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PREVENTION OF STRESS CORROSION CRACKING IN NUCLEAR WASTE STORAGE TANKS

by

Robert S. Ondrejcin

E. I. du Pont de Nemours & Co.
Savannah River Laboratory
Aiken, South Carolina 29808

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ABSTRACT

Stress corrosion cracking (SCC) has occurred in the early versions of carbon steel primaries of nuclear waste tanks at the Savannah River Plant. (Secondary containment was provided by a vessel surrounding the lower portion of the primary tank.) Evaporated alkaline nitrate wastes in the form of crystallized salts are being dissolved from some of these tanks for transfer to new tanks of a different design. To prevent the SCC sequence from occurring during salt dissolution, the levels of inhibitors required to prevent cracking at yield stresses were determined. Special statistically designed experiments were performed to evaluate the probability of cracking under the combined influences of nitrate, nitrite, hydroxide, and temperature. Experimentally, samples were tested by a potentially controlled constant extension rate test and by wedge opening loaded samples. Two equations were derived by multivariable regression analyses that correlated probability of cracking as the dependent variable to nitrate, nitrite, and hydroxide concentrations and temperature as the independent variables. From these equations, simple operating standards were developed by setting the probability of cracking equal to zero and solving for the four independent variables.

INTRODUCTION

Approximately 30 million gallons of radioactive waste are stored at the Savannah River Plant (SRP) in large underground carbon steel tanks. Most of the wastes at SRP are byproducts of the Purex and enriched uranium processes. In the Purex process, plutonium and uranium are recovered from irradiated natural or depleted uranium. In the enriched uranium process, uranium enriched in ^{235}U and ^{236}U is recovered from irradiated uranium fuel for reuse. Other recovery processes have also been used from time to time in both areas for the separation of other isotopes.[1] However, generalization of waste compositions.

in storage tanks based on flowsheet or process analyses is impossible because wastes are mixed and evaporated, salts and insolubles precipitate, and radiation induces changes in composition.

Wastes are present in SRP tanks in three forms:

1. supernate (an aqueous solution)

2. sludge (a gel containing the insoluble components of the wastes that settle to the tank bottom with some trapped supernate)

3. salt cake (salt crystals formed by evaporation of water from the supernate)

The carbon steel in the tanks is susceptible to stress corrosion cracking (SCC) in nitrate and caustic solutions both present in the nuclear waste. SCC has been observed in the primary steel shells of some of the older high-heat waste (HHW) tanks. To help alleviate the problem, newer tanks were built, then annealed to remove construction stresses.

This paper reviews some technical investigations to identify the composition of solutions that would prevent cracking during radioactive salt removal from nuclear waste tanks. The quantitative effects of a large number of ions and temperatures on nitrate SCC were required. Because of the complexity of the solutions, testing was based on statistical formats with analyses primarily by multivariable regression. Modifications in waste management resulted from these studies; these modifications helped to maintain the integrity of the tanks, providing more secure containment.

Experimental Procedures

Crack initiation was measured by the slow strain rate method.[2] In this procedure, a tensile test sample is slowly pulled to failure while immersed in a test solution. The potential of the sample is held at its open circuit value by a potentiostat. At the end of the experiment, which normally lasts 20 to 30 hours, the broken sample is examined for cracking.

Crack propagation was measured by the wedge-opening loaded sample method.[3] This procedure is based on the Naval Research Laboratory's assumption that no large man-made structure is without flaws no matter how carefully inspected. In this method, a previously cracked steel specimen is bolt-loaded to a predetermined stress intensity at the crack tip. The sample is then immersed in a test solution for a predetermined length of time to permit any crack propagation. Crack propagation will occur in waste tanks under the same conditions as those of the test. The stress intensity at the crack tip when the crack stops is the stress intensity necessary to initiate the stress corrosion sequence.

Both the crack initiation and crack propagation tests were based on a special statistical format performed in random order. A standard design such as a Box-Behnkin[4] or Box-Wilson[5] could not be used because these designs require a combination of high salt concentrations and low temperature which is chemically impossible to achieve. These high concentrations were of interest at high temperatures, however. Therefore a specially designed experimental series was devised with temperature at three levels and ionic concentrations at four levels.

There is an important basic assumption in all these experiments; namely, that the stresses on the waste tanks will be at the yield point as a minimum. Stress calculations on the waste tanks normally indicate that stresses are about one-half of yield. Therefore, standards based on this type of data would be quite conservative.

BACKGROUND

Waste Storage Operations

Radioactive HHW from the reprocessing plant is transferred to a tank containing cooling coils that remove decay heat (Figure 1). Fresh waste is aged from 1 to 2 years to permit solid material to settle and short-lived fission products to decay. During this aging period, insoluble materials form a layer of sludge at the bottom of the tank. The sludge consists of oxides and hydroxides of manganese, iron, and aluminum, small amounts of uranium, plutonium, and mercury, and most of the longer lived fission products originally in the irradiated fuel, except cesium. The aged supernate solution containing dissolved salts, including radioactive cesium, is transferred to a continuous evaporator. The concentrate from the evaporator is transferred to a waste tank equipped with cooling coils. In the tank, the salts crystallize and settle as the liquid cools. The remaining supernate is returned to the evaporator for further concentration. This process continues until the liquid has been converted to a damp salt cake. Aging and processing cause changes in the chemical and radionuclide composition. The major changes are:

1. radiolytic conversion of nitrate to nitrite
2. absorption of CO_2 from air, converting some NaOH to Na_2CO_3
3. separation of radionuclides into soluble and insoluble fractions
4. decay of radionuclides.

The composition of the wastes in individual tanks varies widely, depending on the detailed history of their contents. Concentration ranges of the major components in the high-heat storage tanks are given in Table 1. Nitrate is the major anion, but nitrite from radiolysis of nitrate is a major component after aging and evaporation. The relative amount of hydroxide has increased because of the difficulty in crystallizing sodium hydroxide.

The only radionuclides present at high concentration in the supernate (Table 2) are the isotopes of cesium, which were relatively minor originally. Some ruthenium is also present. Uranium and plutonium are expected to remain in the sludge; their presence in the supernate probably indicates a colloidal suspension.

Waste tanks used for storing HHW at SRP are designated Types I, II, and III.[6] Twelve Type I waste tanks (Figure 2) were originally built between 1951 and 1953. The tanks are free-standing, right circular cylinders, with primary and secondary containers made of American Society for Testing and Materials (ASTM) A285-B steel. The secondaries are encased in reinforced concrete.

Volume is 0.75 million gal, and radioactive decay heat is removed with water that circulates through cooling coils. Air in the annular space is dried and heated to limit corrosion of the exterior of the primary tank and the interior of the secondary.

Four Type II waste tanks (Figure 3) were built between 1955 and 1956. The design is similar to that of Type I except that a single central support column is used (compared to 12 in Type I tanks) and the volume was increased to 1 million gal.

A series of eighteen new tanks, Type III (Figure 4), were completed in 1981 for transfer of wastes from some of the older cracked tanks. At that time thirteen Type III tanks were already in service. Each primary tank holds 1.3 million gal and has a secondary liner the full height of the primary tank wall.

An assortment of standard SCC specimens, including welded and notched samples, was exposed to actual wastes, but no specimens ever cracked. The tanks, however, continued to crack occasionally. The results of an inspection program for the cracked tanks are shown in Table 3.

Of the original 16 HHW tanks, 9 contain one or more leak sites on the primary tank wall. The largest number of cracks was observed in Tank 16. This tank has been emptied, and the annular space is being cleaned out. Seven of the original tanks, some of which have been in service for ~26 years, show no evidence of leakage through the primary. None of the thirty-one Type III tanks has leaked to date.

RESULTS AND DISCUSSION

Investigation of Corrosion of SRP Waste Tanks

To determine whether cracking of SRP waste tanks was caused by nitrate or hydroxide stress corrosion, the open-circuit potentials of 4 SRP waste tanks containing alkaline nitrate radioactive wastes were measured against saturated calomel electrodes (SCE). The potentials were -0.44, -0.12, -0.085, and -0.064 V. These potentials fall generally in the range for cracking in pure 4M sodium nitrate (-0.30 to +1.0 V)[7] rather than for cracking in hydroxide, which would be expected to occur in the range -0.90 to -1.04 V.[8]

Waste Solution Compositions - A large number of supernate solutions were taken from 14 SRP waste tanks and analyzed to determine general compositions and specifically the nitrate concentration. The solutions represented about 42 million liters (11 million gallons) of radioactive waste. Measured concentration ranges are shown in Table 4.

Plackett-Burman[9] - To determine which independent varibles were most effective in causing nitrate SCC, a statistically designed series of experiments, known as the Plackett-Burman series, were performed. The Plackett-Burman design is generally used for screening a variable space in selected portions of a 2^n factorial design where one variable is changed at a time with a high and a low value for each. As a screening design, the Plackett-Burman series has the advantage that a small number of experiments are required to investigate a large number of independent variables.

Because many independent variables can affect the cracking, the Plackett-Burmann test series included seven independent variables: temperature and six anionic concentrations. This approach required only 12 experiments rather than 128 for a two-level 2^n factorial design. The variables are shown in Table 5.

Four dependent variables, ultimate tensile strength (UTS) and three measures of ductility, were chosen as values that might be affected by the independent variables based on a stress-strain curve.

The data showed that temperature and NO_3^- concentration stood out above interactions and experimental error in affecting ductility parameters (Table 6). Calculated minimum factor effects had to be exceeded by each independent variable to be significant at the 90 percent level. All three ductility (dependent) variables correlated with temperature and NO_3^- concentration. However, no statistically significant relationship was found between UTS and any of the independent variables. Probably a design with more trials should have been used to increase the degrees of freedom and lower the experimental error.

To evaluate the hydroxide effect, a known inhibitor for nitrate stress corrosion, UTS was measured in a series of electrochemical tension tests. These strength data are plotted in Figure 5 against OH^- concentration. Obviously there is a hydroxide effect; as hydroxide concentration increases, so does UTS. The lowest value observed was for high nitrate that was acidified with nitric acid. The next three were synthetic solutions representing fresh wastes from fuel reprocessing facilities and a hypothetical waste composition (H Purex) based on flow sheet calculations. The others were representative of wastes from actual waste tanks.

Metallographic examination of the cracked specimens showed that the failures were intergranular stress corrosion cracks that would be typical of nitrate stress corrosion (Figure 6). The cracks contained some loose grains and corrosion products.

Corrosion Reactions

Corrosion reactions that occur during cracking of carbon steel in nitrate solutions are not agreed upon.[10,11,12] Steel is proposed to react according to

$$10\ Fe + 6\ NO_3^- + 3\ H_2O \rightarrow 5\ Fe_2O_3 + 6\ OH^- + 3\ N_2 \qquad (1)$$

by Engell and Baumel[10] or, after oxidation of the iron to ferrous ion, by the reaction

$$2\ Fe^{2+} + NO_3^- + H_2O \rightarrow 2\ Fe^{3+} + NO_2^- + 2\ OH^- \qquad (2)$$

as proposed by Smialowski et al,[11] or anodically by the reaction

$$3/4\ Fe + H_2O \rightarrow 1/4\ Fe_3O_4 + 2\ H^+ + 2\ e^- \qquad (3)$$

according to Hoar and Galvele,[12] they propose at least two cathodic reactions probably take place, with the result being

$$NO_3^- + H_2O + 2\ e^- \rightarrow NO_2^- + 2\ OH^- \qquad (4)$$

On the basis of Reactions 3 and 4, the H^+ produced in the anodic reaction and the OH^- produced in the cathodic reaction may react, depending on the distances between the anode and cathode. If the electrode surfaces are separated, for example, if the anode is the top of a crack or the bottom of a pit, and the cathode is the wall of the crack or pit, the anode becomes more acidic and the cathode more basic.

Stress corrosion work at the Naval Research Laboratory (NRL) has shown that during cracking of a number of high-strength steels, the tip of the crack becomes acidic,[13] as inferred from Reaction 3. Measurements showed the solutions at the crack tip consistently to have a pH of ~3. Sandoz et al[13] concluded that the pH was controlled by the hydrolysis of the ferrous ion, that is, that the reaction

$$Fe^{2+} + HOH \rightarrow Fe(OH)^+ + H^+ \qquad (5)$$

was controlling.

Parkins and Usher[14] showed that in nitrate solutions the severity of cracking increases according to the cation series $Na^+ < Ca^{2+} < NH_4^+$. This series is also one of increasing acidity due to cation hydrolysis which causes the open-circuit potential of the steel to become more and more anodic.[12] Increasing anodic potential in the active portion of the polarization curve either increases anodic current density or stimulates cathodic reactions.

Corrosion, the precursor to SCC, is normally under the control, of cathodic reactions in aqueous solutions[15] and is relatively unaffected by minor changes in steel composition. The rate is influenced by the reduction kinetics and diffusion of reactants to cathodic sites. Nitrate, which takes part in the cathodic reaction is reduced more easily as the solution becomes more acidic.

To reduce nitrate SCC, the best theoretical approach, on the basis of Reactions 1 through 4 and information in the previous two paragraphs, is to reduce the cathodic reaction. The cathodic reaction can be reduced either by increasing the concentration of OH^- alone or by increasing the OH^- and NO_2^- concentrations together depending on whose reaction you accept.

Multivariable Statistical Series - The simultaneous effects of temperature, nitrate, nitrite, and hydroxide on cracking were systematically evaluated using a statistically designed series of experiments. The final result of this series of experiments is a response surface equation that correlates a dependent variable, such as probability of cracking to a series of independent variables, such as ionic concentrations. With independent variables specified, the dependent variable can be calculated once the equation is established.

The usual method of varying each variable individually (factorial design) to obtain an equation would have required prohibitively extensive testing as seen in Table 7. The conditions selected for the experimental series are shown in Table 8.

Temperature and nitrate were chosen on the basis of the Plackett-Burman series of experiments, and hydroxide and nitrite were chosen from actual test data (Figure 5) and previous work. Tests in appropriate combinations of the low, intermediate, and high values of the independent variables were run. The combinations were assigned to each test according to the design; the corresponding tests were performed in random order.

For the data reduction, a multiple regression, least squares program was used to generate the equations. None of the 33 results from either the crack initiation or propogation experiments were rejected on the basis of the computer analysis of residuals. The data points were significant at the 95 percent confidence level based on the "t"-test. These equations are shown in Appendix 1. The equations are relatively long, having 15 terms for crack initiation, and 9 terms for crack propagation but are relatively simple because they are quadratics.

The range of probabilities (dependent variable) is 0 (0%) to 1 (100%). Since a general solution was used in developing the equations from the data, it is possible to get probabilities <0 or >1 which have no physical meaning. Values <0 and >1 are interpreted as 0 and 1, respectively.

The probability of crack initiation is affected by all four independent variables studied: temperature from 35 to 75°C, nitrate concentration 5.5 to 8.5 M, nitrite concentration 0 to 0.5M, and hydroxide concentration 0 to 1M.

The probability of crack propagation is affected by the concentration of the inhibitors NO_2^- and OH^-. It is independent of temperature and nitrate concentration within the ranges studied.

Both equations were solved for $Y = 0$ probability of crack initiation and propogation. The value of $Y = 0$ for cracking is rather restrictive and gives a better than 3σ (99%) confidence level that the event will not occur. Such a low probability value was chosen for two reasons. First, there is a variation in susceptibility to stress corrosion cracking from heat to heat for a given alloy. Although this variation may not be large, it is usually demonstrable[1]. Second, the statistics of the analysis could be improved if about ten samples were run at each of the 33 points. This is not experimentally feasible because of time constraints, but the effect of possible error is decreased by solving for a low probability.

Data are illustrated in apparent three dimensional plots. Each equation was solved for $Y = 0$ and, where the solutions to the two equations were superimposed, the data were plotted. These plots are shown in Figures 7-15.

The volumes inside these plots represent the envelope of recommended operation. The changes in the hyperparaboloid existing in hyperspace (4 dimensions) can be imagined by scanning the series of temperature plots sequentially.

Through the use of data such as these, standards for compositional and temperature limitations have been set in the storage of nuclear waste as one means of preventing nitrate stress corrosion cracking. The other major means used is annealing of the waste tanks to reduce stresses from welding and fabrication. Thus both the stresses and the corrosion are reduced to prevent the possibility of nitrate stress corrosion cracking.

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REFERENCES

1. Wallace, R. M., Hull, H. L. Bradley, R. F., Solid Forms for SRP High-Level Waste, DP-1335, E. I. du Pont de Nemours & Co., Savannah River Laboratory, Aiken, SC (1974).

2. Ondrejcin, R. S. Stress Corrosion Cracking: The Slow Strain Rate Technique, ASTM STP 665, G. M. Ugiansky and J. H. Payer, eds., American Society for Testing and Materials, Philadelphia, PA, p 203 (1979).

3. Novak, S. R., Rolfe, S. T., J. of Materials, Vol 4, No. 3, p. 701 (September 1969).

4. Box, G.E.P., Behnken, D. W., Technometrics, Vol 2, p. 455-475 (1960).

5. Box G.E.P., Wilson, K. B., Jour. Royal Statistical Soc., Series B, pp. 1-45 (1951).

6. Integrated Radioactive Defense Waste Management Plans, Savannah River Plant, Savannah River Operations Office, Aiken, SC, SRO-TWM-77-1 (1977).

7. Humphries, M. J., Parkins, R. N., in Proceedings of Symposium — Fundamental Aspects of Stress Corrosion Cracking, National Association of Corrosion Engineers, Houston, TX, p. 389 (1969).

8. Reinoehl, J. E., Berry, W. E., Corrosion, Vol 28, p. 151 (1972).

9. Plackett, R. L., Burnman, J. P., Biometrika, Vol 33, p. 505 (1946).

10. Engell, H. J. Bamel, A., Physical Metallurgy of Stress Corrosion Fracture, T. N. Rhodin, Ed., Interscience Publishers, New York, NY, p. 341 (1959).

11. Smialowski, M., Szklarska-Smialowski, Z., Corrosion, Vol 18, p. 1t (1970).

12. Hoar, T. P., Galvele, J. R., Corrosion Science, Vol 10, p. 211 (1970).

13. Sandoz, G., Fujii, C. T., Brown, B. F., Corrosion Science, Vol 10, p. 839 (1970).

14. Parkins, R. N., Usher, R., First International Congress on Metallic Corrosion, Butterworth, London, p. 289 (1969).

15. Legault, R. A., Mori, S., Leckie, H. P., Corrosion, Vol 6, p. 121 (1970).

TABLE 1

Concentration Range of Major Constituents in Aged HHW Supernates

Constituent	Concentration Range, M
Na^+	4.0 - 12.5
NO_3^-	1.6 - 6.4
NO_2^-	0.2 - 3.2
$Al(OH)_4^-$	0.4 - 1.6
OH^-	0.8 - 6.3

TABLE 2

Concentration Range of Major Radioactive Constituents of Aged HHW Supernates

Constituent	Concentration Range, Ci/L
^{134}Cs	0.05 - 1.2
^{137}Cs	0.4 - 11
^{103}Ru	ND* - 0.05
^{89}Sr	$<10^{-7}$ - 8×10^{-6}
^{90}Sr	5×10^{-5} - 1×10^{-3}

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* Not Detected

TABLE 3

Inspection Results for Cracked Tanks

Tank Design	Tank #	Observed Number of Leak Sites	Salt Depth in Annulus (cm)
Type I	1	---	0 - 6
	9	---	20 - 25
	10	---	5 - 8
	11	1	None
	12	1	None
Type II	13	2	0 - 6
	14	50	30 - 33
	15	15	None
	16	300	Removed partially

TABLE 4

Ionic Concentrations of SRP Waste Supernates

Ion	Concentration Range
NO_3^-	1.6 to 4.5
NO_2^-	0.5 to 3.2
OH^-	0.8 to 6.3
$Al(OH)_4^-$	0.4 to 1.6
CO_3^{2-}	<0.1 to 0.3
SO_4^{2-}	0.02 to 0.20
PO_4^{3-}	0.01 to 0.08
Cl^-	0.005 to 0.11
CrO_4^{2-}	0.01 to 0.009
F^-	0.001 to 0.004

TABLE 5

Plackett-Burman Variables and Constants

Independent Variables	Values* Low	Values* High	Dependent Variables**	Constants*,†	
Temperature, °C	50	100	UTS	CO_3^{2-}	0.1
NO_3^-	1.5	5.5	TE	SO_4^{2-}	0.1
NO_2	0	3.5	UE	PO_4^{3-}	0.05
$Al(OH)_4$	0	1.6	RA	CrO_4^{2-}	0.005
OH^-	0	6.0			
Cl^-	0.005	0.15			
$HHgO_2^-$	0	0.002			

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* All ionic values are molar concentrations.

** UTS = ultimate tensile strength, T = total, E = elongation, U = uniform, and RA = reduction of area.

† Added to simulate actual waste

TABLE 6

Plackett-Burman Factor Effects

Independent Variables	Total Elongation	Uniform Elongation	Reduction in Area	Ultimate Tensile Strength
Temperature	6.2	4.6	28.7	5.4
$[NO_3^-]$	5.9	4.3	28.0	6.2
$[NO_2^-]$	1.3	1.7	5.3	3.3
$[Al(OH)_4^-]$	2.5	1.4	9.7	7.6
$[OH^-]$	2.7	2.2	9.7	5.6
$[Cl^-]$	1.0	1.6	3.7	6.4
$[HHgO_2^-]$	0.9	0.3	7.0	4.0
Minimum factor effect	3.6	3.2	20.2	11.9

TABLE 7

Statistical Designs

Independent Variables	Number of Experiments Three-Level Factorial	Box-Behnkin Design	Special Design
3	27	15	-
4	81	27	33
5	243	46	-

TABLE 8

Statistical Design Conditions

Independent Variables	Range	Dependent Variable
Temperature°C	35 - 75	Probability of Cracking
NO_3^-, M	5.5 - 8.5	
NO_2^-, M	0 - 0.5	
OH^-, M	0 - 1	

APPENDIX 1. CRACKING EQUATIONS

Crack Initiation Equation

$$Y = 0.089 + 0.050\ X_1 - 0.024\ X_2 - 0.020\ X_3 - 0.41\ X_4$$
$$+ 0.019\ X_1X_2 + 0.16\ X_1X_3 - 0.15\ X_1X_4 - 0.049\ X_2X_3 + 0.14\ X_2X_4 - 0.073\ X_3X_4$$
$$+ 0.0062\ X_1^2 + 0.046\ X_2^2 + 0.12\ X_3^2 + 0.29\ X_4^2$$

where

Y = probability of crack initiation in the range of:

$X_1 = \frac{\text{temp} - 55}{20}$ 35 to 75°C

$X_2 = \frac{NO_3^- - 6.4}{0.9}$ 5.5 to 8.5M

$X_3 = \frac{NO_2^- - 0.25}{0.25}$ 0 to 0.50M

$X_4 = \frac{OH^- - 0.50}{0.50}$ 0 to 1.0M

Crack Propagation Equation

$$Y = 0.037 - 0.37\ X_3 - 0.50\ X_4$$
$$+ 0.0017\ X_3X_4 - 0.0042\ X_3^2X_4 + 0.37\ X_3X_4^2 - 0.34\ X_3^2X_4^2$$
$$+ 0.34\ X_3^2 + 0.46\ X_4^2$$

where

Y = probability of crack propagation in the range of:

35 to 75°C

5.5 to 8.5M NO_3^-

$X_3 = \frac{NO_2^- - 0.25}{0.25}$ 0 to 0.5M

$X_4 = \frac{OH^- - 0.5}{0.5}$ 0 to 1.0M

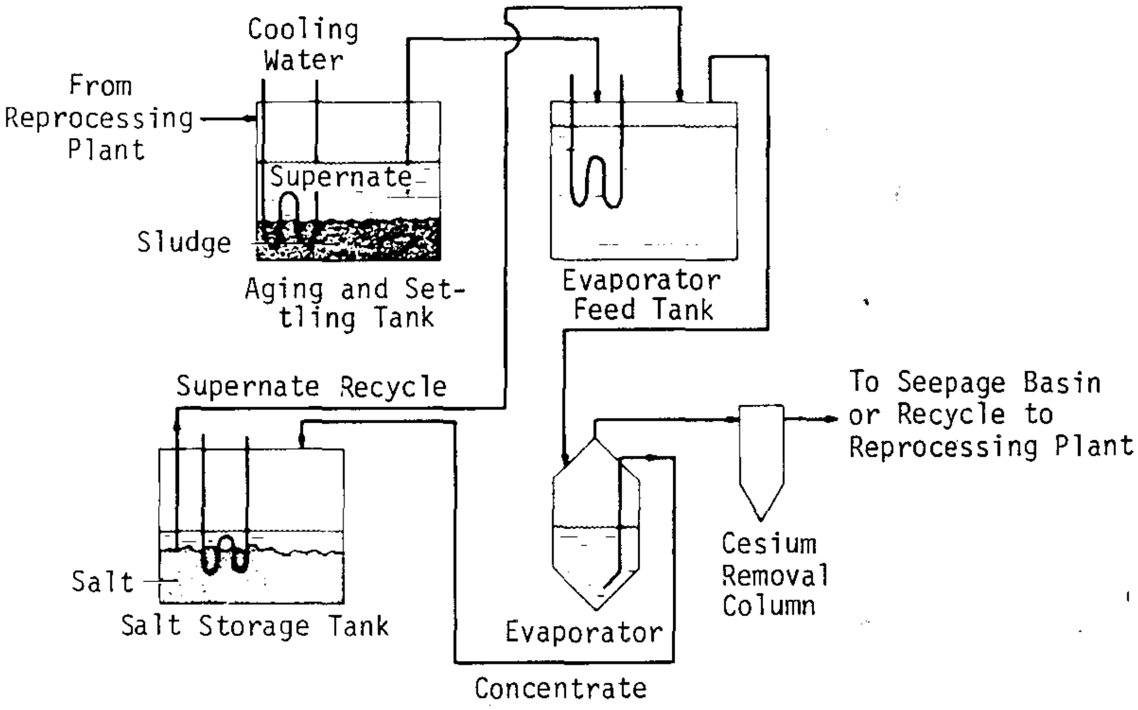

Figure 1. High-Heat Waste Processing in Tank Farm

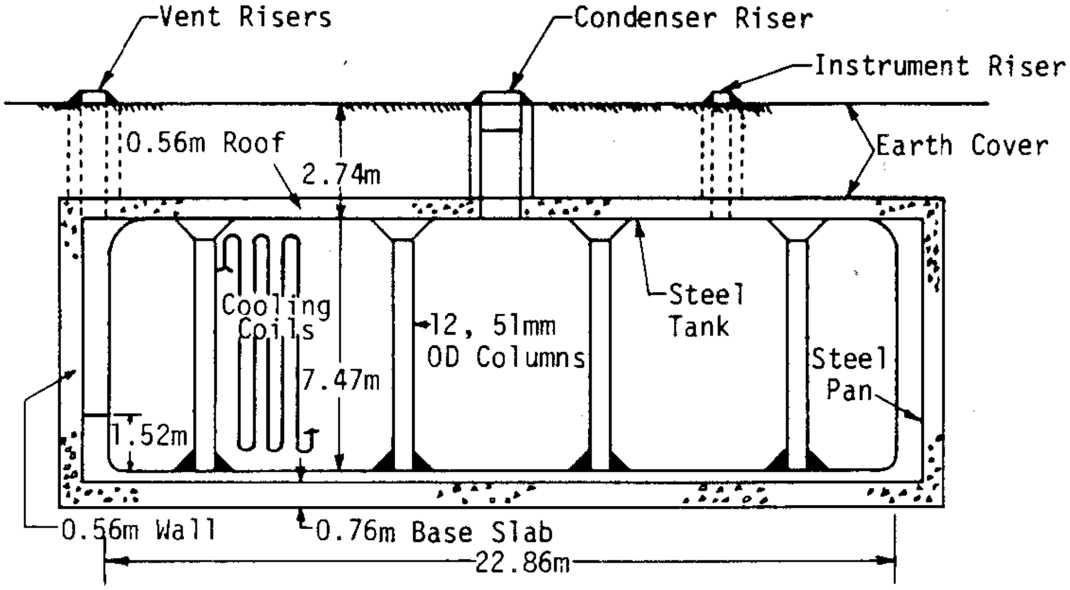

Figure 2. Type I High-Heat Waste Tank, 0.75 Million Gallons

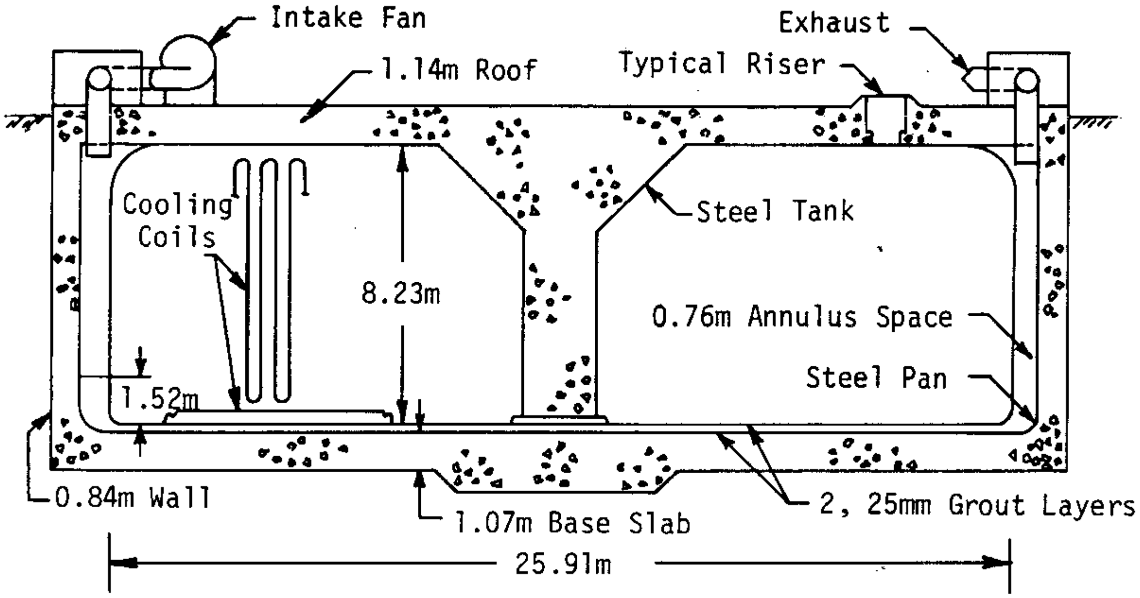

Figure 3. Type II High-Heat Waste Tank, 1.0 Million Gallons

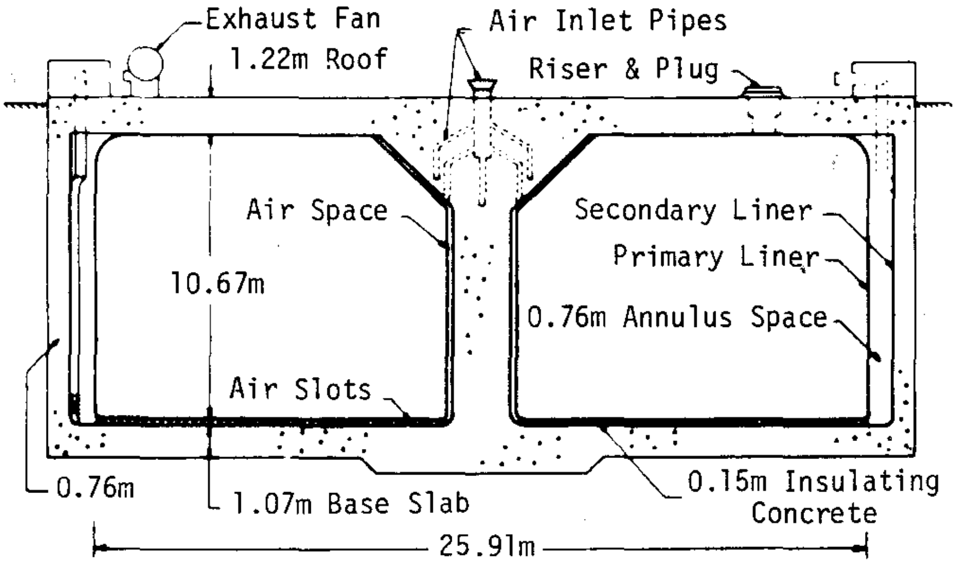

Figure 4. **Type III High-Heat Waste Tank, 1.3 Million Gallons**

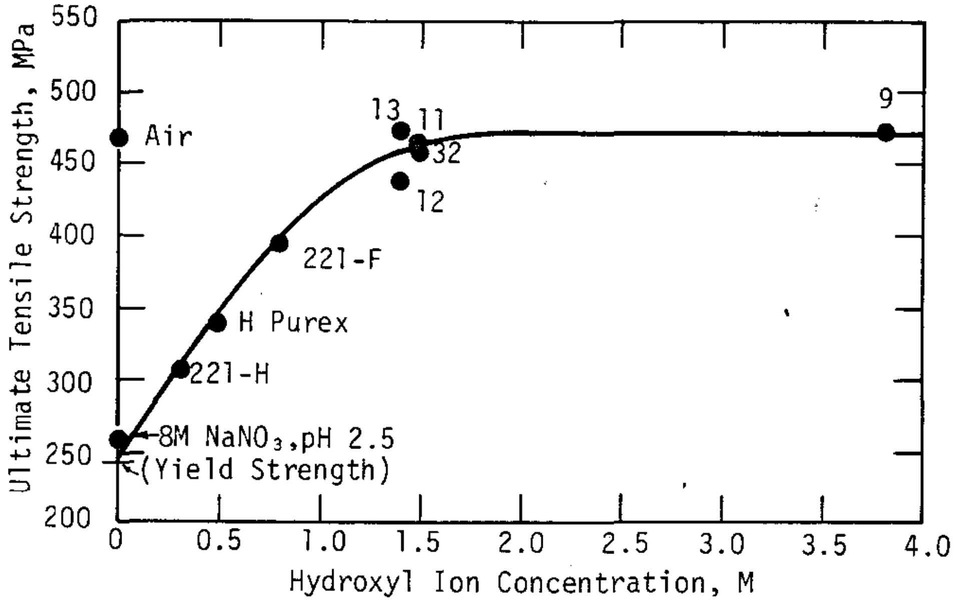

Figure 5. Effect of Hydroxyl Ion Concentration on Steel Strength

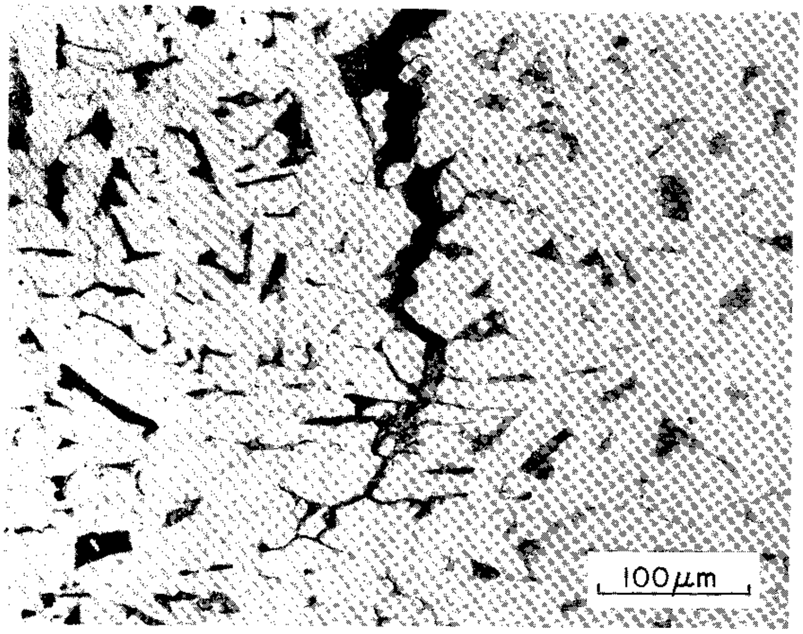

Figure 6. Intergranular Cracking in Constant Potential Tension Test

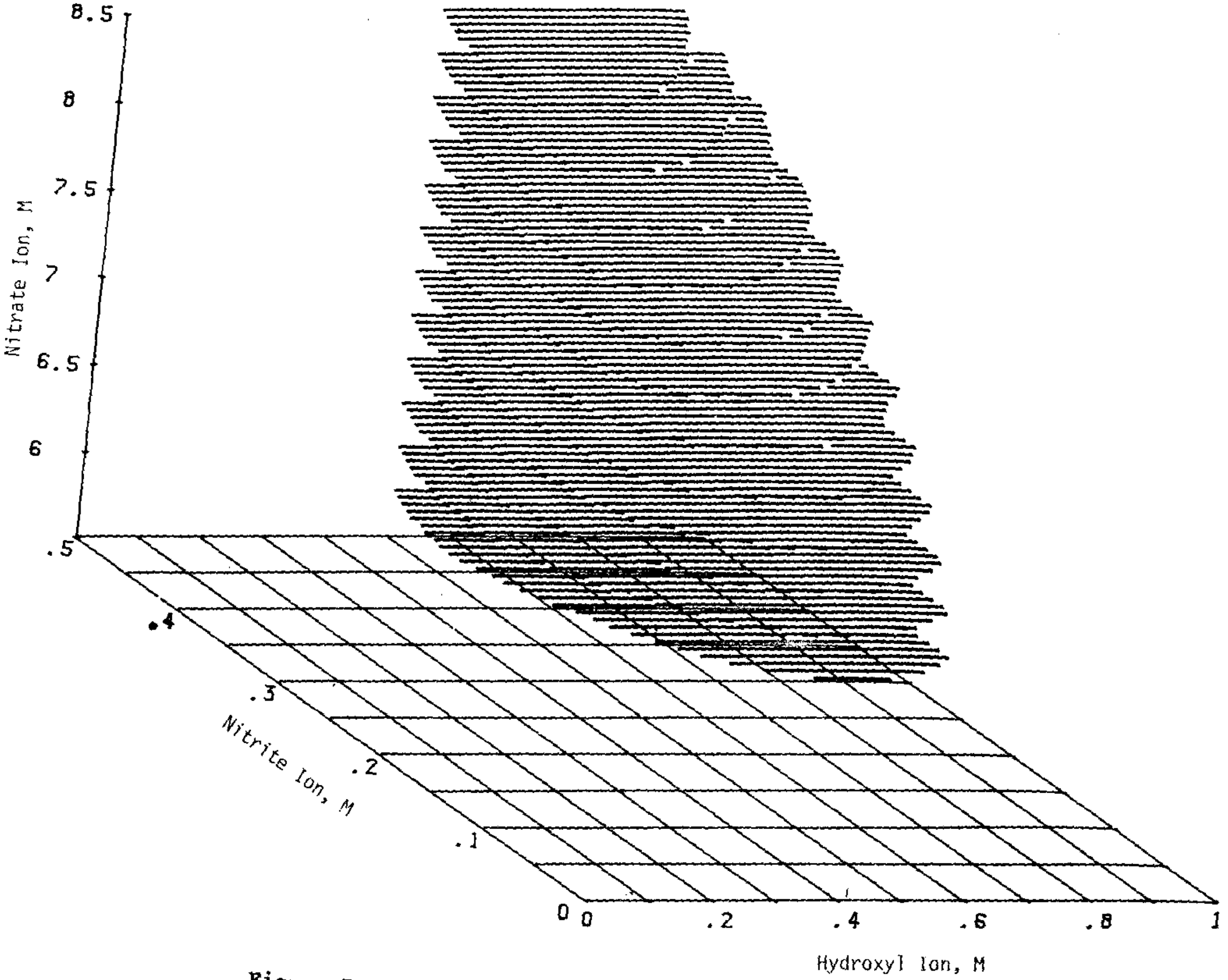

Figure 7. Superposition of Crack Initiation and Crack Propagation Equations - 35°C

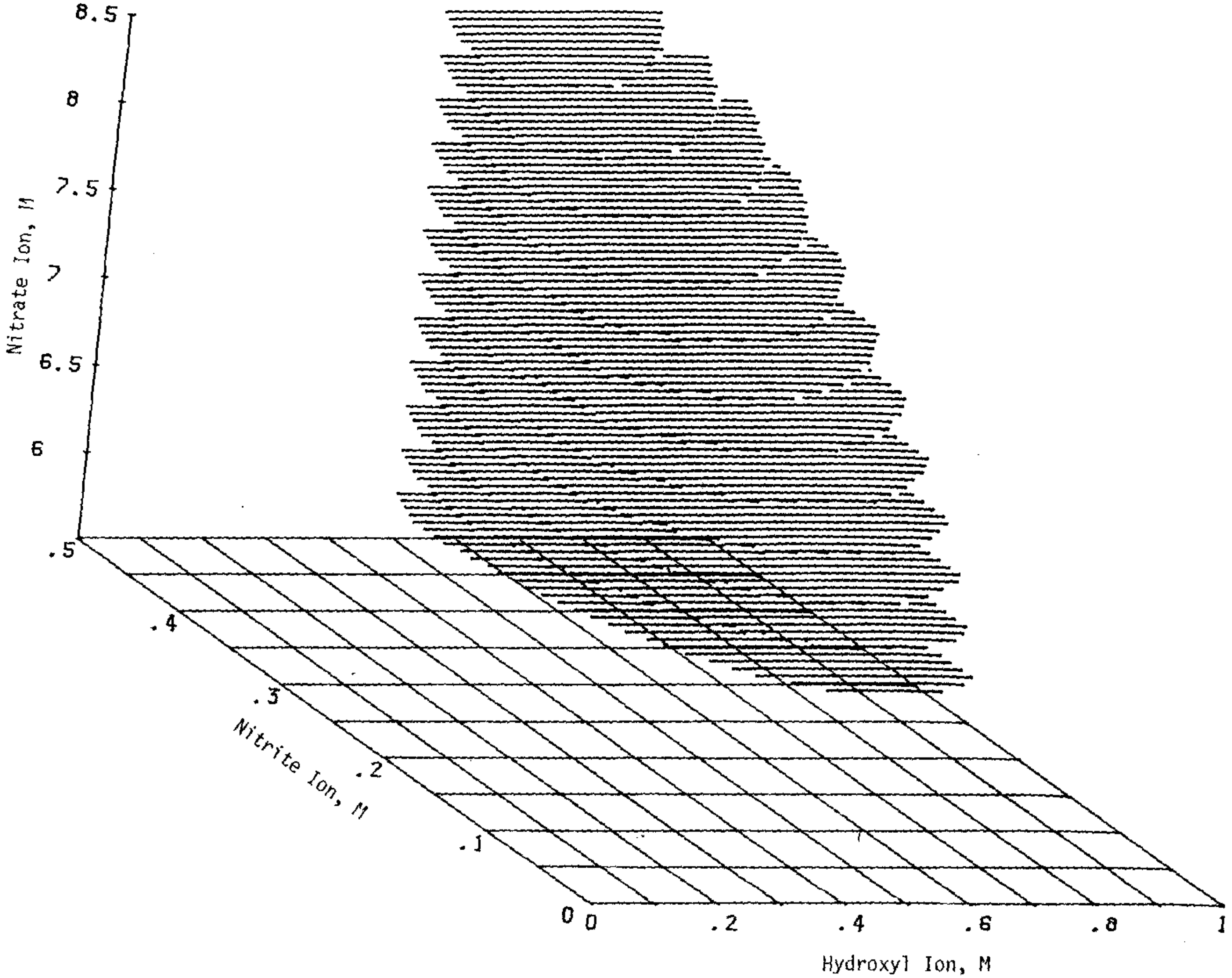

Figure 8. Superposition of Crack Initiation and Crack Propagation Equations - 40°C

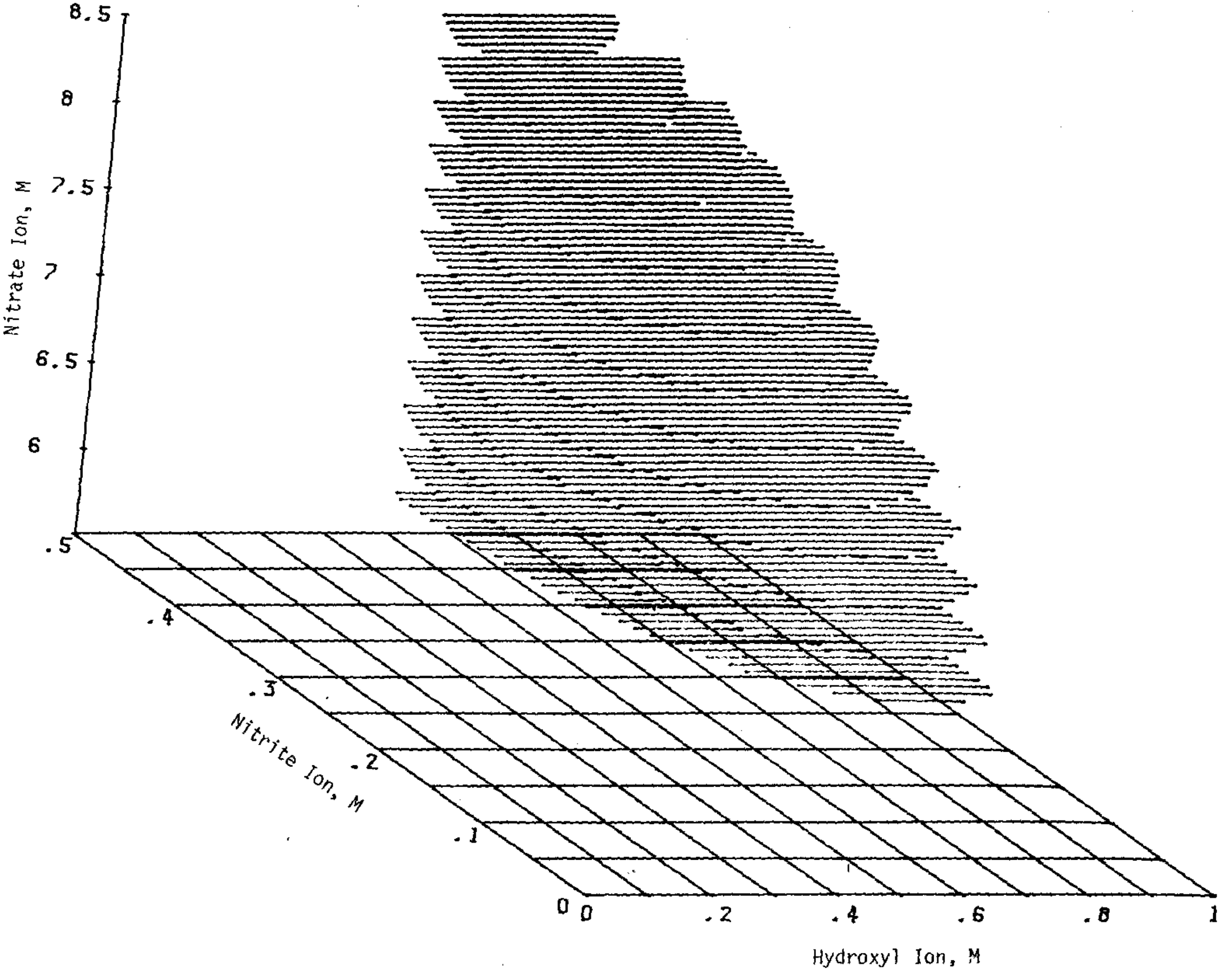

Figure 9. Superposition of Crack Initiation and Crack Propagation Equations - 45°C

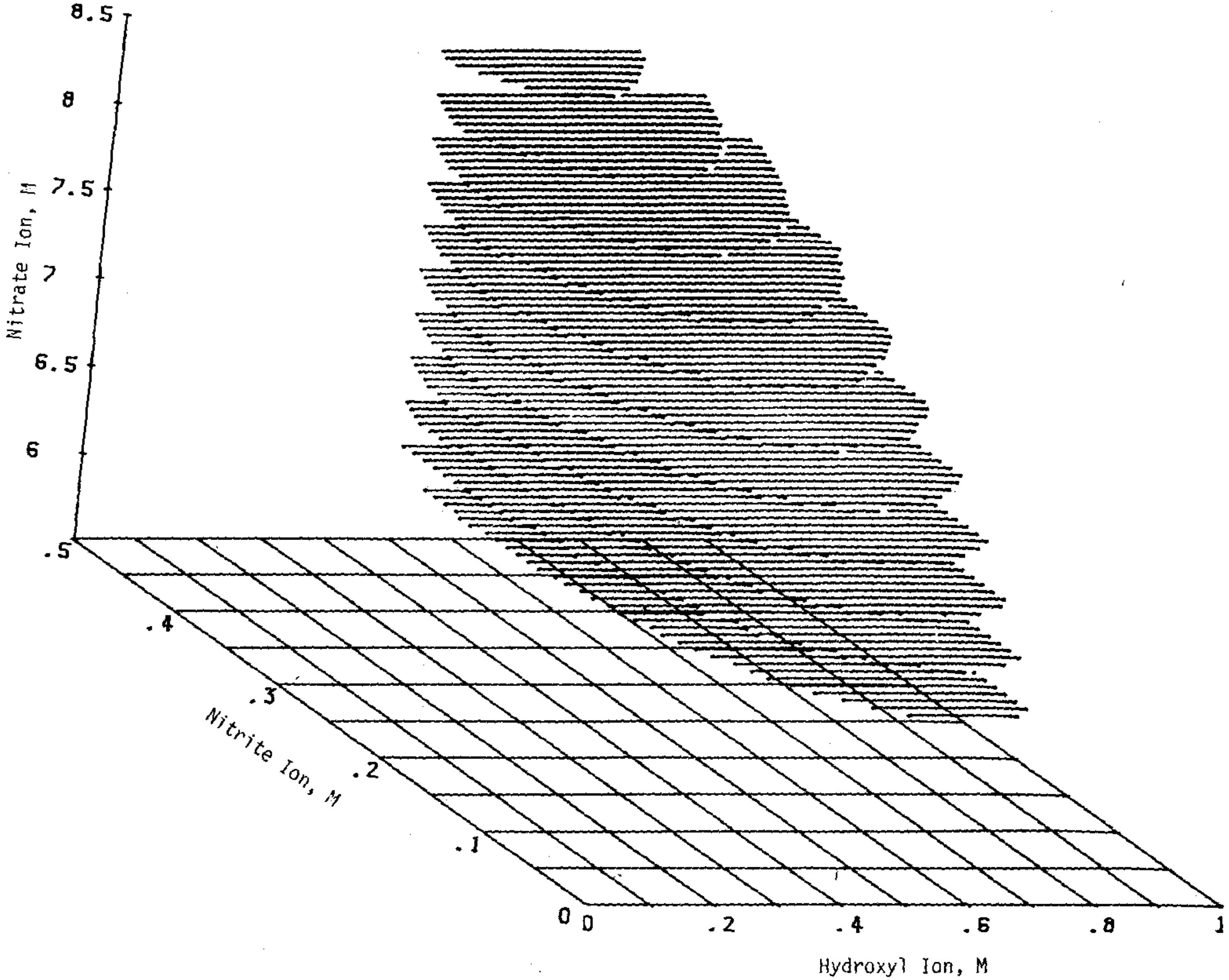

Figure 10. Superposition of Crack Initiation and Crack Propagation Equations - 50°C

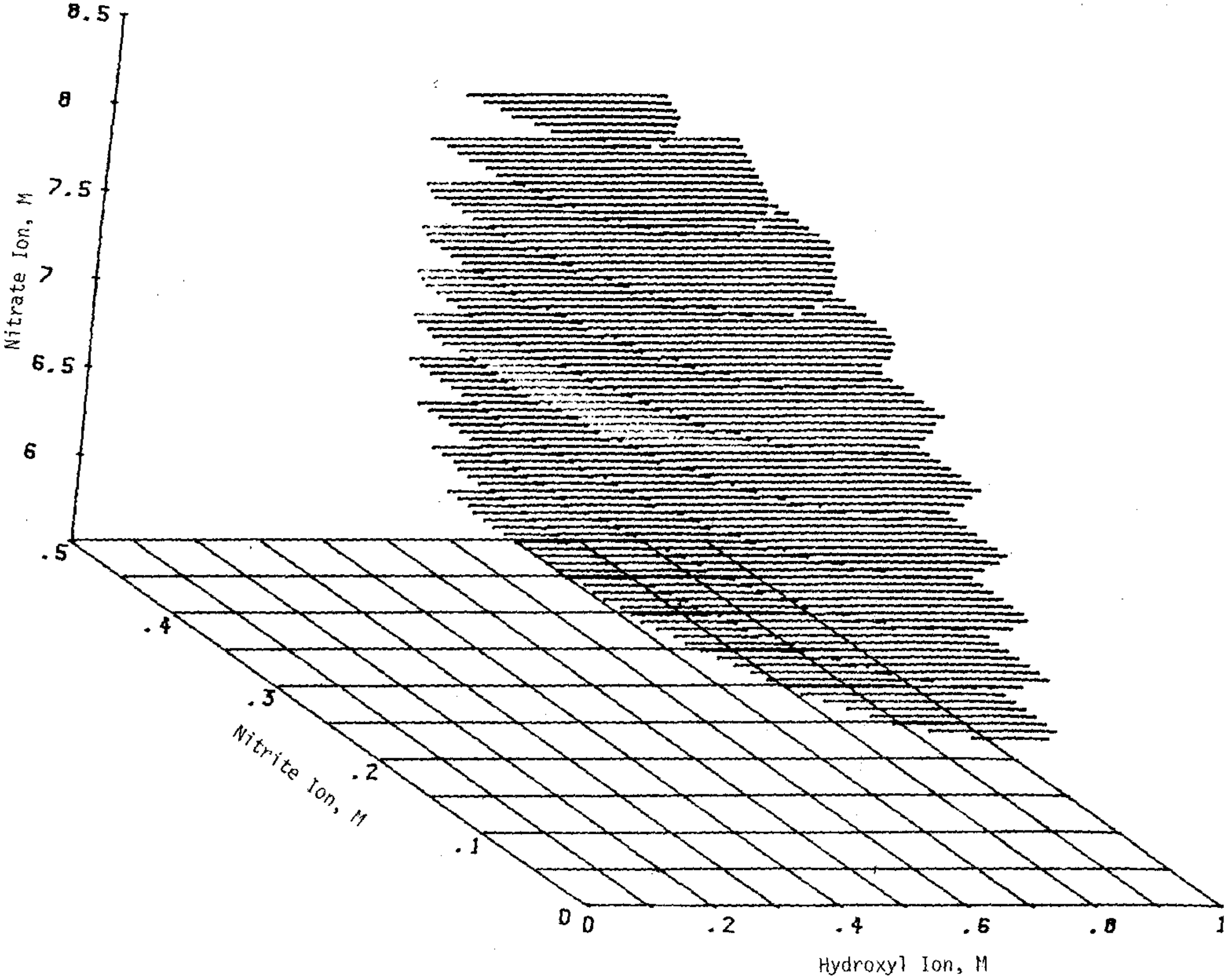

Figure 11. **Superposition of Crack Initiation and Crack Propagation Equations - 55°C**

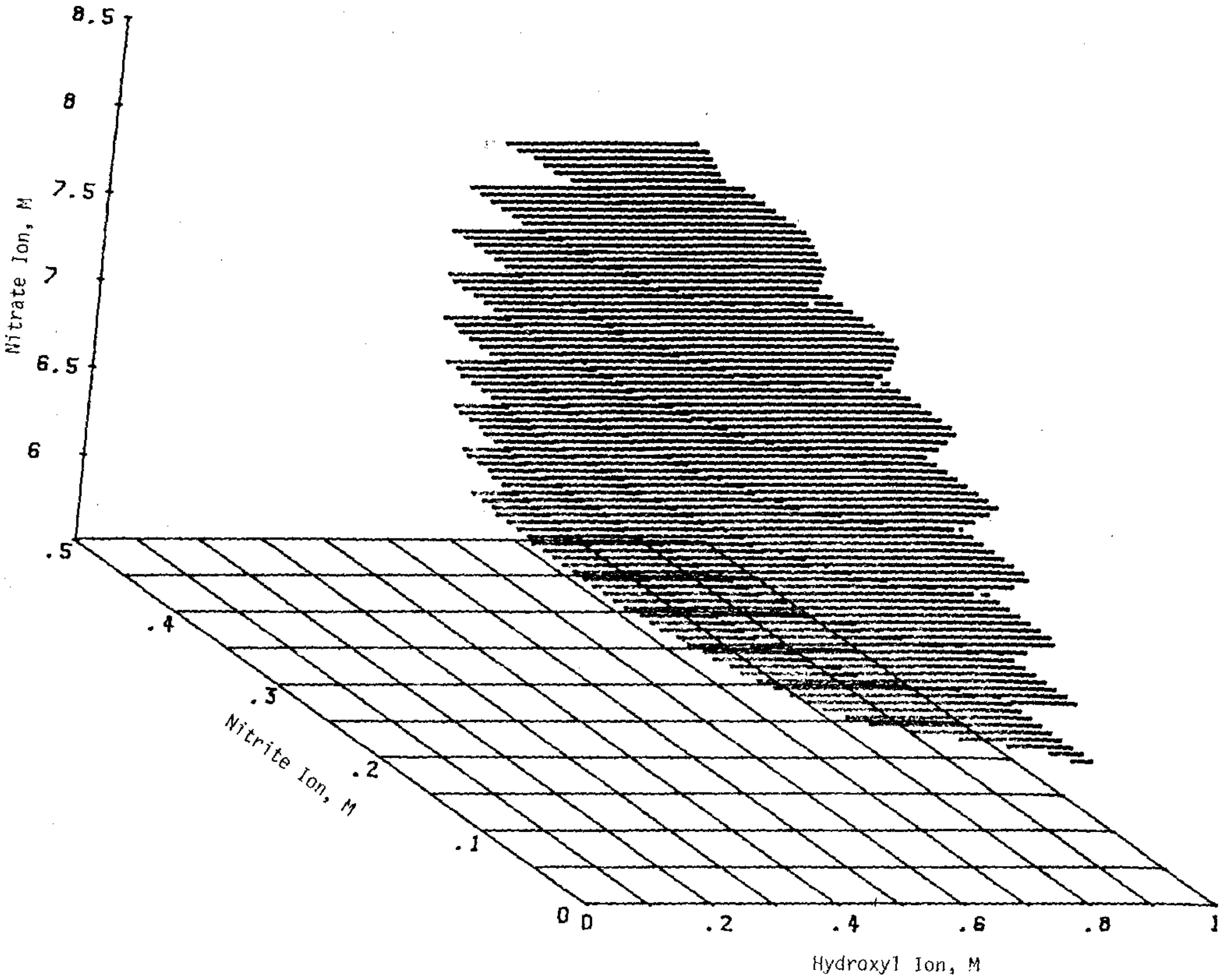

Figure 12. Superposition of Crack Initiation and Crack Propagation Equations - 60°C

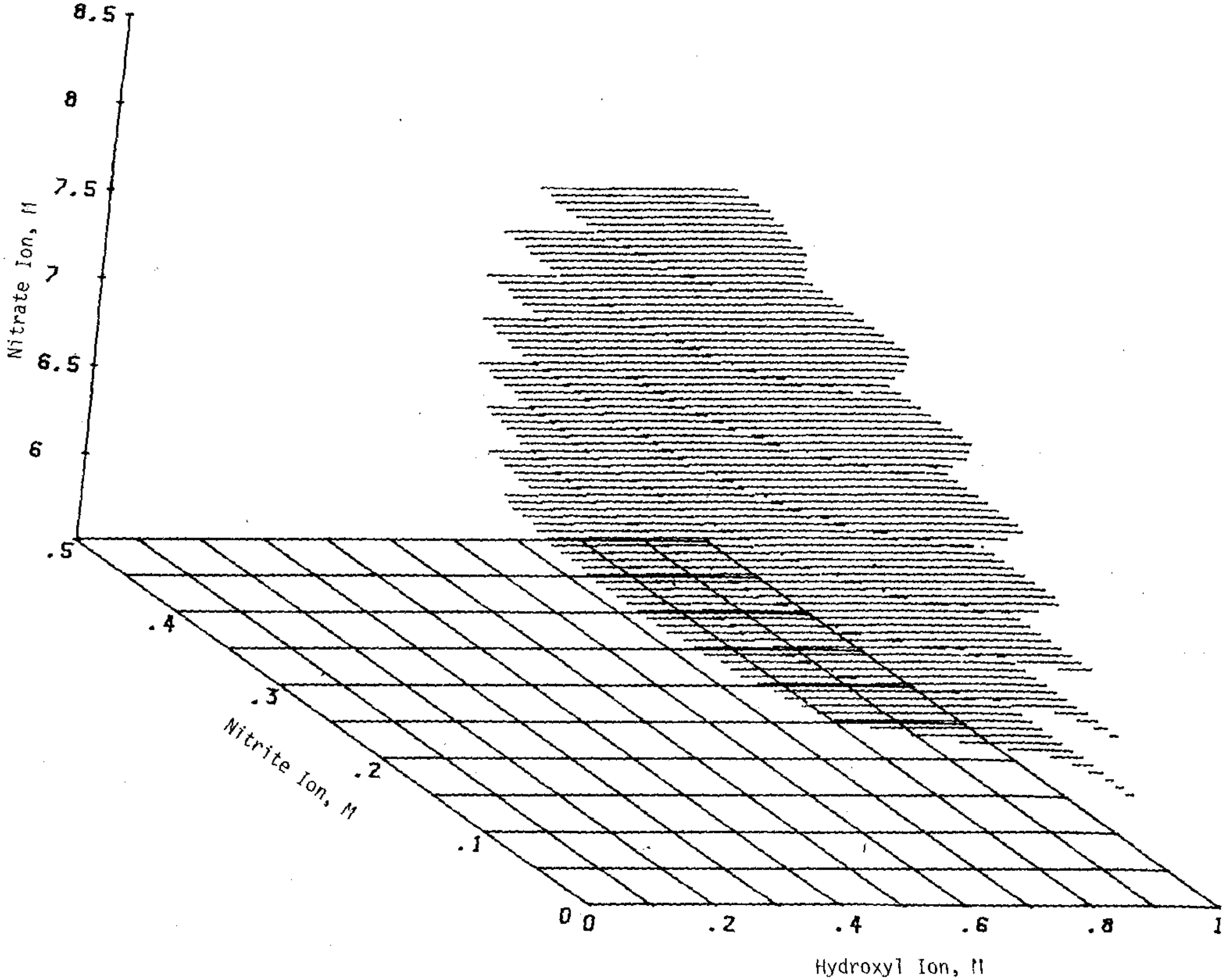

Figure 13. Superposition of Crack Initiation and Crack Propagation Equations - 65°C

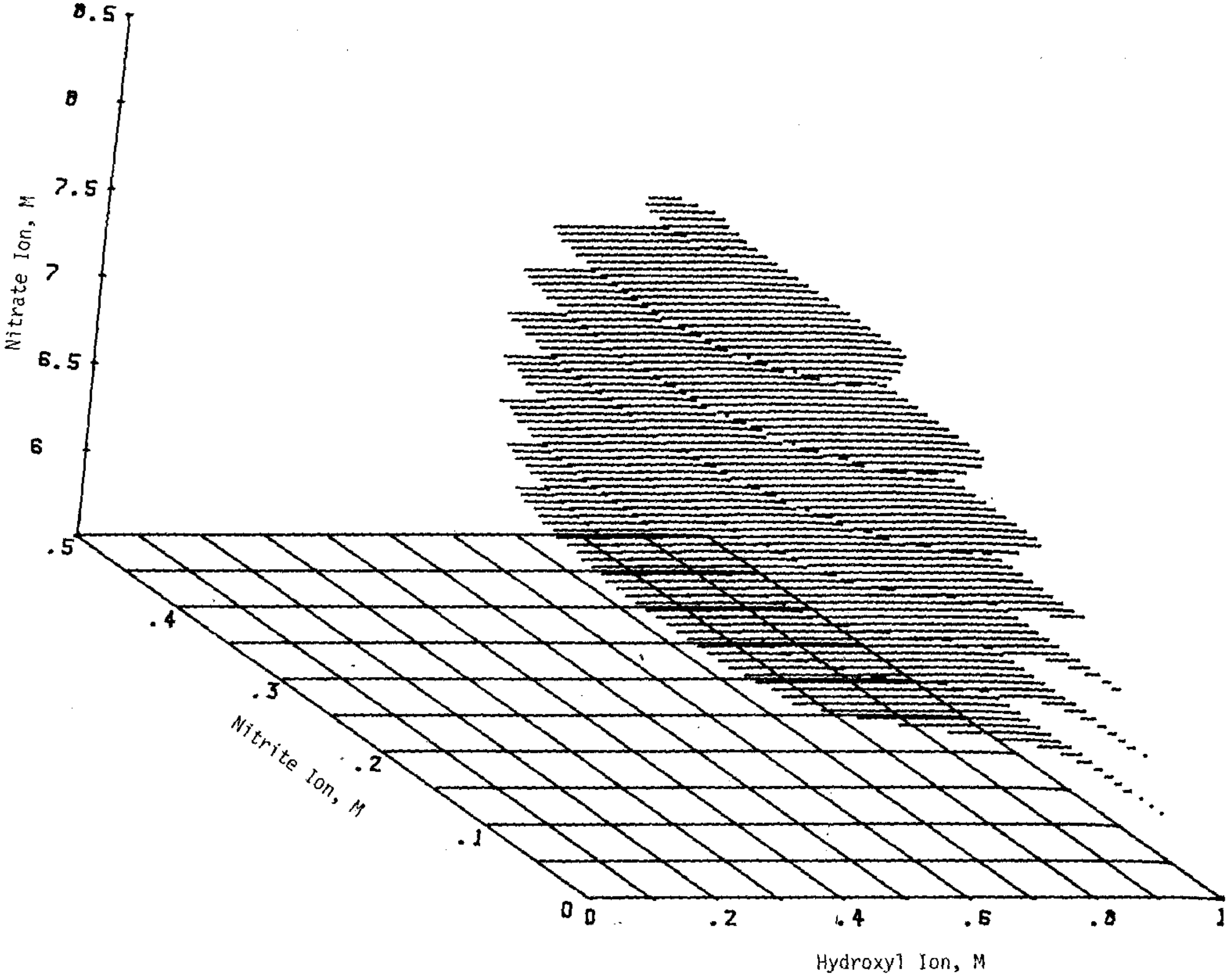

Figure 14. Superposition of Crack Initiation and Crack Propagation Equations - 70°C

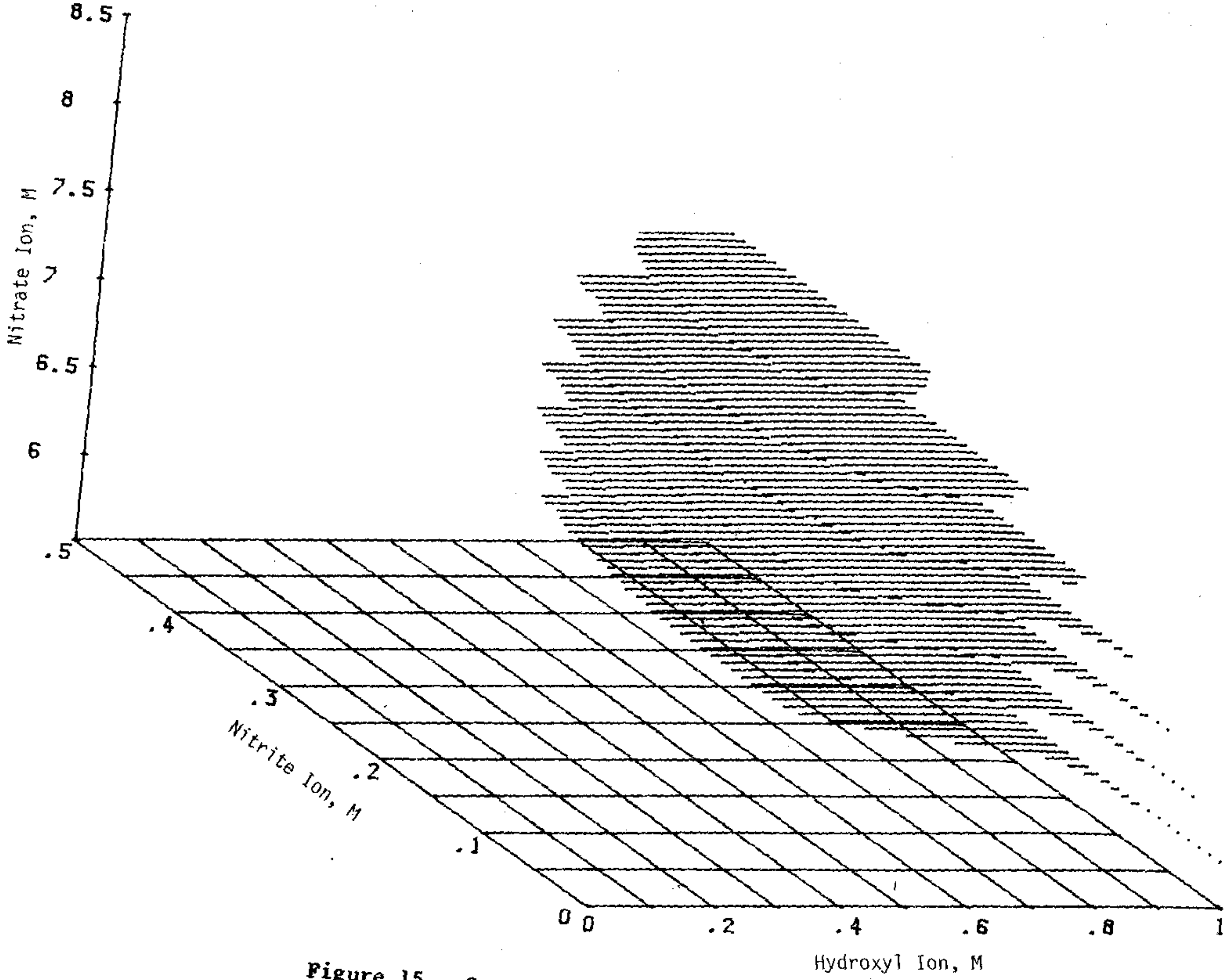

Figure 15. Superposition of Crack Initiation and Crack Propagation Equations - 75°C

FIGURE CAPTIONS

Figure 1. High-Heat Waste Processing in Tank Farm

Figure 2. Type I High-Heat Waste Tank, 0.75 Million Gallons

Figure 3. Type II High-Heat Waste Tank, 1.0 Million Gallons

Figure 4. Type III High-Heat Waste Tank, 1.3 Million Gallons

Figure 5. Effect of Hydroxyl Ion Concentration on Steel Strength

Figure 6. Intergranular Cracking in Constant Potential Tension Test

Figure 7. Superposition of Crack Initiation and Crack Propagation Equations - 35°C

Figure 8. Superposition of Crack Initiation and Crack Propagation Equations - 40°C

Figure 9. Superposition of Crack Initiation and Crack Propagation Equations - 45°C

Figure 10. Superposition of Crack Initiation and Crack Propagation Equations - 50°C

Figure 11. Superposition of Crack Initiation and Crack Propagation Equations - 55°C

Figure 12. Superposition of Crack Initiation and Crack Propagation Equations - 60°C

Figure 13. Superposition of Crack Initiation and Crack Propagation Equations - 65°C

Figure 14. Superposition of Crack Initiation and Crack Propagation Equations - 70°C

Figure 15. Superposition of Crack Initiation and Crack Propagation Equations - 75°C