Prediction of Extent of Cracking in BWR Core Internals using GE PLEDGE Code

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" The understanding of the root cause of cracking is a necessary pre-condition for the correct application of mechanistically-based crack prediction models. The limits and the sensitivity characteristics of a predictive model are essential aspects concerning the justification and applicability of a model in terms of decisions of the authority"

"----- serious doubts on the exclusive IASCC-hypothesis in the case of KKMs core shroud"

" ----- Absence of a well-grounded root cause analysis and the unconservative crack growth predictions raised serious doubts whether the problem was sufficiently understood and predictable"

J. Noggerath & G. Prantl

ICGEAC / IASCC Meeting Toronto, 1996

Outline

1. Crack Propagation Model for "Deep" Cracks
   in Unirradiated Components

   - Basis of Model
   - Validation vs. Laboratory Data
   - Extension to cover BWR Components
     Definition of System
     Treatment of "Crack Initiation"

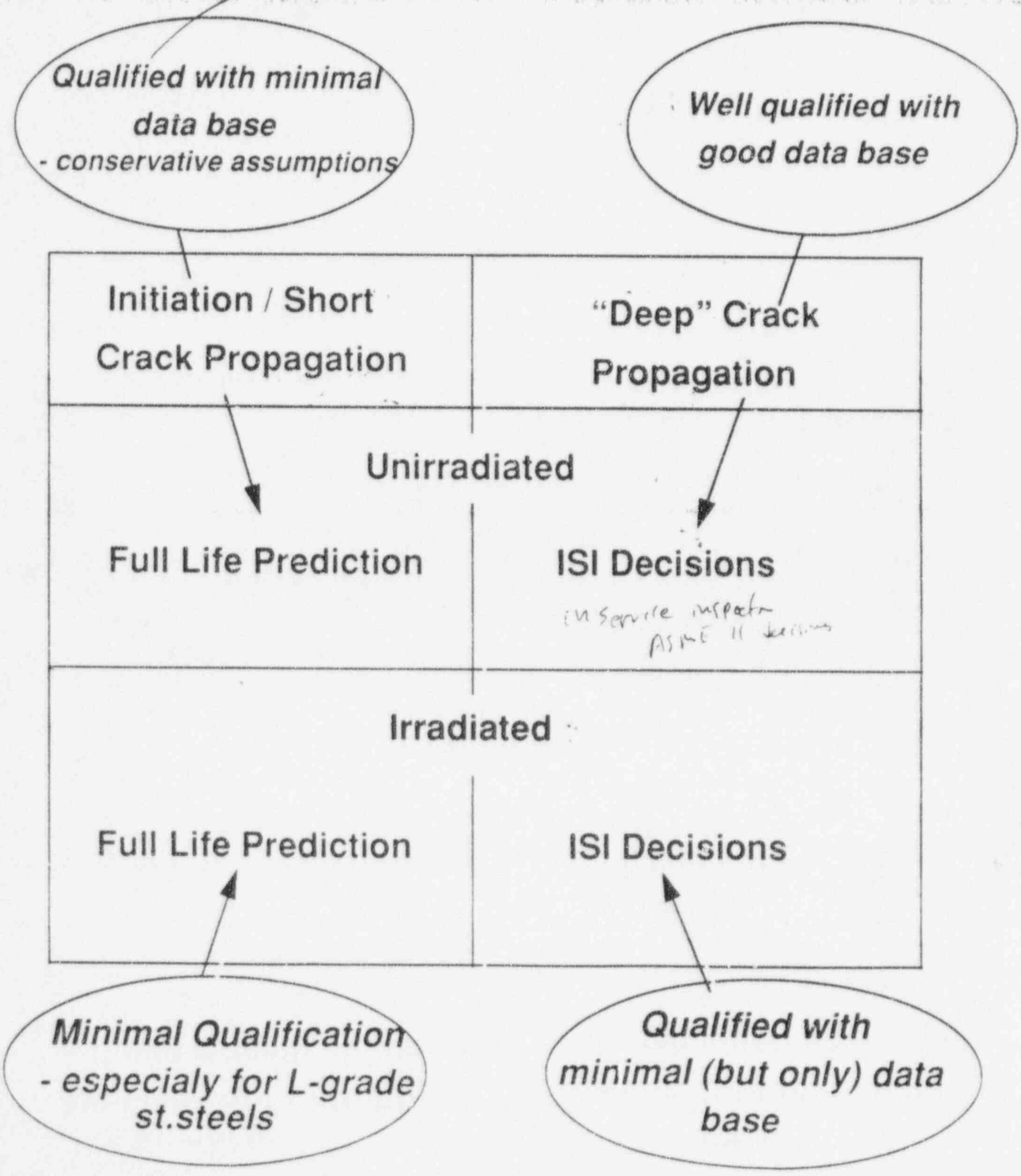
2. Modification of Model to cover Irradiated Components

3. Prediction of Cracking in BWR-4 #1 Core Shroud

4. Remaining Uncertainties

5. Conclusions

IGSCC / IASCC of 304 /316 Stainless Steel BWR Components by PLEDGE Code



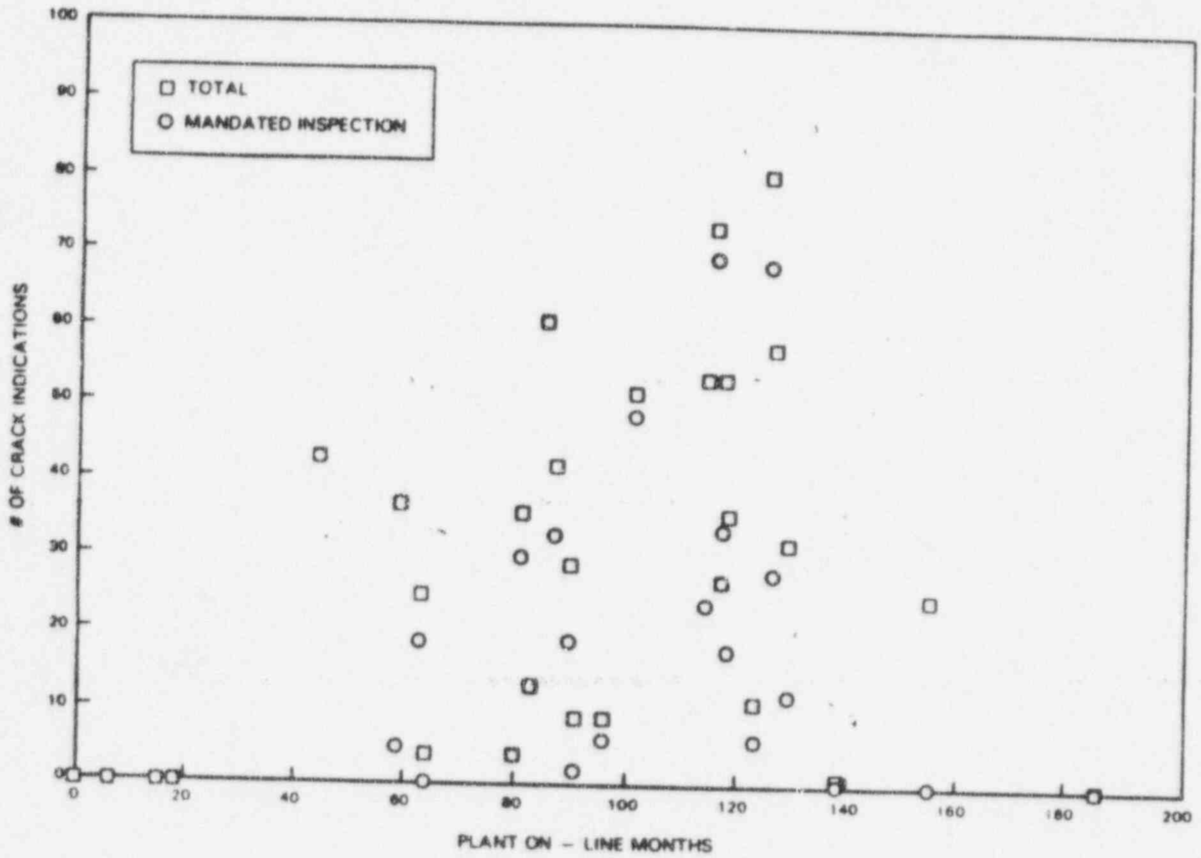
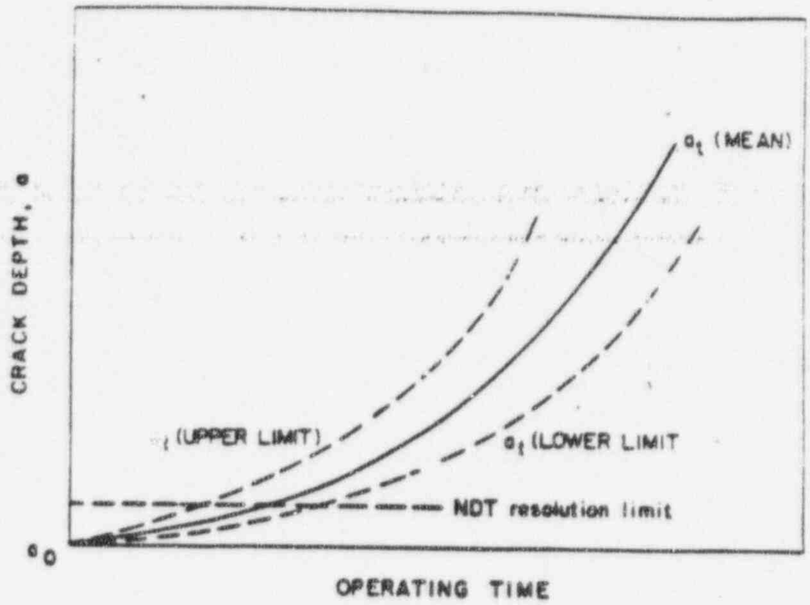


Figure 1. Number of cracking incidents of IGSCC in BWR stainless steel, piping in 1970's as a function of operating time(1).

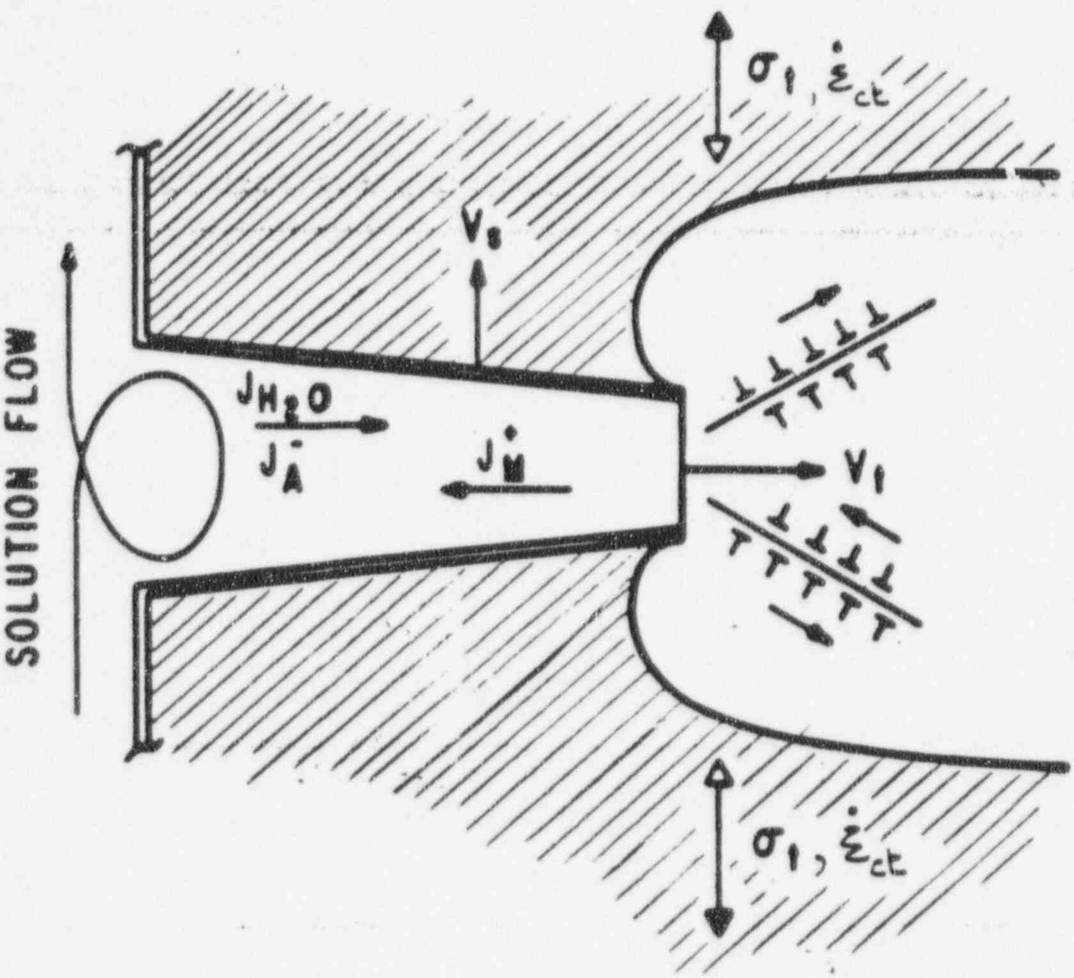
HISTORICAL INCIDENCE RATE NOT NECESSARILY A GOOD INDICATOR OF FUTURE PERFORMANCE



a_t = f [Material, Stress, Environment]

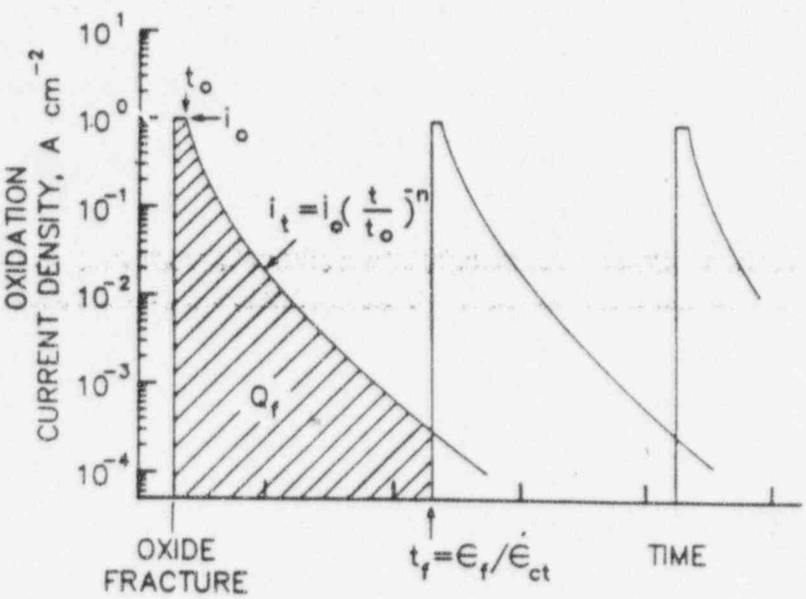
Chromium	Primary	Oxidizing Species
Silicon	Static	Corrosion Potential
Sulphur	Dynamic	Anionic Species
Phosphorus	Residual	Type
Nickel	Crack Depth	Activity
Carbon	Neutron Fluence	Flow Rate
%CW		Temperature
Heat Input		Neutron/γ flux
Neutron fluence		Crack Depth

- **EAC IS A MULTIVARIANT PROBLEM**
- **THEREFORE, UNDERSTAND AND QUANTIFY THE RATE DETERMINING PHENOMENA**



$$V_t = A\dot{\varepsilon}^n$$

- USE SLIP-DISSOLUTION MECHANISM AS WORKING HYPOTHESIS
- QUANTIFY THE FOLLOWING FUNDAMENTAL PHENOMENA
  - OXIDATION RATES AT CRACK TIP
  - MASS-TRANSPORT RATES WITHIN CRACK
  - CRACK TIP STRAIN RATE



$$V = \frac{da}{dt}\ ; \quad \overline{V}_{av} = \frac{M}{Z\zeta F}\cdot\frac{Q_f}{t_f}$$

FOR HIGH $\dot{\epsilon}_{ct}$ AND/OR LONG t_o :

$$\overline{V}_{av} = \frac{M}{Z\zeta F}\cdot i_o$$

FOR LOW $\dot{\epsilon}_{ct}$ AND/OR SHORT t_o :

$$\overline{V}_{av} = \frac{M}{Z\zeta F}\ \frac{i_o t_o^n}{(1-n)\epsilon_f^n}\ \dot{\epsilon}_{ct}^n = f(n)\,\dot{\epsilon}_{ct}^n$$

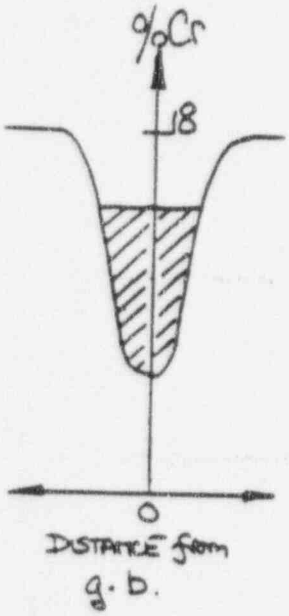
Define / Measure following " fundamental parameters

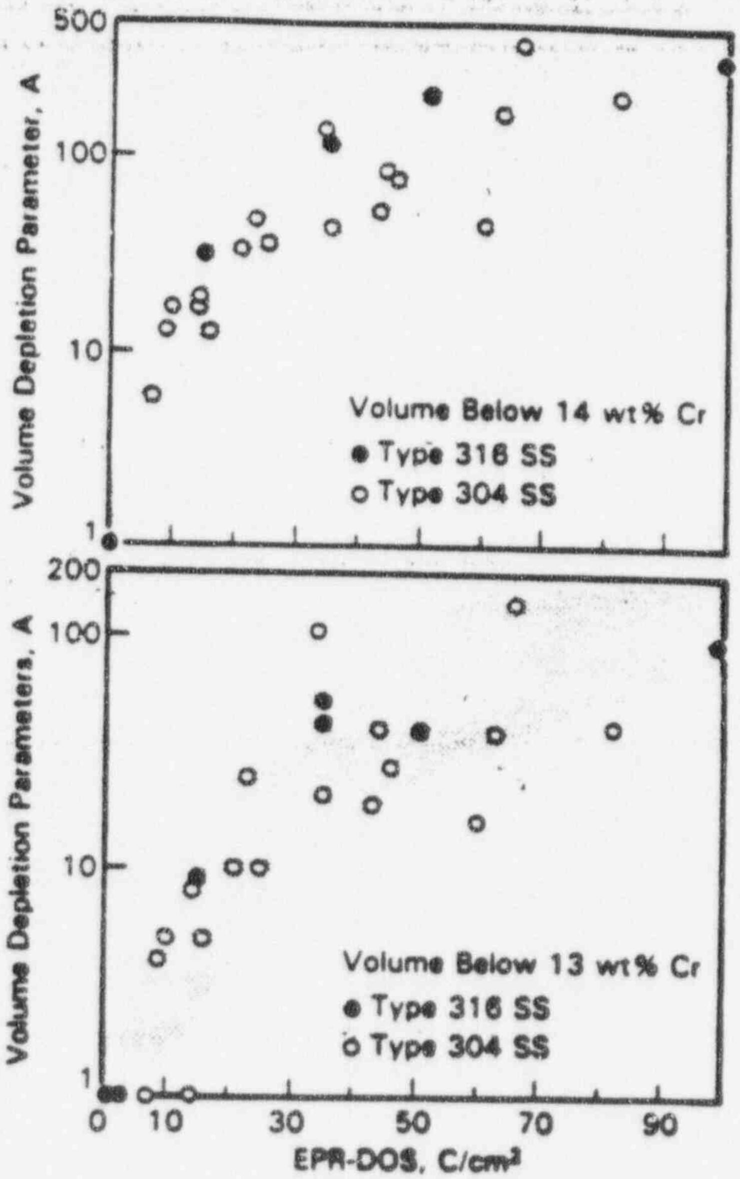
- Crack tip material and environment conditions
- Crack tip oxidation rates on bared surface
- Crack tip strain rate

Define above conditions in terms of "engineering "parameters

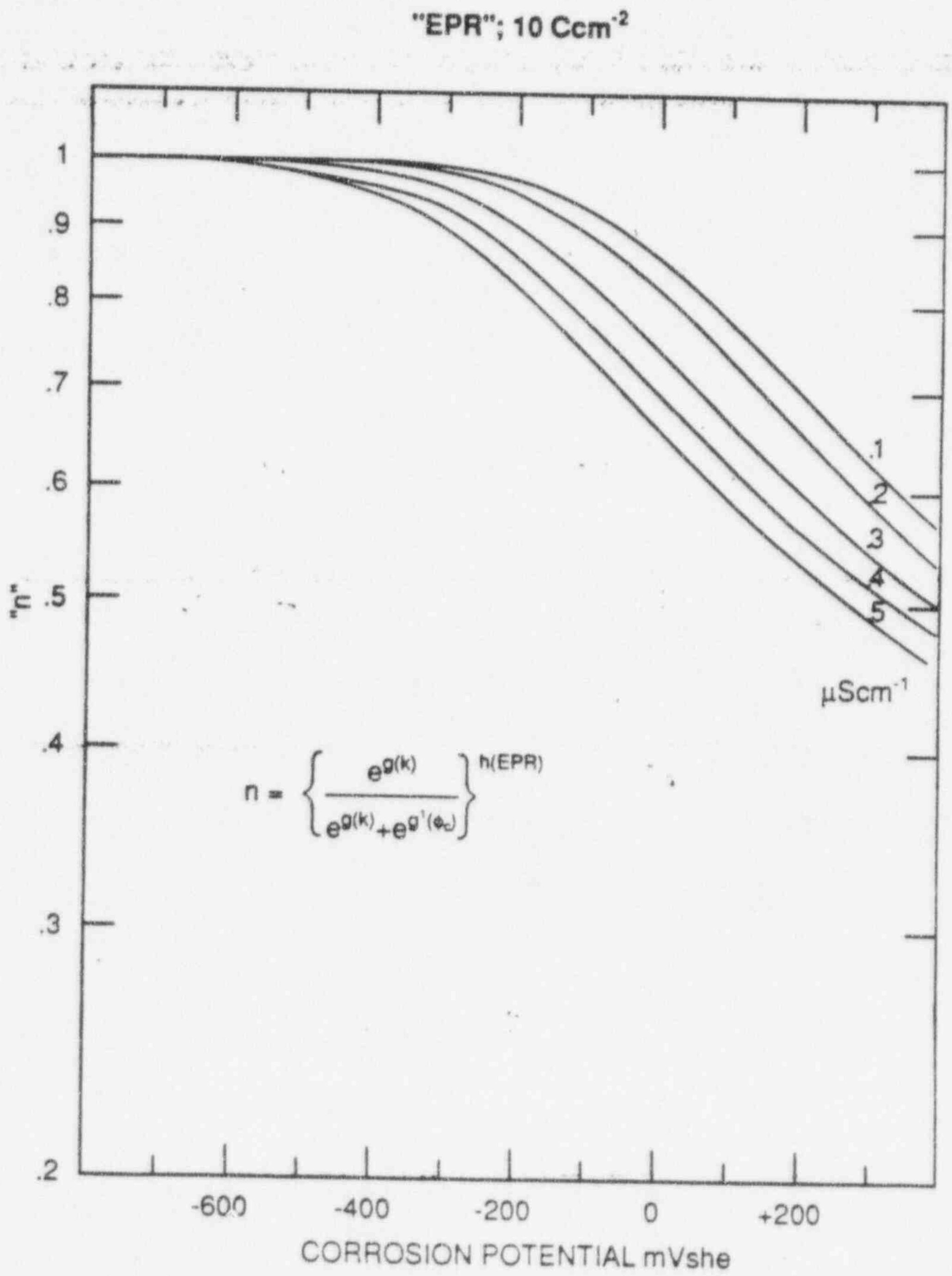
- Stress, stress intensity, (time dependence)
- Coolant Conductivity (anionic activity)
- Chromium gb Depletion (EPR)
- Corrosion Potential = f(H2,O2,H2O2,...)

10 Years Work !

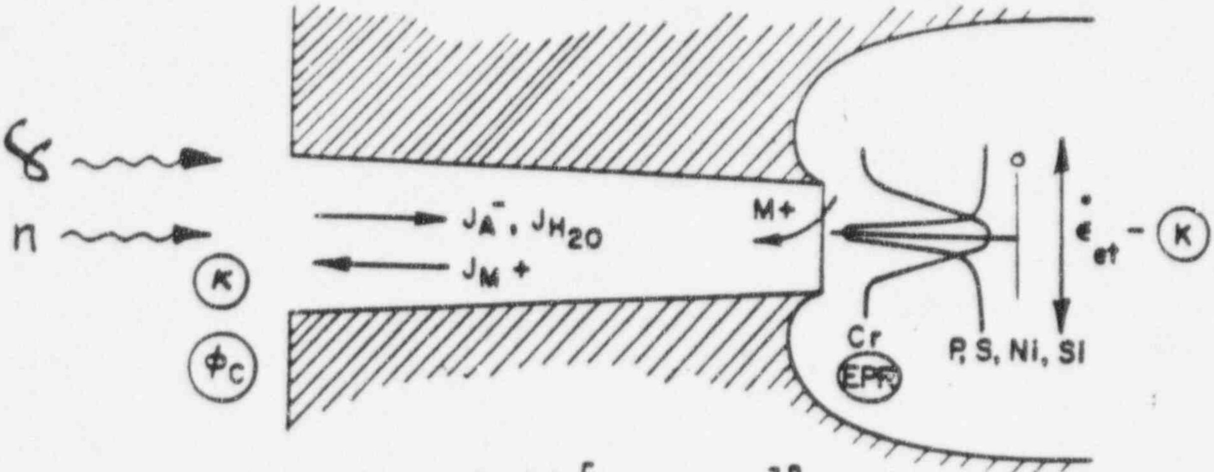




Relationship between the EPR value and the chromium depletion volume adjacent to sensitized grain boundaries of type 304 and 316 stainless steels.


"EPR"; 10 Ccm⁻²
1
.9
.8
.7
.6
.5
.4
.3
.2
"n"
.1
2
3
4
5
μScm⁻¹
$n = \left\{ \frac{e^{g(k)}}{e^{g(k)} + e^{g'(\phi_c)}} \right\}^{h(EPR)}$
-600
-400
-200
0
+200
CORROSION POTENTIAL mVshe

$$V_T = A\,\dot{\epsilon}_{ct}^{\,n}$$



$$V_T = 7.8 \times 10^{-3}\, n^{3.6} \left[6 \times 10^{-14} K^4 \right]^n$$

$$n = \left\{ \frac{e^{f(K)}}{e^{f(K)} + e^{f(\phi)_c}} \right\}^{f(EPR)}$$

Formulate Cracking Susceptibility in Terms of Fundamental Knowledge of Micromechanics, Microchemistry and Electrochemistry at Crack Tip

$$V_t = \frac{M}{z\rho F} \frac{i_o t_o^n}{(1-n)\varepsilon_f^n} \cdot \dot{\varepsilon}_{ct}^n$$

$$= 7.8\times10^{-3}\, n^{3.6}\, \dot{\varepsilon}_{ct}^n .$$

$$n = \left\{ \frac{e^{f(K)}}{e^{f(K)} + e^{f'(ECP)}} \right\}^{g(EPR)}$$

$$\dot{\varepsilon}_{ct} = 6\times10^{-14} K^4 \quad ; \quad \dot{\varepsilon}_{ct} = 5\times\dot{\varepsilon}_{app} \quad ; \quad \dot{\varepsilon} = f(\Delta K, R, \dot{\nu})$$

↓

V = f(stress intensity (K), conductivity (κ), corrosion potential (ECP), grain boundary sensitization (EPR).

How Good are the Predictions ?

- Compare with well-controlled crack propagation data

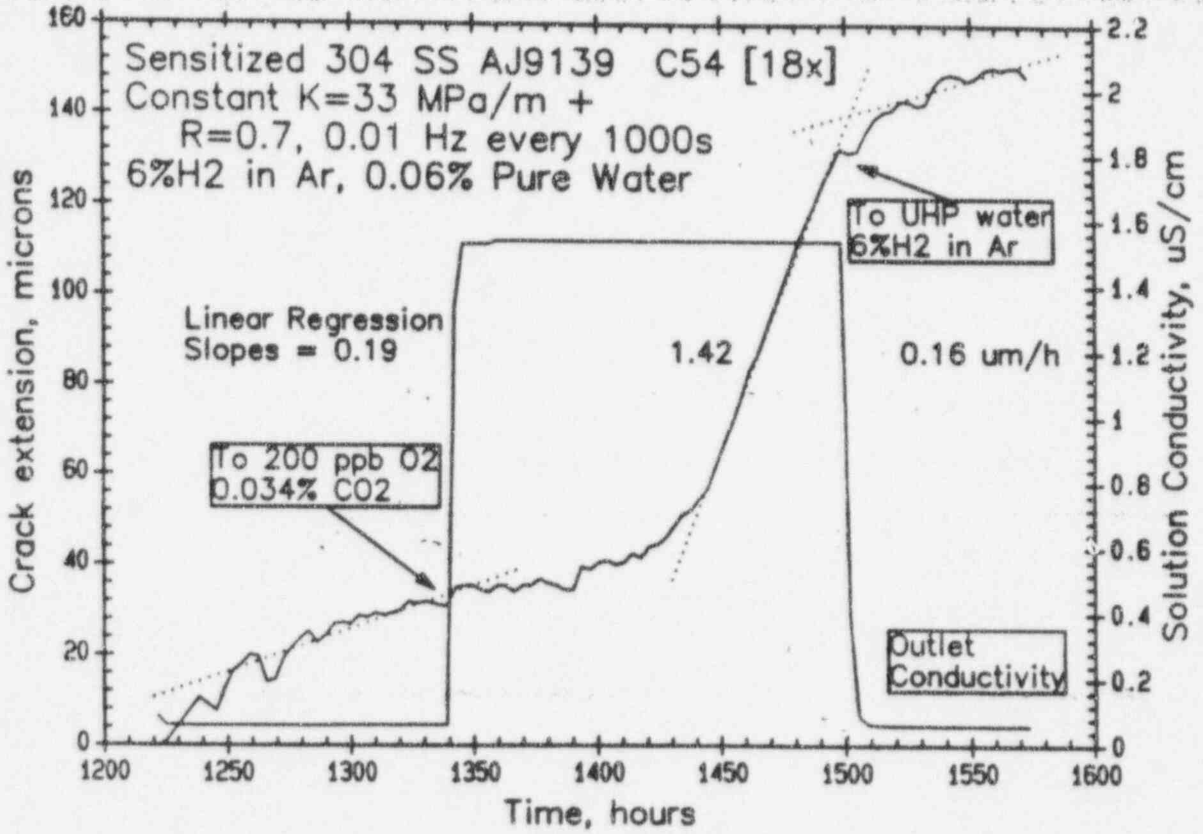
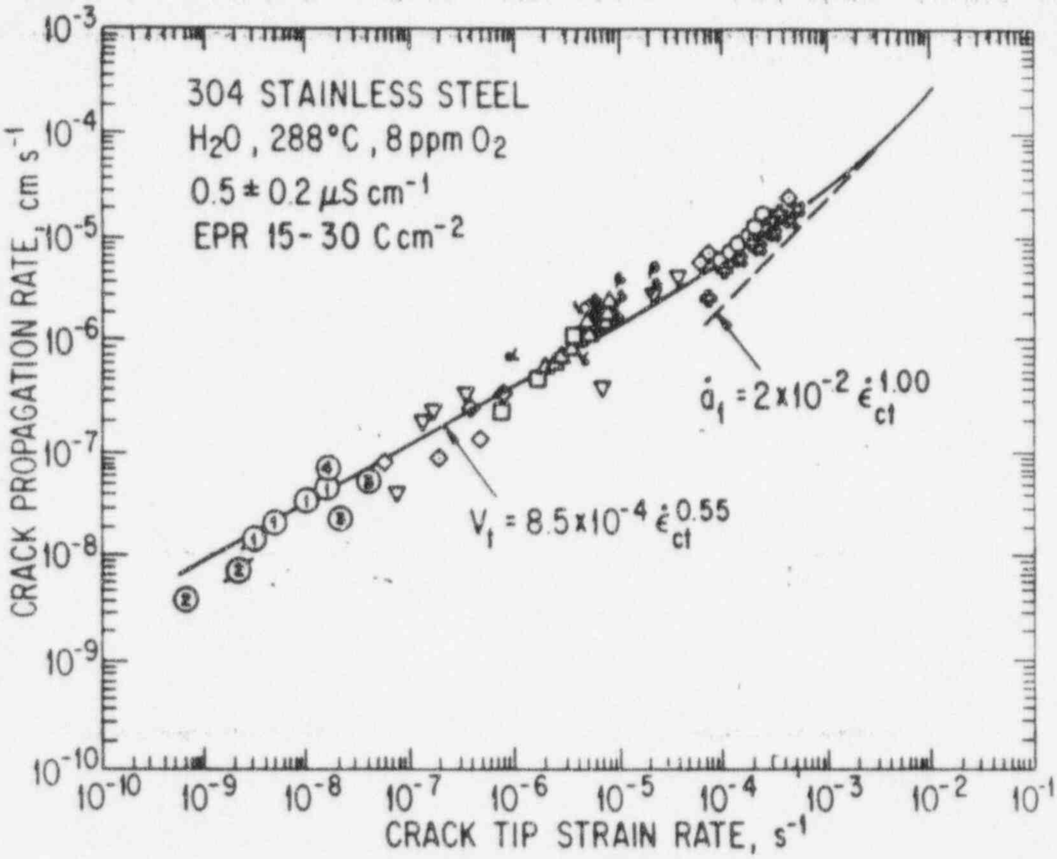
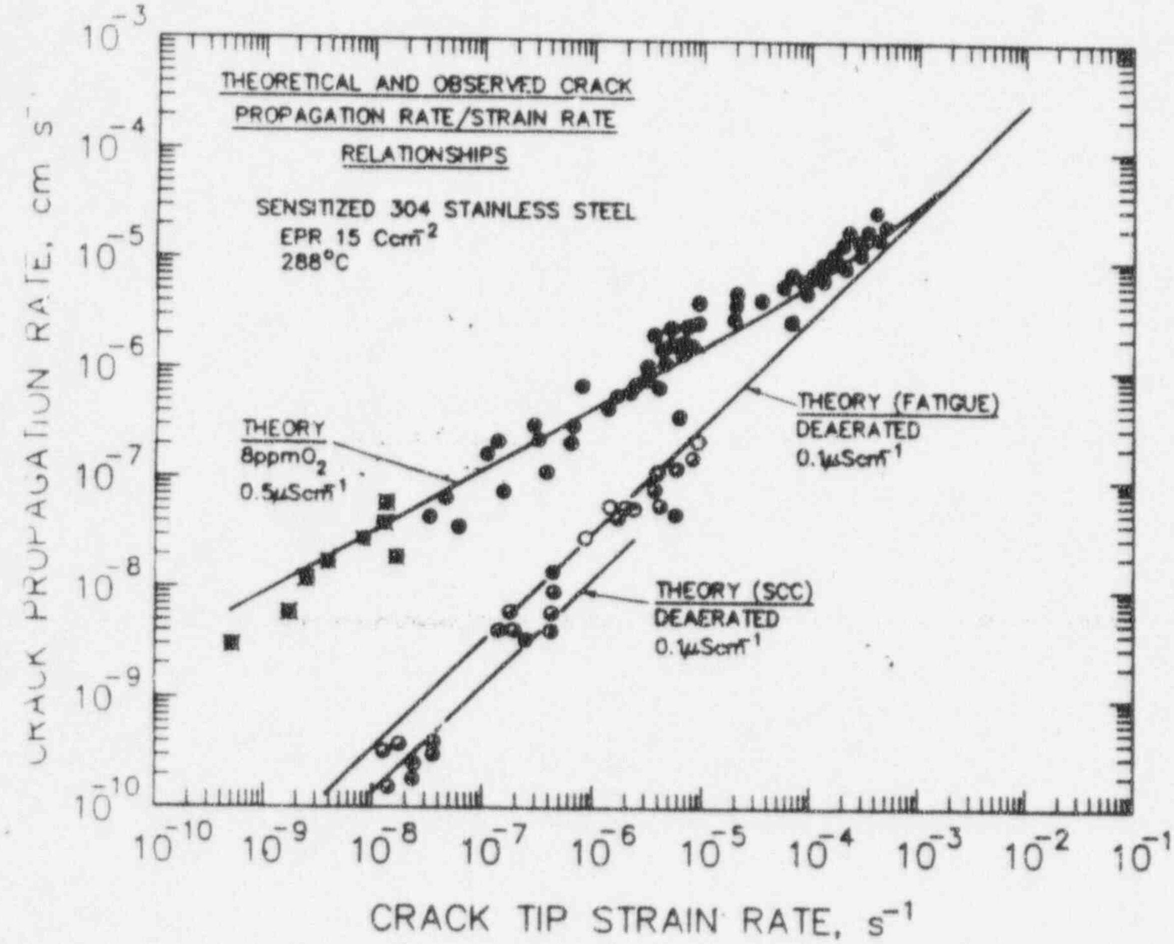


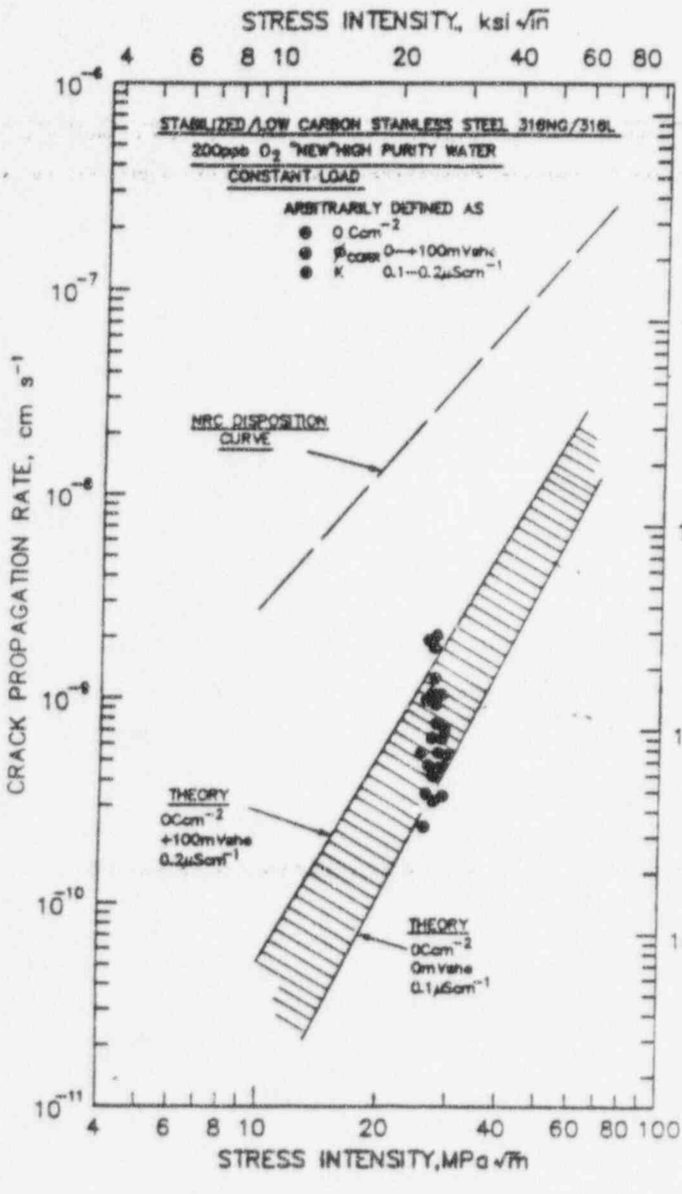
Figure 29. Illustration of crack following capability with reversing dc potential technique, where changes in cracking susceptibility due to controlled changes in loading mode and/or water chemistry may be unambiguously defined. The symbols represent data from different laboratories.

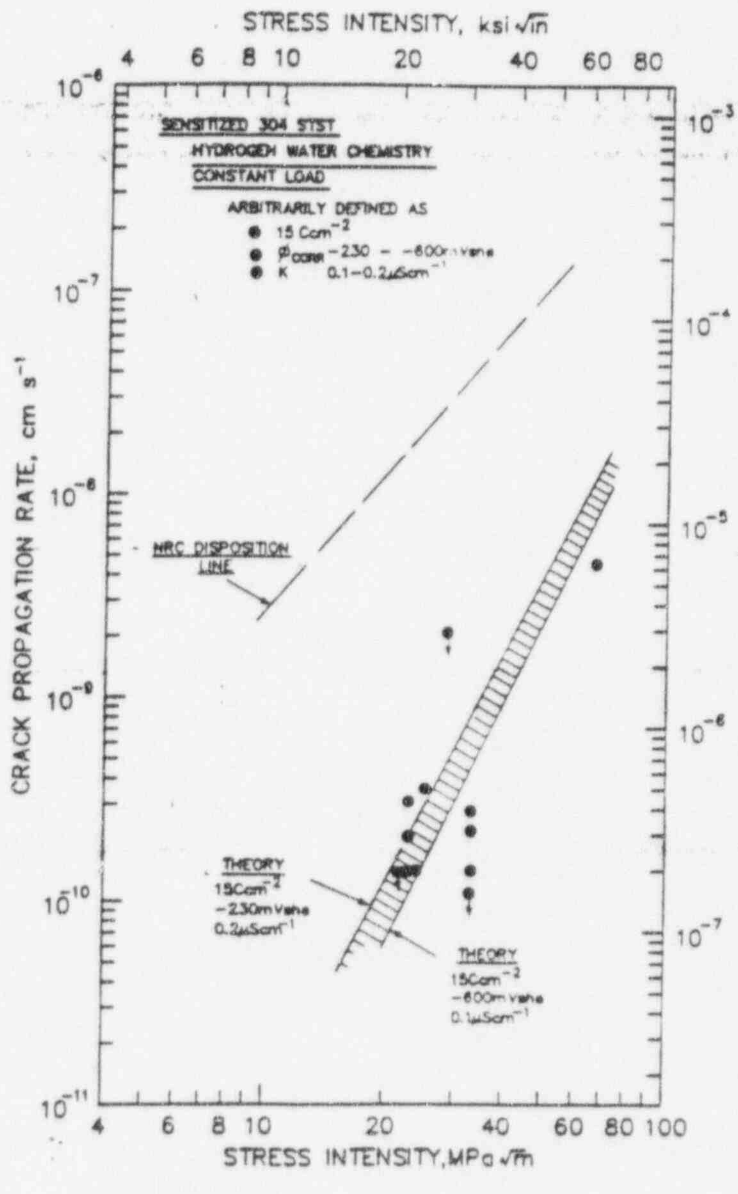


Predicted and observed crack propagation rate/crack tip strain rate relationships for sensitized type 304 stainless steel in 8 ppm oxygenated, $0.5 \mu Scm^{-1}$ purity water at 288°C.



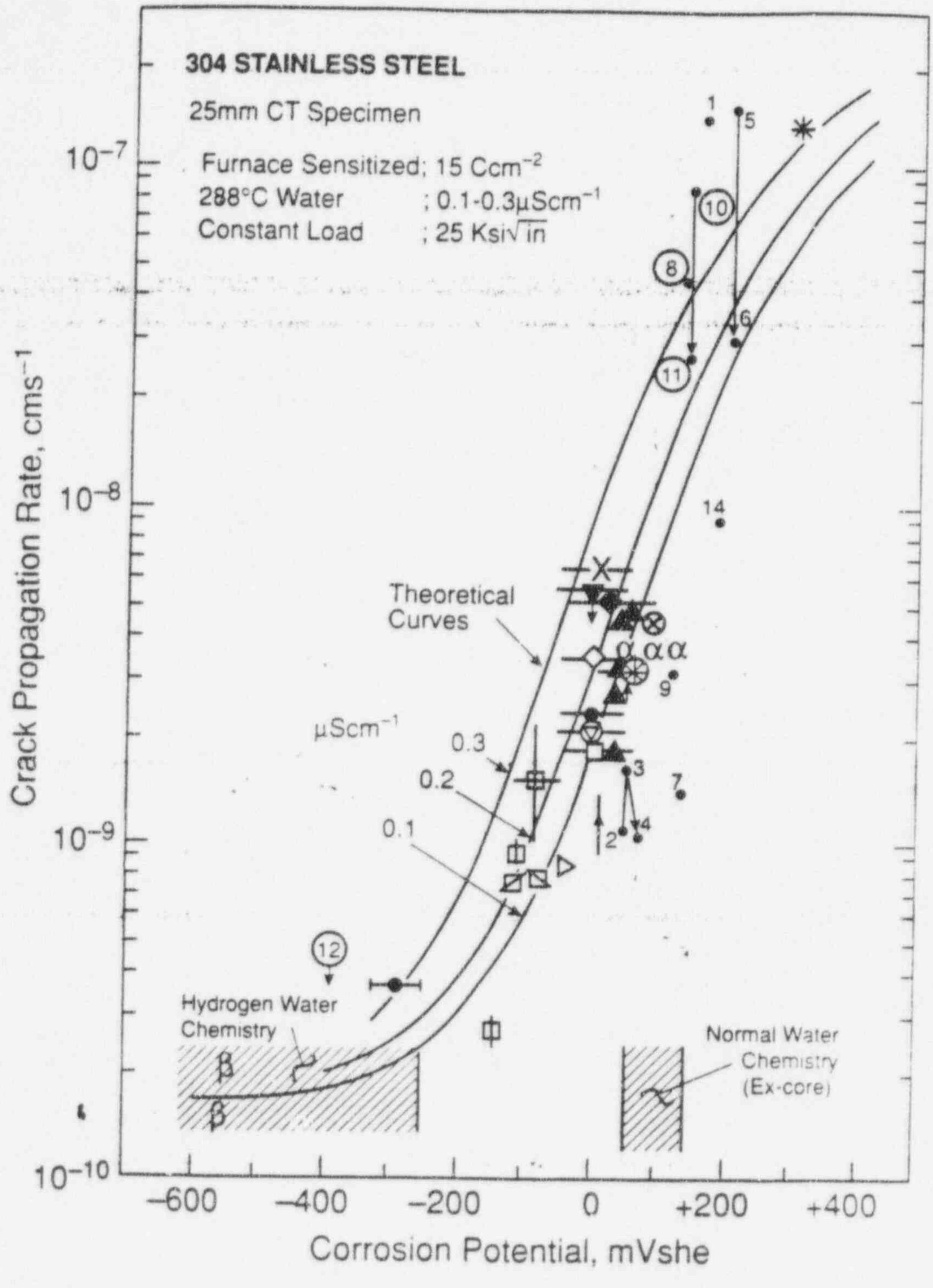
Predicted and observed crack propagation rate/crack tip strain rate relationships for stainless steels in a variety of material/environment systems.





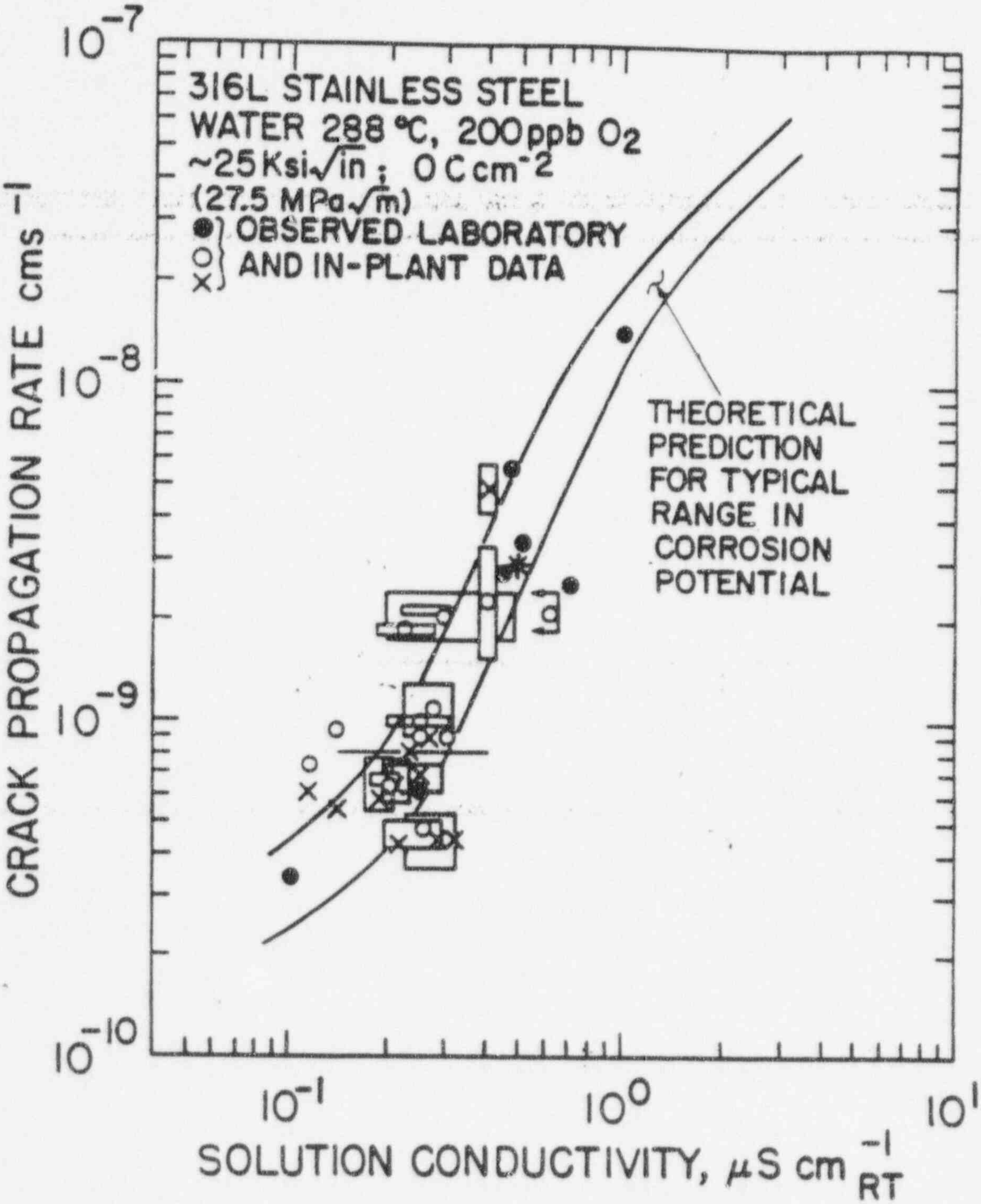
EFFECT OF MATERIAL AND ENVIRONMENTAL CHANGES ON CRACK PROPAGATION RATE/ STRESS INTENSITY RELATIONSHIP CORRECTLY PREDICTED.

-RELEVANCE TO ISI DECISIONS



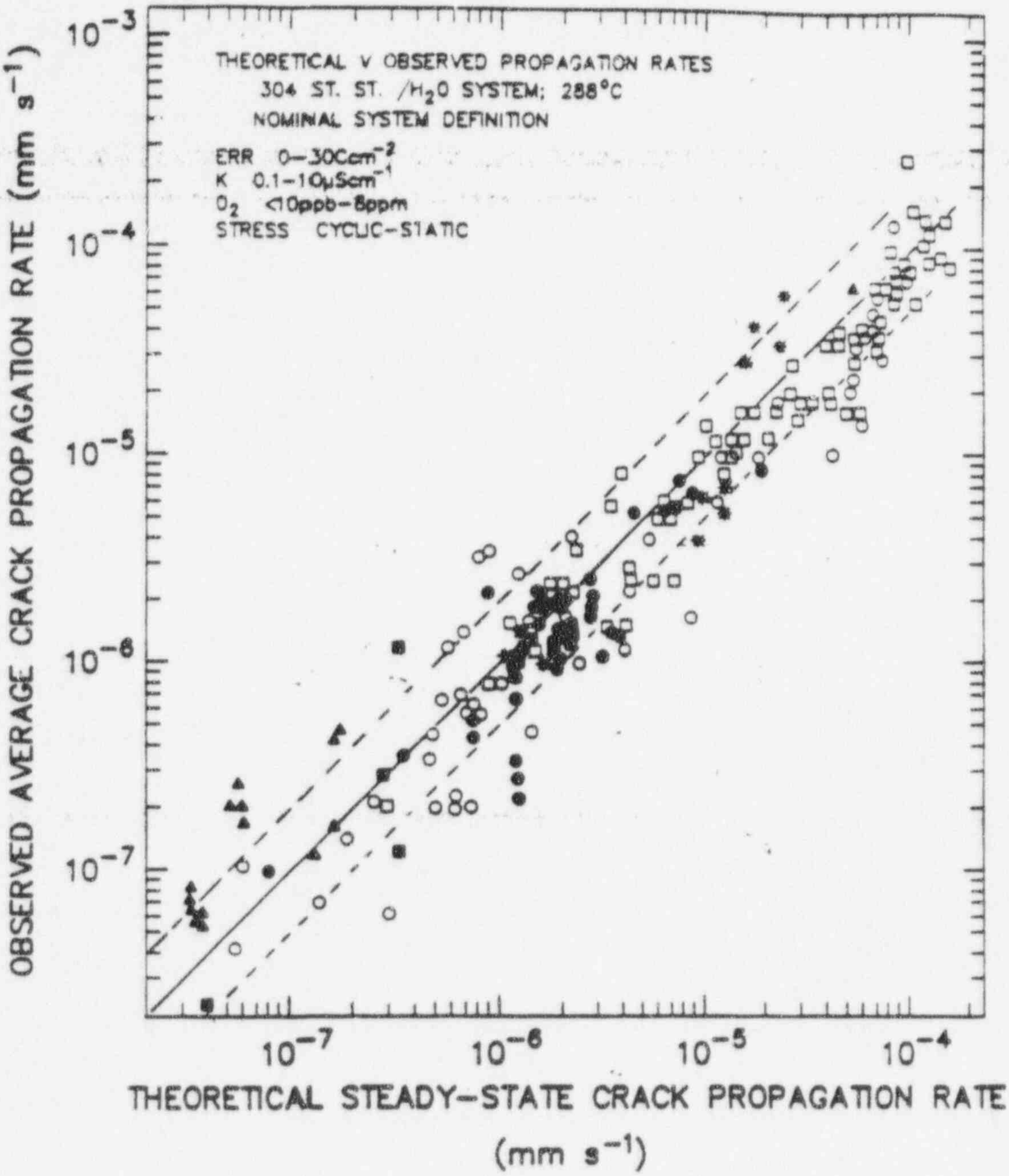
THEORY CORRECTLY PREDICTS THE STRONG DEPENDENCY BETWEEN CRACK PROPAGATION AND CORROSION POTENTIAL

-BASIS FOR SPECIFICATIONS FOR "HYDROGEN WATER CHEMISTRY"



THEORY CORRECTLY PREDICTS RELATIONSHIPS BETWEEN CRACK PROPAGATION AND SOLUTION-CONDUCTIVITY

-BASIS FOR COOLANT PURITY CONTROL



GOOD AGREEMENT BETWEEN OBSERVED AND THEORETICAL CRACK PROPAGATION RATES FOR 304/316 STAINLESS STEEL OVER WIDE RANGE OF MATERIAL, ENVIRONMENT AND STRESSING CONDITIONS

Extend Validated "Deep" Crack Propagation Model to ;

- Plant Components
    - System definition is the issue

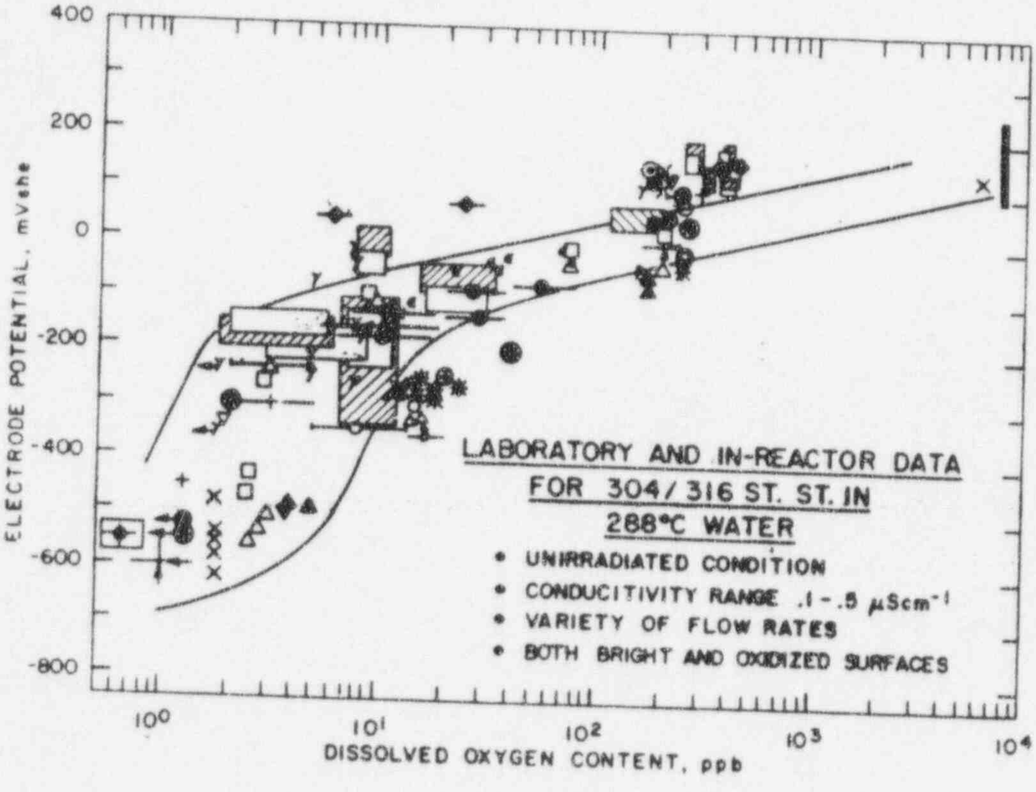
↓ resolution

In-reactor monitors
ECP models
Residual stress models
Water chemistry models

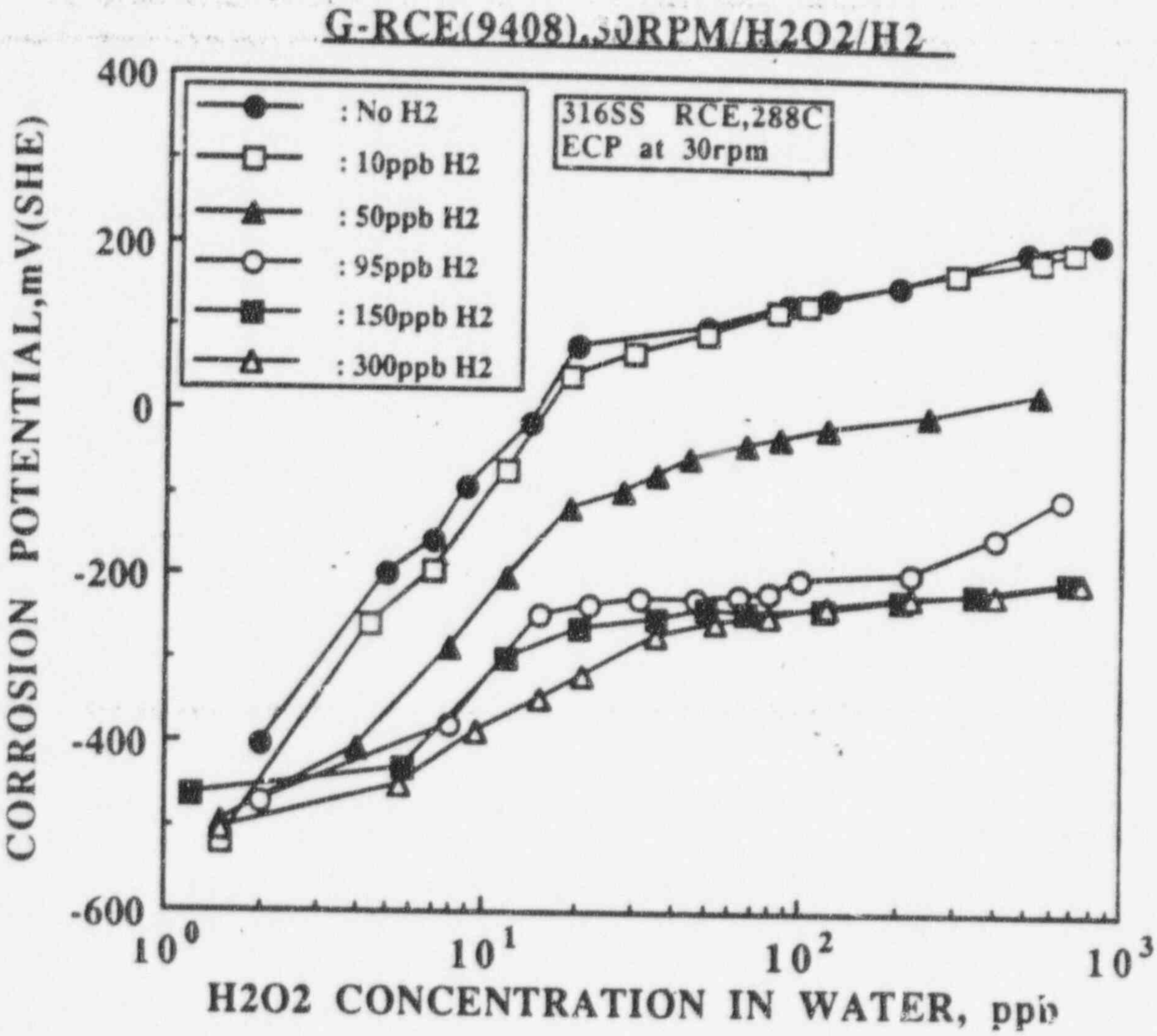
- Crack Initiation
    - Treatment of pitting, IGA and growth of very shallow cracks is the issue

↓ resolution

use concept of an initial "intrinsic" defect

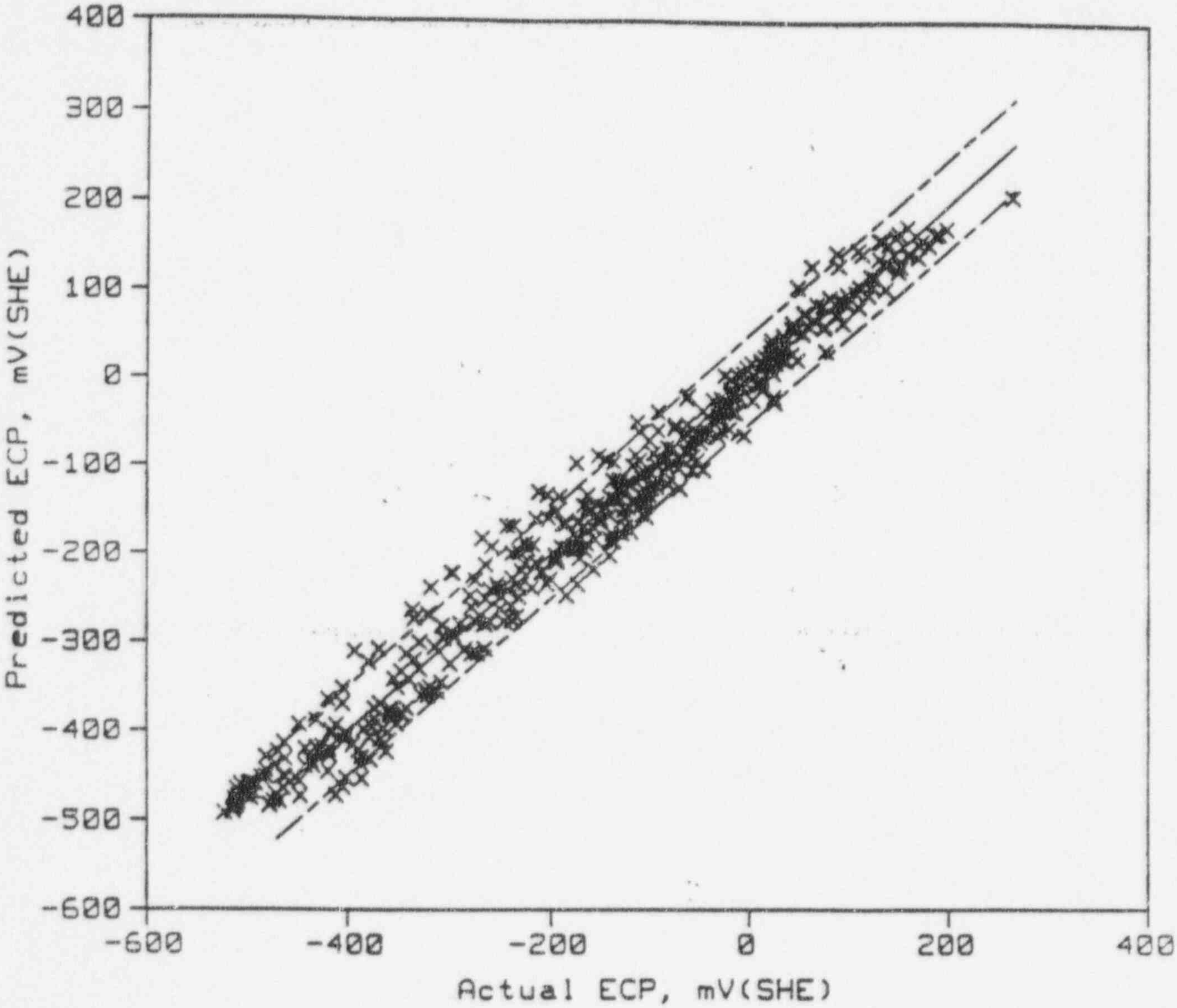


Corrosion potentials for type 304/316 stainless steels in 288°C water observed in various laboratory and reactor experiments, as a function of measured dissolved oxygen.

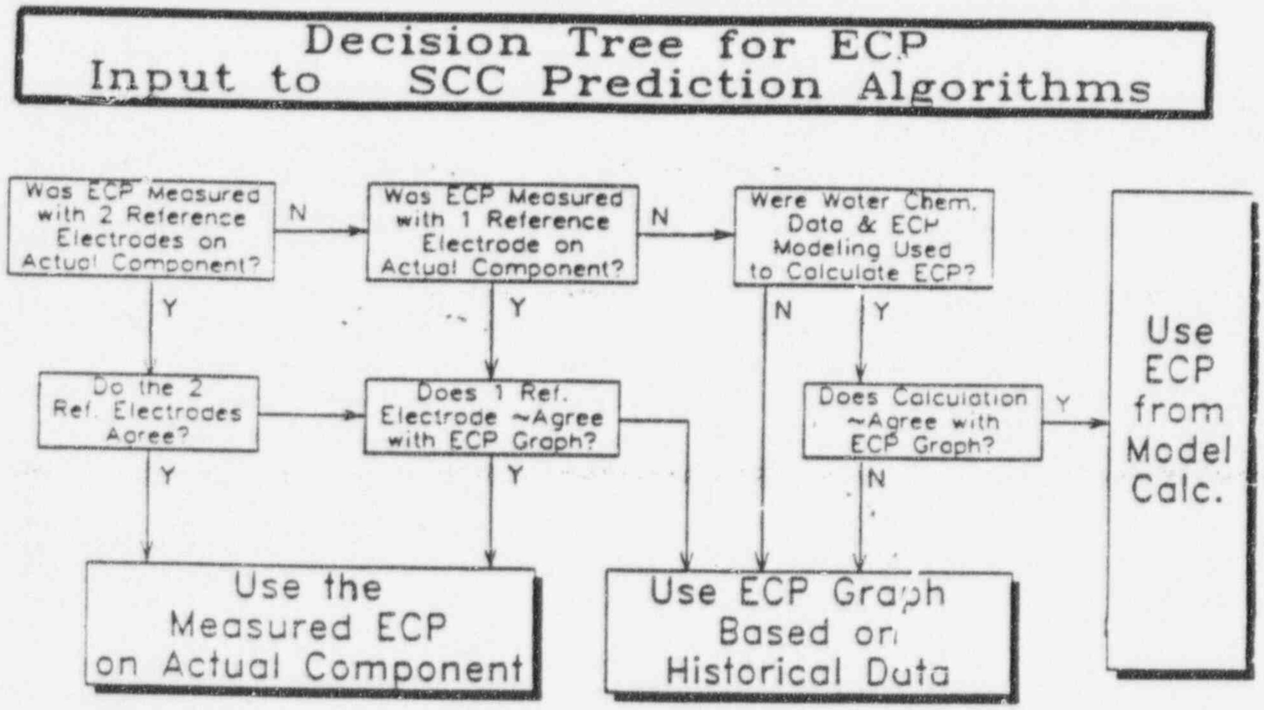


Corrosion potential of type 316 stainless steel in 288°C water (containing <1.0 ppb O_2) as a function of dissolved H_2O_2 and H_2.

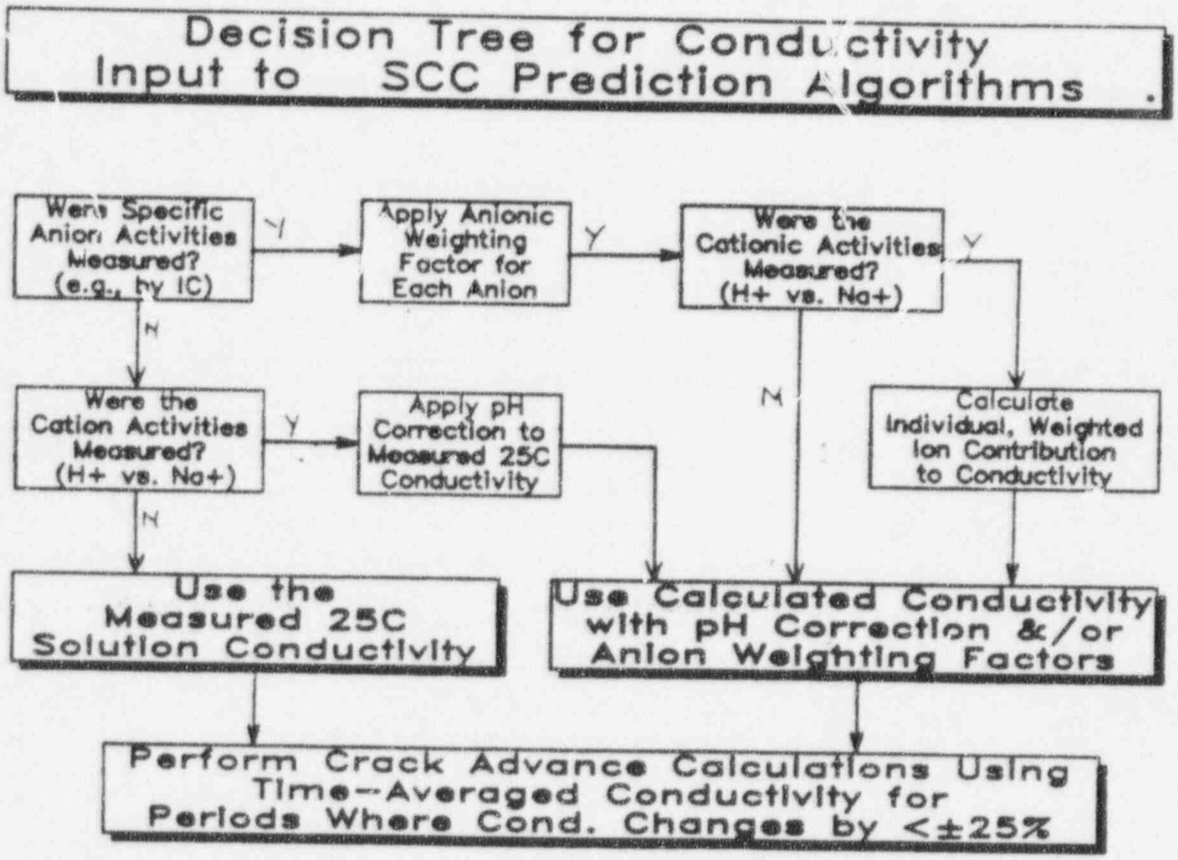
don't yet have
flow rate involved



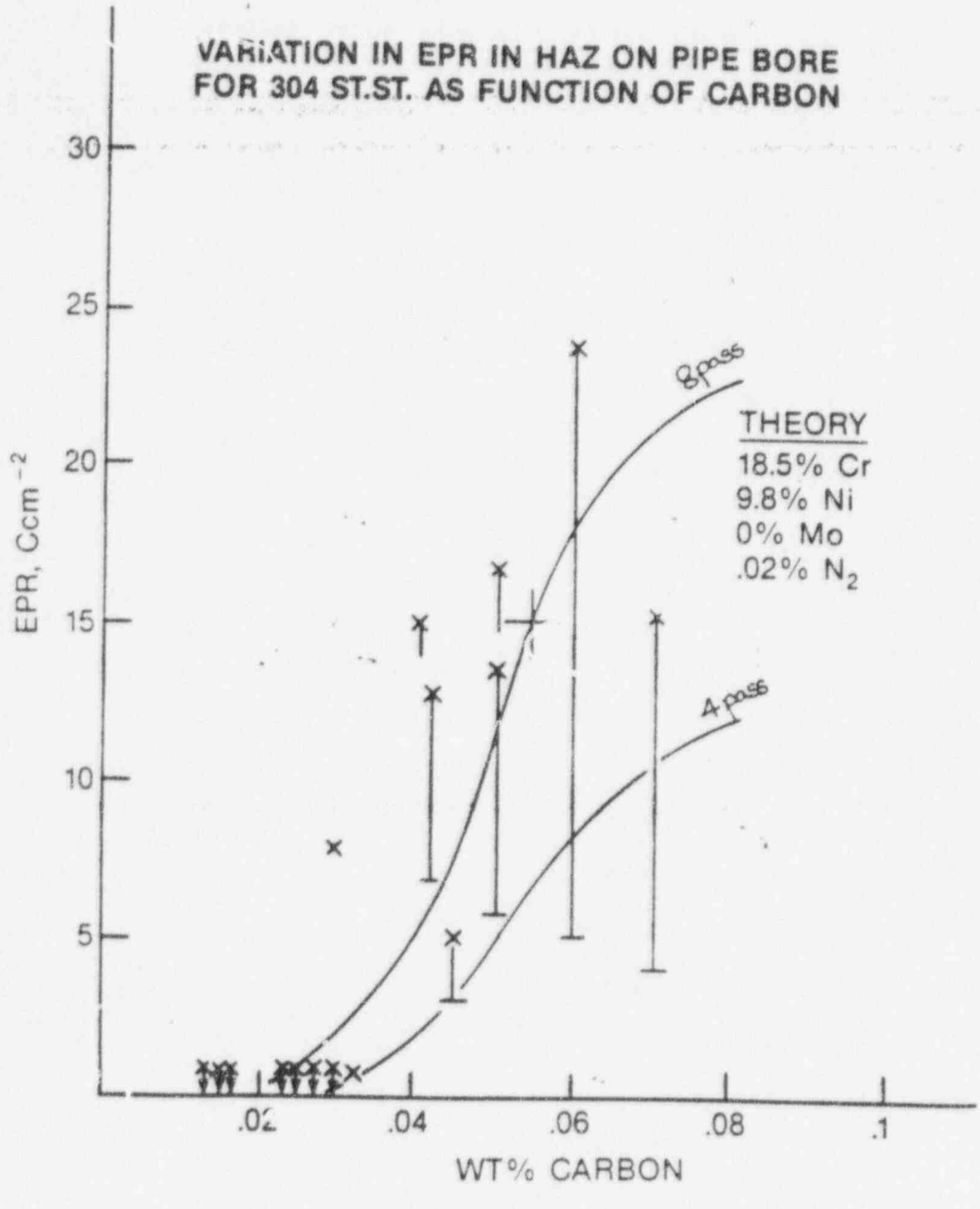
Comparison between theoretical and observed corrosion potential of type 316 stainless steel in 288°C water as a function of dissolved oxygen (191).



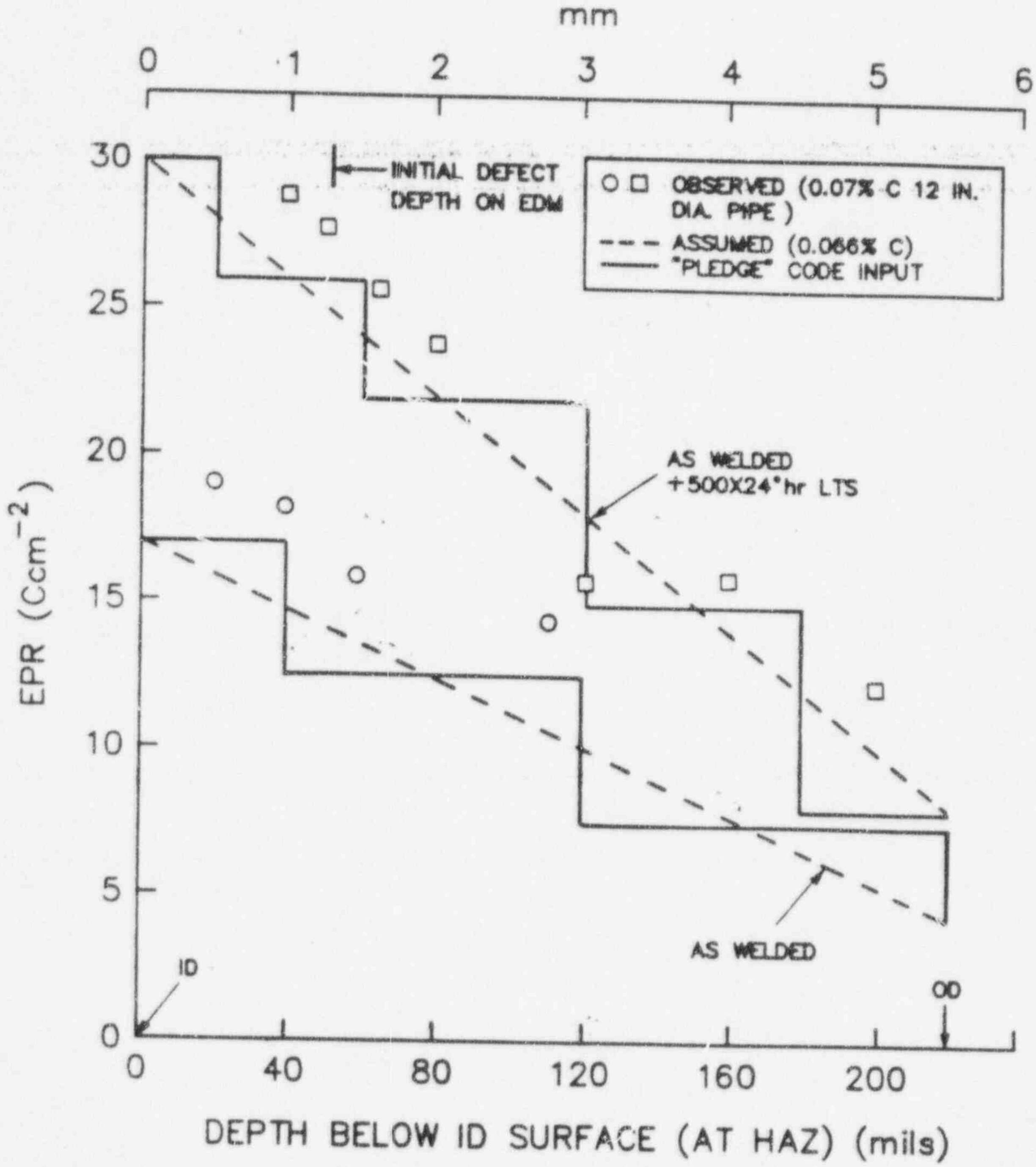
Decision tree for determining corrosion potential to be used in PLEDGE prediction methodology for stainless steel in 288°C water.



Decision tree for determining the solution conductivity value to be used in the PLEDGE prediction methodology.

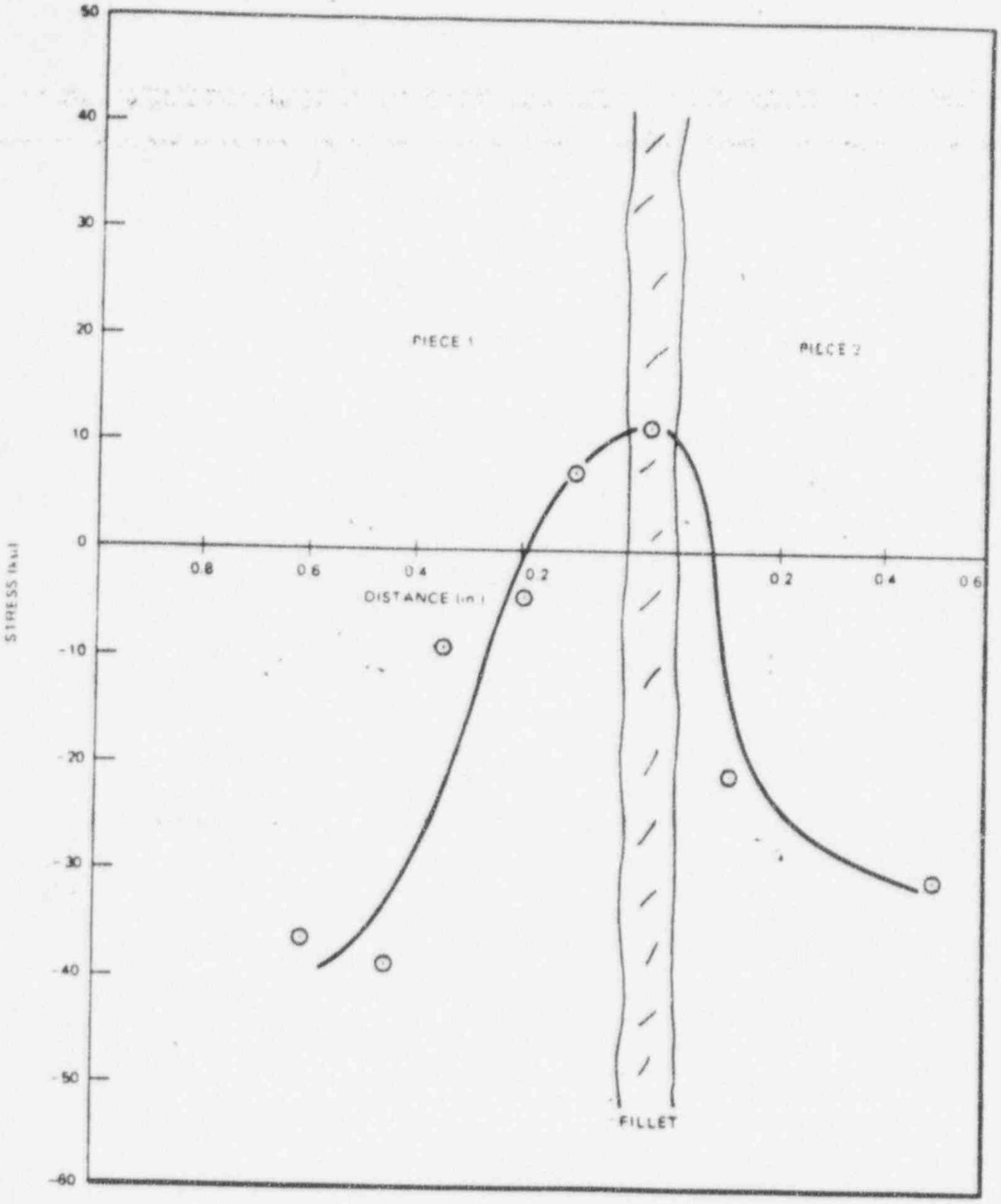


Measured relationship between EPR in the HAZ adjacent to welds at the internal diameter surface of 4" schedule 80 type 304 pipes, and the carbon content of the base material (192,193). Also shown are the theoretical relationships predicted after a given number of weld passes (194).

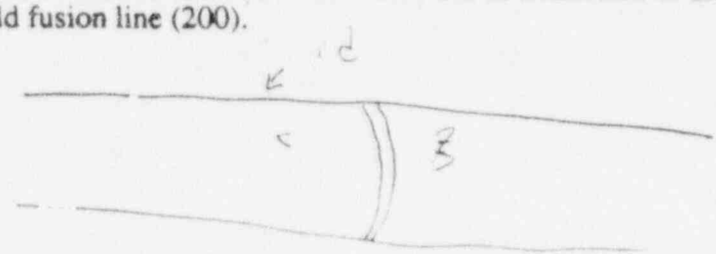


Variation in EPR value through the thickness of a pipe at 3mm from the weld fusion line (195).

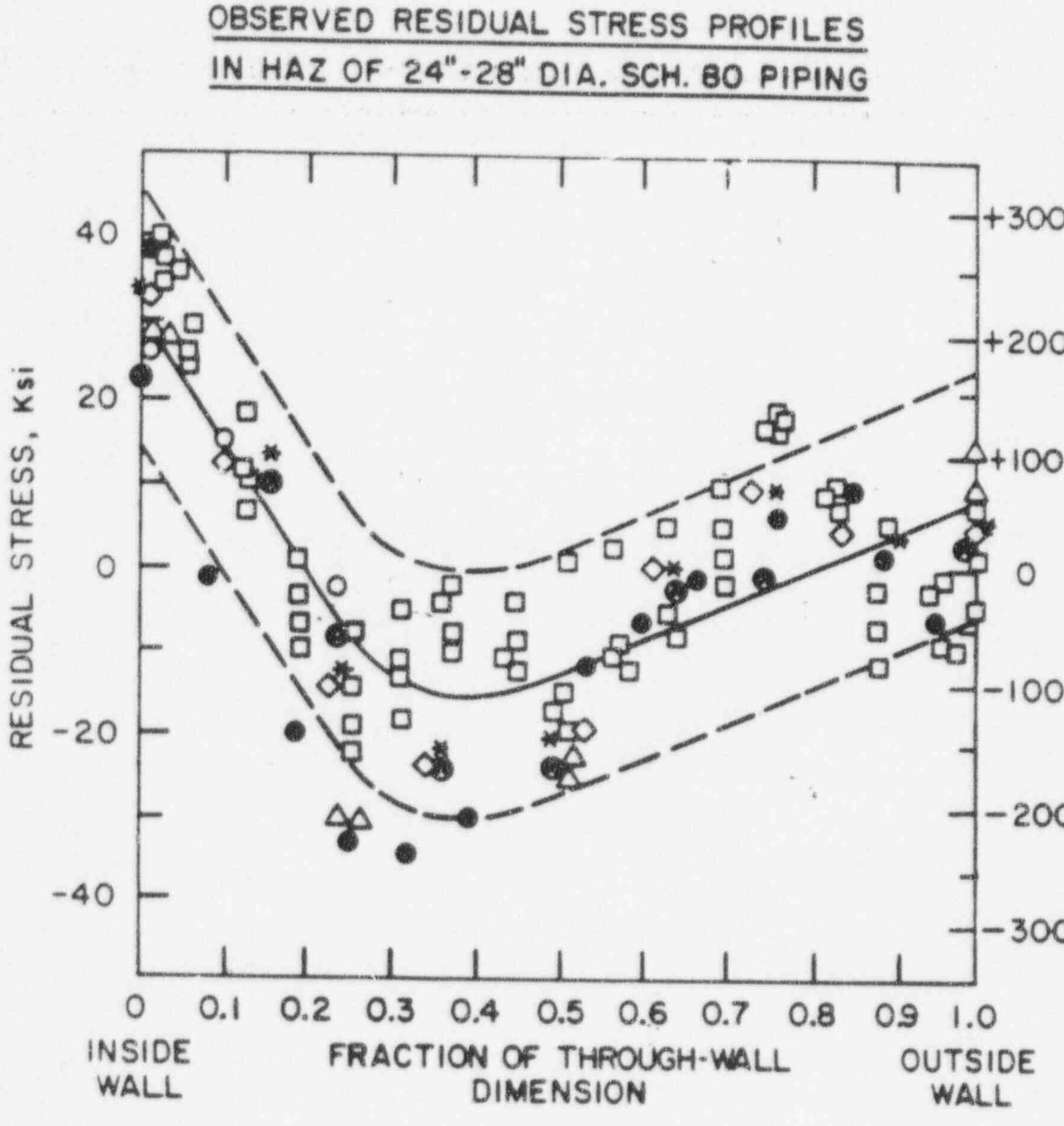
bulky pipe is at plane strain.
.375" thick.



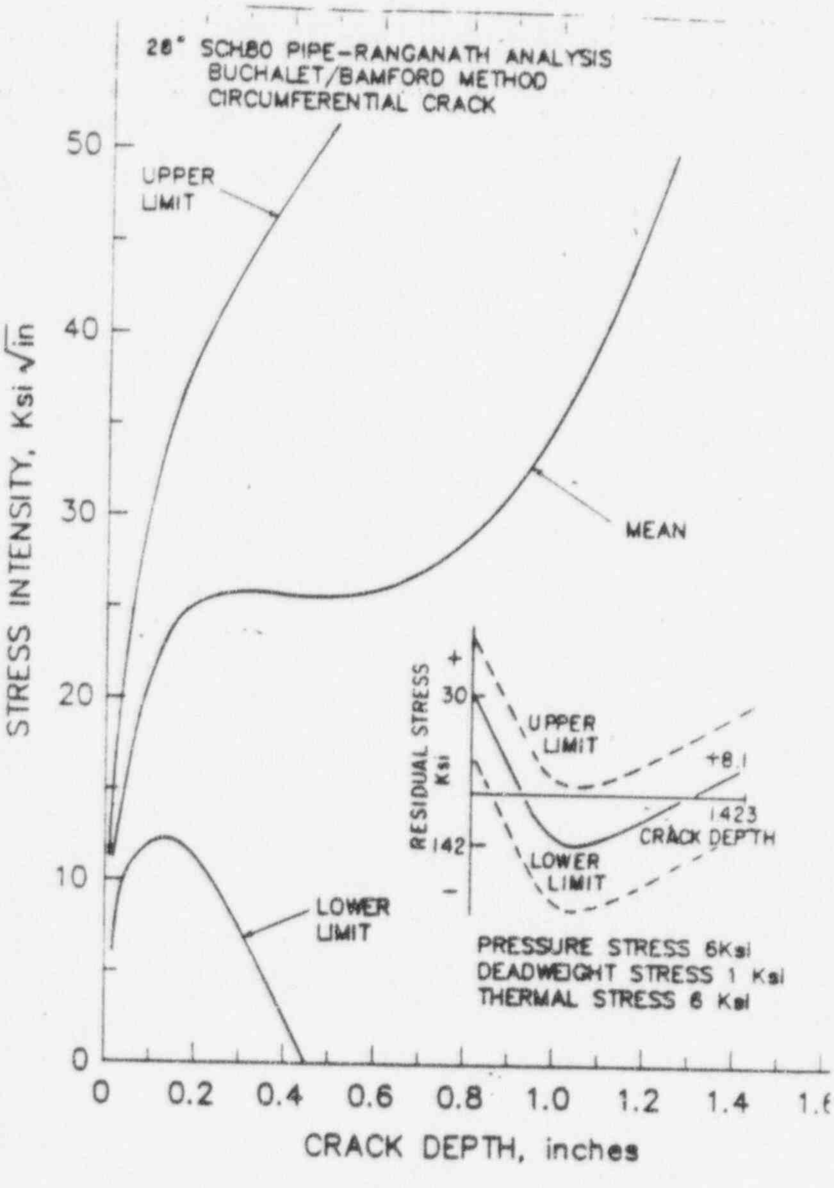
Maximum longitudinal residual stress (Ksi) on the internal bore of a 4" diameter Sch 80 stainless steel butt weld as a function of distance from weld fusion line (200).



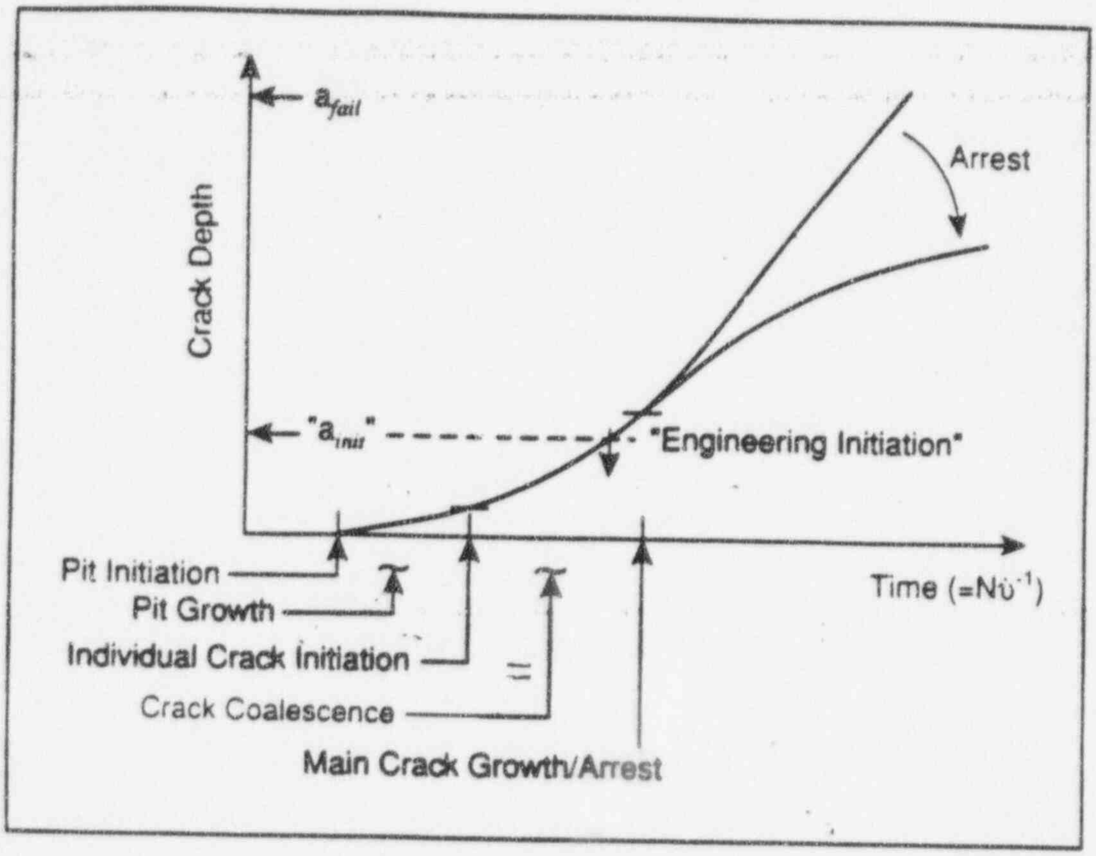
Scotta!



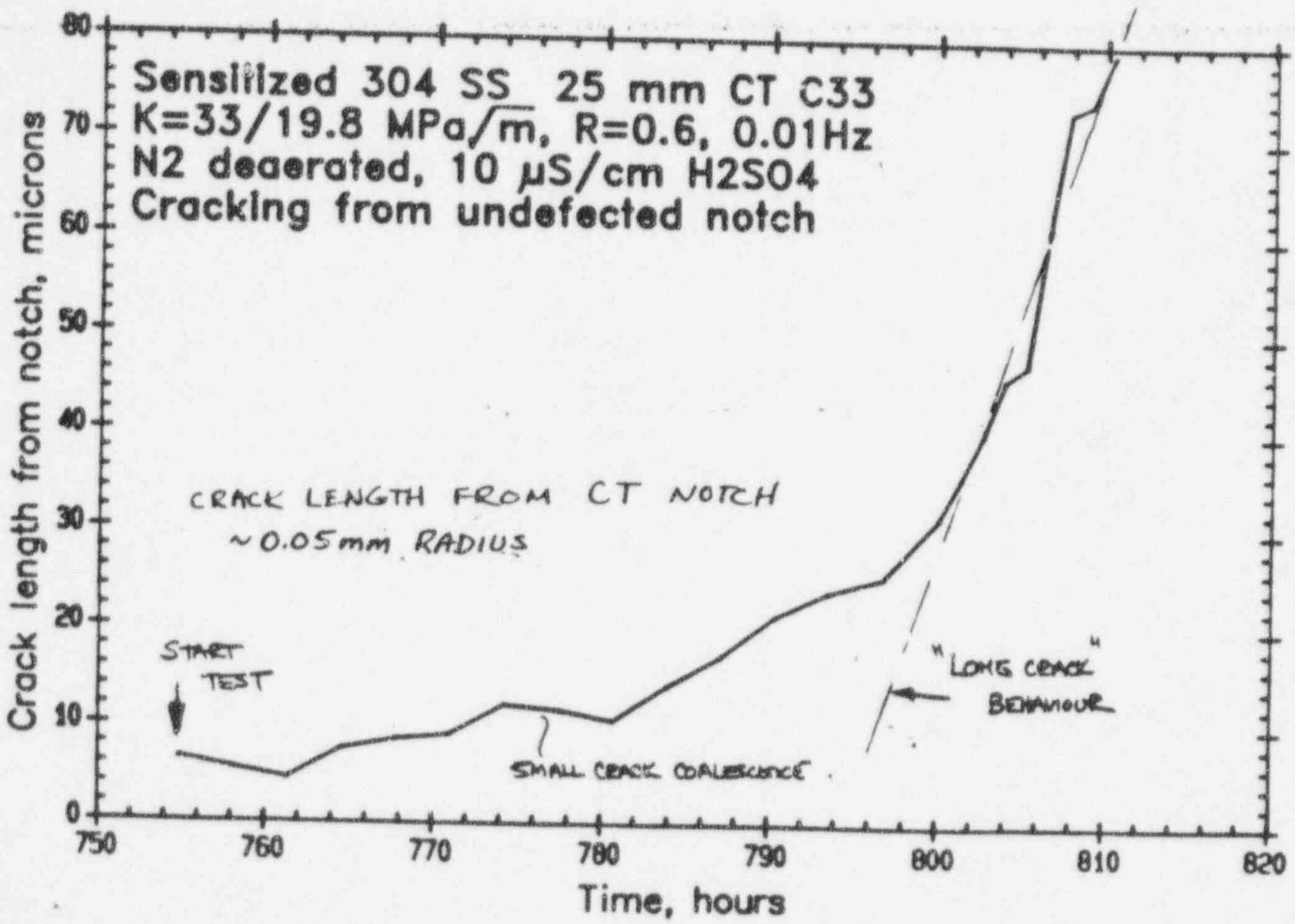
Variation of residual stress adjacent to a weld in a 28" diameter Sch 80 stainless steel pipe as a function of through wall distance from the internal bore.



Variation in stress intensity as a circumferential crack advances in the HAZ of a 28" diameter Sch 80 stainless steel pipe. Stress attributed, as shown, to pressure, deadweight and thermal stresses, plus the residual stresses shown in Figure 58.



- **ENGINEERING CRACK INITIATION CORRESPONDS TO A "DEEP" CRACK**
- **PRACTICALLY, LIFE PREDICTION/EXTENSION HINGES ON UNDERSTANDING CRACK PROPAGATION**



Crack depth / time relationship for intergranular cracks initiating, coalescing and growing in a notched 1T CT specimen of sensitized stainless steel in 288 C water [15].

A ssum

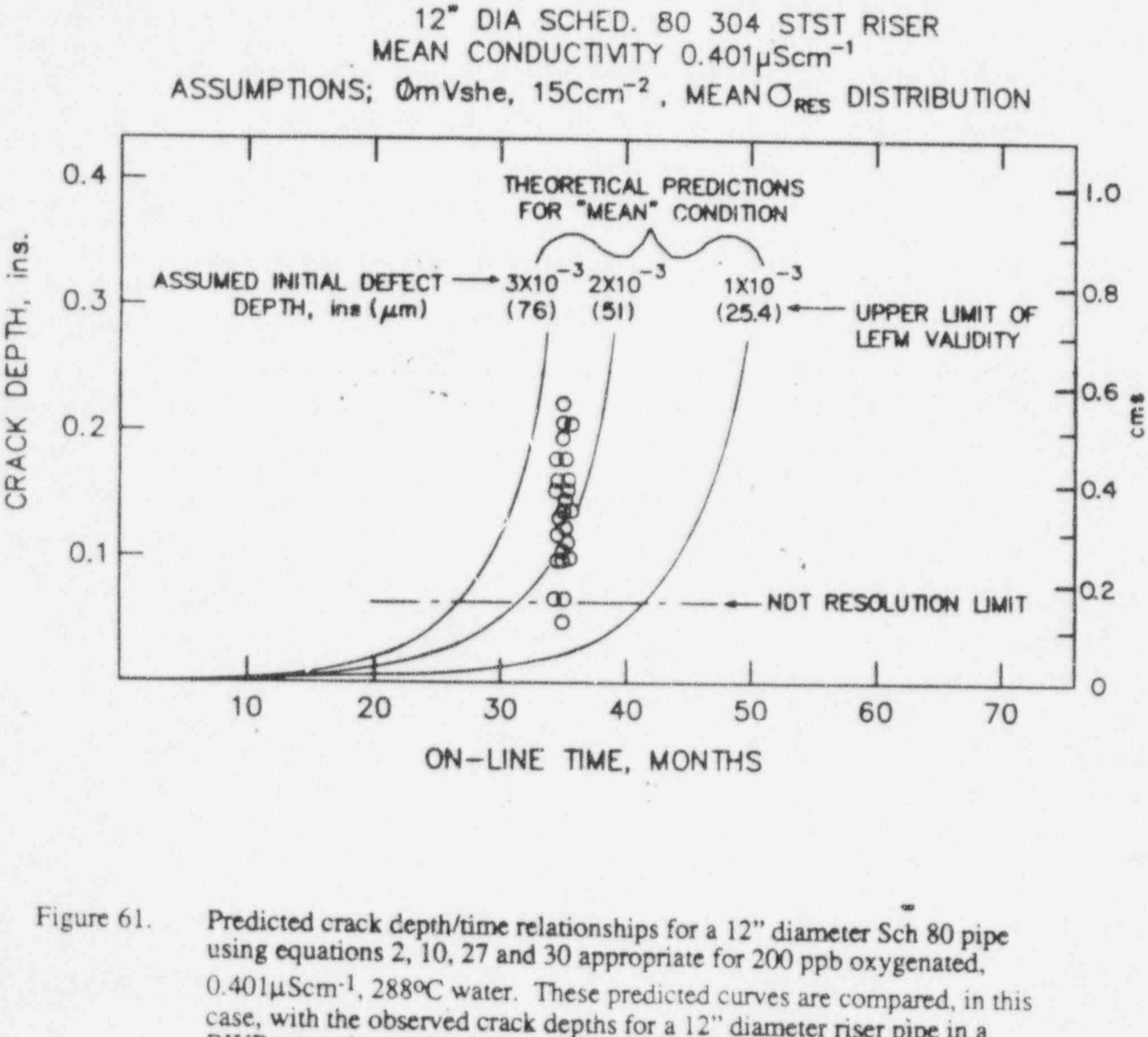
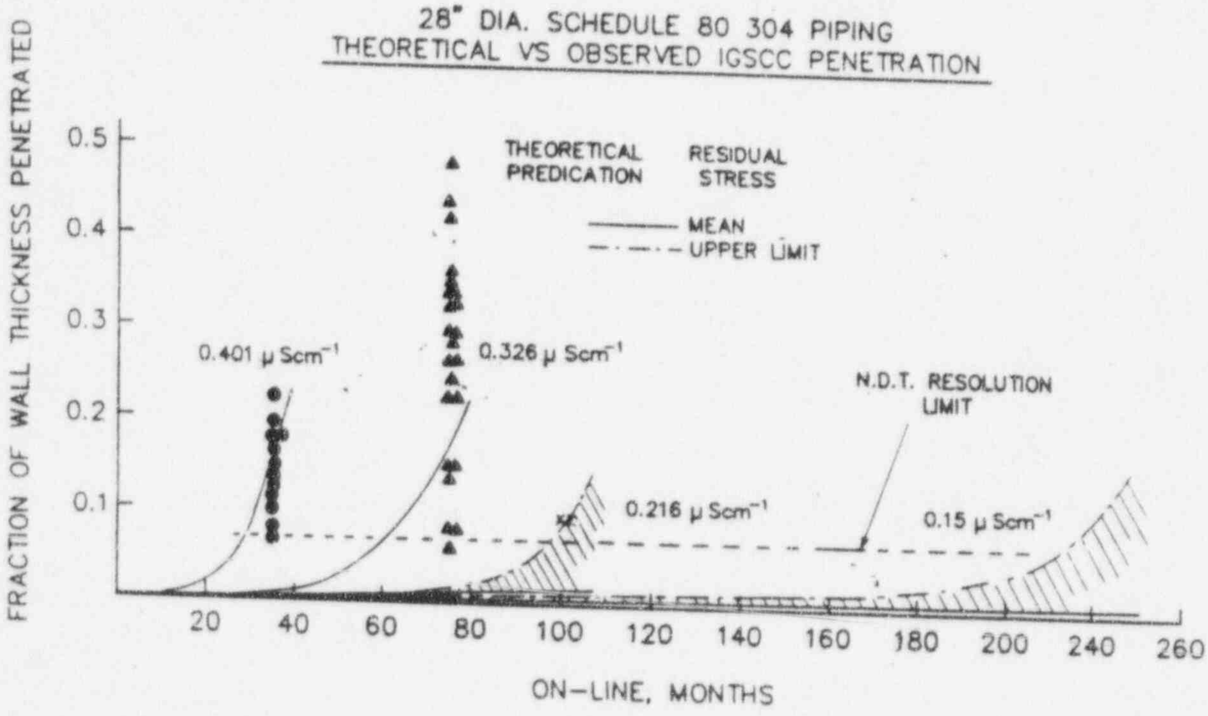
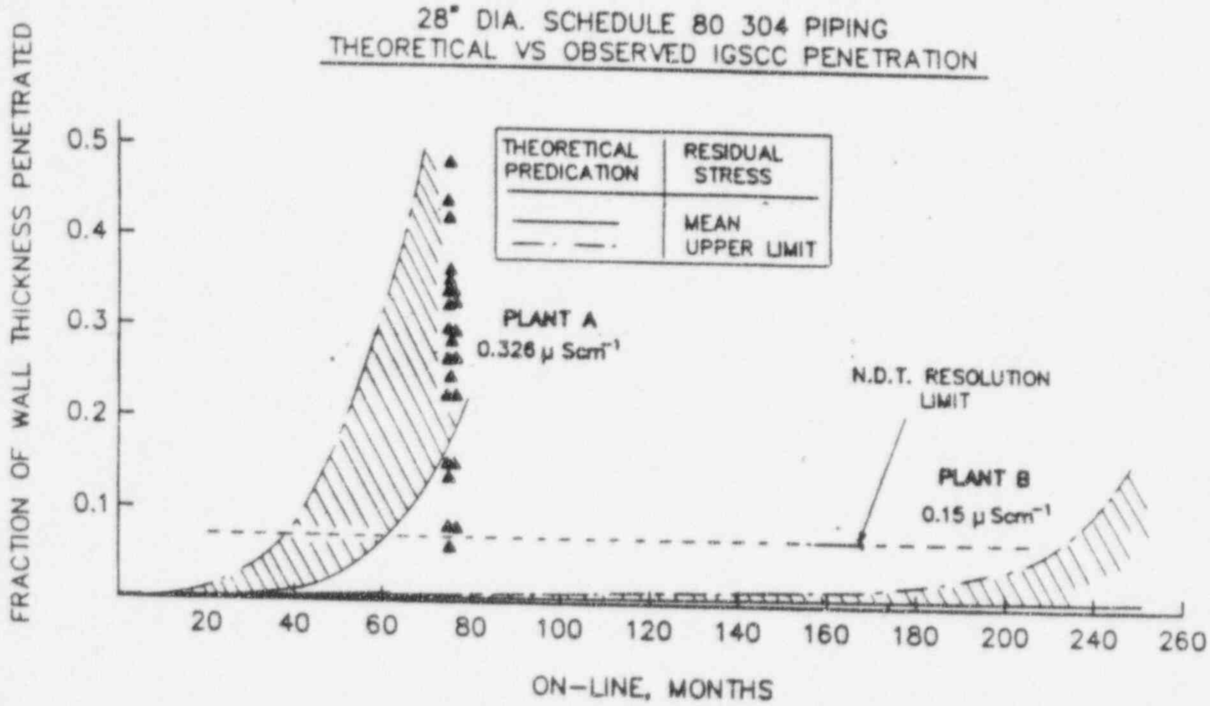


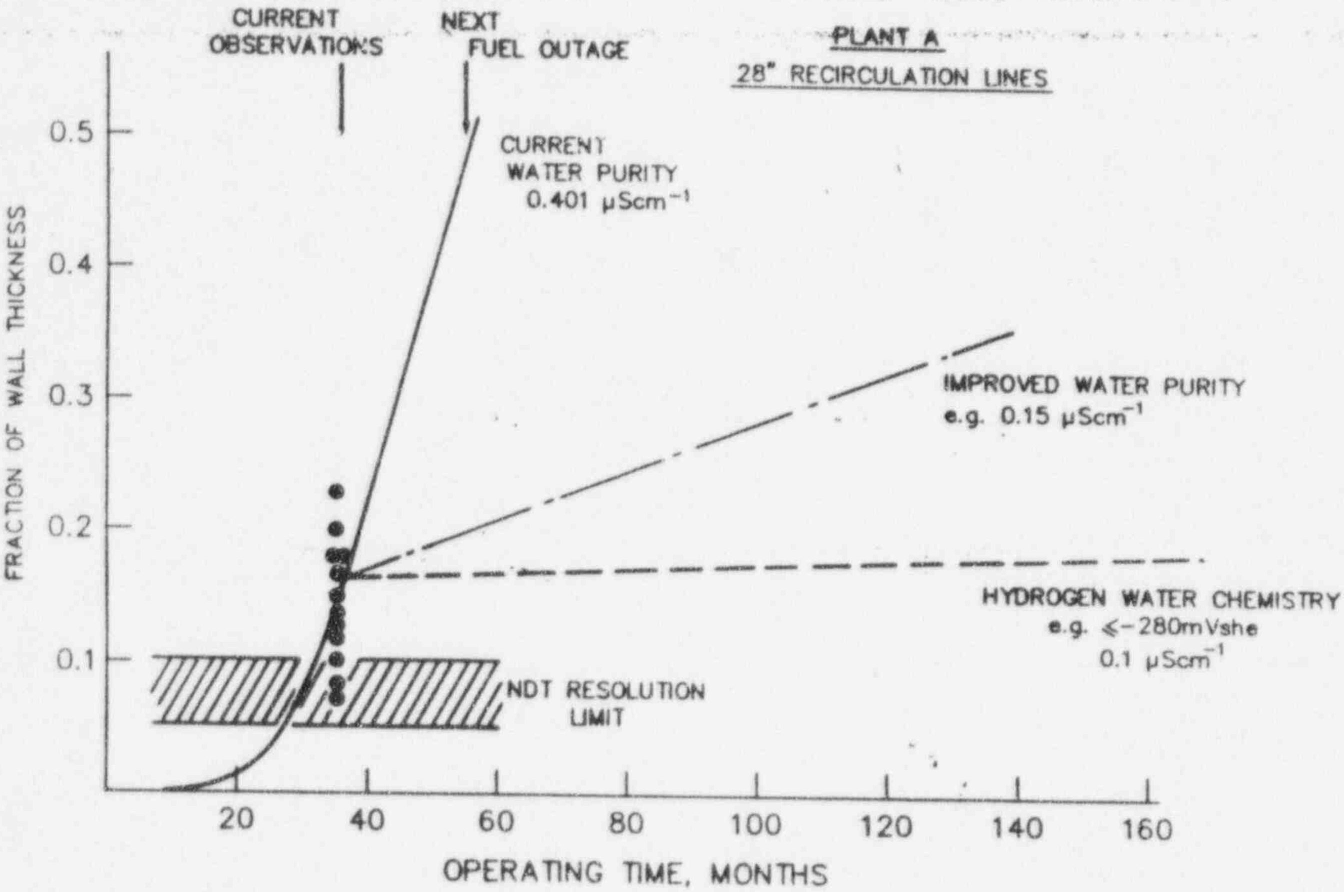
Figure 61. Predicted crack depth/time relationships for a 12" diameter Sch 80 pipe using equations 2, 10, 27 and 30 appropriate for 200 ppb oxygenated, $0.401 \mu Scm^{-1}$, 288^oC water. These predicted curves are compared, in this case, with the observed crack depths for a 12" diameter riser pipe in a BWR operating under this water chemistry. It is seen that good agreement between observation and theory is obtained with a value of a_0 in equation 30 of 0.002".



Comparison between observed and predicted crack depth/time relationships for 28 inch diameter Sch 80 piping in a number of BWRs. The predicted curves correspond to the use of either the "mean" or "upper limit" residual stress profile for the weld HAZ in this classification of piping.



Theoretical and observed crack depth vs. operational time relationships for 28-inch diameter schedule 80 type 304 stainless steel piping for two BWRs operating at different mean coolant conductivities. Note the bracketing of the maximum crack depth in the lower-purity plant by the predicted curve that is based on the maximum residual stress profile and the predicted absence of observable cracking in the higher-purity plant (in 240 operating months).



Predicted crack depth vs. time response for defected 28 inch diameter Sch 80 recirculation piping in a given BWR to defined changes in water chemistry.

SELECTED LITERATURE PUBLICATION LIST FOR CORROSION, COATING AND JOINING PROGRAM (APRIL 1996)

1. Life Prediction for Systems Susceptible to Stress Corrosion and Corrosion Fatigue

1.1 General

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2. F.P. Ford, "Mechanisms of Environmental Cracking in Systems Peculiar to the Power Generation Industry", EPRI Report N P 2589, September 1982.

3. F.P. Ford, "Stress-Corrosion of Iron-Based Alloys", Treatise on Materials Science and Technology, Vol. 25, p. 235, (Ed. C.L. Briant), Academic Press, 1983. ISBN 0-12-341825-9.

4. F.P. Ford, "Mechanistic Interpretation of Design and Evaluation Codes for Environmentally Assisted Cracking", Paper 327, Corrosion 86, Houston, 1986.

5. P.L. Andresen, R.P. Gangloff, L.F. Coffin, F.P. Ford, "Applications of Fatigue Analyses; Energy Systems", Proceedings of Fatigue 87 Conf., Univ. of Virginia, June 28-July 3, 1987.

6. F.P. Ford, "Crack Tip System and Its Relevance to the Prediction of Cracking in Aqueous Environments", Proceedings of First International Conference on Environmental Cracking. AIME/TMS/NACE. Kohler, Wisconsin, 1988.

7. P.L. Andresen, F.P. Ford, H.D. Solomon and D.F. Taylor, "Monitoring and Modeling Stress Corrosion and Corrosion Fatigue Damage in Nuclear Reactors", J. of Metals, December 1990, pp. 7-11.

8. F.P. Ford, "Slip-Dissolution Model", Proceedings of "Ecole D'Automne - Corrosion sous constrainte", Bombannes, France, (Eds. Des Jardins, Oltra), Les Editions de Physique, pp 307-344, 1990.

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12. P.L. Andresen and L.M. Young, "Characterization of the Roles of Electrochemistry, Convection and Crack Chemistry in Stress Corrosion Cracking", Proceedings of 7th Int.

Symp. on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, NACE, 1995.

1.2 Stainless Steels

1. H.D. Solomon, "Continuous Cooling and Sensitization of Type 304 SS", Corrosion, 34, pp. 183-193, 1978.

2. F.P. Ford and MJ Povich, "The Effect of O_2/T Combinations on the Stress Corrosion Susceptibility of Sensitized 304 Stainless Steel in High Purity Water", Corrosion, 35, pp 569-574, 1979.

3. H.D. Solomon, "Influence of Prior Deformation on Isothermal and Continuous Cooling Sensitization", Corrosion, 36, pp.356-361, 1980.

4. H.D. Solomon and D.C. Lord, "Influence of Straining During Continuous Cooling Sensitization", Corrosion, 36, pp. 395-399, 1980.

5. F.P. Ford and M. Silverman, "Effect of Loading Rate on Environmentally Controlled Cracking of Sensitized 304 Stainless Steel in High Purity Water", Corrosion, 36, 597, 1980.

6. F.P. Ford and M. Silverman; "The Mechanisms of Stress Corrosion Cracking of Sensitized 304 Stainless Steel in 0.01 M Na_2SO_4 at 95°C", Corrosion, 36,558, 1980.

7. P.L. Andresen, "The Effect of Dissolved Oxygen, Chloride Ion and Applied Potential on the SCC Behavior Type 304 Stainless Steel in 290°C Water", Corrosion, 36, 8, pp.409, 1980.

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9. M. Silverman and D.F. Taylor, "The Influence of Crevice Chemistry on Constant Extension Rate Tensile (CERT) Tests of 304L Stainless Steel in 288°C Water", Corrosion 37, 58, 1981.

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13. H.D. Solomon, "Age Hardening in a Duplex Stainless Steel. International Conference on Duplex Stainless Steels, ASM, pp. 41-69, 1983. Also published J. Heat Treating 3, pp. 3-15, 1983.

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