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~~Battelle,~~ Pacific Northwest Laboratory

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1.0 INTRODUCTION AND PURPOSE

Design and analysis of Hanford double-shell waste storage tanks has made use of the finite element computer code SAFE-CRACK as a check of the concrete portion of the tank design after completion of design. Rockwell Hanford Operations, the site contractor responsible for operation of the tanks, has requested Battelle Pacific Northwest Laboratory (PNL) to evaluate the use of the Hanford concrete property data at elevated temperatures by the SAFE-CRACK code. Specifically, it was requested that the following questions be addressed using, as a data base, the PCA-developed data on Hanford concrete properties documented in the Rockwell report RHO-C-54.(1)

1. Does SAFE-CRACK properly account for the temperature degradation effects to the physical properties of concrete?
2. Can the physical properties of the tested high temperature concrete be justifiably extrapolated for 50 years?
3. Do other physical characteristics of concrete such as chemical reactivity, crystalline changes, bonding, etc., support the long-term extrapolation?

The purpose of this investigation is to evaluate the proper use of the mathematical expressions in SAFE-CRACK to best define the physical concrete properties extrapolated from the RHO-C-54 data when subjected to elevated temperatures and cyclic temperature variations.

2.0 SUMMARY AND CONCLUSIONS

An evaluation of SAFE-CRACK's use of Hanford elevated-temperature concrete properties data indicates:

1. From a practical standpoint, the values of modulus of elasticity and compressive strength predicted by SAFE-CRACK are either conservative or approximately equal to values indicated by curves fitted to PCA data. They appear to be sufficiently conservative to use (from a practical standpoint) to perform design-by-analysis of Hanford waste storage tanks using SAFE-CRACK. It is recommended that future refined data fits be compared to predictions of SAFE-CRACK to assure proper application of the code.
2. From a statistical standpoint, the fitted curves for modulus of elasticity and compressive strength at temperature show some lack-of-fit and are, therefore, not completely defensible as is. Additional statistical analysis is recommended to try to obtain more defensible extrapolation equations. The fitted curves, Figures 4 to 15, are presented as illustrations of something close to what final answers might be.
3. The SAFE-CRACK prediction equations for creep and tensile strength need to be modified to fit the PCA data better.

The answers to the three questions above are:

1. SAFE-CRACK predicts temperature degradation in physical properties that are generally consistent with available data. However, some future changes in predictive equations are recommended to improve the accuracy of the predictions.
2. A 50 year extrapolation of the PCA data for Hanford concrete can be performed, but not on the basis of customary statistical theory alone. Improved statistical extrapolation utilizing experience and knowledge of elevated temperature effects on concrete (physical and chemical) requires further study to possibly minimize effects of random variables in the test data. This would increase confidence in extrapolated data.
3. Physical and chemical characteristics of concrete support a gradual, continuing degradation of its properties at elevated temperatures. Rates

of degradation are not available from current literature on concrete chemistry or crystalline changes.

3.0 THE PCA-DEVELOPED DATA BASE

The concrete property data to be used in the evaluation are contained in RHO-C-54, "Effects of Long-Term Exposure to Elevated Temperatures on the Mechanical Properties of Hanford Concrete," October 1981, performed for Rockwell by the Portland Cement Association's (PCA) Construction Technology Laboratories, Skokie, Illinois.

The PCA conducted the tests over a five year period. The concrete specimens (standard ASTM size 6 in. x 12 in.) were prepared at the PCA Laboratories using "basalt" (Hanford) aggregate and ASTM C 150 Type II portland cement, both shipped to the PCA from Hanford. Two concrete mixture designs were tested; specified minimum 3000 psi and 4500 psi mixtures (compressive strength at 28 days). Specimens were continuously moist-cured at 70 F in a fog room until placed in the oven. They were then continuously heated at 250 F, 350 F and 450 F for up to 920 days, removed from the oven, and tested while hot. One set of specimens was continuously heated to 350 F for 1300 days. Some specimens were subjected to temperature cycles of 70 F to 350 F and back to 70 F, for up to 18 cycles of 14- and 28-day duration.

The following properties were measured:

- modulus of elasticity
- compressive strength
- splitting tensile strength
- Poisson's ratio

In addition, six 4500 psi cylinders were tested to obtain creep strain data at 250 F and 350 F for 650 days.

4.0 LITERATURE REVIEW AND GENERAL FINDINGS

This section discusses the general effects of elevated temperature on portland cement concrete. The results of the literature review were in good agreement with the data in RHO-C-54. The RHO-C-54 data is of greater duration at temperature than any other study found.

4.1 EFFECTS OF ELEVATED TEMPERATURE ON CONCRETE PROPERTIES - GENERAL

"Exposure to temperatures greater than 70 or 80 F has a deteriorating effect on the physical properties of portland cement concrete. However, for constant exposure at temperatures up to 150 or 200 F, the loss in strength, if any, is quite small; and for temperatures as high as 500 to 600 F, the deterioration in structural properties is ordinarily tolerable."(2)

Exposure of concrete to elevated temperatures accelerates drying of the concrete and removal of water required by the chemical process of hydration. At temperatures above 200 F, some of the water of hydration is removed from the hardened paste in addition to evaporable water which may be in the concrete. It is generally agreed that heating portland cement concrete to 800 F or above will completely dehydrate the hardened paste. However, concrete at 800 F still has about 50% of its strength which is progressively reduced if the temperature is increased.(2) At about 950 to 1100 F, the calcium hydroxide in concrete decomposes to calcium oxide and water with a resultant loss of most of its remaining strength. In the 600 to 1100 F range, concretes made with siliceous or limestone aggregates change to a pink or red color and from 1100 to 1650 F to a grey, probably friable and porous state. At higher temperatures, concrete changes to a buff and then a yellow color.(3)

In general, the effects of heating on the properties of concrete are less on concrete where the moisture is allowed to evaporate than on concrete in which the water is sealed in.* In specimens where the water is free to evaporate, losses in compressive strength range from none to 30% for 200 F exposure and from none to 67% at 500 F depending upon the length of heating and testing conditions [see Table 1(2)]. As pointed out in RHO-C-54, Abrams found that concrete that had an applied stress during heating lost significantly less compressive strength than unstressed specimens. This phenomenon, also reported by Malhotra,(4) adds an unknown conservatism to the design of concrete structures subject to heating.

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*Unless otherwise noted, the discussion of elevated temperature effects on concrete in this report are confined to the case of unsealed concrete, where the water is able to evaporate or be driven out by heating.

Heating has a pronounced effect on the modulus of elasticity of concrete, reducing it to as low as 33% of its 90-day value after exposure to 660 F for 106 days. Exposure to 392 F for 106 days reduced it to 67% of its 90-day value in one test.(2)

Fewer data are available in the literature on the effect of heating on flexural, tensile, and bond strength than for compressive strength. However, the data indicate that somewhat greater losses in flexural and tensile strength occur when specimens are exposed to high temperatures for longer periods of time. In the case of bond strength, shrinkage of concrete, which occurs during heating, apparently destroys the bond between the concrete and its reinforcing and causes a high loss in bond strength at low values of slip. However, the ultimate bond strength is little affected when deformed steel is used since, with higher values of slip, the concrete is brought to bear against the protrusions of the reinforcing steel.(2)

TABLE 1. Compressive Strength of Heated Specimens Expressed as Percent of Strength of Unheated Specimens*

Source	Ref[a]	Oven Temperature, deg F[b]											Comments
		200	300	400	500	600	800	900	1100	1300	1500	1700	
Hannant........	[7]	70	80	...	...	...	...	...	...	...	...	...	Moisture allowed to evaporate.
		70	60	...	...	...	...	...	...	...	...	...	Moisture loss restricted.
Saemann........	[8]	80	100	100	100	...	...	...	...	...	...	...	*W/C* = 0.48 Heated 24 hr and tested hot.
		87	100	100	100	...	...	...	...	...	...	...	*W/C* = 0.84
Malhotra........	[9]	97	95	88	75	~53	...	...	...	...	...	...	Heated under 1041 psi load and tested hot.
		94	87	77	58	...	...	...	...	...	...	...	Heated at zero stress and tested hot.
		75	66	53	33	...	...	...	...	...	...	...	Heated at zero stress & tested at about 75 F.
Miller...........	[19]	84	87	...	55	...	48	...	14	4	...	4	*W/C* = 0.90. Tested cold at 28 days.
Heiskill.........	[20]	100	...	...	85	...	...	...	79	56	46	...	28-day moist cure.
		100	...	...	66	...	...	...	63	42	23	...	7-day moist cure.
Binner..........	[21]	100	...	...	...	55	...	39	...	...	...	...	Heated 7 days.
		100	...	...	...	47	...	40	...	...	...	...	Heated 14 days.
Germany........	[2]	...	...	...	...	88	...	50	...	18	...	...	7-day moist cure and 10 hr at 572 F.
Hanford........	[6]	...	...	...	...	...	...	...	23 to 25	...	...	...	Grout with fine sand.
		...	...	...	...	...	...	...	47 to 92	...	...	...	Grout with coarser sand.
		83	71	90	...	60	...	...	...	...	...	...	Concrete K
		...	...	...	...	77	...	...	...	...	...	...	Concrete G

[a] From list of references.

[b] Specimens were oven heated at the respective temperatures, cooled, and then tested at or near room temperature, except as noted.

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*Reference 1, page 453

An important point brought out in the literature review is that the data from testing of small specimens apply only qualitatively to full-sized structures because the deterioration of concrete in small specimens can be expected to be greater than in large structures. Also, concrete exposed to heating from one side only is less affected than concrete heated from all sides.(2) Both of these phenomena contribute an unquantified amount of conservatism to the design of concrete structures subjected to elevated temperatures.

4.2 CHEMICAL AND PHYSICAL MECHANISMS AT ROOM AND ELEVATED TEMPERATURES

The chemical reactions that occur in concrete are complex and there are many involved. Figure 1 lists the major chemical reactions in concrete formation. These reactions are all a part of the hydration process where the water becomes bound as water of hydration and water of crystallization. The hydration process continues in concrete for many years provided that water, either that trapped within the concrete as in large structures, dams, etc., or that available to concrete kept wet or under high humidity conditions is present. The strength at 28 days is only a reference strength; the strength continues to gain indefinitely as shown in Figure 2 (if kept wet). "The strength finally stops increasing after the concrete dries out completely."(5)

As shown in Figure 2, the curing time prior to heating influences the "starting strength". That is, the longer the structure or specimen is cured, the higher its strength at the start of a heating cycle, with higher hypothesized strength at the end of the heat cycle. Structures such as the Hanford waste tanks will have been moist-cured for at least 28 days and, because of their thickness, residual curing compounds, and the fact that they are subsequently buried, are expected to continue to gain strength from hydration. Thus, the concrete in the waste tanks is adequately hydrated by the time heating begins. This is important for minimizing the deteriorating effects of heating on concrete.(6)

Exposure of concrete to temperatures above normal accelerates drying removal of water required by the chemical processes of cement hydration. At

$2Ca_3SiO_5 + 6H_2O = Ca_3Si_2O_7 \cdot 3H_2O + 3Ca(OH)_2$

(tricalcium silicate) (water) (calcium silicate hydrate) (calcium hydroxide)

$2Ca_2SiO_4 + 4H_2O = Ca_{3.3}SiO_{7.3} \cdot 3.3H_2O + 0.7Ca(OH)_2$

(dicalcium silicate) (water) (calcium silicate hydrate) (calcium hydroxide)

$4CaO \cdot Al_2O_3 \cdot Fe_2O_3 + 10H_2O + 2Ca(OH)_2 = 6CaO \cdot Al_2O_3 \cdot Fe_2O_3 \cdot 12H_2O$

(tetracalcium aluminoferrite) (water) (calcium hydroxide) (calcium aluminoferrite hydrate)

$3CaO \cdot Al_2O_3 + 12H_2O + Ca(OH)_2 = 3CaO \cdot Al_2O_3 \cdot Ca(OH)_2 \cdot 12H_2O$

(tricalcium aluminate) (water) (calcium hydroxide) (tetracalcium aluminate hydrate)

$3CaO \cdot Al_2O_3 + 10H_2O + CaSO_4 \cdot 2H_2O = 3CaO \cdot Al_2O_3 \cdot CaSO_4 \cdot 12H_2O$

(tricalcium aluminate) (water) (gypsum) (calcium monosulfoaluminate)

FIGURE 1. Major Chemical Reactions in Concrete Formation (Ref. 10, p. 10)

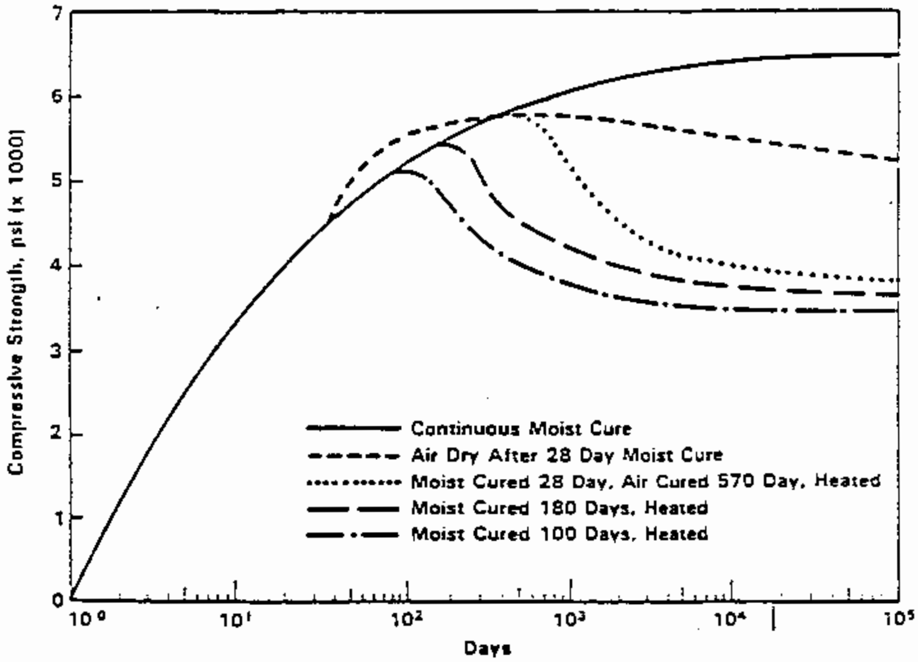

FIGURE 2. Concrete Compressive Strength Versus Curing/Heating Conditions

temperatures above about 200 F, some of the water of hydration is removed from the hardened paste in addition to evaporable water which may be in the concrete.

4.3 CHEMICAL CHANGES ON HEATING

Differential thermal analysis (DTA) investigations provide a convenient illustration of the reactions that may occur when heating a full hydrated concrete specimen in air at atmospheric pressure. Figure 3 shows a DTA diagram for a representative aged portland cement paste.(7)

A broad endotherm is observed at less than 212 F extending to about 850 F. The initial portion of this endotherm is due to the removal of free water from the cured cement paste. Dehydration and dehydroxylation of the various hydrated cement phases account for the endotherm from 212 F to 850 F. Tobermorite gel (cement paste) and hydrated calcium sulfoaluminate are the first phases affected.(7)

The pronounced endotherm between 930 and 1100 F is due to the decomposition of $Ca(OH)_2$. An endotherm sometimes observed at around 1472 F is due to the decomposition of $CaCO_3$.(7)

Reference (7) states that "concrete heated below 500 F at atmospheric pressure exhibits a partial dehydration of hydrated cement phases and a loss of evaporable water." The same phenomenon was shown in the PCA study by the reduced specimen weights after heating. It is this loss of both evaporable and non-evaporable water that is responsible for the majority of the strength loss and property degradation of concrete upon heating. That is the reversible reaction of CaO plus H_2O to form calcium hydroxide, $Ca(OH)_2$ also contributes to the degradation of properties. At temperatures around 1000 F, the calcium hydroxide decomposes rapidly to form CaO and H_2O. At temperatures in the 250 to 500 F range, the reaction is also able to occur but at a much reduced (barely perceptible) rate.

X-ray analysis of cured neat cement samples exposed to 250 and 500 F for 14 days showed increasing loss of $Ca(OH)_2$ with temperature. The results also indicated that in the period of time during which the sample is being heated and still retains free moisture, accelerated hydration of unreacted anhydrous

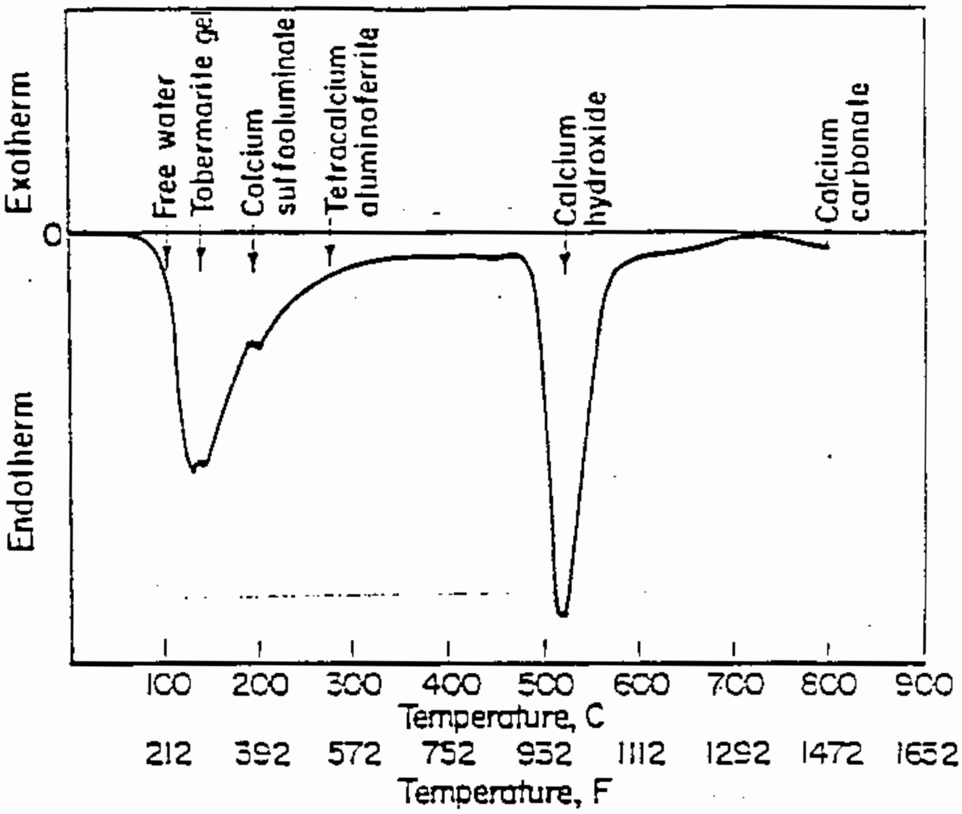

FIGURE 3. Representative DTA Diagram of Aged Portland Cement Paste (in Air, at Atmospheric Pressure) (Ref. 10, page 13)

cement can occur.(7) This would normally occur in the first few weeks or months of heating.

It is the two reactions, loss of water (free water, water of hydration and water of crystallization) and the slow change of $Ca(OH)_2$ to calcium oxide and water, that are believed to be primarily responsible for a slow, continual degradation of concrete properties in the 250 to 500 F range.

4.4 DIMENSIONAL CHANGES DURING HEATING

Aged concrete that is subsequently heated in air will incur dimensional changes as a result of losing its evaporable and chemically combined (non-evaporable) water and from thermal expansion of the concrete.

Loss of Free Water - The loss of the evaporable water produces an isotropic shrinkage phenomenon in the concrete that is termed drying shrinkage. A complete desorption-readasorption cycle over the 100-0-100% relative humidity range produces a hysteresis in the shrinkage strain versus moisture loss curve which indicates that a portion of the initial drying shrinkage is irrecoverable.

The complete removal of evaporable water as a result of heating can result in a shrinkage of over 2% in the volume of the cement paste. However, the presence of aggregate limits the shrinkage of concrete to about one tenth of that possible in the cement.(7)

Loss of Chemically Combined Water from the Hydrated Cement - Removal of chemically combined water from hydrated cement by heating also results in overall shrinkage of the cement. Removal of such water from tobermorite gel causes a considerable decrease in the interlayer dimension. Both bonded and dissociated (OH) water are driven from the hydrated paste during heating in air to 500 F.(7)

The shrinkage accompanying water losses causes cracking of the cement paste and subsequently the concrete itself.

Reference (7) states that "carbonation of $Ca(OH)_2$ can also occur on heating cured cement phase at atmospheric pressures." The extent of carbonation dictates the dimensional changes this reaction will produce in the heated gel.(7)

Thermal Expansion - On initial heatup of saturated concrete, both the aggregate and cement phase will exhibit an expansion. Values reported in the literature for the thermal expansion of concrete range from about 3×10^{-6} in. per in. per F to as high as 18×10^{-6} in. per in. per F, although the majority of data fall in the 3 to 6×10^{-6} in. per in. per F range.(7) The PCA study obtained a thermal expansion of 3.3×10^{-6} in. per in. per F for Hanford concrete.(1)

The combined dimensional changes that occur on initial heating of concrete are 1) reversible expansion of the aggregate, and 2) simultaneous thermal expansion and shrinkage contraction (due to loss of evaporable and non-evaporable water) in the cement paste.

4.5 PHYSICAL CHANGES DURING HEATING

The study described in reference (7) and the PCA study made fractographic/petrographic analyses of concrete specimens after heating to temperatures up to 500 F. Both studies found evidence of substantial microcracking leading to loss of bond to the aggregate. These cracks occurred primarily along a paste-aggregate interface although they also extended into the paste itself. It was believed that the cooling to room temperature (to allow examination) may have been responsible for part of the bond loss along with the shrinkage accompanying the dessication at temperature. Specimens that were rapidly cooled from 500 F by water quenching showed significantly more disruptive cracking than specimens that were slowly cooled to room temperature.(7) This microcracking is due, in part, to the differences in thermal expansion among the various mineralogical constituents in concrete, and partly to the existence of thermal gradients.

The combination of loss of water, which alters the crystalline structure of the cement paste, and microcracking that occur during heating are believed to be the primary causes of reductions of strength and modulus of elasticity that occur. The changes in modulus of elasticity from heating, which were greater than for other properties such as compressive and tensile strength, were believed to be caused primarily by the loss of evaporable water.(7)

5.0 STATISTICAL EVALUATION OF THE PCA-DEVELOPED DATA BASE

The statistical evaluations and analyses performed on the PCA concrete property data are discussed in this section. The primary goal is to address the question of extrapolation: "Is it justifiable (defensible) to fit mathematical models to the data, and then use the models to extrapolate concrete properties out to 50 years?"

5.1 PCA DATA CONSIDERED

It should be noted that because of the short time frame available to complete the study, only a limited statistical analysis could be performed. Consequently, not all the data were examined and identification of defensible extrapolation equations was not completed. Additional statistical analysis is indicated. The data considered are contained in Tables B-2 and B-3 of RHO-C-54(1) and in Tables 2 and 3 of Gillen.(9) These data consist of modulus of elasticity, compressive strength, splitting tensile strength, and Poisson's ratio measurements on 6 x 12 in. concrete cylinders. Cylinders were made using one of two mix types (3,000 or 4,500 psi, nominal) and were either moist-cured at approximately 70 F, or moist-cured and then held at a temperature of 250, 350 or 450 F. The four concrete properties were measured several times over the test period while the cylinders were being moist-cured or were at temperature.

Several sources of variation exist in the PCA data. Mix type, temperature, and time-at-temperature are the three experimental variables which form the basis for the PCA test results. Variations not quantitatively accounted for but which were present in the PCA experiment are:

- Within-Batch Variation. For almost all tests, each property was measured on two or three cylinders for each mix type, temperature, and time-at-temperature combination. The properties varied significantly within batches.
- Batch-to-Batch Variation. Property measurements over time for a specific mix type/temperature combination were typically made on cylinders from several different batches. The specimens were made in separate batches, 16 for 3000 psi concrete and 13 for the 4500 psi concrete. The water/cement ratio, air content and cement content varied significantly between batches of the same nominal strength.
- Time Moist-Cured Before At Temperature. Not all cylinders for a given mix type/temperature combination had the same moist-cured time before being subjected to temperature. The curing time in the fog room before heating was about 190 days for part of the specimens and about 280 days for the remainder of the specimens. Time in the fog room affects the initial strength of the specimens.

The above variations affected the concrete properties, and hence must be taken into account when analyzing the data. The within-batch variation is best treated as random "noise", and it can be estimated and accounted for in data analyses via statistical methods. The batch-to-batch variation can be treated as random noise, or as correctable differences. If the variation between batches in the PCA data is representative of the potential variation of waste tank concrete mixes, then it should be treated as random variation (and included with within-batch variation) in the estimate of the experimental error variance. If the batch-to-batch variation is not representative and/or results over time for a fixed-batch concrete are desired, then it would be better to try to adjust (correct) the property values for the batch-to-batch differences. The time a given cylinder was cured before being put at temperature is not random noise, and an attempt to adjust the data should be made.

In the following sections of this chapter, no adjustment of data has been performed.

5.2 WITHIN-BATCH STANDARD DEVIATIONS

As noted above, the PCA experiments involved the measurement of concrete properties for two or three cylinders for a given mix type/temperature/time-at-temperature combination. Almost always the "replicate" cylinders were from the same batch. Within-batch standard deviations were computed for each mix type/temperature combination (the standard deviations do not seem to vary with changing time-at-temperature, at least for the times in the PCA experiment). The standard deviations for each of the four concrete properties are summarized in Table 2.

TABLE 2. Within-Batch Standard Deviations for Modulus of Elasticity, Compressive Strength, Splitting Tensile Strength, and Poisson's Ratio

Mix Type	Temperature (°F)	Modulus of Elasticity (Million psi)	Compressive Strength (psi)	Splitting Tensile Strength (psi)	Poisson's Ratio
3.0K	70	0.18	148	24.7[a]	0.012
	250	0.09	113	22.0	0.014
	350	0.11	169	20.5	0.015
	450	0.13	243	22.4	0.020
4.5K	70	0.16	222	34.9[b]	0.008
	250	0.24	160	23.8	0.013
	350	0.16	215	26.0	0.017
	450	0.09	250	16.1	0.023

(a) Without the 861 day replicates. With these data, the value is 29.3.
(b) Without the 1198 day replicates. With these data, the value is 35.7.

5.3 SAFE-CRACK VERSUS PCA DATA

SAFE-CRACK used the following equations to predict modulus of elasticity and compressive strength in the most recent (1982) analysis of the 241-AP tank:(8)

$$E = 10^6[6.0 - 0.007\ \mathrm{TEMP} - 0.195\ \ln\ (\text{days at temp} + 1)] \tag{1}$$

$$f_c{}' = 6000 - 270.0\ \ln\ (\text{days at temp} + 1) \tag{2}$$

These curves were plotted along with PCA data to see how well they compared. In some cases, the SAFE-CRACK predictions were close to the bulk of the data for a given mix type (3.0K or 4.5K) and temperature[(a)] (250, 350, 450 F), while in other cases, the SAFE-CRACK predictions were above or below the bulk of the data. It was concluded that the basic form[(b)]

$$\text{Property} = a + b\ \ln\ (\text{days at temp} + 1) \tag{3}$$

of the SAFE-CRACK equations for modulus of elasticity and compressive strength was suitable for further evaluation of the prediction equations, but the dependence on mix type and on temperature should be reviewed. Therefore, curves were examined for each combination of temperature and mix type.

5.4 LEAST SQUARES FITS AND 95% CONFIDENCE BANDS

Equations of the form (3) were fit (using ordinary least squares) to the PCA modulus of elasticity and compressive strength data for each combination of mix type and temperature. The coefficient estimates are given in Table 3. It should be noted that a few outlying data points were discarded, and that observations for early time-at-temperatures were deleted for some mix type/temperature combinations before the coefficients were estimated. This was done to remove the effects of points that otherwise would have adversely affected the curve fitting.

(a) Comparing SAFE-CRACK equations (1) and (2) to 70° moist-cured data produced very poor comparisons. The equations are apparently not valid for the moist-cured, no-heat cases.

(b) A temperature term is not needed since each curve is for a separate temperature.

TABLE 3. Least Squares Estimated Coefficients From Equation (3) for Modulus of Elasticity and Compressive Strength

Modulus of Elasticity

Mix Type	Temperature (°F)	a	b
3.0K	250	4.0338	-0.1854
	350	3.2623	-0.1476
	450	2.7073	-0.1622
4.5K	250	4.2464	-0.1617
	350	3.6143	-0.1795
	450	3.1196	-0.2396

Compressive Strength

Mix Type	Temperature (°F)	a	b
3.0K	250	5829.4	-126.97
	350	5943.1	-217.18
	450	5117.0	-126.31
4.5K	250	6625.4	- 67.22
	350	5758.8	-255.72
	450	6290.3	-270.83

Before making use of the fitted curves in Table 3, it is important to check (statistically) whether they adequately fit the data. Using the within-batch variation to estimate the "pure-error" variance, a statistical test for lack-of-fit(11) was performed for each fitted curve of the form (3). All fitted curves showed statistically significant lack-of-fit. This says that there is additional variation in the data not explained by fitting an equation of the form (3) nor by the within-batch variation. This may be due to the other sources of variation discussed in Section 5.1 or the need for a different equation form than (3).

The equations of the form (3) with coefficients a and b given in this table have a statistically significant lack-of-fit. From a statistical viewpoint, the equations of the form (3) and the associated fitted curves of Table 3 should not be used because of the significant lack-of-fits. However, despite the lack-of-fit, it was decided to illustrate what can be done when the lack-of-fit problems are resolved. Along these lines, 95% confidence bands were computed for each fitted curve, and are displayed in Figures 4 to 15 along with the least squares line, the SAFE-CRACK line, and the raw data. Were it valid to develop 95% confidence bands for the fitted curves of Table 3, they would be interpreted as follows:

> "We have 95% confidence that the true unknown equation relating time-at-temperature to modulus of elasticity or compressive strength lies between the upper and lower confidence bands."

It can be seen from Figures 4 to 15 that the equation (3) takes the form of a straight line when the property of interest is plotted against time-at-temperature on a logarithmic scale. Both the SAFE-CRACK and least squares fits have the form (3), and hence appear as straight lines in Figures 4 to 15. The lines are extrapolated out to 50 years, with the fact that extrapolation is occurring indicated by the lack of plotted data symbols.

Whether an extrapolation of a given equation is reasonable is not entirely a statistical question. Statistics can address whether a given equation adequately fits the available data; if so, then extrapolation may be allowable if the underlying theory or knowledge supports the equation being used. For the concrete property data studied here, the theory and knowledge support the general deterioration trend; however, the equation fitted to the data has a significant lack-of-fit. Therefore, (from a statistical standpoint) extrapolation is not recommended. Additional analyses to obtain a better fit are recommended so that more justifiable extrapolations can be made.

5.5 STATISTICAL RESULTS

- Constant-temperature PCA data for the following properties were considered: modulus of elasticity (static method), compressive strength, splitting tensile strength, and Poisson's ratio (static method). Several sources of variation occur in the data, including within- and between-batch variation, and differences in moist-cure time before being at temperature.
- SAFE-CRACK predictions for modulus of elasticity and compressive strength were compared to the constant temperature PCA data. Qualitatively,

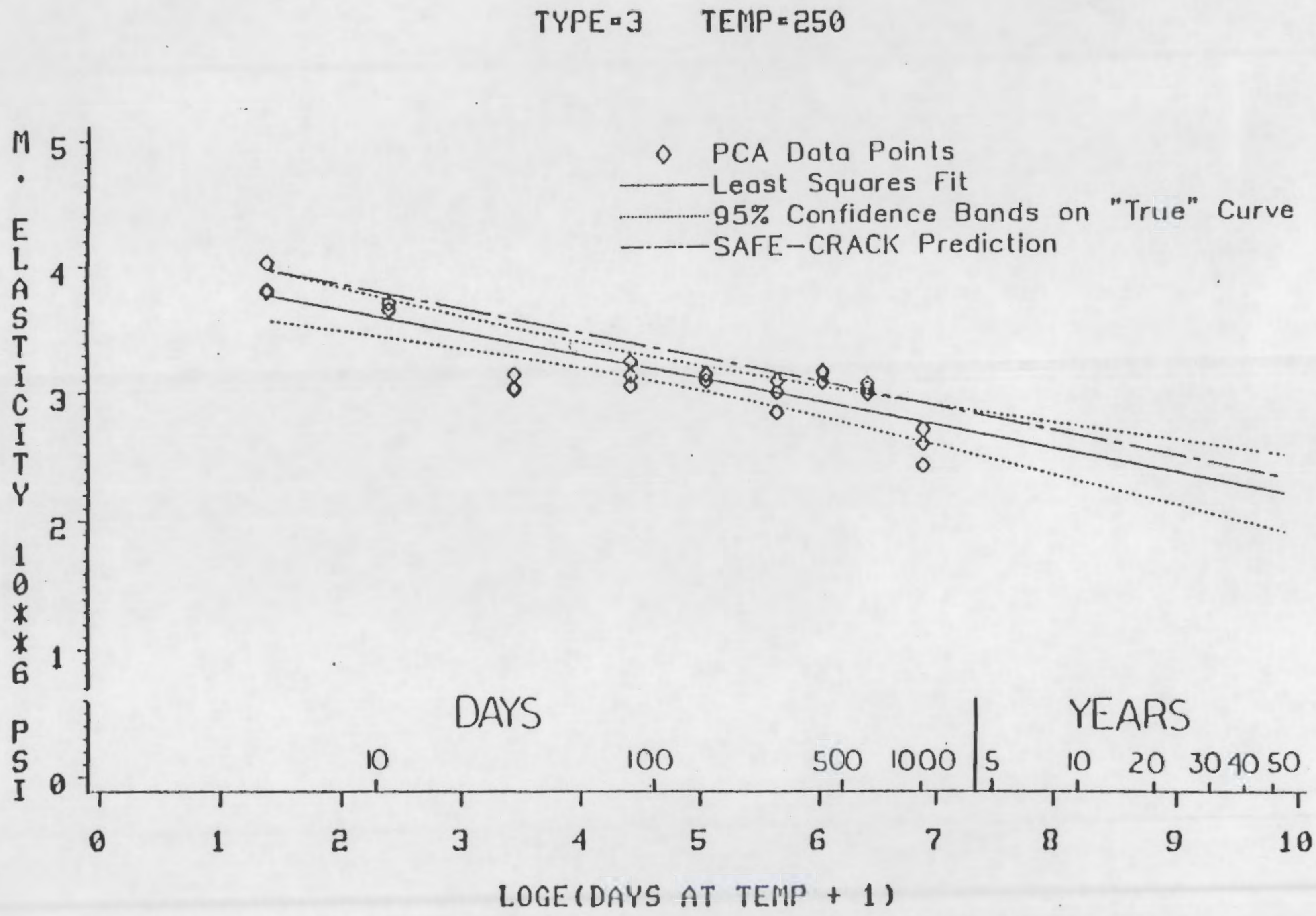

FIGURE 4. Modulus of Elasticity Versus Days at 250 F for 3000 psi Hanford Concrete

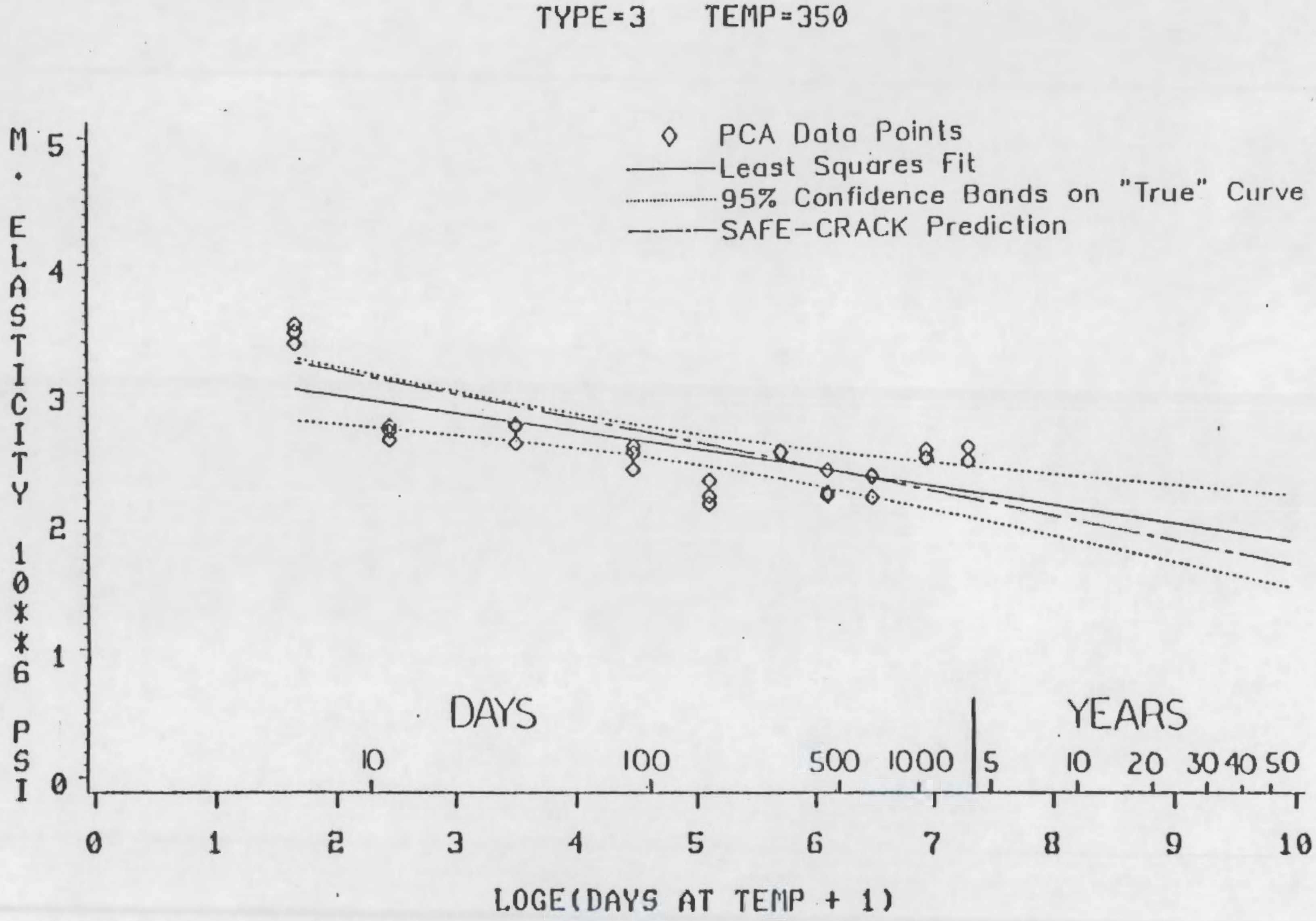

FIGURE 5. Modulus of Elasticity Versus Days at 350 F for 3000 psi Hanford Concrete

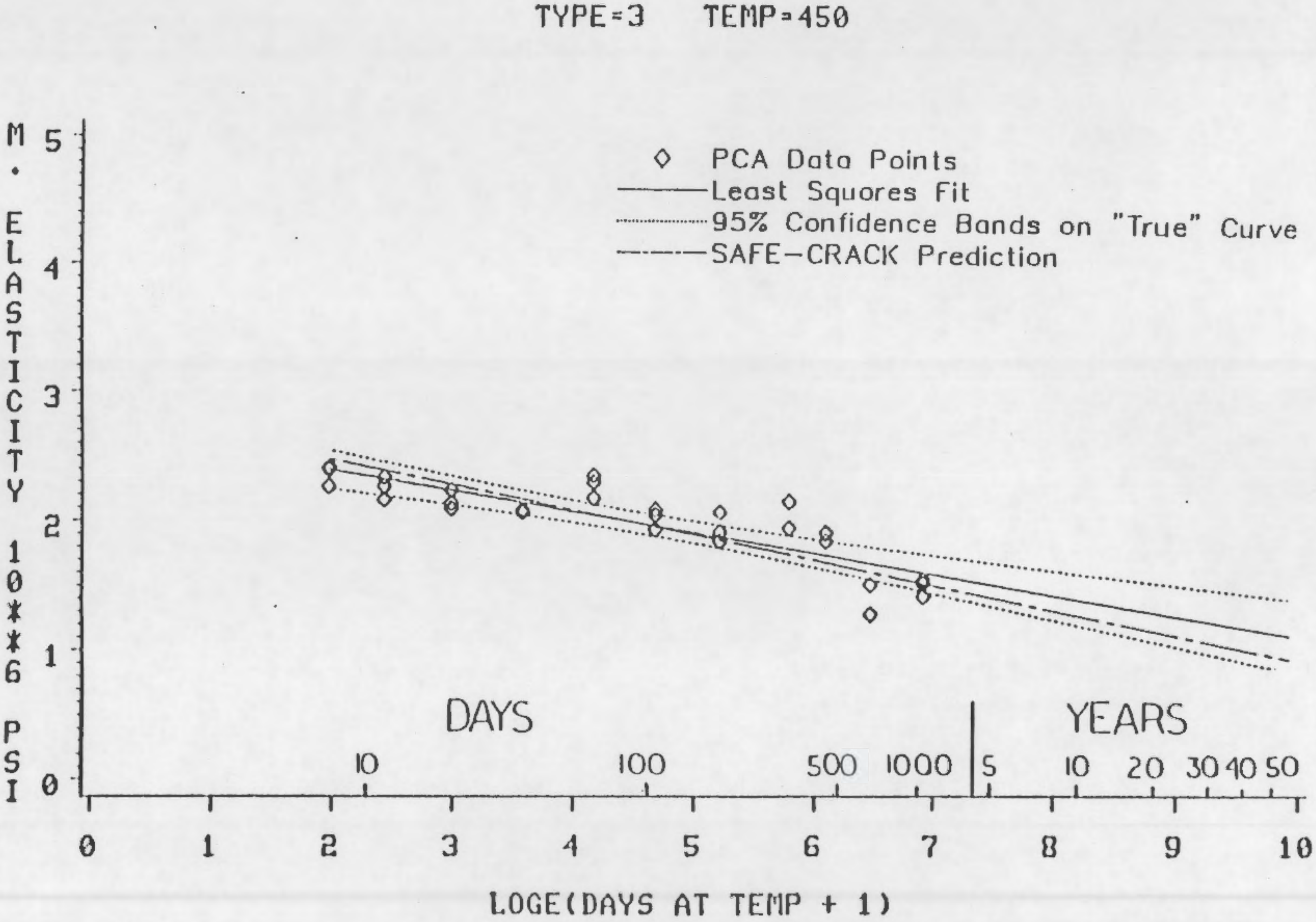

FIGURE 6. Modulus of Elasticity Versus Days at 450 F for 3000 psi Hanford Concrete

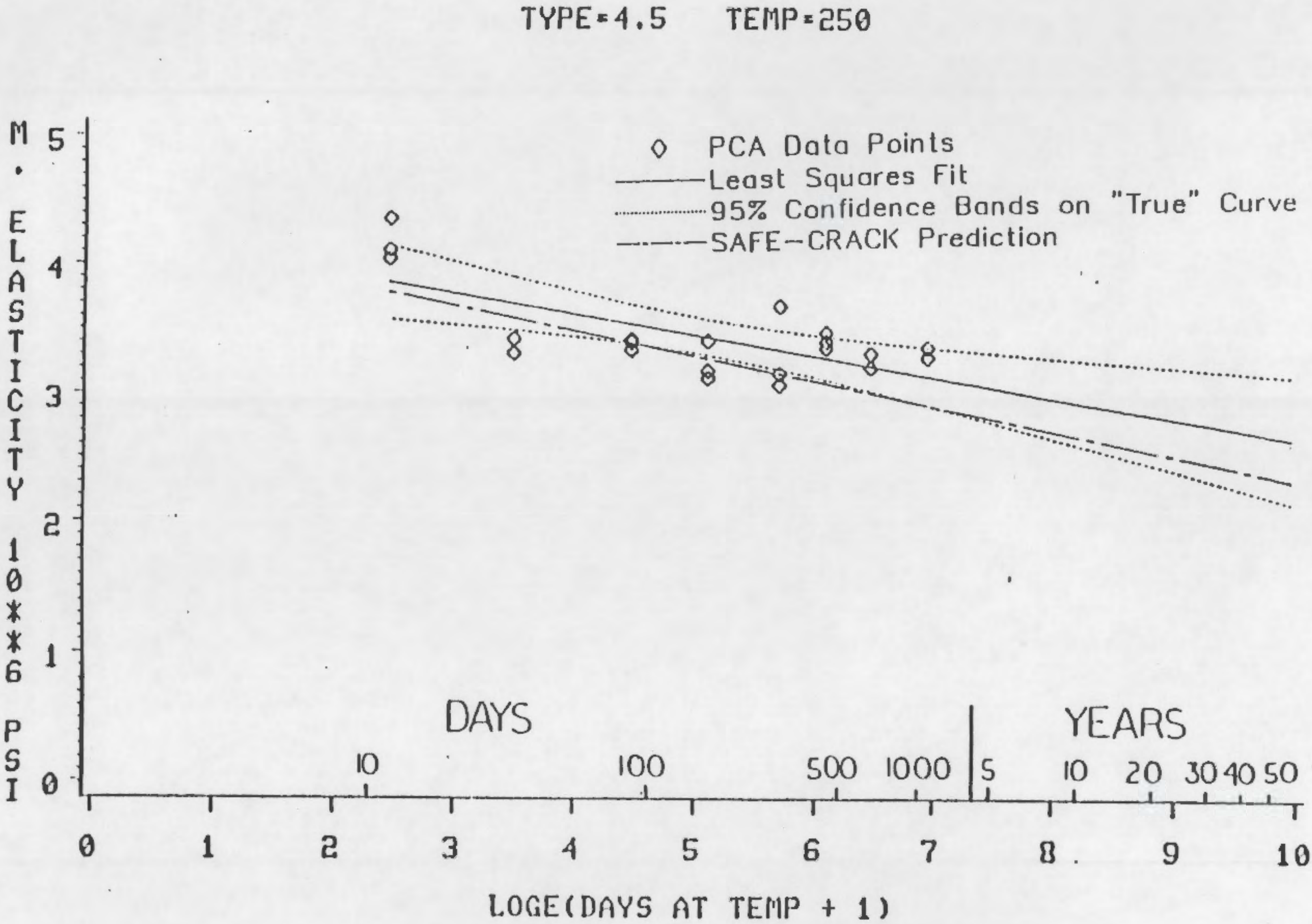

FIGURE 7. Modulus of Elasticity Versus Days at 250 F for 4500 psi Hanford Concrete

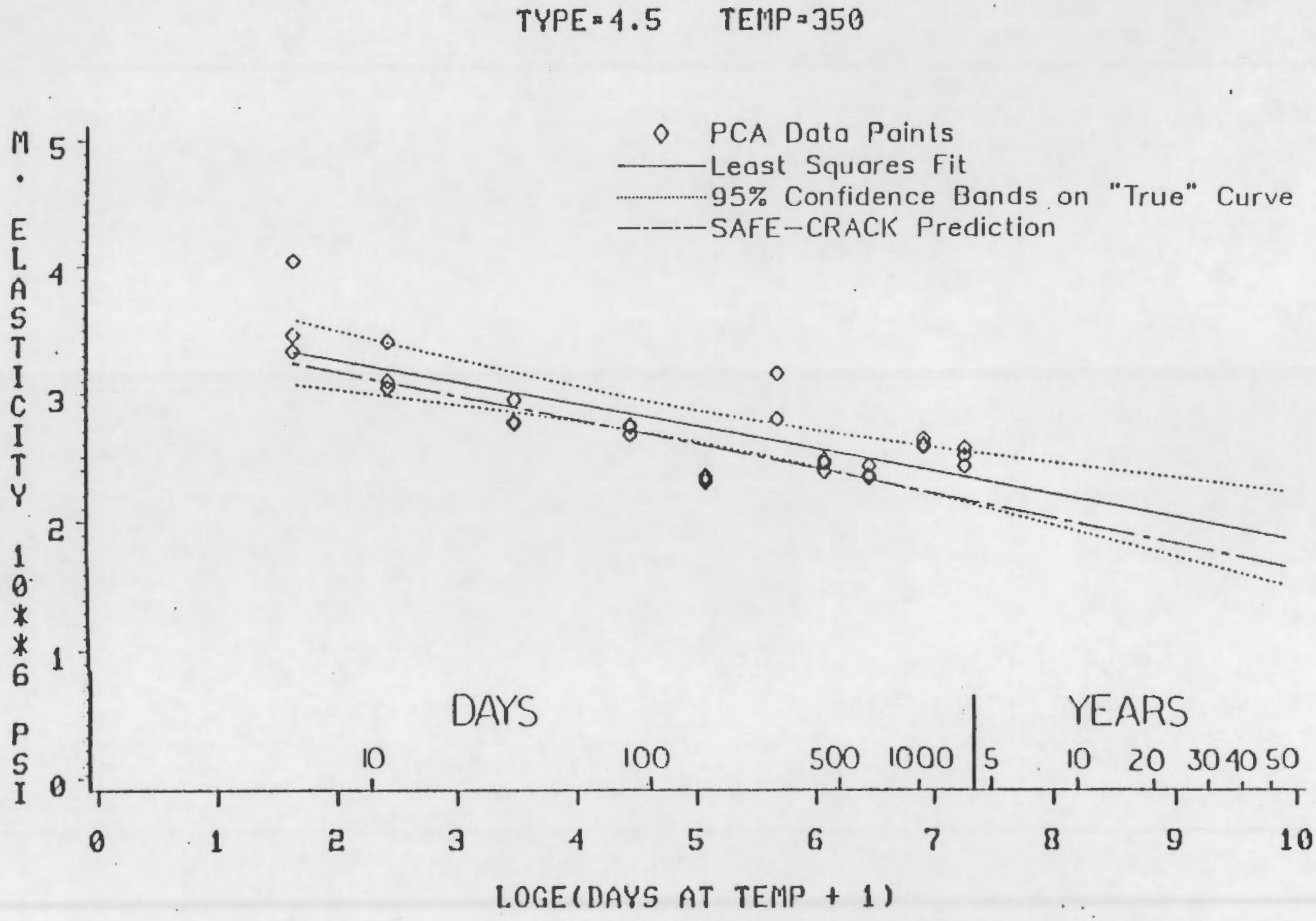

FIGURE 8. Modulus of Elasticity Versus Days at 350 F for 4500 psi Hanford Concrete

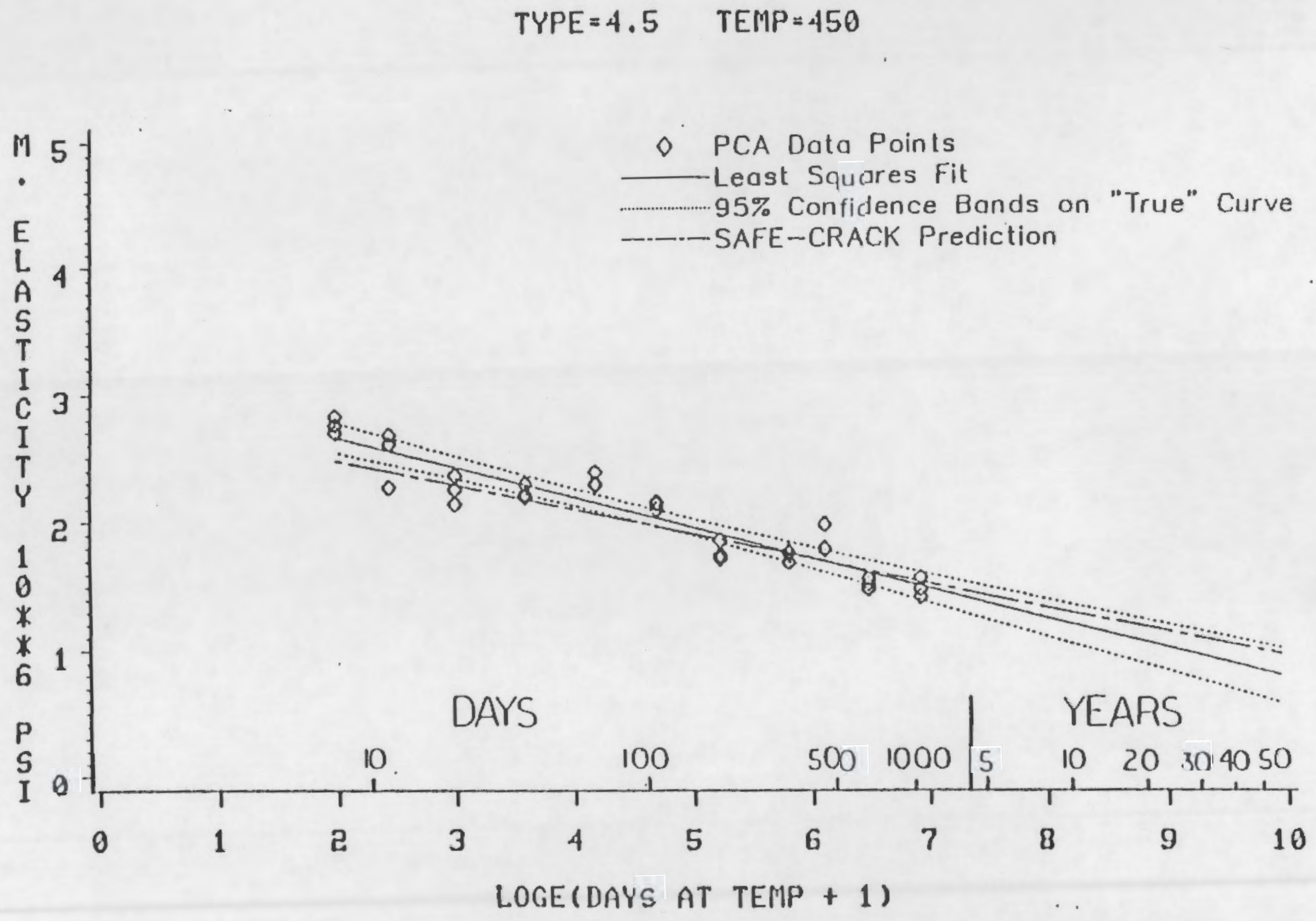

FIGURE 9. Modulus of Elasticity Versus Days at 450 F for 4500 psi Hanford Concrete

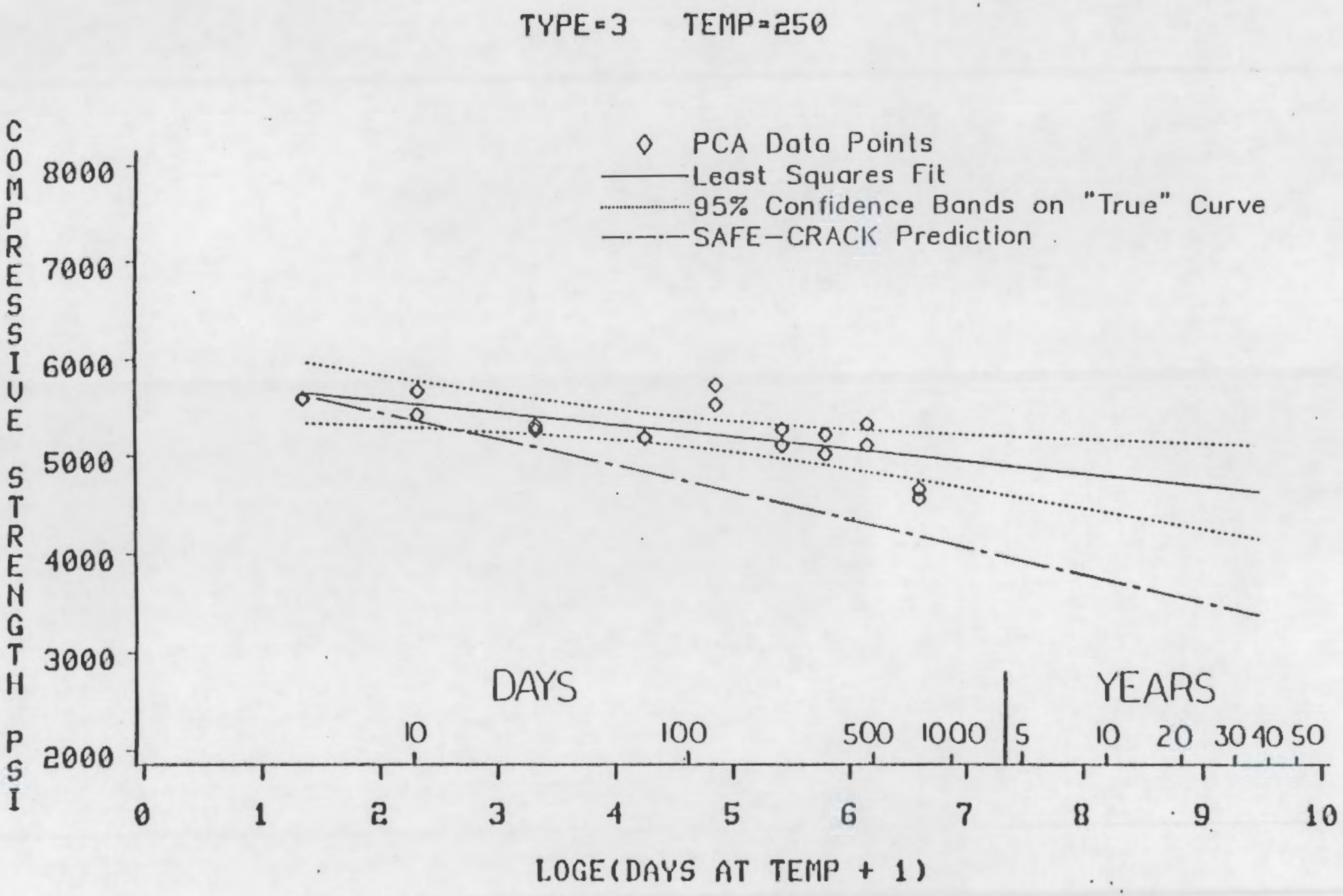

FIGURE 10. Compressive Strength Versus Days at 250 F for 3000 psi Hanford Concrete

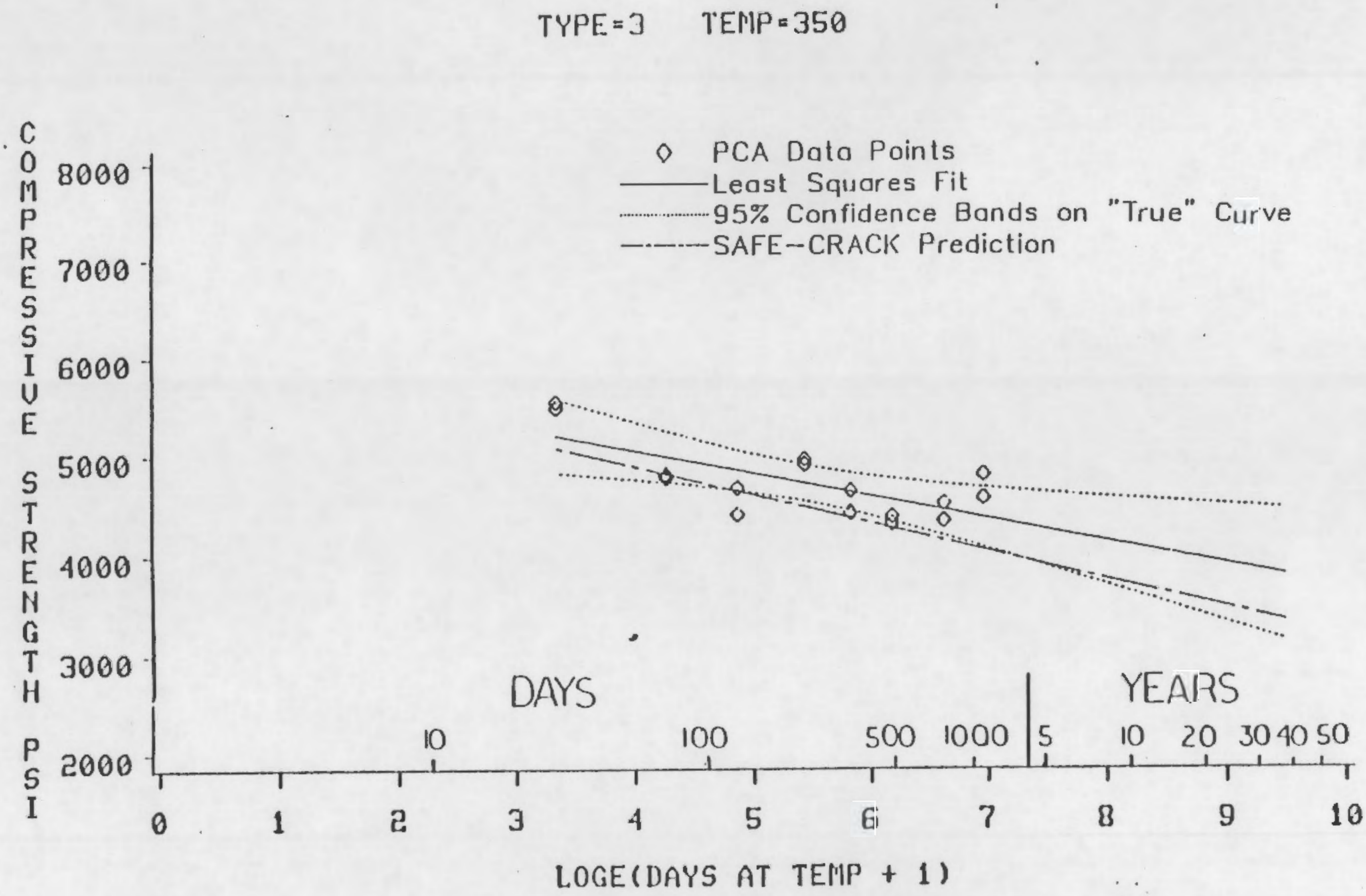

FIGURE 11. Compressive Strength Versus Days at 350 F for 3000 psi Hanford Concrete

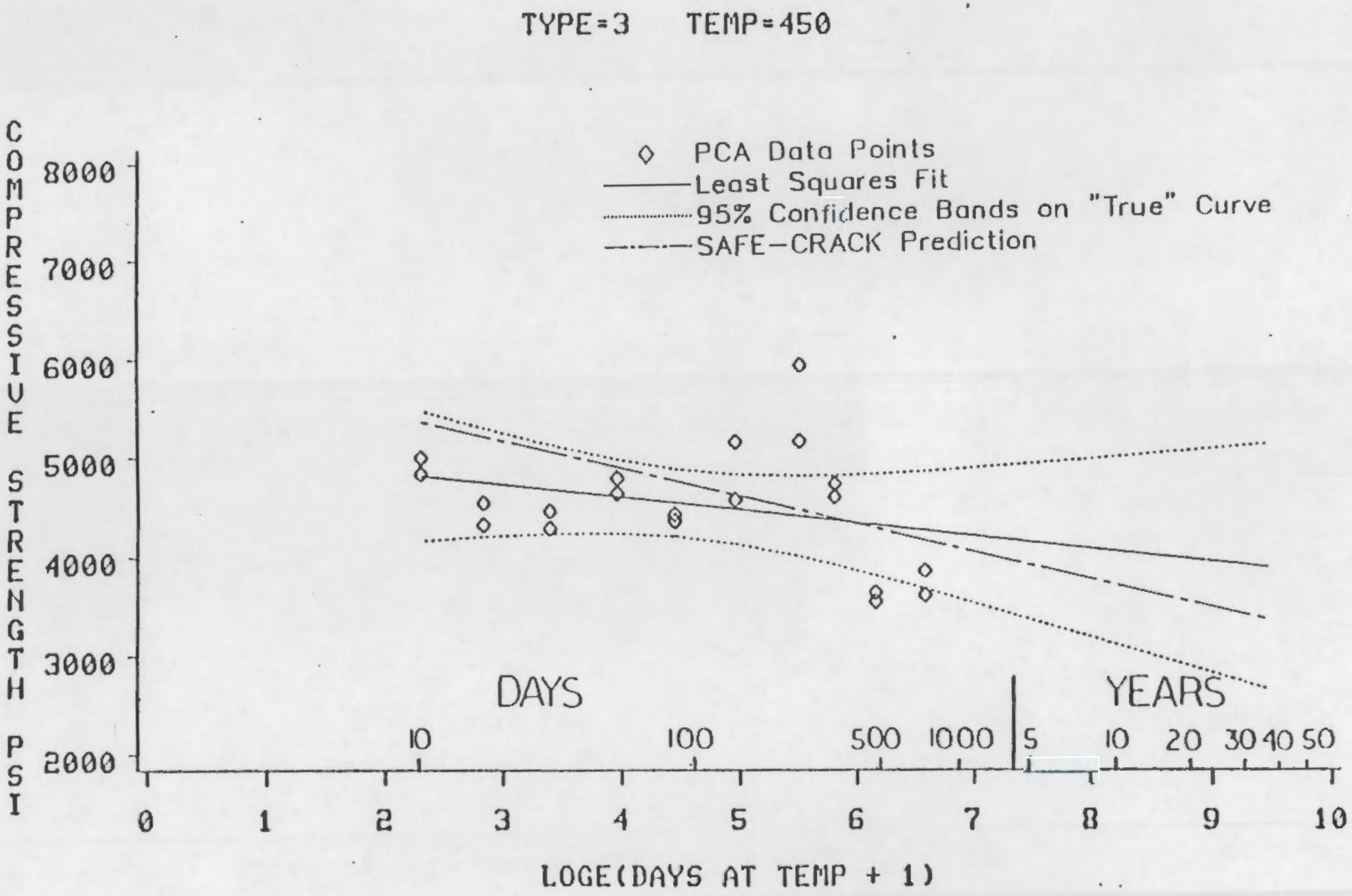

FIGURE 12. Compressive Strength Versus Days at 450 F for 3000 psi Hanford Concrete

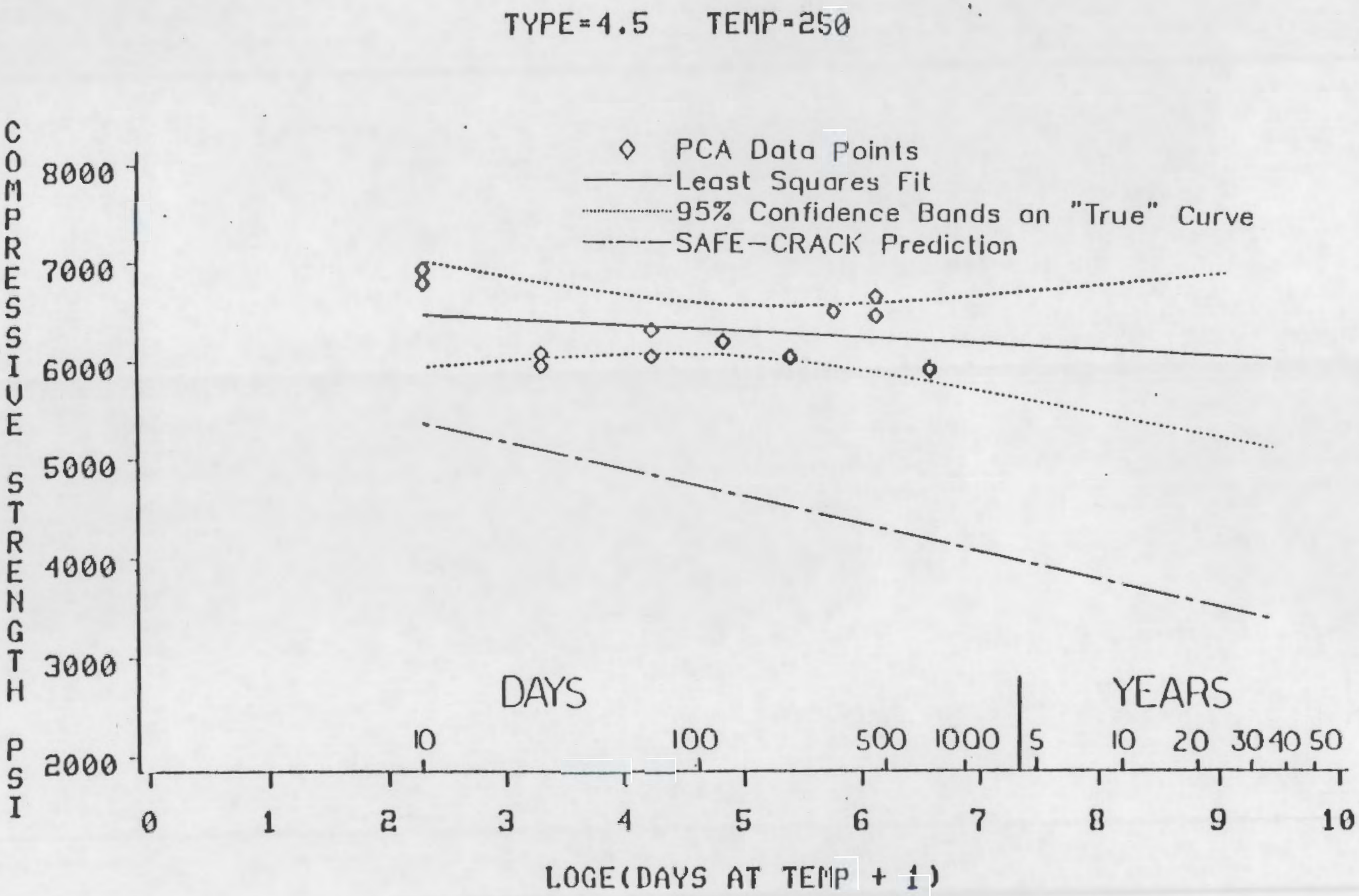

FIGURE 13. Compressive Strength Versus Days at 250 F for 4500 psi Hanford Concrete

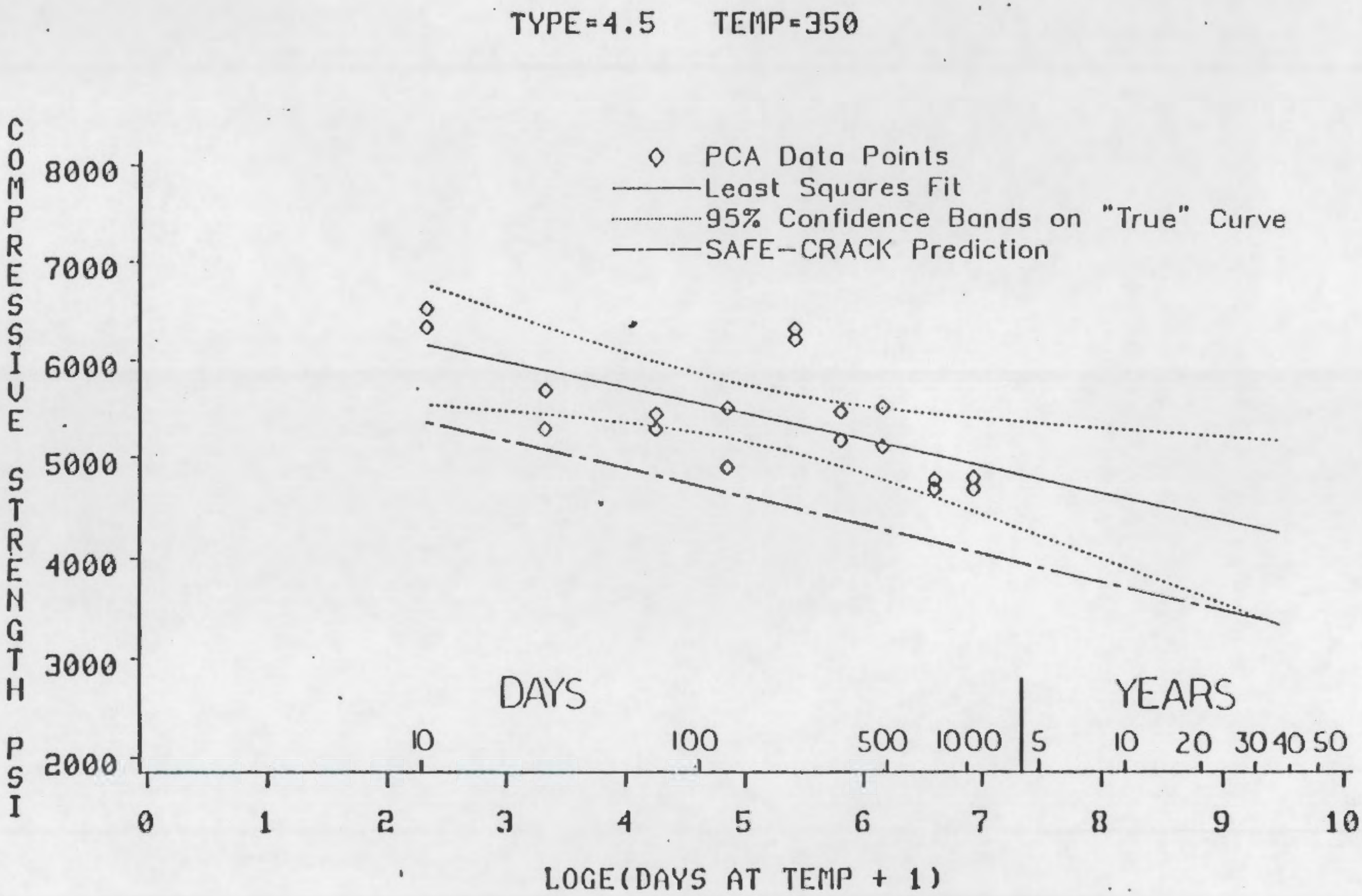

FIGURE 14. Compressive Strength Versus Days at 350 F for 4500 psi Hanford Concrete

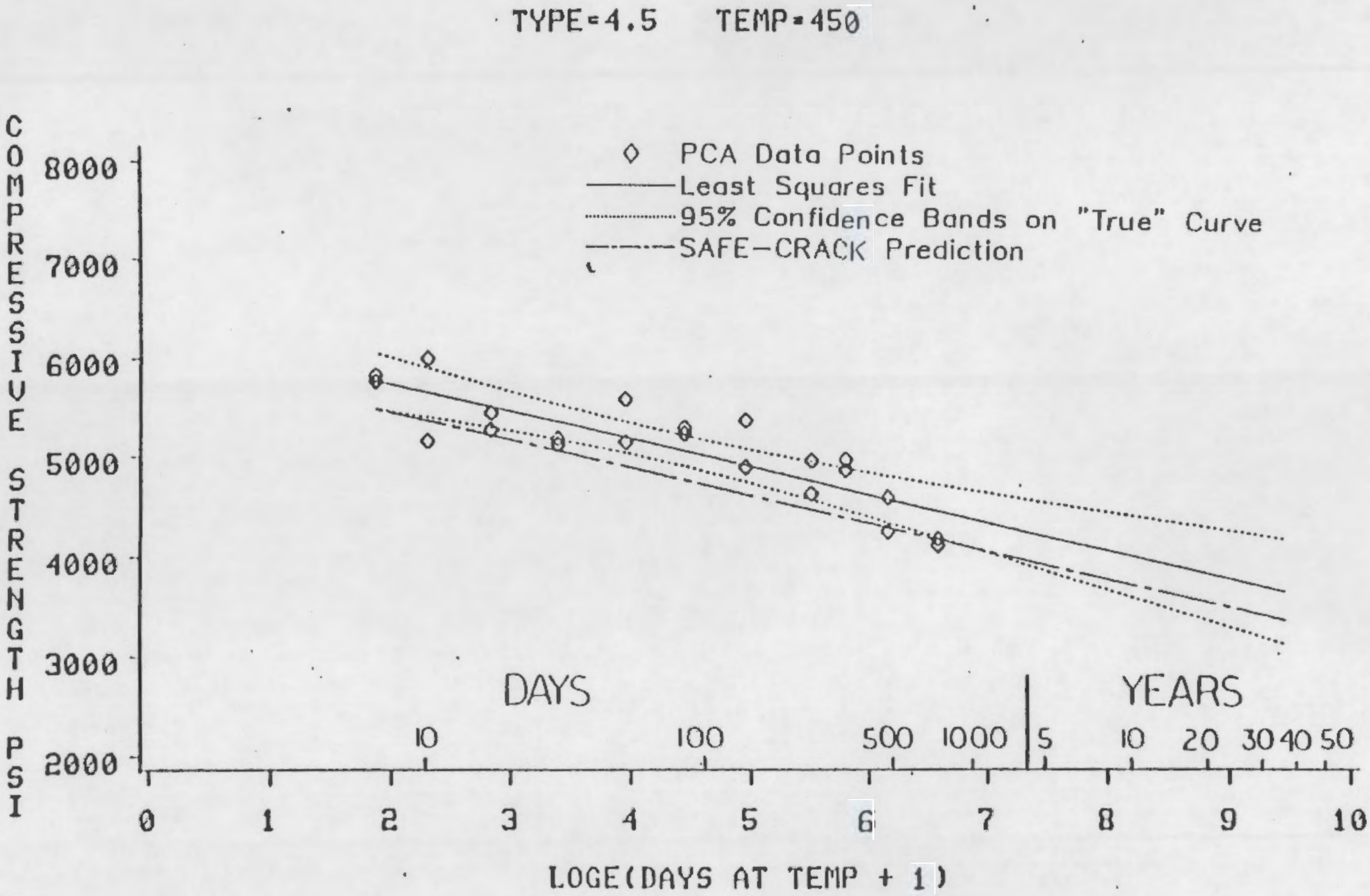

FIGURE 15. Compressive Strength Versus Days at 450 F for 4500 psi Hanford Concrete

agreement was reasonable, but differences were observed. It can be inferred that SAFE-CRACK does not adequately model the PCA data based on lack-of-fit for the least squares fits (see next bullet).

- Least squares fits of the equation

  $$\text{Property} = a + b \ln(\text{days at temp} + 1)$$

  were obtained for each combination of mix type (3.0K or 4.5K) and temperature (250, 350, 450 F) for modulus of elasticity and compressive strength. This equation is the basis of the SAFE-CRACK equations, but provides a better fit because it was fitted separately for each mix type/temperature combination.(a) The equation has a significant lack-of-fit for all cases.

- The significant lack-of-fit could be due to 1) differences in moist-curing times, 2) differences in batches of the same mix type, 3) the need for another equation which might better explain the modulus and compressive strength properties as a function of time-at-temperature, or 4) any combination of these.

- Even though significant lack-of-fit prescribes not making use of fitted equations, the equations were used to extrapolate modulus of elasticity and compressive strength out to 50 years. The purpose of doing so was to illustrate the 95% confidence band concept and to provide for graphically comparing the data, SAFE-CRACK predictions, and least squares predictions. The 95% confidence bands address the uncertainty in the curve fitting process. The fitted curves and confidence bands in Figures 4 to 15 are not completely defensible as is, and are presented only as illustrations of something close to what final answers may be.

The following items need to be done to try to remedy the unresolved questions.

(a) This does not say that separate fits for each mix type/temperature combination are preferred. Having an equation valid for both mix types and all temperatures in the range 250-450 F is certainly desirable as a final goal. However, the fitting of separate equations is the best approach for the first step of a model development effort.

- Additional data analysis and development of defensible prediction models for constant-temperature modulus of elasticity and compressive strength properties are required. Adjustment for between-batch differences and differences in moist-curing time should be attempted. Other model forms also need to be considered.
- The PCA thermal cycling data should be analyzed statistically.
- Confidence bands (of a specified high % confidence) should be developed for conservative or "worst case" prediction equations. While an "expected behavior model is appropriate for certain planning needs, it is anticipated that "conservative" or "worst case" behavior models should also be utilized.

6.0 EVALUATION OF OTHER ASPECTS OF SAFE-CRACK

This section discusses SAFE-CRACK's treatment of creep and tensile data, and its capabilities to accommodate changes in property data.

6.1 SAFE-CRACK'S USE OF CREEP DATA

The PCA study measured the creep (long time deformation under load) of Hanford concrete specimens at 250 F and 350 F. A total of six specimens (6 in. x 12 in. cylinders) were tested for about 650 days under two loadings, 500 psi at 350 F and 1500 psi at 250 and 350 F. Figure 16 shows the PCA's best fit curve of creep strain data to a logarithmic equation, the type of equation normally used to describe creep behavior. The equation used is of the form:

$$E_{cr} = K \log_{10} (t) + E_o \tag{4}$$

Superimposed on the chart is a plot of the creep predicted for 1500 psi at 350 F by the exponential equation used in SAFE-CRACK which is of the form (simplified):

$$E_{cr} = A (1 - e^{-r*time}) + b * time \tag{5}$$

As can be seen on the chart, the SAFE-CRACK equation predicts the creep correctly at about five days but at 50 or more days, the prediction is significantly higher than the PCA data indicate. Figures 17, 18 and 19 show

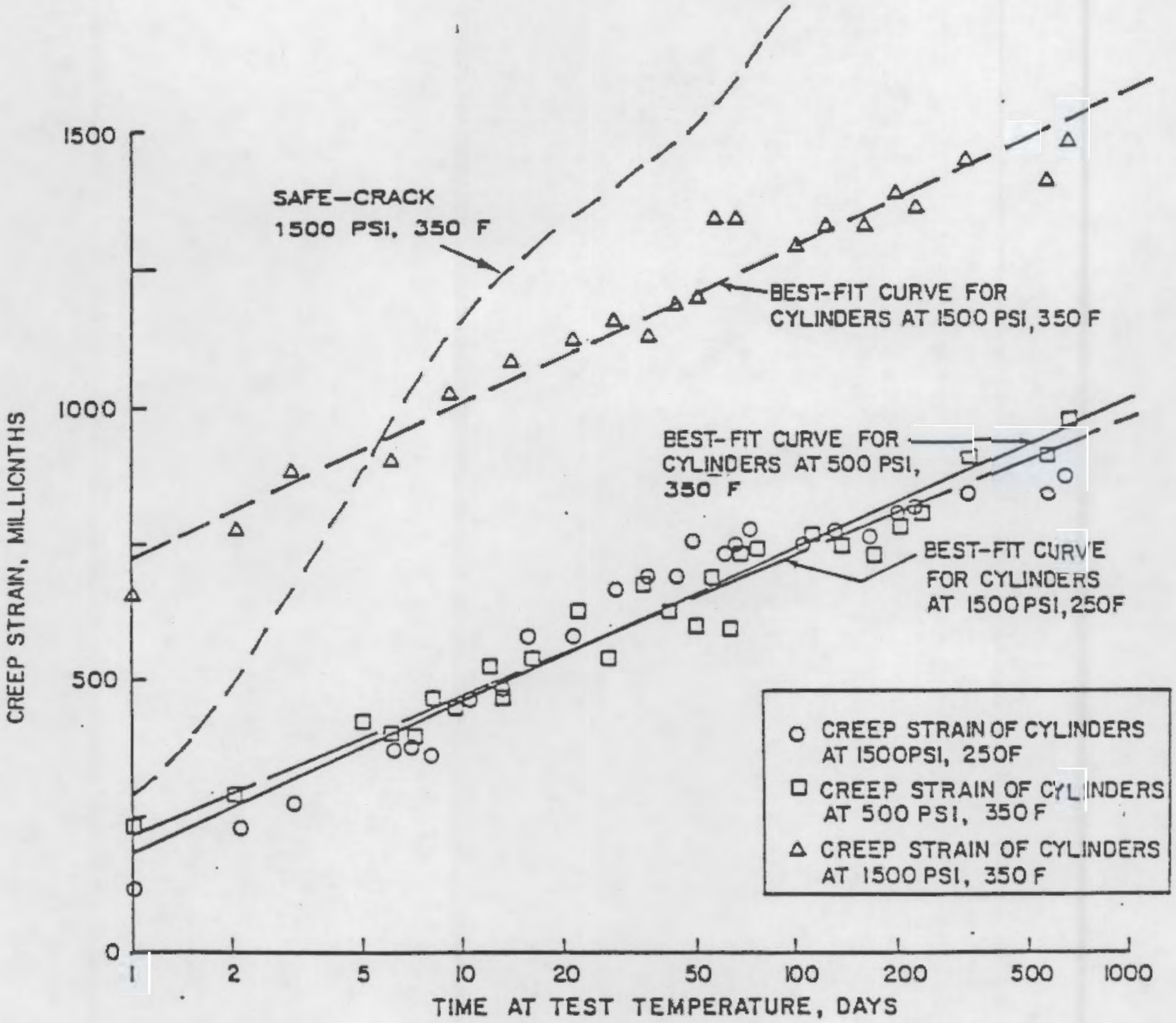

FIGURE 16. Best Fit of Creep Strain Data to Logarithmic Equation,
$\epsilon_{cr} = A \cdot \log_{10} (\text{TIME}) + B$

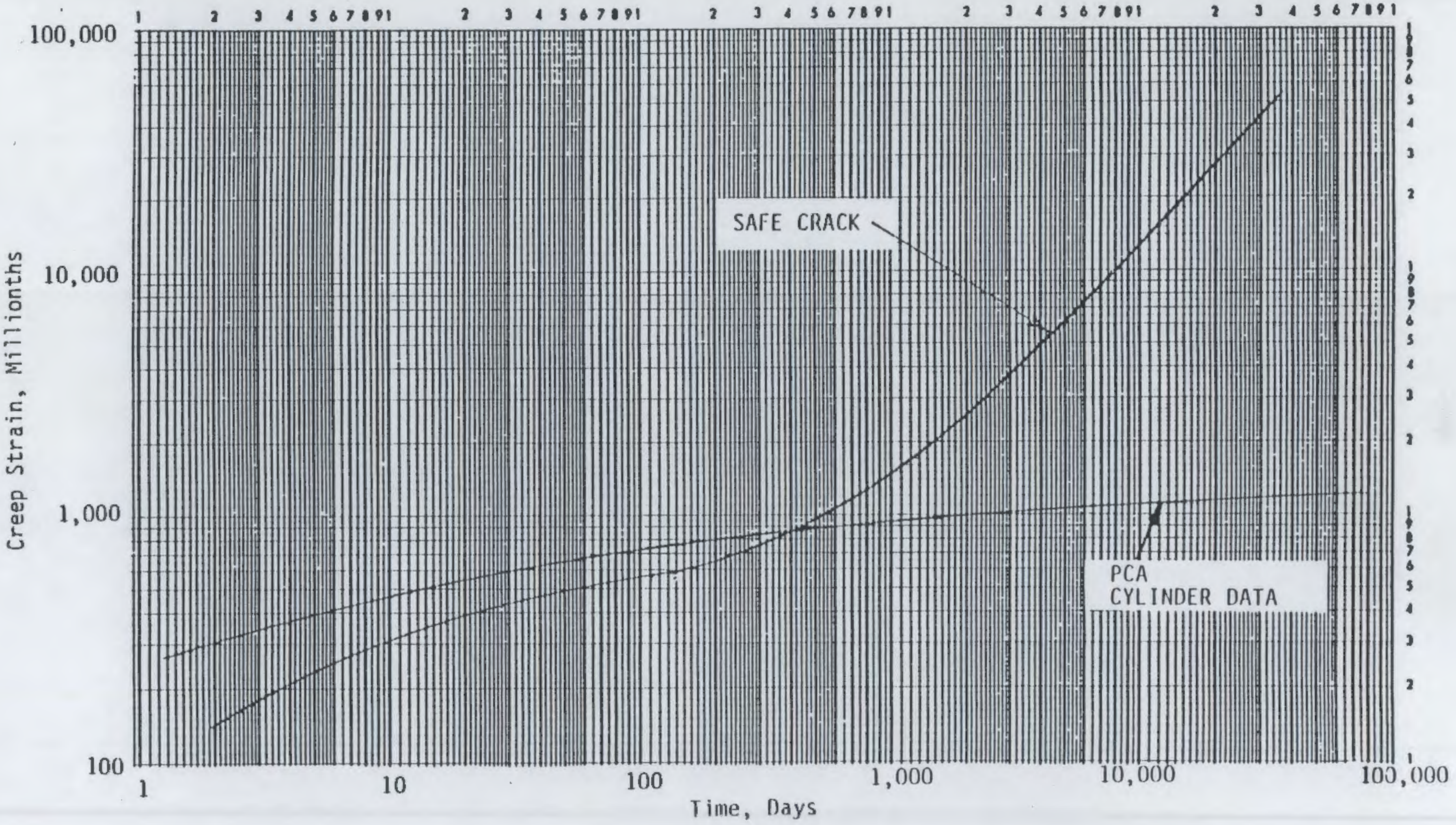

FIGURE 17. SAFE CRACK Creep Exponential Equation Versus PCA Cylinder Data (Logarthmic equation, best-fit Curve) for 500 psi Stress, 350°F

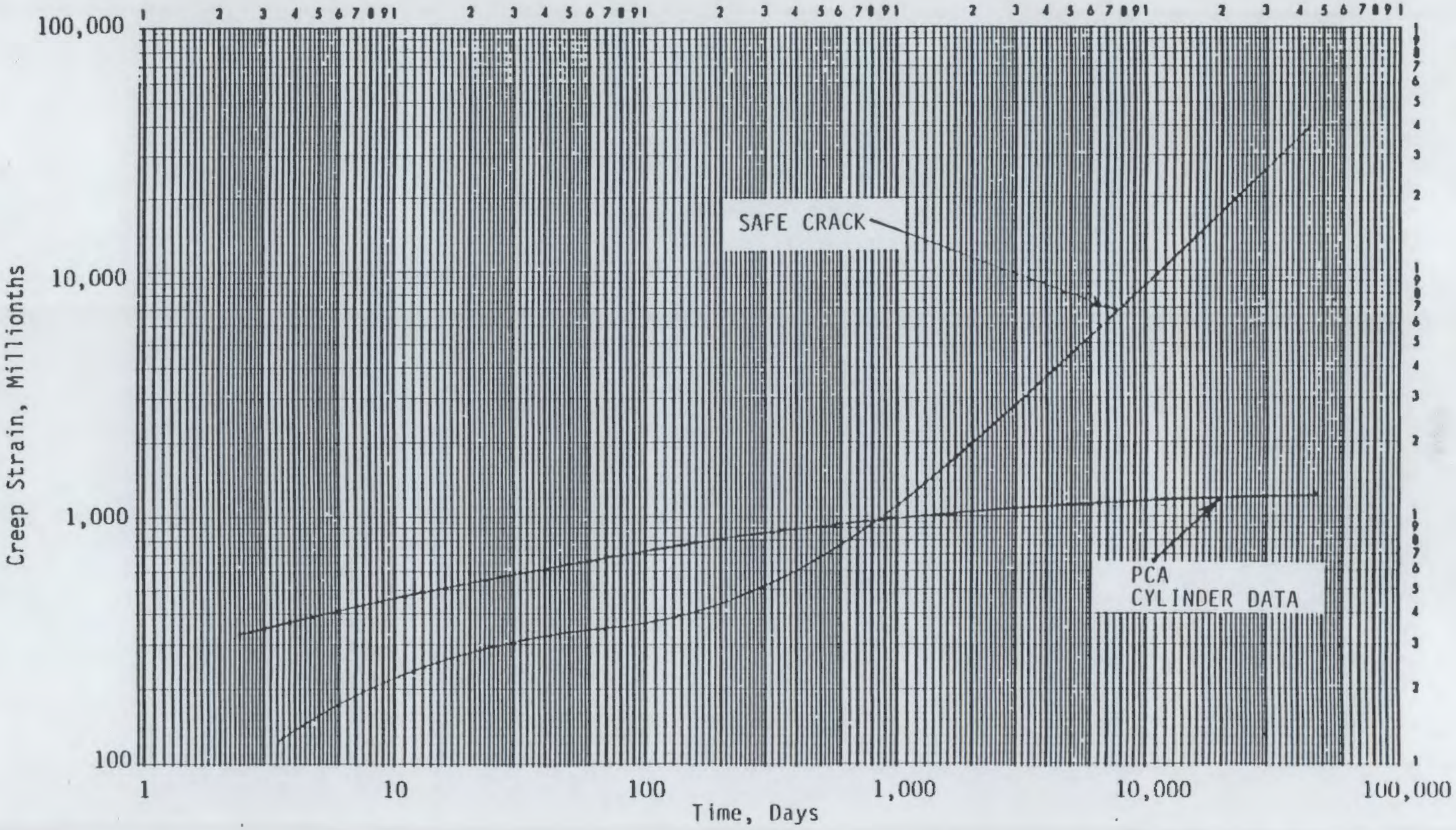

FIGURE 18. SAFE-CRACK Creep Exponential Equation Versus PCA Cylinder Data (Logarthmic Equation, Best-Fit Curve) for 1,500 psi Stress, 250°F)

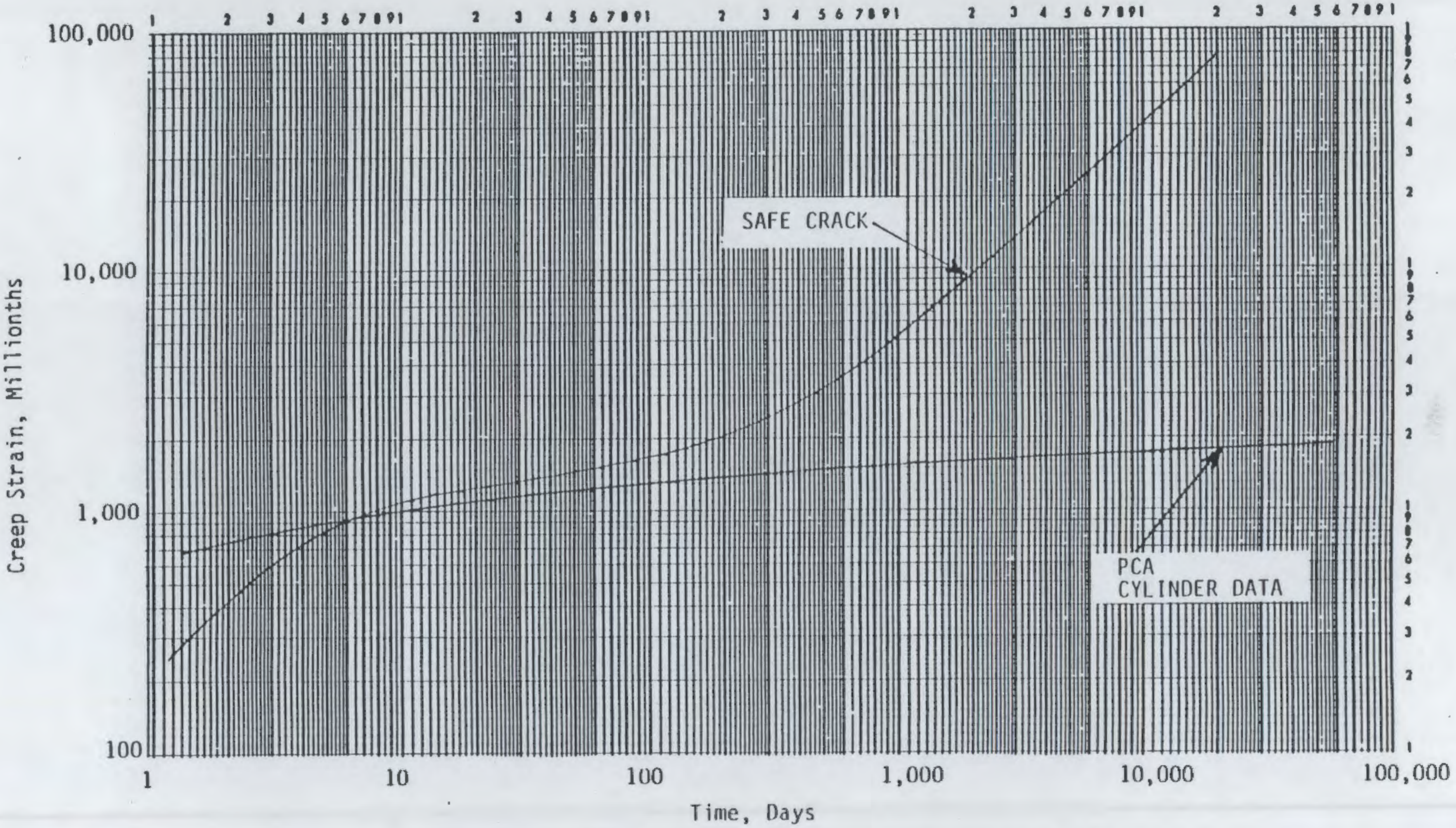

FIGURE 19. SAFE-CRACK Creep Exponential Equation Versus PCA Cylinder Data (Logarthmic Equation, Best-Fit Curve) for 1,500 psi Stress, 350°F)

the difference between the PCA extrapolation of the data (the first 600 days of which are actual) and the SAFE-CRACK equation on log-log paper out to 50 years (18,250 days). Again, it can be seen that the SAFE-CRACK equation over predicts the creep strain significantly beyond the time region of about 100 days. For example, for concrete at 1500 psi and 350 F for 600 days, SAFE-CRACK predicts about 3700 millionths versus the measured strain of about 1500 millionths, an over prediction of 2-1/2.

Since the effect of creep is to relax the concrete stresses in a reinforced concrete structure, there is some uncertainty whether the over prediction of creep tends to be conservative. The SAFE-CRACK equation should be modified to more closely model the actual and logarithmically extrapolated creep of Hanford concrete when used to analyze the Hanford waste tanks. Rashid notes that the exponential equation is much more convenient for incremental analysis than the logarithmic formula.(8) Provided that the exponential form can be modified to provide a closer fit to the Hanford creep data, the exponential form should be used.

Information supplied by Rashid indicates that the equation presently used in SAFE-CRACK modeled the Hanford concrete creep data that were available from the first approximately 70 days of elevated temperature creep testing by PCA.(8) This would explain why the equation does not match the data beyond about the 100 day point.

6.2 SAFE-CRACK'S USE OF TENSILE DATA

The tensile strength is used in SAFE-CRACK to calculate where concrete cracks will occur. SAFE-CRACK presently uses 10% of the absolute value of f'_c for the tensile strength of concrete. The values of f'_c at 900 days heating at 250 and 350 F are of the order 4500 psi and above for both the 3000 psi and the 4500 psi specimens; this would give a value of 450 psi for the tensile strength. However, the splitting tensile strength of the specimens at about 900 days is of the order 400 psi. A model (predictive equation) fitted to the actual test values (which are more conservative) should be used in the calculations.

6.3 SAFE-CRACK CAPABILITIES TO ACCOMMODATE CHANGES IN PROPERTIES

The finite element (FE) computer program SAFE-CRACK has many essential features that permit structural behavior calculations for reinforced concrete structures; the program can be reasonably adjusted or modified to some extent.

As discussed in Section 6.1, SAFE-CRACK calculates creep data needed for calculations within the program. This creep equation can be modified to accommodate Hanford concrete creep data.

As discussed in Section 5, SAFE-CRACK calculates the modulus of elasticity for use in the program using equation (1). Rashid's treatment of this equation in the SAFE-CRACK code allows for partial recovery of the modulus upon cooling and accounts for an irrecoverable amount that depends upon the heating time. In effect, the code addresses cyclic heating behavior by inserting new, lower values of the modulus for temperature cycles followed by partial recovery, when indicated by input data. However, the PCA data do not indicate recovery of modulus on cooling. This equation could be modified or replaced with an equation consistent with the PCA data. SAFE-CRACK should also be augmented (once an equation with adequate goodness-of-fit is obtained) to include capabilities for producing conservative or worst-case predictions as suggested by the confidence band method of Section 5.

The ultimate compressive strength, a basic material property used ordinarily in concrete design, is not used directly by SAFE-CRACK. SAFE-CRACK calculates the ultimate compressive strength values and can be used to calculate the stresses in the structure for comparison. It requires converting some of the SAFE-CRACK output into forces suitable for calculating concrete stresses. The equation used in SAFE-CRACK to extrapolate ultimate compressive strength is of the same form as the equation for extrapolating the modulus. It could be modified or replaced in a manner similar to that discussed in the preceding paragraph to produce lower bound or best fit values for compressive strength.

7.0 MITIGATING FACTORS IN ELEVATED TEMPERATURE CONCRETE DESIGN

There are several mitigating factors in the design of structures for elevated temperatures. One is that concrete heated from one side only is less affected than concrete heated from all sides.$^{(2)}$ Thus the temperature effects on the tank structures in the field will not be as severe as those for the cylinders heated from all sides in the PCA testing program.

Second, concrete stressed to about 1000 psi,(4) or to 0.4 f'_c,(1) and tested hot shows higher compressive strengths for exposures up to 500 F and above than concrete a) heated at zero stress and tested hot or b) heated at zero stress and tested at room temperature. The differences are significant [plots are shown in RHO-C-54(1)] and the net result will be that the concrete in the tanks, which are under load during heating, will not show as great a reduction in strength as the test cylinders that were not loaded during heating.

A third mitigating factor, which should be taken into account in the analysis, is that the tanks will not actually be at an elevated temperature for the full 50 years of their projected service life. Therefore the degradation of properties will not be as great as indicated by the end point on a 50-year extrapolation plot. This can be taken into account by using temperature histories simulating actual or expected operating conditions.

8.0 RECOMMENDATIONS

It is recommended that:

1. Since time constraints did not permit a complete statistical treatment of the data, some of the extrapolated data provided is preliminary, i.e., statistical defensibility does not exist yet. It is recommended that additional statistical analysis be done as described below.
2. The PCA data be corrected for batch-to-batch mixture differences and for differences in the fog room curing time before heating. Then, the statistical analysis should be extended to try to obtain defensible extrapolation equations.
3. Least squares regression be used to obtain fitted curves (to the PCA data) which do not have significant lack-of-fits. This may require modifying, augmenting, or replacing the equations used in SAFE-CRACK. The final result is not expected to show drastic changes in predicted properties. The practical fit of the SAFE-CRACK equations for modulus of elasticity and compressive strength to the PCA data appears to be sufficiently conservative to justify their use on an interim basis for

design-by-analysis of Hanford waste storage tanks. Changes in values brought about by establishing statistically defensible extrapolation equations are believed likely to be only a few percent.

4. The 95% confidence lower bound of the extrapolated property data be used for "design by analysis" with the SAFE-CRACK code.
5. The least squares fit to the data be used to predict structure deflections for comparison with field surveillance measurements.
6. A "worst case" prediction be used for determining suitable times for detailed scheduled surveillance of the tanks in service. (Provided that the worst case is significantly different from the lower bound extrapolation - worst case is a curve from upper bound high point at the beginning of the data through the lower bound low point at the end of the data, extrapolating from there to the time of interest.)
7. The data extrapolation be extended to include the properties determined for specimens thermally cycled in the 28-day heat cycles (particularly the modulus of elasticity) since these conditions appear to have caused greater deterioration of the properties than exposure to constant temperature. These extrapolations would govern in cases where significant thermal cycling is anticipated since they would show lower values.
8. The SAFE-CRACK equations for creep compliance be modified to better match the Hanford concrete creep data in the PCA-developed data base.
9. The PCA-determined values of tensile splitting strength of Hanford concrete be used to develop a predictive model for use in the SAFE-CRACK code rather than the current 10% of compressive strength.
10. Modifications to SAFE-CRACK equations use formulations which are compatible with the capabilities of the computational methods used in SAFE-CRACK.
11. The modifications to SAFE-CRACK be verified as capable of predicting the properties as intended by running the code after the modifications. Other controls by Rockwell to assure that the proper version is being used and maintained without undesired modifications may also be in order.

REFERENCES

1. Portland Cement Association, "Effects of Long-Term Exposure to Elevated Temperature on the Mechanical Properties of Hanford Concrete", RHO-C-54, Rockwell Hanford Operations, Richland WA, October 1981.

2. Davis, H. S., "Effects of High-Temperature Exposure on Concrete", Materials Research and Standards, Vol. 7, No. 10, 1967, pp. 452-459.

3. Neville, A. M., "Properties of Concrete", Pitman Publishing Limited, London, Second Edition 1973, reprinted (with corrections) 1978.

4. Malhotra, H. L., "The Effect of Temperature on the Compressive Strength of Concrete", Magazine of Concrete Research, (London), Vol 8., No. 23, August 1956.

5. Popovics, S., "Effect of Curing Method and Final Moisture Condition on Compressive Strength of Concrete", ACI Journal, July/August 1986.

6. Davis, H. S., "Thermal Considerations in the Design of Concrete Shields", Proceedings Paper 1755, Am Soc. Civil Engrs., ST 5, September 1958.

7. Lankard, D. R., et al, "Effects of Moisture Content on the Structural Properties of Portland Cement Concrete Exposed to Temperatures up to 500 F", Paper SP 25-3, American Concrete Institute Special Publication SP-25, 1970.

8. Rashid, Y. R., "Thermal Creep and Cyclic Analysis of 241-AP Tank", URS/JRB 8162 Appendix A, URS/John A. Blume and Assoc., April 1982.

9. Gillen, Michael, "Strength and Elastic Properties of 1580-Day Hanford Concrete Cylinders at Room Temperature and 350F", report by PCA to Battelle, PNL (for Rockwell), October 1979, 17 p.

10. Birkimer, D. L., et al., "Heat-Resistant Concrete for Prestressed-Concrete-Pressure-Vessel (PCPV) Reactors, (Task No. 2)", Battelle Memorial Institute BMI-1855 (EURAEC 2084) January 1, 1969 (this report forms the basis for the reference No. 7 report).

11. Draper, N. R. and H. Smith, 1981. Applied Regression Analysis, Second Edition, John Wiley and Sons, New York.