2.98	.03	3.28	.03	3.30	.04	3.18	.04	--	--	2.77	.07
1174	--	--	--	--	4.13	.10	4.40	.27	4.05	.49	3.39	1.18
1190	3.57	.64	2.63	.76	3.14	.89	3.10	.95	3.32	1.06	2.54	1.45
1218	2.31	.56	2.78	.66	2.21	.72	2.09	.76	2.94	.83	1.99	1.04
1234	4.29	.28	4.32	.50	4.50	.68	4.31	.80	4.01	.96	3.47	1.70
1250	4.32	.84	4.21	1.42	4.30	1.91	4.46	2.26	4.18	2.75	4.14	5.19
1263	--	--	4.43	.21	4.50	.40	4.72	.53	4.38	.73	4.13	1.51
1289	4.04	.47	4.14	1.06	3.91	1.61	4.05	1.98	3.83	2.51	--	--
1307	4.04	.16	4.28	.20	--	--	4.21	.26	3.99	.30	3.48	.45
1323	3.75	1.53	3.62	1.92	3.60	2.32	3.37	2.45	3.17	2.77	--	--
1349	3.22	.51	3.02	.56	3.09	.60	3.20	.62	3.11	.66	2.99	.80
1365	--	--	4.17	.07	4.04	.14	4.35	.19	4.12	.26	3.66	.67
1412	--	--	--	--	--	--	--	--	--	--	--	--
1438	3.41	.12	3.62	.15	3.74	.17	4.12	.19	3.90	.21	3.60	.31
1543	3.46	2.75	3.30	3.92	3.08	4.71	3.17	5.40	3.20	6.31	--	--
1632	--	--	--	--	--	--	--	--	--	--	--	--

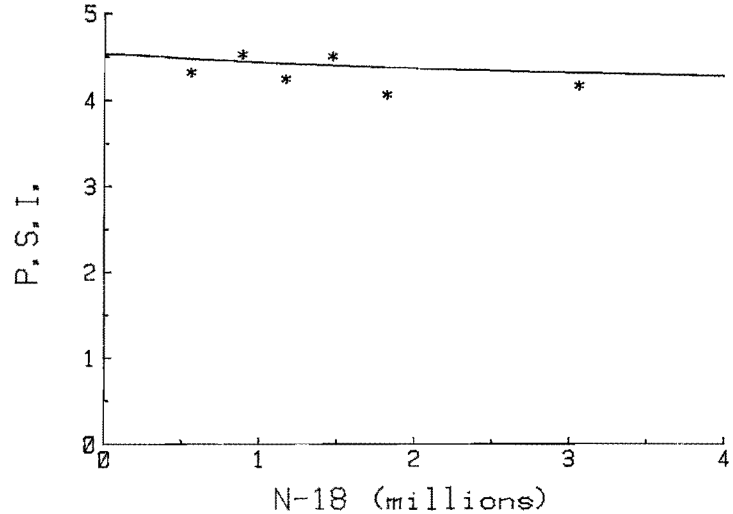
YEAR

Test Section Number	73		74		75		76		77		80	
	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}
1674	3.60	.26	3.56	.46	3.17	.60	3.58	.69	--	--	2.87	1.41
1734	--	--	--	--	--	--	--	--	--	--	--	--
1750	3.31	.37	3.34	.46	3.03	.53	3.56	.57	3.16	.67	3.47	.90
1776	3.50	.36	3.67	.42	3.22	.49	3.10	.51	--	--	--	--
1836	4.04	.40	4.24	.54	4.09	.61	4.34	.71	4.36	.90	4.26	1.29
1852	--	--	--	--	2.92	.05	2.94	.08	3.39	.13	2.94	.25
1865	3.86	.20	3.86	.28	3.57	.35	3.90	.39	--	--	2.84	.61
1894	3.47	.48	3.35	.98	3.28	1.37	3.36	1.70	3.01	2.48	2.74	4.00
1941	3.67	1.07	--	--	3.23	1.20	3.94	1.26	3.90	1.35	3.39	1.58
1967	--	--	--	--	--	--	--	--	--	--	--	--
1983	3.52	1.48	--	--	3.56	1.90	3.78	2.10	3.53	2.36	2.73	3.20
2002	--	--	--	--	4.59	.24	4.71	.61	4.42	1.22	3.91	3.46
2015	3.65	.10	3.52	.30	3.50	.47	3.28	.56	--	--	2.98	1.34
2044	3.58	.68	--	--	3.23	.93	3.20	.99	--	--	--	--
2060	--	--	--	--	3.73	.64	3.76	.69	3.82	.78	3.32	1.10
2120	3.11	.03	--	--	--	--	3.79	.08	3.37	.10	3.31	.17
2133	3.80	.22	--	--	--	--	3.36	.40	3.41	.47	3.34	.71
2159	--	--	--	--	3.95	.07	4.10	.11	3.50	.19	3.91	.44
2308	--	--	--	--	--	--	--	--	--	--	--	--
2324	4.36	1.78	--	--	--	--	4.36	3.57	3.98	4.21	3.45	6.57
2337	--	--	3.88	.01	--	--	3.86	.01	3.92	.01	3.72	.02
2353	3.63	.40	3.46	.47	3.52	.52	3.36	.58	3.30	.64	2.80	.83
2468	--	--	--	--	4.49	.15	4.74	.33	4.26	.52	4.09	1.12
2502	4.33	.19	4.58	.22	4.58	.35	4.76	.54	4.57	.68	4.26	1.17

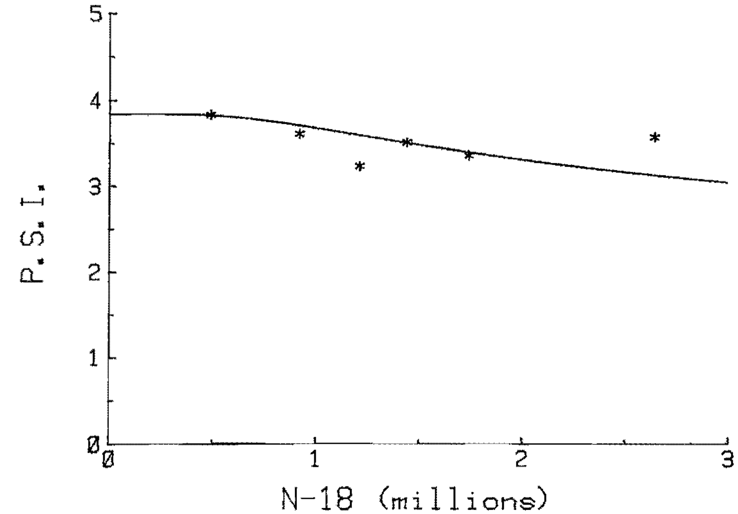
YEAR

Test Section Number	73		74		75		76		77		80	
	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}	PSI	N_{18}
2620	4.38	.41	4.47	.46	4.39	.75	4.76	1.19	4.30	1.50	4.14	2.70
2659	3.91	.33	--	--	3.56	.49	3.21	.67	3.40	.81	--	--
2808	--	--	--	--	--	--	4.66	.16	4.34	.27	4.49	.65
2811	--	--	--	--	--	--	4.73	.16	4.34	.27	4.49	.65
2984	--	--	1.99	.66	2.06	.71	.91	.79	1.72	.85	--	--
3061	--	--	2.47	.50	2.73	.54	1.78	.59	2.56	.63	2.24	.75
3074	--	--	3.35	.23	3.49	.26	3.10	.30	3.17	.34	3.26	.46
3147	--	--	4.15	.12	3.93	.27	3.86	.52	3.46	.73	3.67	1.35
3150	--	--	4.38	.07	4.41	.09	4.31	.11	3.93	.14	3.75	.21
3163	--	--	4.47	.04	4.50	.05	4.51	.06	3.90	.07	3.80	.11

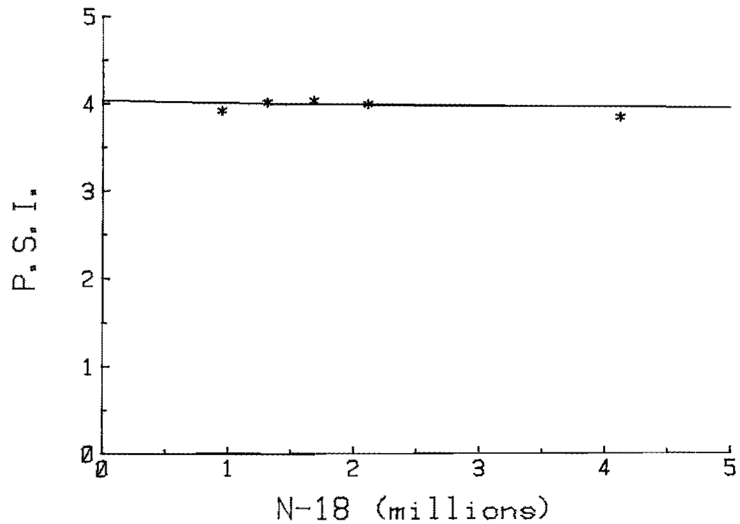
APPENDIX 2
PSI-PERFORMANCE CURVES



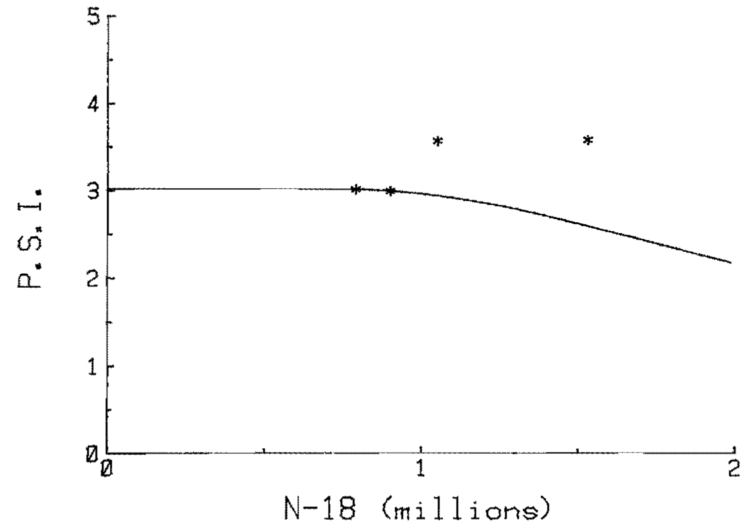
SECTION 3Ø6



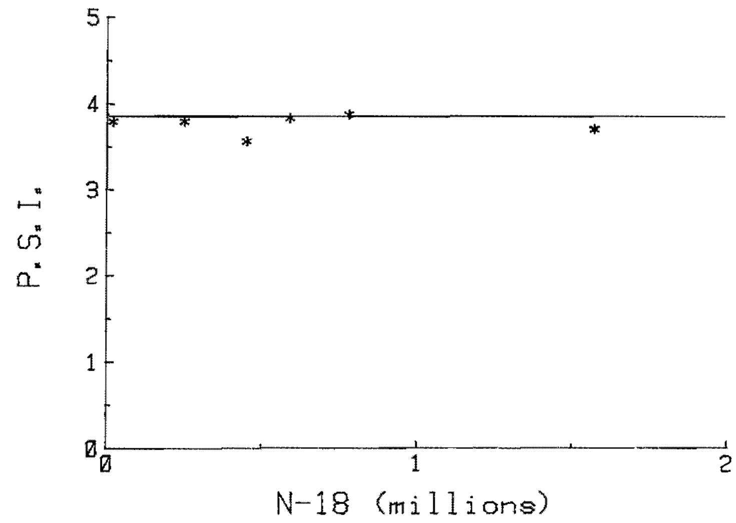
SECTION 1556



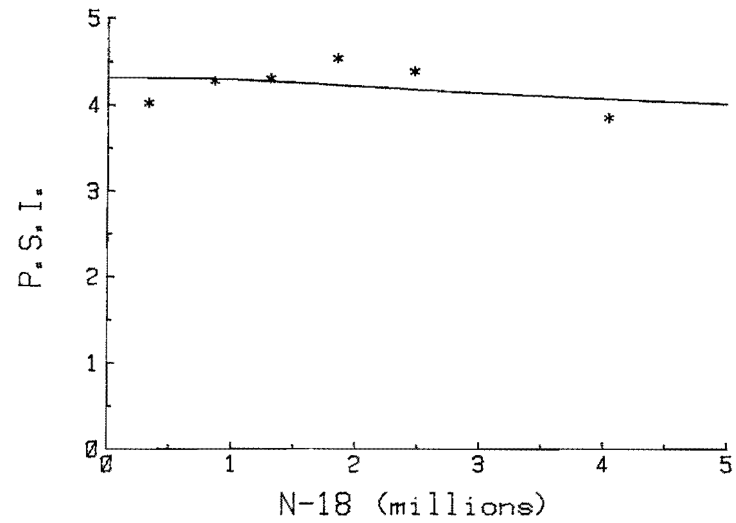
SECTION 1572



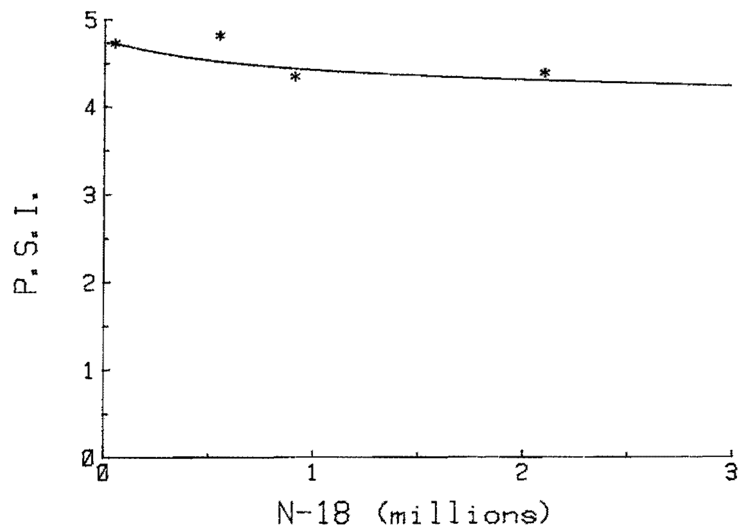
SECTION 16Ø3



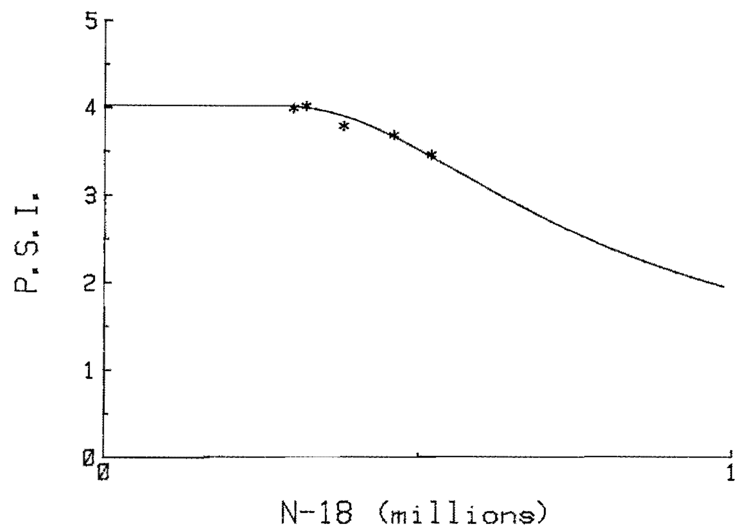
SECTION 169Ø



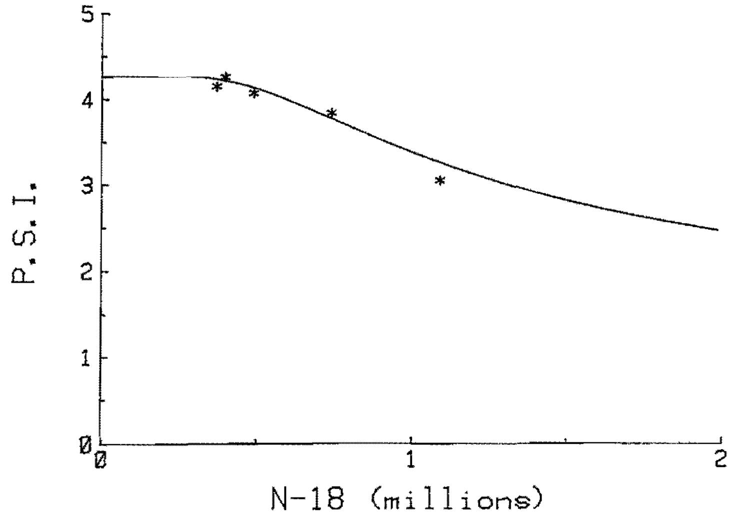
SECTION 2251



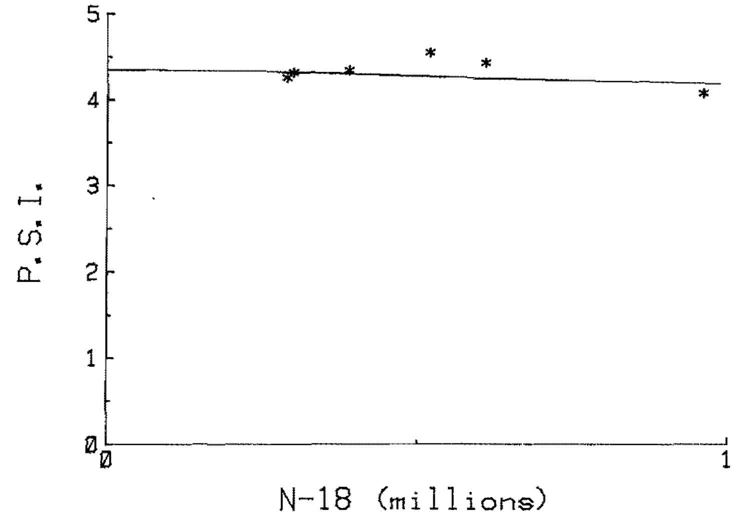
SECTION 2455



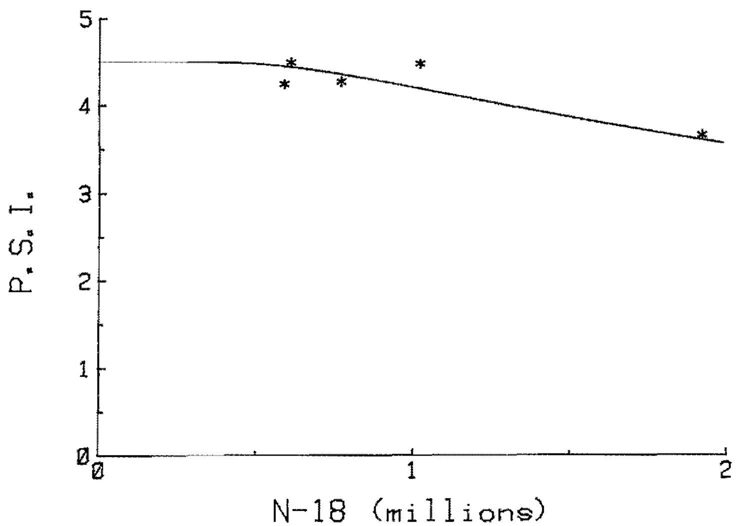
SECTION 2515



SECTION 2528



SECTION 2531



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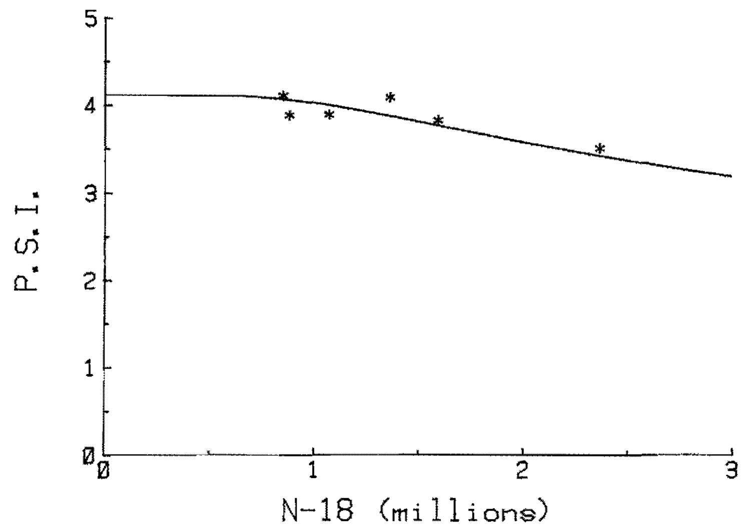

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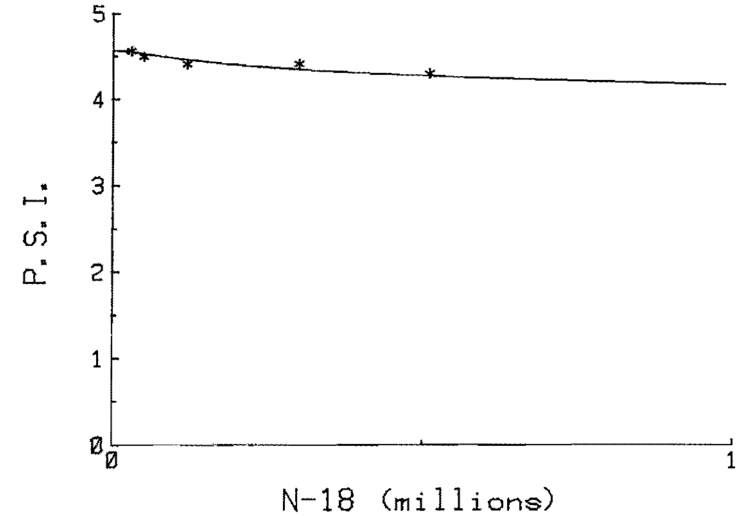

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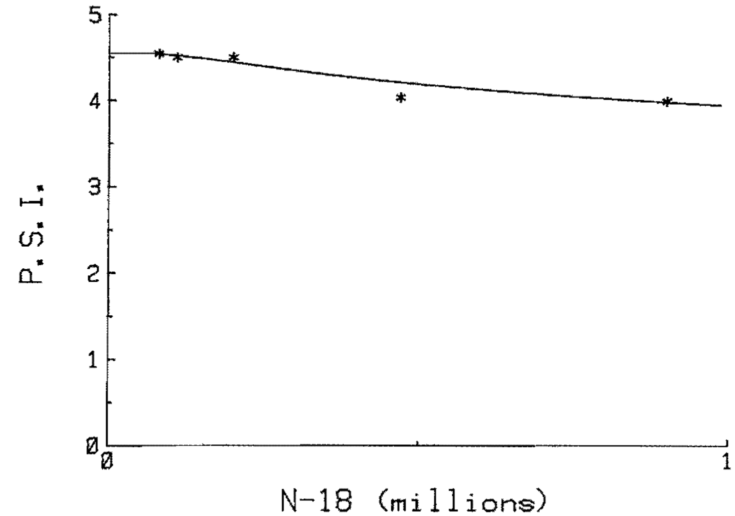

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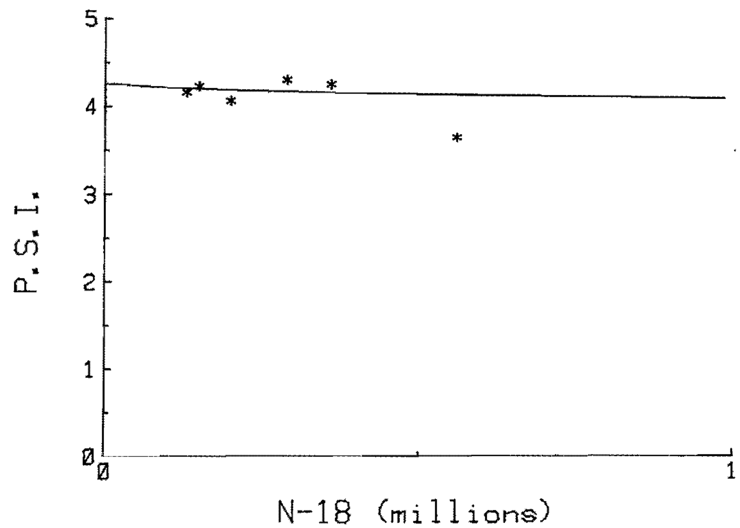

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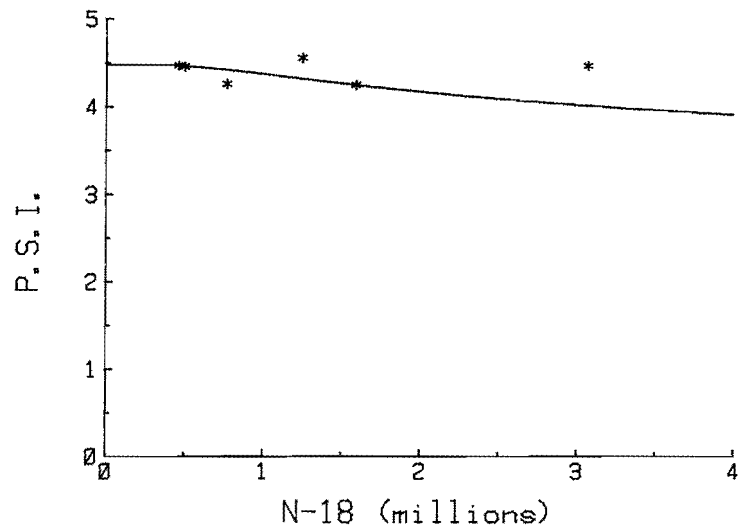

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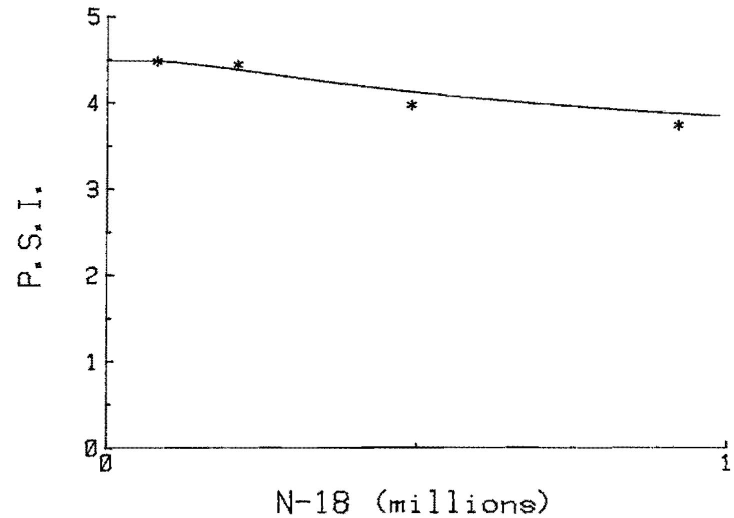

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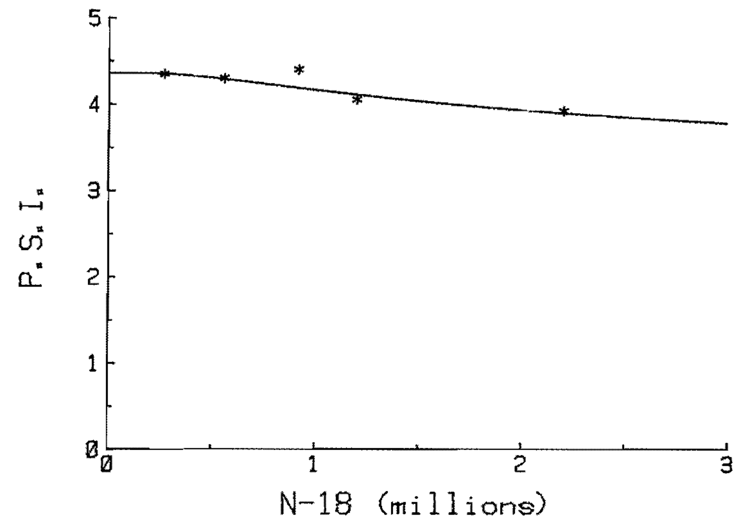

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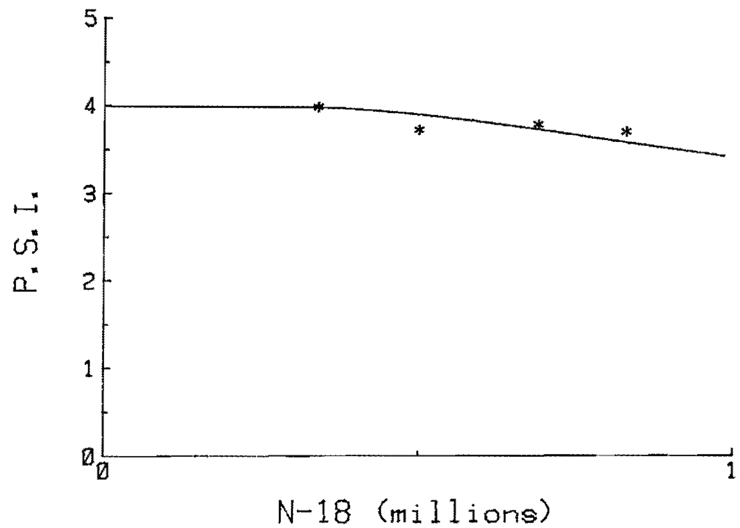

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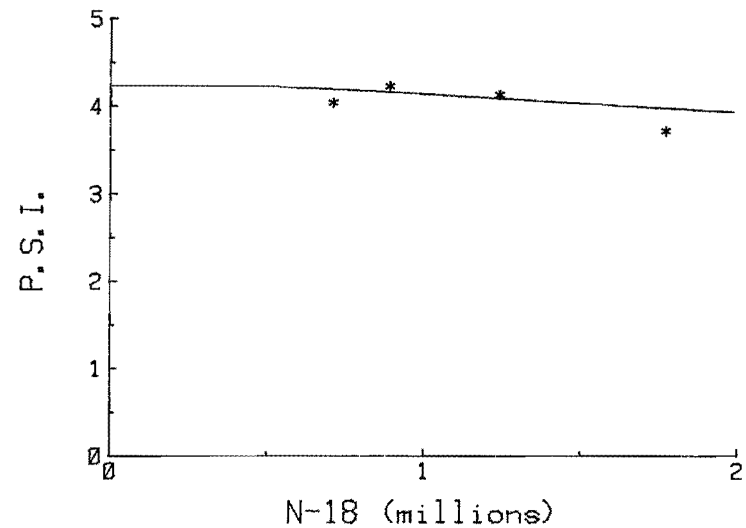

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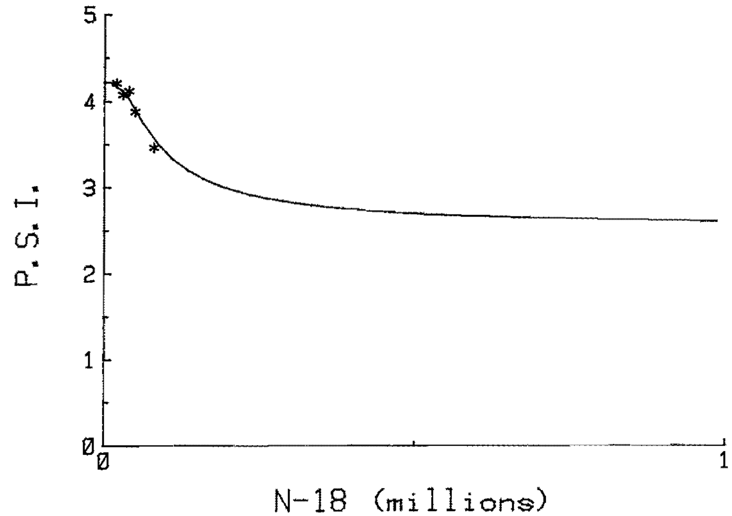

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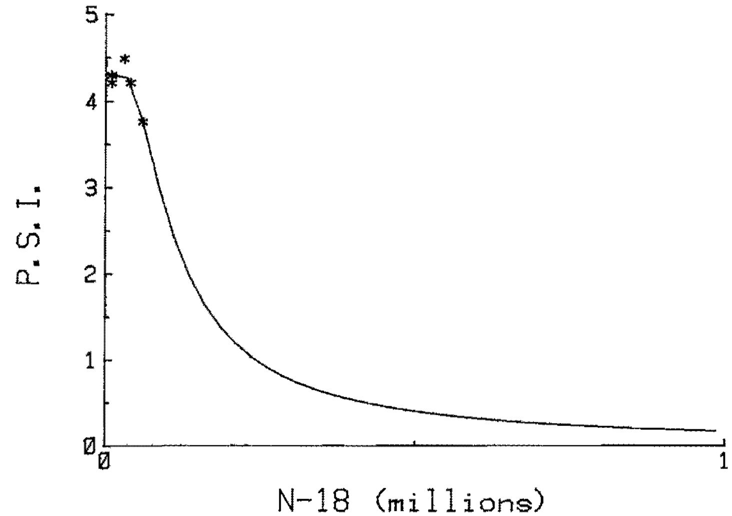

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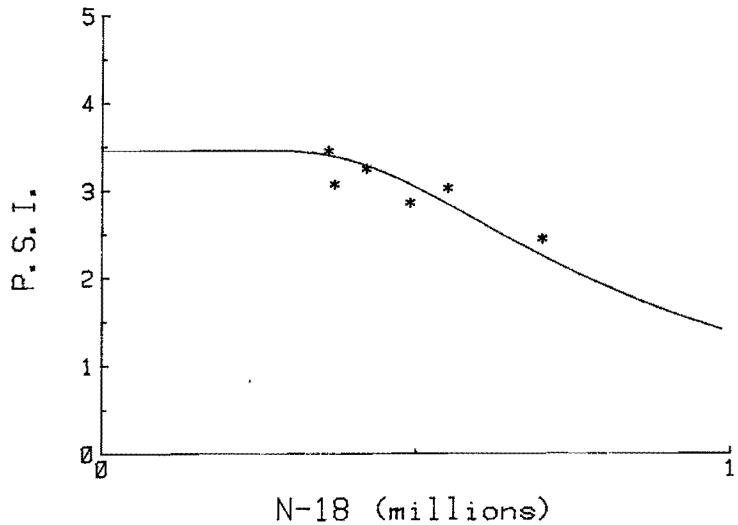

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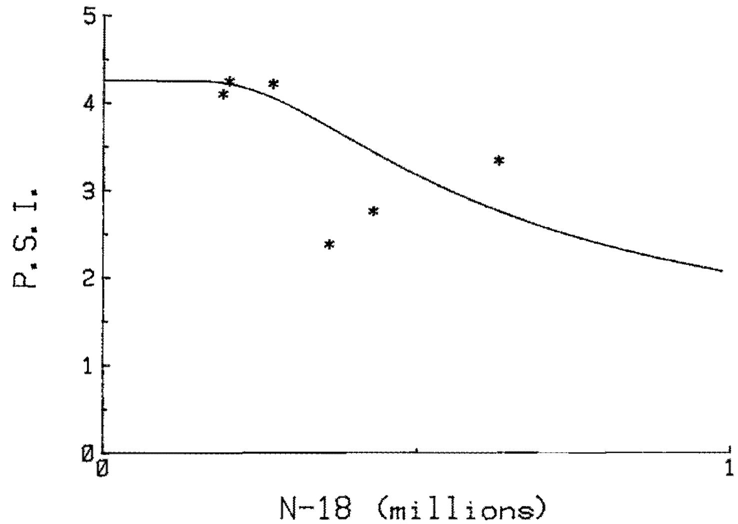

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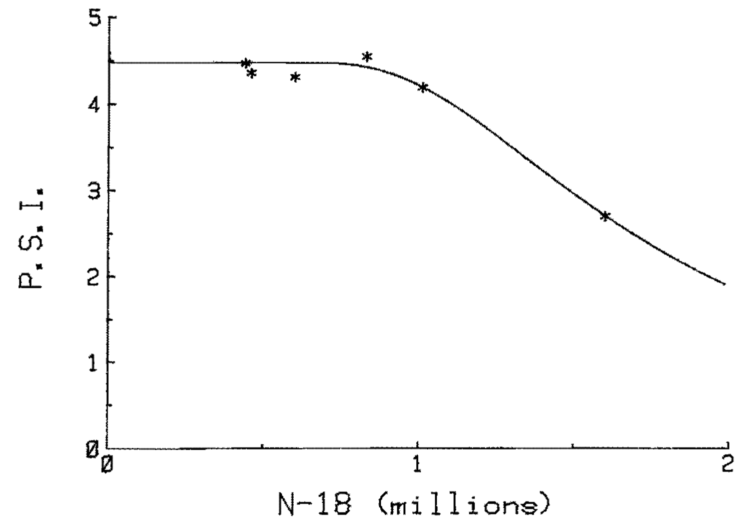

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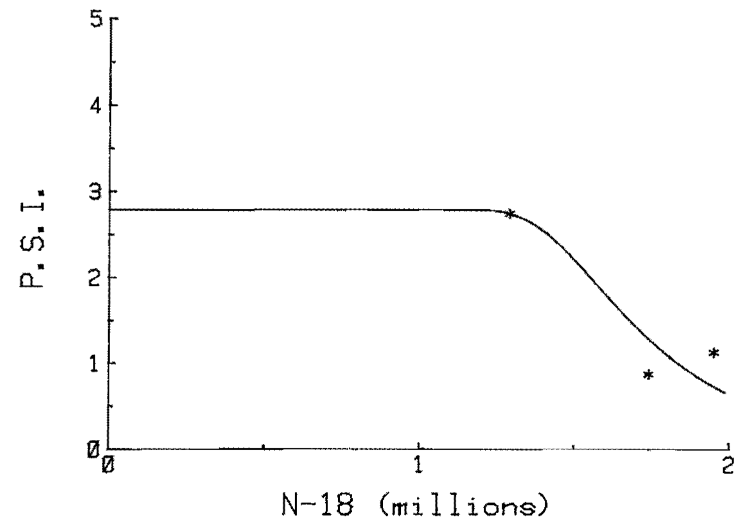

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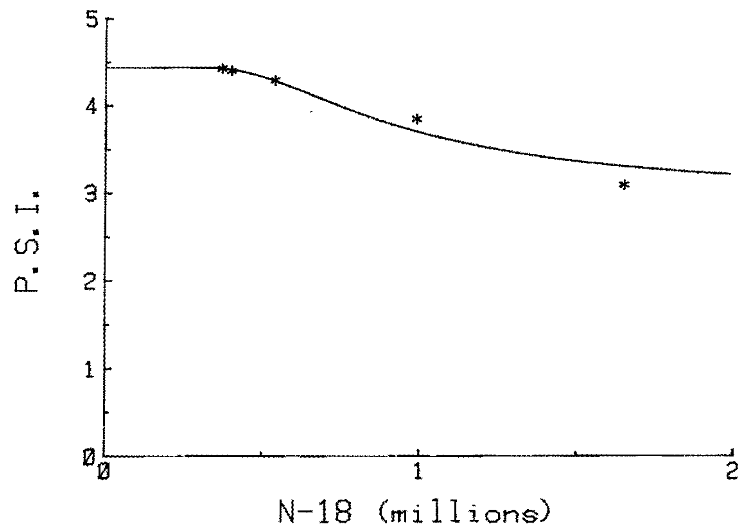

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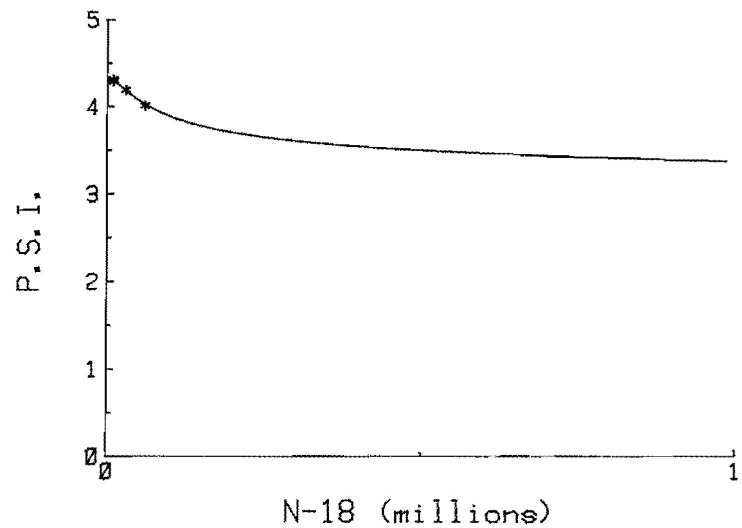

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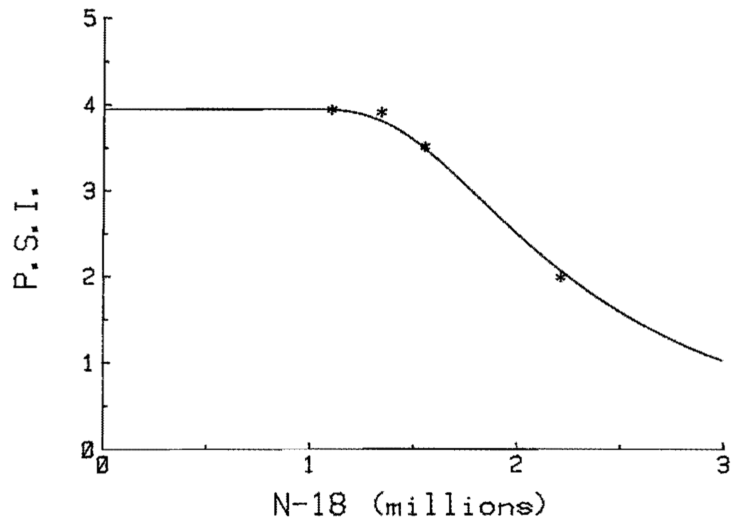

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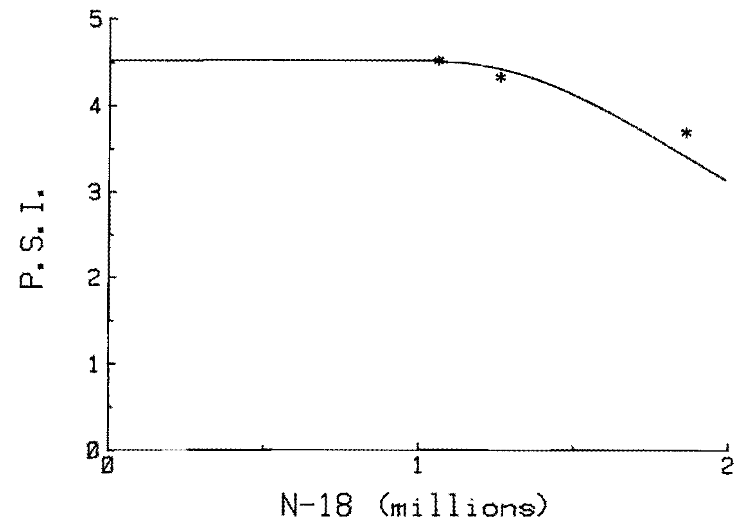

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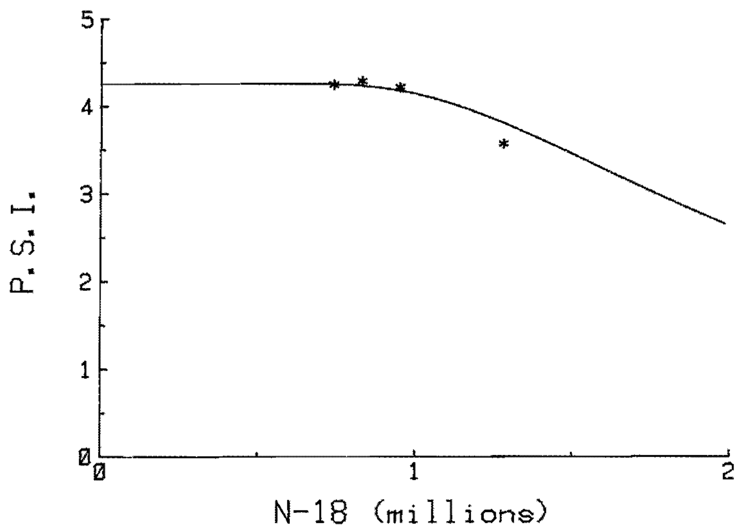

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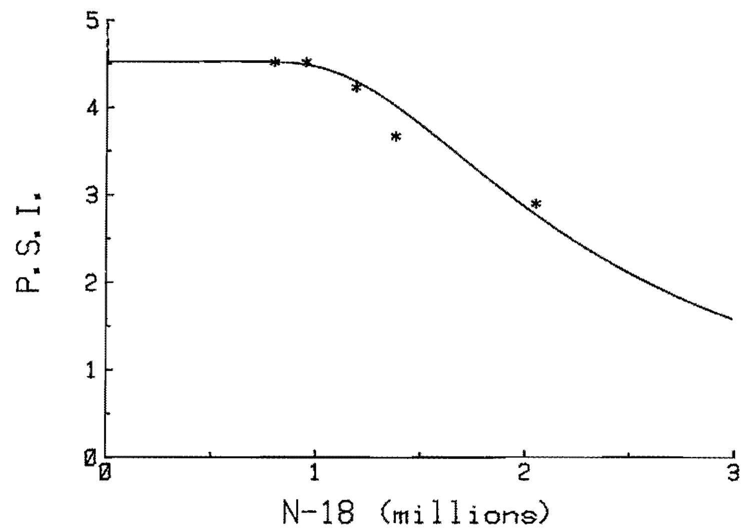

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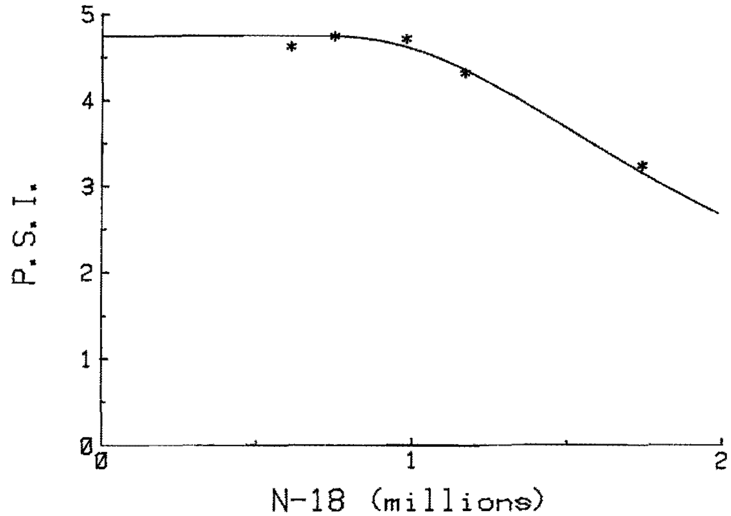

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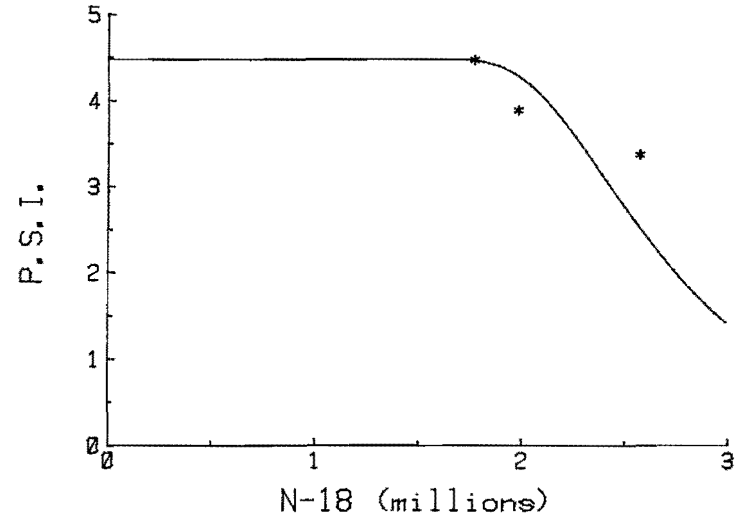

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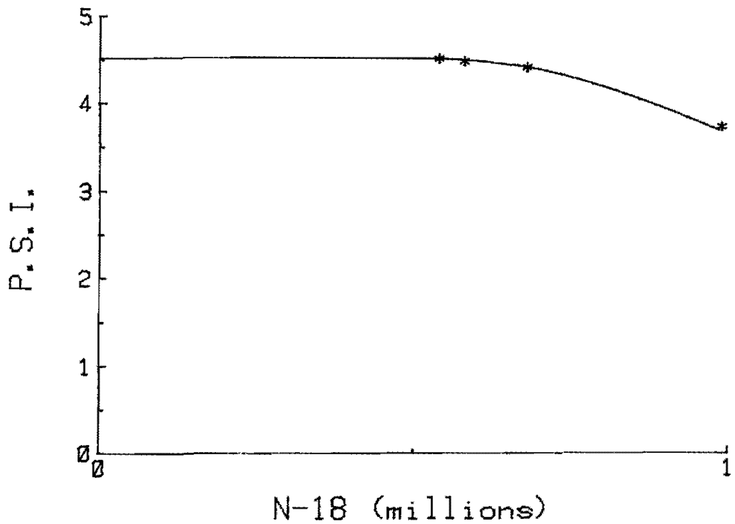

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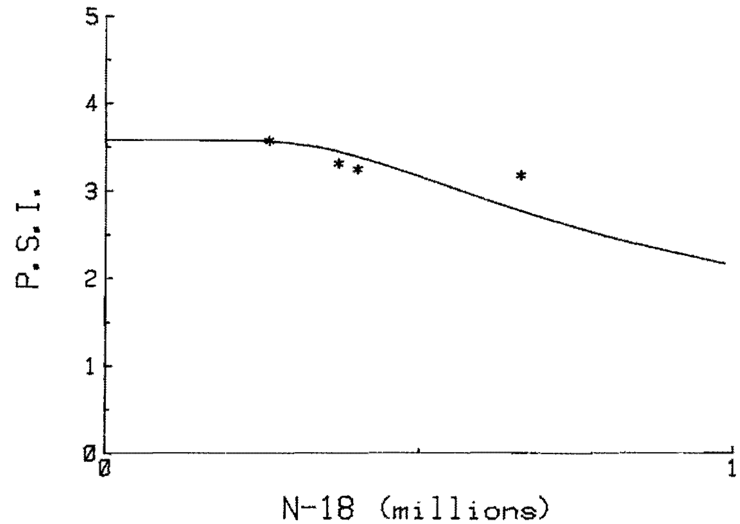

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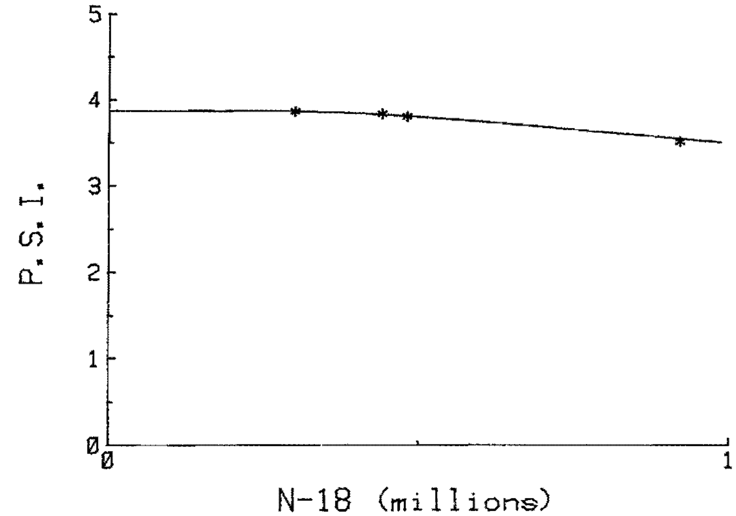

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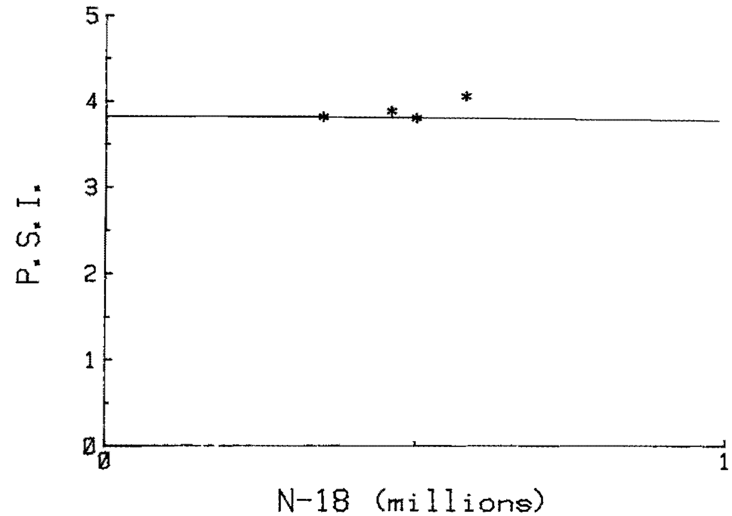

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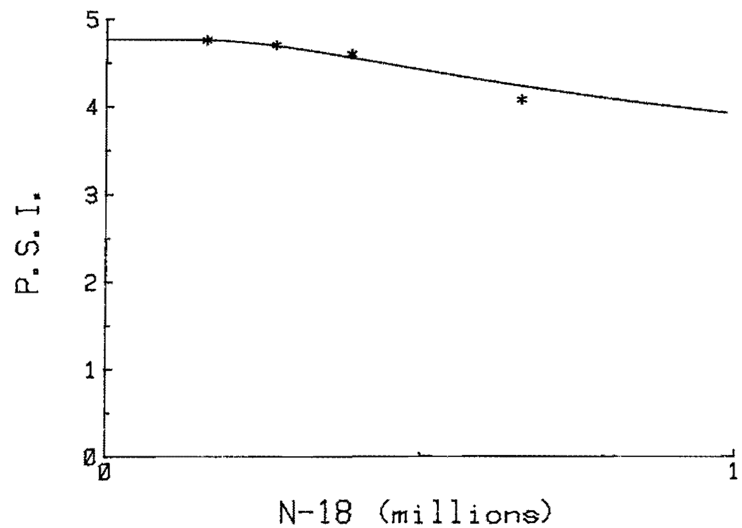

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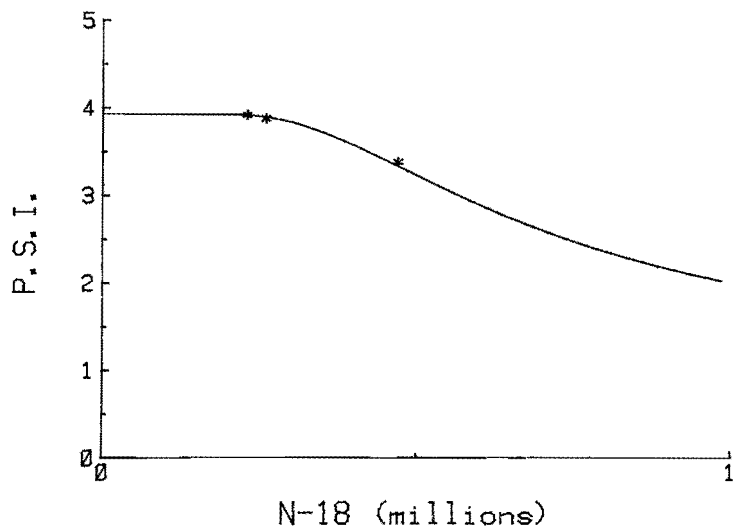

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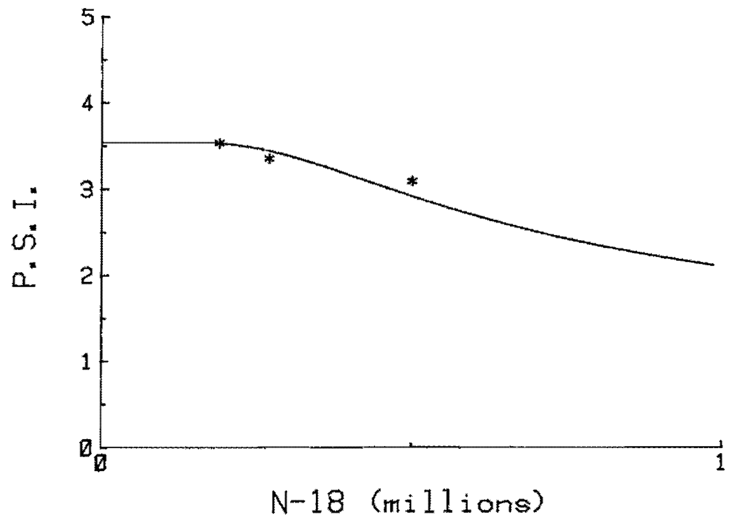

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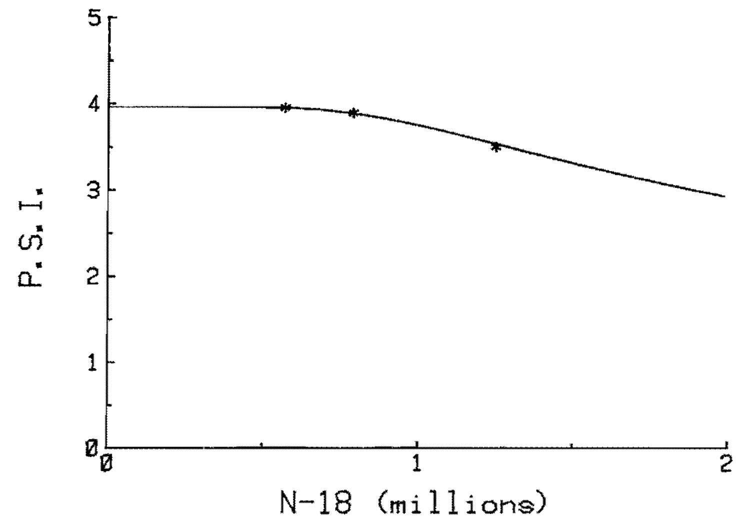

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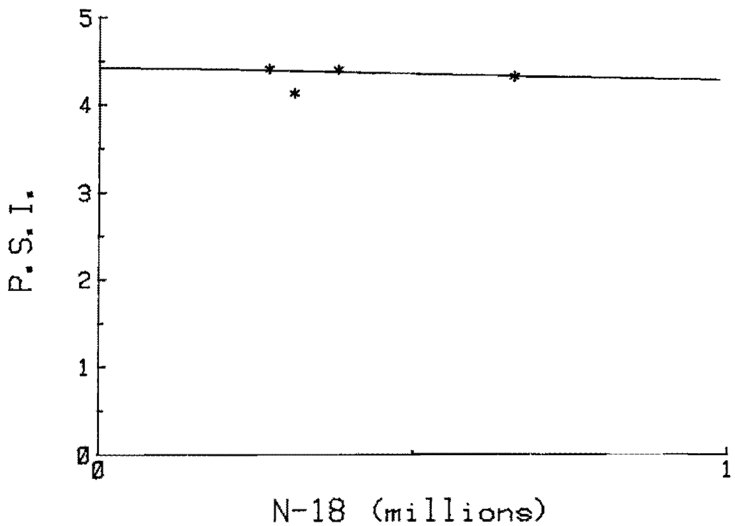

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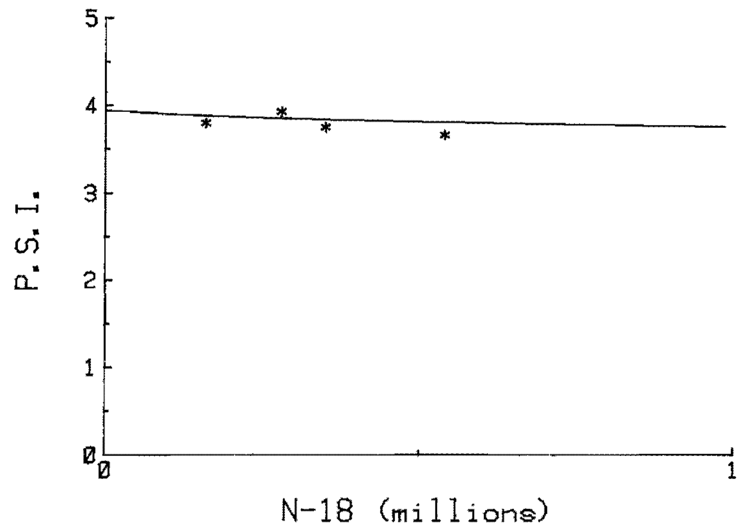

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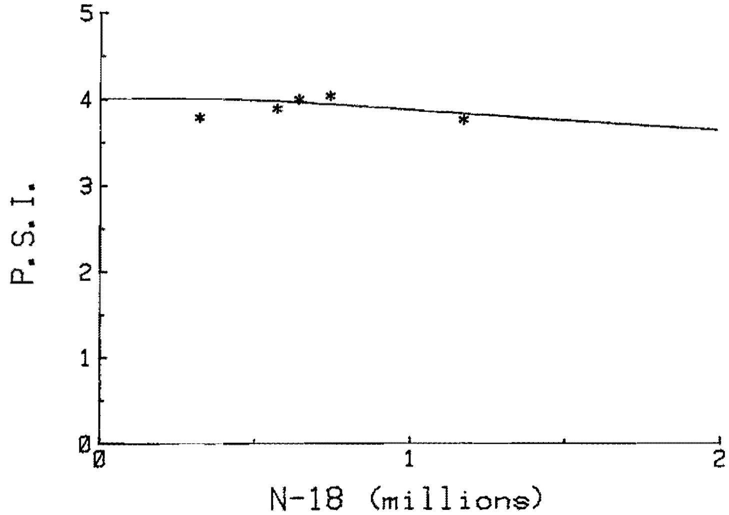

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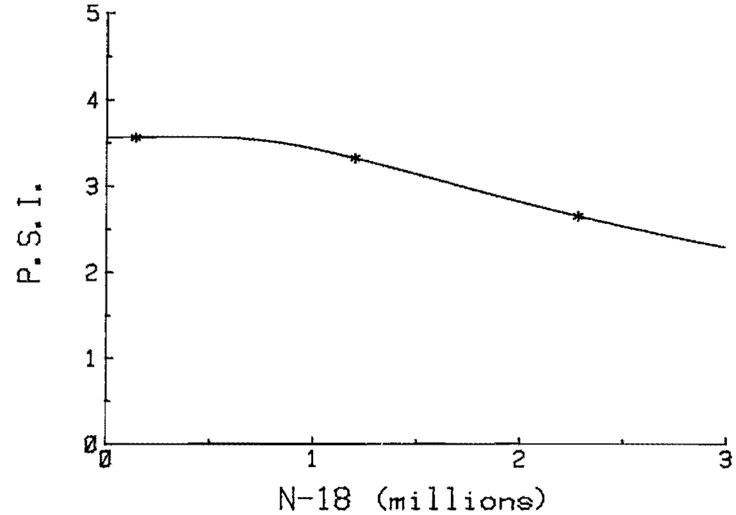

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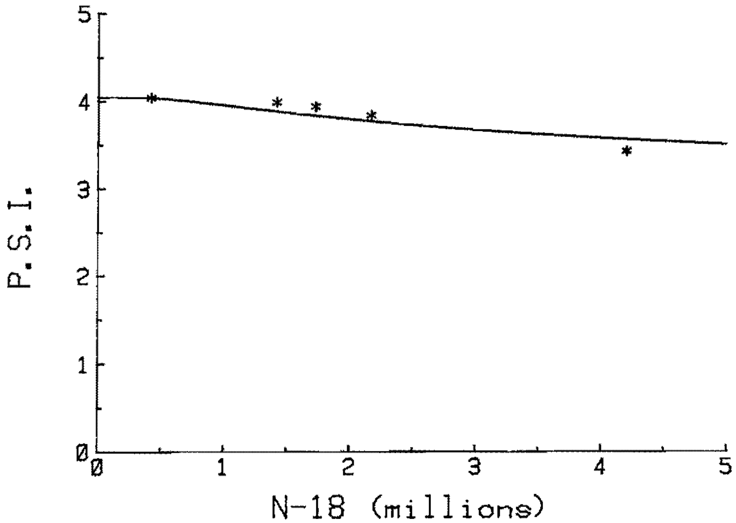

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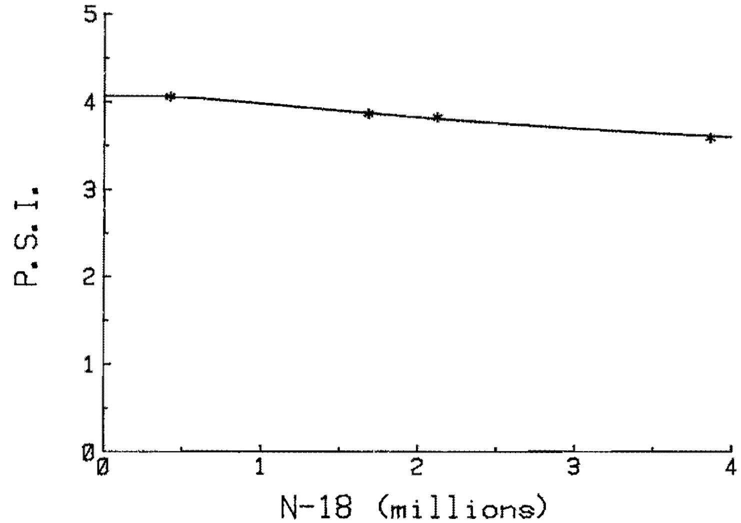

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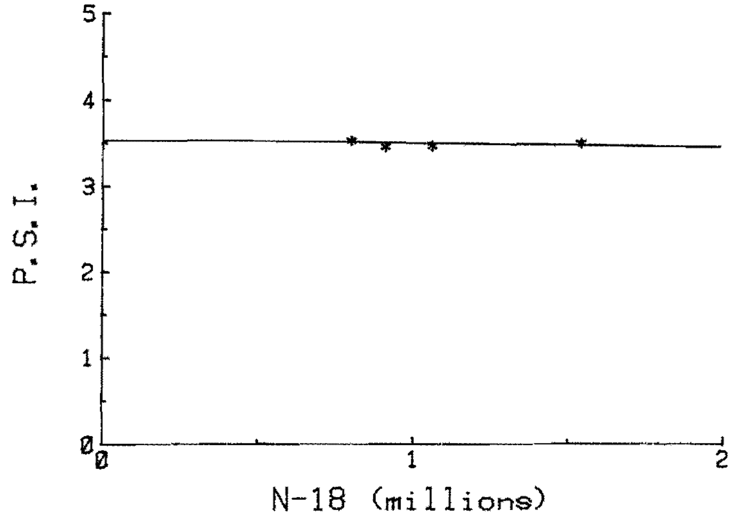

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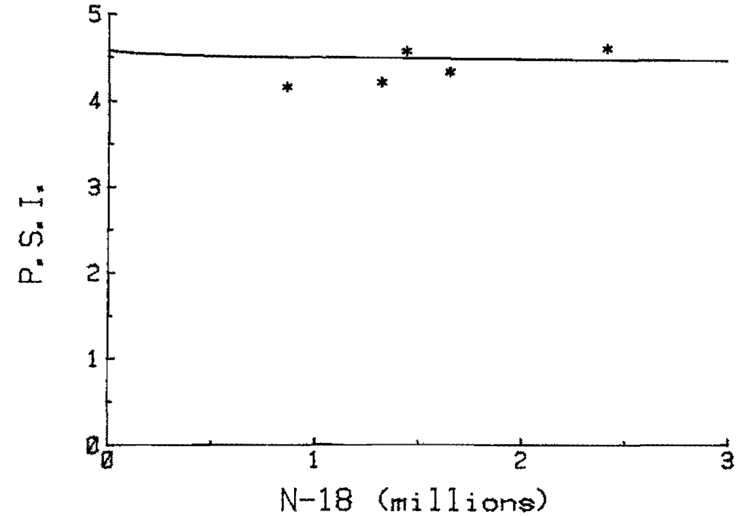

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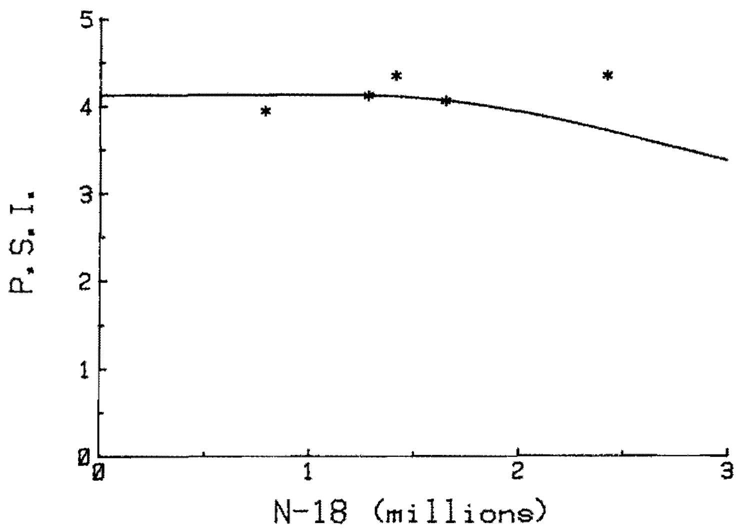

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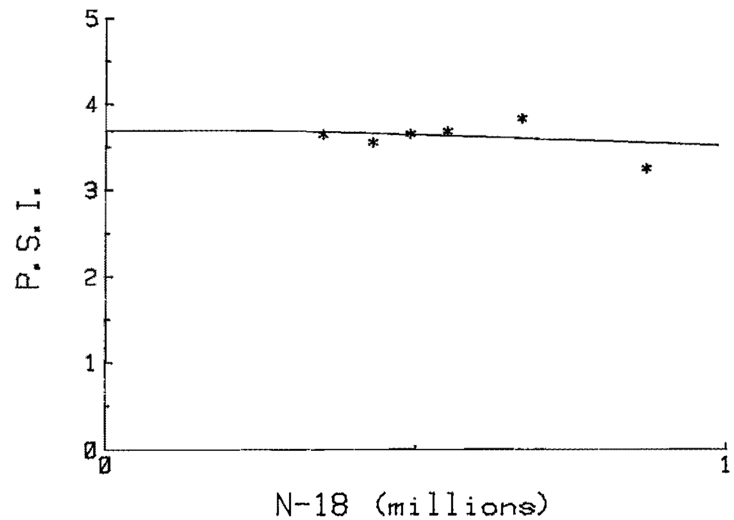

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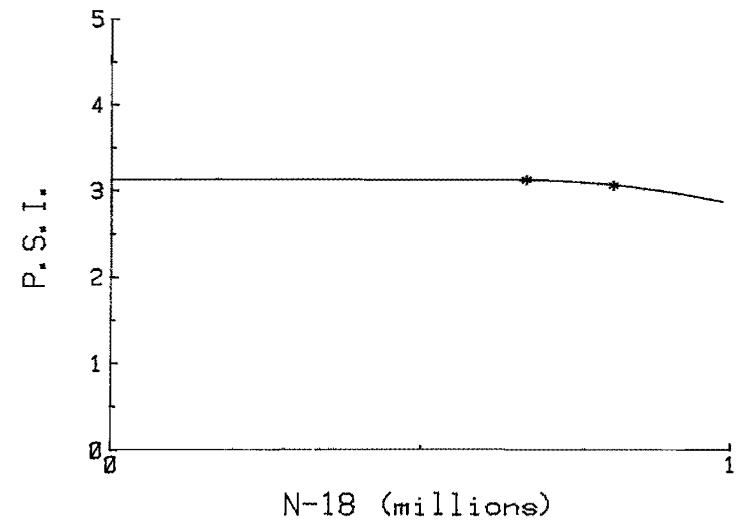

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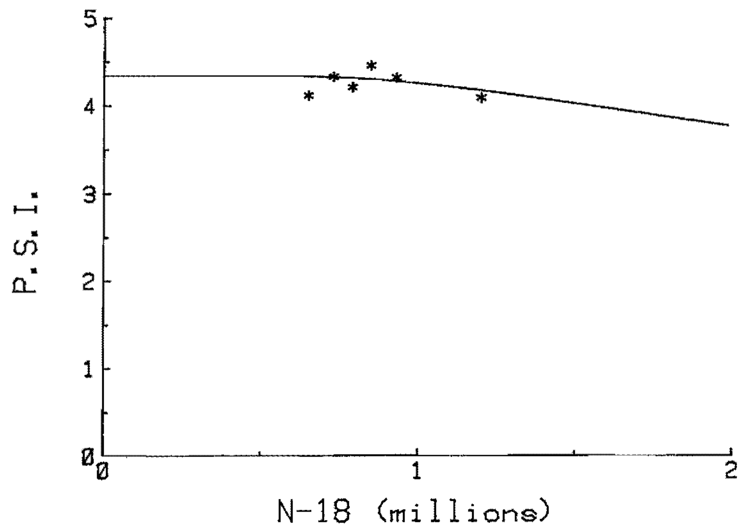

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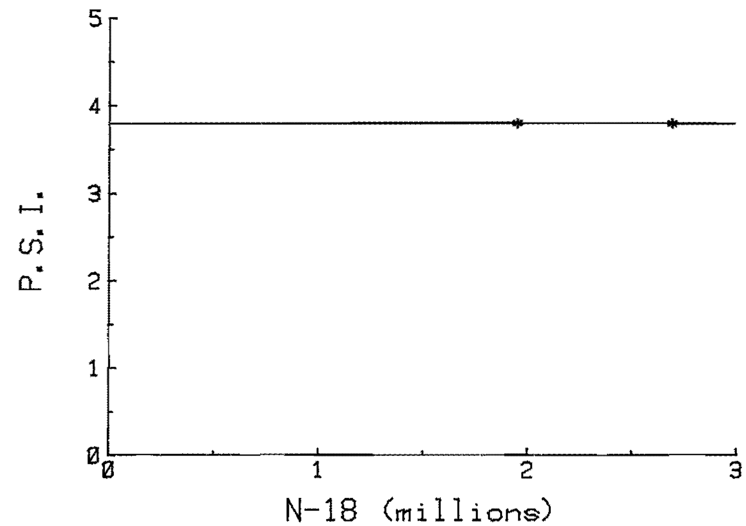

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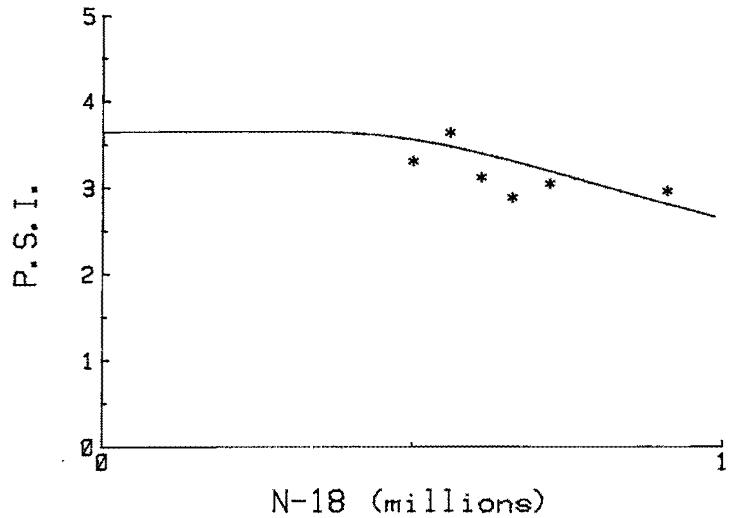

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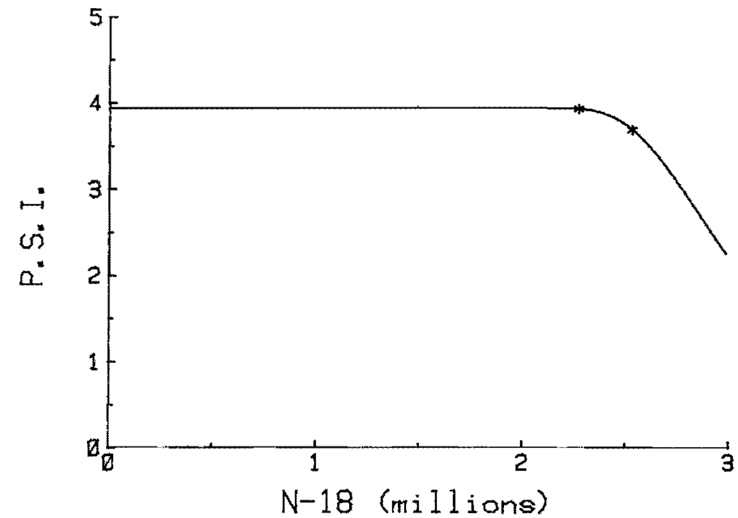

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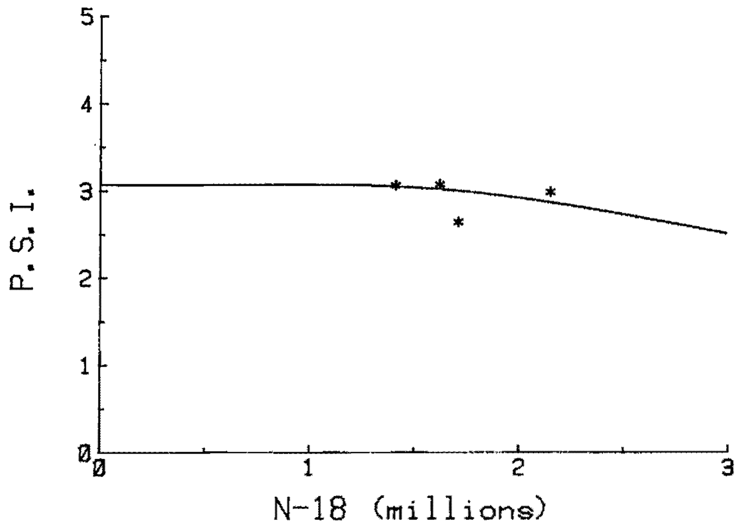

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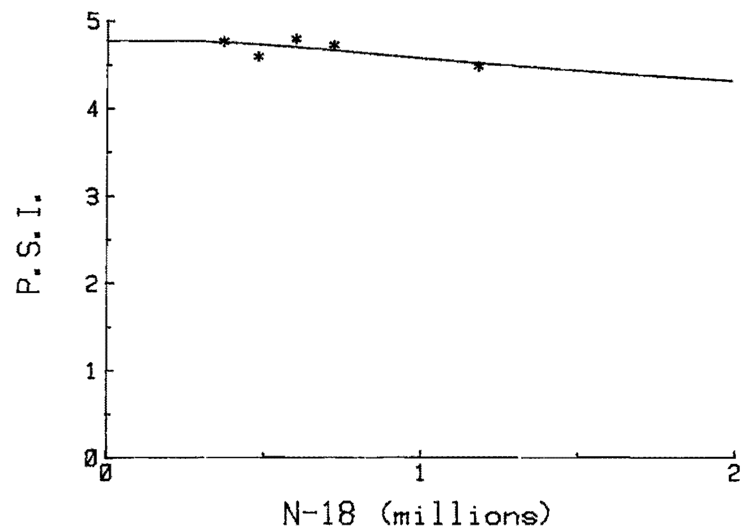

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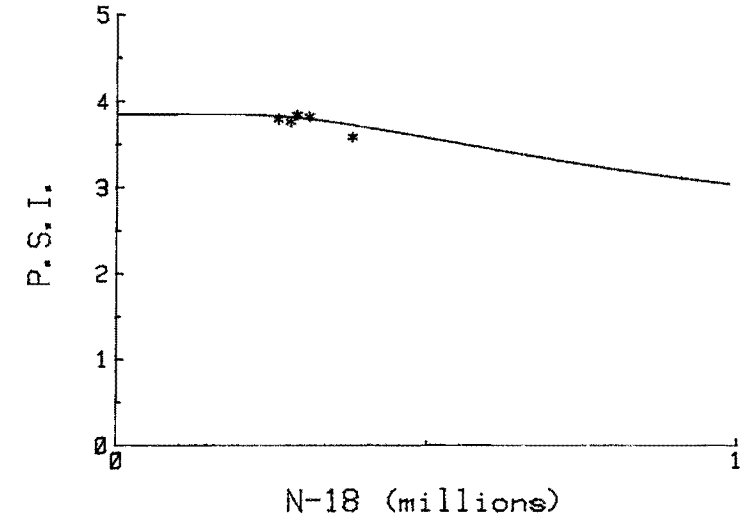

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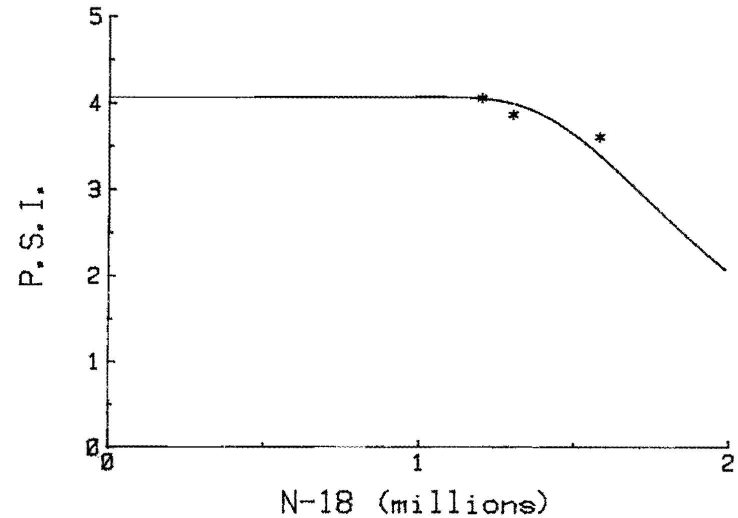

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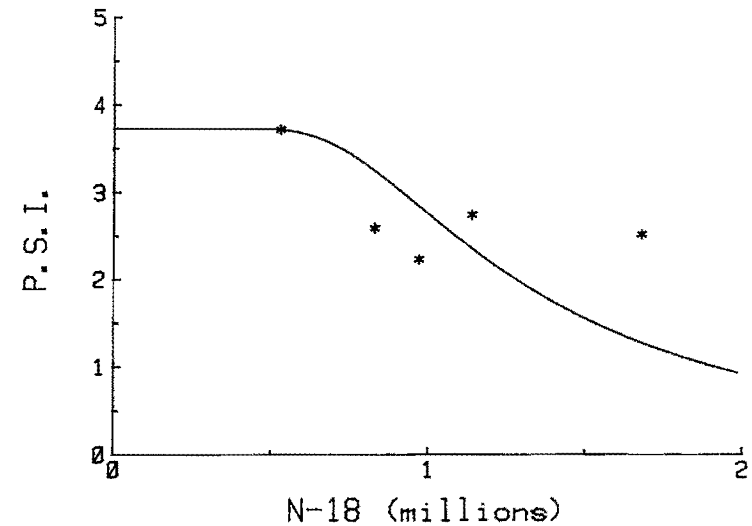

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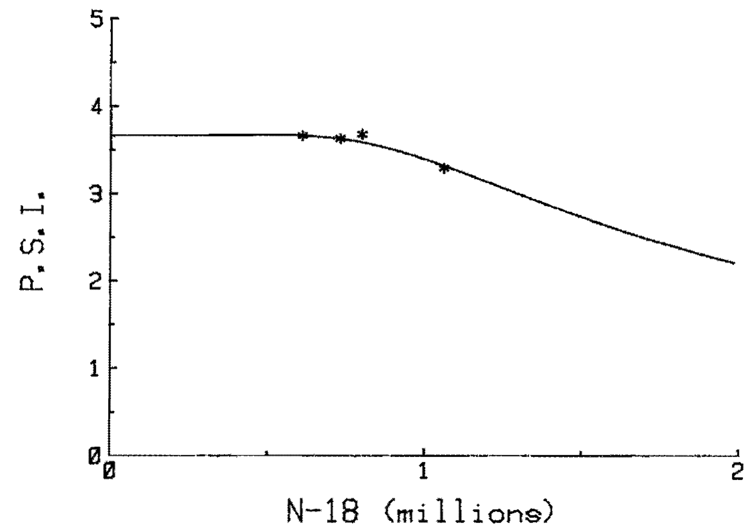

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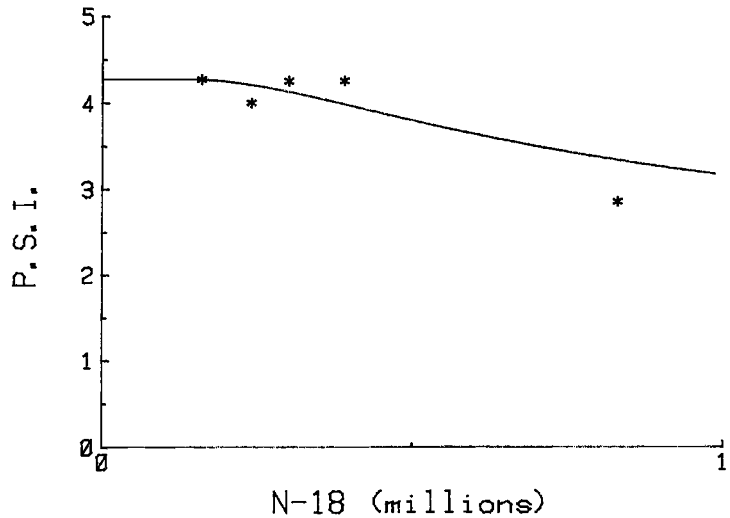

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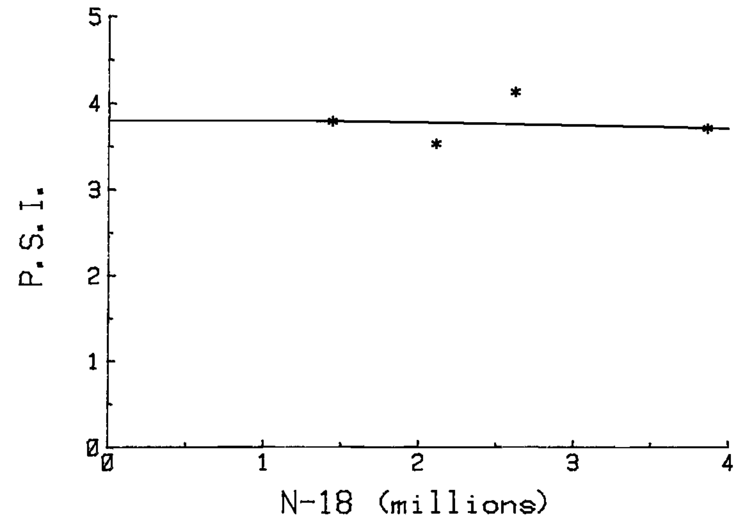

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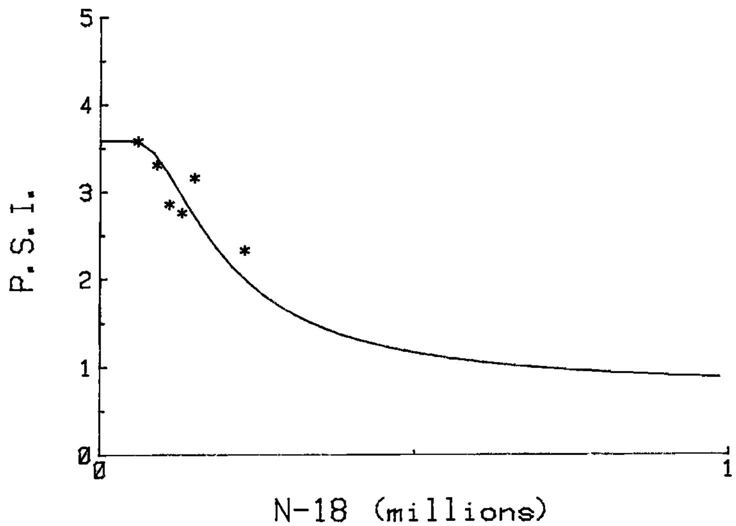

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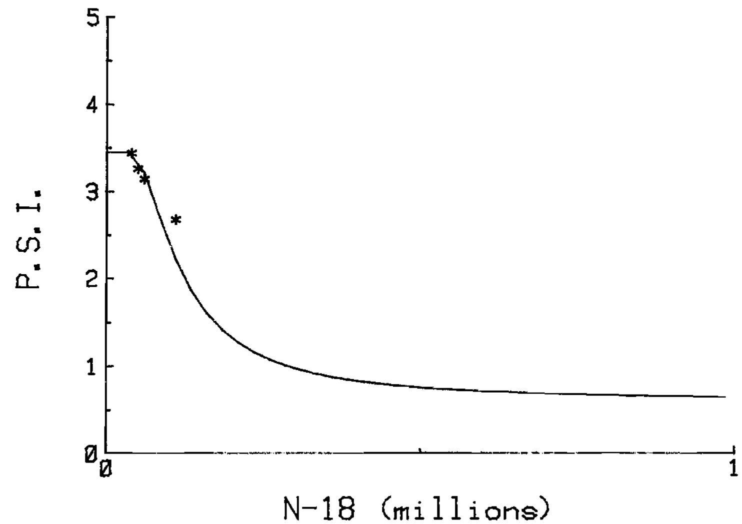

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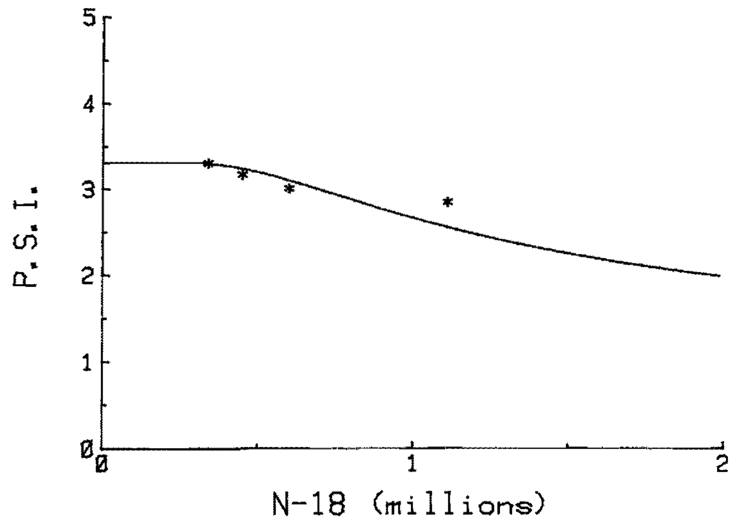

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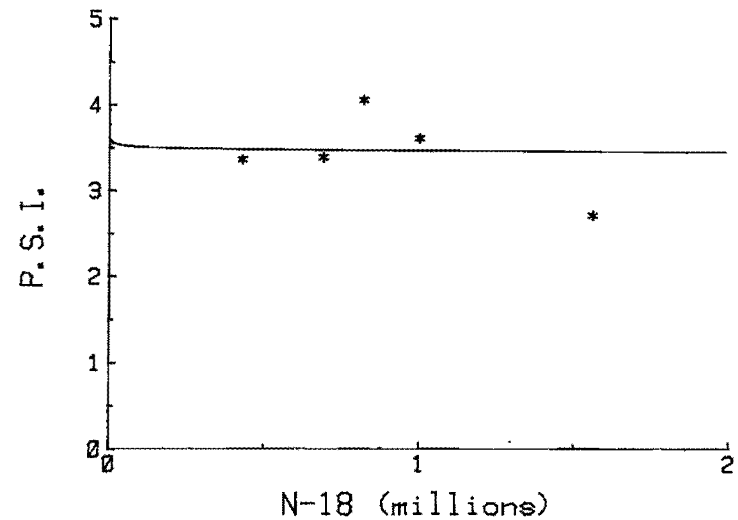

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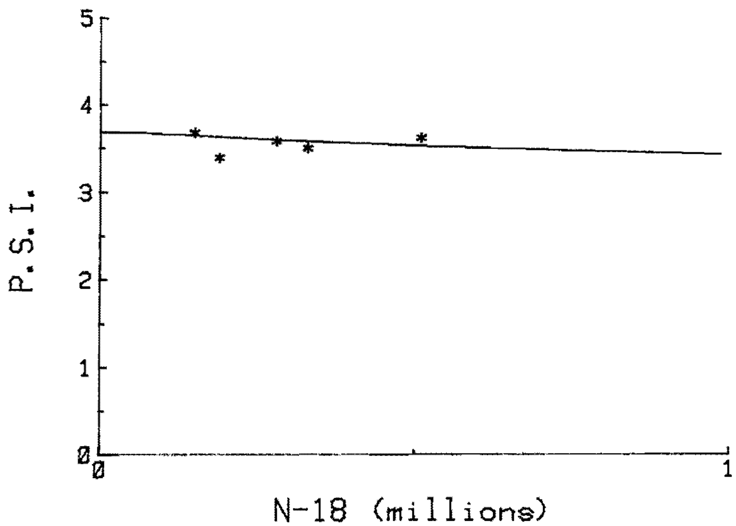

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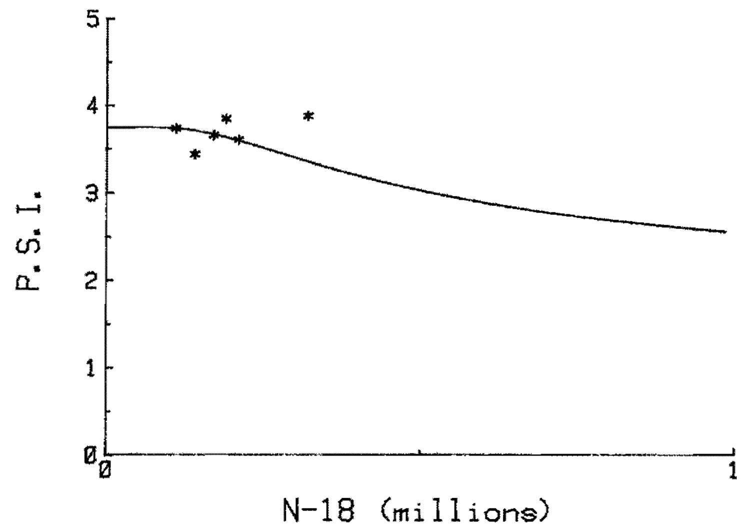

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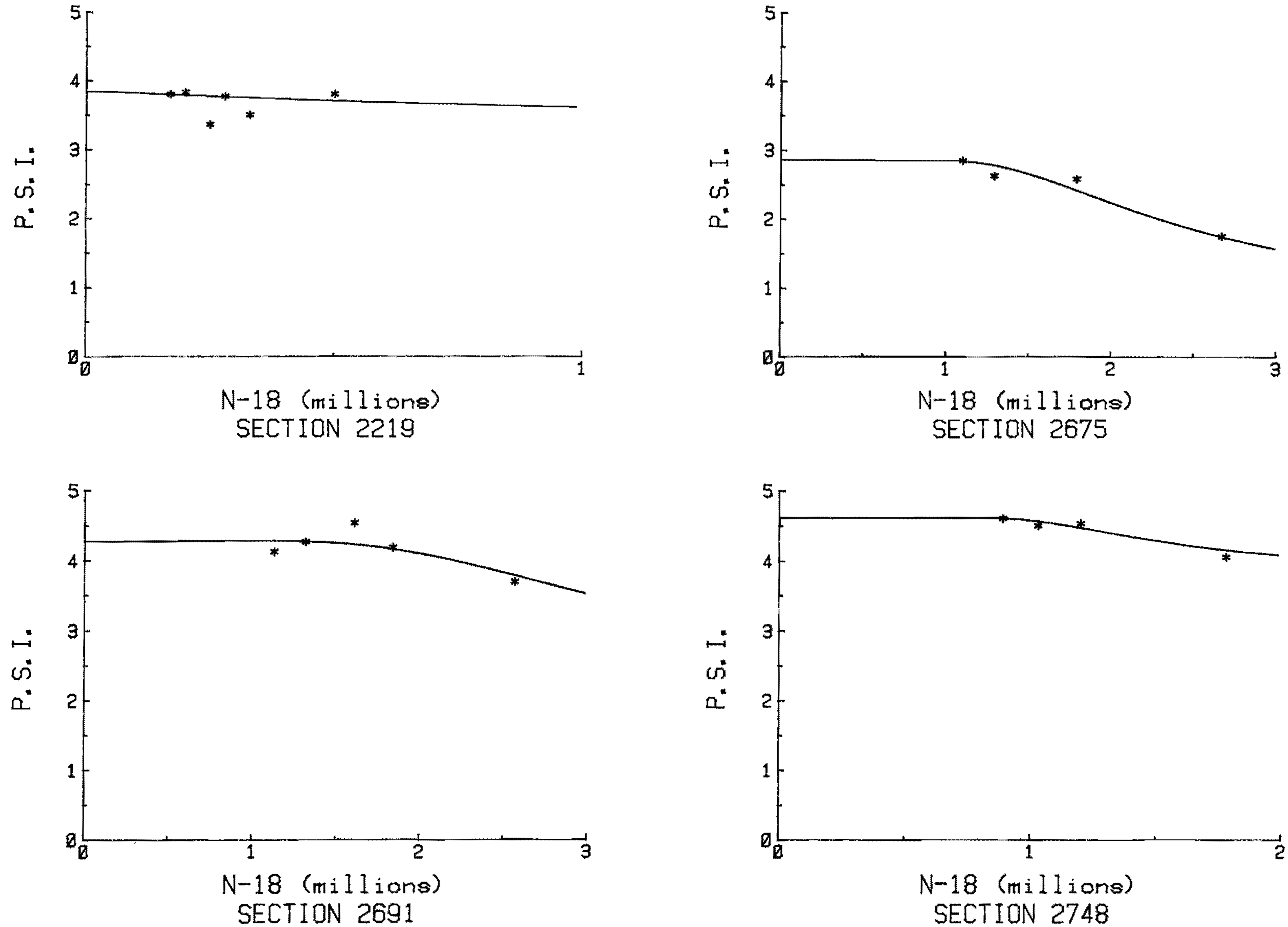
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SECTION 2219
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P.S.I.
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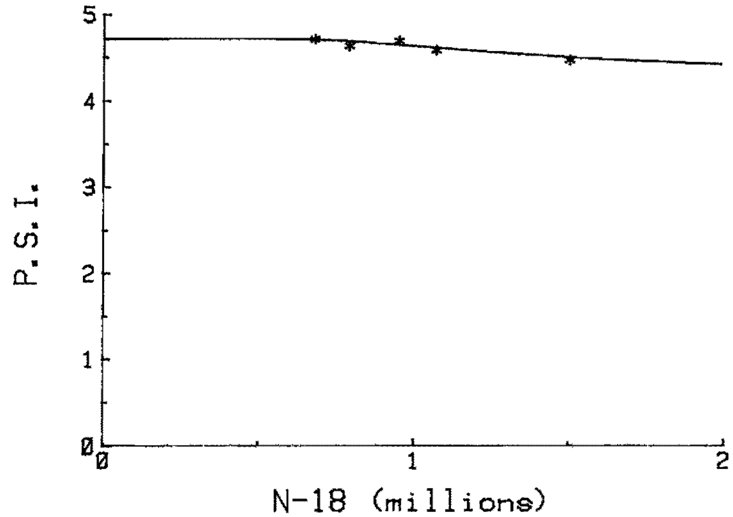

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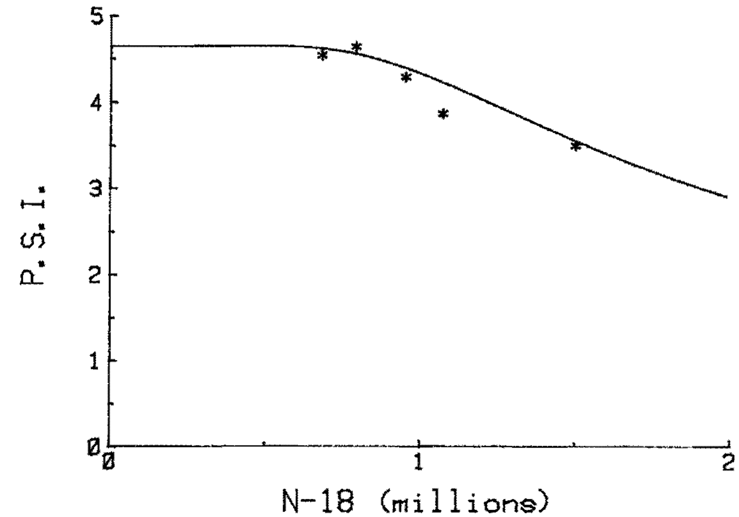

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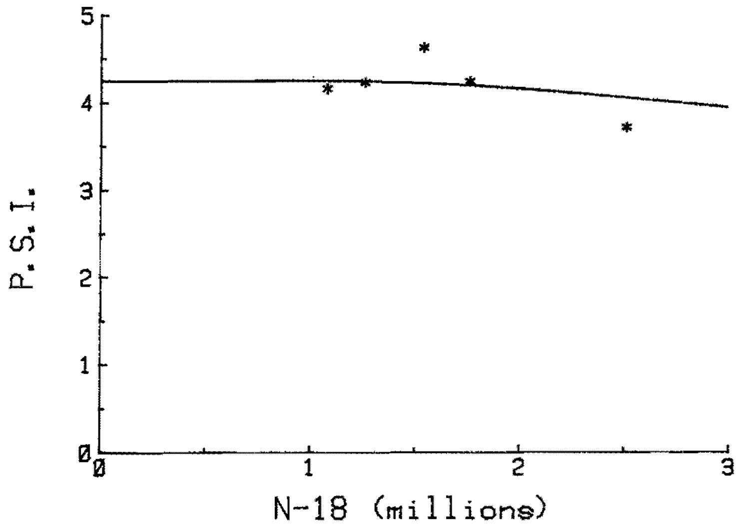

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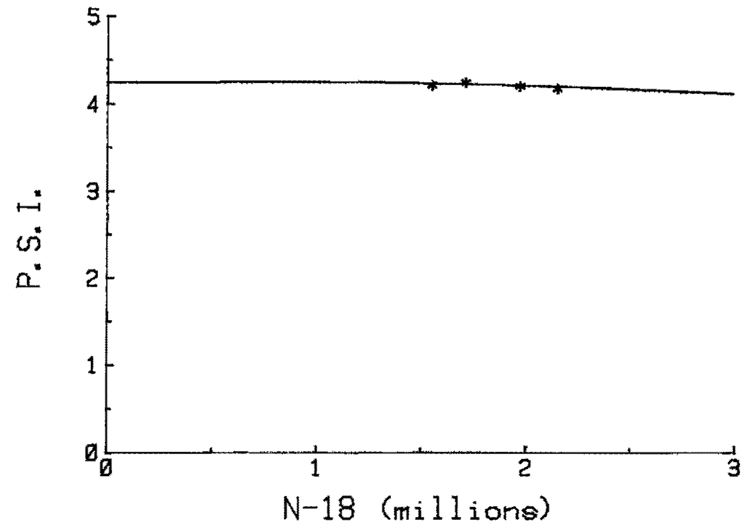

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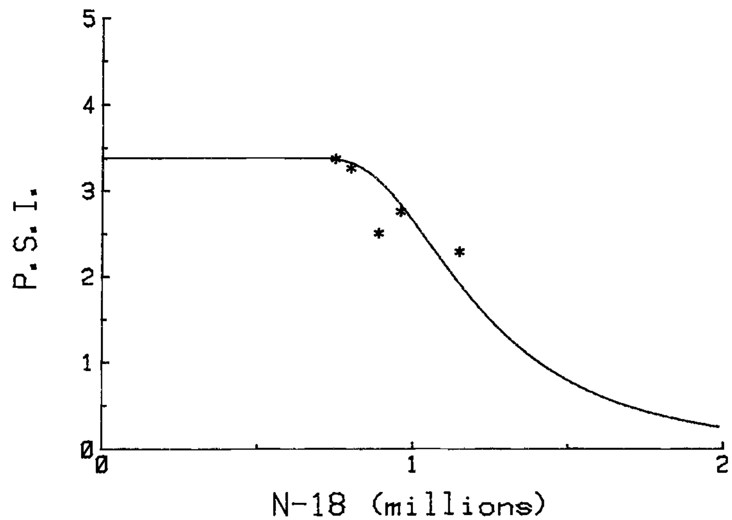

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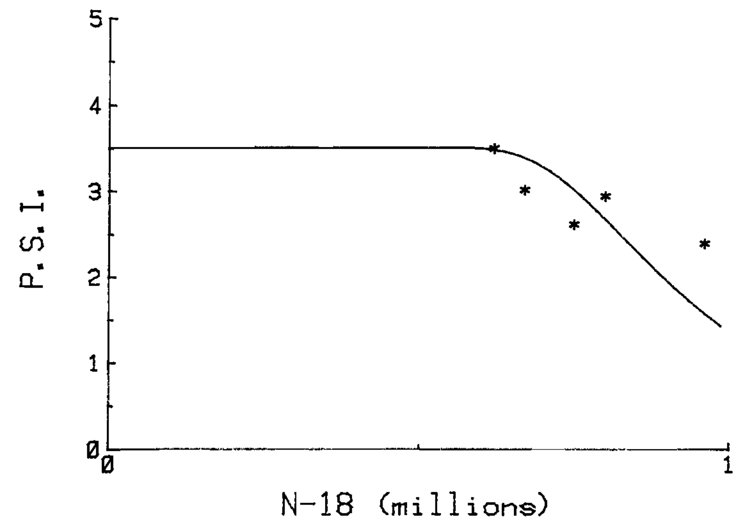
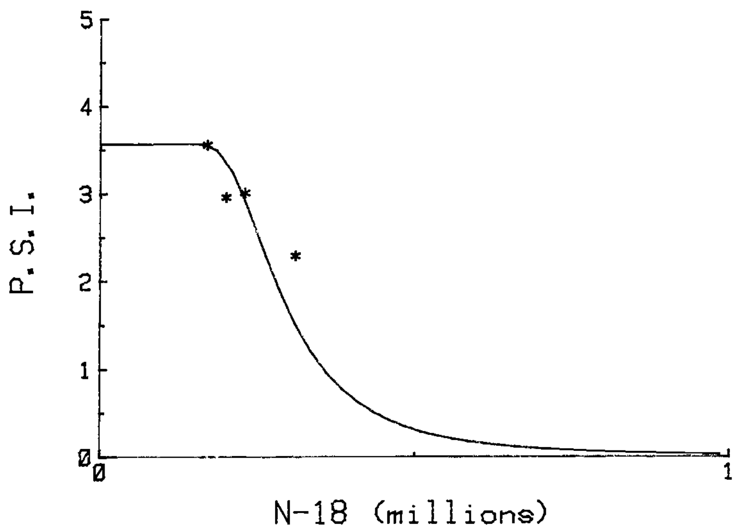
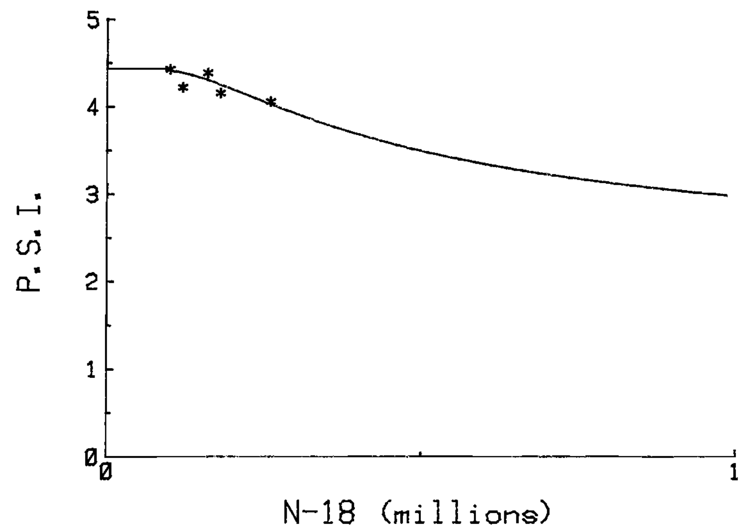


SECTION 2997



SECTION 3003



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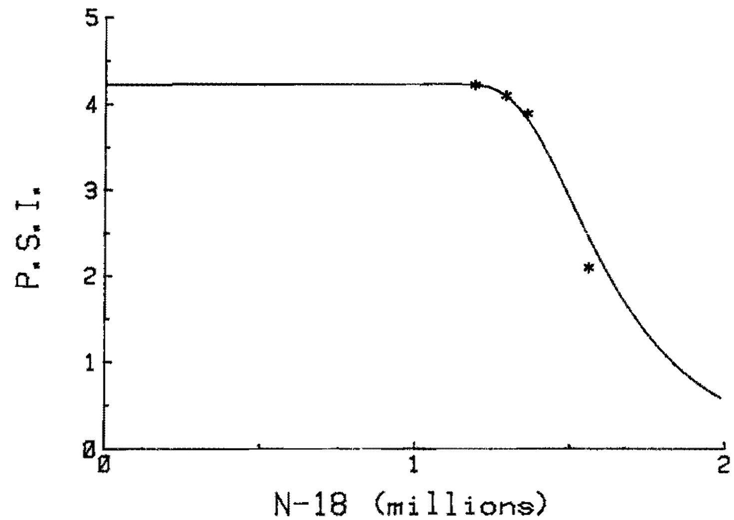

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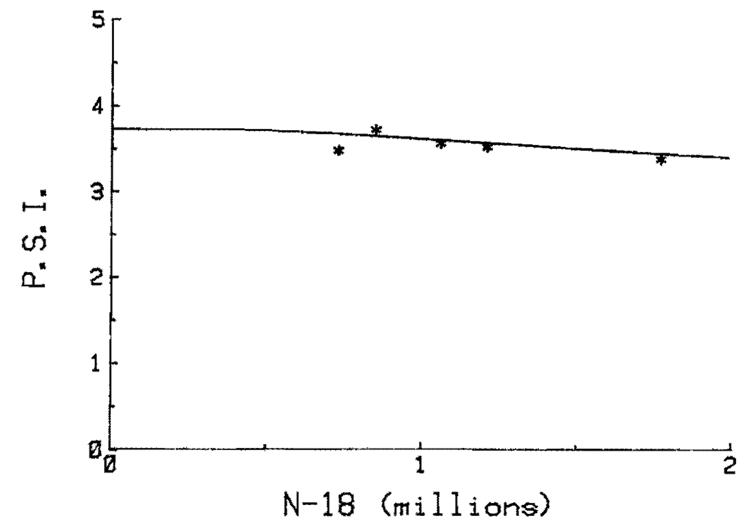

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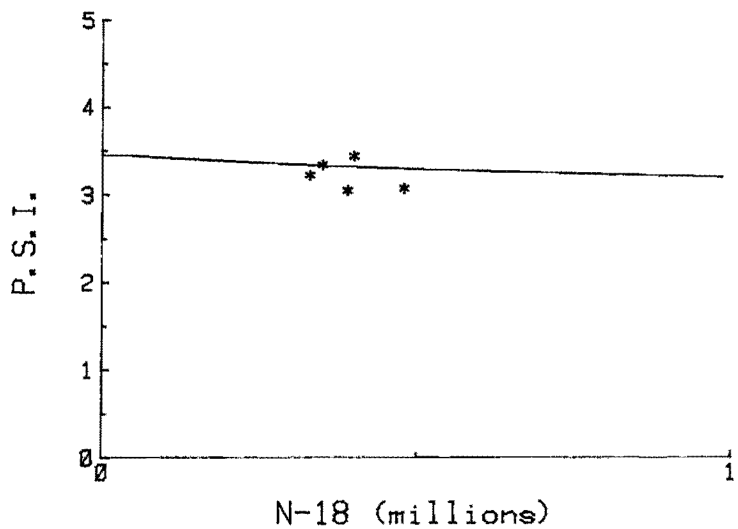
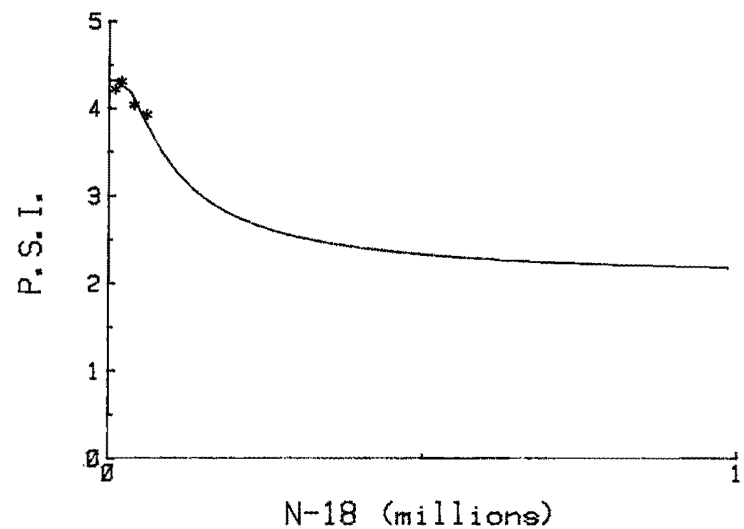
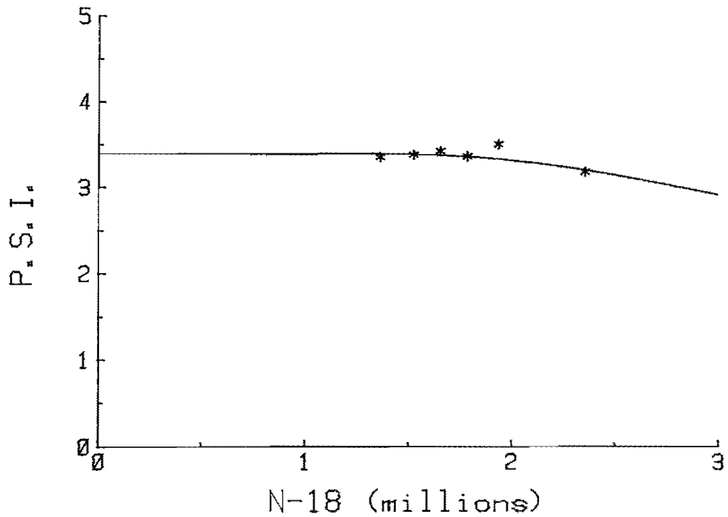


SECTION 31Ø5



SECTION 3121



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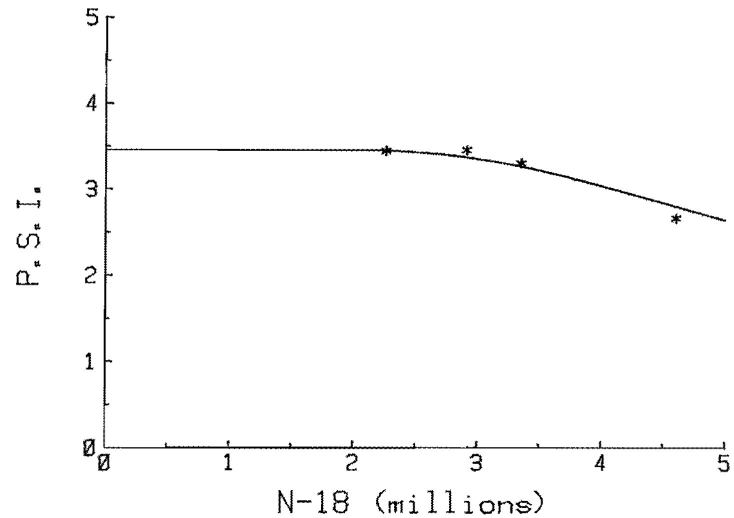

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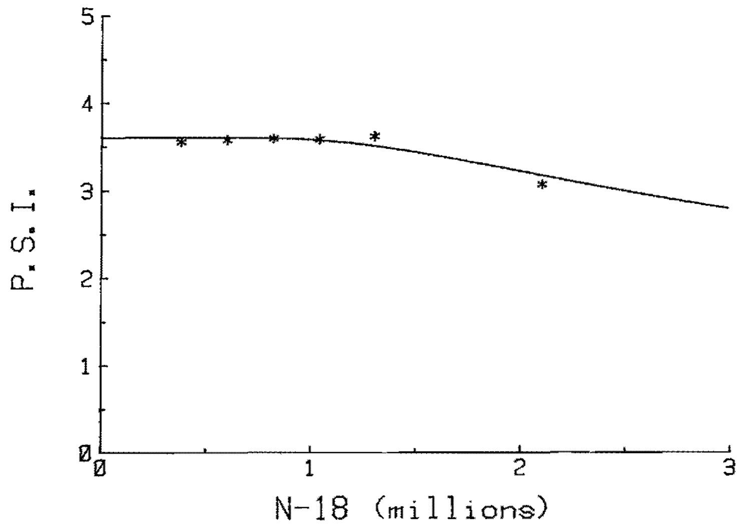

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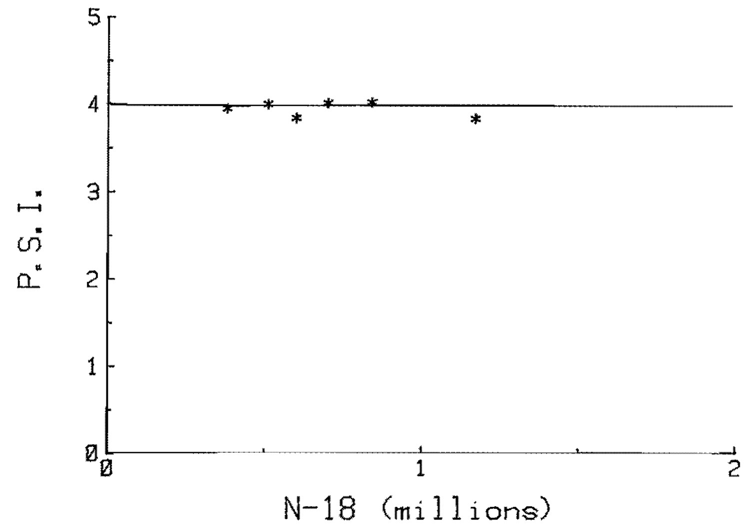

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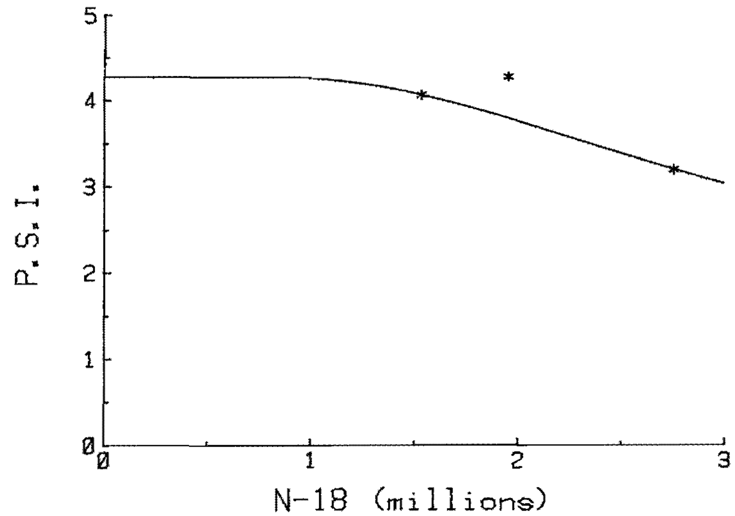

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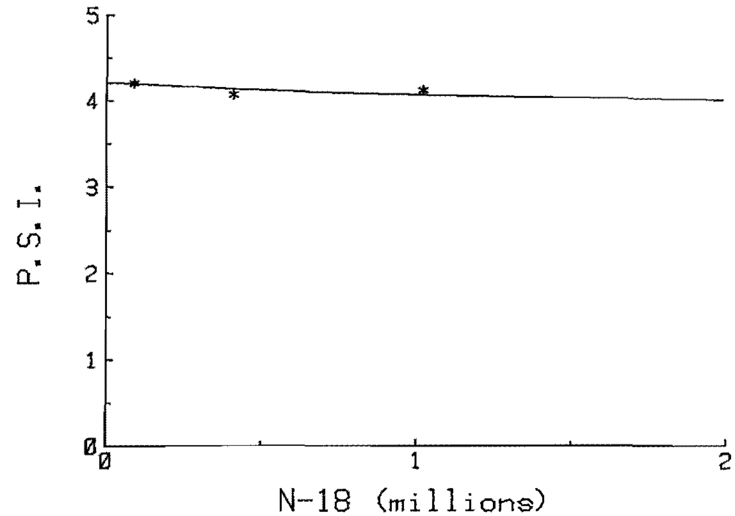

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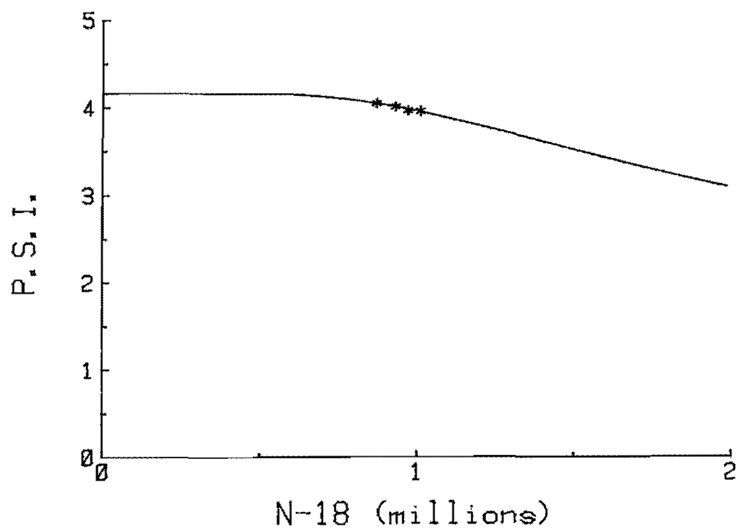

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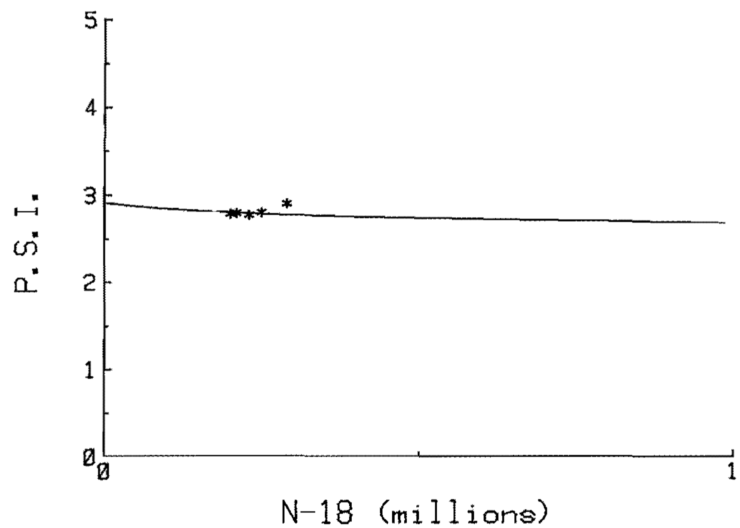

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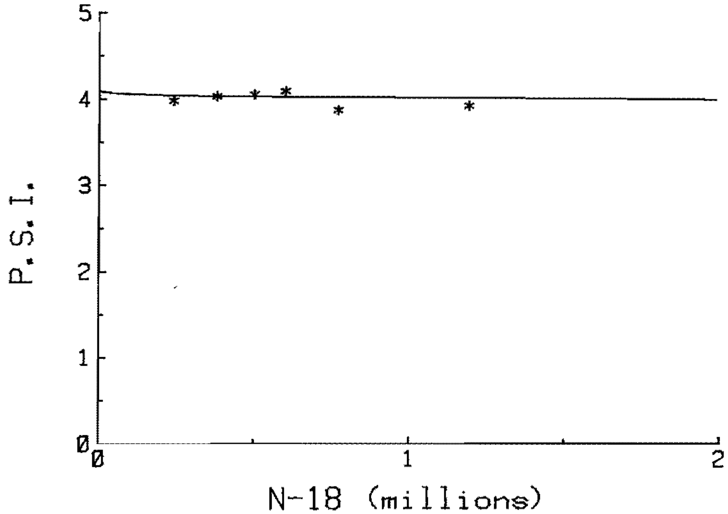

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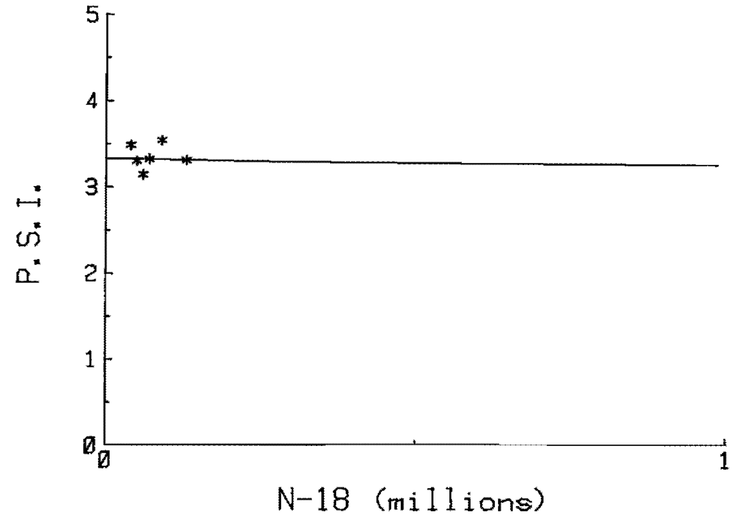

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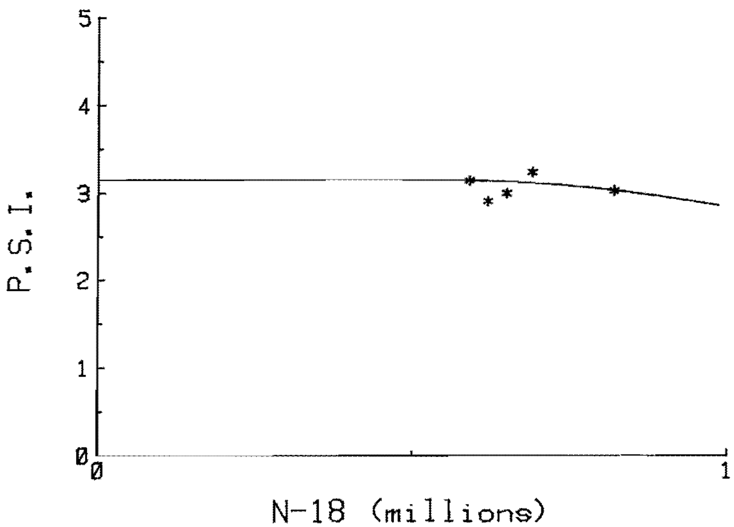

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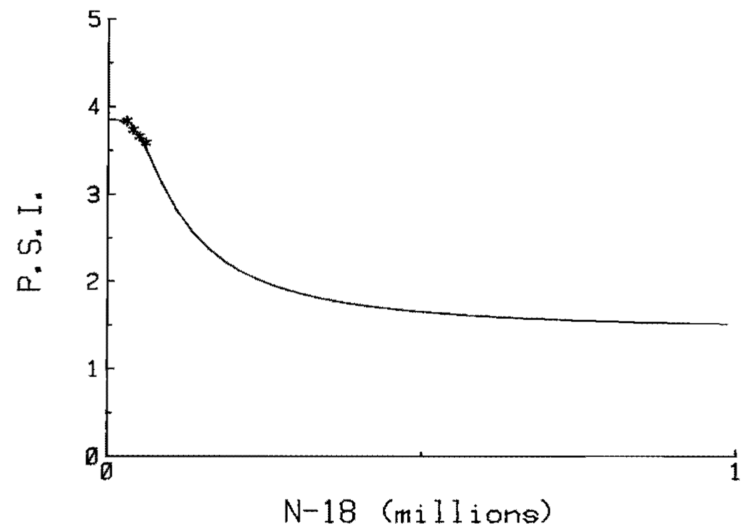

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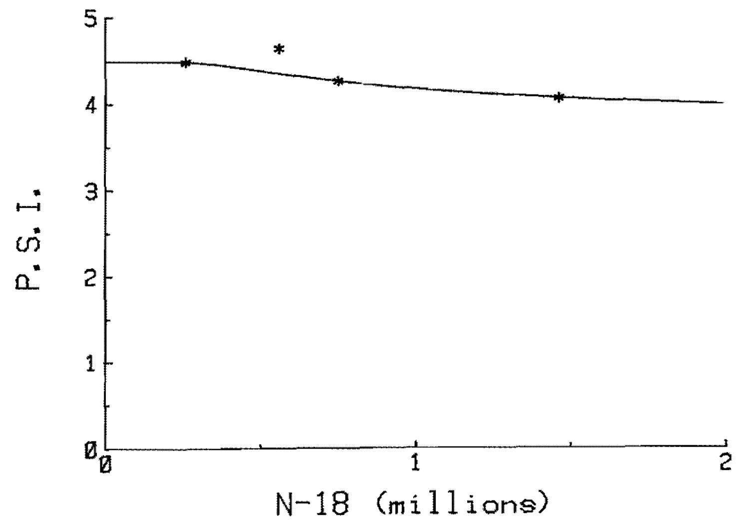

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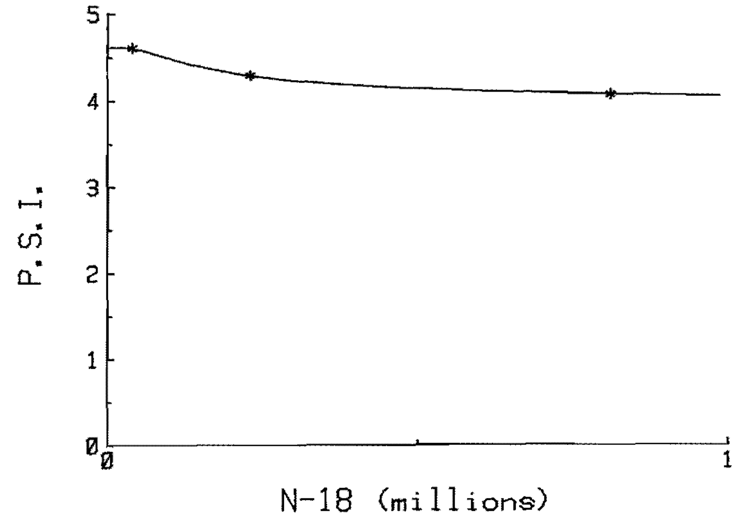

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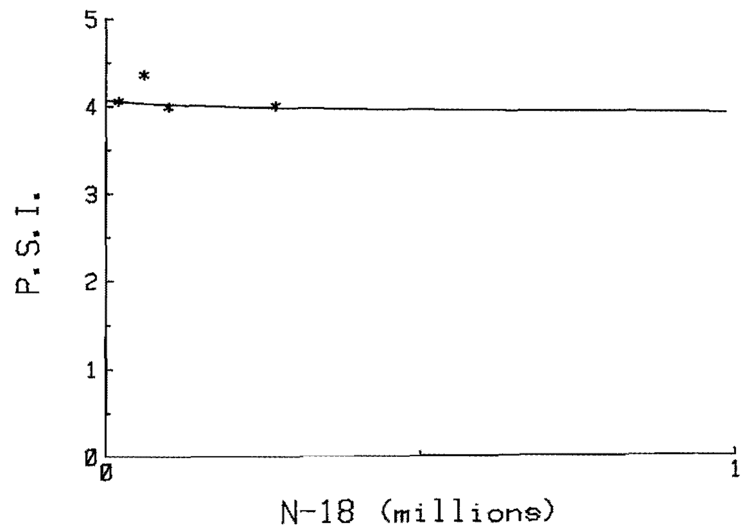

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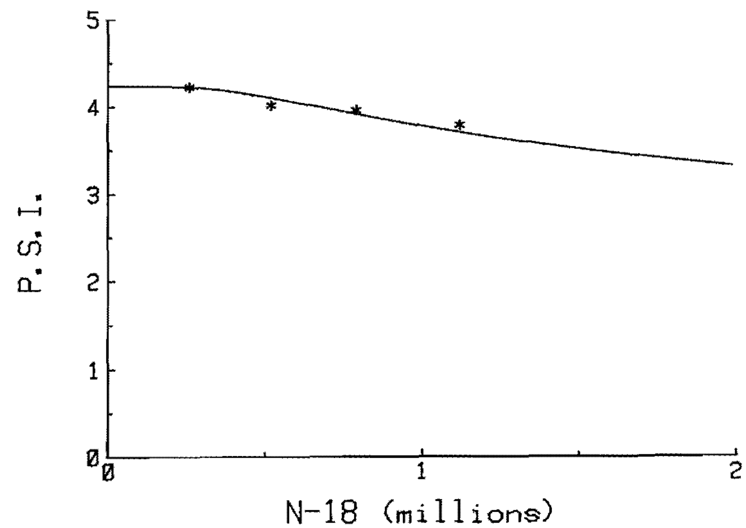

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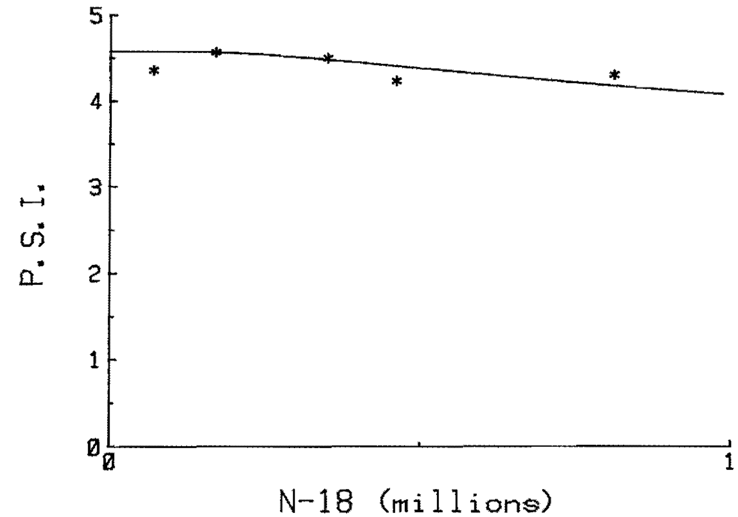

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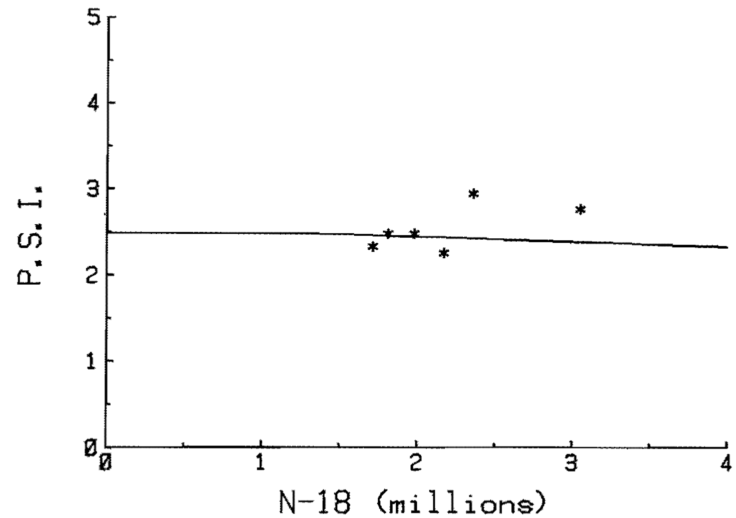

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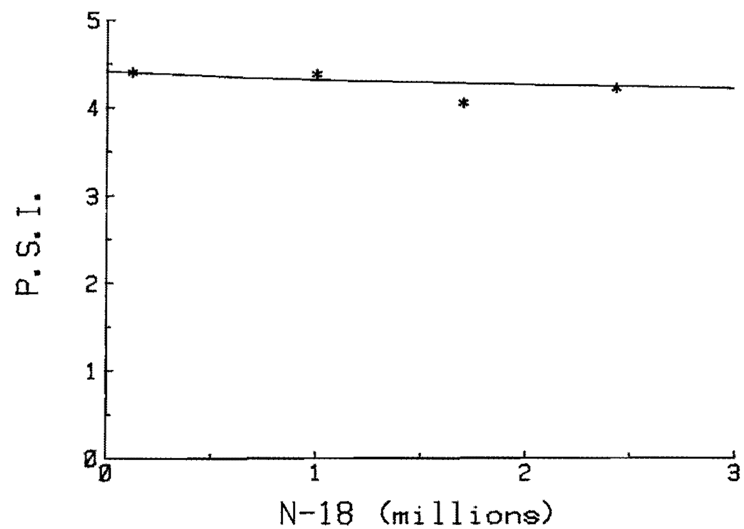

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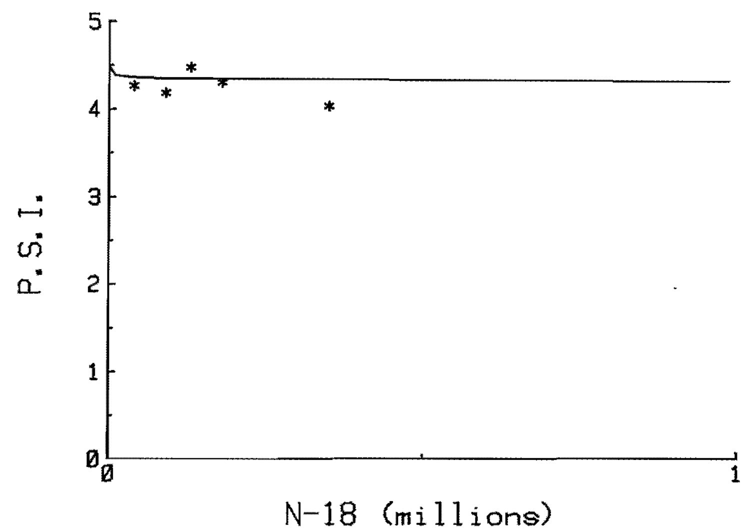

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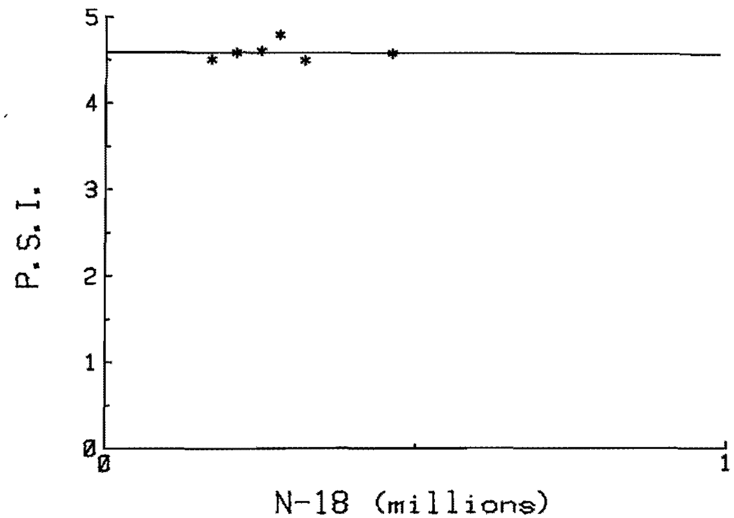

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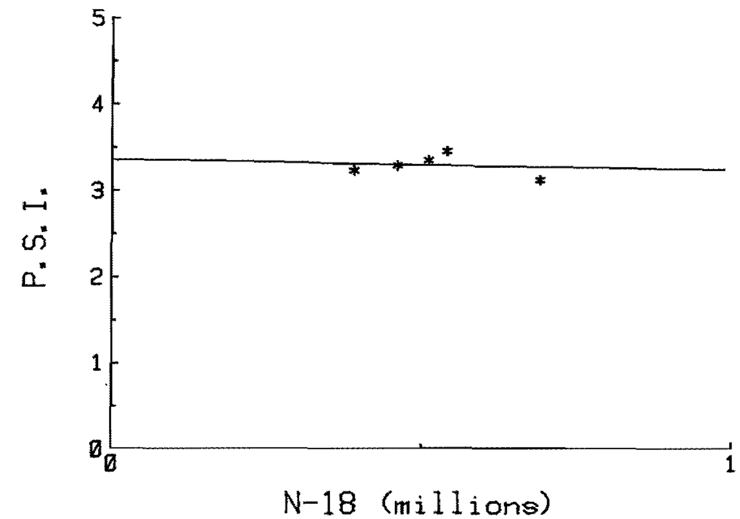

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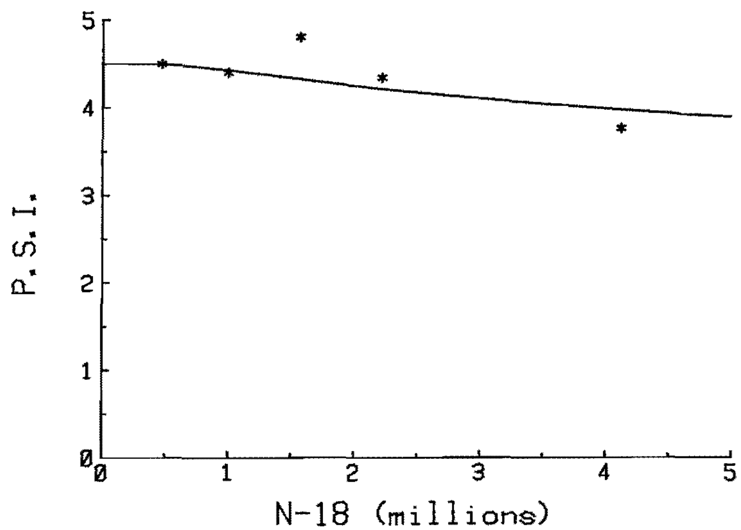

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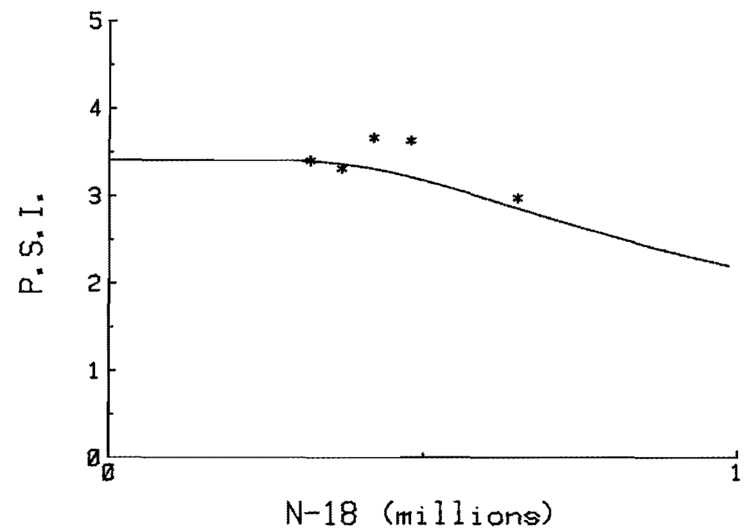

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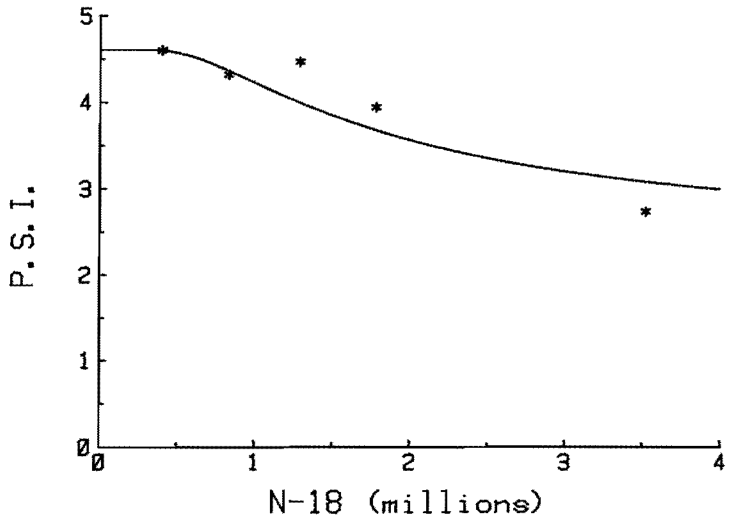

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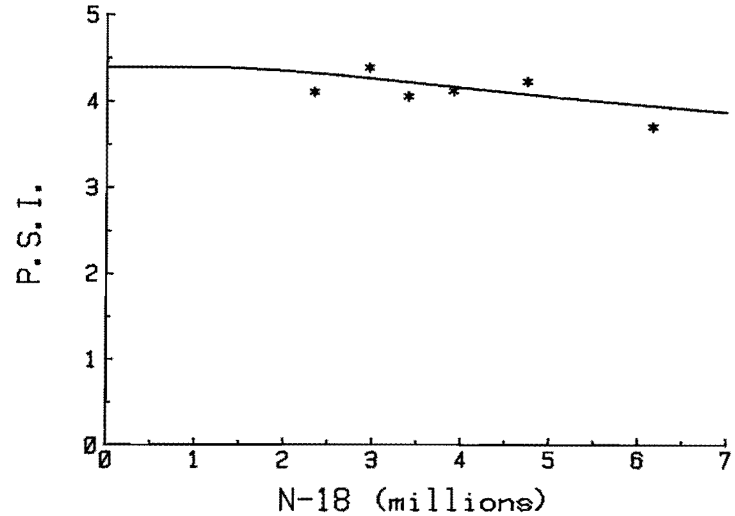

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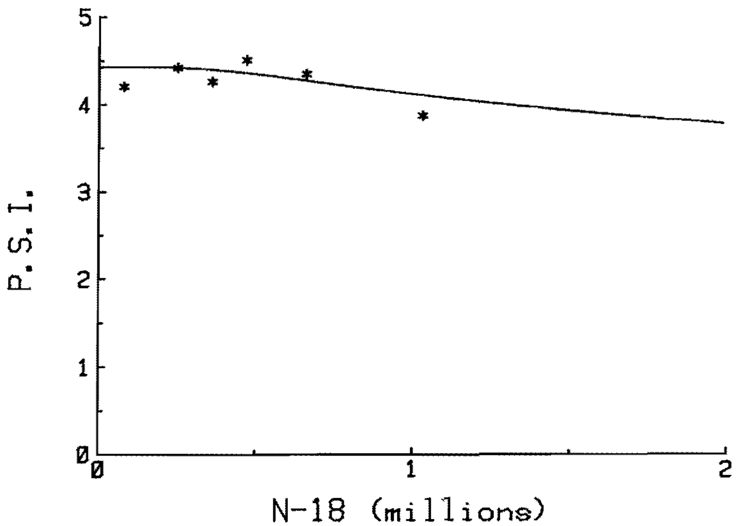

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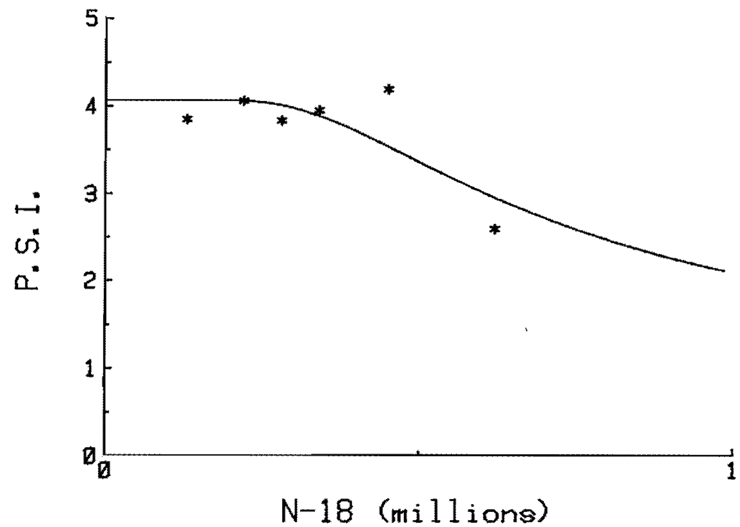

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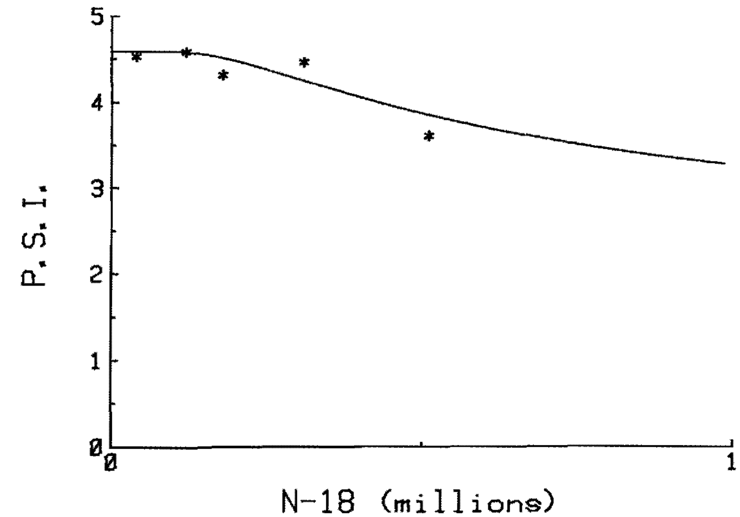

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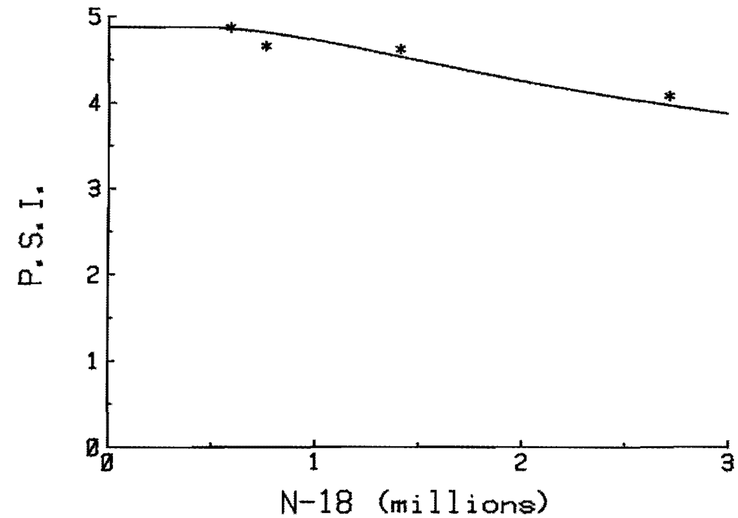

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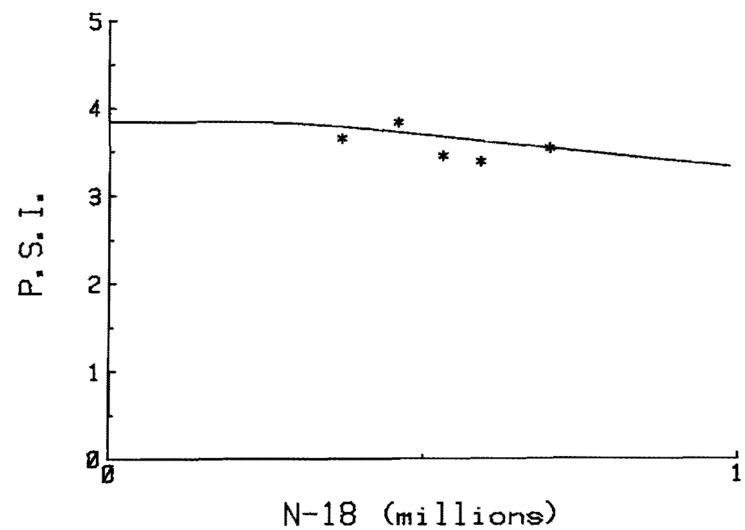

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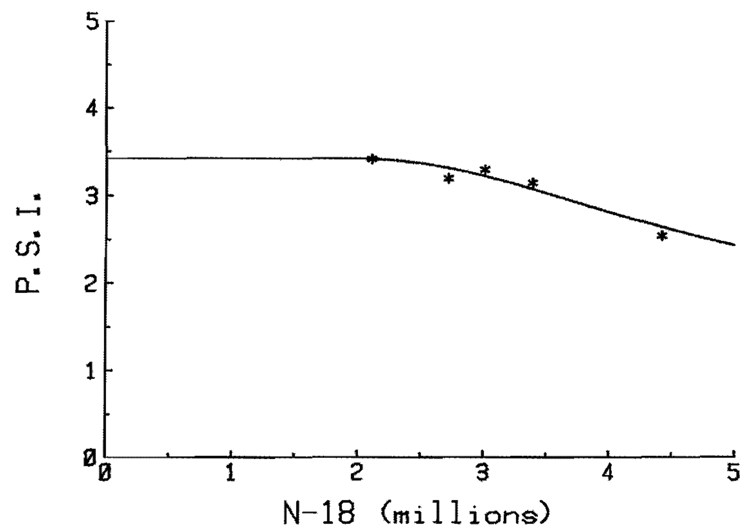

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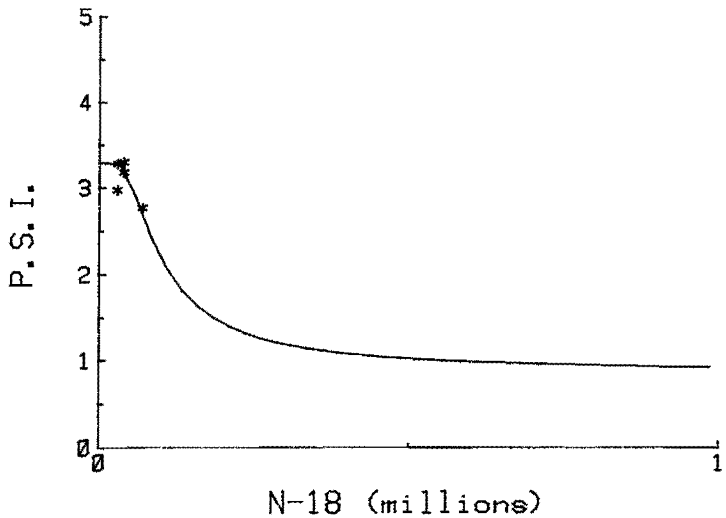

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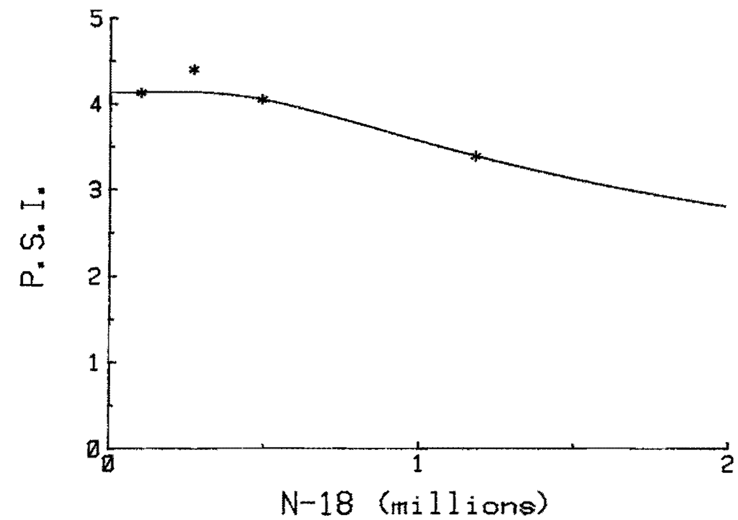

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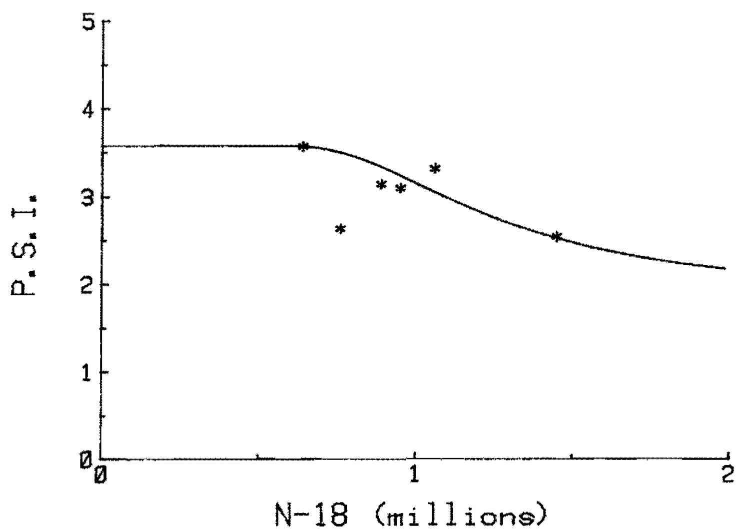

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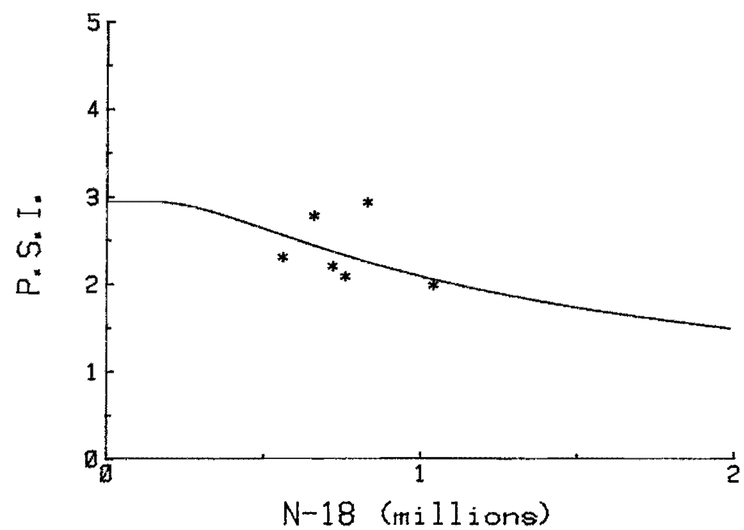

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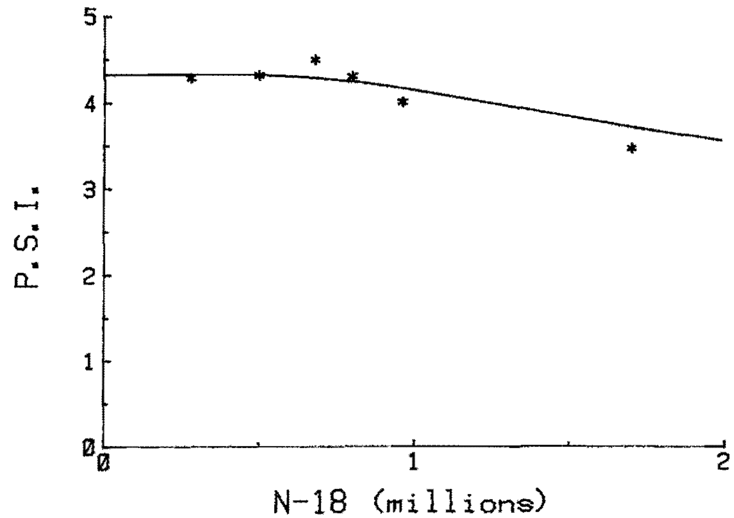

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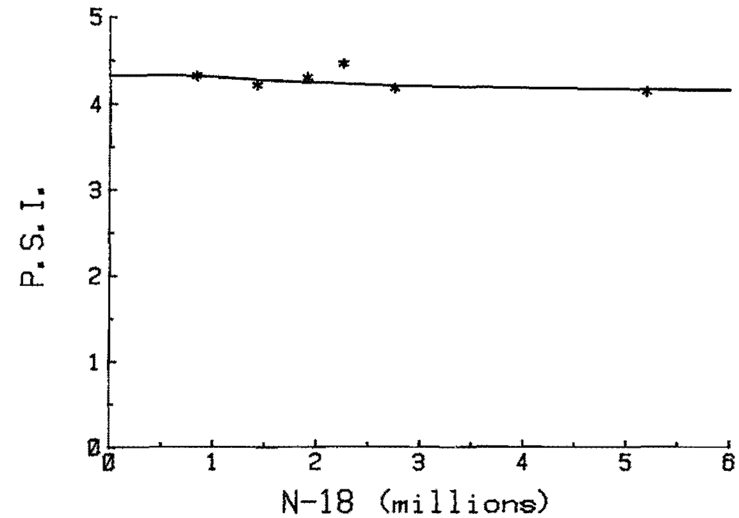

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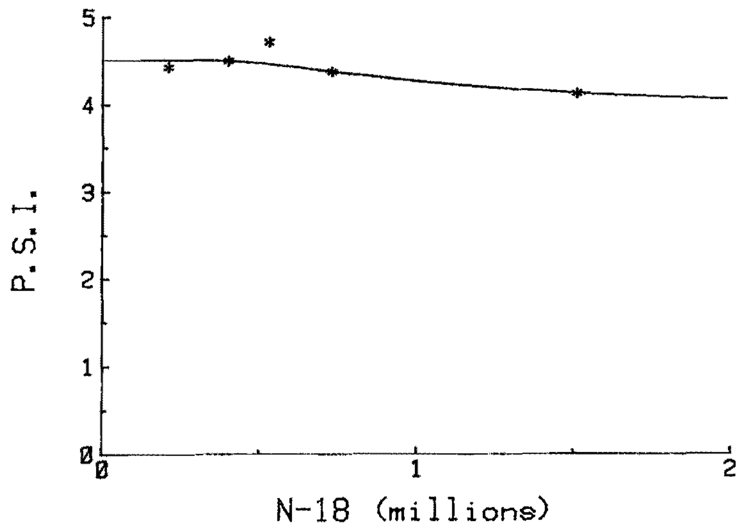

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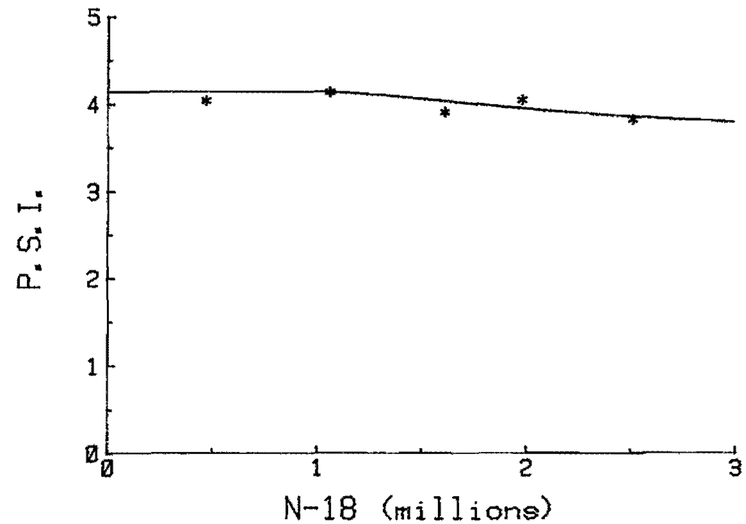

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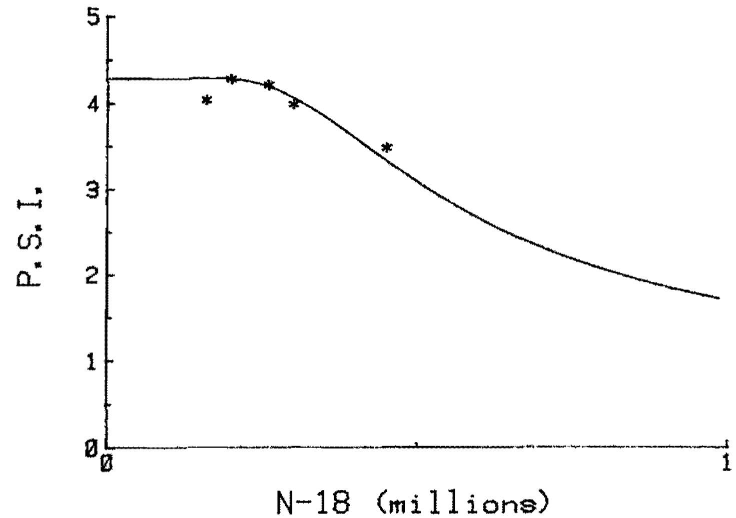

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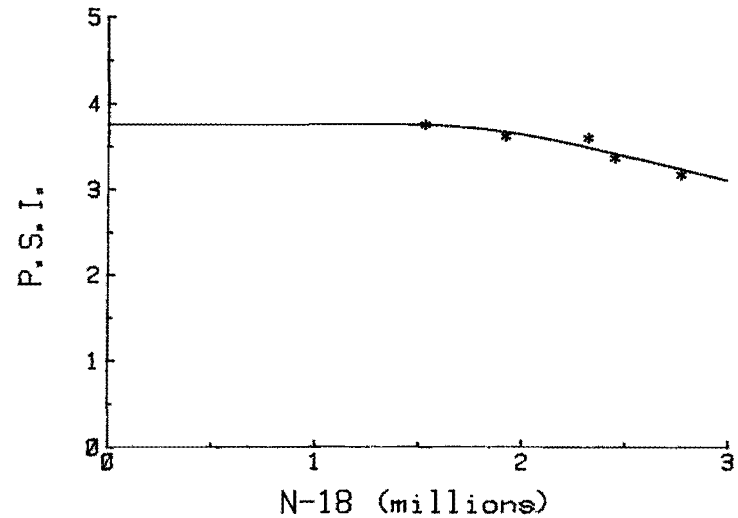

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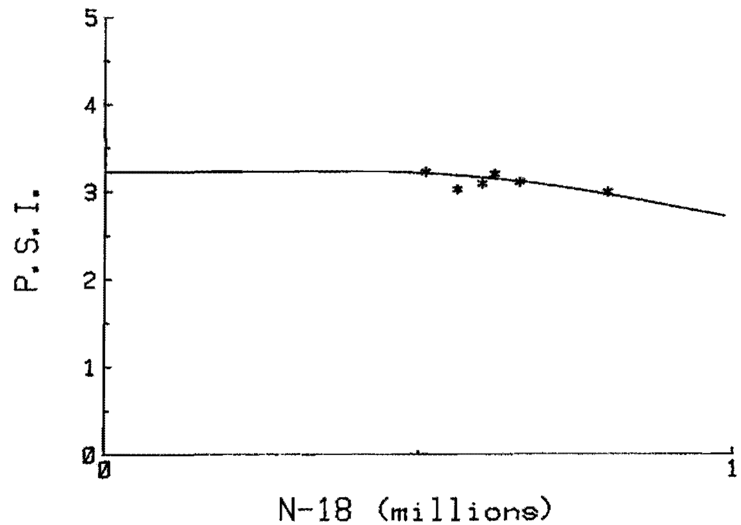

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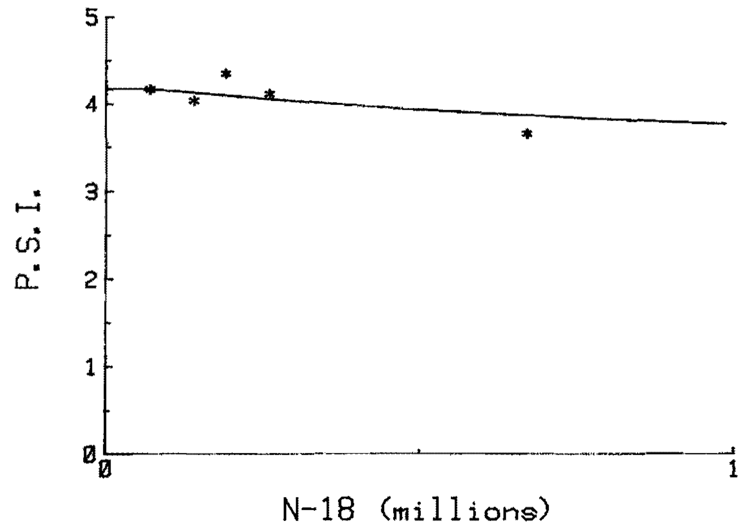

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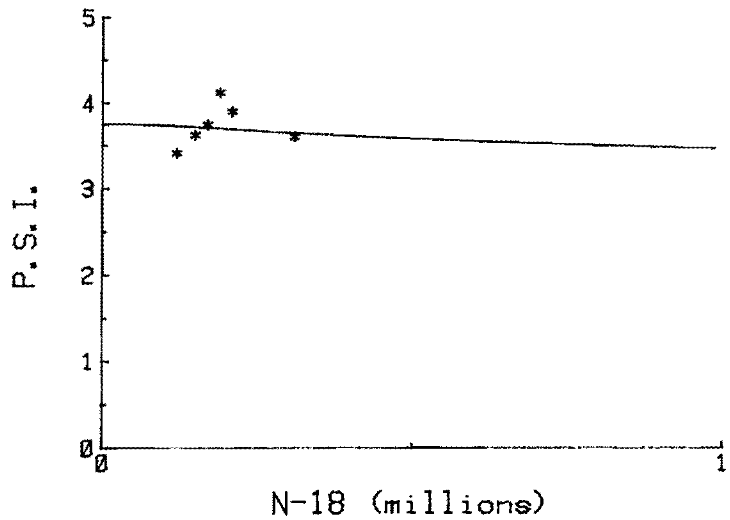

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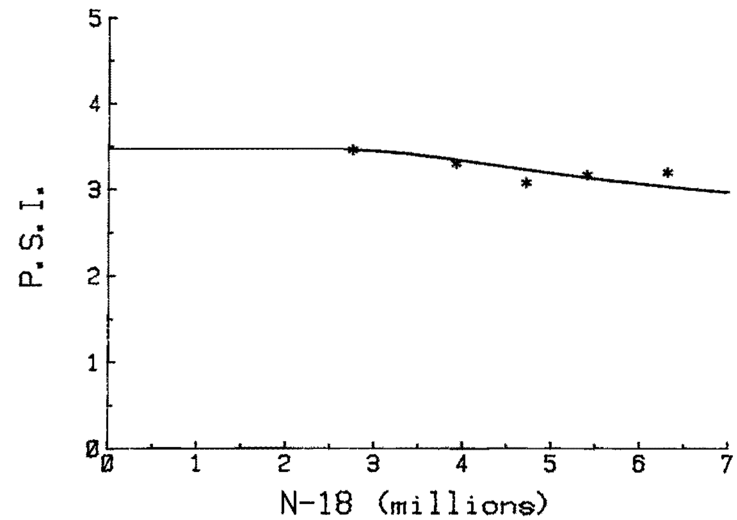

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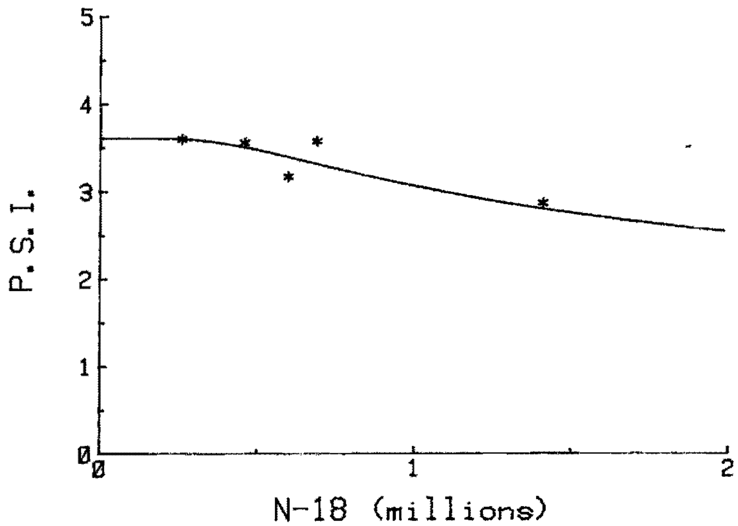

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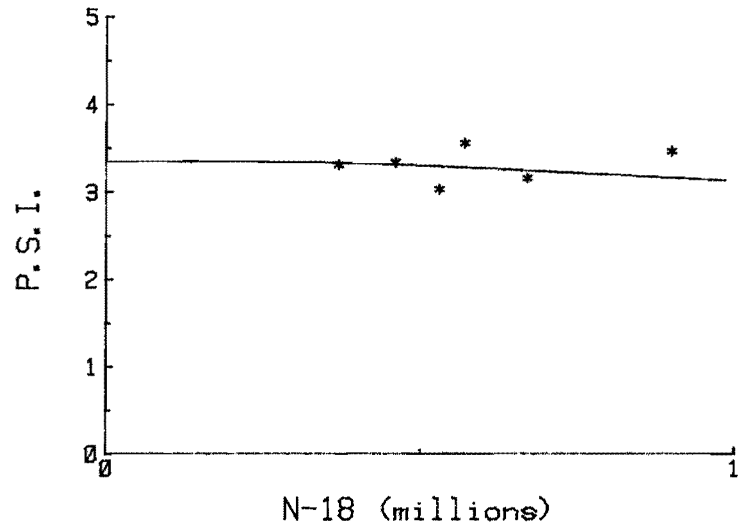

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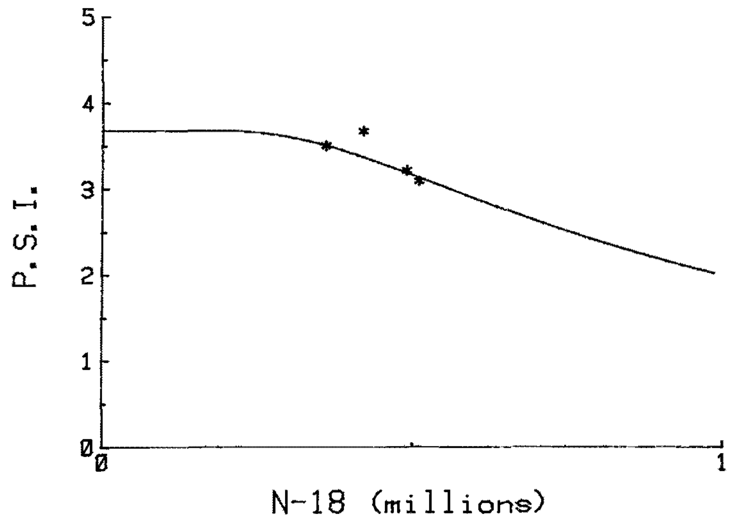

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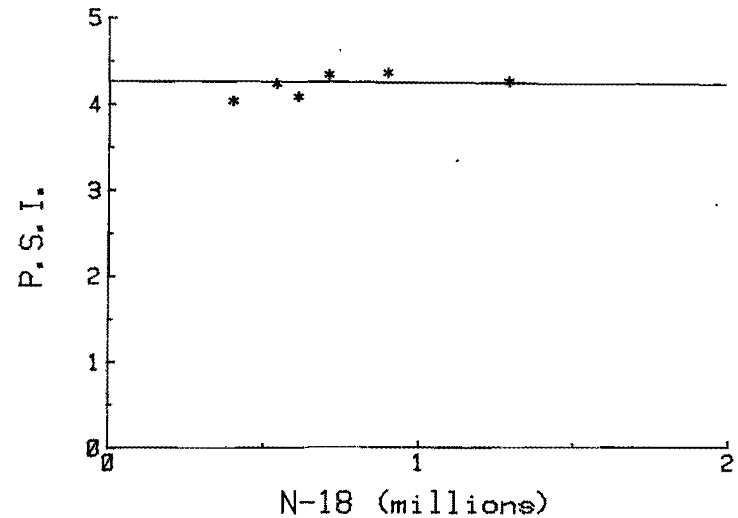

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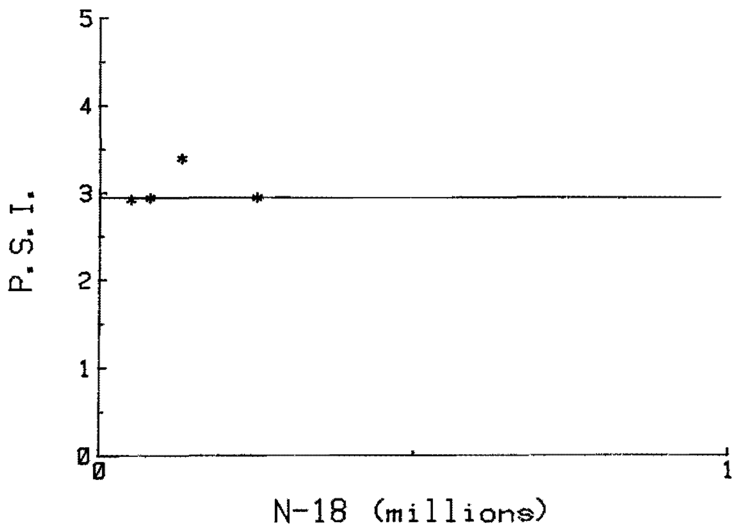

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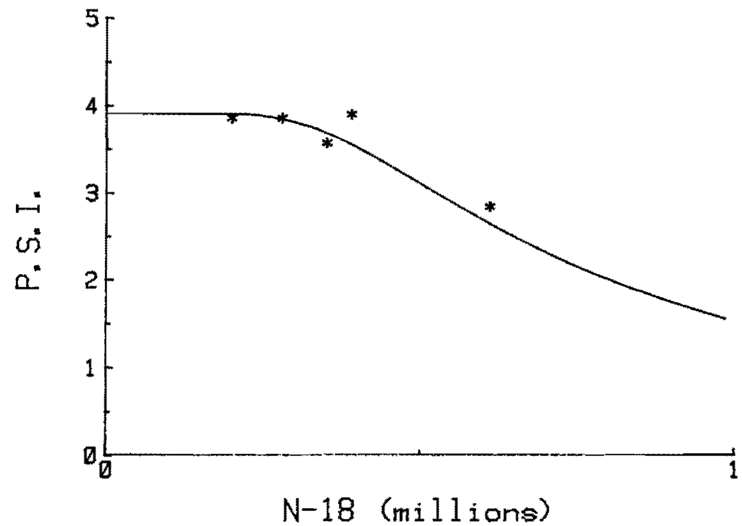

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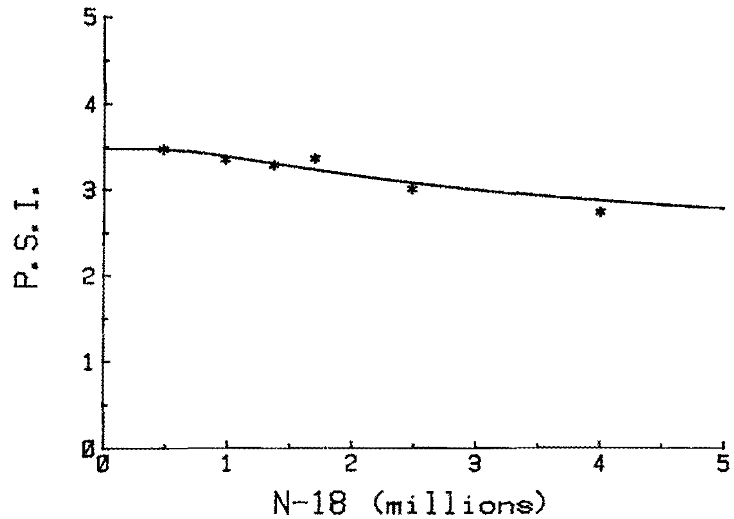

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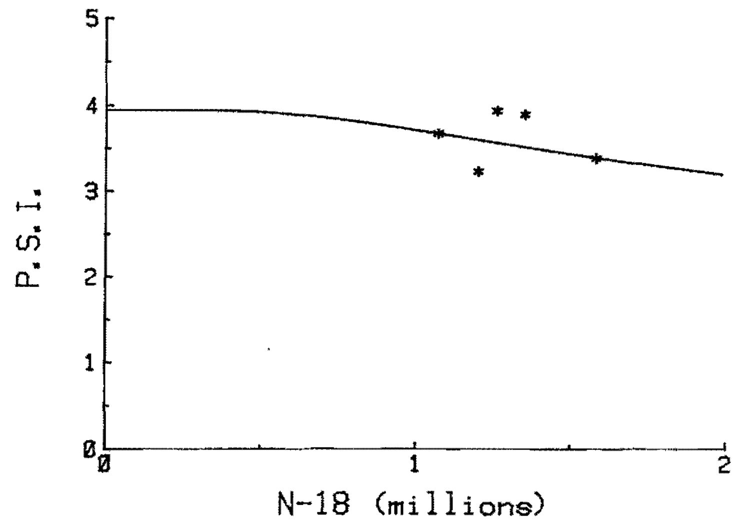

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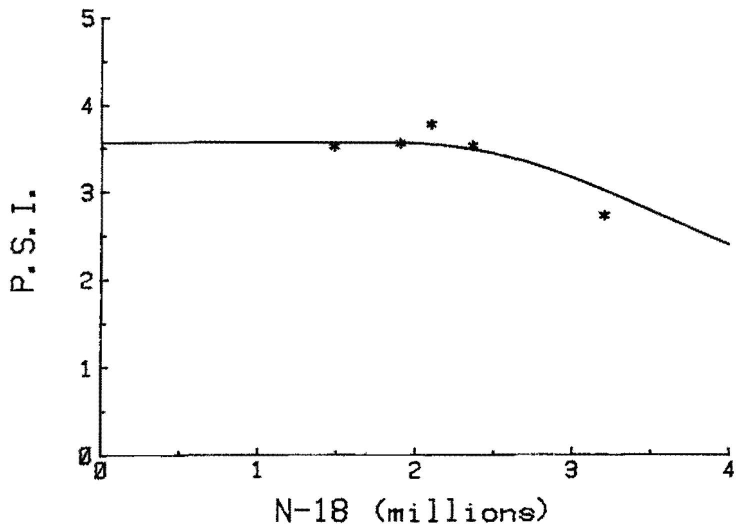

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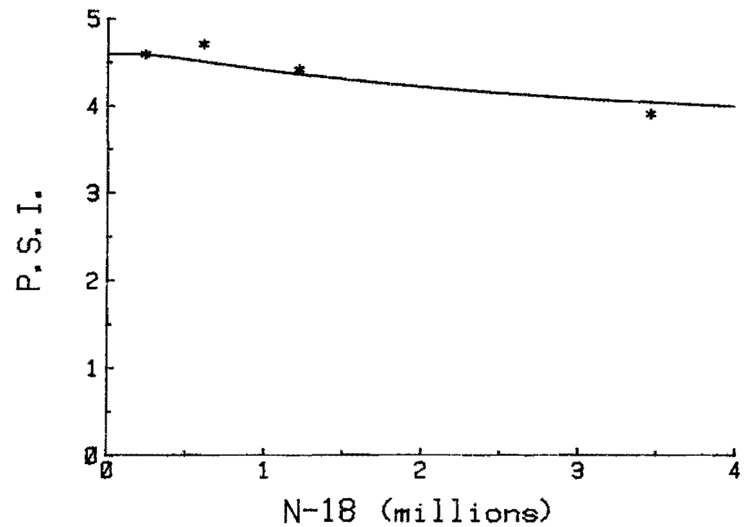

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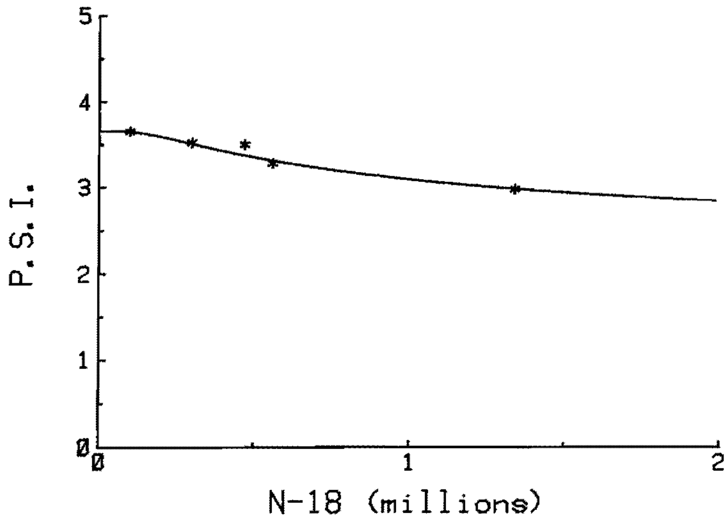

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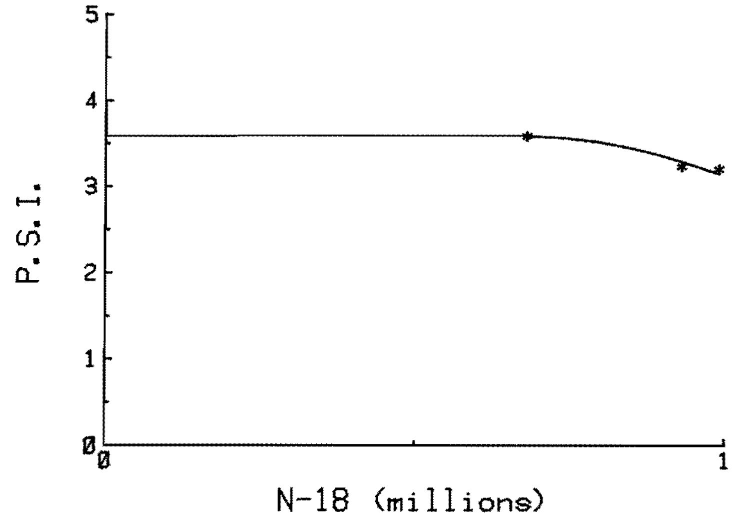

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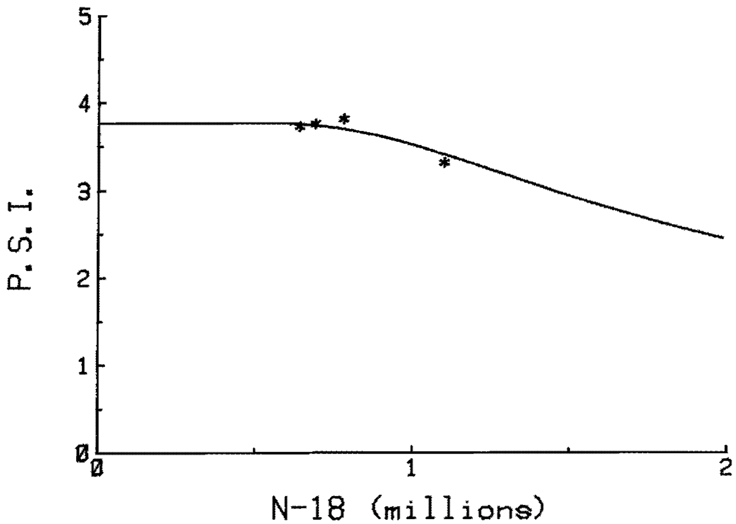

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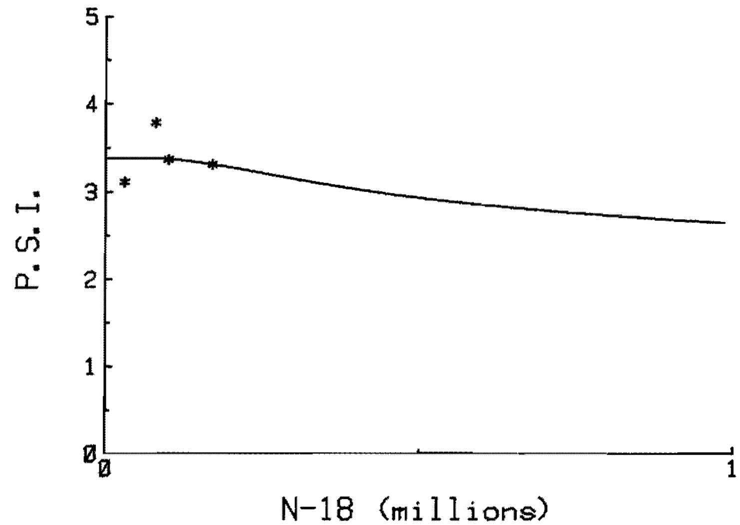

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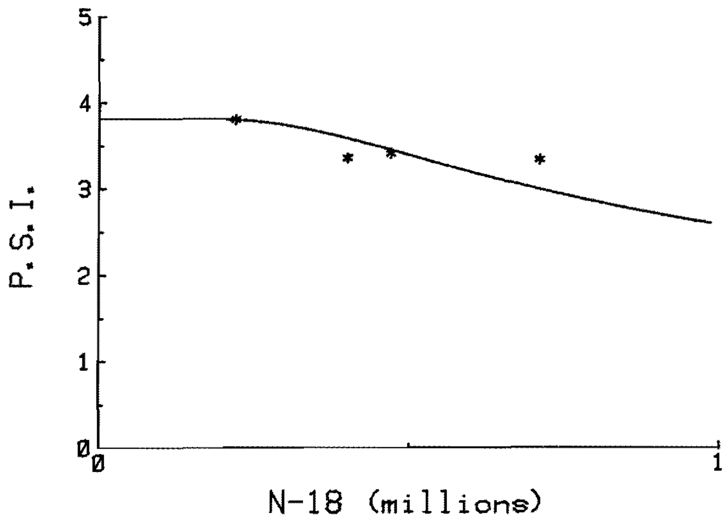

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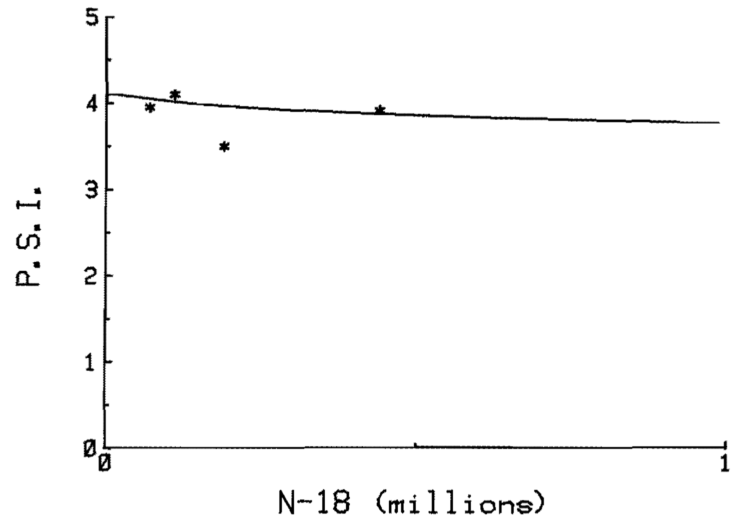

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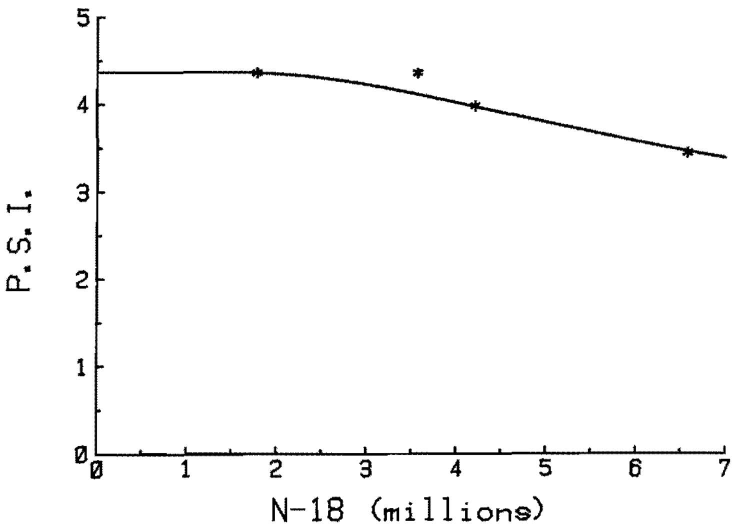

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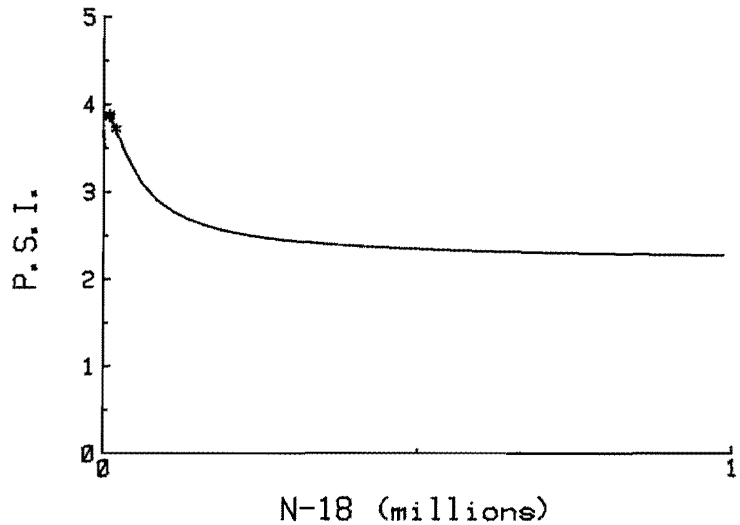

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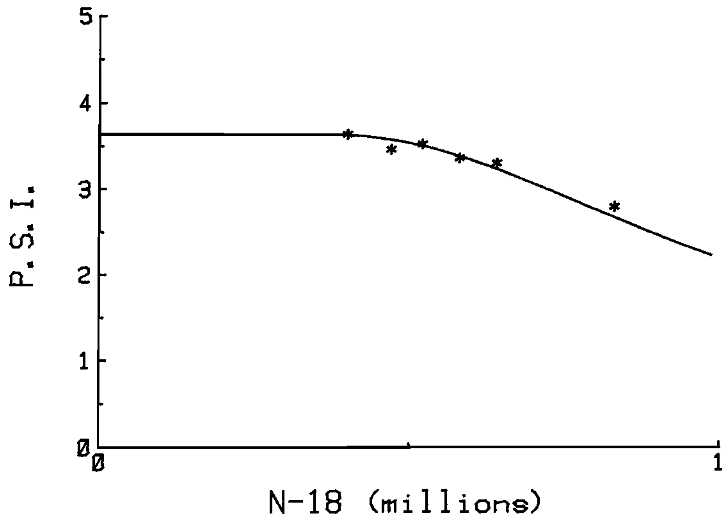

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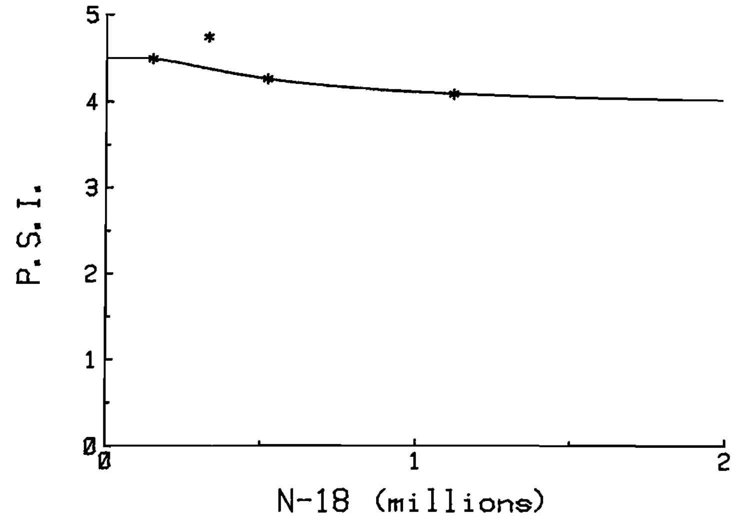

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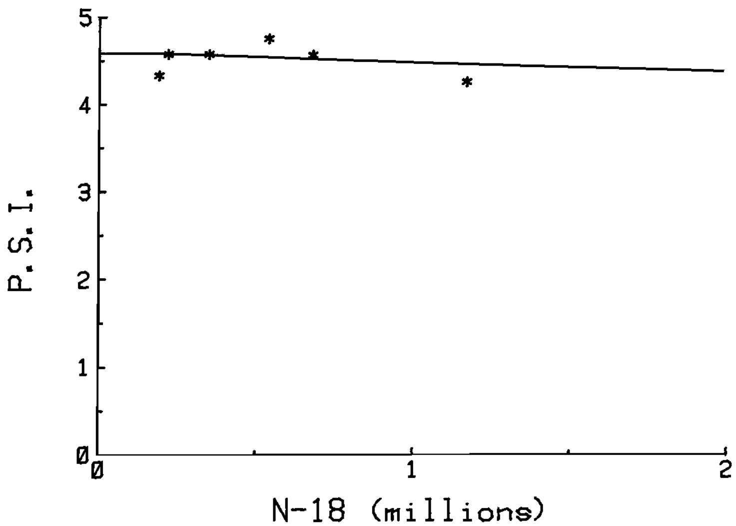

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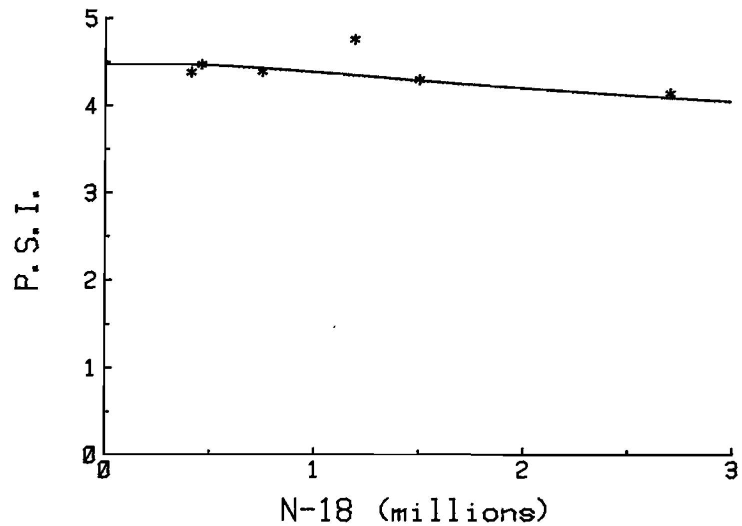
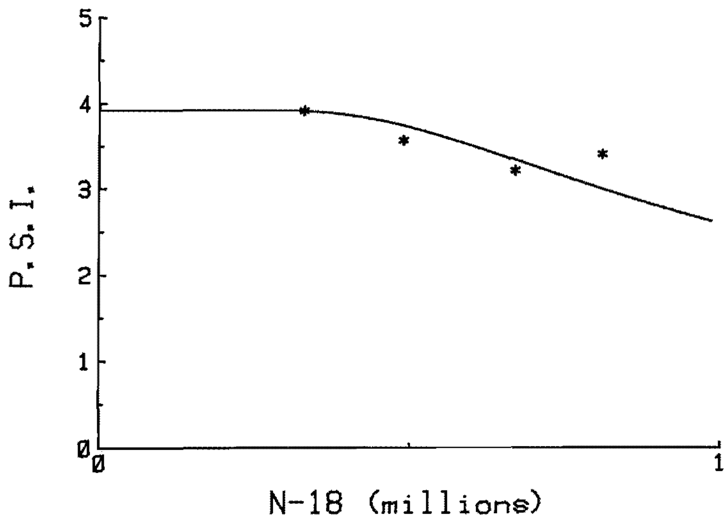


SECTION 262Ø



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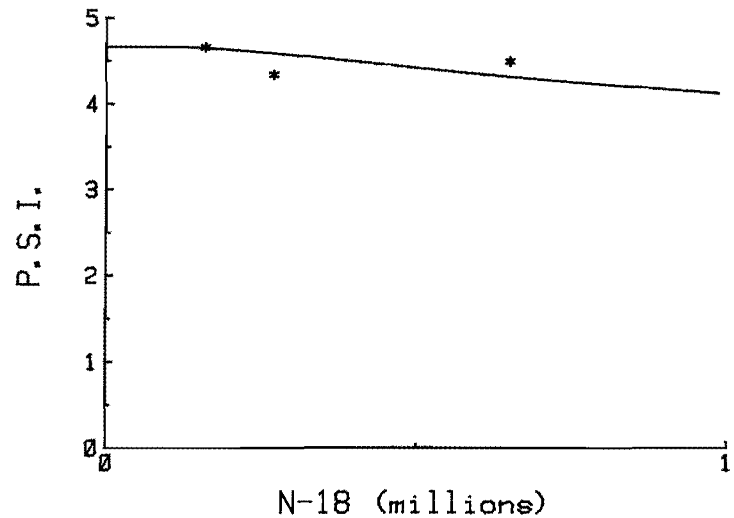

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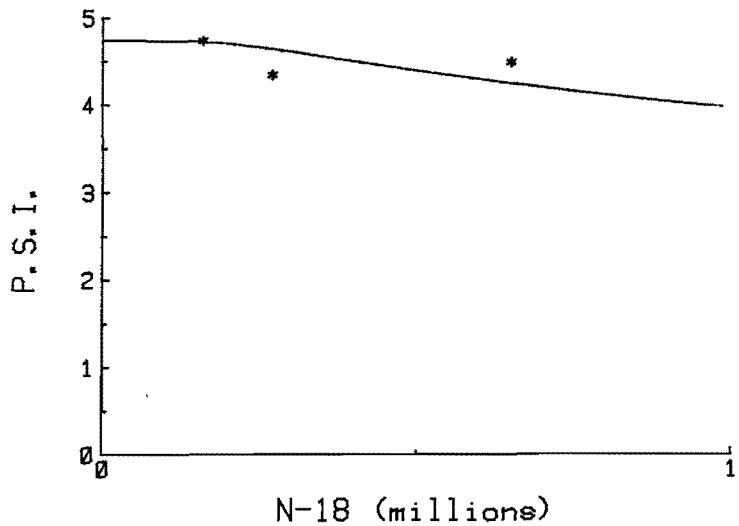

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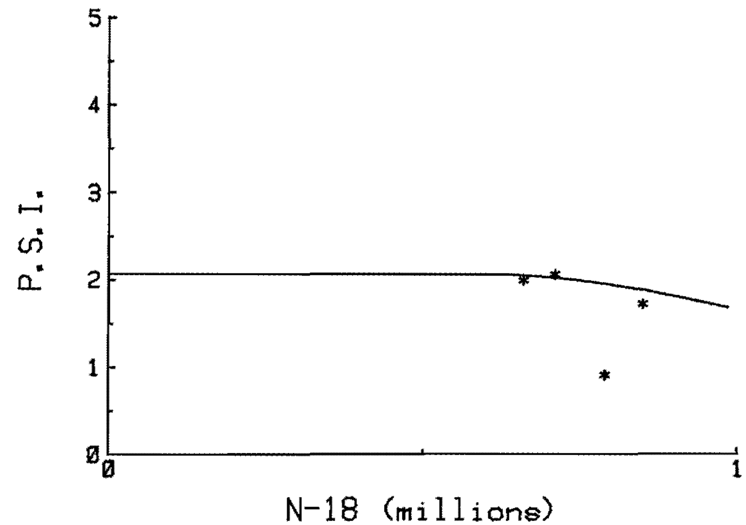

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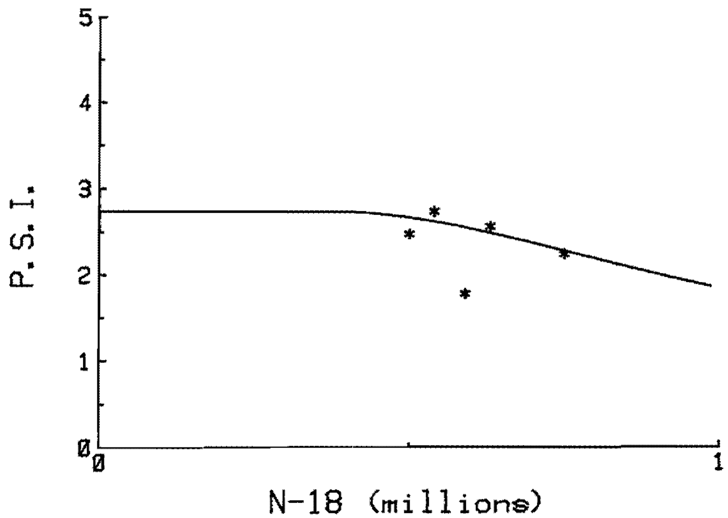
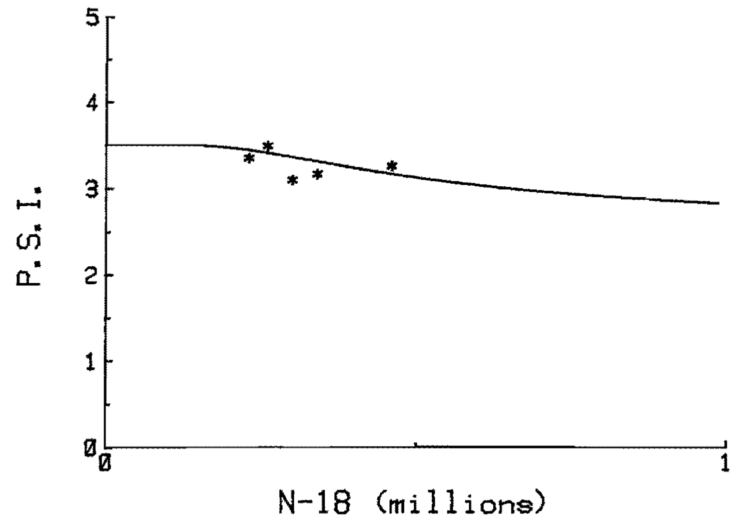


SECTION 3Ø61



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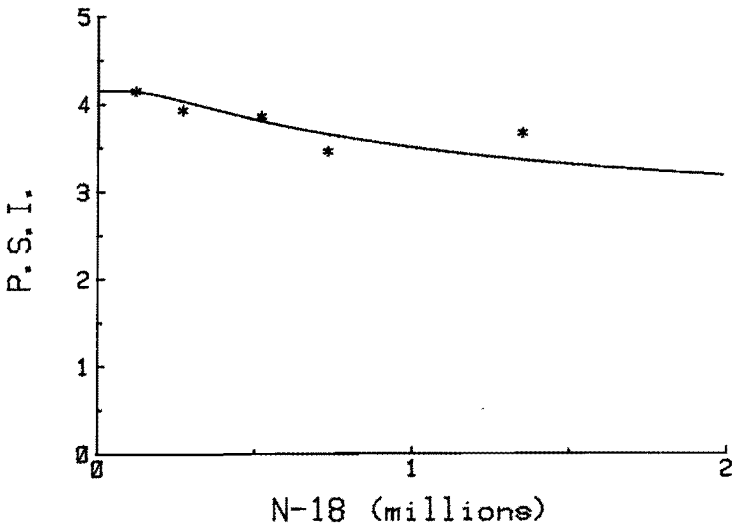
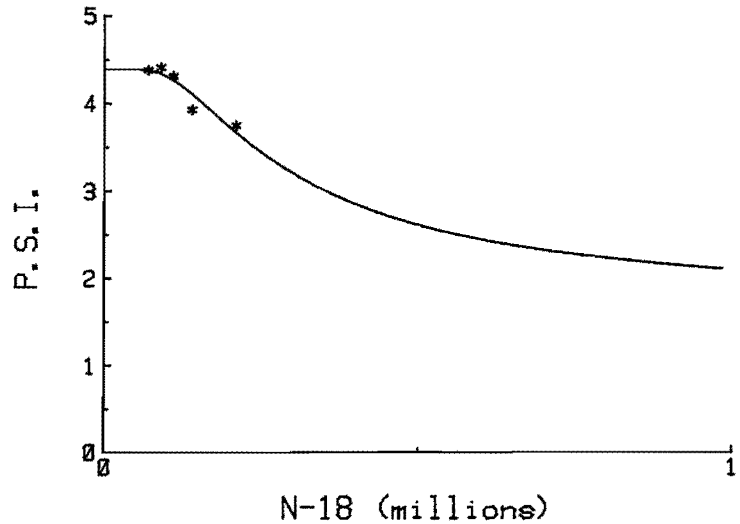
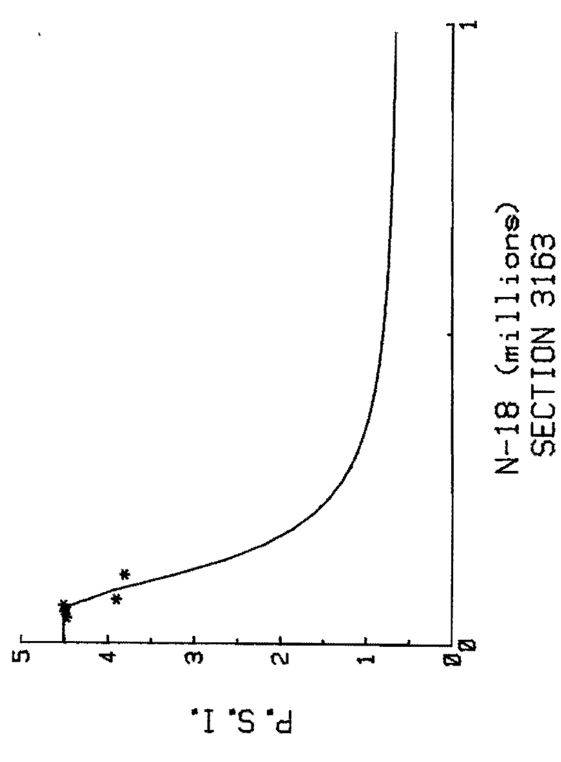


SECTION 3147



SECTION 315Ø


P. S. I.
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4
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2
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1
N-18 (millions)
SECTION 3163

APPENDIX 3
DESIGN PARAMETERS

Test Section Number	P_c	P_f	β	ρ
306	4.53	3.761	.438	4.940
1556	3.84	1.917	.936	2.604
1572	4.04	3.661	.300	17.239
1603	3.02	0.089	1.649	2.266
1690	3.88	3.838	0.140	0.005
2251	4.32	3.381	0.742	5.749
2455	4.74	3.775	.470	1.252
2515	4.03	.711	2.021	.678
2528	4.27	1.419	1.348	1.116
2531	4.35	3.573	0.615	2.006
2544	4.50	1.761	1.047	2.142
2560	4.12	1.734	1.115	2.837
2573	4.57	3.719	.470	.551
2586	4.55	3.125	.693	.778
2599	4.26	3.704	.336	1.590
2604	4.48	3.264	.833	2.889
2617	4.49	3.031	.742	.749
2633	4.36	2.932	.718	2.558
2646	3.99	1.713	1.209	1.291
2662	4.24	2.877	.788	3.297
2824	4.22	2.529	1.209	0.076
2837	4.31	0.040	1.493	0.097
2840	3.46	0.008	2.041	0.717
2853	4.26	1.060	1.526	0.524

Test Section Number	P_o	P_f	β	ρ
2866	4.48	0.007	2.366	1.546
2879	2.79	0.004	6.277	1.609
2882	4.44	2.985	1.967	0.810
2895	4.32	3.107	0.615	0.105
2913	3.95	0.011	3.003	1.996
2926	4.53	0.001	2.530	2.121
2939	4.26	0.063	1.909	1.946
2942	4.53	0.019	2.104	1.991
2955	4.75	0.033	2.067	1.804
2968	4.48	.000	5.112	2.476
3176	4.52	0.043	2.067	1.268
3189	3.58	0.902	1.558	0.740
3192	3.87	2.140	1.030	1.503
3207	3.82	3.359	0.560	3.858
3210	4.77	2.639	0.975	.916
3223	3.93	0.942	1.714	.619
3236	3.54	1.153	1.399	.615
3249	3.96	1.409	1.459	1.856
3281	4.42	3.683	0.501	2.710
3294	3.94	3.335	0.372	1.584
3309	4.01	2.727	0.854	2.570
3312	3.57	.195	1.082	2.905
3325	4.05	2.897	0.742	3.467
3338	4.07	2.750	0.693	4.143

Test Section Number	P_o	P_f	β	ρ
3341	3.53	2.859	0.470	9.580
3354	4.58	4.295	0.300	1.857
3367	4.13	0.825	1.609	3.816

Test Section Number	P_o	P_f	β	ρ
102	3.69	2.673	.742	2.123
217	3.13	0.010	2.180	1.494
408	4.34	2.076	1.238	2.578
437	3.81	3.80	0.095	0
479	3.65	0.747	1.686	1.035
500	3.94	0.006	7.135	2.916
513	3.07	0.049	1.411	4.337
615	4.78	3.274	0.765	2.491
673	3.85	1.959	1.209	0.854
775	--	--	--	--
791	4.07	0.001	4.043	1.826
1145	3.73	0.013	2.256	1.136
1276	3.67	0.884	1.848	1.566
1292	4.28	1.943	1.082	0.755
1687	3.80	3.039	0.718	11.098
1747	3.59	0.740	1.649	0.166
1878	3.45	0.593	1.775	0.100
1909	3.31	1.118	1.281	1.170
1925	3.62	3.312	0.182	0.116
2099	3.69	2.858	0.501	1.324
2191	--	--	--	--
2206	3.75	1.940	1.147	0.460
2219	3.84	3.002	0.470	1.709
2675	2.86	0.798	2.303	2.161

Test Section Number	P_o	P_f	β	ρ
2691	4.28	1.189	1.732	3.653
2719	--	--	--	--
2722	--	--	--	--
2735	--	--	--	--
2748	4.62	3.866	3.170	1.392
2751	4.72	4.305	2.134	1.207
2764	4.65	1.040	1.749	1.655
2777	4.25	2.268	1.194	5.101
2793	4.25	2.894	0.916	7.445
2971	3.38	0.000	4.329	1.103
2997	3.51	0.000	4.807	0.862
3003	3.57	0.001	3.778	0.265
3016	4.44	2.265	1.065	0.418
3029	4.23	0.005	7.259	1.528
3087	3.73	2.351	0.788	3.131
3090	--	--	--	--
3105	3.45	2.681	0.470	1.306
3121	4.32	2.046	1.147	0.086

Test Section Number	P_o	P_f	β	ρ
13	3.39	0.916	1.808	3.947
39	3.45	0.656	1.932	5.568
71	3.61	1.407	1.348	2.994
160	4.03	3.935	0.140	0.020
186	4.28	0.075	1.322	3.469
199	4.21	3.573	0.405	2.722
220	4.17	1.011	1.335	2.107
233	2.91	2.261	0.336	1.048
246	4.10	3.833	0.223	1.543
259	3.33	3.103	0.405	1.161
288	3.15	0.557	1.800	1.530
291	3.85	1.412	1.411	0.098
319	4.49	3.818	1.295	0.789
335	4.62	3.958	1.030	0.161
351	4.07	3.719	0.372	0.557
393	4.24	2.346	0.956	1.429
424	4.58	2.921	0.811	1.249
555	2.49	1.871	0.916	5.506
602	4.41	3.808	0.405	4.264
657	4.49	4.190	0.140	0.013
660	4.59	4.391	0.336	5.439
759	3.36	2.866	0.501	1.936
848	4.51	2.978	0.718	4.411
877	3.41	0.788	1.668	0.843

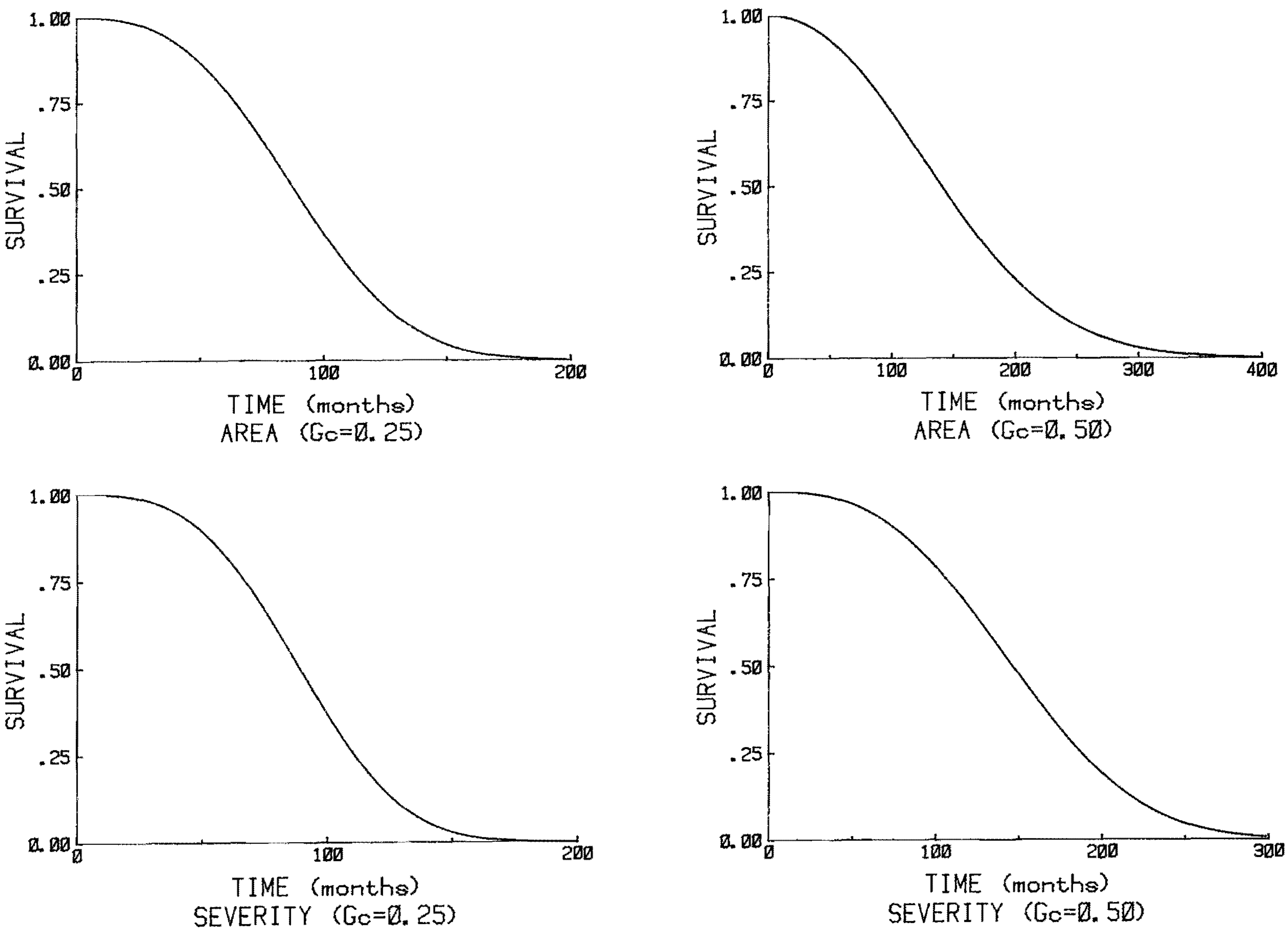
Test Section Number	P_o	P_f	β	ρ
893	4.61	2.381	1.224	1.582
924	4.40	2.608	0.875	8.785
937	4.43	2.812	0.833	1.818
953	4.07	0.955	1.696	0.627
966	4.59	2.208	1.011	0.590
995	4.88	2.289	0.993	2.835
1001	3.85	2.047	0.975	1.245
1043	3.42	1.416	2.303	4.304
1072	3.29	0.881	1.589	0.086
1174	4.14	1.289	1.082	1.542
1190	3.58	1.884	2.893	1.115
1218	2.95	0.300	0.916	1.133
1234	4.33	2.045	1.224	2.122
1250	4.33	4.130	1.493	1.709
1263	4.51	3.907	1.639	0.946
1289	4.15	3.661	2.303	1.885
1307	4.29	0.841	1.864	0.512
1323	3.76	1.769	2.303	3.126
1349	3.23	0.903	1.658	1.269
1365	4.18	3.146	0.615	0.903
1412	--	--	--	--
1438	3.75	3.039	0.615	0.861
1543	3.47	2.647	2.303	5.148
1632	--	--	--	--

Test Section Number	P_o	P_f	β	ρ
1674	3.61	1.682	1.082	1.234
1734	--	--	--	--
1750	3.35	2.168	0.916	1.754
1776	3.68	0.004	1.322	0.831
1836	4.27	3.951	0.438	9.188
1852	2.95	2.94	0.095	0.000
1865	3.91	0.028	1.677	0.652
1894	3.48	2.076	0.833	3.242
1941	3.95	1.440	0.975	2.395
1967	--	--	--	--
1983	3.57	0.019	2.313	4.180
2002	4.60	3.237	0.642	2.920
2015	3.66	2.260	0.742	0.867
2044	3.59	0.010	2.772	1.287
2060	3.77	1.012	1.705	1.669
2120	3.38	2.141	0.975	0.502
2133	3.81	1.348	1.335	0.765
2159	4.11	3.355	0.438	0.591
2308	--	--	--	--
2324	4.37	1.689	1.253	7.037
2337	3.89	2.185	0.993	0.046
2353	3.64	0.004	1.924	0.959
2468	4.50	3.935	1.253	0.457
2502	4.59	3.781	0.560	3.458

Test Section Number	P_o	P_f	β	ρ
2620	4.48	3.009	0.718	3.977
2659	3.92	0.881	1.696	0.897
2808	4.67	2.946	0.742	1.200
2811	4.74	2.681	0.854	0.973
2984	2.07	0.007	2.393	1.219
3061	2.74	0.482	1.848	0.959
3074	3.50	2.536	1.411	0.478
3147	4.16	2.441	0.765	0.949
3150	4.39	1.699	1.335	0.257
3163	4.51	0.612	2.054	0.116

APPENDIX 4

SURVIVOR CURVES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SURVIVAL
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TIME (months)
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SURVIVAL
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TIME (months)
SEVERITY (Gc=0.25)
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TIME (months)
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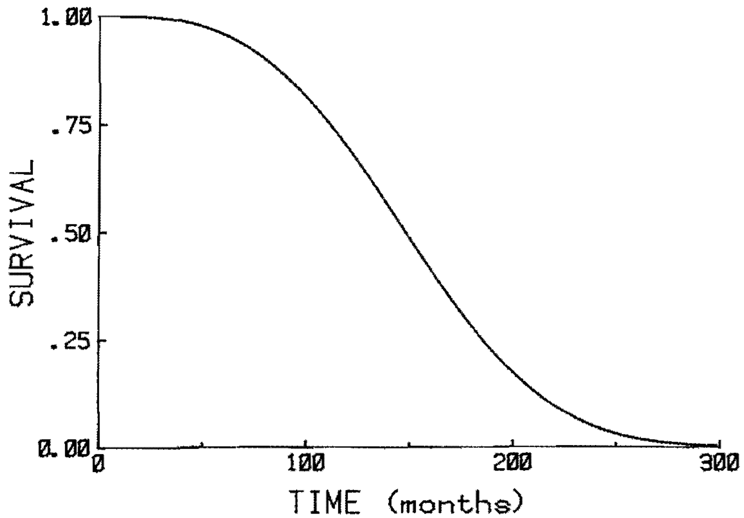

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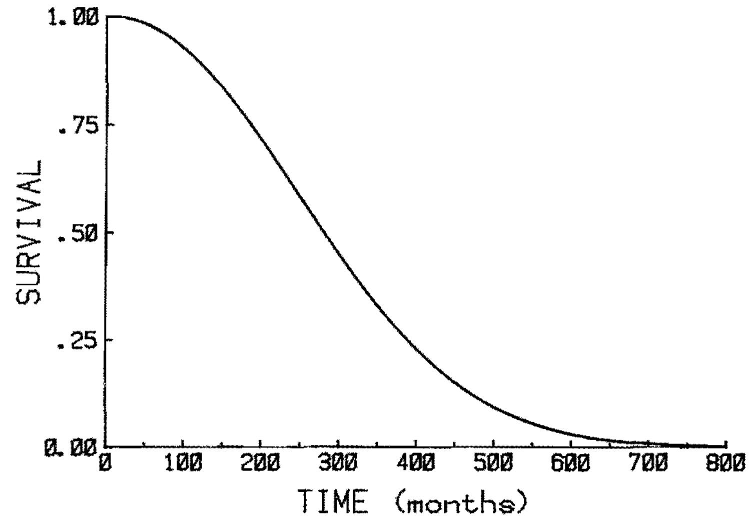

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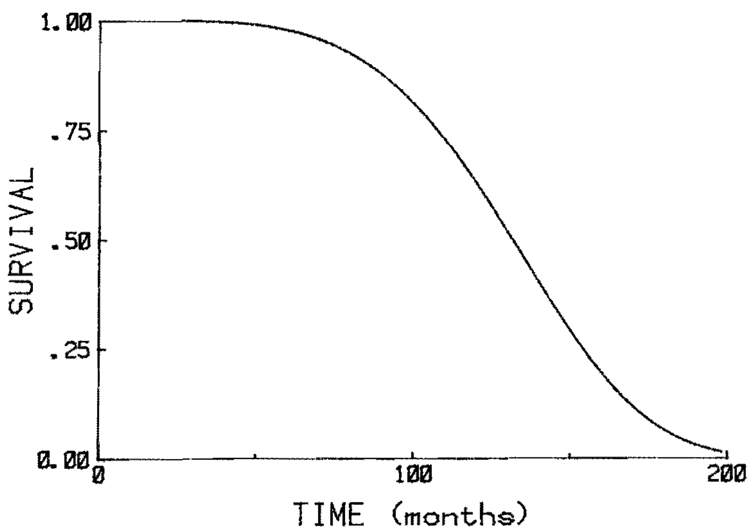

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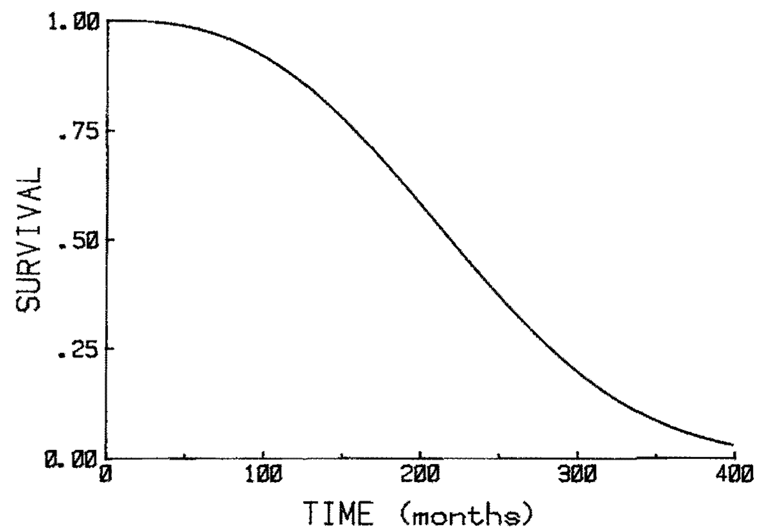

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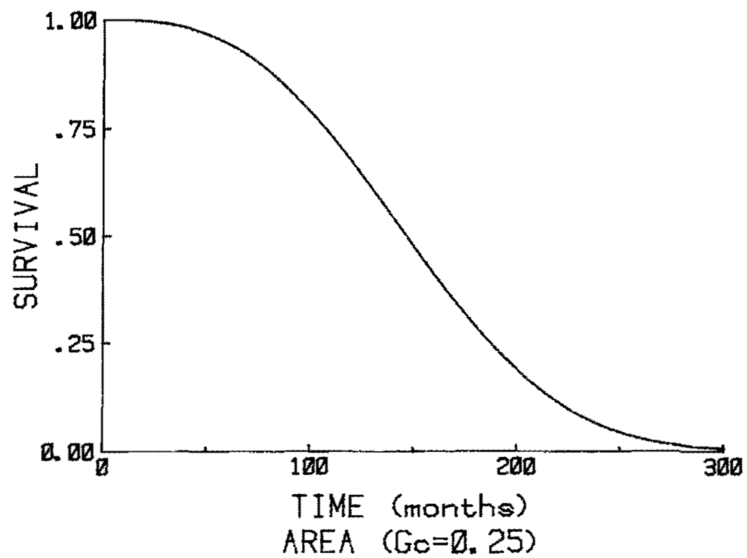
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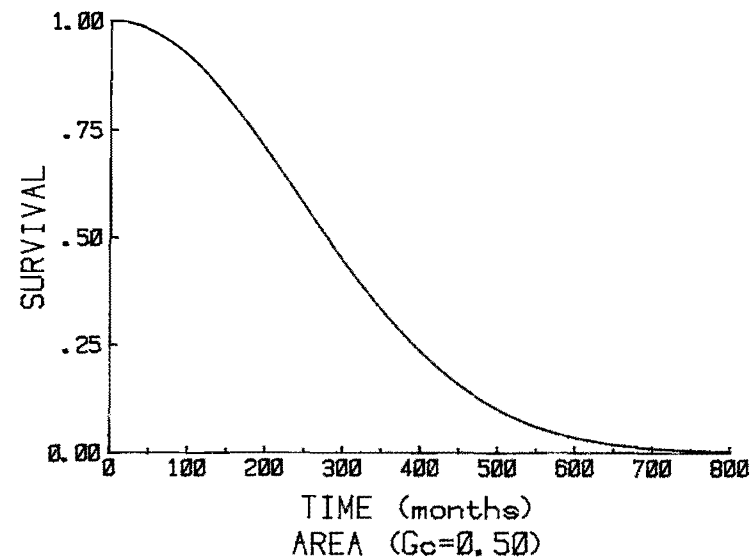
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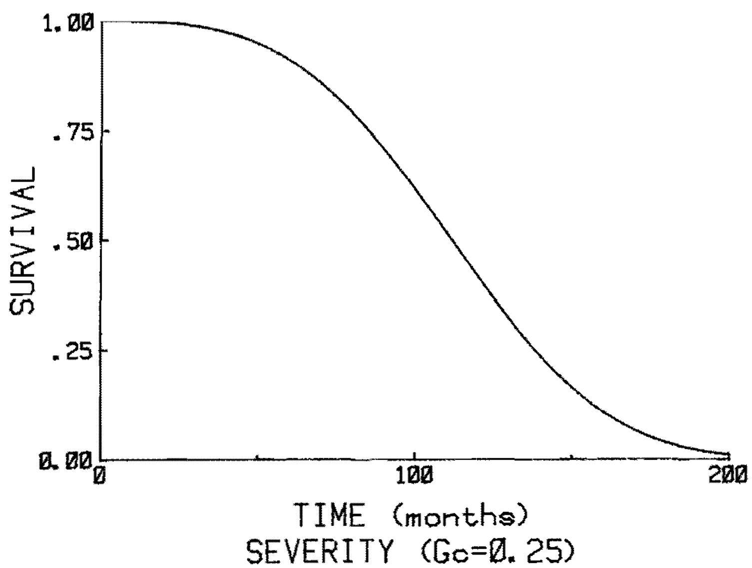
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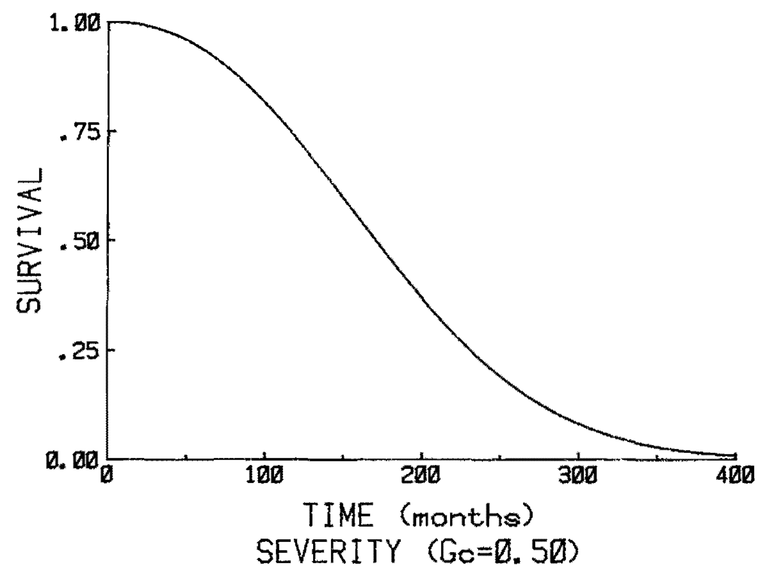
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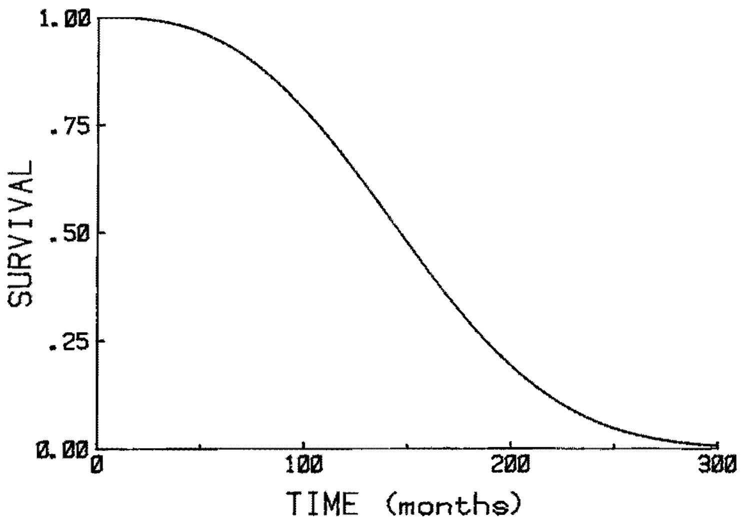

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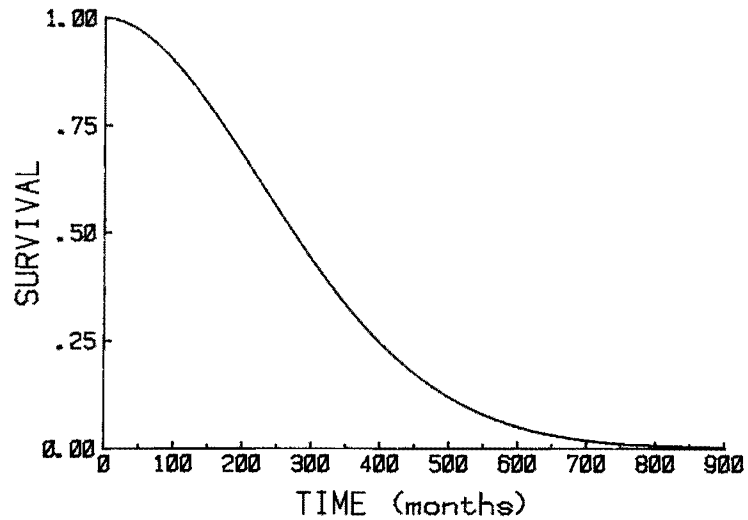

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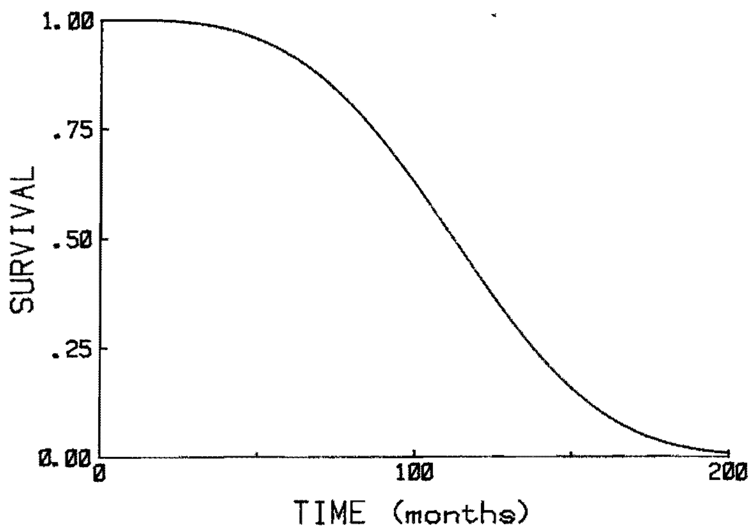

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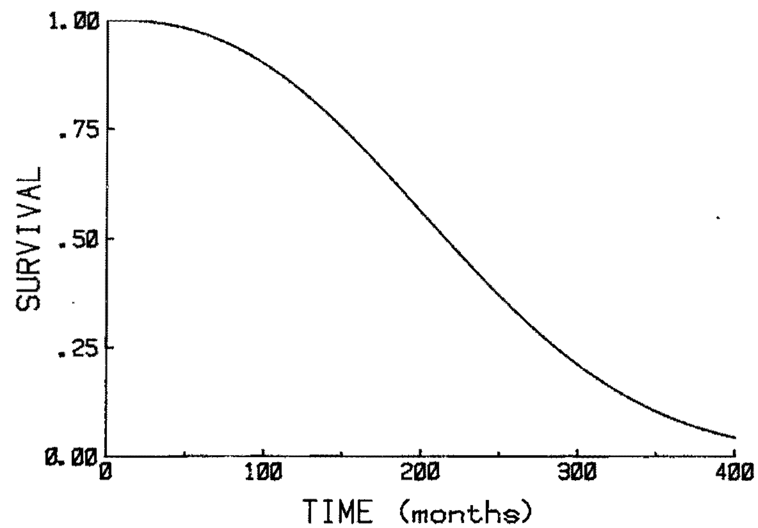

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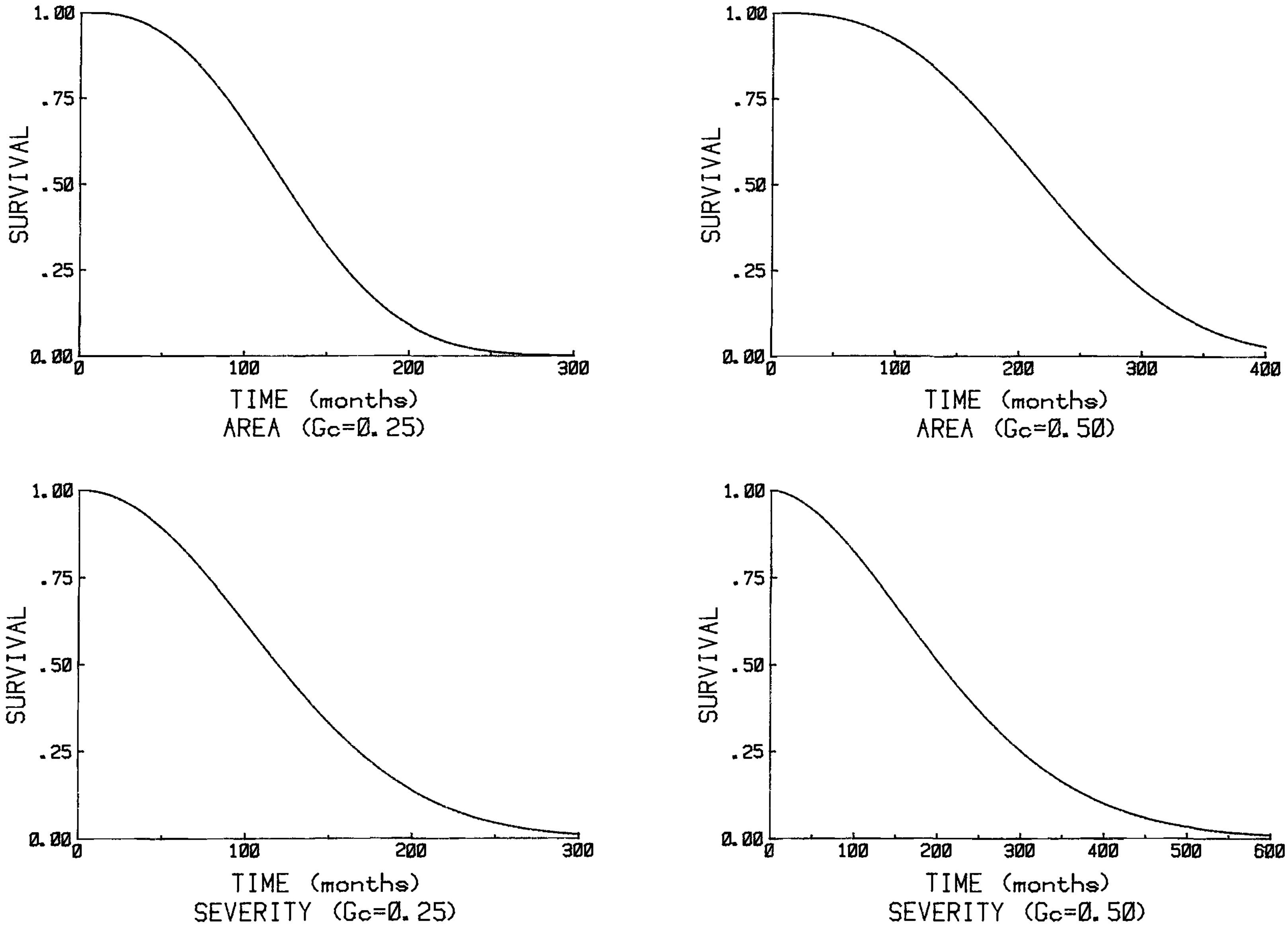

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200
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400
TIME (months)
AREA (Gc=0.50)
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SURVIVAL
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200
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TIME (months)
SEVERITY (Gc=0.25)
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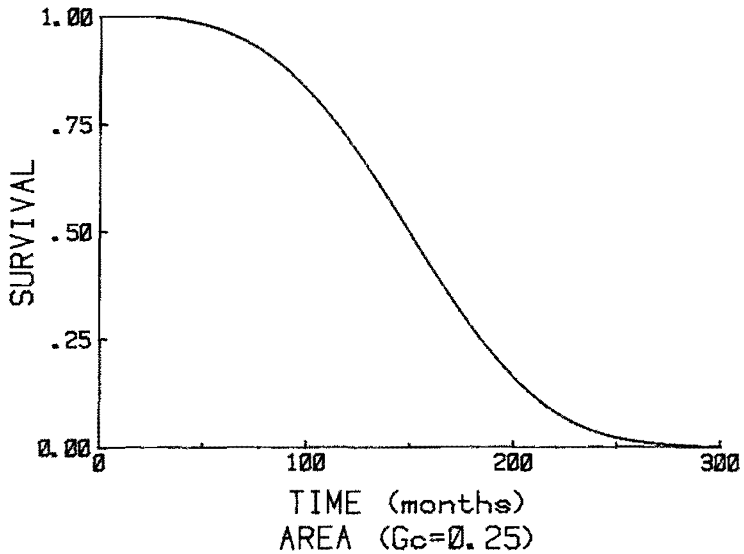
SEVERITY (Gc=0.50)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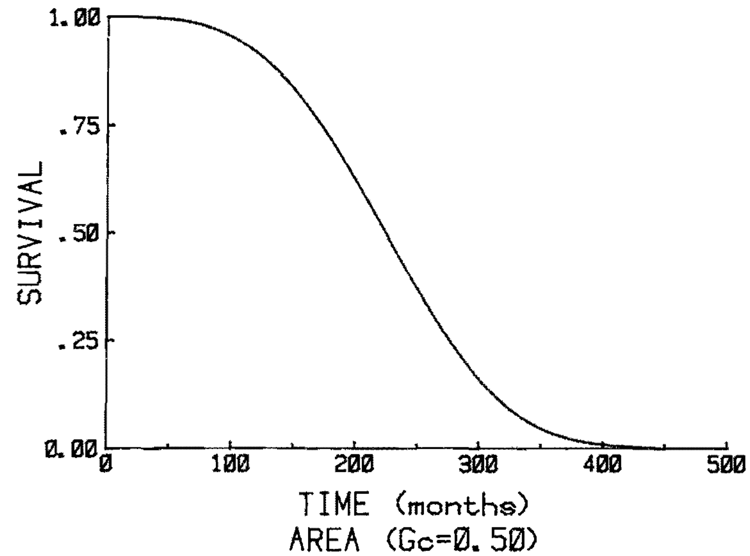
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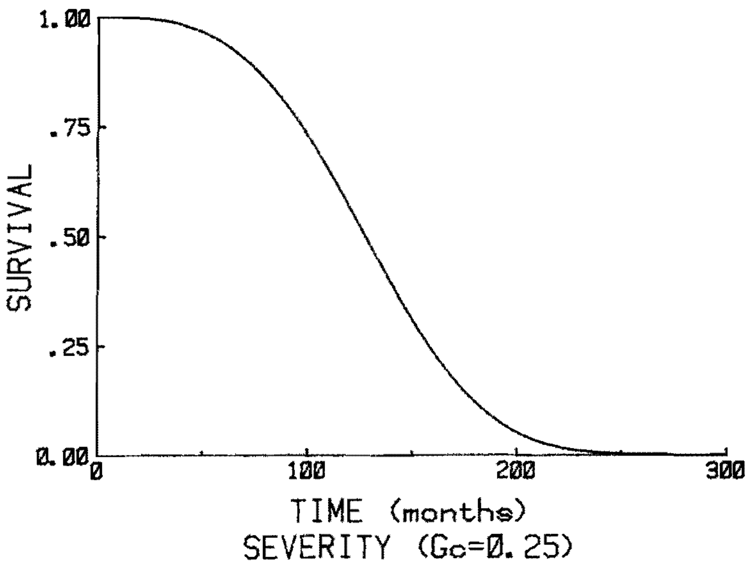
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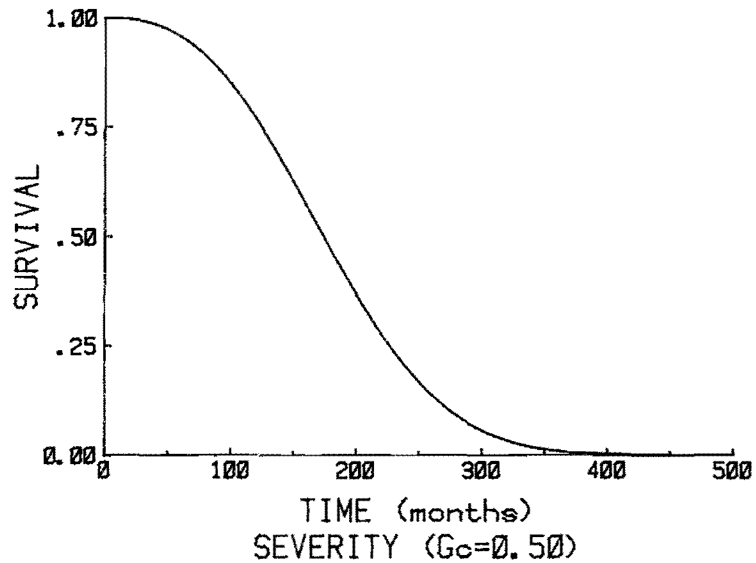
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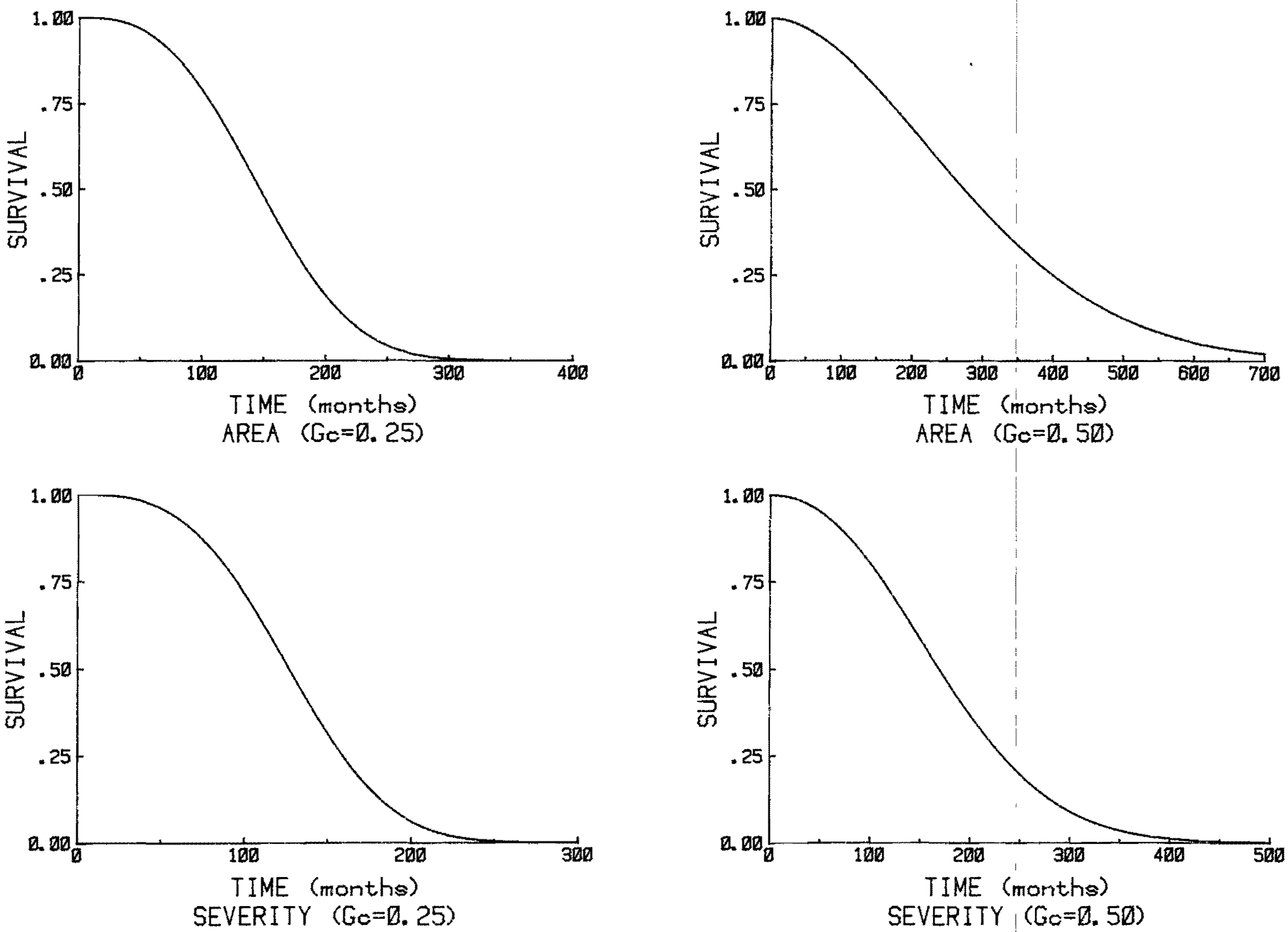
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TIME (months)
AREA (Gc=0.50)
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TIME (months)
SEVERITY (Gc=0.25)
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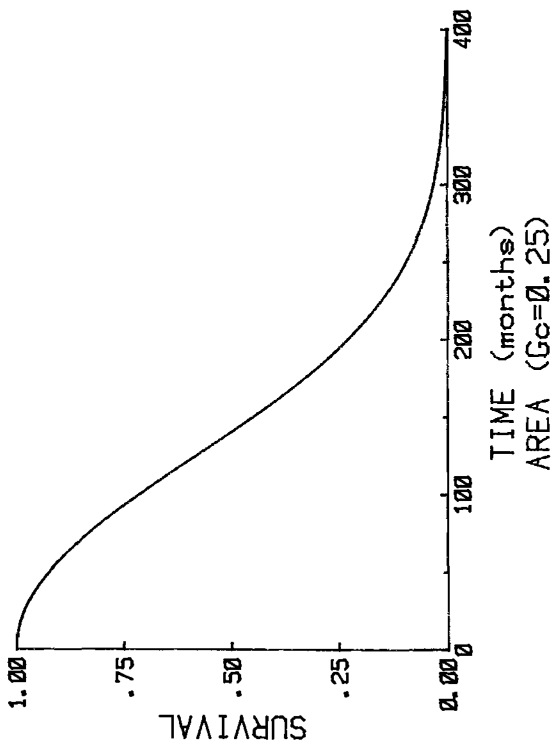
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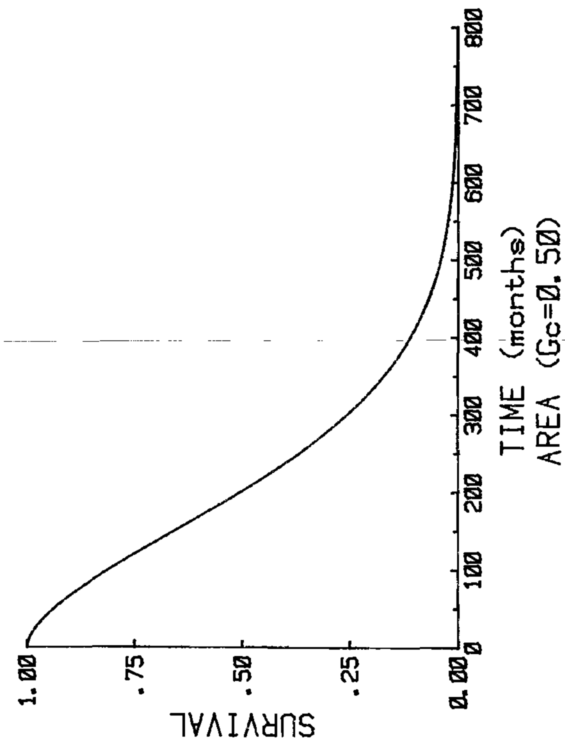
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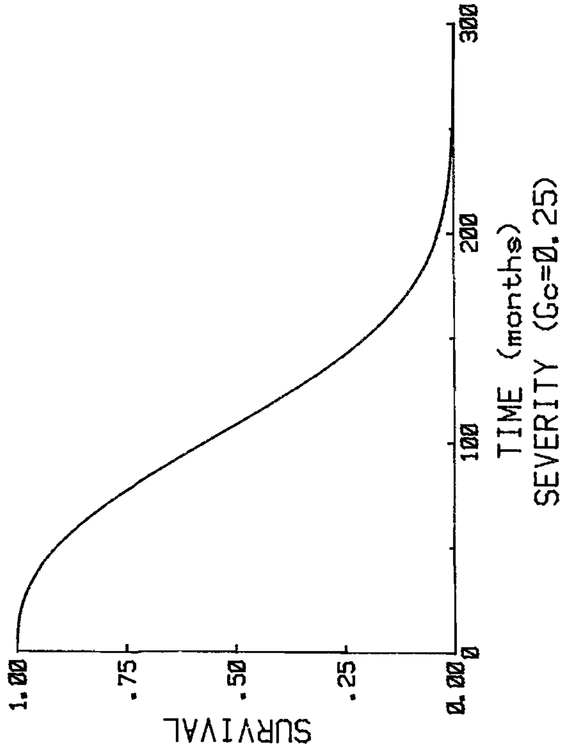
AREA (Gc=0.50)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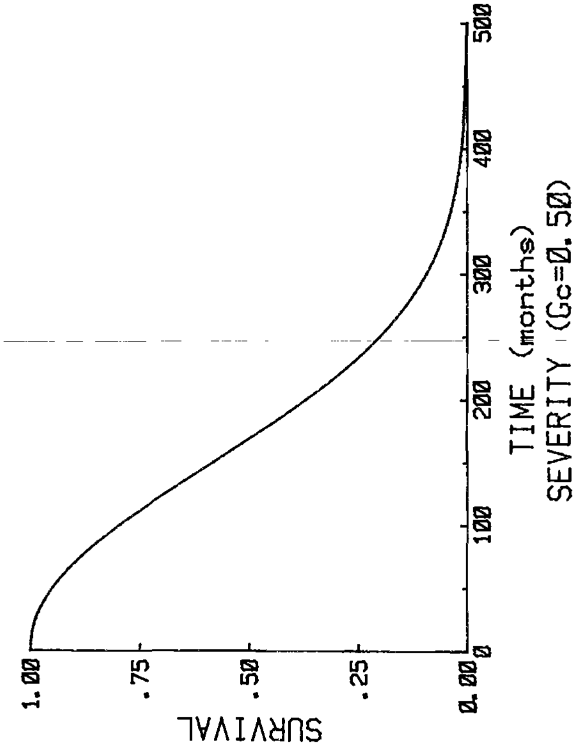
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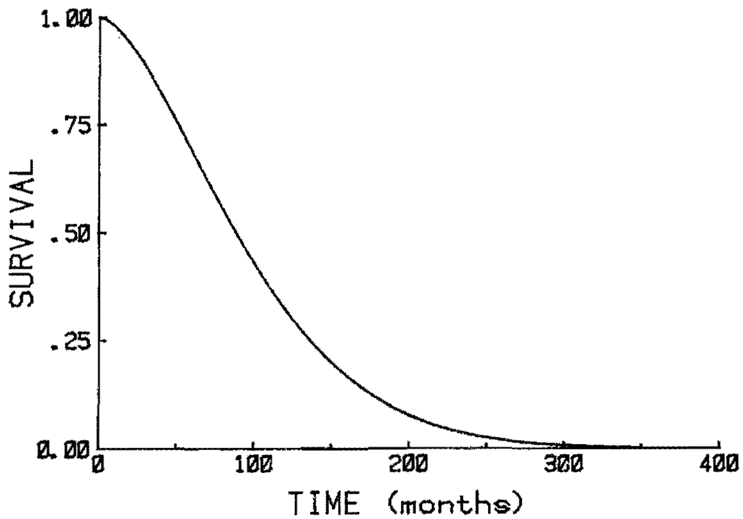
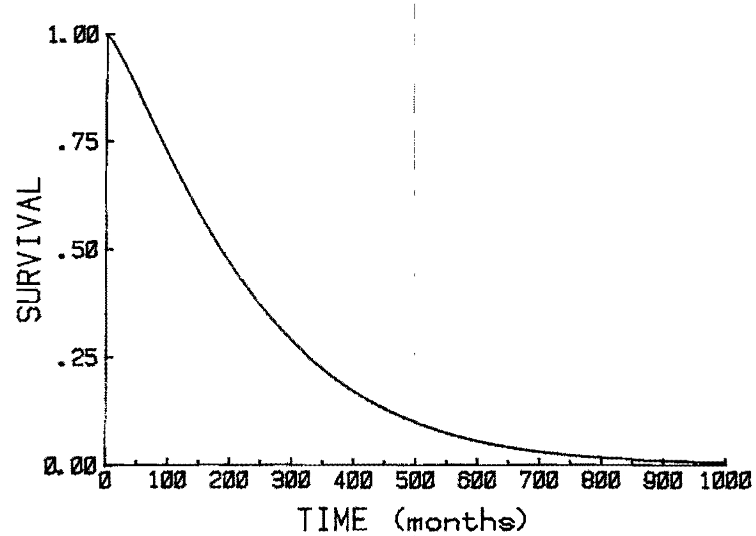
500
TIME (months)
SEVERITY (Gc=0.50)



AREA (Gc=0.25)



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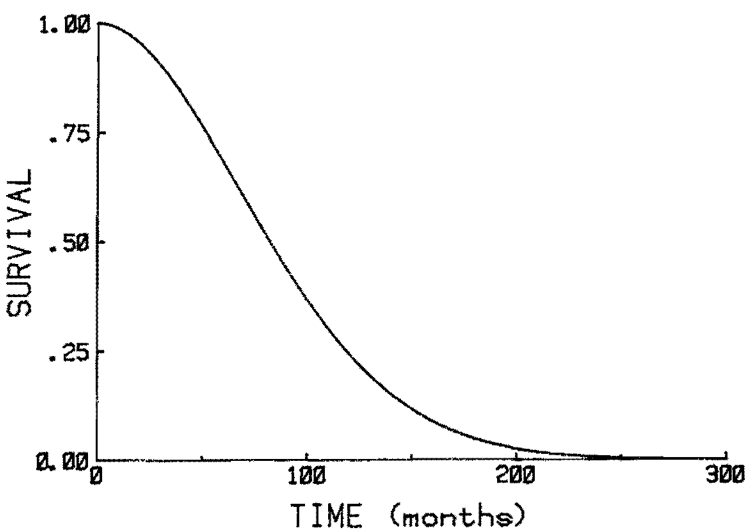
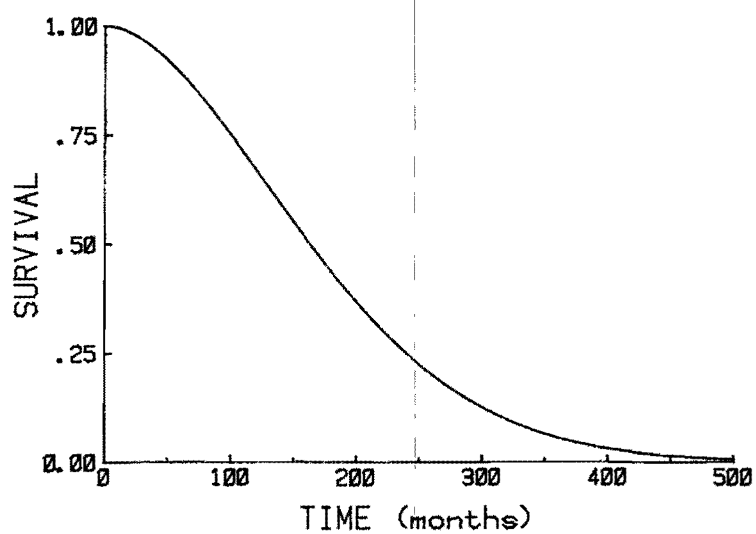
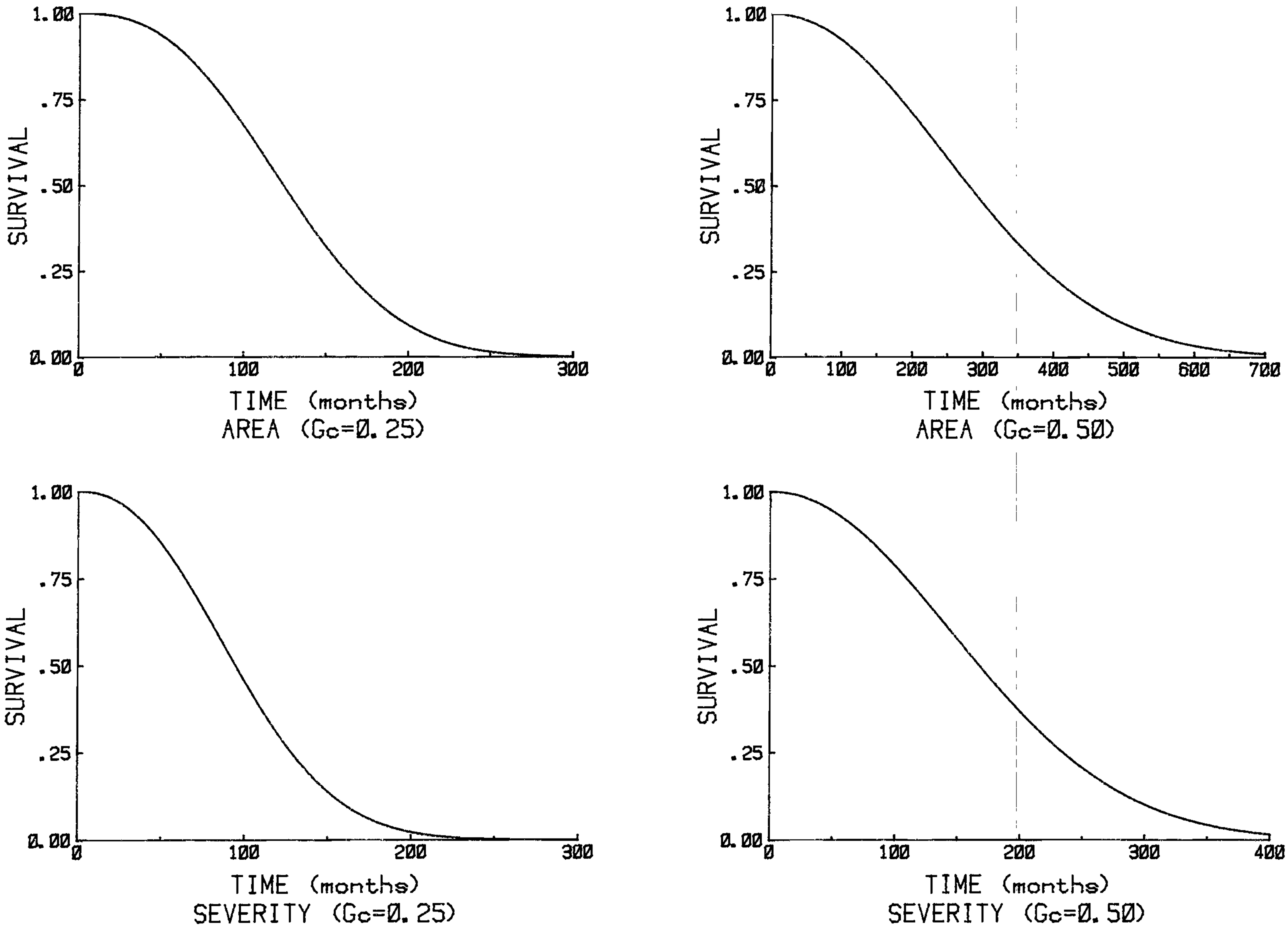


SEVERITY (Gc=0.25)



SEVERITY (Gc=0.50)


1.00
.75
.50
.25
0.00
SURVIVAL
0
100
200
300
TIME (months)
AREA (Gc=0.25)
1.00
.75
.50
.25
0.00
SURVIVAL
0
100
200
300
400
500
600
700
TIME (months)
AREA (Gc=0.50)
1.00
.75
.50
.25
0.00
SURVIVAL
0
100
200
300
TIME (months)
SEVERITY (Gc=0.25)
1.00
.75
.50
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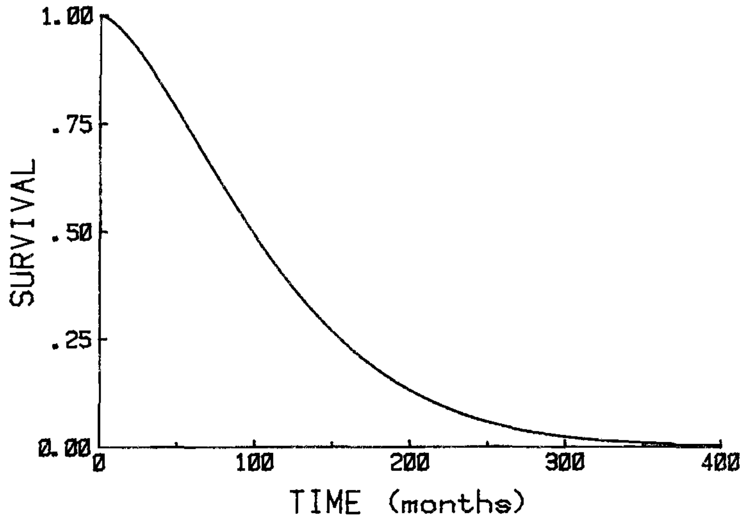
0.00
SURVIVAL
0
100
200
300
400
TIME (months)
SEVERITY (Gc=0.50)



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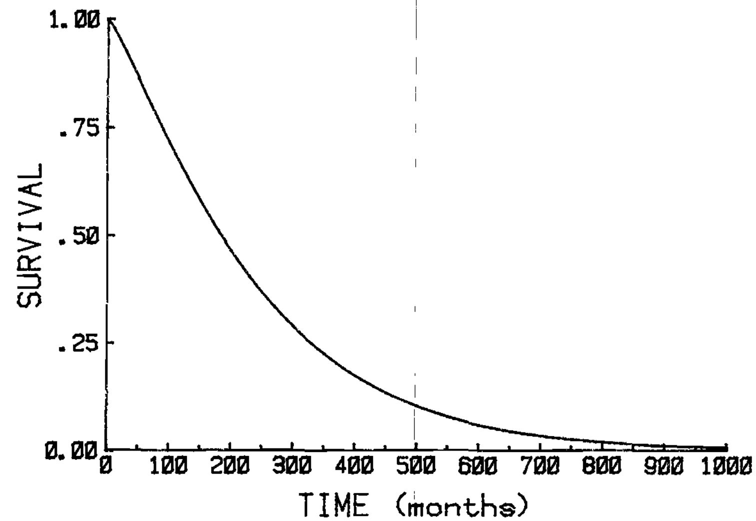
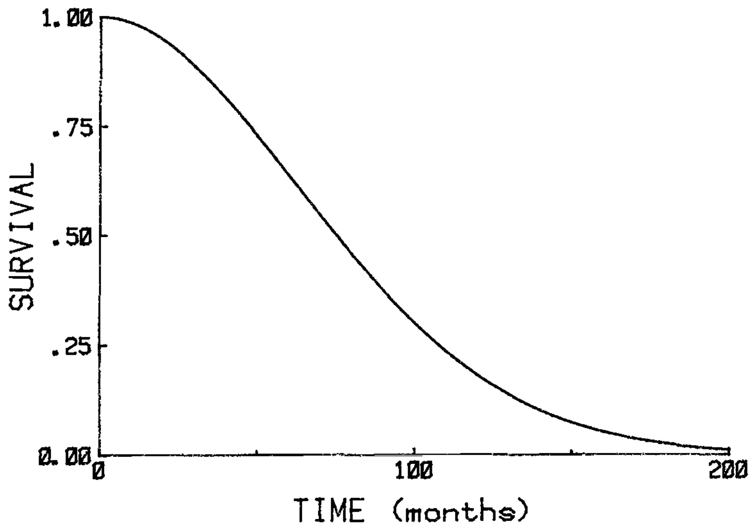


AREA (Gc=0.50)



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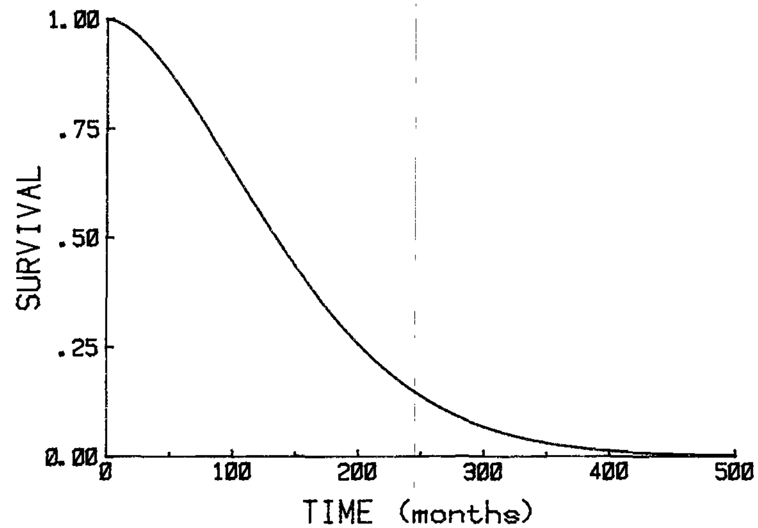
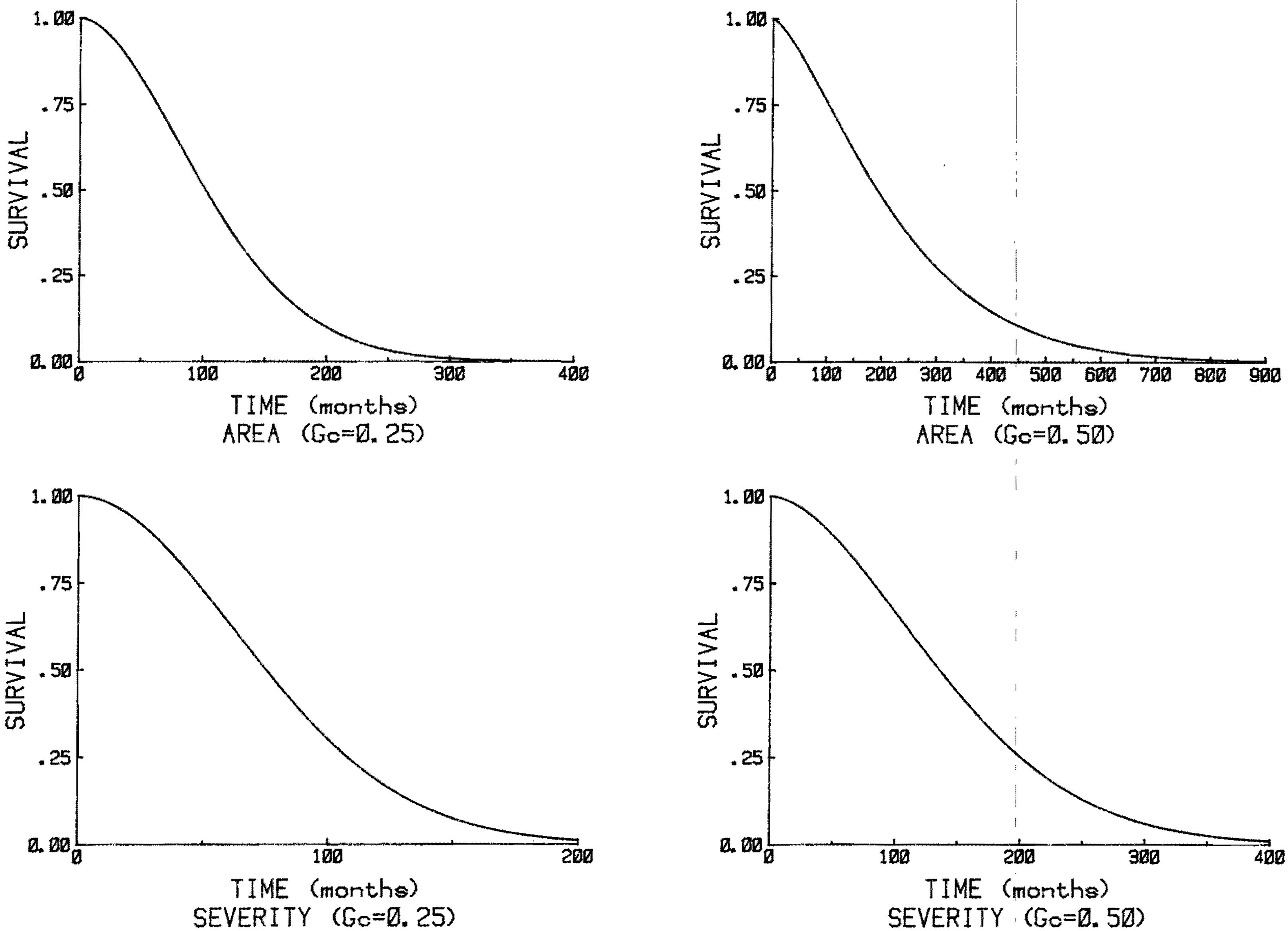
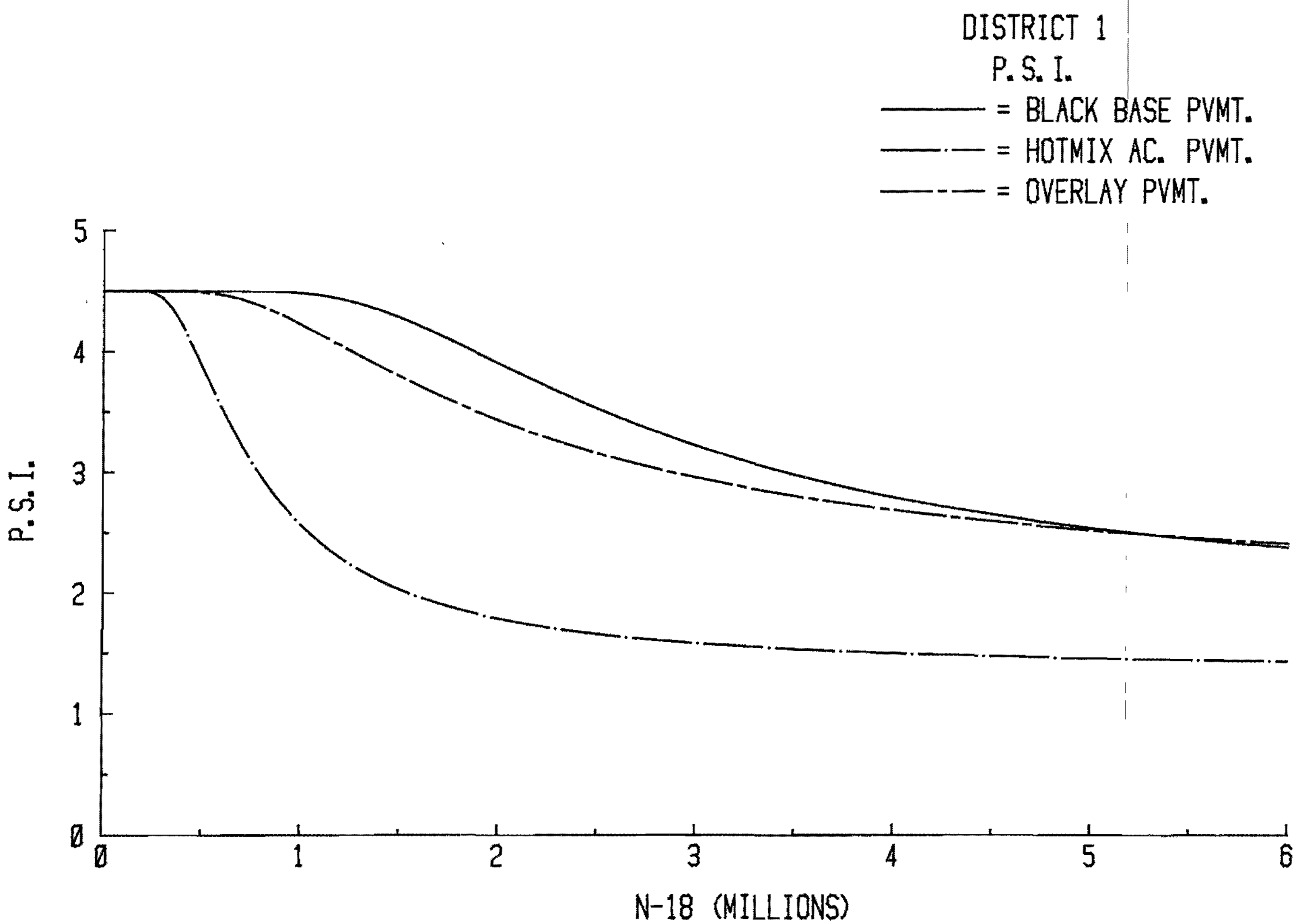


SEVERITY (Gc=0.50)


SURVIVAL
1.00
.75
.50
.25
0.00
0
100
200
300
400
TIME (months)
AREA (Gc=0.25)
SURVIVAL
1.00
.75
.50
.25
0.00
0
100
200
300
400
500
600
700
800
900
TIME (months)
AREA (Gc=0.50)
SURVIVAL
1.00
.75
.50
.25
0.00
0
100
200
TIME (months)
SEVERITY (Gc=0.25)
SURVIVAL
1.00
.75
.50
.25
0.00
0
100
200
300
400
TIME (months)
SEVERITY (Gc=0.50)

APPENDIX 5

SENSITIVITY STUDY RESULTS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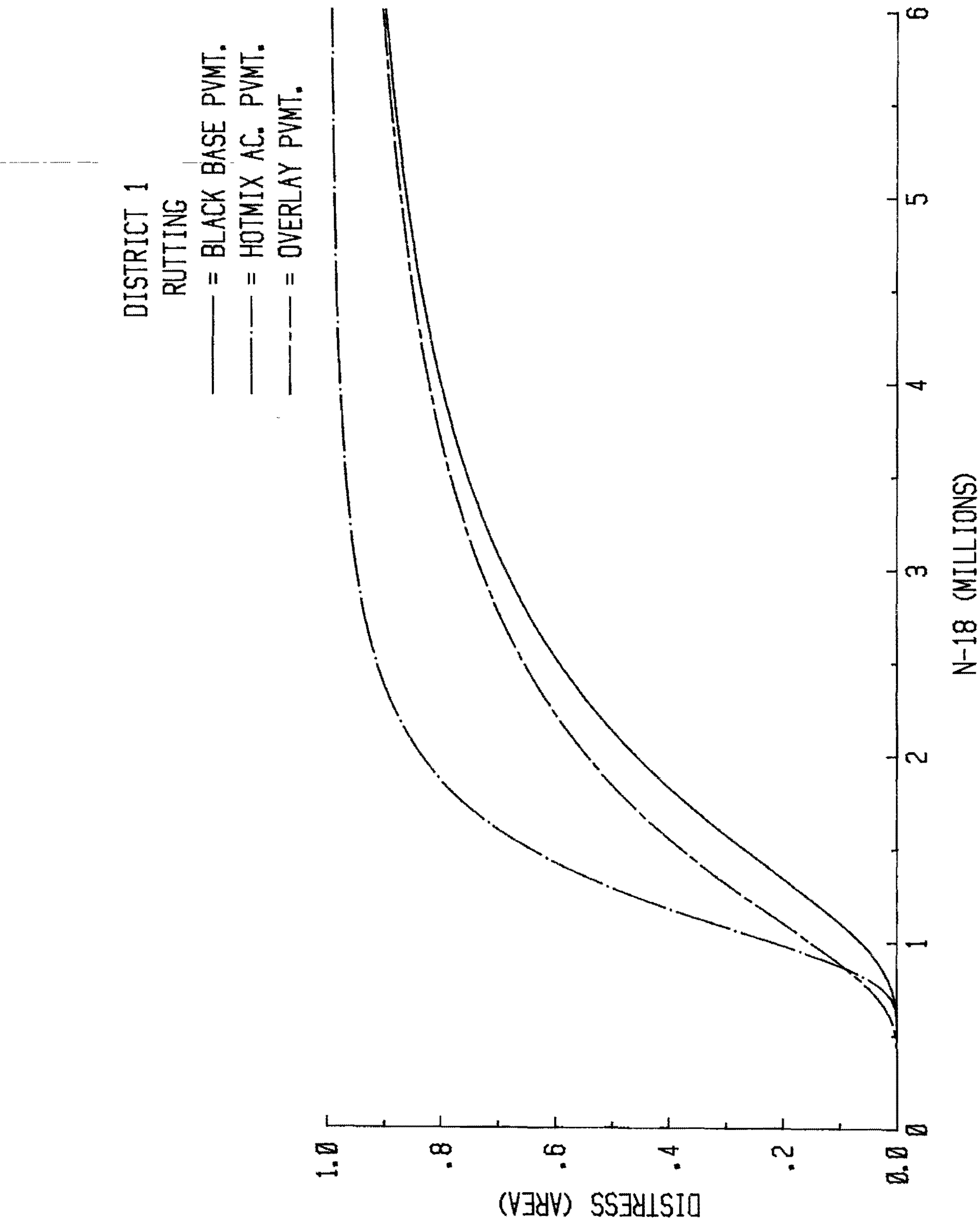
P.S.I.
= BLACK BASE PVMT.
= HOTMIX AC. PVMT.
= OVERLAY PVMT.
P.S.I.
5
4
3
2
1
Ø
Ø
1
2
3
4
5
6
N-18 (MILLIONS)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RUTTING
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= HOTMIX AC. PVMT.
= OVERLAY PVMT.
DISTRESS (AREA)
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0.0
0
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2
3
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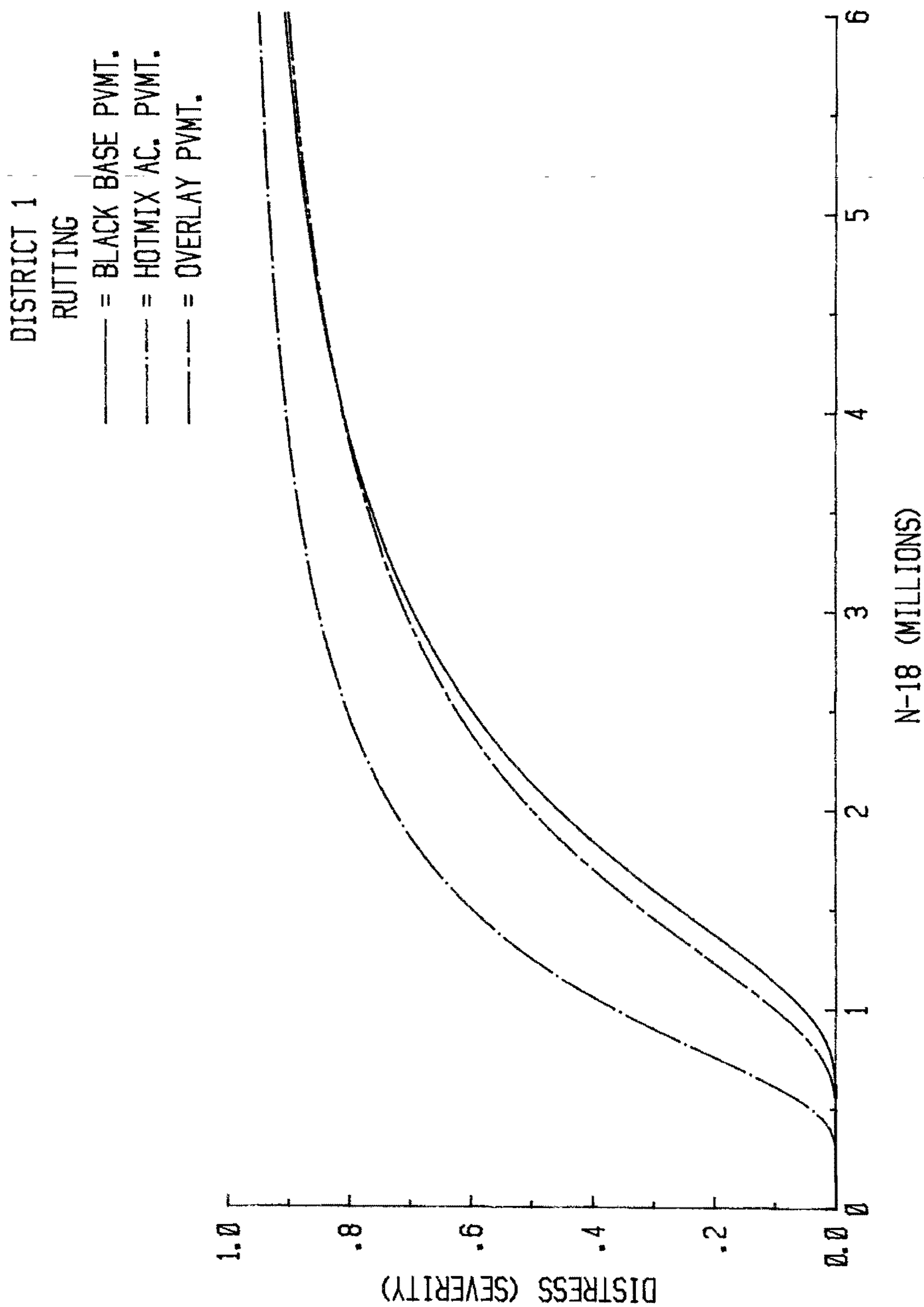
5
6
N-18 (MILLIONS)



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= OVERLAY PVMT.
DISTRESS (SEVERITY)
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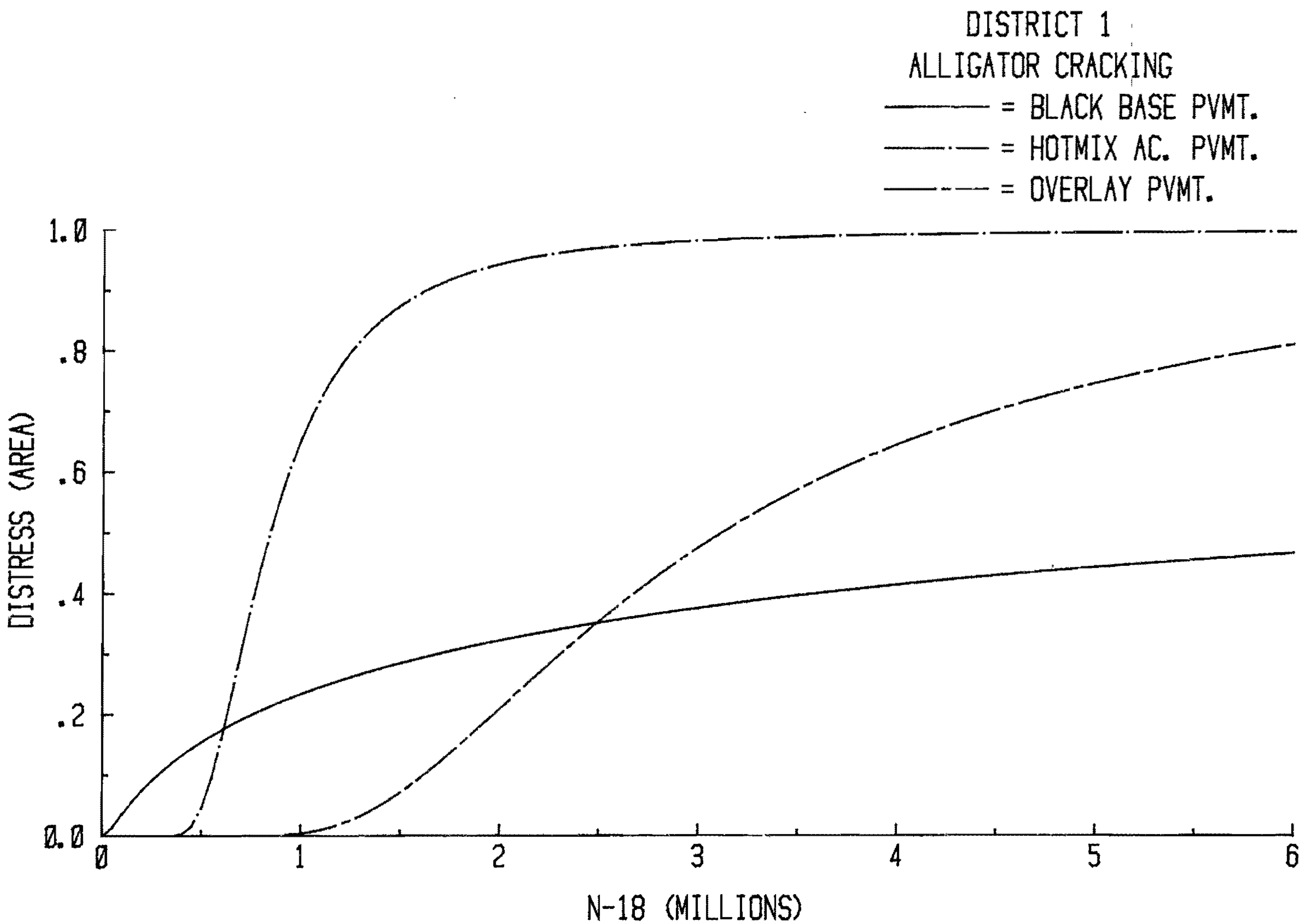
.6
.4
.2
0.0
0
1
2
3
4
5
6
N-18 (MILLIONS)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ALLIGATOR CRACKING
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= OVERLAY PVMT.
1.Ø
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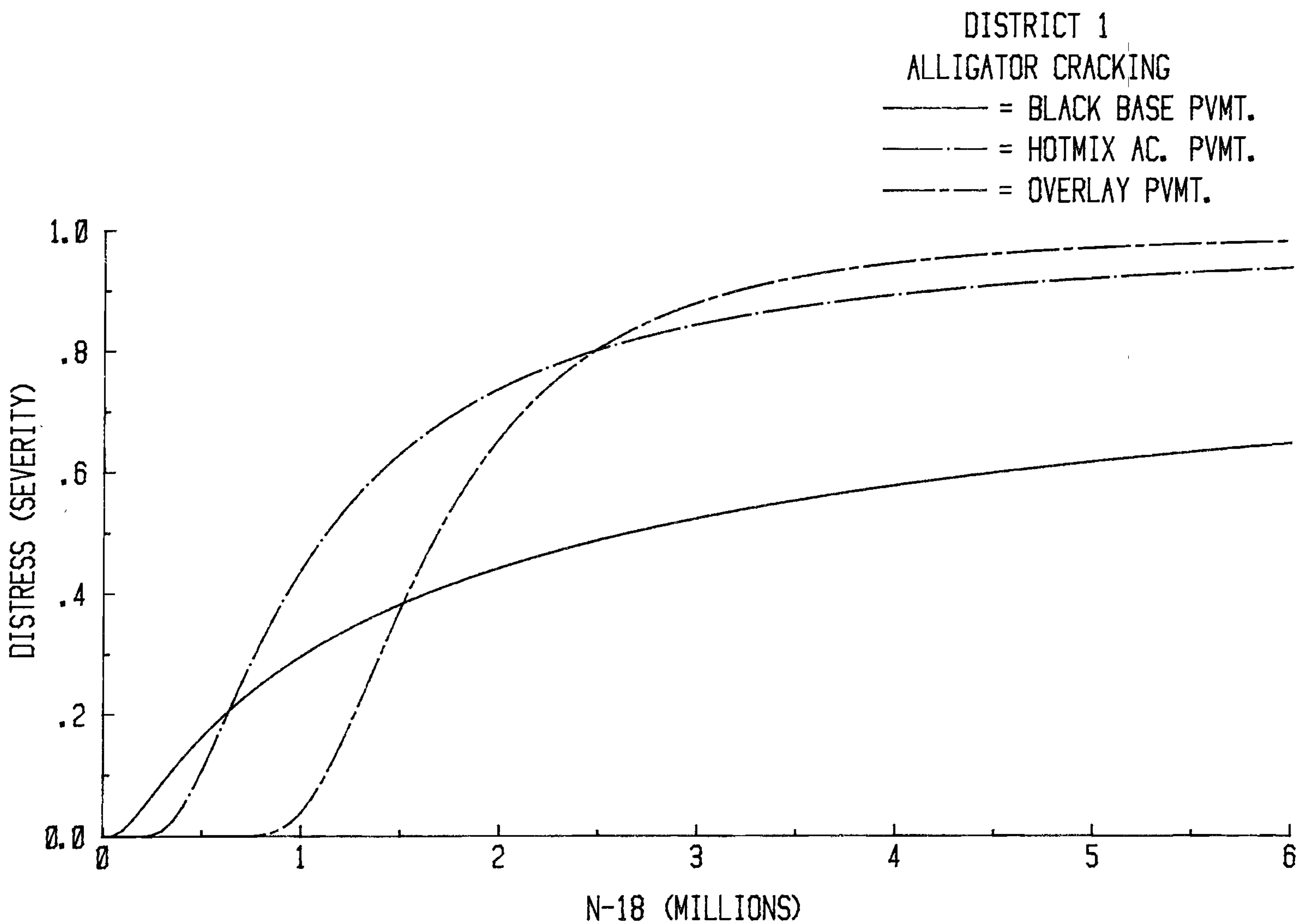
5
6
N-18 (MILLIONS)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= HOTMIX AC. PVMT.
= OVERLAY PVMT.
DISTRESS (SEVERITY)
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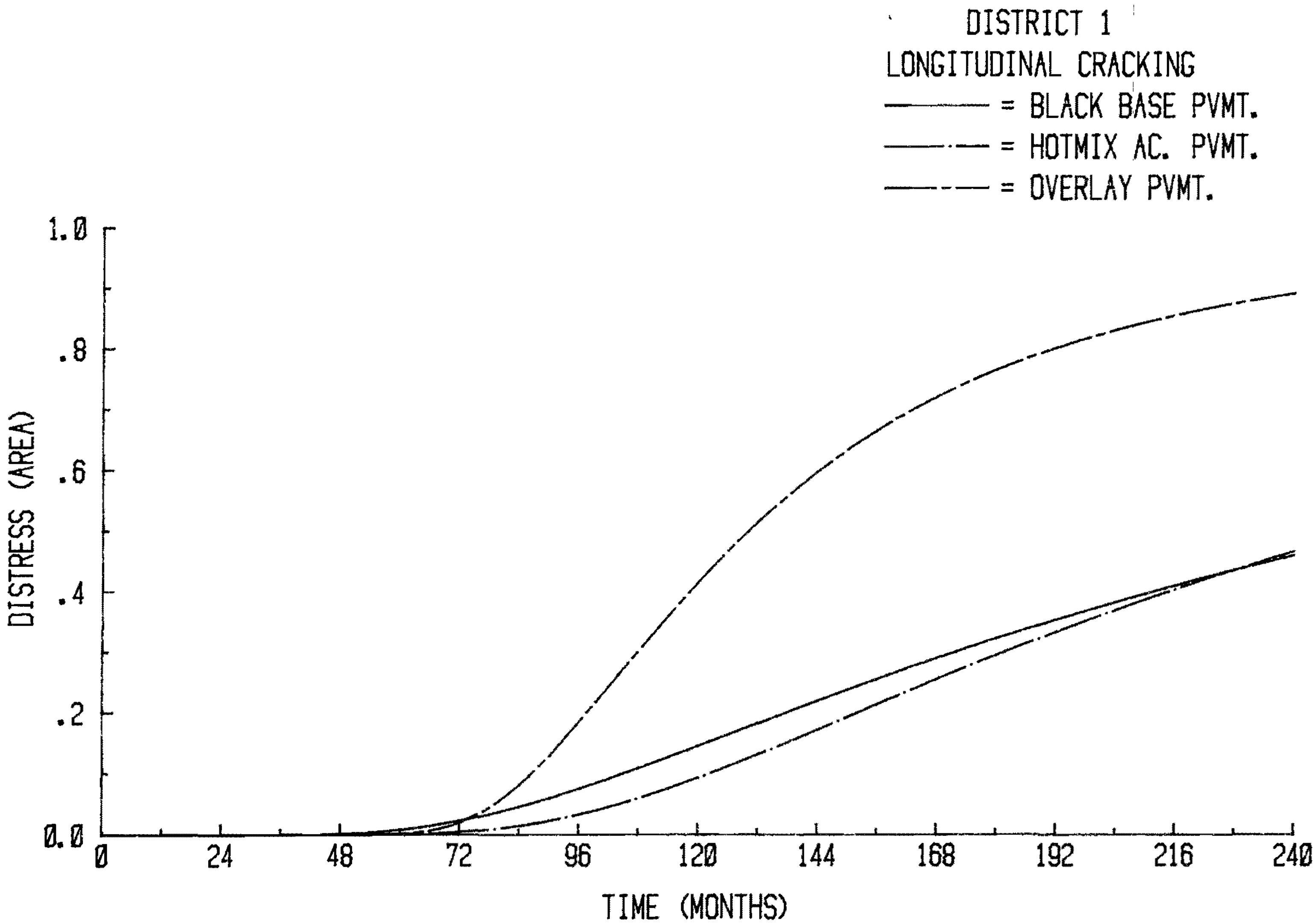
.6
.4
.2
Ø.Ø
Ø
1
2
3
4
5
6
N-18 (MILLIONS)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= OVERLAY PVMT.
DISTRESS (AREA)
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.2
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0
24
48
72
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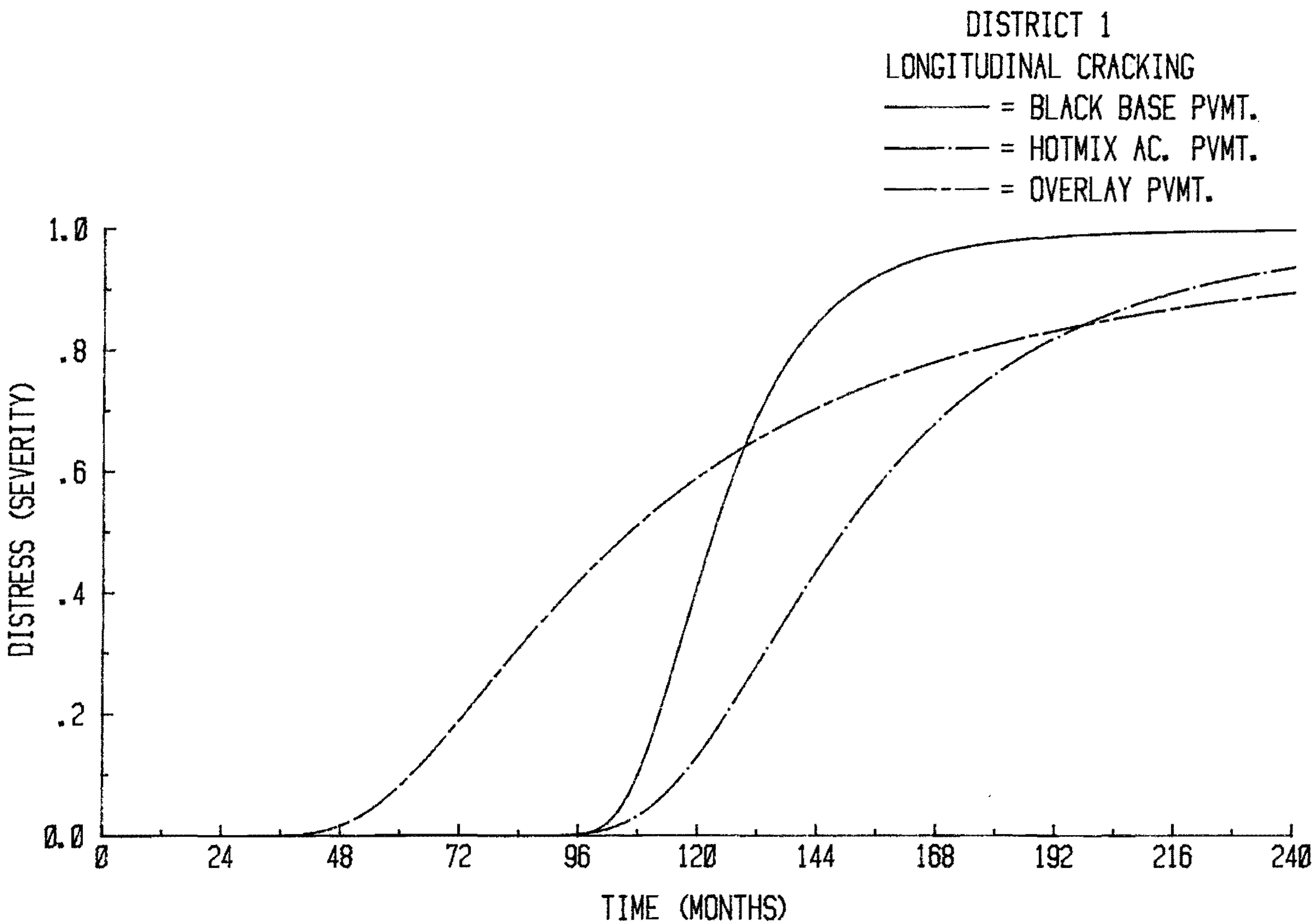
120
144
168
192
216
240
TIME (MONTHS)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= HOTMIX AC. PVMT.
= OVERLAY PVMT.
DISTRESS (SEVERITY)
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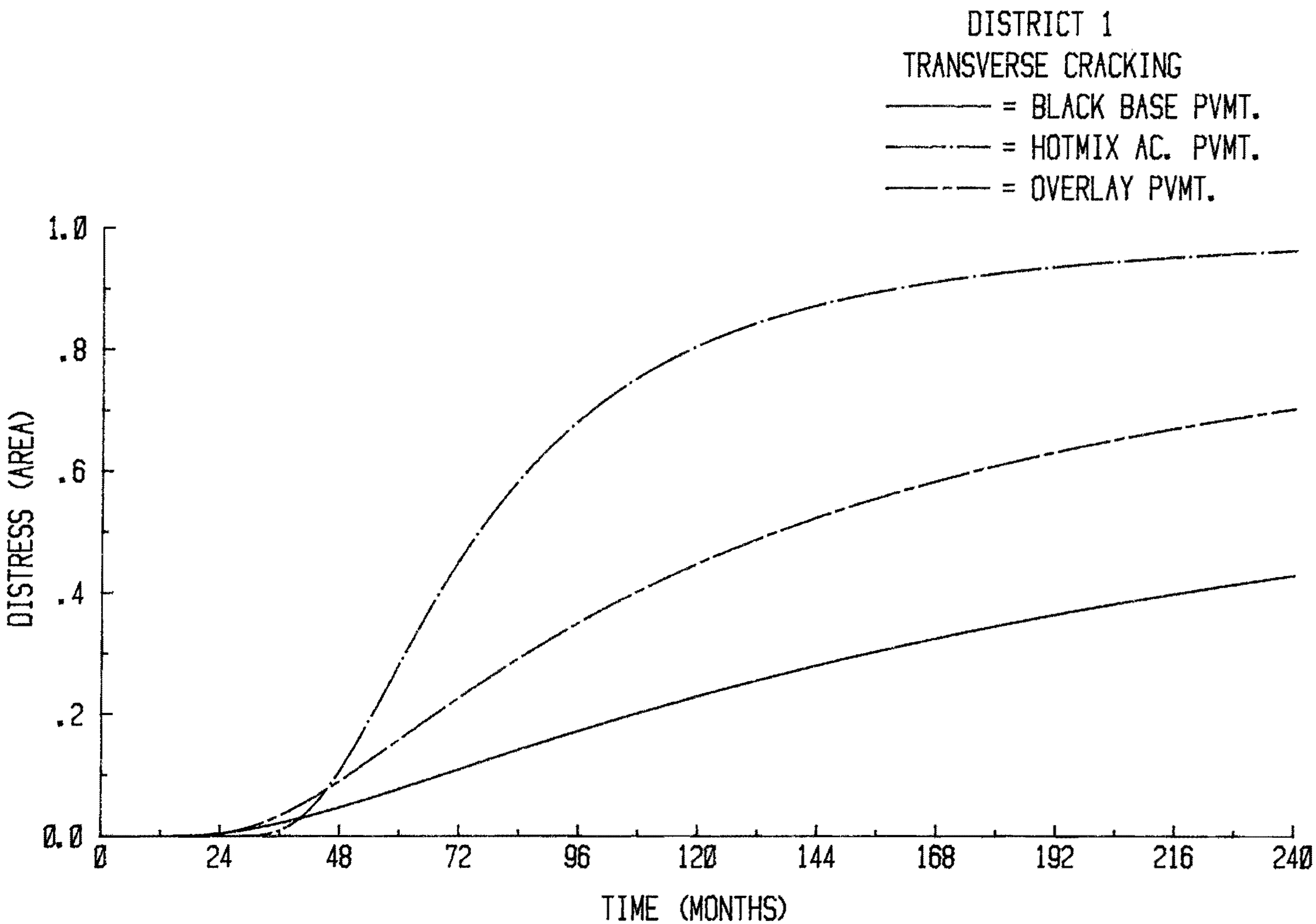
.2
0.0
0
24
48
72
96
120
144
168
192
216
240
TIME (MONTHS)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= HOTMIX AC. PVMT.
= OVERLAY PVMT.
DISTRESS (AREA)
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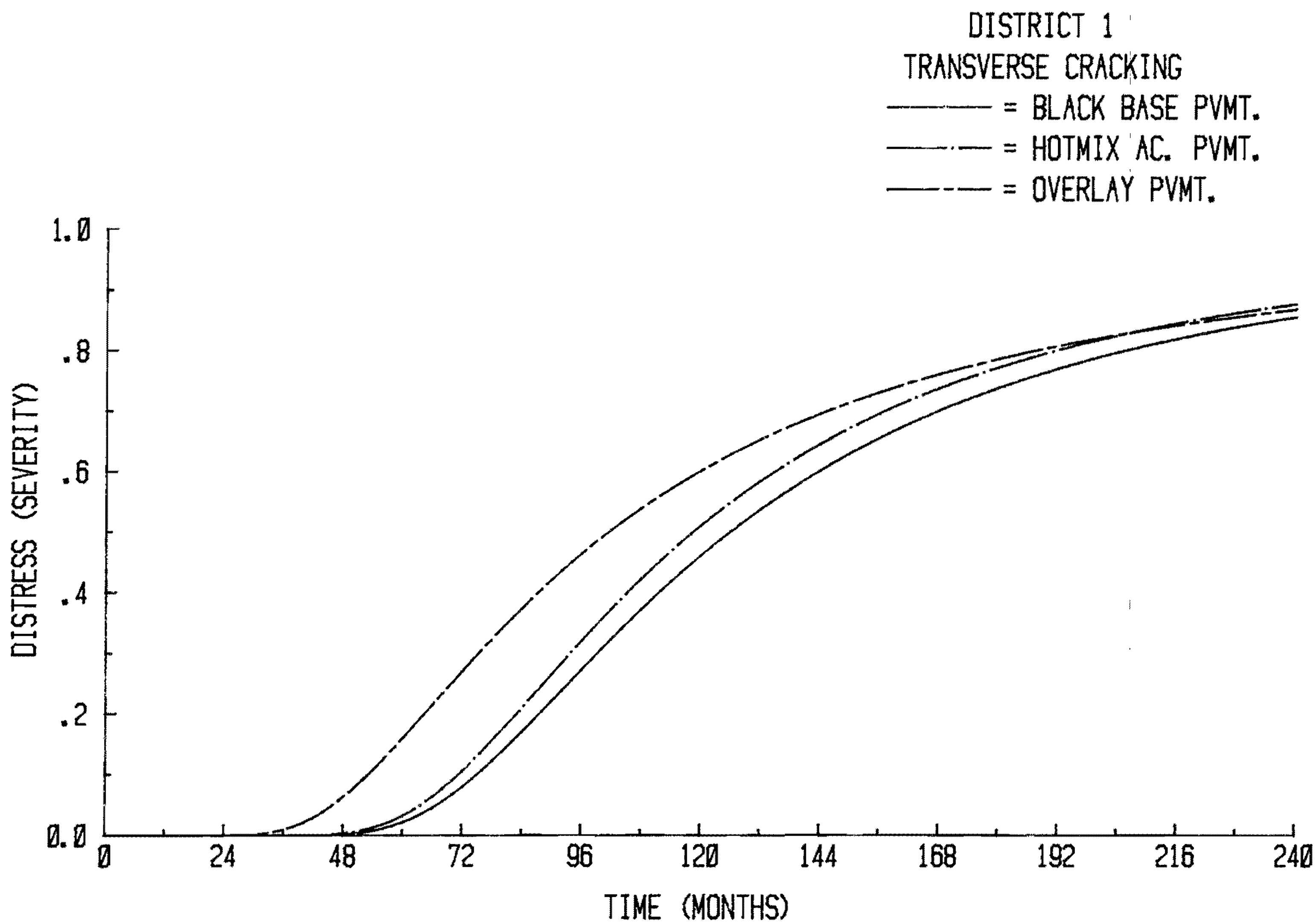
24
48
72
96
120
144
168
192
216
240
TIME (MONTHS)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= HOTMIX AC. PVMT.
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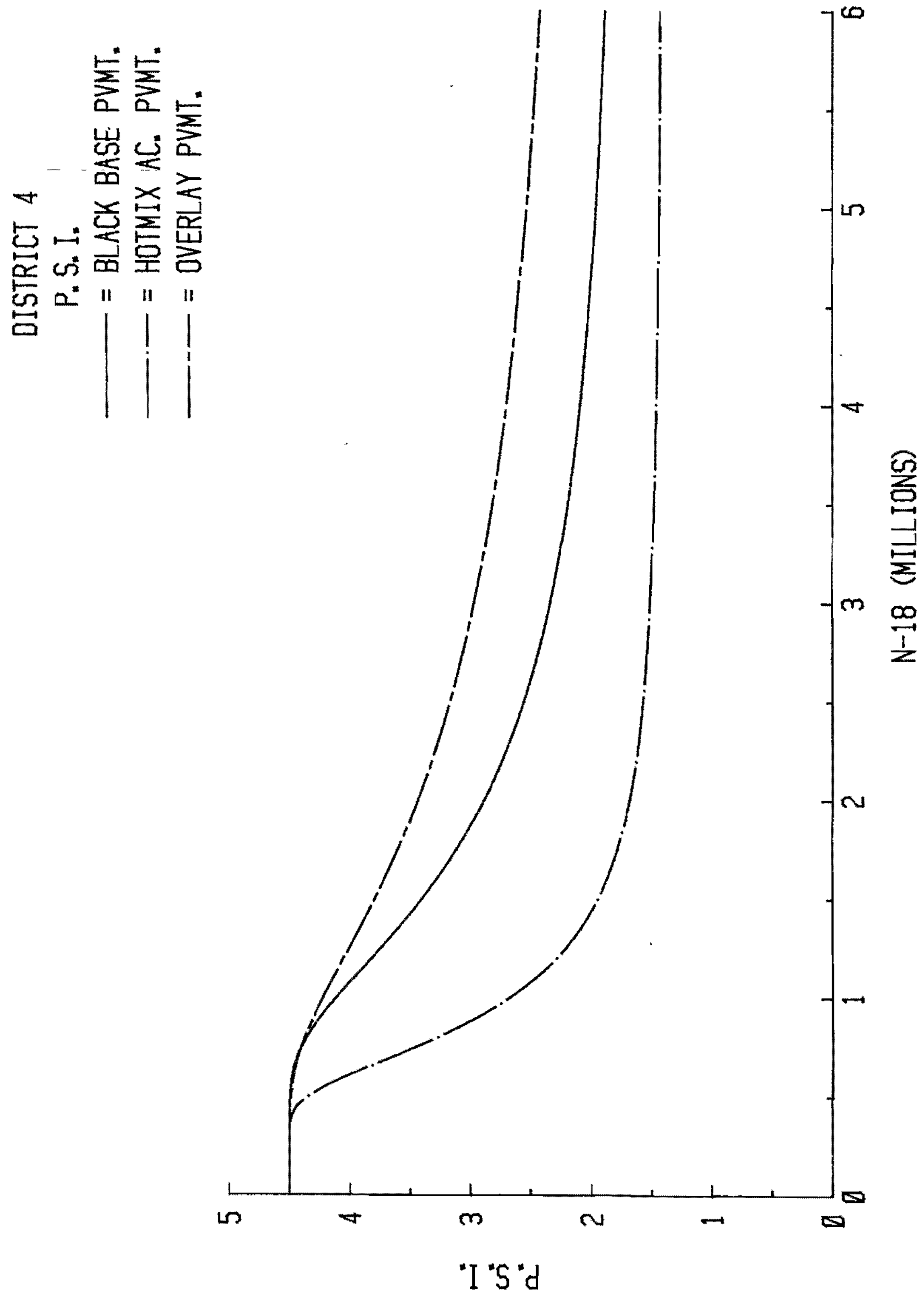
24
48
72
96
120
144
168
192
216
240
TIME (MONTHS)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P. S. I.
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Ø
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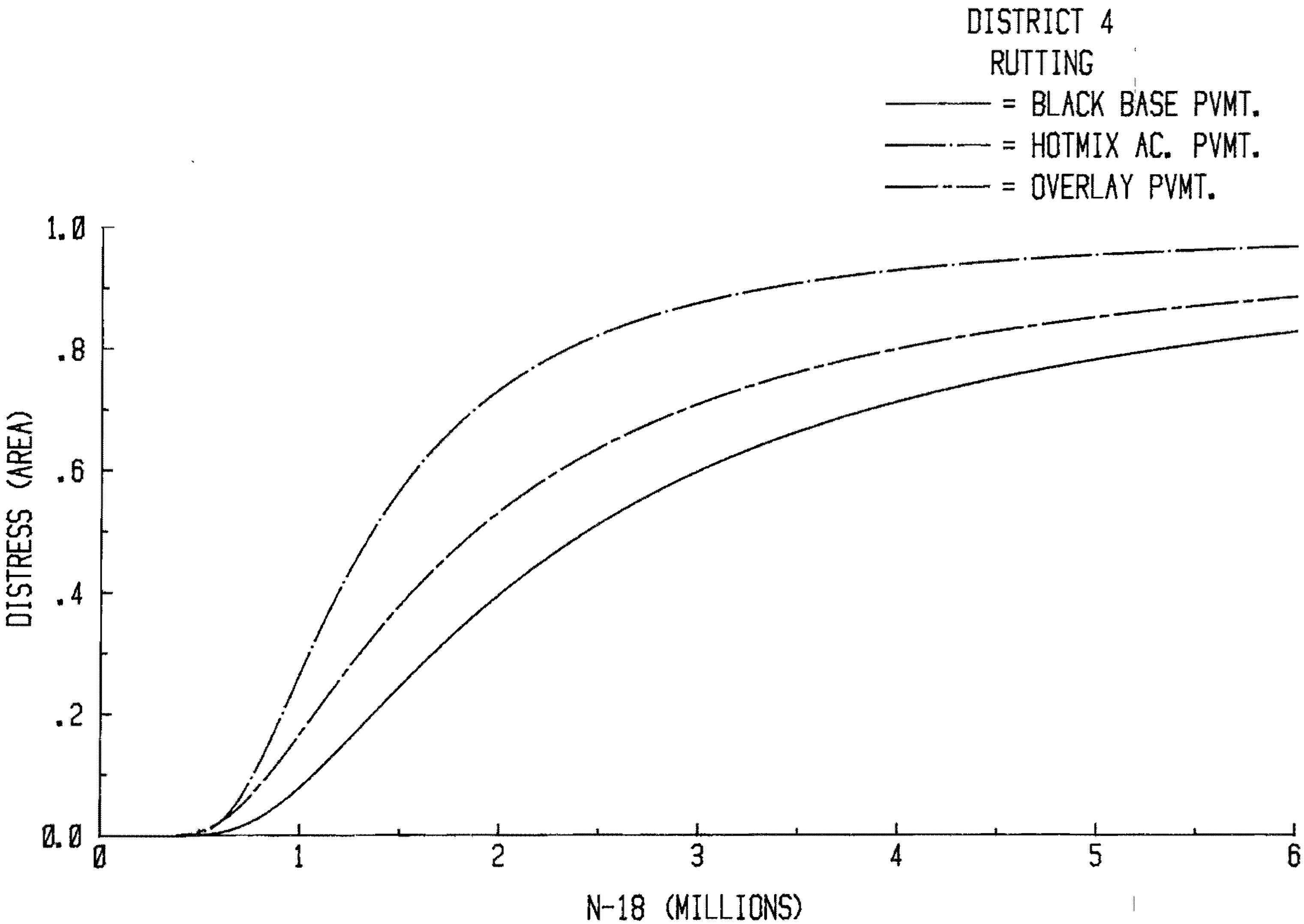
6
N-18 (MILLIONS)



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= OVERLAY PVMT.
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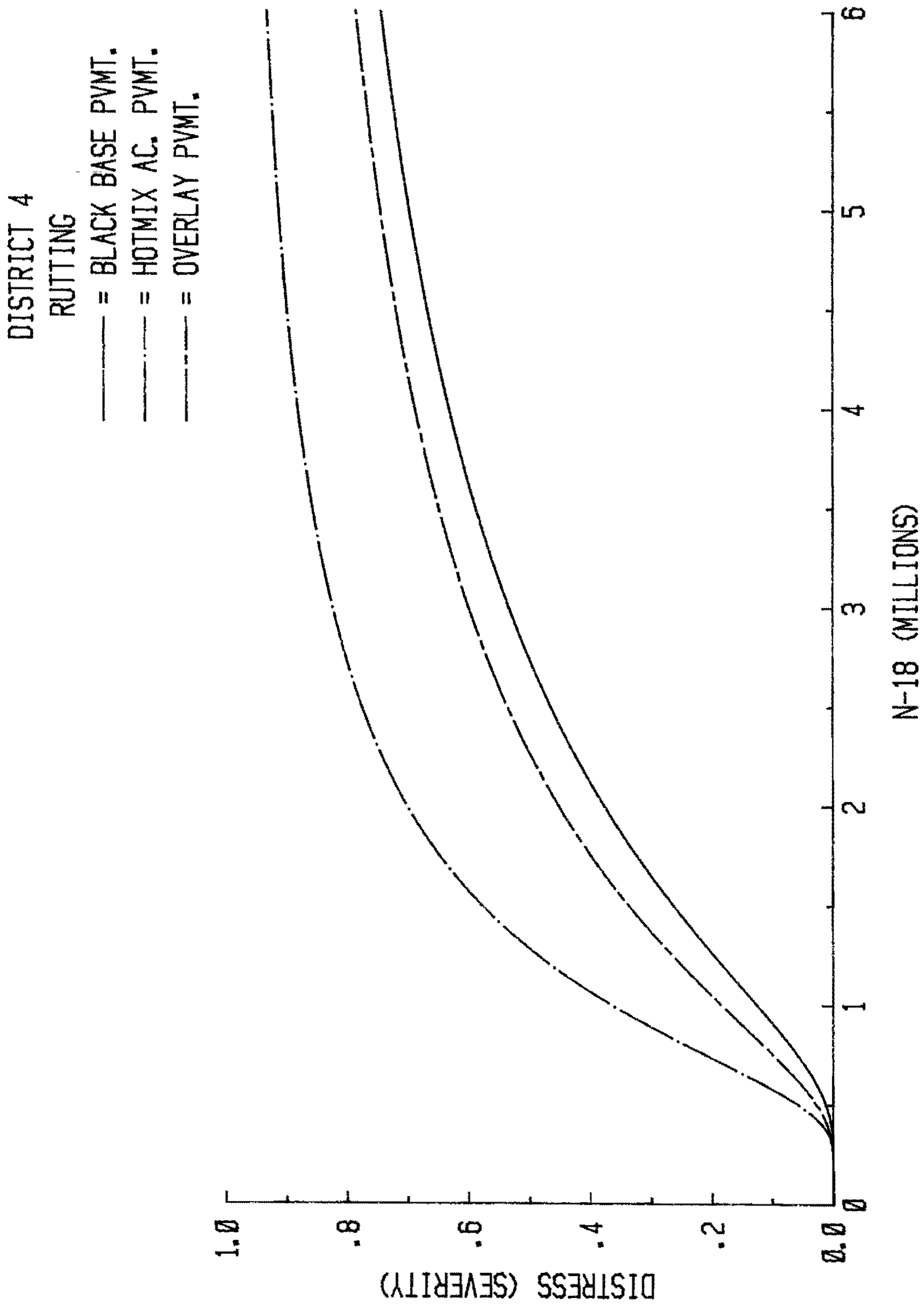
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= OVERLAY PVMT.
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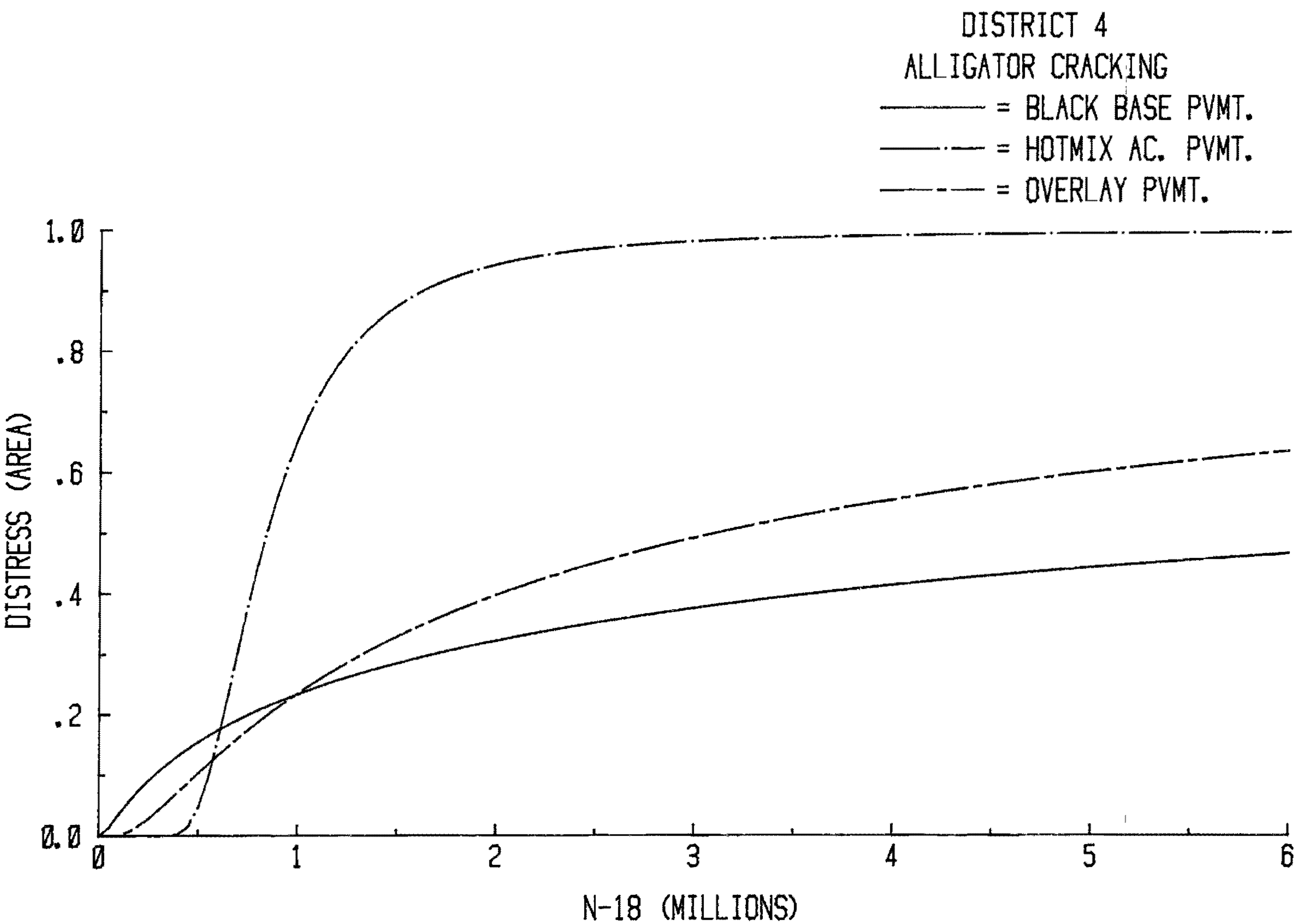
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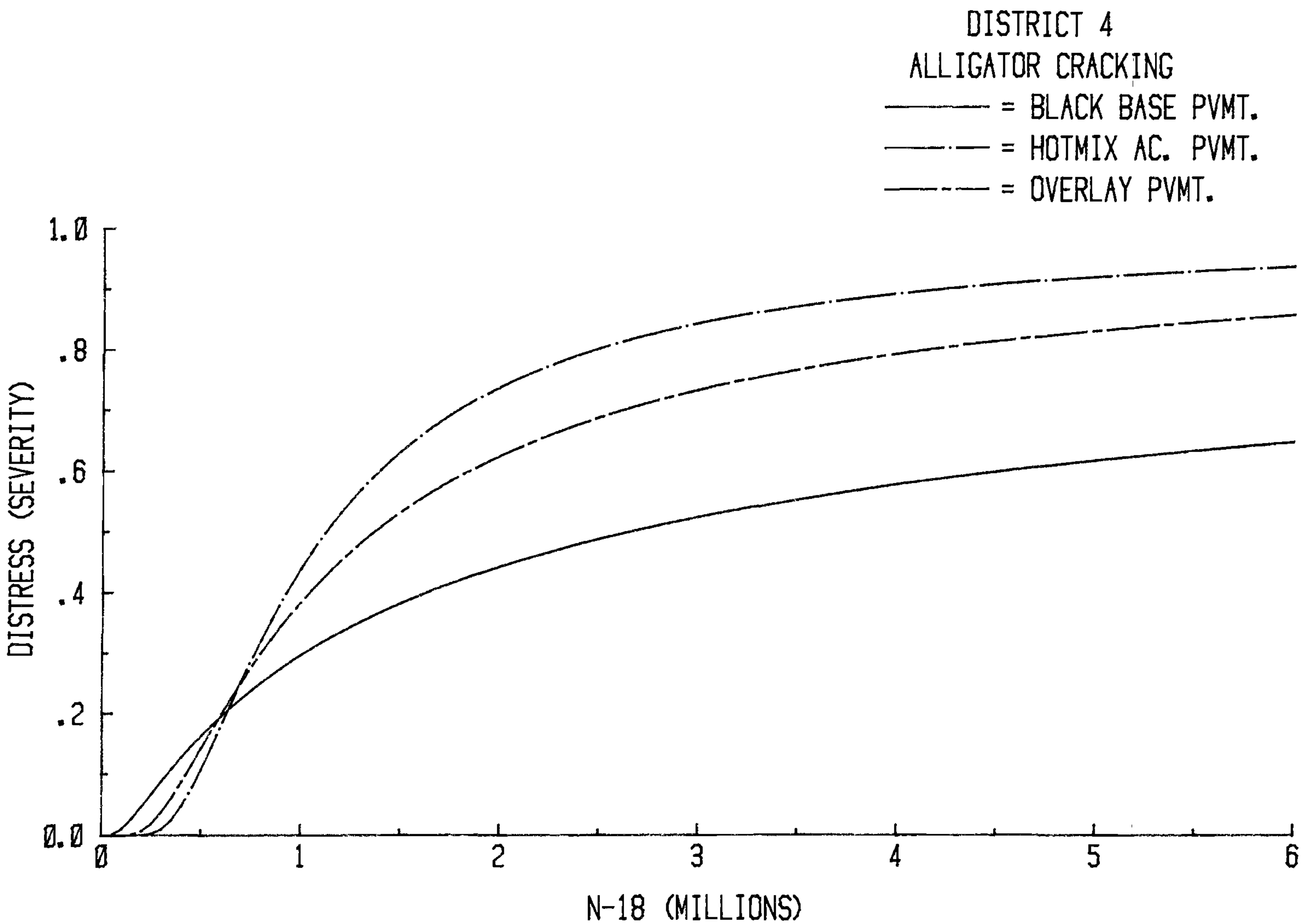
N-18 (MILLIONS)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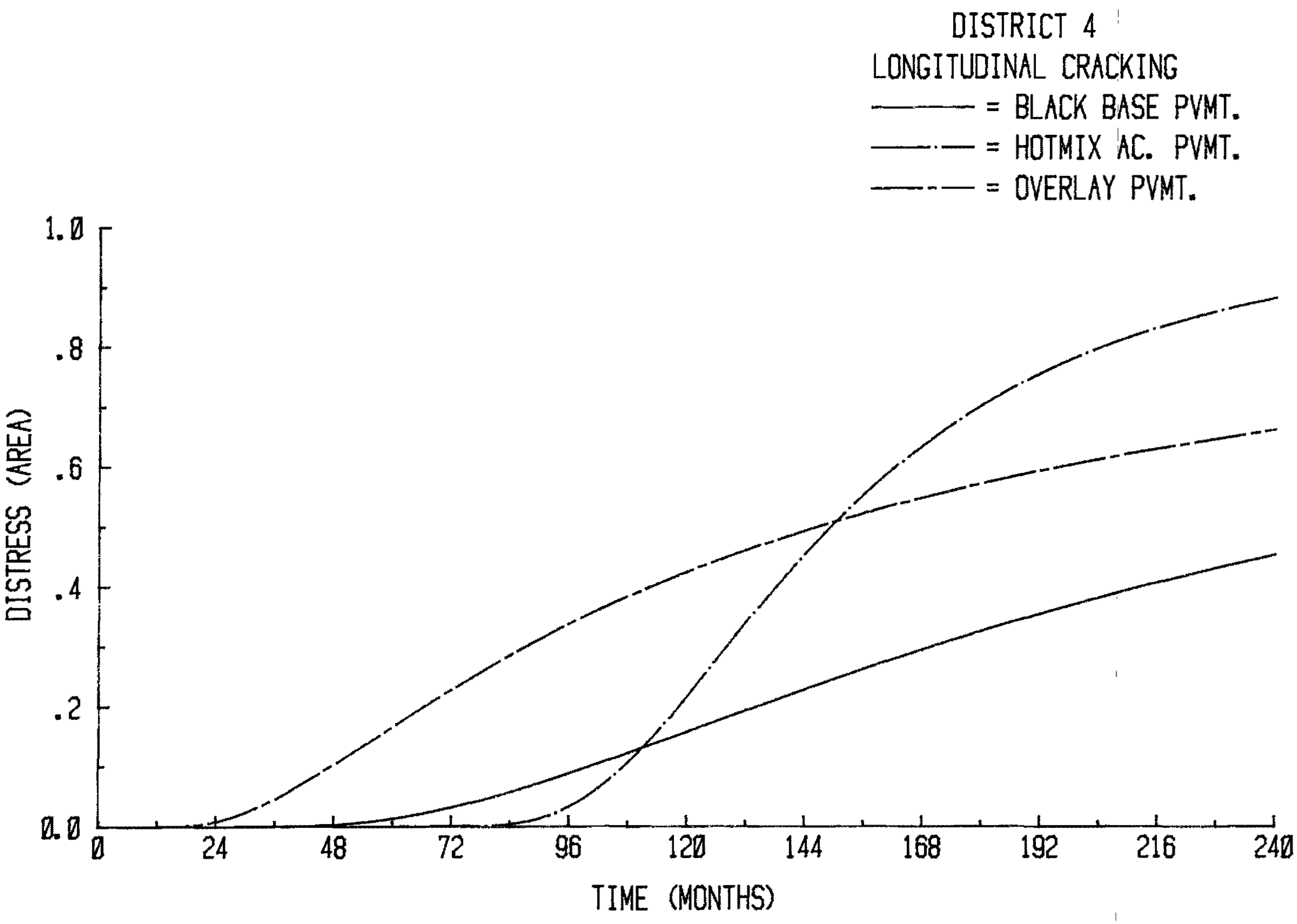
6
N-18 (MILLIONS)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= OVERLAY PVMT.
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0
24
48
72
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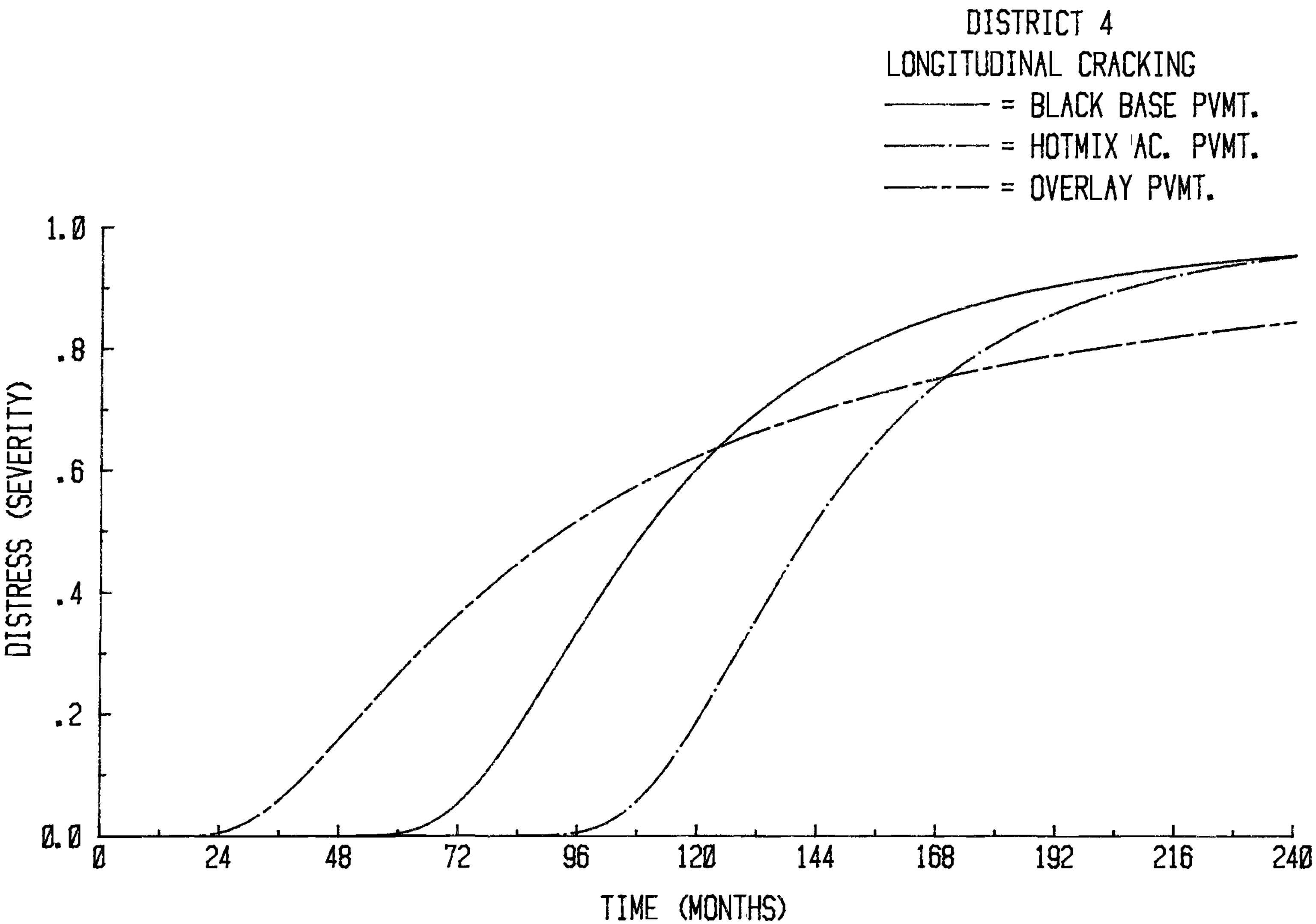
120
144
168
192
216
240
TIME (MONTHS)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= HOTMIX AC. PVMT.
= OVERLAY PVMT.
1.0
.8
.6
.4
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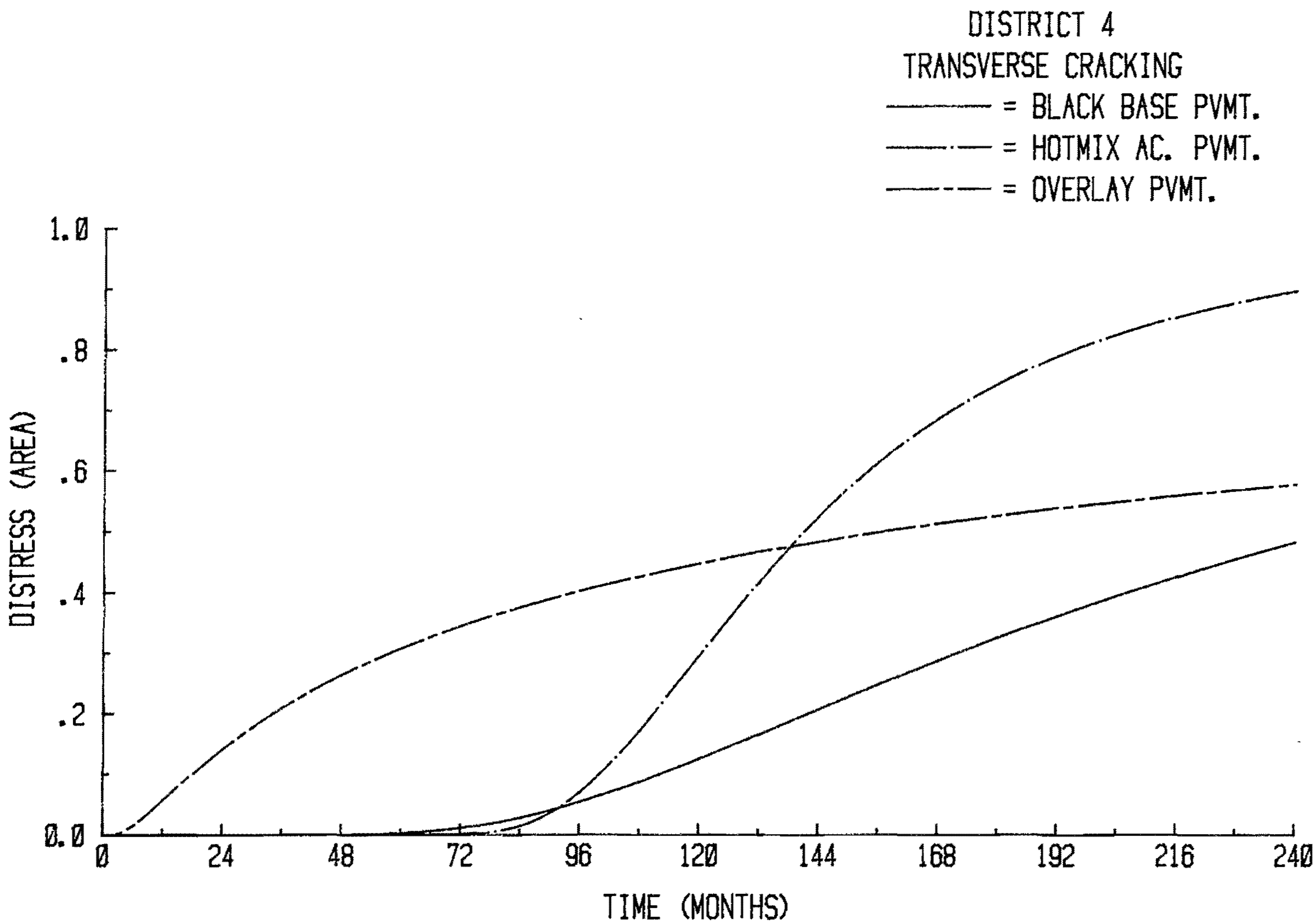
0.0
DISTRESS (SEVERITY)
0
24
48
72
96
120
144
168
192
216
240
TIME (MONTHS)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= HOTMIX AC. PVMT.
= OVERLAY PVMT.
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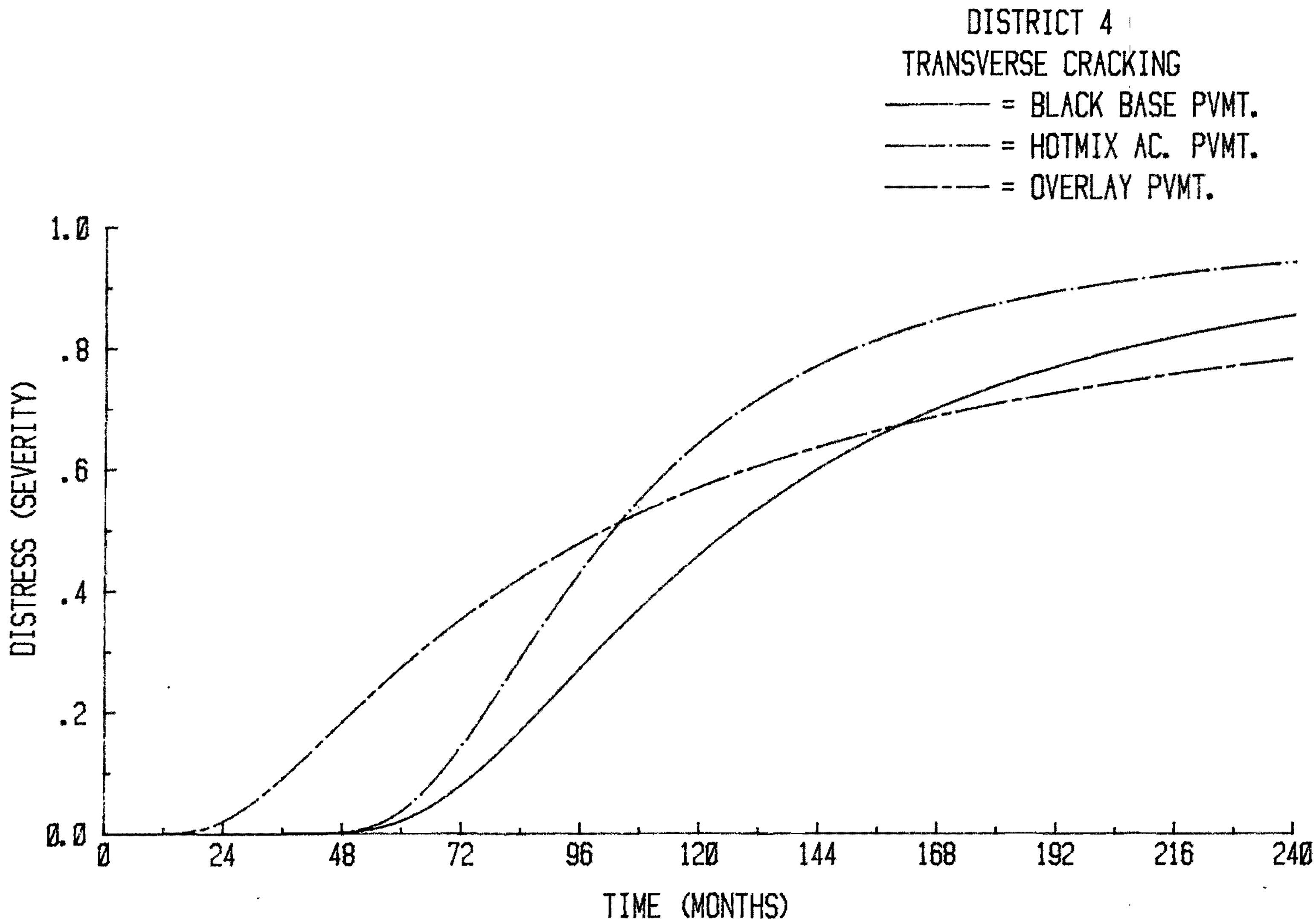
TIME (MONTHS)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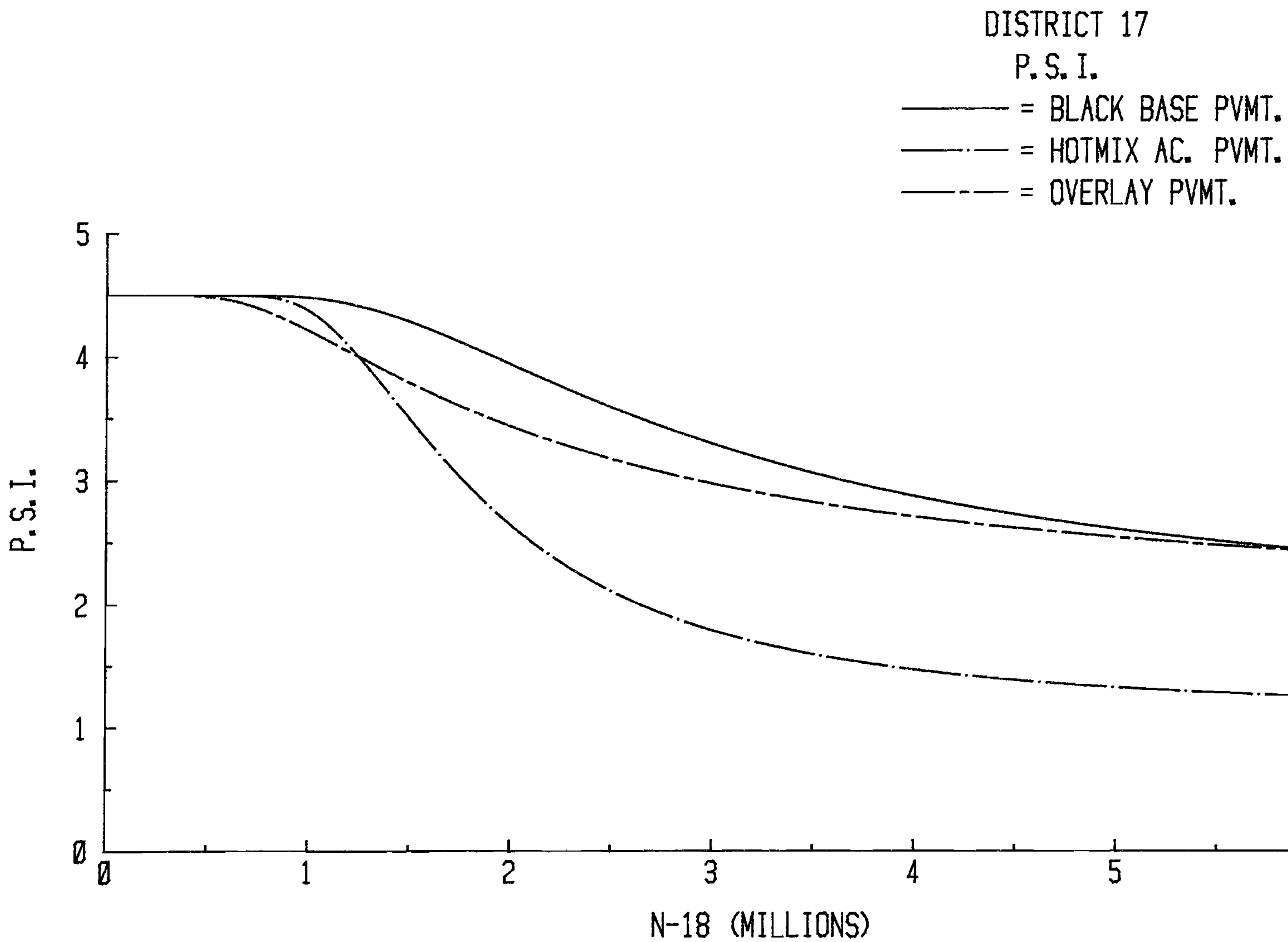
TIME (MONTHS)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= OVERLAY PVMT.
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Ø
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2
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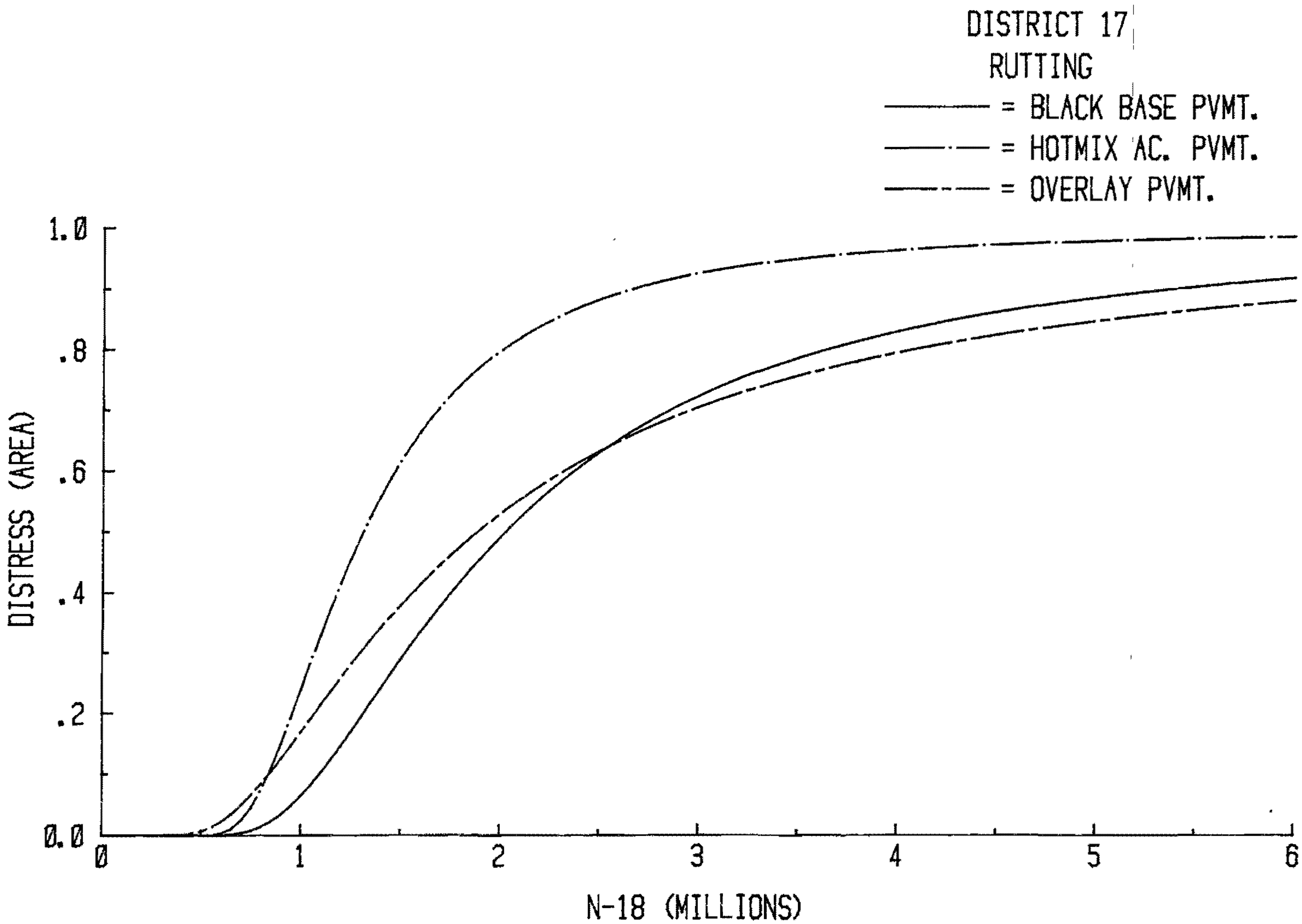
6
N-18 (MILLIONS)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= OVERLAY PVMT.
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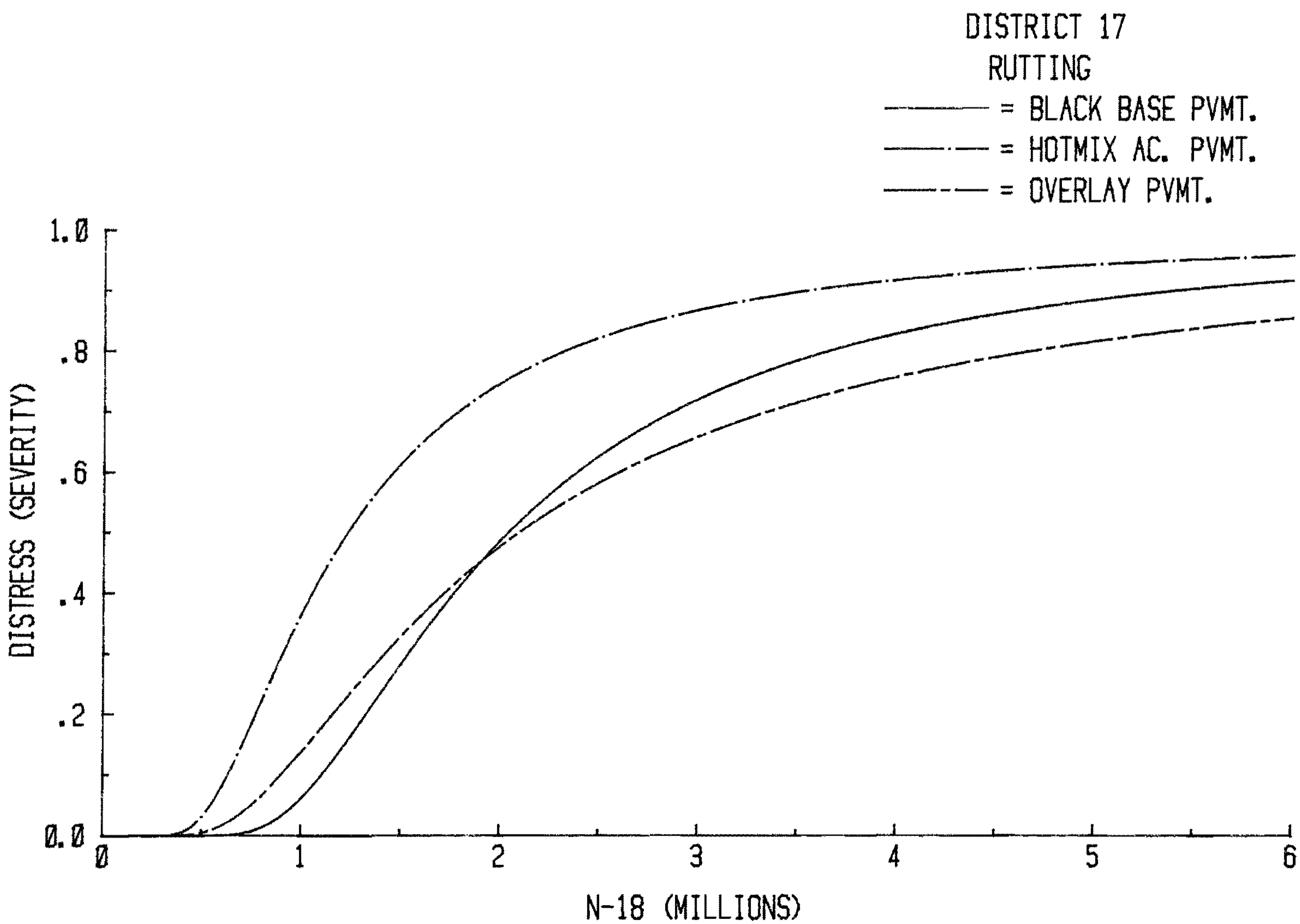
N-18 (MILLIONS)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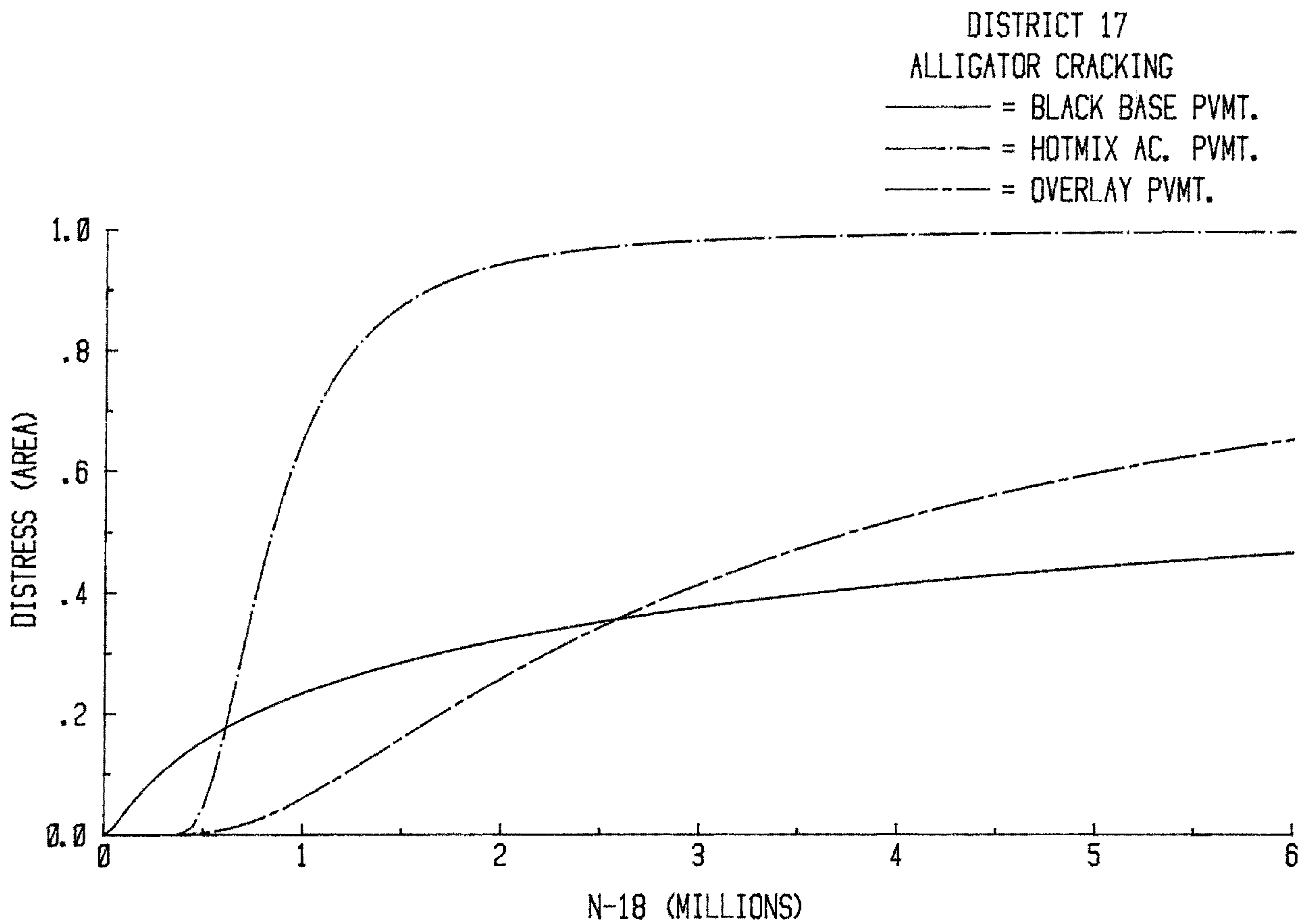
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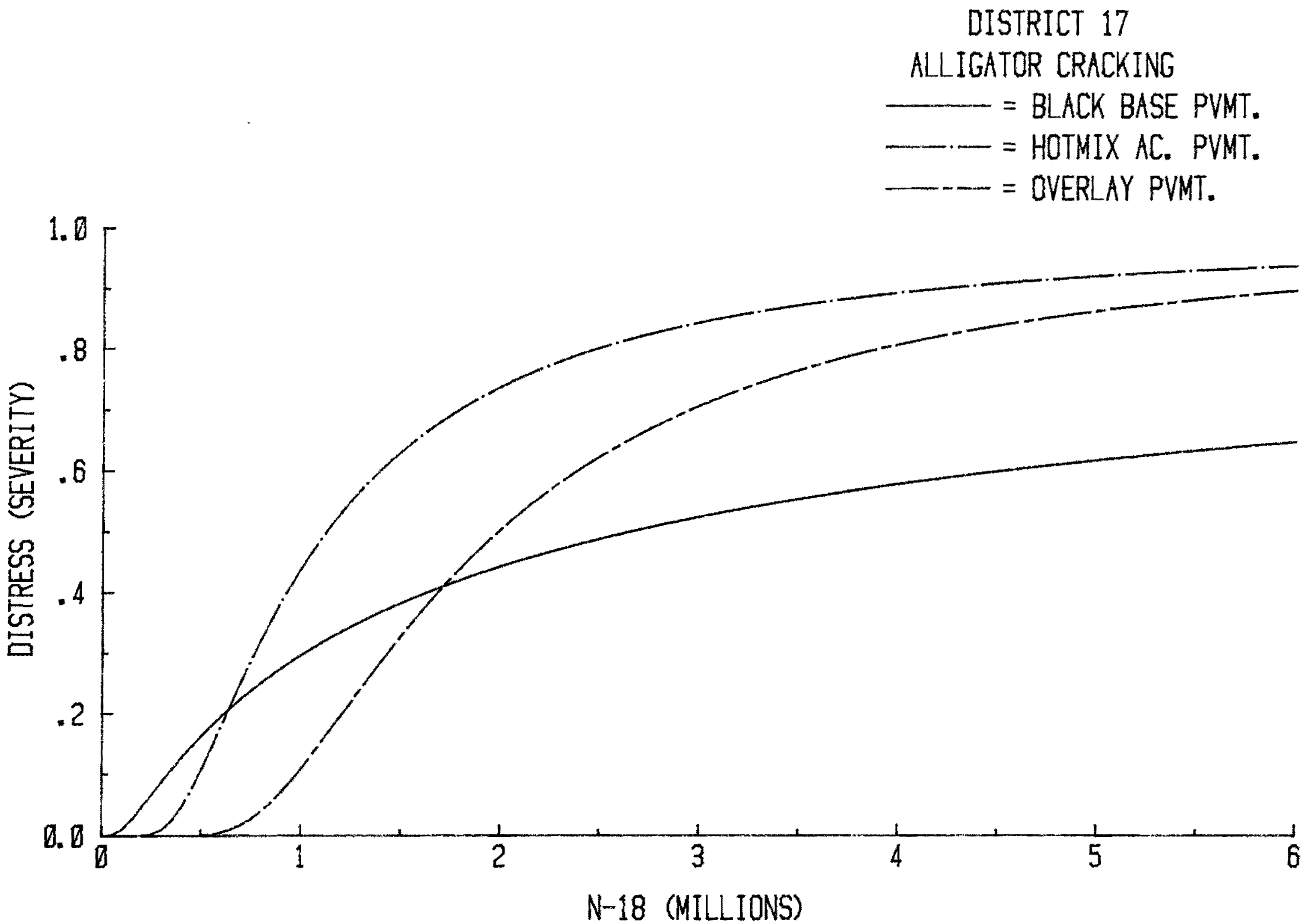
N-18 (MILLIONS)



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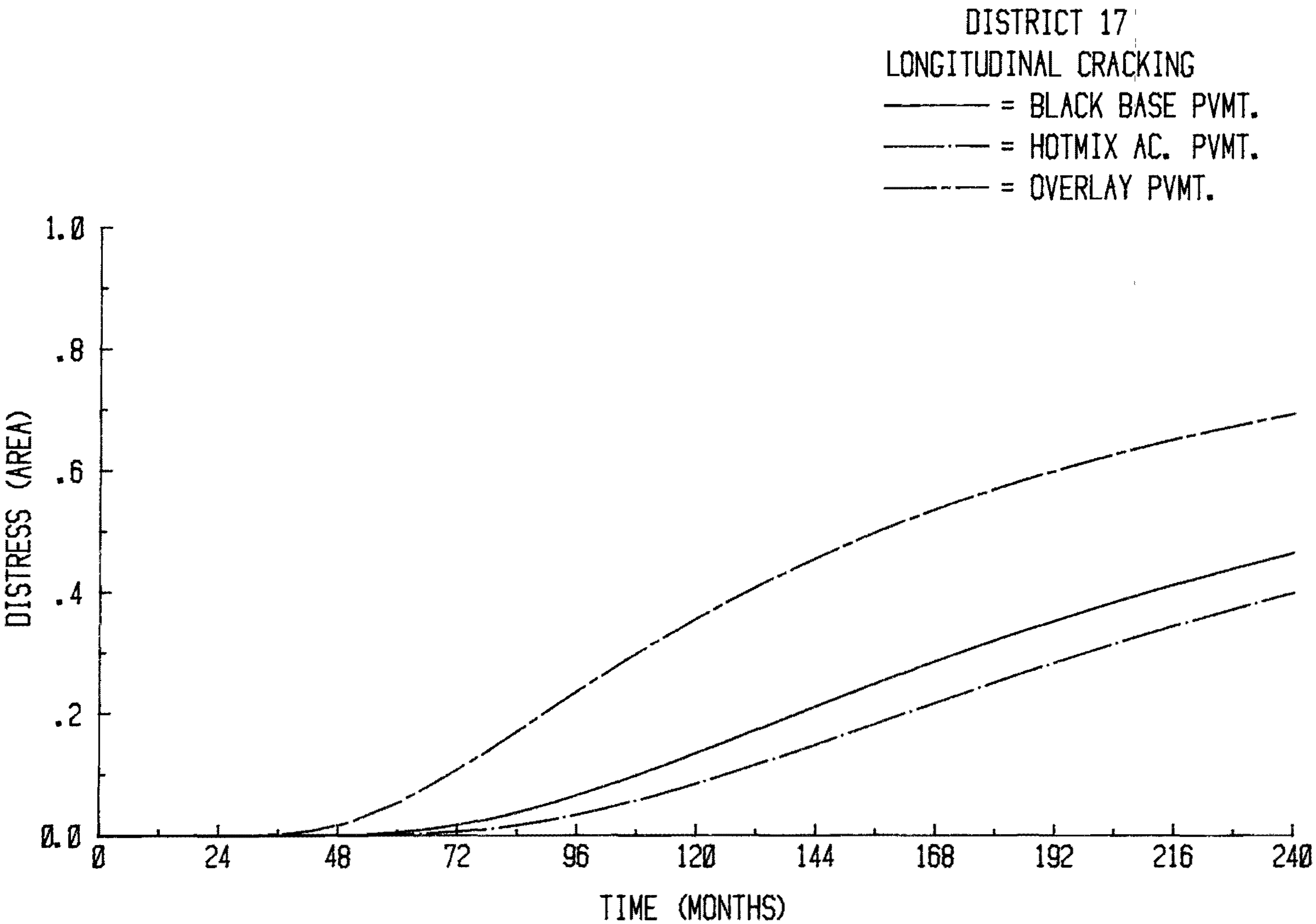
N-18 (MILLIONS)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= OVERLAY PVMT.
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DISTRESS (AREA)
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72
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120
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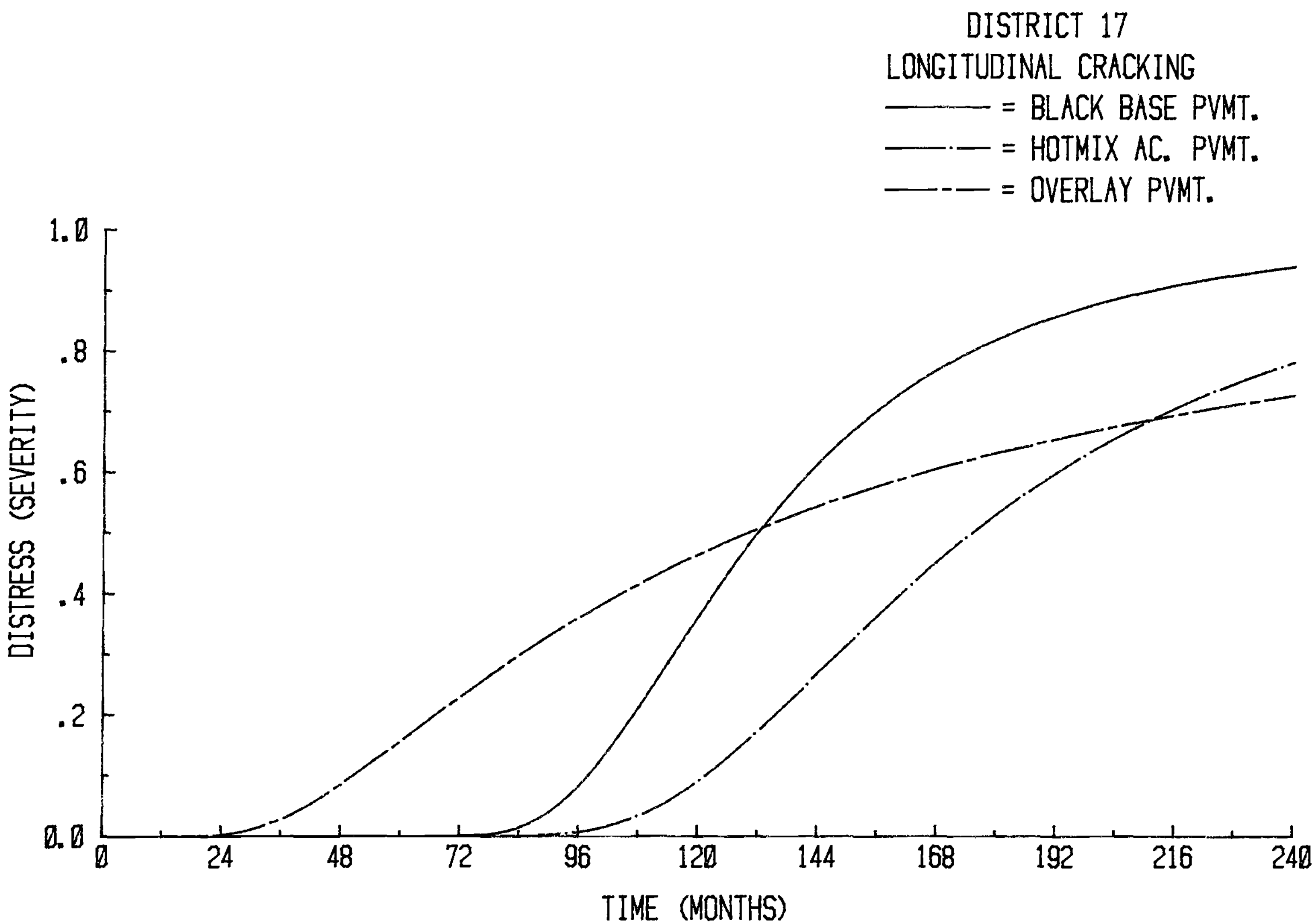
240
TIME (MONTHS)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= OVERLAY PVMT.
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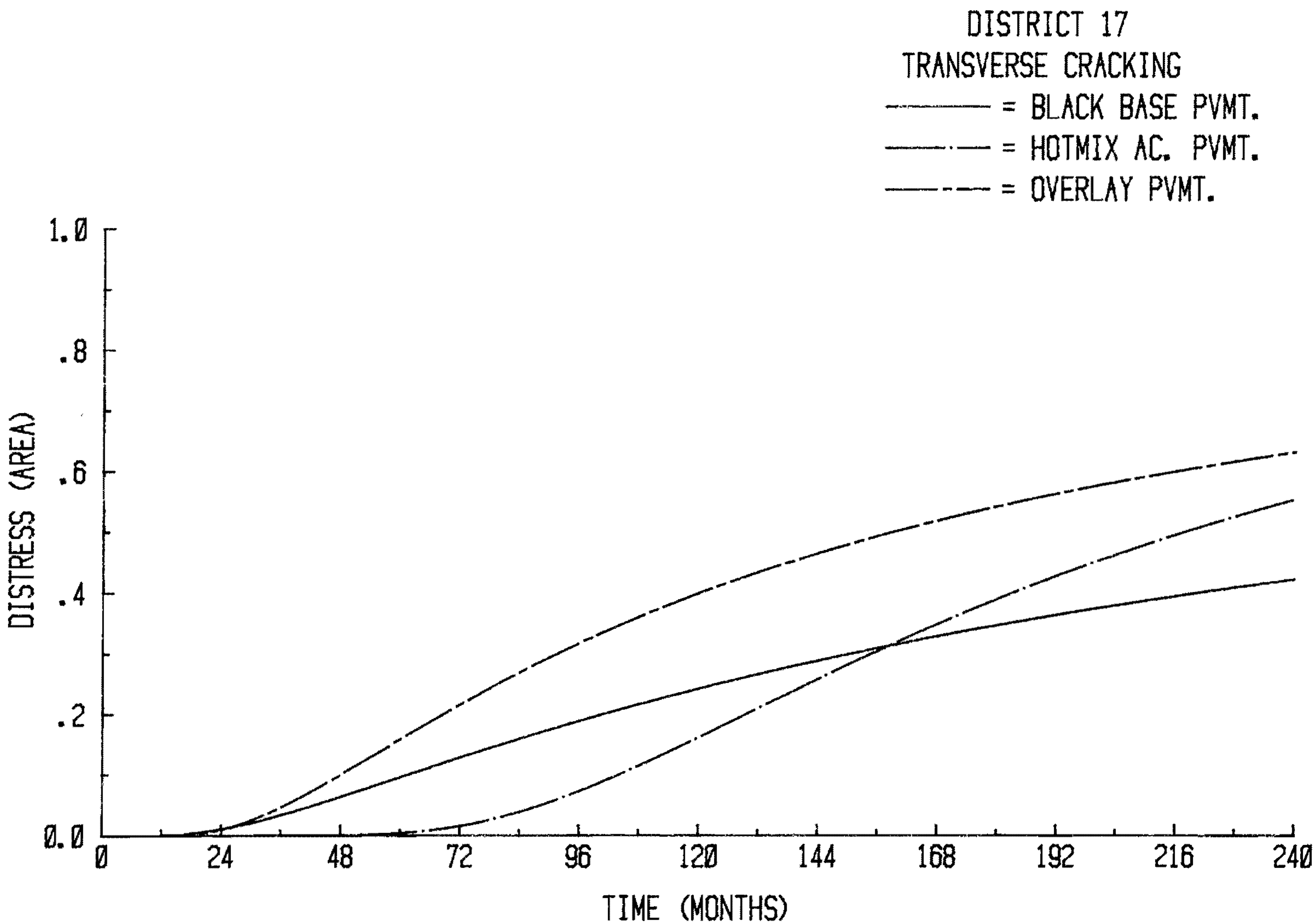
TIME (MONTHS)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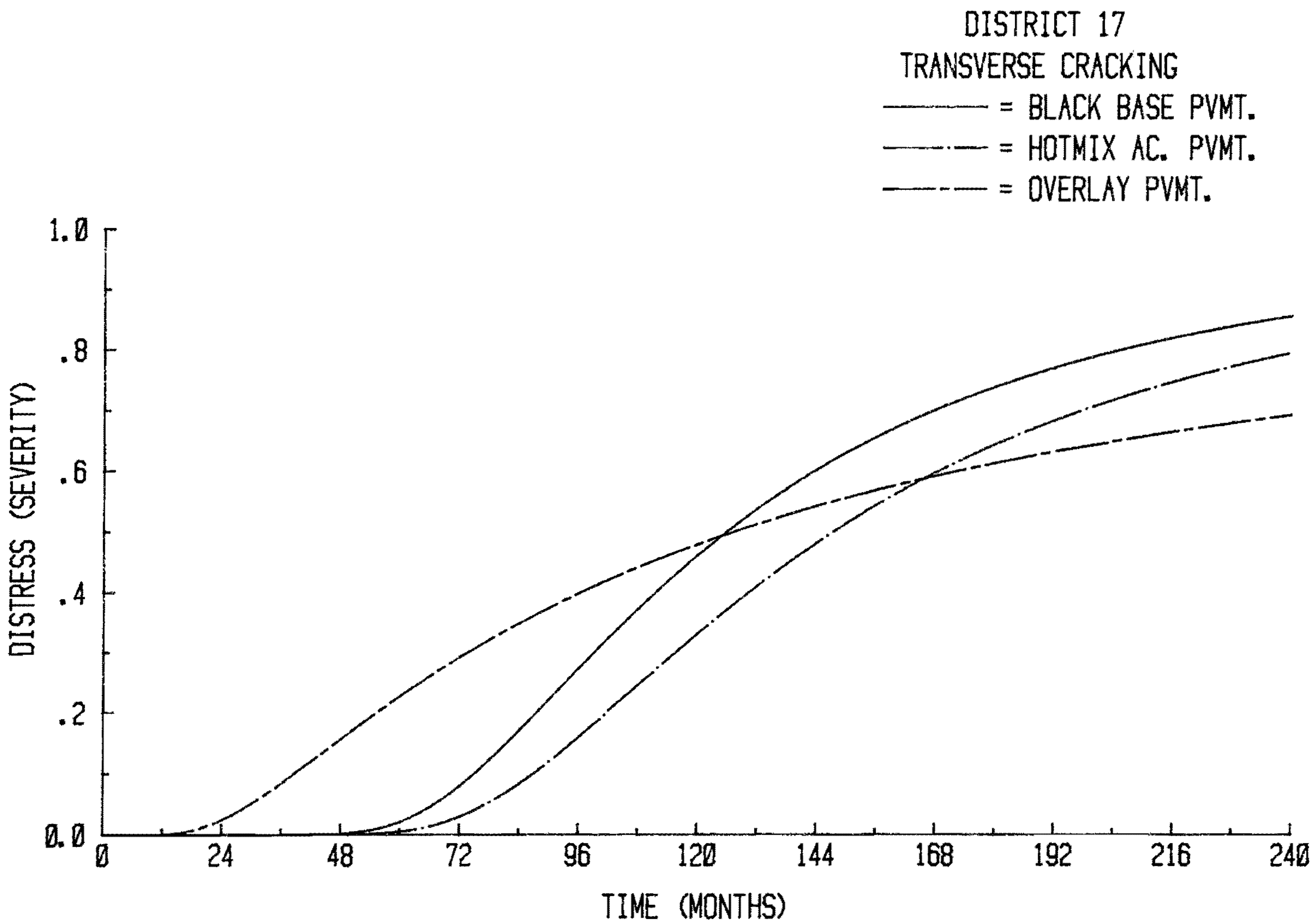
0.Ø
Ø
24
48
72
96
12Ø
144
168
192
216
24Ø
TIME (MONTHS)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DISTRESS (SEVERITY)
0
24
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72
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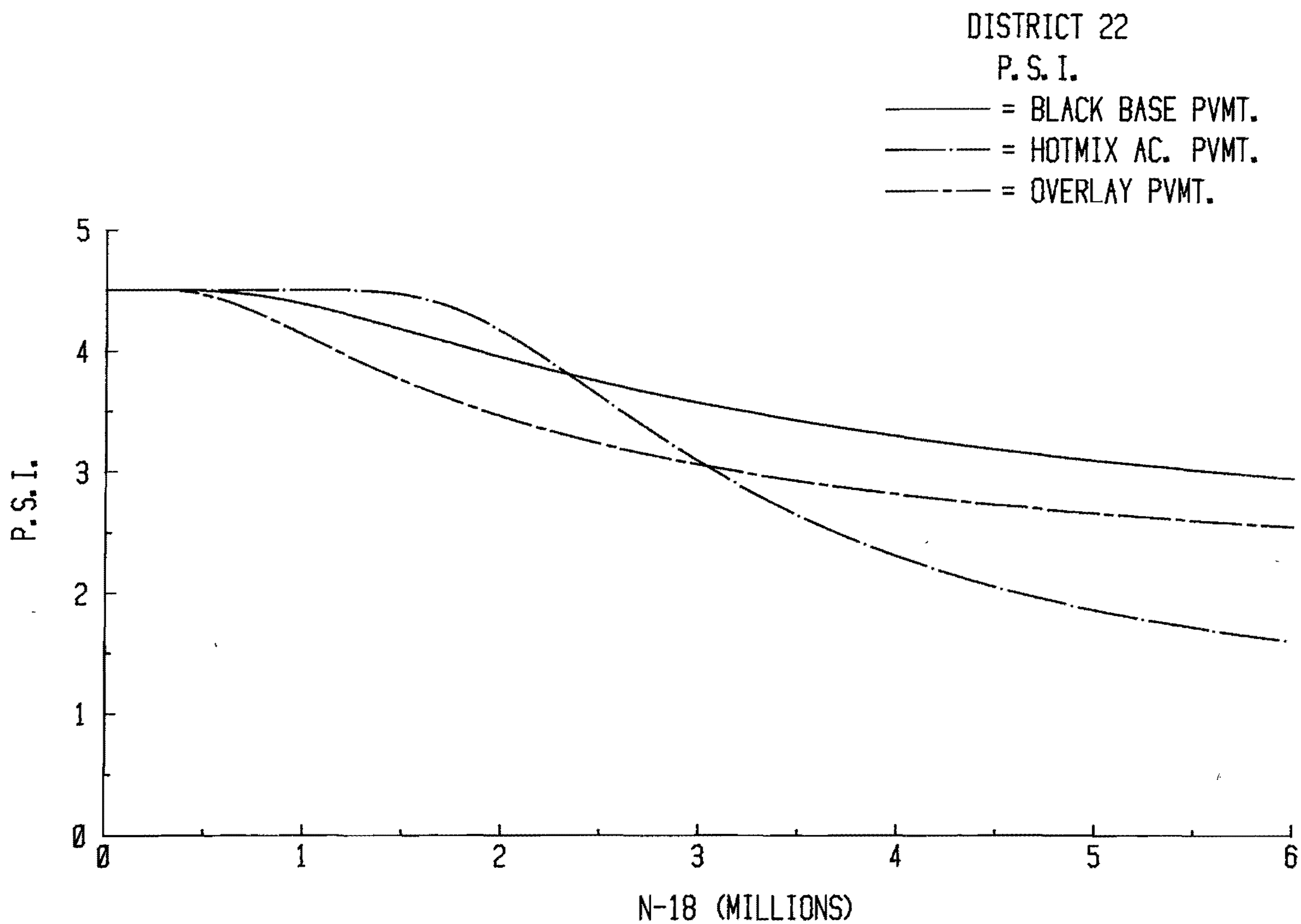
192
216
240
TIME (MONTHS)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= OVERLAY PVMT.
P. S. I.
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4
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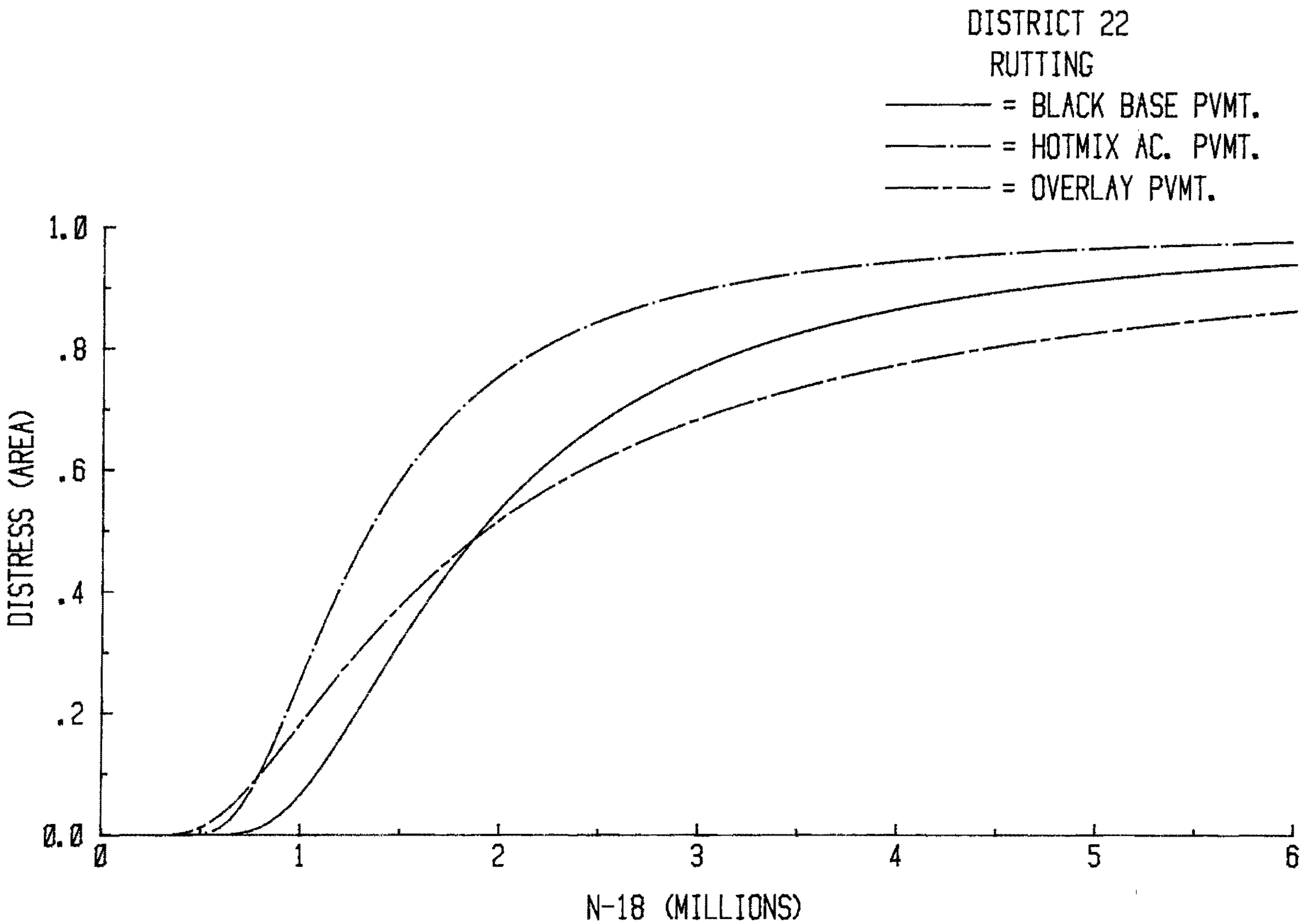
1
Ø
Ø
1
2
3
4
5
6
N-18 (MILLIONS)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= OVERLAY PVMT.
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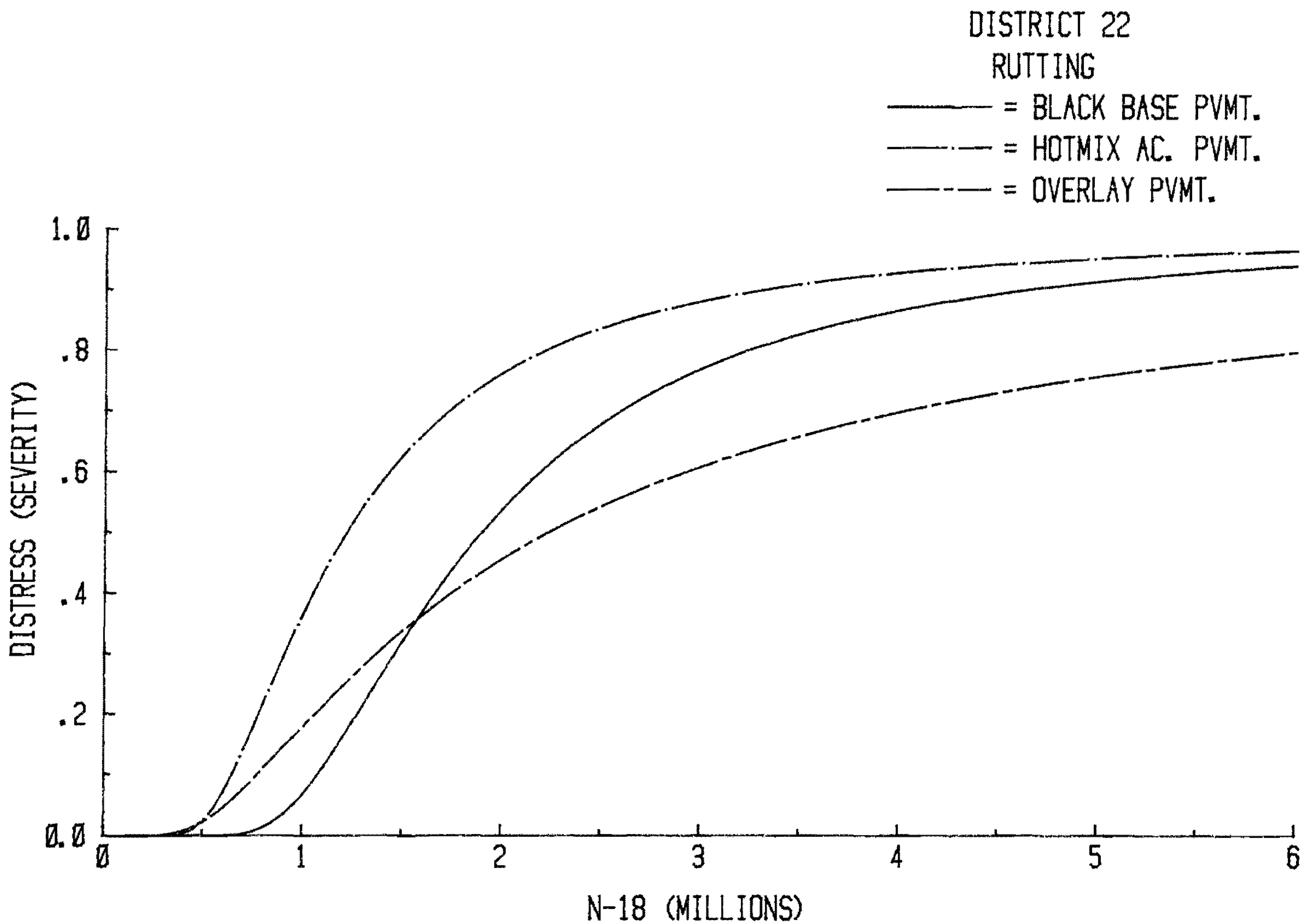
6
N-18 (MILLIONS)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= OVERLAY PVMT.
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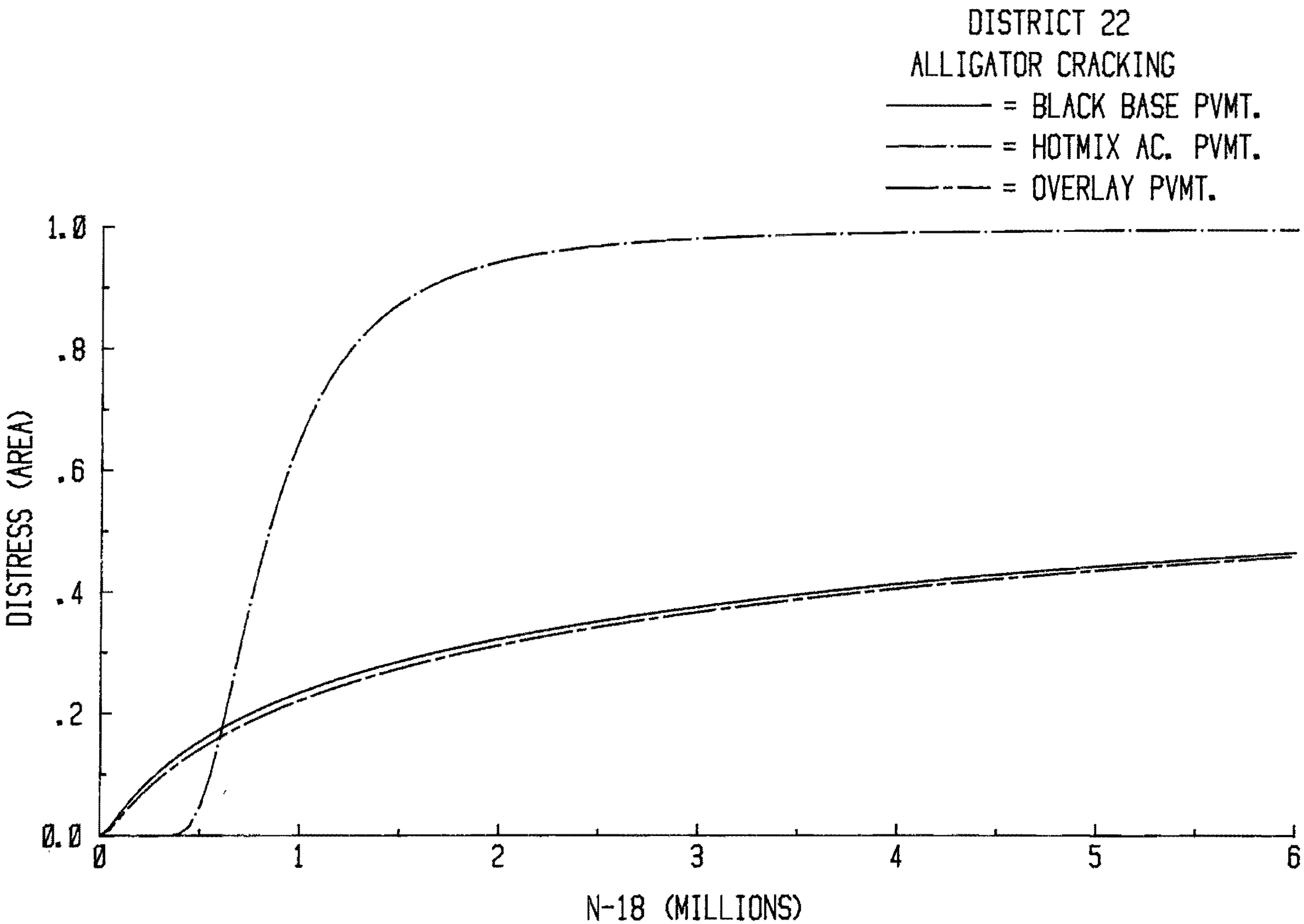
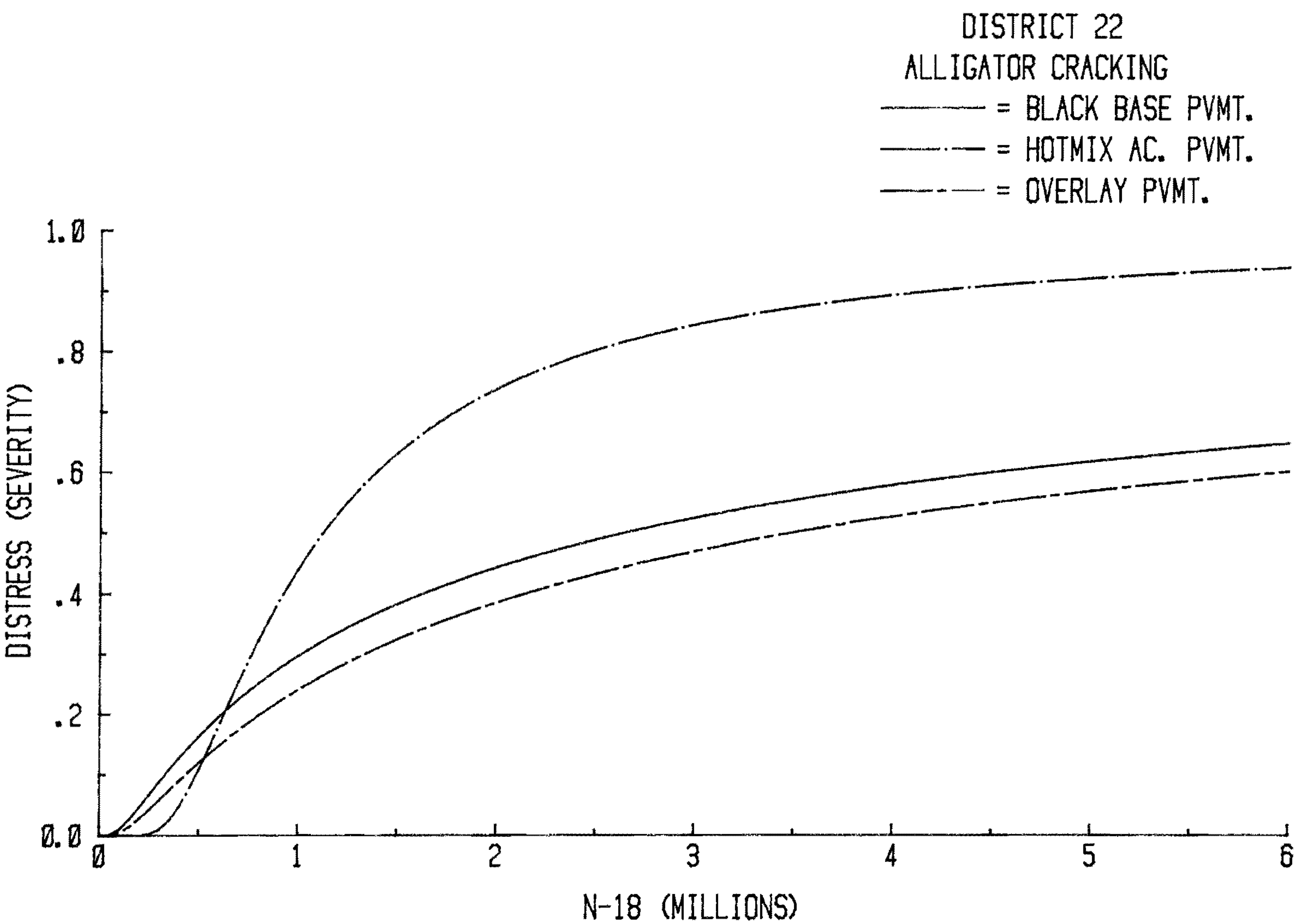
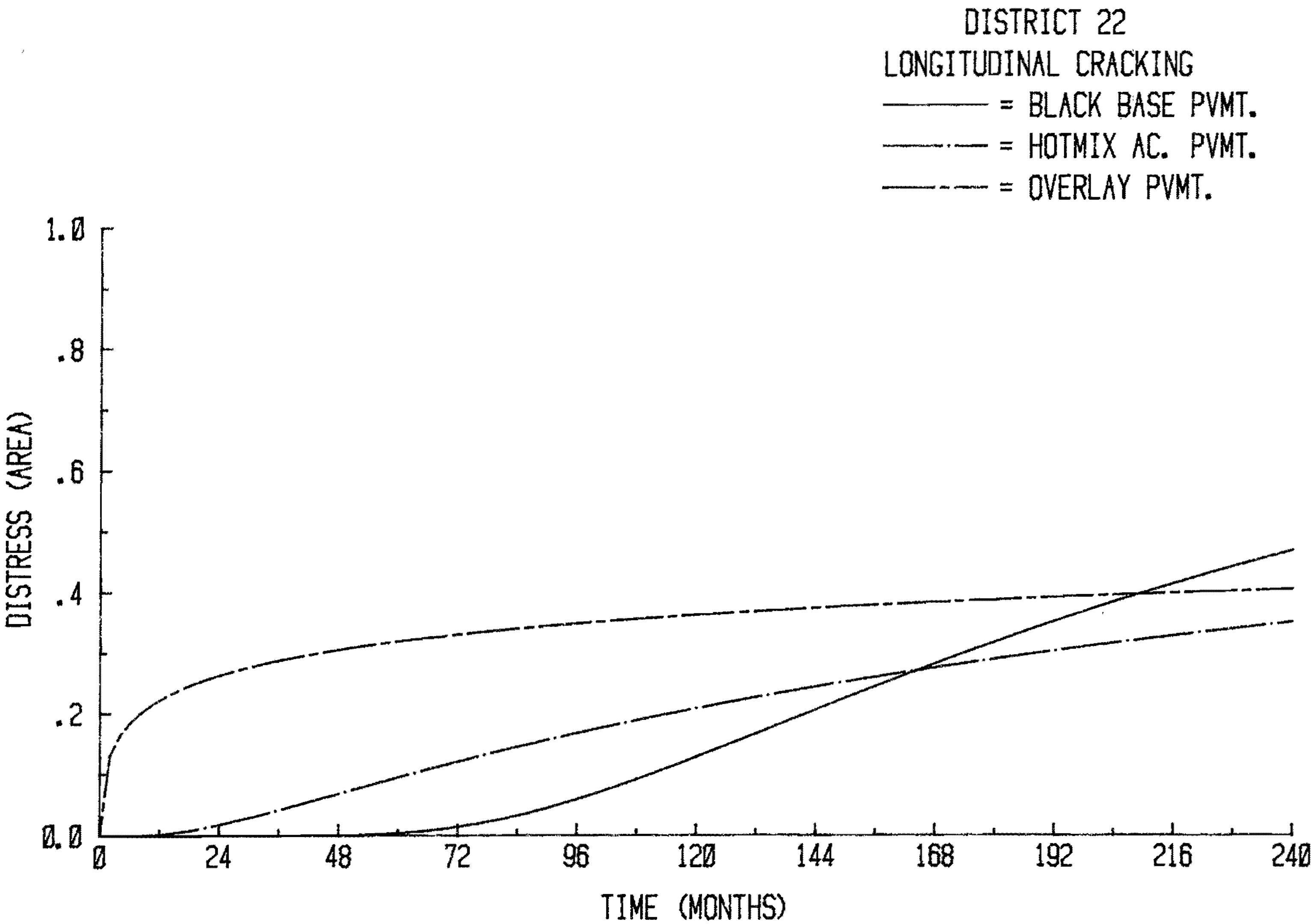
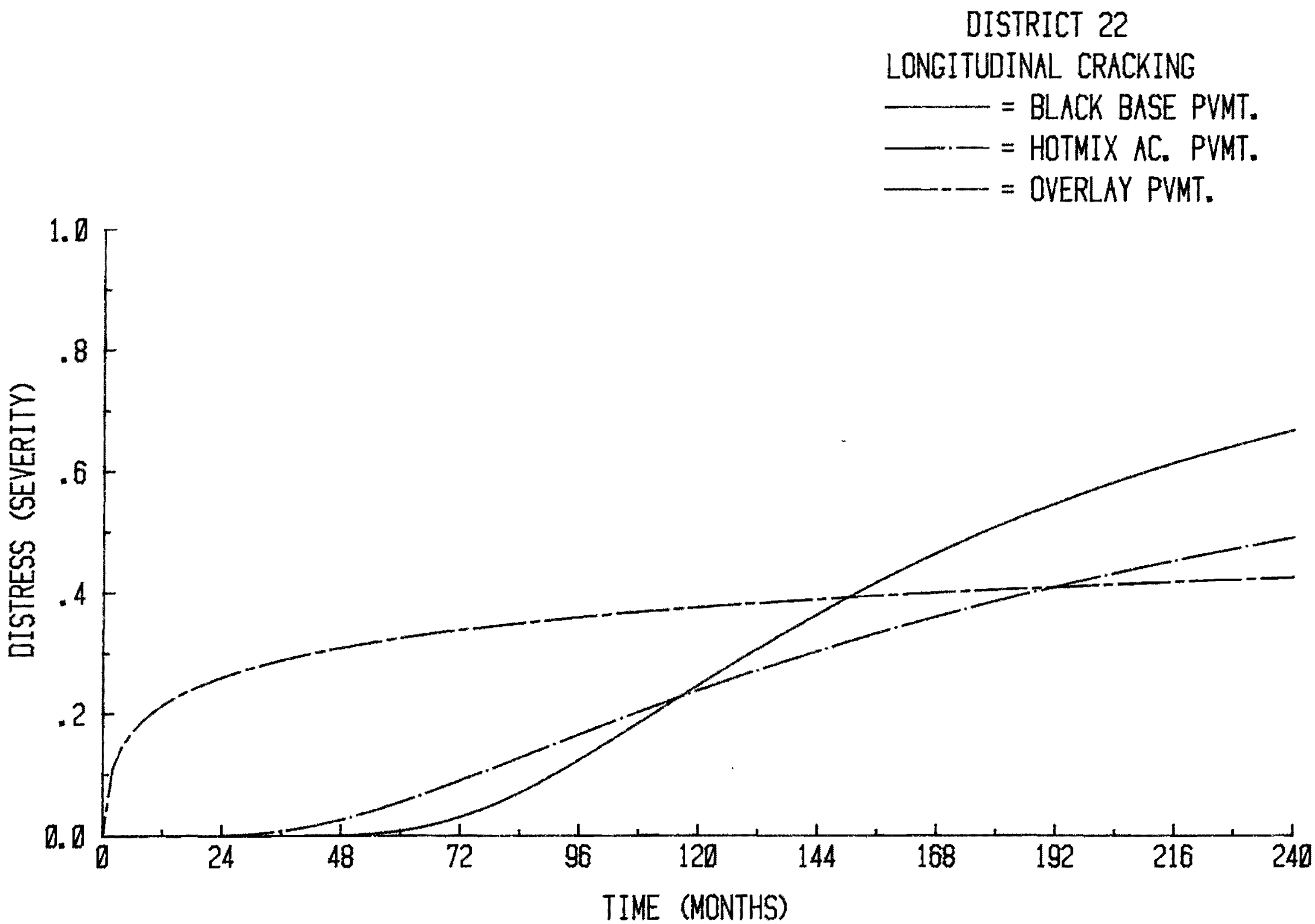
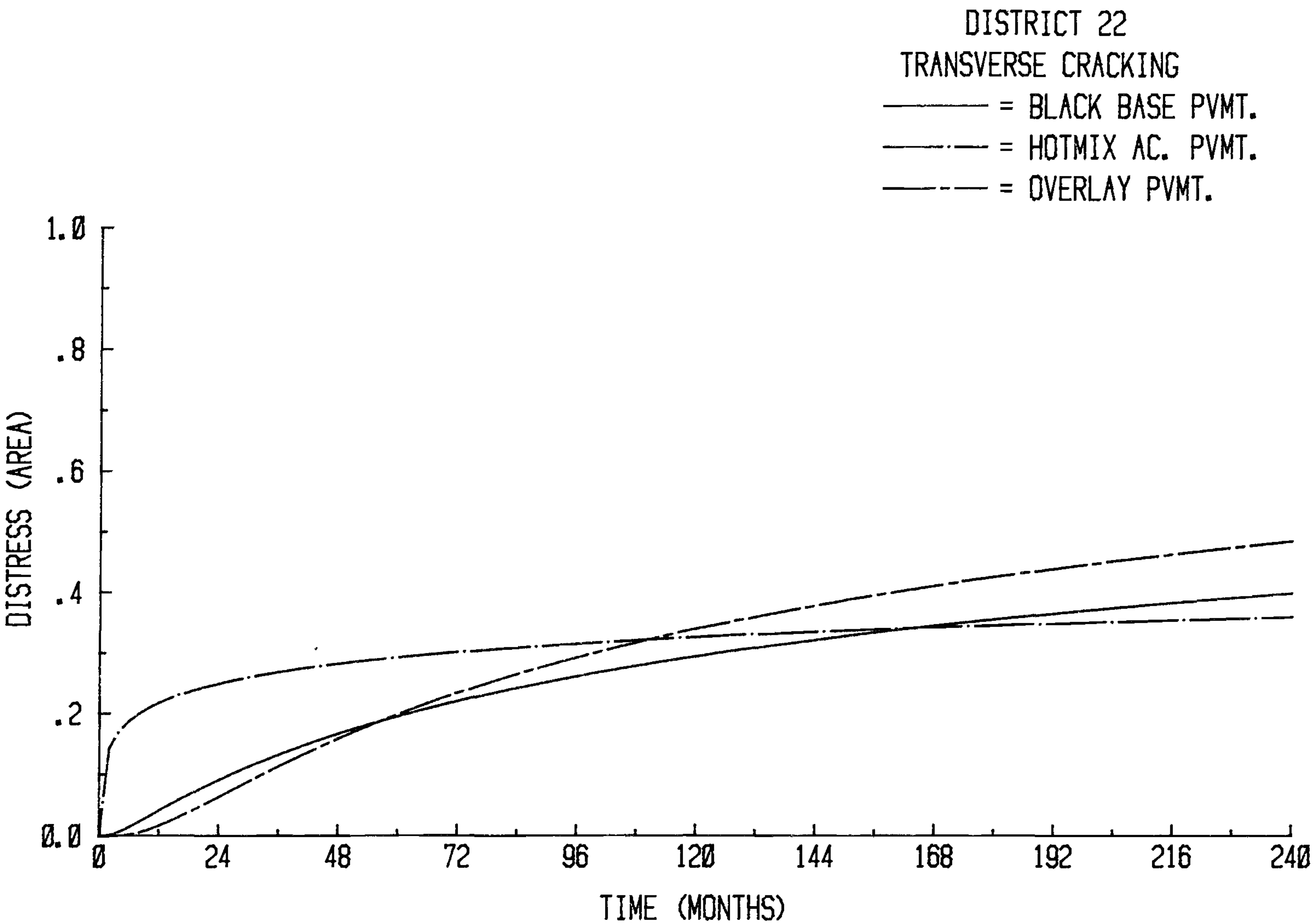
.2
Ø.Ø
Ø
1
2
3
4
5
6
N-18 (MILLIONS)


DISTRICT 22
ALLIGATOR CRACKING
= BLACK BASE PVMT.
= HOTMIX AC. PVMT.
= OVERLAY PVMT.
DISTRESS (AREA)
1.Ø
.8
.6
.4
.2
Ø.Ø
Ø
1
2
3
4
5
6
N-18 (MILLIONS)

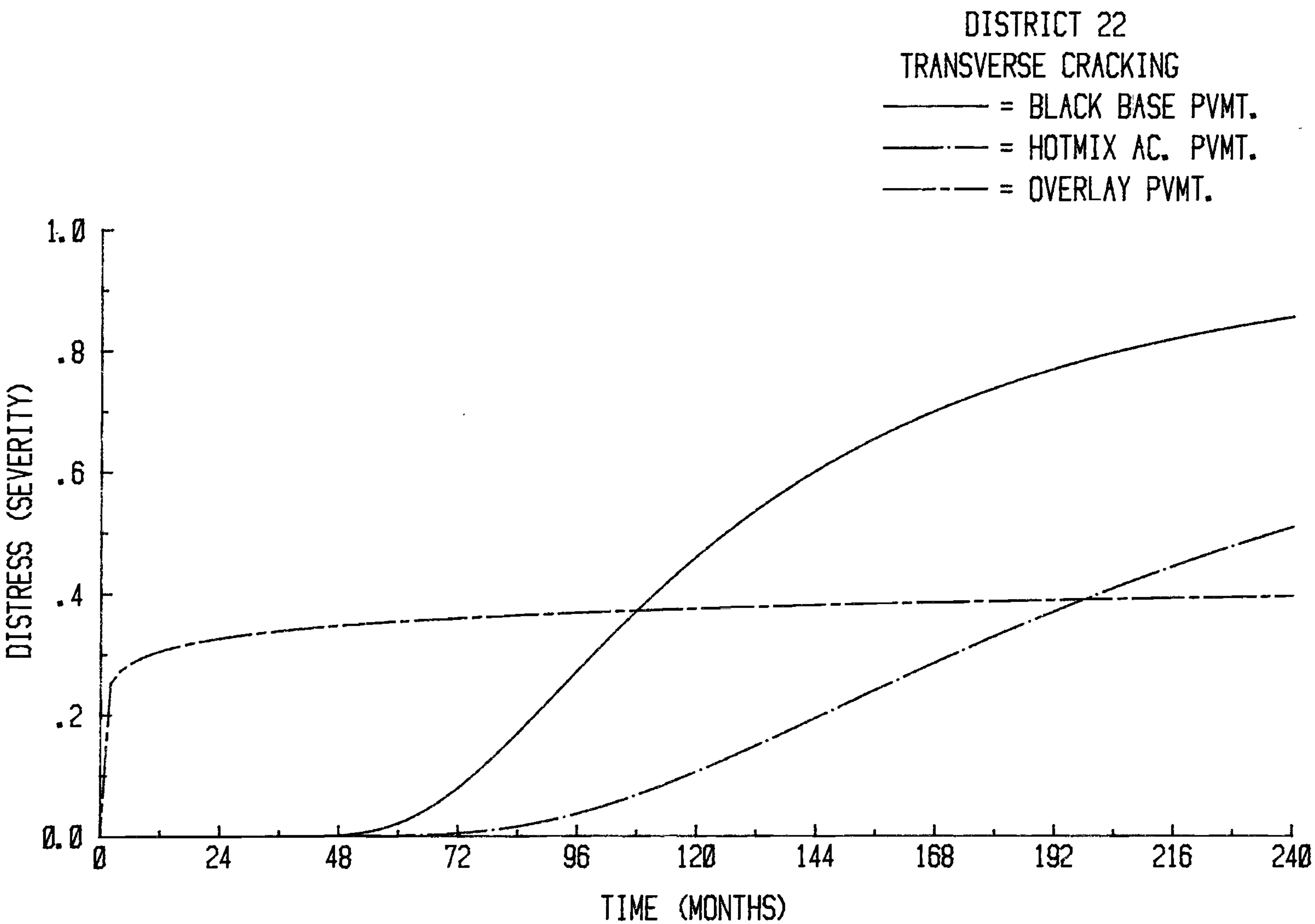

DISTRICT 22
ALLIGATOR CRACKING
= BLACK BASE PVMT.
= HOTMIX AC. PVMT.
= OVERLAY PVMT.
DISTRESS (SEVERITY)
1.0
.8
.6
.4
.2
0.0
0
1
2
3
4
5
6
N-18 (MILLIONS)


DISTRICT 22
LONGITUDINAL CRACKING
= BLACK BASE PVMT.
= HOTMIX AC. PVMT.
= OVERLAY PVMT.
DISTRESS (AREA)
1.0
.8
.6
.4
.2
0.0
0
24
48
72
96
120
144
168
192
216
240
TIME (MONTHS)


DISTRICT 22
LONGITUDINAL CRACKING
= BLACK BASE PVMT.
= HOTMIX AC. PVMT.
= OVERLAY PVMT.
DISTRESS (SEVERITY)
1.0
.8
.6
.4
.2
0.0
0
24
48
72
96
120
144
168
192
216
240
TIME (MONTHS)



DISTRICT 22
TRANSVERSE CRACKING
= BLACK BASE PVMT.
= HOTMIX AC. PVMT.
= OVERLAY PVMT.
1.0
.8
.6
.4
.2
0.0
DISTRESS (AREA)
0
24
48
72
96
120
144
168
192
216
240
TIME (MONTHS)


DISTRICT 22
TRANSVERSE CRACKING
= BLACK BASE PVMT.
= HOTMIX AC. PVMT.
= OVERLAY PVMT.
DISTRESS (SEVERITY)
1.0
.8
.6
.4
.2
0.0
0
24
48
72
96
120
144
168
192
216
240
TIME (MONTHS)

APPENDIX 6

COMPUTER PROGRAMS

Program 1: Performance Equations
Program 2: Survivor Curves

PROGRAM 1

PERFORMANCE EQUATIONS

```
10 ! THIS PROGRAM FINDS THE MO.
   ! ACCEPTABLE VALUES OF    Pf
   ,BETA,RHO FOR A FIXED Po
20 OPTION BASE 1
30 DIM A(50),B(50),D(50),Z(6),T
   (6),P(6),X(6),E(50)
40 DISP "RECORD NUMBER REQUESTE
   D ?" @ BEEP
50 INPUT G
60 ! FOR G=1 TO 91
70 ASSIGN# 1 TO "OLDATA"
80 READ# 1,G ; S,N,P(),X()
90 ASSIGN# 1 TO *
100 IF N=0 THEN 1060
110 B9=0
120 FOR H=1 TO N
130 IF P(H)>B9 THEN B9=P(H)
140 NEXT H
150 I=B9+.01
160 E5=.05
170 A7=0
180 A8=0
190 FOR J=1.05 TO 10 STEP .05
195 DISP "C=";J
200 F=0
210 H0=0
220 B0=0
230 C0=0
240 D0=0
250 E0=0
260 F0=0
270 G0=0
280 H0=0
290 I0=0
300 J0=0
310 FOR K=1 TO N
320 Z(K)=LOG(I-P(K))
330 T(K)=LOG(1/X(K))
340 A1=J^T(K)
350 A0=A1+A0
360 B1=J^(2*T(K))
370 B0=B1+B0
380 C1=Z(K)
390 C0=C1+C0
400 D1=C1*A1
410 D0=D1+D0
420 E1=T(K)*A1
430 E0=E1+E0
440 F1=Z(K)*E1
450 F0=F1+F0
460 G1=T(K)*B1
470 G0=G1+G0
480 H1=EXP(-C1)
490 H0=H1+H0
500 I1=C1*H1
510 I0=I1+I0
520 J1=A1*H1
530 J0=J1+J0
540 NEXT K
550 A(J)=(B0*C0-A0*D0)/(N*B0-A0*
    A0)
    B(J)=(-1*N*D0+A0*C0)/(N*E0-A
    0*A0)
    D(J)=F0-A(J)*E0+B(J)*G0
    E6=ABS(D(J))
    DISP "C,error=";E6
    IF E6>=E5 THEN F=1
    E5=E6
    A5=EXP(A(J))
    A6=I-A5
    DISP "Pf=";A6
    IF A6>=0 THEN F=F+1
    IF ABS(A7-A6)<=.05*ABS(A6) T
    HEN F=F+1
    DISP "Pf,DIFF=";ABS(A7-A6)
    A7=A6
    B5=LOG(J)
    E(J)=I0+N*H(J)/A5-A(J)*H0-C0
    /A5+B(J)*J0-B(J)/A5*A0
    IF F=3 THEN 710
    NEXT J
    PRINT "SECTION NUMBER-";S
    PRINT "Po =";I
    PRINT "Po,ERROR (%)=";E(J)*1
    00
    PRINT "C =";J
    PRINT "C,ERROR (%)=";D(J)*10
    0
    PRINT "Pf =";A6
    PRINT "BETA =";B5
    IF B(J)>=0 THEN 820
    A8=1
    PRINT "RHO IS NEGATIVE FOR T
    HIS DATA"
    GOTO 840
    R5=B(J)^(1/B5)
    PRINT "RHO =";R5
    PRINT
    X7=IP(X(N))+2
    GCLEAR
    SCALE -.25,X7,-.5,5
    XAXIS 0,.5,0,X7
    YAXIS 0,.5,0,5
    FOR L=1 TO N
    MOVE X(L),P(L) @ LORG 5
    LABEL "*"
    NEXT L
    IF A8=1 THEN 1000
    MOVE 0,I
    FOR M=.01 TO X7 STEP .025
    Y8=I-A5*EXP(-(R5/M)^B5)
    DRAW M,Y8
    NEXT M
0 COPY
0 PRINT
0 PRINT
0 PRINT
0 PRINT
0 PRINT
0 ! NEXT G
0 END
```

PROGRAM 2

SURVIVOR CURVES

```
C
C*******************************************************************************
C*
C*    PARAMETERS ESTIMATION FOR WEIBULL DISTRIBUTION AS SURVIVAL FUNCTION
C*
C*                                TEXAS TRANSPORTATION INSTITUTE
C*                                         OCTOBER,1983
C*
C*******************************************************************************
      INTEGER SIDNO
      REAL LAMDA
      DIMENSION SIDNO(1000),PO(1000),PF(1000),RHO(1000),BETA(1000)
      DIMENSION TI(1000),SRV(40),GI(1000),PLOTTI(40),NSEQ(1000)
      CHARACTER SIGN*1,LABELS*51
      INTEGER PTYPE(5),MEASUR(5),DAMAGE(5),DATATY(5)
      DATA SIGN/1H*/,NPLOT/40/
      DATA LABELS/'SURVIVAL RATE'/
      WMAX=7.0
C
C   READ AND ECHO THE INPUT DATA
C
      DO 90000 IRUN=1,20
      READ(5,125,END=9999)PTYPE,MEASUR,DAMAGE,DATATY
  125 FORMAT(4(5A4))
      WRITE(6,235)PTYPE,MEASUR,DAMAGE,DATATY
  235 FORMAT(1H1,4(5A4))
C
C
      WRITE(6,110)
  110 FORMAT(//, T21,2X,'INPUT NO.',
     2           T31,5X,'SIDNO',
     3           T41,8X,'PO',
     4           T51,8X,'PF',
     5           T61,6X,'BETA',
     6           T71,7X,'RHO')
C
      INO=0
C
      DO 900  I=1,1000
      READ(5,105)SIDNO(I),PO(I),PF(I),BETA(I),RHO(I)
  105 FORMAT(I4,F5.0,3F7.0)
C
      IF(SIDNO(I).LE.1) GO TO 2222
      INO=INO+1
C
      WRITE(6,175)I,SIDNO(I),PO(I),PF(I),BETA(I),RHO(I)
  175 FORMAT(T21,2I10,F10.2,3F10.3)
  900 CONTINUE
C
C  THE END OF EVERY SET OF DATA IS A BLANK CARD
C
 2222 DO 88000 IPC=1,3
      PC=IPC*1.
C
      NDATA=0
      DO 1000 I=1,INO
      IF(PC.LE.PF(I).OR.PC.GE.PO(I)) GO TO 1000
      GI(I)=(PO(I)-PC)/(PO(I)-PF(I))
      TI(I)=RHO(I)/((-ALOG(GI(I)))**(1./BETA(I)))
```

```
      IF(TI(I).GE.WMAX) GO TO 1000
      NDATA=NDATA+1
      NSEQ(NDATA)=I
      PO(NDATA)=PO(I)
      SIDNO(NDATA)=SIDNO(I)
      PF(NDATA)=PF(I)
      BETA(NDATA)=BETA(I)
      RHO(NDATA)=RHO(I)
      TI(NDATA)=TI(I)
      GI(NDATA)=GI(I)
 1000 CONTINUE
C
C
         DO 2000 I=1,NDATA
         IF(I.NE.1) GO TO 1111
         TIMIN=TI(1)
         TIMAX=TI(1)
 1111    IF(TI(I).GE.TIMAX) TIMAX=TI(I)
         IF(TI(I).LT.TIMIN) TIMIN=TI(I)
 2000    CONTINUE
      WRITE(6,210)
  210 FORMAT(1H1,T11,3X,'DATA NO.',
     2           T21,3X,'ORG. SEQ',
     3           T31,5X,'SIDNO',
     4           T41,8X,'PO',
     5           T51,8X,'PF',
     6           T61,6X,'BETA',
     7           T71,7X,'RHO',
     8           T81,5X,'PERFORMANCE (G)',
     9           T101,8X,'TRAFFIC INDEX (T)')
C
      DO 2500 I=1,NDATA
      WRITE(6,115)I,NSEQ(I),SIDNO(I),PO(I),PF(I),BETA(I),RHO(I),
     2            GI(I),TI(I)
  115 FORMAT(T11,3I10,F10.2,3F10.3,F20.3,F25.3)
 2500 CONTINUE
C
C  NEWTON-RAPHSON METHOD
C
      CALL NEWRAP(TI,NDATA,GAMMAV)
C
        SUMTIG=0.
        DO 3000 I=1,NDATA
        SUMTIG=TI(I)**GAMMAV+SUMTIG
 3000   CONTINUE
C
      LAMDA=(NDATA/SUMTIG)**(1./GAMMAV)
C
      WRITE(6,195)PC,GAMMAV,LAMDA
  195 FORMAT(3(/),T21,'CRITICAL P                       =',F9.3,
     2       2(/),T21,'GAMMA OF WEIBULL DISTRIBUTION =',F9.3,
     3       2(/),T21,'LAMDA OF WEIBULL DISTRIBUTION =',F9.3)
          XMAX=5.7
          XMIN=0.0
          XDIST=(XMAX-XMIN)/NPLOT
C
C
             DO 4000 I=1,NPLOT
             PLOTTI(I)=XDIST*I
             SRV(I)=1./(EXP((LAMDA*PLOTTI(I))**GAMMAV))
```

```
 4000         CONTINUE
88000 CONTINUE
90000 CONTINUE
 9999 WRITE(6,555)
  555 FORMAT(1H1)
      STOP
      END
C
C
C
      SUBROUTINE NEWRAP(TI,NDATA,N21)
C
C NEWTON-RAPHSON METHOD FOR SEARCHING ROOT(S) OF WEIBULL DISTRIBUTION
      DIMENSION TI(1000),SUM(4),GUESS(5)
      DATA GUESS/1.0,0.5,0.25,0.2,0.0001/
      REAL K1,KN,N2,N21
      DATA EPSI/0.1E-03/
      DELK=0.10
C
        SUMTI=0.
        DO 100 I=1,NDATA
        SUMTI=TI(I)+SUMTI
  100   CONTINUE
C
      MEANTI=SUMTI/NDATA
C
            SUMVAR=0.
            DO 200 I=1,NDATA
            SUMVAR=(TI(I)-MEANTI)**2+SUMVAR
  200       CONTINUE
C
      VARTI=SUMVAR/(NDATA-1.)
C
      CV=(SQRT(VARTI))/MEANTI
C
            DO 300 I=1,5
            IF(I.EQ.5) GO TO 33333
            IF(CV.GT.I) GO TO 300
            K1=GUESS(I)
            GO TO 222
  300       CONTINUE
C
33333       K1=GUESS(5)
C
  222   ICHECK=1
C
        CALL SUMS(TI,NDATA,SUM,K1,ICHECK)
        FOFK1=SUM(1)/SUM(2)-(1./K1)-(SUM(3)/NDATA)
  204   KN=K1+DELK
        CALL SUMS(TI,NDATA,SUM,KN,ICHECK)
        FOFKN=SUM(1)/SUM(2)-(1./KN)-(SUM(3)/NDATA)
        IF(FOFK1*FOFKN)206,205,207
  205   CONTINUE
        IF(FOFK1.EQ.0.) N21=K
        IF(FOFKN.EQ.0.) N21=KN
        RETURN
  207   K1=KN
        FOFK1=FOFKN
        GO TO 204
  206   N2=KN
```

```
C
         ICHECK=2
C
  208    CALL SUMS(TI,NDATA,SUM,N2,ICHECK)
         FOFKN=SUM(1)/SUM(2)-(1./N2)-(SUM(3)/NDATA)
         DFDN=(SUM(2)*SUM(4)-SUM(1)**2)/(SUM(2)**2)+(1./(N2**2))
         N21=N2-FOFKN/DFDN
C        PRINT,'N21=',N21,'N2=',N2
         IF(ABS(N21-N2)-EPSI)210,210,209
  209    N2=N21
         GO TO 208
  210    FOFN21=SUM(1)/SUM(2)-(1./N21)-(SUM(3)/NDATA)
  999 RETURN
      END
C
C
C
      SUBROUTINE SUMS(TI,NDATA,SUM,GAMA,ICHECK)
C
       DIMENSION TI(1000),SUM(4)
      DO 5000 I=1,4
      SUM(I)=0.
 5000 CONTINUE
C
         DO 6000 I=1,NDATA
         SUM(1)=(TI(I)**GAMA)*ALOG(TI(I))+SUM(1)
C     PRINT,'TI(I)=',TI(I),'SUM(1)=',SUM(1),'GAMMA=',GAMA
 6000    CONTINUE
C
      DO 7000 I=1,NDATA
      SUM(2)=TI(I)**GAMA+SUM(2)
 7000 CONTINUE
C
         DO 8000 I=1,NDATA
         SUM(3)=ALOG(TI(I))+SUM(3)
 8000    CONTINUE
C
      IF(ICHECK.EQ.1) GO TO 9999
      DO 9000 I=1,NDATA
      SUM(4)=(ALOG(TI(I))**2)*(TI(I)**GAMA)+SUM(4)
 9000 CONTINUE
C
 9999 RETURN
      END
```