

February 2, 2001

D. C. Agarwal
Vice-president, Technical Marketing
Krupp VDM Technologies Corporation
11210 Steeplecrest
Suite #120
Houston, Texas 77065-4939

Dear Mr. Agarwal:

Thank you for your letter of December 26, 2000, concerning materials to be used in waste packages at a potential geologic repository at Yucca Mountain, Nevada. I found your discussion of the merits of alloy 59 versus alloy 22 to be interesting and informative. However, the U.S. Department of Energy (DOE) has the responsibility for assessing the various attributes of waste package materials and deciding upon an alloy for use in the potential repository. Although the U.S. Nuclear Regulatory Commission (NRC) does conduct independent, audit reviews of DOE's repository activities, our efforts are focused more on evaluating DOE's proposed waste package materials rather than identifying specific alternatives. Nonetheless, as mentioned in William Reamer's letter of November 17, 2000, the information you provided was reviewed by NRC staff and the staff of our Center for Nuclear Waste Regulatory Analysis. Concerning your request to receive information related to Catholic University's activities in evaluating various alloys, I am told by NRC staff that during a telephone conversation on January 3 and 4, 2001, you were provided a clarification of what information the NRC has, stemming from the Advisory Committee on Nuclear Waste 122nd meeting, which is enclosed.

If you have any further questions or comments, please contact Mrs. Tamara Bloomer of my staff at (301) 415-6626.

Sincerely,
/RA/

John T. Greeves, Director
Division of Waste Management
Office of Nuclear Material Safety
and Safeguards

Enclosure: As stated

Distribution EDO G20010024 ML:

Central File	HLWB r/f	EDO r/f	NMSS Dir. Ofc r/f	Jholonich	DWM t/f
JGreeves	CPaperiello	WTravers	FMiraglia	PNorry	
SBurns	AThadani	JLinehan	CPoland	PTressler	

S:\dwm\hlwb\teb\agarwalthanks.wpd

*see previous concurrence

OFC	HLWB*	HLWB*	HLWB*	DWM
NAME	TBloomer:mm	KStablein	WReamer	JGreeves
DATE	1/30/01	1/31/01	1/31/01	1/2/01

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UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

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A handwritten signature in cursive script, reading "John T. Greeves for".

John T. Greeves, Director
Division of Waste Management
Office of Nuclear Material Safety
and Safeguards

Enclosure: As stated

OVERSIGHT ASSESSMENT OF THE ENGINEERED BARRIER SYSTEM (EBS) PROGRAM

State of Nevada, Nuclear Waste Project Office

**TASK 1: OVERSIGHT ASSESSMENT OF
BOROSILICATE WASTE GLASS**

**TASK 2: OVERSIGHT ASSESSMENT OF
ALLOY C-22**

**TASK 3: OVERSIGHT ASSESSMENT OF THE
TITANIUM DRIP SHIELD**

Program Team Members:

Maury Morgenstein, Team Leader

Geosciences Management Institute, Inc.

Don Shettel,

Geosciences Management Institute, Inc.

Roger Staehle,

Staehle Consulting

Aaron Barkatt

The Catholic University of America

April Pulvirenti

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Mohammed Adel Hadadi

The Catholic University of America

Jeffrey Gorman

Dominion Engineering, Inc.

Robert Varrin, Jr.

Dominion Engineering, Inc.

Charles Marks

Dominion Engineering, Inc.

**PRELIMINARY
SCOPING STUDIES FOR TASK 2:
OVERSIGHT ASSESSMENT OF ALLOY C-22**

**Our Purpose is Strictly Oversight.
Our Team is Not in the Business of Site
Characterization.**

WE HAVE THREE PRESENTATIONS:

**1. NATURAL LEAD AND MERCURY VALUES AT
YUCCA MOUNTAIN**

**Maury Morgenstein
Don Shettel**

2. SCOPING EXPERIMENTS WITH C-22

**Aaron Barkatt
Jeffrey Gorman**

**3. WASTE PACKAGE CORROSION
ENVIRONMENT**

Roger Staehle

YUCCA MOUNTAIN NATURAL LEAD AND MERCURY VALUES: THE NEAR-FIELD REPOSITORY ENVIRONMENT WITH RESPECT TO ALLOY C-22

**Maury Morgenstein and Don Shettel
Geosciences Management Institute, Inc.**

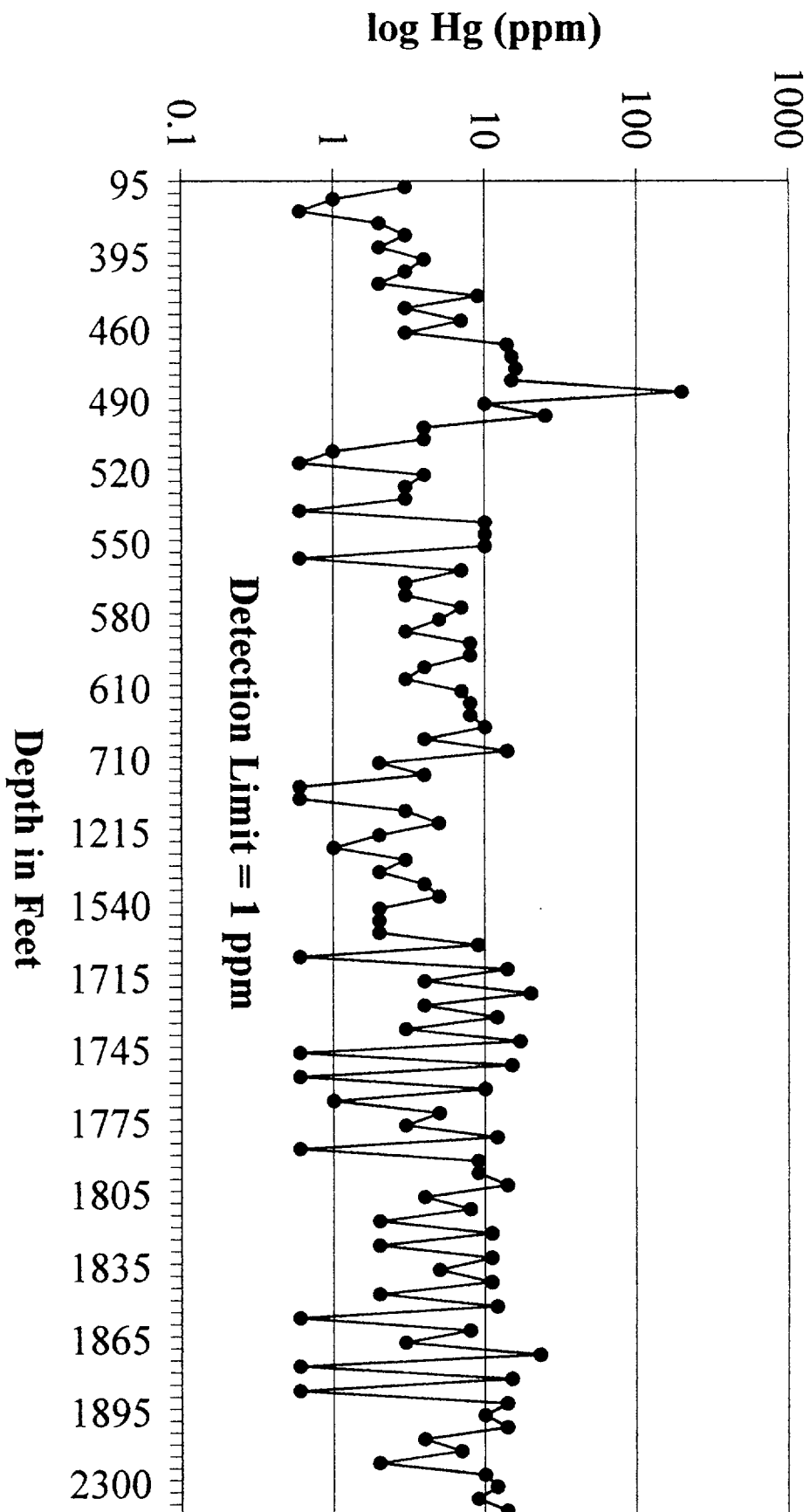
The issue:

Lead and mercury concentrations in the near-field

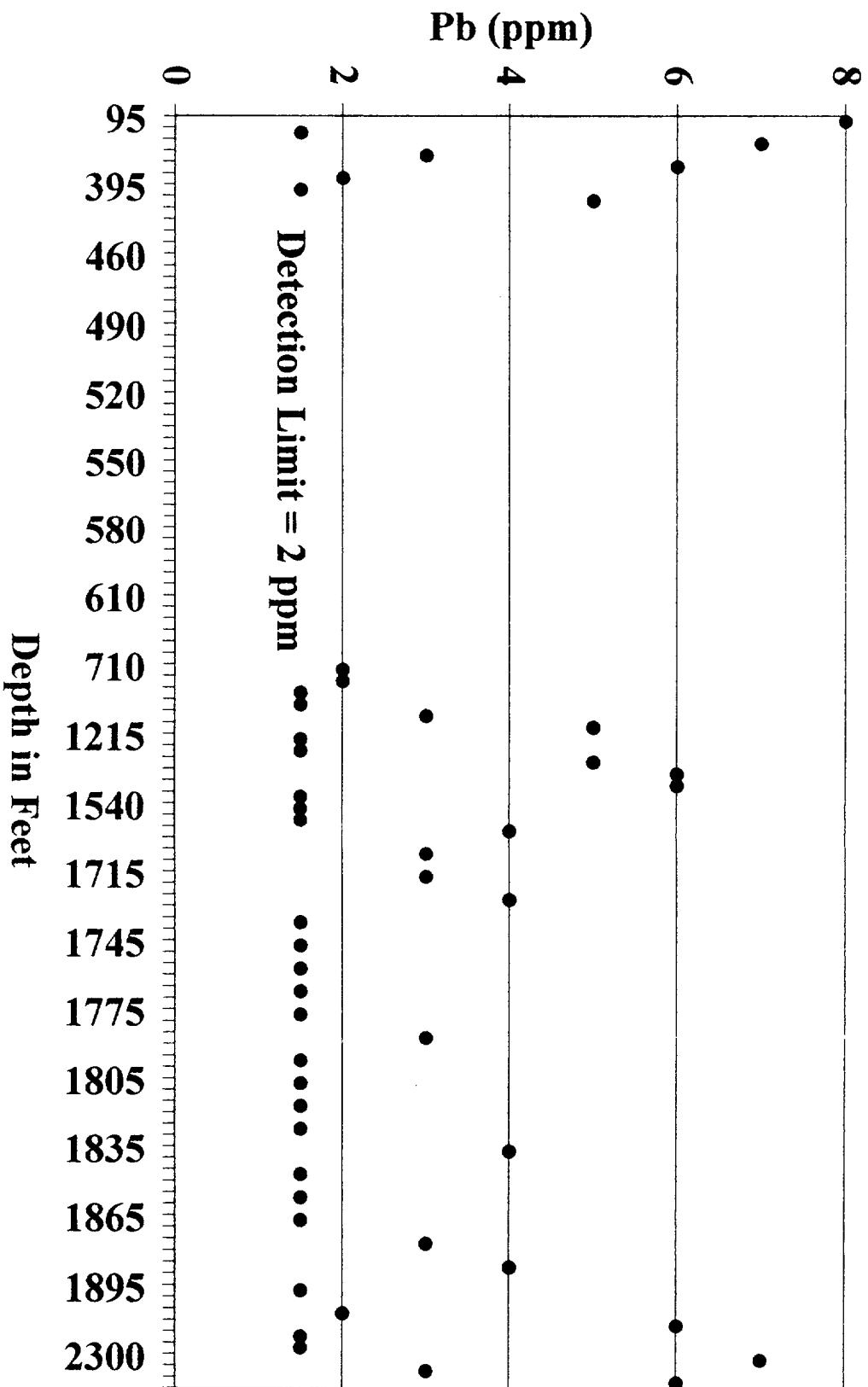
We present concentrations of lead and mercury in:

- Fault and fracture system diagenetic carbonate and silicate precipitates that are a function of meteoric down-fluxed water in the vadose zone (e.g. Trench 14);
- Yucca Mountain hydrogeochemistry; and
- Yucca Mountain tuffs and sediments (pyritic and non-pyritic).

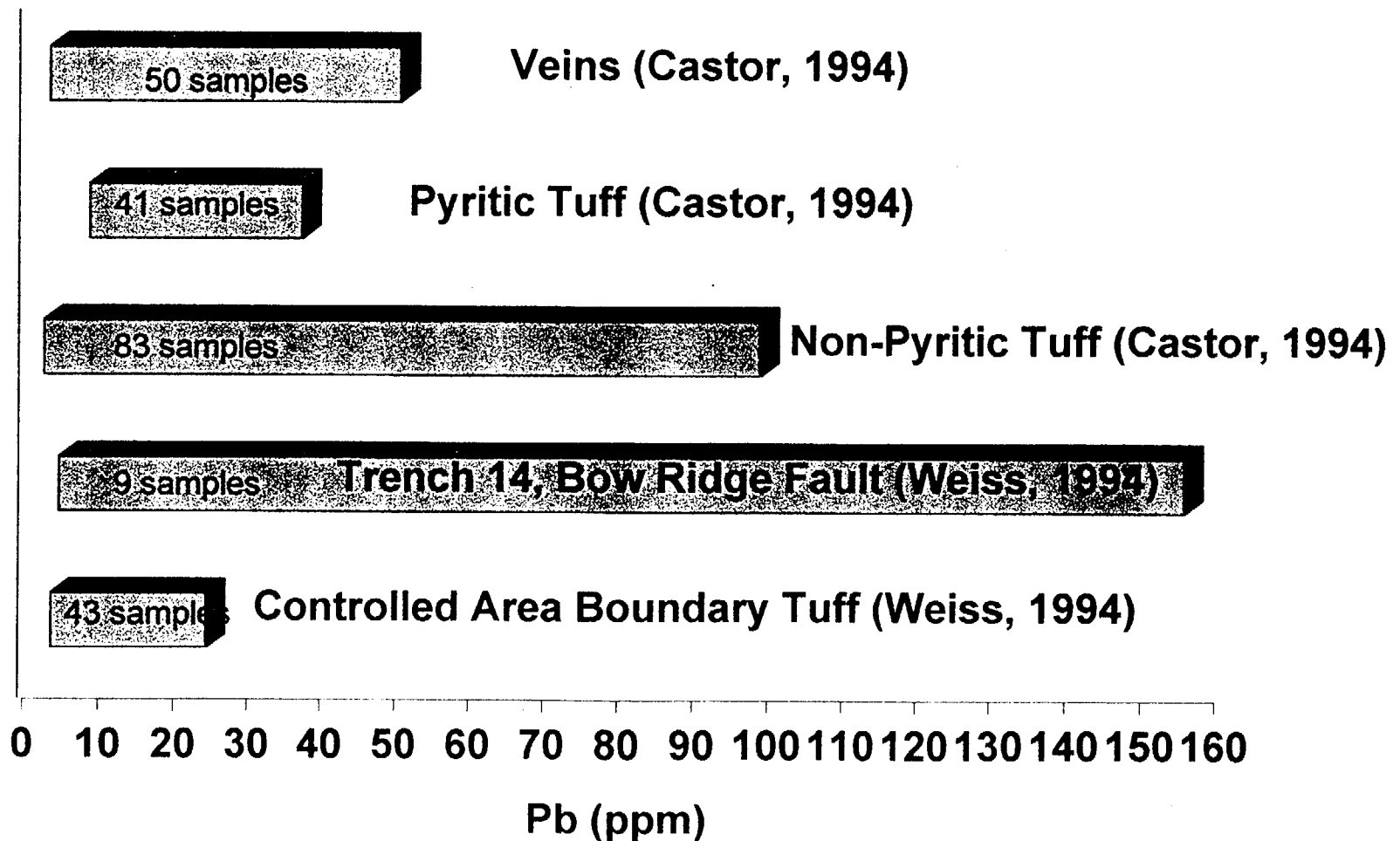
NC-EWDP-3D Mercury with Depth by Neutron Activation Analysis



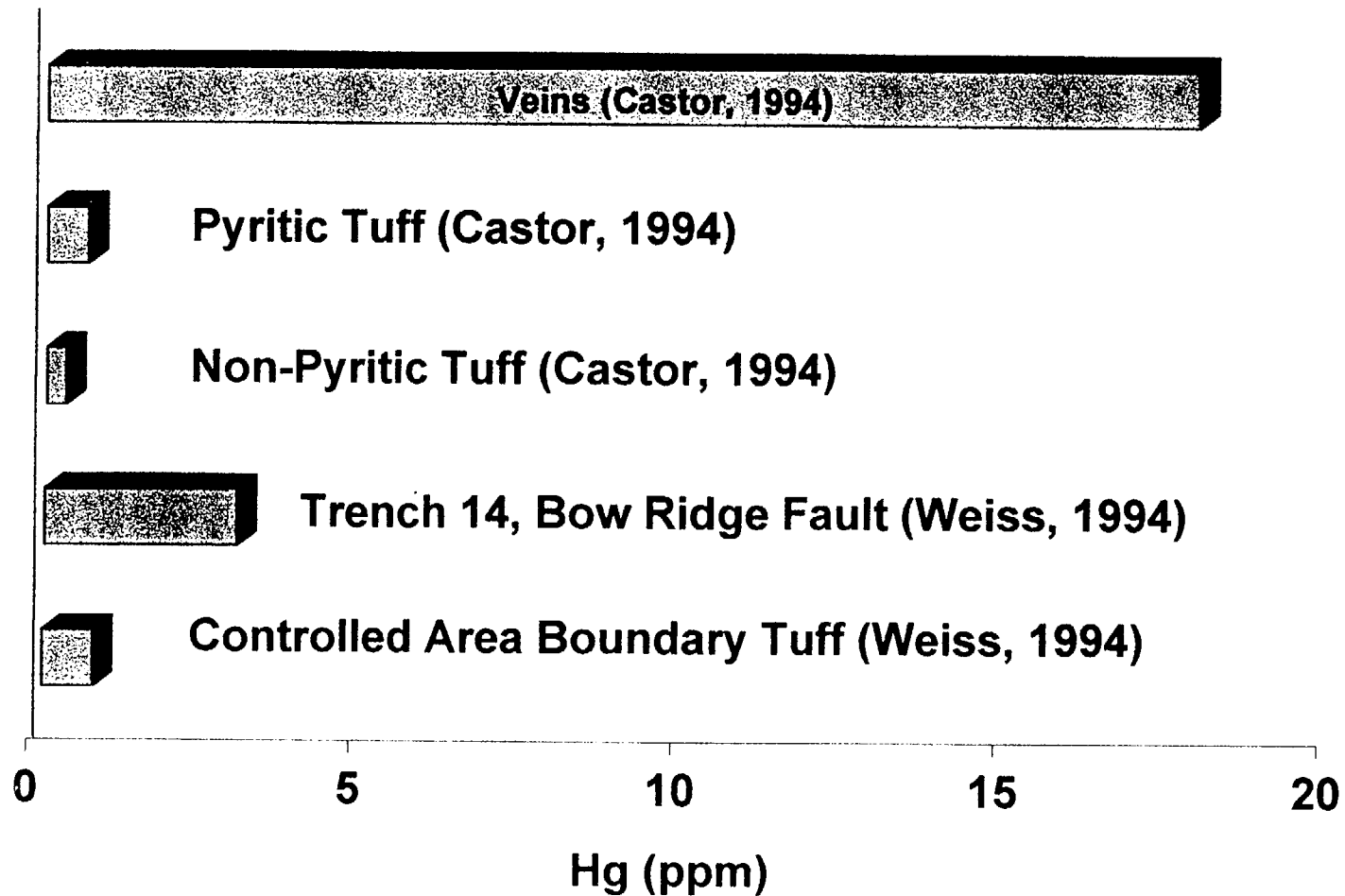
NC-EWDP-3D Lead with Depth by Inductively Coupled Plasma (ICP)



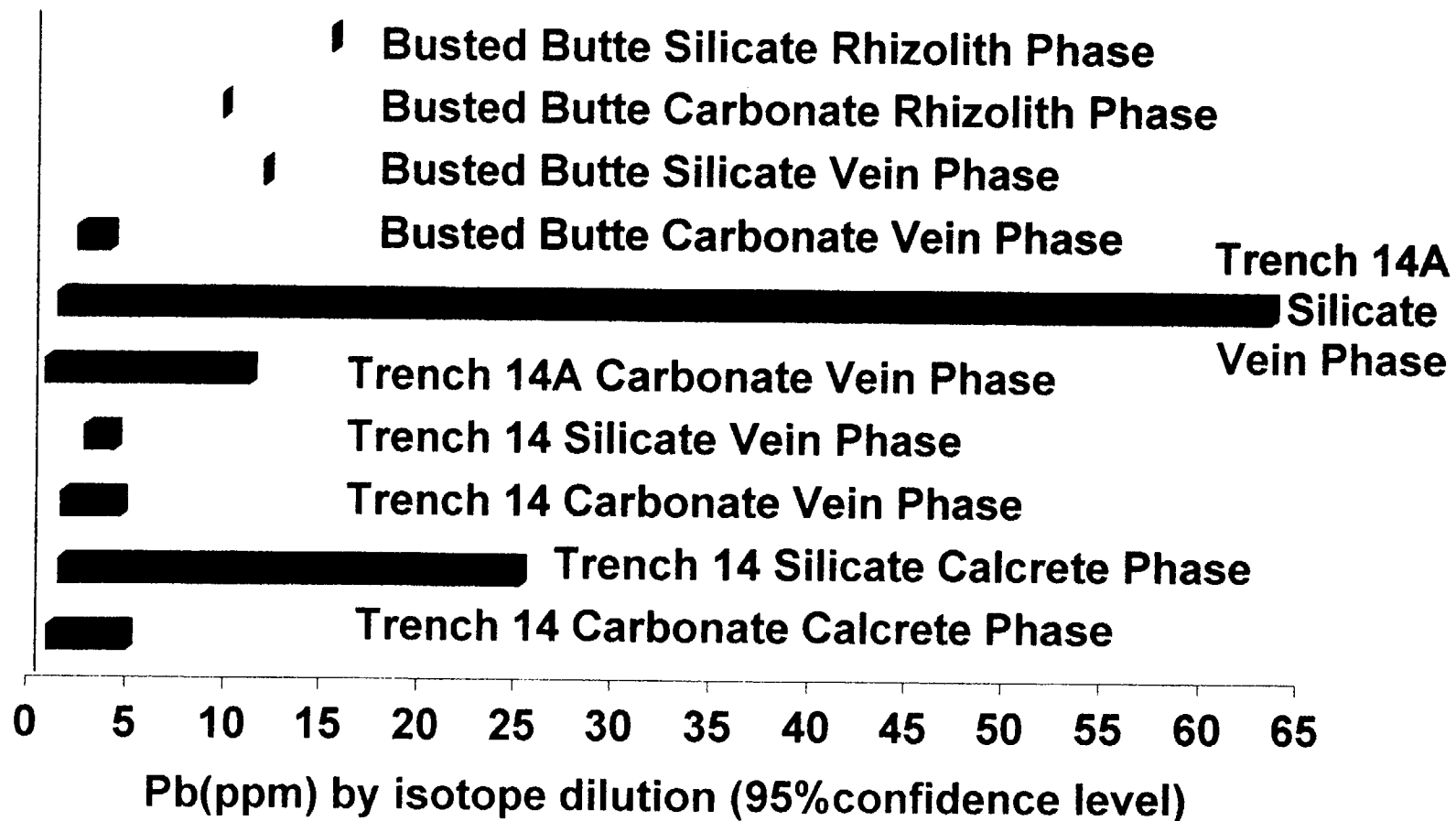
Tuff and Vein Filling Lead Concentrations, Yucca Mountain



Tuff and Vein Filling Mercury Concentrations, Yucca Mountain



Lead Concentrations from Carbonate-Silicate Veins, Calcrete and Rhizoliths , Data from: Zartman and Kwak (USGS:OFR-93-690)



A Regional Vadose Water Lead Signal

Zartman and Kwak (USGS-OFR-93-690) conclude from lead isotope studies that:

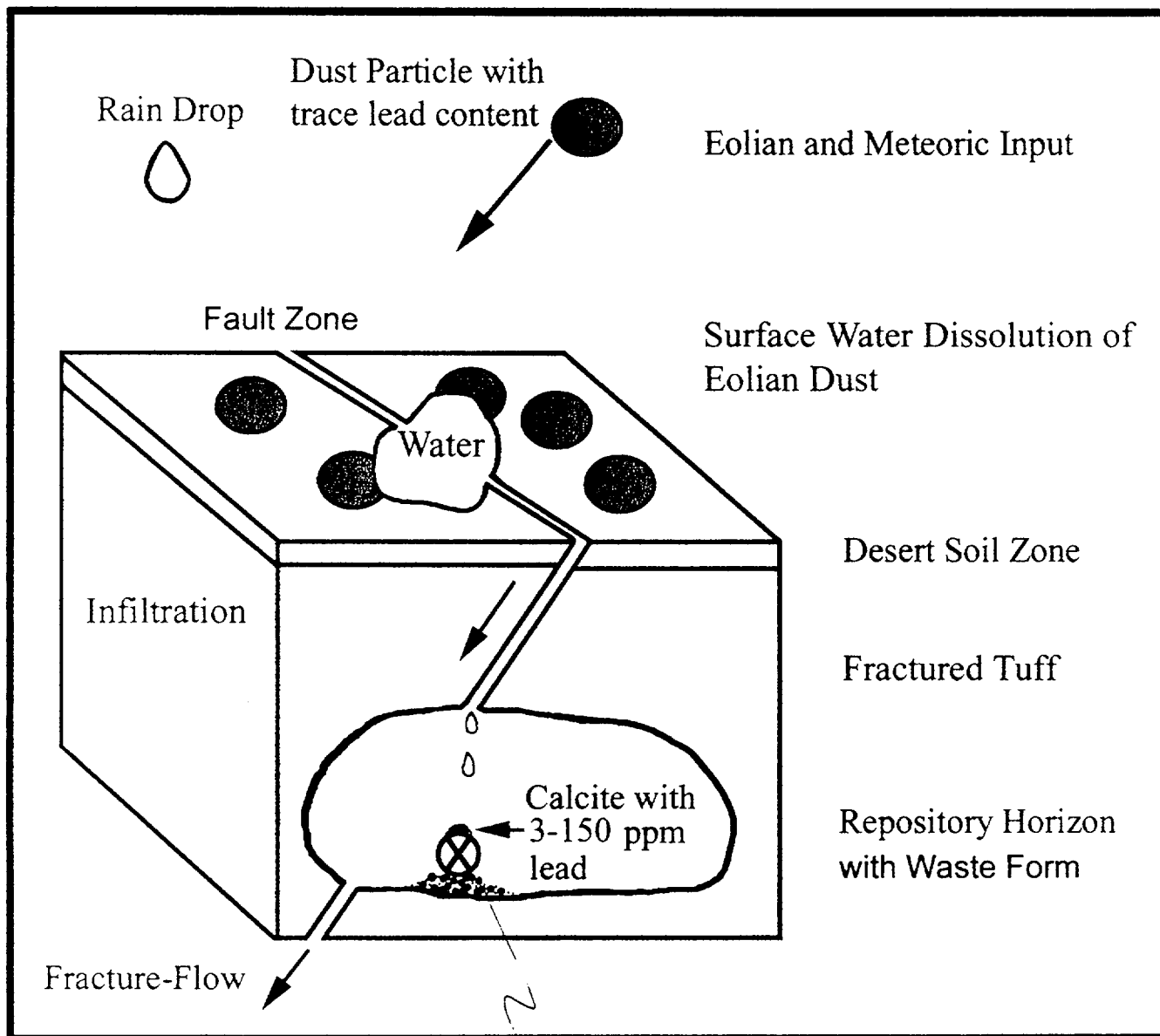
“Because the lead isotope field defined by the vein material are virtually identical to those of soil calcrete, one need not look any further to explain the observed lead isotope data.” page 10

Trench 14 and other similar carbonate and silicate vein fillings are precipitates from meteoric water.

“The ultimate source of this radiogenic lead is as yet unknown, but it may accompany an eolian contribution to the soils derived from exposed Paleozoic and Late Proterozoic carbonate rocks in surrounding mountains.” page 9

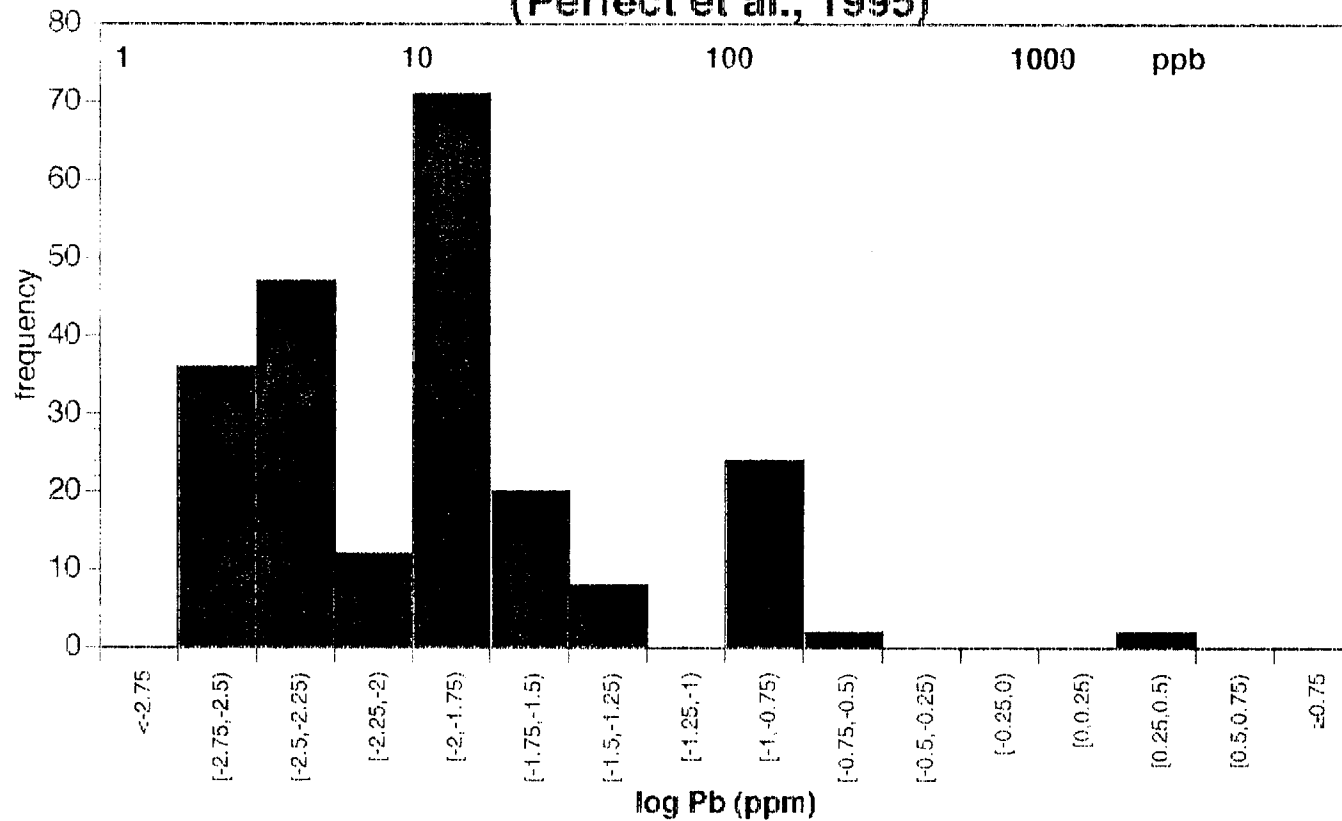
These conclusions suggest that there is a regional background signal for lead values due to an eolian lead contribution to the soil horizon. With meteoric water dissolution of the regional eolian dust at the ground surface, the resultant vadose water background lead signal may be similar at most fault zones (e.g. the Bow Ridge and the Ghost Dance Faults). Transmissive fault and fracture structures supporting vadose zone infiltration to the repository horizon contains this regional $\text{Pb}_3(\text{CO}_3)_2(\text{OH})_2$ lead fingerprint.

A Regional Eolian and Meteoric Lead Signal at the Yucca Mountain Area, Nevada



PH 8

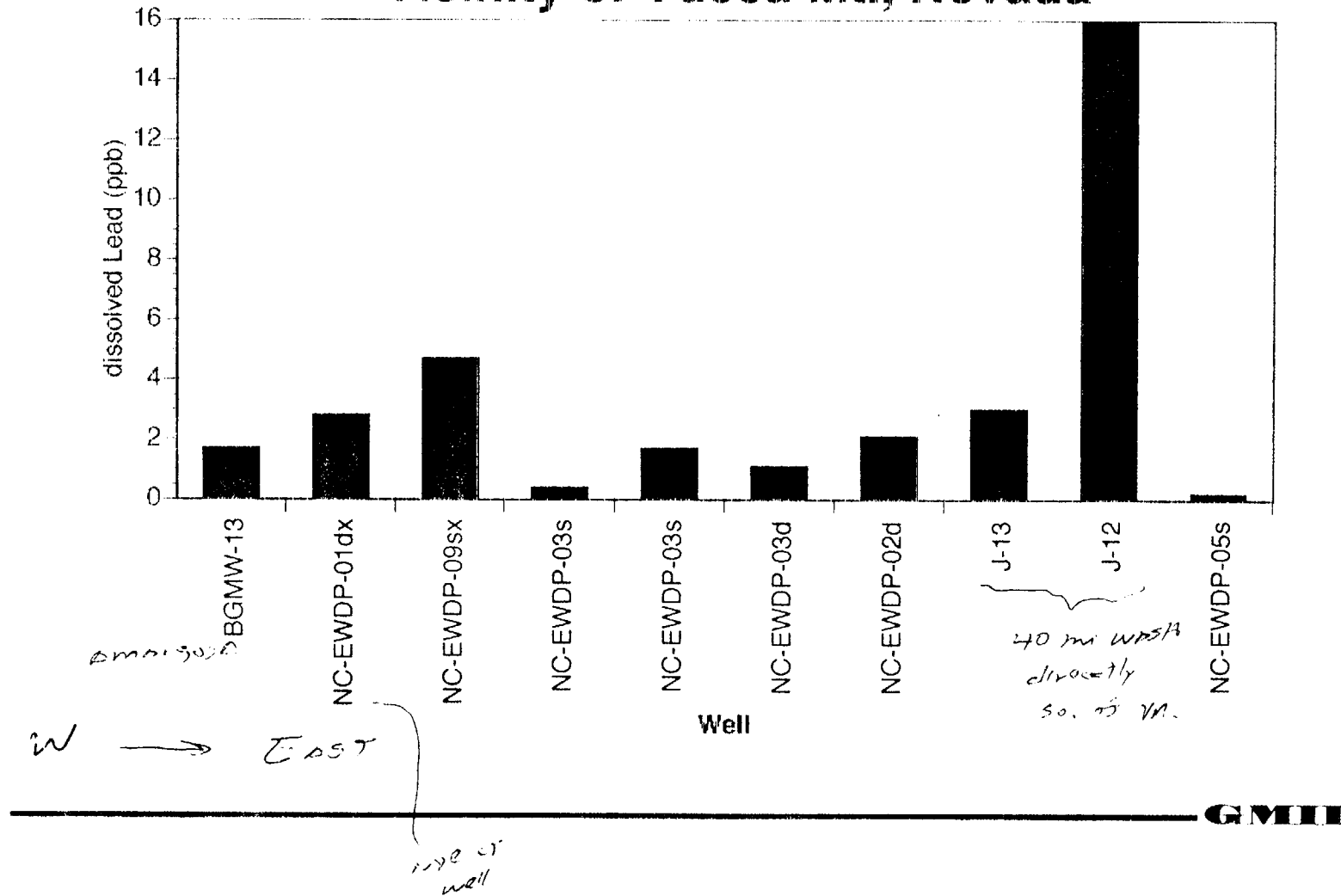
Dissolved Lead Values Around Yucca Mountain (Perfect et al., 1995)



GMII

3,000 samples over 100 km²
from evaporate ponds
some well water

Dissolved Lead Concentrations in Immediate Vicinity of Yucca Mt., Nevada



{ nothing in radon or not zone
they haven't looked for this

- ONLY looking at Pb & Hg, but there may be other trace elements

Dissolved Mercury Concentrations (near Yucca Mt., Nevada)

- Castor et al.: 1 value => 0.5 ppb, location unknown.
- Perfect et al. Database: less than 100 values, all zero.

CONCLUSION: site characterization incomplete & unfinished.

↳ look for trace elements in
SDT & VPDose zone
DOE should look further.

strongly believe trace elements exist
in the SDT zone, but no precise data.

Best lab: minimum amount of water
used for analysis 1 L.

MIT Tests: also has anions like Cl
know the pH

Digression on Use of J-13 Water

- **Currently J-13 is reference water for all experiments for Yucca Mt.**
- **No dripping fractures sampled in ESF that would represent vadose zone water**
- **Worse, experiments use synthetic J-13 (only major cations + anions), no minor or trace elements considered.**

CONCLUSIONS:

- **Site Characterization incomplete & unfinished**
- **Experiments missing important component (*Trace elements*)**
- **Realistic aqueous environments not considered in experiments**

REFERENCES for Whole Rock Values:

Castor, et al., 1994. Pyritic Ash-Flow Tuff, Yucca Mountain, Nevada. *Econ. Geol.*, v.89, p. 401-407.

Morgenstein, M., in prep. Quaternary Epithermal Uranium Silicate and Trace Element Sulfide Mineralization in Tertiary Tuffs and Sediments from Drill Hole NC-EWDP-3D. *Environmental & Engineer. Geosci.* (Stellavato Memorial Vol.).

Weiss, et al., 1994. Evaluation of Mineral Resource Potential, Caldera Geology, and Volcano-Tectonic Framework at and near Yucca Mountain. Part II, Major and Trace-element Geochemical Data. *Econ. Geol.*, v. 90, pages 2081-2090.

Zartman, R.E. and L. M. Kwak, Preliminary study of lead isotopes in the carbonate-silica veins of Trench 14, Yucca Mountain, Nevada. *USGS-OFR 93-690*, p. 1-18.

REFERENCES for Aqueous Values:

Castor, et al., 1996. Volcanic Rock-Hosted Uranium Deposits in Northwestern Nevada and Southeastern Oregon – Possible Sites for Studies of Natural Analogues for the Potential High-Level Nuclear Waste Repository at Yucca Mountain, Nevada, *NBMG-OFR 96-3*, p. 1-81.

Perfect et al., 1995. Hydrochemical Data Base for the Death Valley Region, California and Nevada. *USGS OFR 94-305*.

Shettel, D.L., in prep. Saturated Zone Hydrogeochemistry of the Early Warning Drilling Program, Nye County, Nevada. *Environmental & Engineer. Geosci.* (Stellavato Memorial Vol.).

Tests to Explore Specific Aspects of the Corrosion Resistance of C-22

Professor Aaron Barkatt
Dr. April Pulvirenti
Catholic University of America

Dr. Jeffrey A. Gorman
Dr. Chuck Marks
Dominion Engineering, Inc.

Performed for the State of Nevada
and Geosciences Management Inc.

October 18, 2000
ACNW meeting
Rockville, Maryland



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Preliminary Tests in Aggressive Environments

- Purpose of tests was to determine in a preliminary fashion whether species such as lead, mercury, arsenic or sulfides could aggravate corrosion of C-22 (e.g., SCC, pitting or crevice corrosion).
- Tests explored acid and caustic environments with and without lead, mercury, arsenic and sulfides.
- Tests of U-bends, mostly at 250 °C.
- Tests of static disks at 163°C

These are very preliminary results, no proper tests



Species Concentration in Simulated 1000x J-13 Concentrate

Species	Concentration (ppm)
Ca ²⁺	30
Cl ⁻	6123
F ⁻	1550
C	1546
Si	8404
K ⁺	4792
NO ³⁻	6729
Na ⁺	44082
SO ₄ ²⁻	15711
Li ⁺	36
B	17

*starting with
aggressive species
such as Pb + Hg
dissolved in J-13
water*



U-Bend Tests - Matrix and Results

Sample ID	Temperature (°C)	pH _{RT}	pH _T		Minerals: [#] (10g/Vessel)	Tuff? (10g/Vessel)	Accelerant *	Potential	Duration (days)	Results
1	250	2.6*	5.6	no	yes	no	none	---	32	tarnished
2	250	2.6*	5.6	no	no	no	none	---	32	slight pitting
3	250	12.5	9.6	no	yes	no	none	---	32	tarnished
4	250	12.5	9.6	no	no	no	none	---	32	tarnished
5	RT	2.6*	2.6	no	yes	no	H ₂	---	61	none
11	200	12.5	9.8	no	yes	yes	none	---	35	none
12	250	0.53 [†]	1.6	no	no	no	Pb	---	15	through specimen crack
14	250	11.92	9.6	no	no	no	S	---	21	tarnished
15	250	1.32 [†]	4.53	no	no	no	Hg	---	8	very severe pitting
W-1	250	2.6*	5.6	yes	yes	no	none	---	32	tarnished
W-2	250	2.6*	5.6	yes	no	no	none	---	32	slight pitting
W-3	250	12.5	9.6	yes	yes	no	none	---	32	tarnished
W-4	250	12.5	9.6	yes	no	no	none	---	32	tarnished
W-5	RT	2.6*	2.6	yes	yes	no	H ₂	---	61	none
W-13	200	12.5	9.8	yes	yes	yes	none	+200mV	35	none
W-14	250	12.11	9.6	yes	no	no	Pb	---	29	tarnished
W-15	250	0.59 [†]	1.6	yes	no	no	S	---	29	severe pitting

* with sulfuric acid; † with hydrochloric acid;

- Hydrogen Gas Saturated and Over-Laid; Lead Acetate at 5000 ppm Pb;
Sodium Sulfite at 3200 ppm S; Mercury Acetate at 6300 ppm Hg;

mineral mixture consists of 70% pyrite (FeS₂), 20% galena (PbS)

5% cinnabar (HgS) and 5% realgar (As₂S₂)



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place in autoclave & cool

Test lasted one month

Tests did not deaerate, oxygen 150 ml / 100 ml air.

800 psi in autoclave

Canister may have their stress level in a changed case

U-Bend Tests - Matrix and Results (Cont.)

Sample ID	Temperature (°C)	pH _{RT}	pH _T	Accelerant	Duration (days)	Concentration in Post Test Solution (mg/L or ppm)					% Weight Lost	Results
						Cr	Ni	Fe	Mo	Pb		
1	250	2.6	5.6	none	32	3	70	120.5	NM	3.1	0.14	tarnished
2	250	2.6	5.6	none	32	21	39	3.2	NM	0.6	0.10	slight pitting
3	250	12.5	9.6	none	32	1	1.2	0.35	NM	0	0.00	tarnished
4	250	12.5	9.6	none	32	43	1.4	0.45	NM	0.65	0.00	tarnished
5	RT	2.6	2.6	H ₂	61	3.4	19	82	0.7	5.85	0.00	none
11	200	12.5	9.8	none	35	0.8	0.7	1.1	3.1	7.3	0.00	none
12	250	0.53	1.6	Pb	15	16	3217	857	31	NM	0.88	through specimen crack
14	250	11.92	9.6	S	15*	2	0.8	6.3	21	NM	0.00	tarnished
15	250	1.32	4.53	Hg	8	5.1	413	65	151	12.1	0.54	very severe pitting
W-1	250	2.6	5.6	none	32	3	70	120.5	NM	3.1	0.12	tarnished
W-2	250	2.6	5.6	none	32	21	39	3.2	NM	0.6	0.13	slight pitting
W-3	250	12.5	9.6	none	32	1	1.2	0.35	NM	0	0.00	tarnished
W-4	250	12.5	9.6	none	32	43	1.4	0.45	NM	0.65	0.00	tarnished
W-5	RT	2.6	2.6	H ₂	61	3.4	19	82	0.7	5.85	0.00	none
W-13	200	12.5	9.8	none	35	0.8	0.7	1.1	3.1	7.3	0.00	none
W-14	250	12.11	9.6	Pb	29	117	0.3	1.8	91	1311	0.00	tarnished
W-15	250	0.59	1.6	S	29	15	2574	507	0.1	4.4	0.42	severe pitting

* mid-test sample, not post-test solution

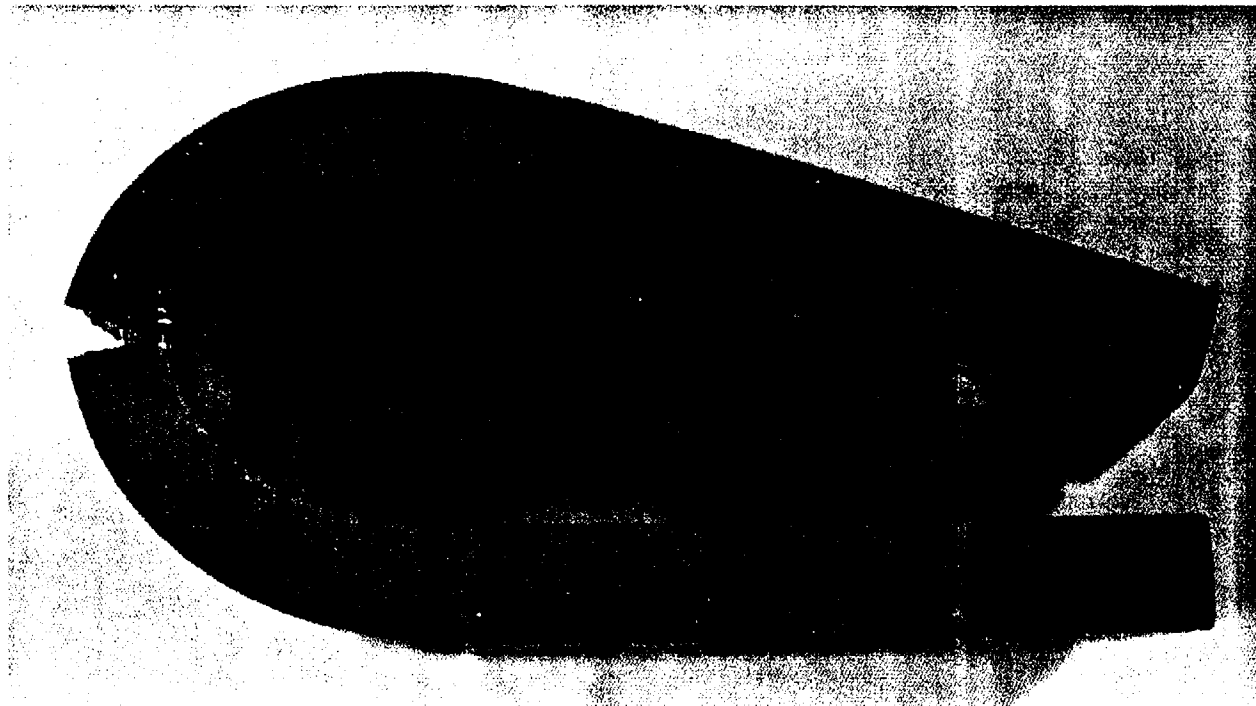
*- such high acidity - want to see something
- not very realistic*



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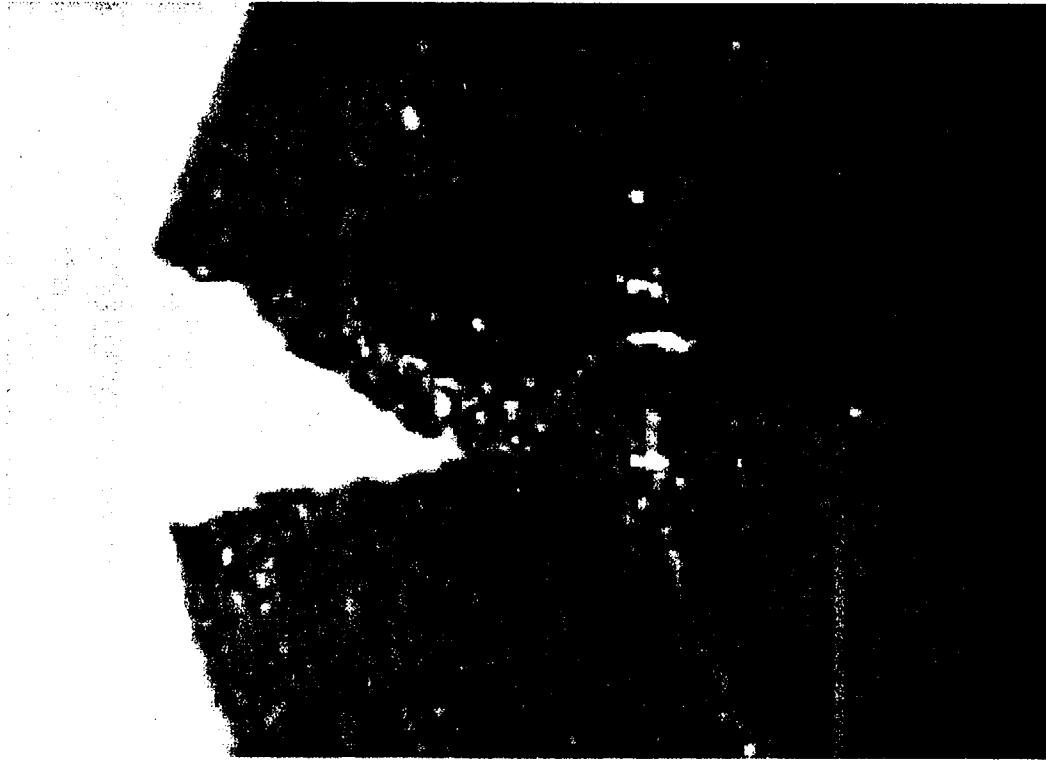
Sample 12 (Lead-Acid)

*Acid
High Temp
High Press*



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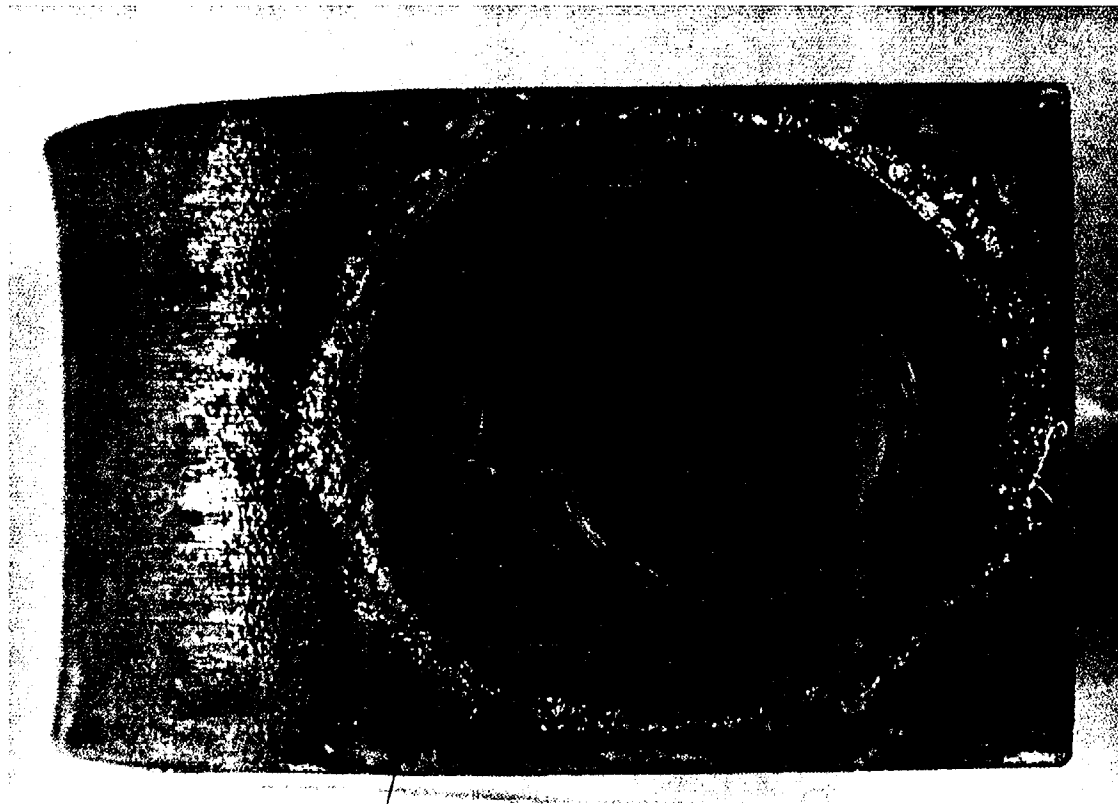
Sample 12 (Lead-Acid)



Sample 12 (Lead-Acid)



Sample 12 (Lead-Acid)



crevice getting
attack
around the water

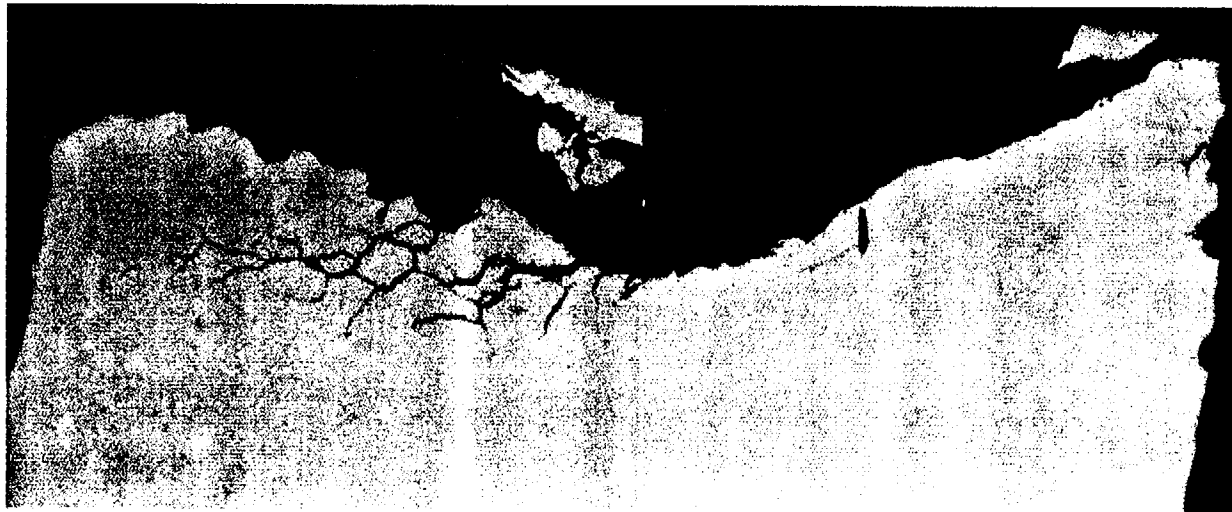
SOLTS
have been
washed
off

fasten effects?
exp. to be
inert?
possibly get
shredded out
of Teflon.



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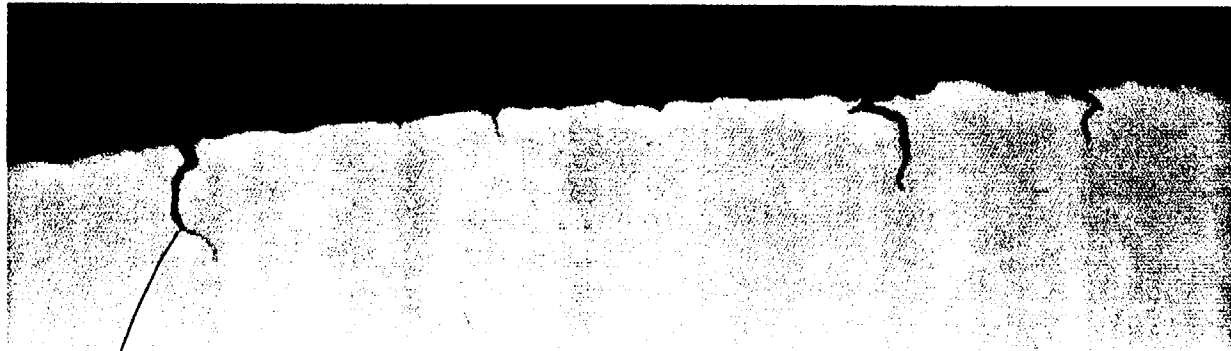
Sample 12 (Lead-Acid)



Sample 12 (Lead-Acid)



Sample 12 (Lead-Acid)

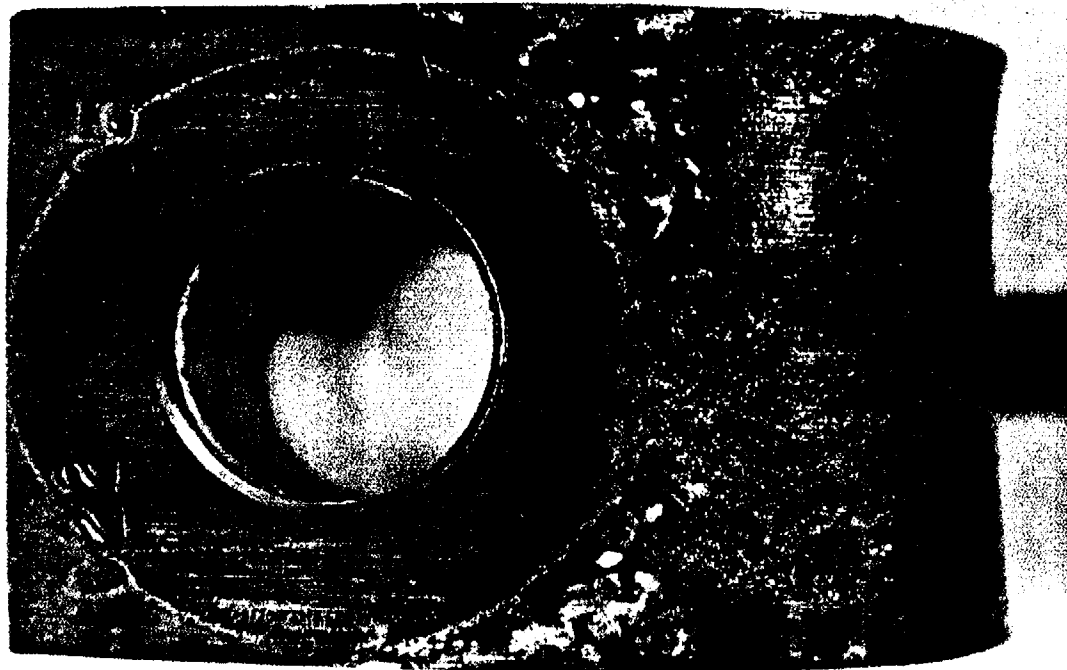


*intergranular
staining*



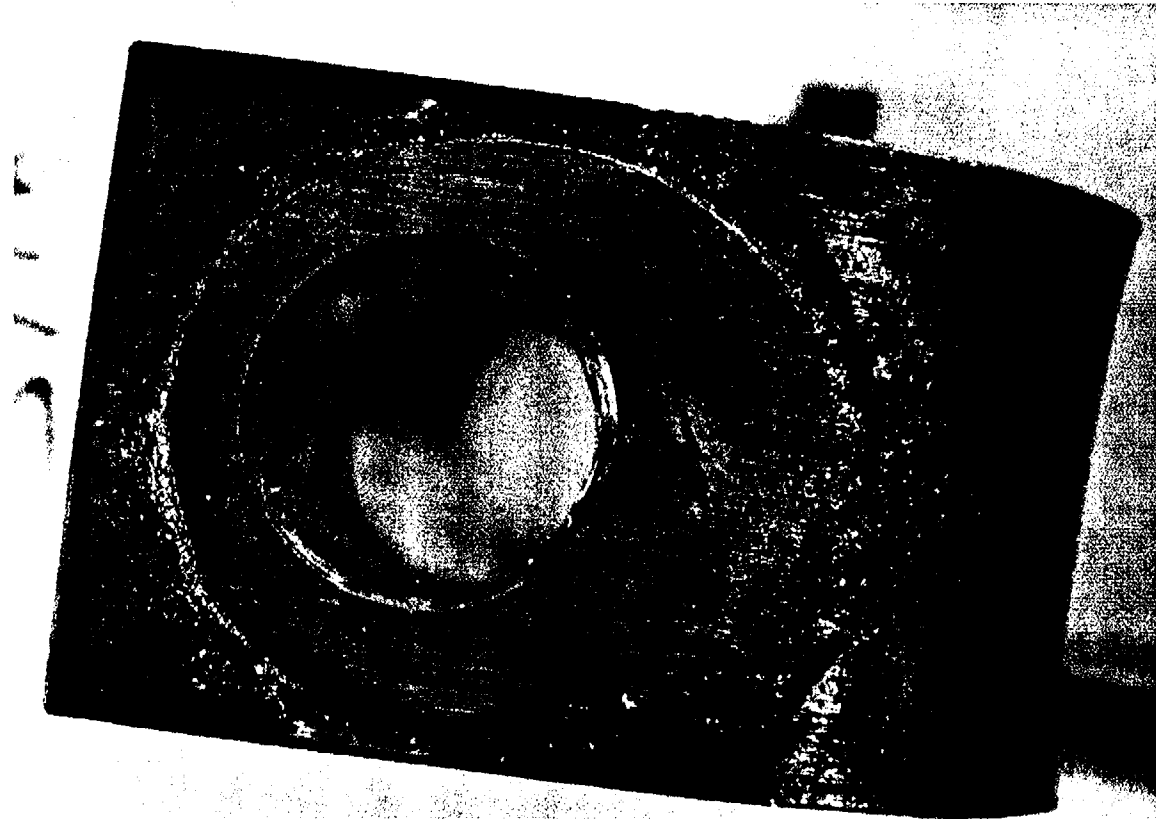
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Sample 15 (Mercury-Acid)



Sample W-15 (Sulfur-Acid)

*~ sodium sulfide
(sulfur leads not better than
others ??)*



- NO STRESS
- COOLING
- FOR ANALYSIS

Concentrations of Main Alloying Elements After Testing

Tests of C-22 Unstressed Disks, 20 mL of solvent, 163°C, 15 days

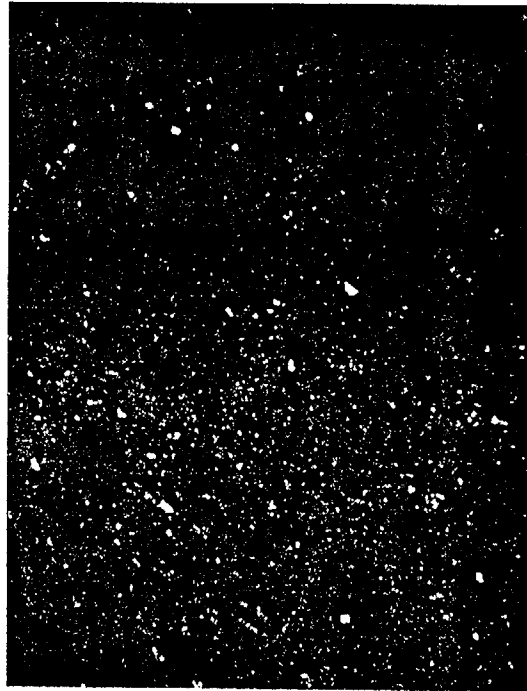
Additives to 1000x J-13 Water	pH _{RT}	Concentrations (mg/L or ppm)			
		Cr	Ni	Fe	Mo
2.25% H ₂ O ₂	12.89	3.8	0.7	1.5	3.3
3.86% Pb(OAc) ₂	13.15	4.3	0.5	0.2	4.1
4.34% CuCl ₂	13.21	2.7	0.4	0.4	2.1
4.50% Na ₂ CO ₃ · 1.5H ₂ O ₂ + 1.93% Na ₂ SiO ₃	13.25	4.4	0.8	2.5	3.3
3.50% As ₂ O ₃	12.90	1.8	0.7	1.3	1.4
4.50% FeCl ₃	13.17	1.2	0.3	0.4	2.3
none	13.20	2.8	1.0	2.1	2.3
4.0% Hg(OAc) ₂	13.15	75.9	0.7	4.2	60.9
3.86% Pb(OAc) ₂ + H ₂ SO ₄	2.52	250.4	1868.8	7.0	22.0
4.0% Hg(OAc) ₂ + H ₂ SO ₄ *	2.65	421.5	1727.5	48.8	266.3

* Test duration only 7 days

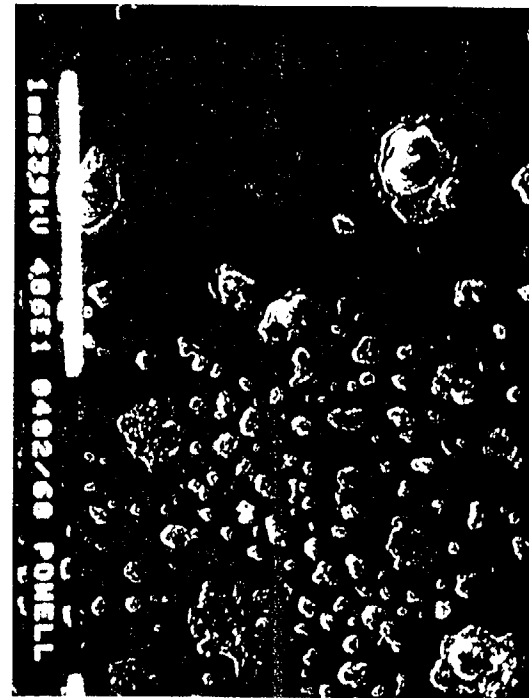
How much C-22 dissolves?



Sample C20 (Lead-Acid)



Stereomicroscope



SEM



Main Findings - Tests of U-Bends

30-day tests were conducted on stressed U-bend samples in modified 1000x concentrated J-13 water at 250°C

↑ why not 100 or 10,000 ~ EAC modeling results, solution used analyzed

- Acidified solution ($\text{pH}_{\text{RT}} 0.5$) without additives:
 - The corrosion is mild and involves shallow general corrosion and pitting, possibly with some deposition.
- Acidified solution ($\text{pH}_{\text{RT}} 0.5$) with mercury:
 - Strong general corrosion, pitting, and deposition of corrosion products are observed.
 - No accumulation of mercury is observed on corroded surface.



Main Findings - Tests of U-Bends (Cont.)

- Acidified solution ($\text{pH}_{\text{RT}} 0.5$) with lead:
 - Cracking occurs first in a transgranular mode.
 - When this cracking relieves the stress (at about the halfway point), crack growth continues in an intergranular mode.
 - Numerous secondary cracks, mostly intergranular, are observed.
 - Corrosion product deposition is observed, mostly in the transgranular (TG) region. The deposit-covered TG region is enriched in silicon and depleted with respect to nickel and tungsten.
 - Pitting may precede the transgranular cracking.
 - A large amount of lead concentrates at the crack surface.
- The corrosion mechanism in the presence of lead appears to be different than the mechanism in the presence of mercury.



Main Findings - Tests of Unstressed Disks

In 15-day tests on unstressed disks in J-13 water concentrated X1000 at 163°C, corrosive attack was identified in specimens exposed to moderately acidic environment ($\text{pH}_{\text{RT}} 2.5$) in the presence of lead.

- The surfaces of the specimens were strongly pitted.
- Extensive deposition of corrosion products was observed.
- A very large amount of lead concentrated on the pitted surface.
- Ongoing tests indicate that mercury aggravates pitting.



Main Findings - Tests of Unstressed Disks: Chemical Analysis of Dissolved Species

- In moderately acidic media ($\text{pH}_{\text{RT}} 2.5$) both lead and mercury caused extensive dissolution of C-22 ingredients, in particular nickel.
- In basic concentrated J-13 ($\text{pH}_{\text{RT}} 13$) mercury, but not lead, caused moderately significant dissolution of chromium and molybdenum.
- In general, surface characterization and wet analysis agree with respect to lead and mercury exhibiting large specific effects of enhancing C-22 corrosion.

*concentration
on the surface*



Conclusions from Preliminary Tests

- The preliminary tests indicate that, in some environments, small amounts of aggressive species that could be present in the repository water, such as lead and mercury, can strongly aggravate pitting, crevice corrosion and SCC of C-22.
- It is concluded that the qualification program for alloy C-22 may need to evaluate the possible presence and effects of aggressive species such as lead, mercury, arsenic, and sulfides.



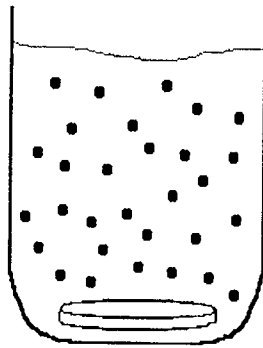
Concentration versus Inventory

- Aggressive species concentrations may be less important than their inventories (total mass in the environment)
- If C-22 adsorbs aggressive species, surface concentrations will be high, even if environmental concentrations are low
- High surface concentrations could be deleterious
- Geological measurements indicate that aggressive species inventories are high, even though concentrations may be low

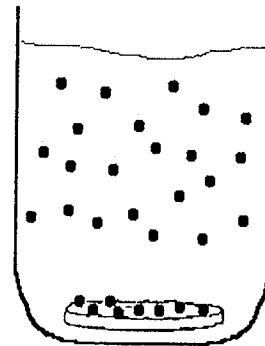


Concentration Hypothesis

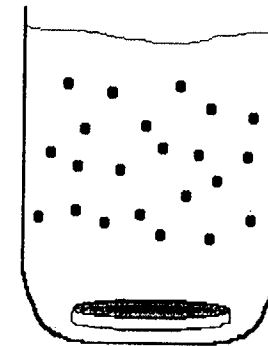
High concentrations of aggressive species
are required for accelerated corrosion



Pb concentrated
in solution



Little or no lead sorbed
to the surface

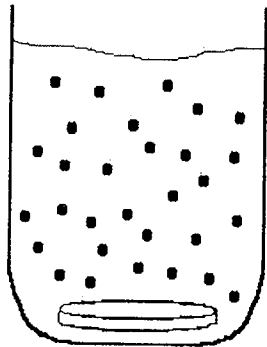


Most Pb remains in
solution and does not
contribute to corrosion

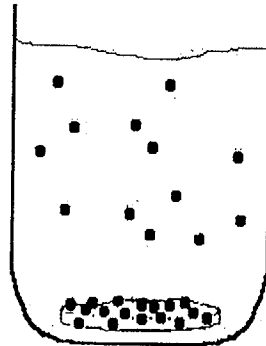


Adsorption Hypothesis

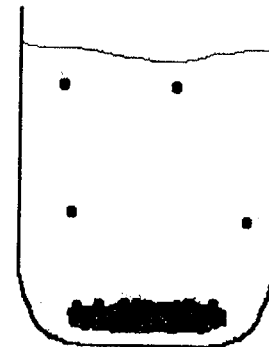
High inventories of aggressive species are required for accelerated corrosion



Pb concentrated
in solution



All Pb is eventually
scavenged by the C-22



All Pb contributes to
corrosion — very little
remains in solution



Lead Adsorption Testing

- Unstressed C-22 Disks
- J-13 x1000, minus lead precipitating species
- 160°C
- 14 day incubation
- Several levels of lead (<0.01 to 275 ppm in 15 ml)
- Measured lead
 - original solution
 - decanted solution



Results of Lead Adsorption Tests

Initial Pb		Pb in Decanted Solution		Percent Sorbed on C-22*	Appearance
Concentration	Inventory	Concentration	Inventory		
ppm	µg	ppm	µg		
<0.01	< 0.01	<0.01	< 0.01	—	Almost unchanged
35	0.518	4.7	0.07	87	Light tarnish
125	1.88	0.9	0.014	99	Light tarnish
275	4.12	14.4	0.216	95	Tarnish

*16 °C
Test Temp*

nitrate and

* Calculated based on fraction of initial inventory absent from the decanted solution

How much Pb is removed and on C-22 in an actual still process also get more C-22 common.



Lessons from Nuclear Power Plant Experience

Numerous materials selected on basis of good general corrosion resistance have turned out to be susceptible to SCC. Examples include:

- Austenitic stainless steels (SS) for BWR structural materials
- Inconel 600 for PWR steam generator (SG) tubes
- X750 in AH heat treatment for bolting and similar hardware
- A286 for reactor internals bolting
- 17-4 PH SS for high temperature valve parts and bolting
- Martensitic SS for bolting and other hardware
- Zircaloy fuel rod cladding

These case histories highlight that, despite apparently careful selection and qualification, significant corrosion in service can occur.



Example 1: BWR Stainless Steel Cracking

- Extensive cracking has occurred at welds in austenitic SS in BWR piping and internals. Lengthy and expensive inspections and repairs have been required.
- Austenitic SS was chosen based on its good general corrosion resistance. Selection failed to adequately consider:
 - Effects of sensitization at welds
 - Effects of oxidizing potentials caused by radiolytically produced oxidants
 - Effects of residual stresses and local cold work due to grinding



Example 2: Inconel 600 SG Tube Cracking

- Extensive cracking has occurred of Inconel 600 SG tubes and has required extensive plant changes, water chemistry upgrades, inspections and SG replacements.
- Selection of Inconel was based on its good general corrosion resistance and resistance to chlorides, but failed to consider:
 - Large variation in susceptibility to SCC as a function of processing history and compositional variations (1000x!)
 - Effects of low potentials, cold work and residual stresses on SCC from primary side
 - Effects of oxidizing potentials, concentration of impurities (leading to high and low pH), and trace aggressive species (such as lead) on intergranular attack (IGA) and SCC from secondary side.
 - Effects of minor elements in the metal, such as boron, on susceptibility to SCC.



Example 3: Failures of High Strength Materials

- Many failures have occurred of high strength materials such as X750, A286, 17-4 PH, and martensitic SS. These have resulted in extensive inspections and replacements.
- Materials were selected based on their good general corrosion resistance. Selection failed to consider:
 - Susceptibility to SCC in long time exposure to reactor environments of material heat treated based on aerospace applications.
 - Effects of local residual stresses and cold work on susceptibility to SCC.
 - Effects of time at temperature on material properties (embrittlement) and susceptibility to SCC.
 - Needs for detailed quality control to assure that desired material conditions (proper heat treatment) are achieved.

*had
fail +
BWR
application.*



Example 4: SCC of Zircaloy Cladding

- Many failures occurred due to SCC of zircaloy fuel rod cladding associated with “pellet clad interaction.”
- Zircaloy was selected for fuel rod cladding because of its good general corrosion resistance and low neutron cross section. Selection failed to consider:
 - Effects of fission products such as iodine and cesium on possible SCC.
 - Effects of high strains and stresses caused by clad creep down onto pellets and subsequent pellet expansion.



Summary of Lessons Learned from Nuclear Power Plant Experience

- Reasons for unexpected failures include:
 - Full range of realistic service environments not considered (potential, pH, aggressive species)
 - Realistic range of material conditions and compositions not evaluated
 - Realistic range of total stresses (including residual stresses) and applied strains not adequately considered
 - Long term susceptibility in realistic environments not adequately tested (need for accelerated testing)
 - Aggravating effects of fabrication details, surface damage, and local residual stresses not adequately considered
 - Long term material aging effects not adequately addressed



Summary of Lessons Learned from Nuclear Power Plant Experience (Cont.)

- Main lesson - all of the above factors need to be addressed.
- Several of these factors may have not been suitably addressed to date for C-22.



Testing Status of Alloy C-22

While significant numbers of tests have been and are being performed of Alloy C-22, some aspects may require more attention:

- Tests thus far reported do not appear to have addressed possible effects of trace aggressive impurities such as lead, mercury, arsenic and sulfides on SCC and other modes of corrosion.
- Tests thus far do not appear to have addressed full range of water chemistries and concentrations that could occur, especially in heated crevices and under deposits.
- Tests thus far do not appear to have addressed full range of base material composition variations (including trace deleterious impurities) and conditions (e.g., welding, cold work and sensitization).



Objectives of the Experimental Program

- Identify the mechanisms of possible corrosion phenomena
 - Pitting
 - Crevice corrosion
 - Under deposit corrosion
 - IGA/SCC
- Determine the effects of crevices and deposits on the near field chemistry (pH, aggressive species concentrations and potentials) and the resultant effects of those chemistry changes on corrosion phenomena



Objectives of the Experimental Program (continued)

- Develop a scientifically based method for predicting the long term performance of Alloy C-22 using temperature accelerated experiments
- Evaluate the ability of Alloy C-22 to scavenge and concentrate aggressive species (lead, mercury, *etc.*)
- Determine the correct measure of aggressive species activity: inventory or concentration



Bases for Prediction of Performance of C-22 and Titanium Grade 7 and Paradigms

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**Meeting of ACNW-NRC
Rockwell Maryland**

00-10-17 to 19

Topics

- 1. Not a critique of AMR (Analysis and Modeling Report) nor PMR (Process Model Report).**
- 2. Mainly, a review of framework for prediction of performance as applied to C-22 and Ti Gr7.**
- 3. Identification of special concerns for storage of radioactive waste.**
- 4. Use of paradigms from commercial nuclear power development**
- 5. Framework of “corrosion based design approach” (CBDA) applied to performance and application of C-22 and Ti Gr7**

Conclusions about the Use of C-22 and Titanium for Yucca Mountain Application

1. Substantially inadequate knowledge about the conditions under which either C-22 or Ti-Gr 7 sustains SCC.
2. No corrosion testing of real environment on surfaces of engineering significance (heated surfaces with Yucca Mountain chemistries).
3. It is doubtful that any testing under isothermal conditions is substantively useful. *~ need heated*
4. Residual stresses on general surfaces of as-fabricated containers are not known and are likely to be adequate for SCC.
5. Global heat treatments necessary to reduce surface stresses may accelerate corrosion.
6. No evaluation of manufactured prototypes.
7. No prototype system for judging real environmental and corrosion systems. *~ history of metallurgy on Rxs.*
8. The development of materials and designs for the Yucca Mountain application could benefit substantially from considering the lessons to be learned from the development and application of commercial nuclear power.
9. Lack of early prediction of presence of water raises questions about other predictions.

Need

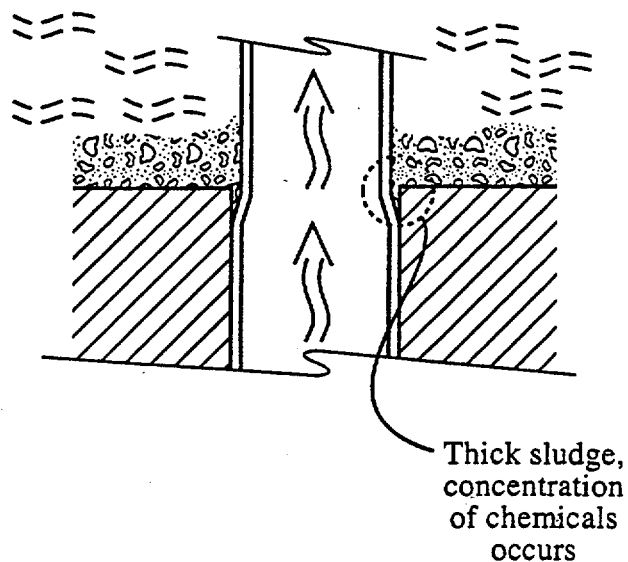
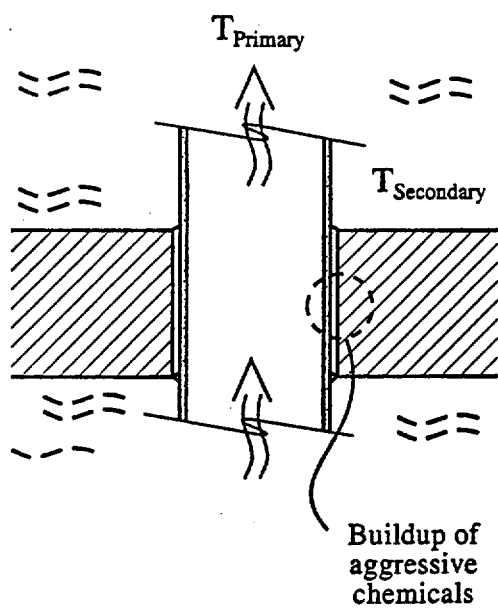
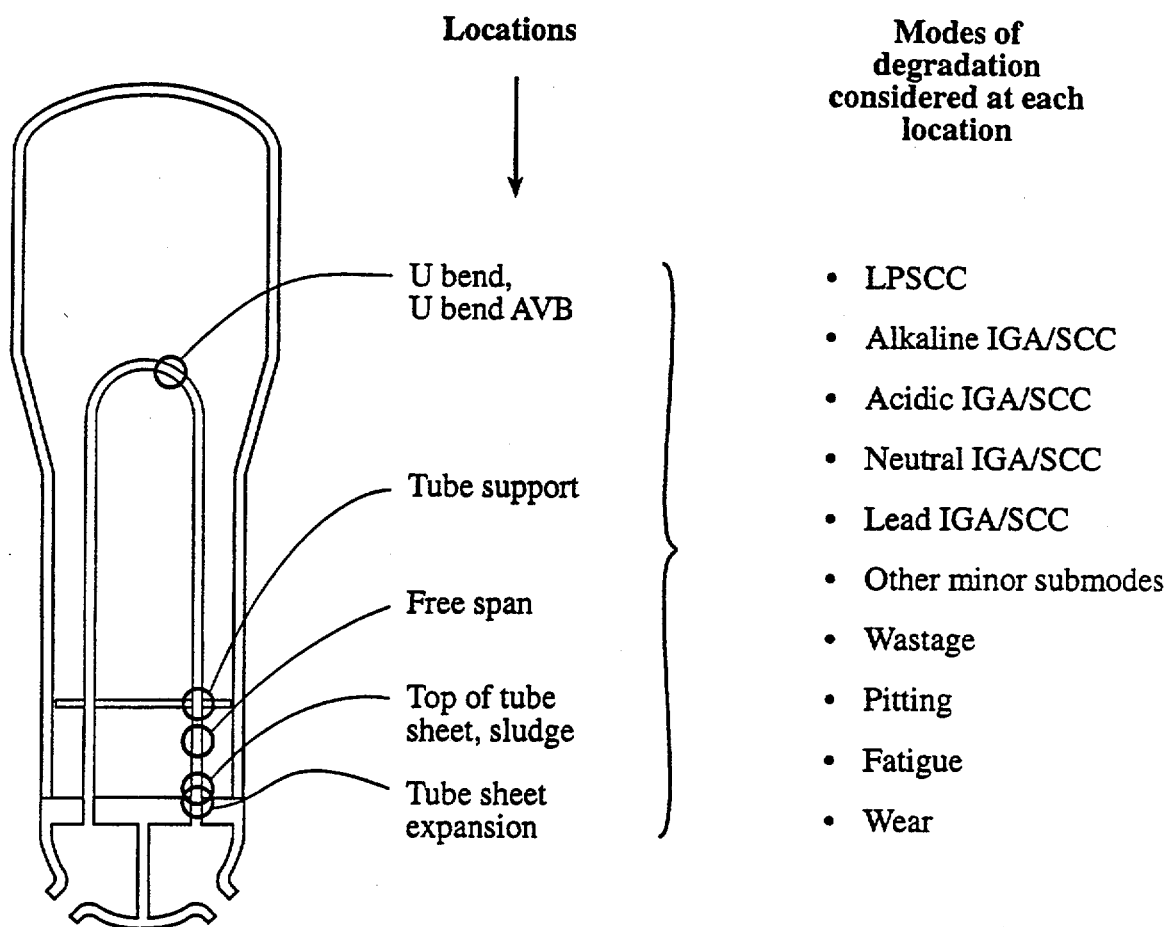
1. Corrosion testing methods for realistically heated surfaces.
2. Consideration of full set of Yucca Mountain chemistries accessible to heated surface
3. SCC mode diagrams for C-22 and Ti Gr7
don't know how materials will behave.
4. Assessment of stresses over whole surface
5. Manufacturing prototypes
6. System prototype where large system of environmental effects on movement of species can be assessed.

Special Concerns

- 1. Long term performance objective without capacity for intermediate inspection.**
- 2. Initial assumption of dry and now wet.**
- 3. Lack of prototype for testing of environment-material interactions**
- 4. Lack of manufactured prototype**
- 5. Lack of perspective on performance of C-22; assumption of "corrosion resistant alloy"**
- 6. Lack of perspective on performance of Ti-Gr7**
- 7. Lack of appreciation for hot surface on container.**
- 8. Lack of definition of chemical environment; Focus on J 13 well water as environment**
- 9. Necessity to use "Guilty until proven innocent approach" -- opposite of justice**
- 10. Metals are chemicals: surprise is not that they fail--surprise is that they work**

Paradigms from Commercial Nuclear Program

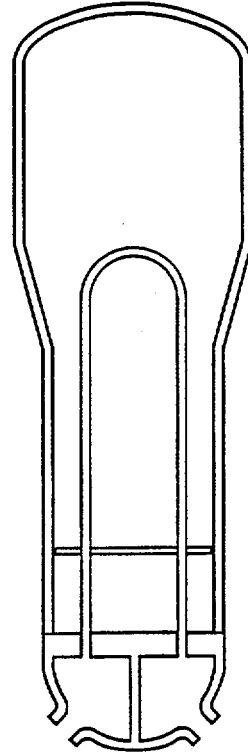
- 1. Enormous resources spent on SARs (Safety analysis reports) and ignore resources to prevent corrosion-related performance problems.**
- 2. Large focus on magical alloy, Alloy 600, with little supporting data.**
- 3. Dependence on "well established material" (Type 304) when large data base on deleterious effects of sensitization were well known.**
- 4. Lack of environmental definition, especially in heat transfer crevices and oxidizing conditions.**
- 5. Assumption that fossil water chemistries were applicable.**
- 6. Selection of basis for assuring life prediction: 40 year fatigue life**
- 7. Failure of fuel elements from inside: iodine SCC**
- 8. Decisions in a hurry (for sales) prevent orderly considerations of performance**
- 9. Use of model boilers and prototypes valuable (although never taken far enough)**
- 10. Global stress relief increases sensitivity to other SCC**
- 11. Residual stresses in as-fabricated and non-welded locations produce SCC**
- 12. Large differences in corrosion produced by slight changes in metallurgical structure**



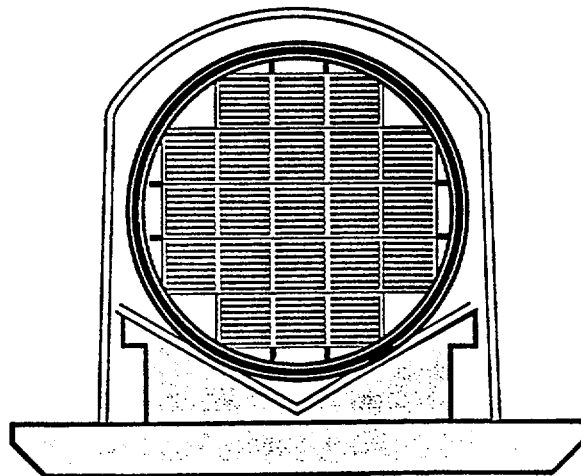
Comparison of Early Designs: Commercial Nuclear, Waste Package

- Paradigm:
- Appearance of adequate test environment
 - Corrosion resistant material but not proven
 - Heat transfer concentration
 - Lifetime objective with questionable mode basis

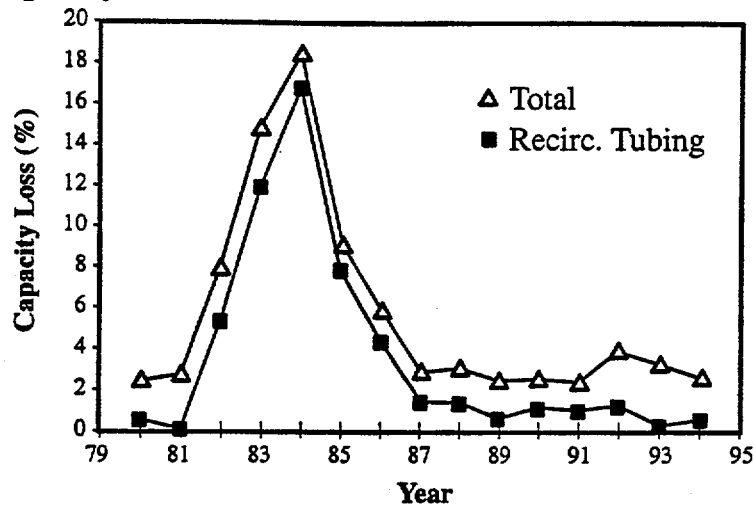
- Fossil water chemistry
> 100 ppm solids
- Alloy 600, not
susceptible to SCC
- Heat through crevices
concentrates impurities
- 40-year life based on
fatigue



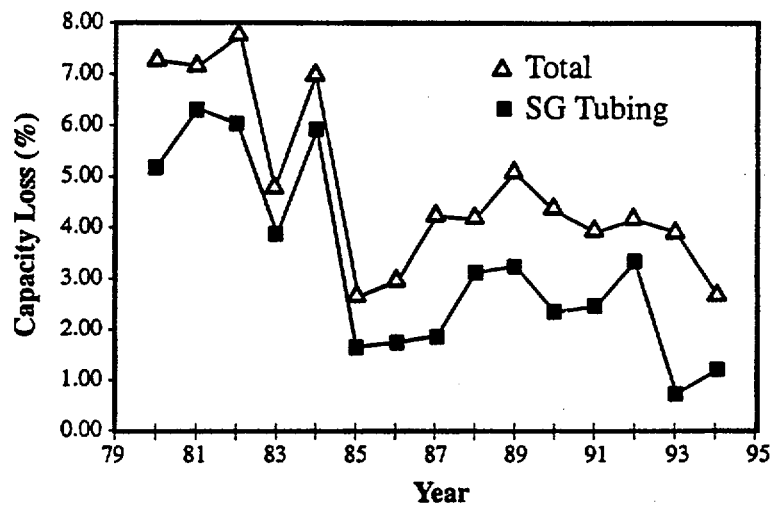
- J 13 well water with
concentrations
- C-22, corrosion
resistant
- Heat through surface
concentrates impurities
- 10,000-year life based
on BWR SCC Model



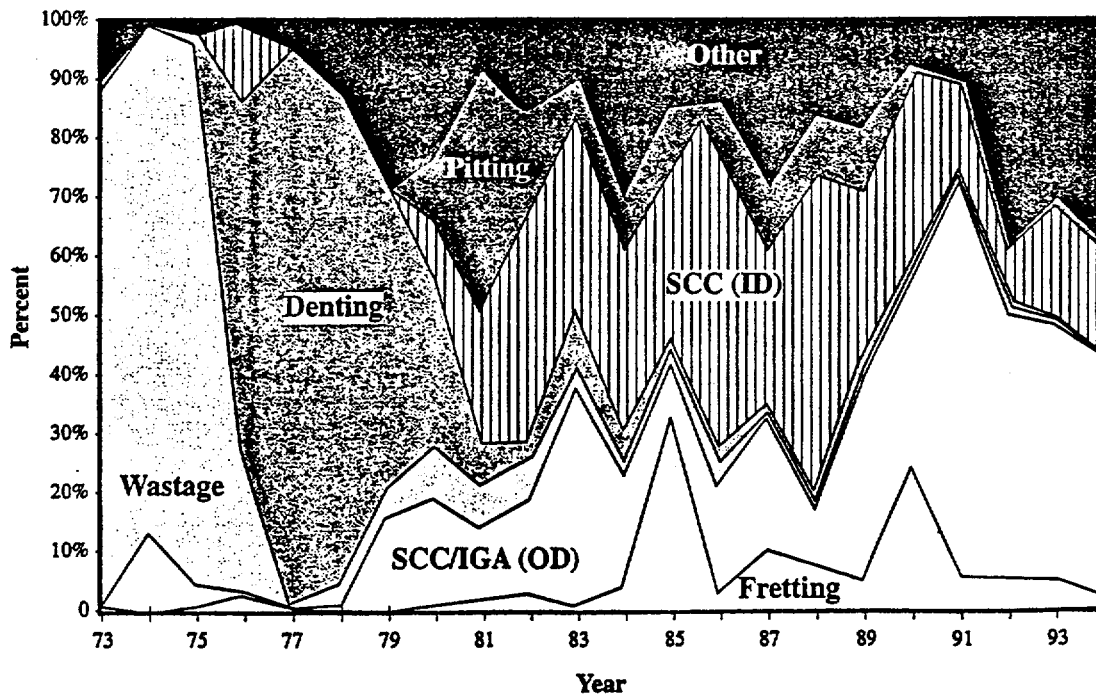
Capacity Factor Losses in US BWRs Due to Corrosion



Capacity Factor Losses in US PWRs Due to Corrosion

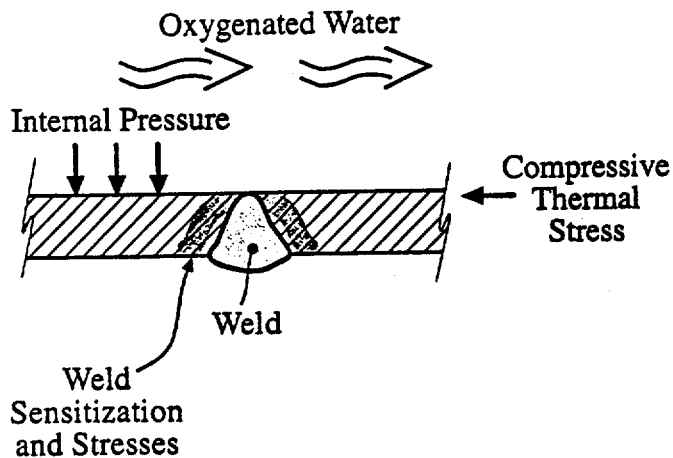
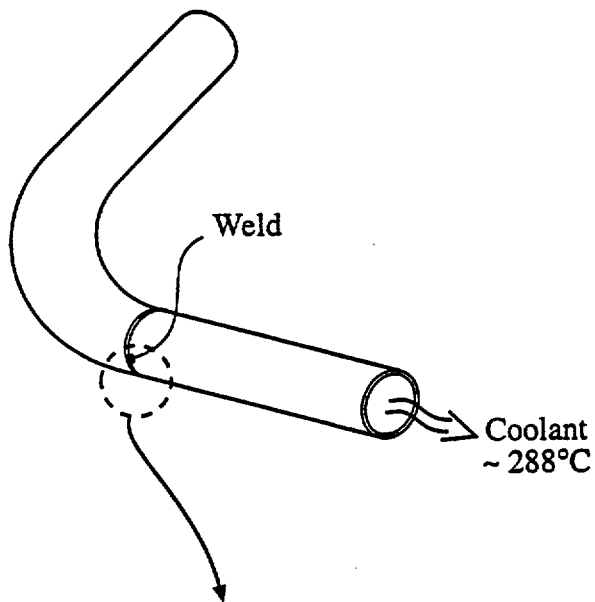


Causes of Steam Generator Tube Plugging in US PWRs

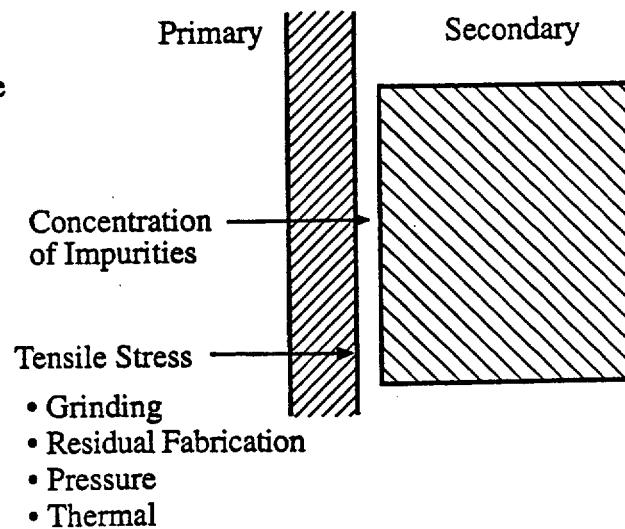
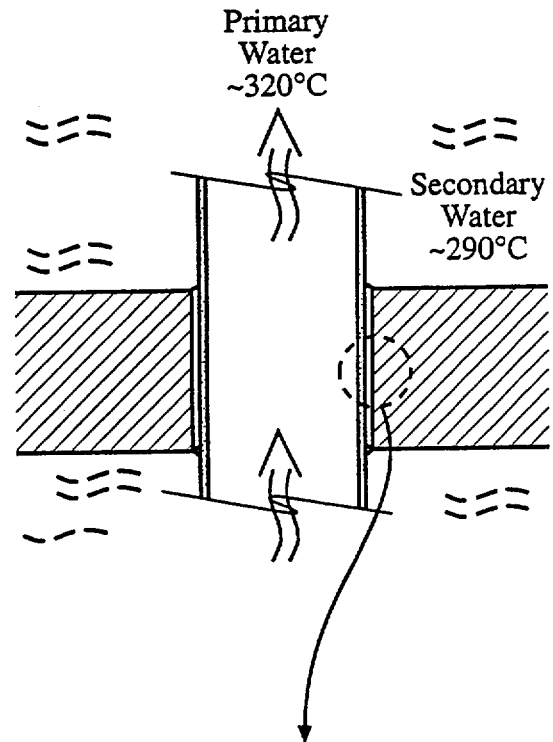


Which Paradigm for Stress Corrosion Cracking?

BWR Piping



PWR Secondary Side

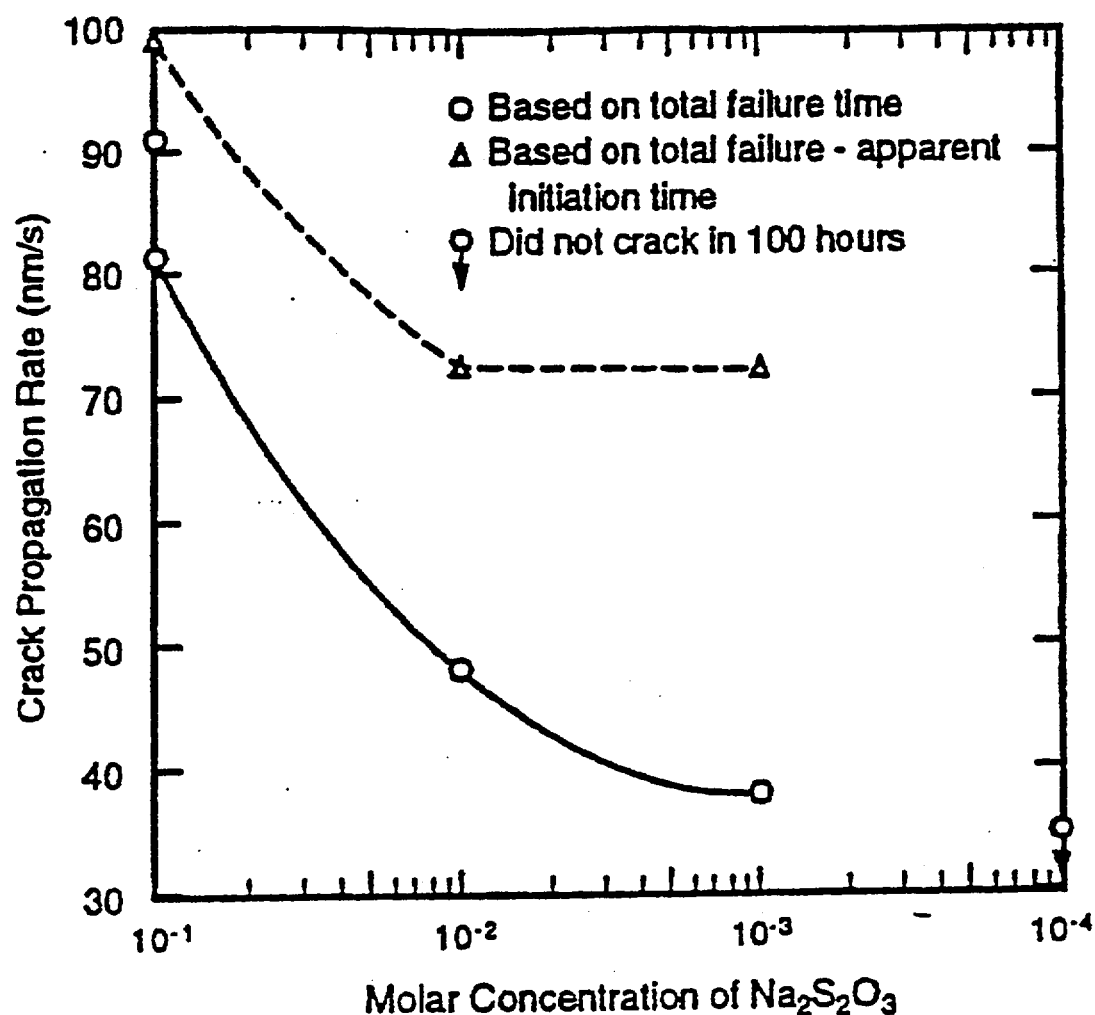


Corrosion Based Design Approach

- 1. Environment definition**
- 2. Material definition**
- 3. Mode definition**
- 4. Superposition**
- 5. Failure definition**
- 6. Statistical framework**
- 7. Accelerated testing**
- 8. Prediction**
- 9. Feedback**
- 10. Fix**

CBDA: Environmental Definition-- Applied to YM

- 1. Chemistry directly on the surface is what produces corrosion.**
- 2. Heated surface produces a totally different condition for corrosion than isothermal surface; heated surfaces are very efficient concentrators of impurities.**
- 3. Entire chemistry in mountain is relevant to heated surface, e.g.:**
 - Impurities in heated crevices of SGs**
 - Thiosulfate in TMI-3**
 - Sea water leakage at Millstone**
 - Sodium in LMFBRs**
- 4. No feedback control on environmental contamination.**
- 5. Thermal gradients in YM site produce new flows of water with new chemistries.**
- 6. Highest concentration (possibly chloride) are not always the most virulent, e.g. lead effects. Other impurities.**
- 7. "Environment" includes stress and temperature**
- 8. Heated surface on outside of drip shield**



Crack propagation rate for sensitized Alloy 600 as a function of concentration of borated thiosulfate at pH 3 based on two different considerations of crack propagation time; specimens held at an initial stress approximately the yield stress. From Bandy et. al.

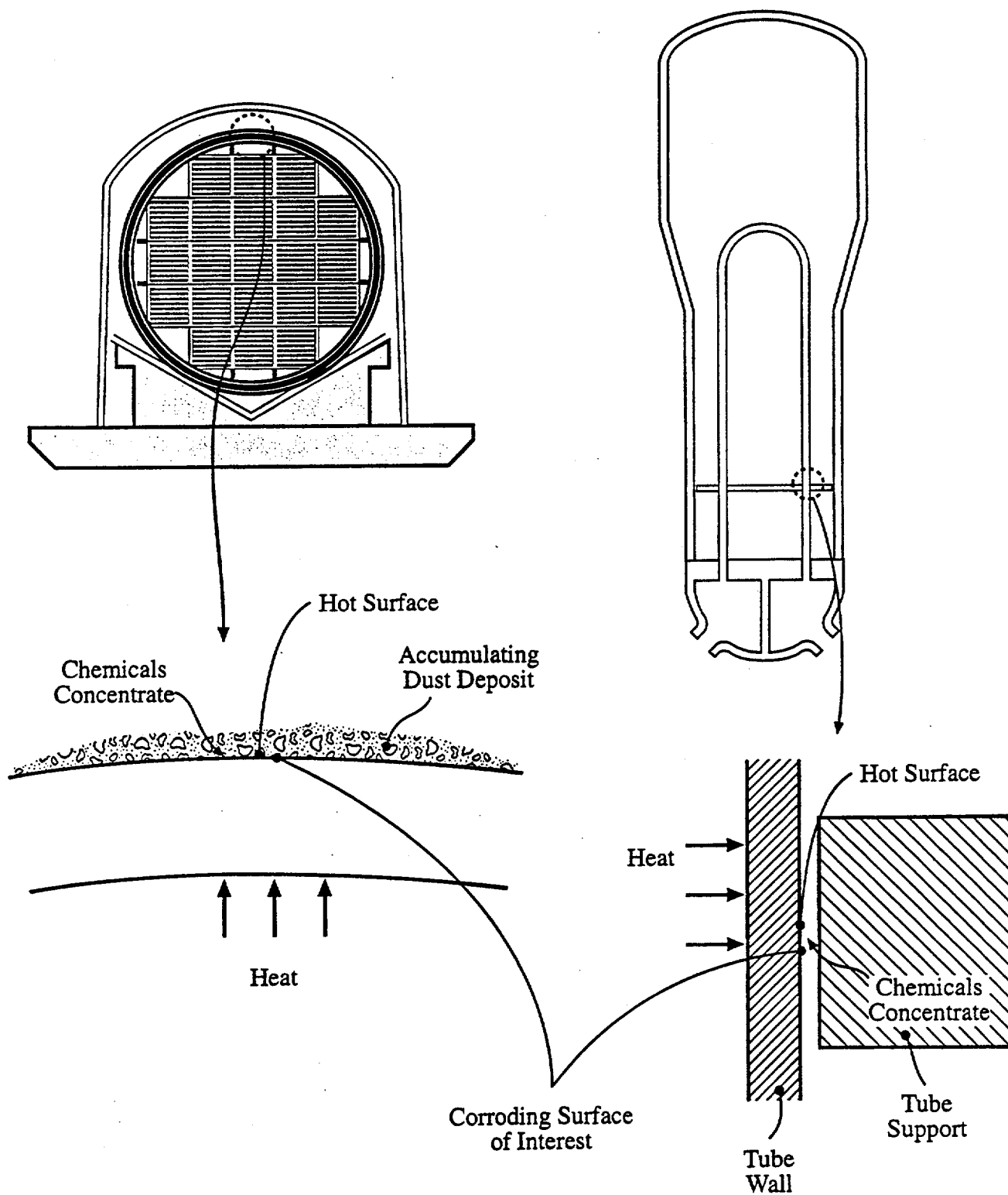
R. Bandy, R. Roberge, and R.C. Newman, *Corrosion*, Vol. 39, October 1983, p. 391.

R.W. Staehle, "Occurrence of Modes and Submodes of IGC and SCC," Control of Corrosion on the Secondary Side of Steam Generators, Eds. R.W. Staehle, J.A. Gorman and A. R. McIlree, Symposium held at Airlie, Virginia, October, 1995, NACE, Houston, 1996, pp. 135 - 208.

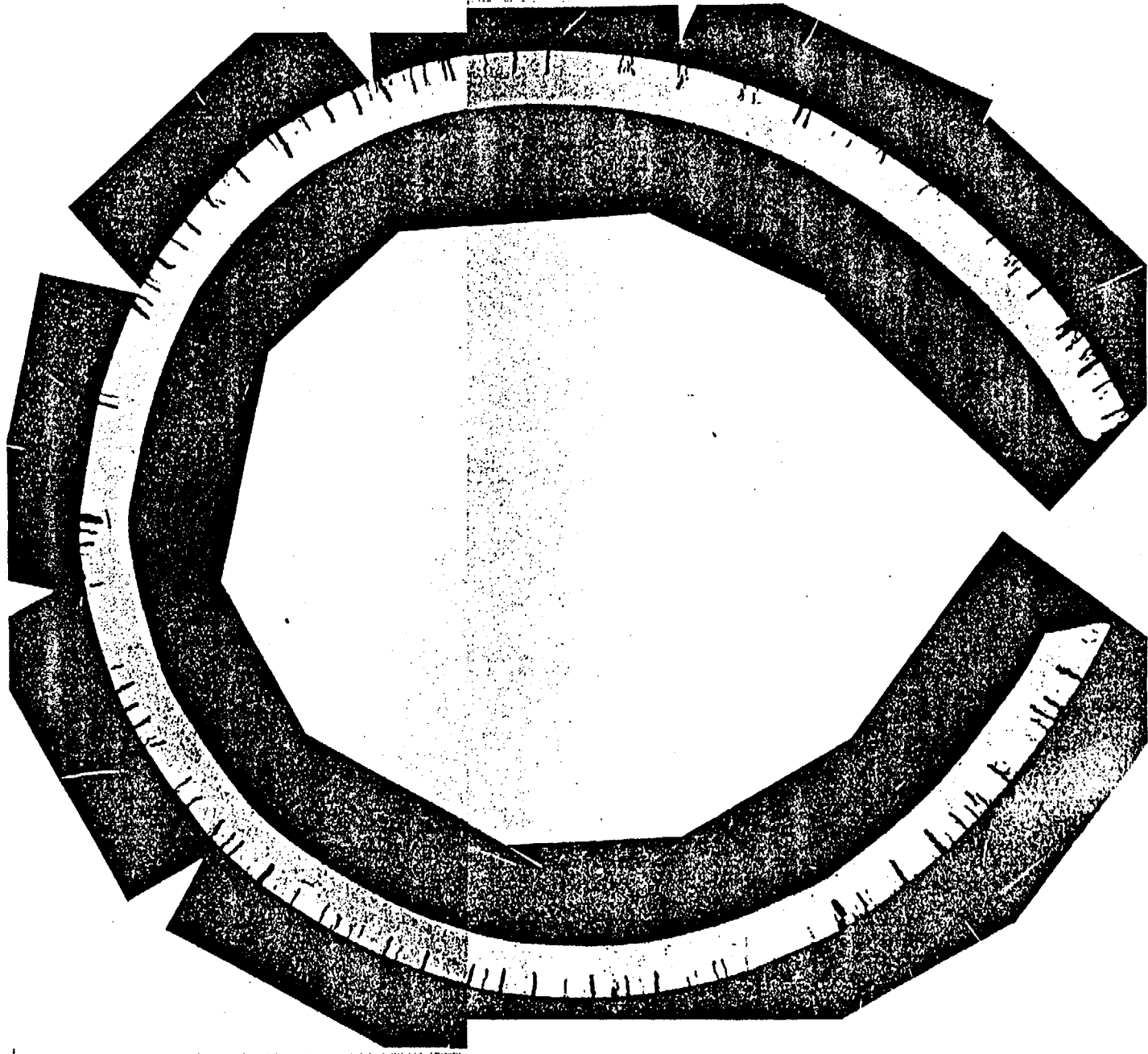
Table 25. The Composition of Several Aqueous Solutions used for Corrosion Testing
(UCRL-ID-132285, UCRL-ID-132286, UCRL-ID-132287)

Ion	Concentration (mg/L)			
	Simulate Dilute Water (SDW)	Simulated Concentrated Water (SCW)	Simulated Acidified Water (SAW)	Simulated Saturated Water (SSW)
	60 & 90°C	60 & 90°C	60 & 90°C	100°C
K	34	3400	3400	141600
Na	409	40900	40900	48700
Mg	1	<1	1000	0
Ca	0.5	<1	1000	0
F	14	1400	0	0
Cl	67	6700	24250	128400
NO ₃	64	6400	23000	1310000
SO ₄	167	16700	38600	0
HCO ₃	947	70000	0	0
Si	27 (60°C); 49 (90°C)	27 (60°C); 49 (90°C)	27 (60°C); 49 (90°C)	—

Hot Surfaces Concentrate Chemicals



CROSS SECTION VIEW OF TUBE R16C60 PULLED FROM
BEAVER VALLEY UNIT 1 STEAM GENERATOR A

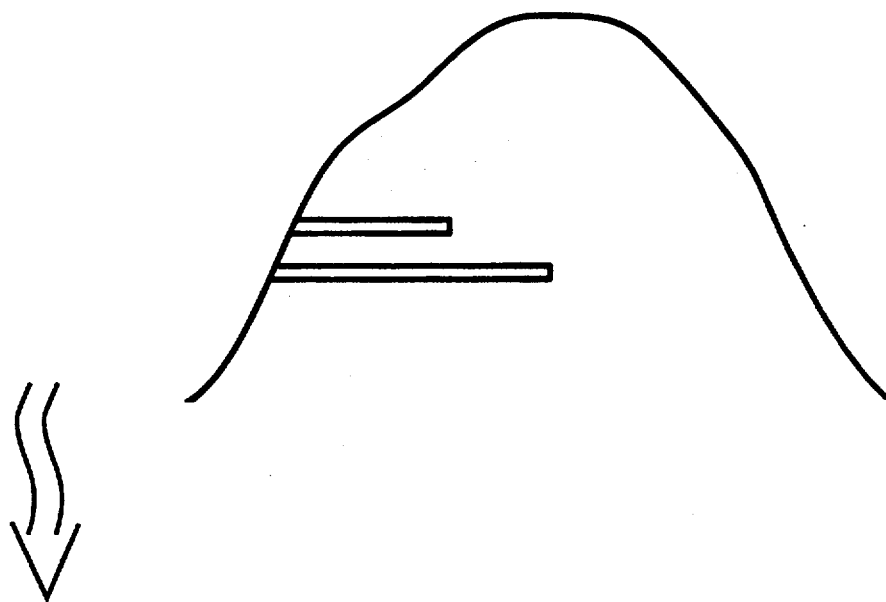


Consider All Available Elements for Deposit Concentration

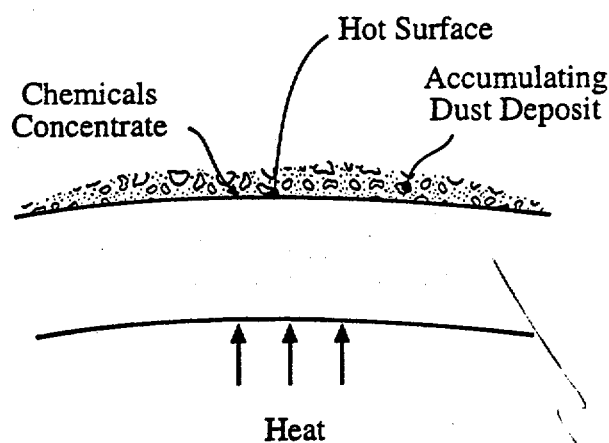
Water, Vapor, Gas Transport

As	Mg
Bi	Mo
C	N
Ca	Na
Cl	Pb
Cu	S
Cd	Sb
F	Se
Hg	Si
K	Te
	Zn

Yucca Mountain



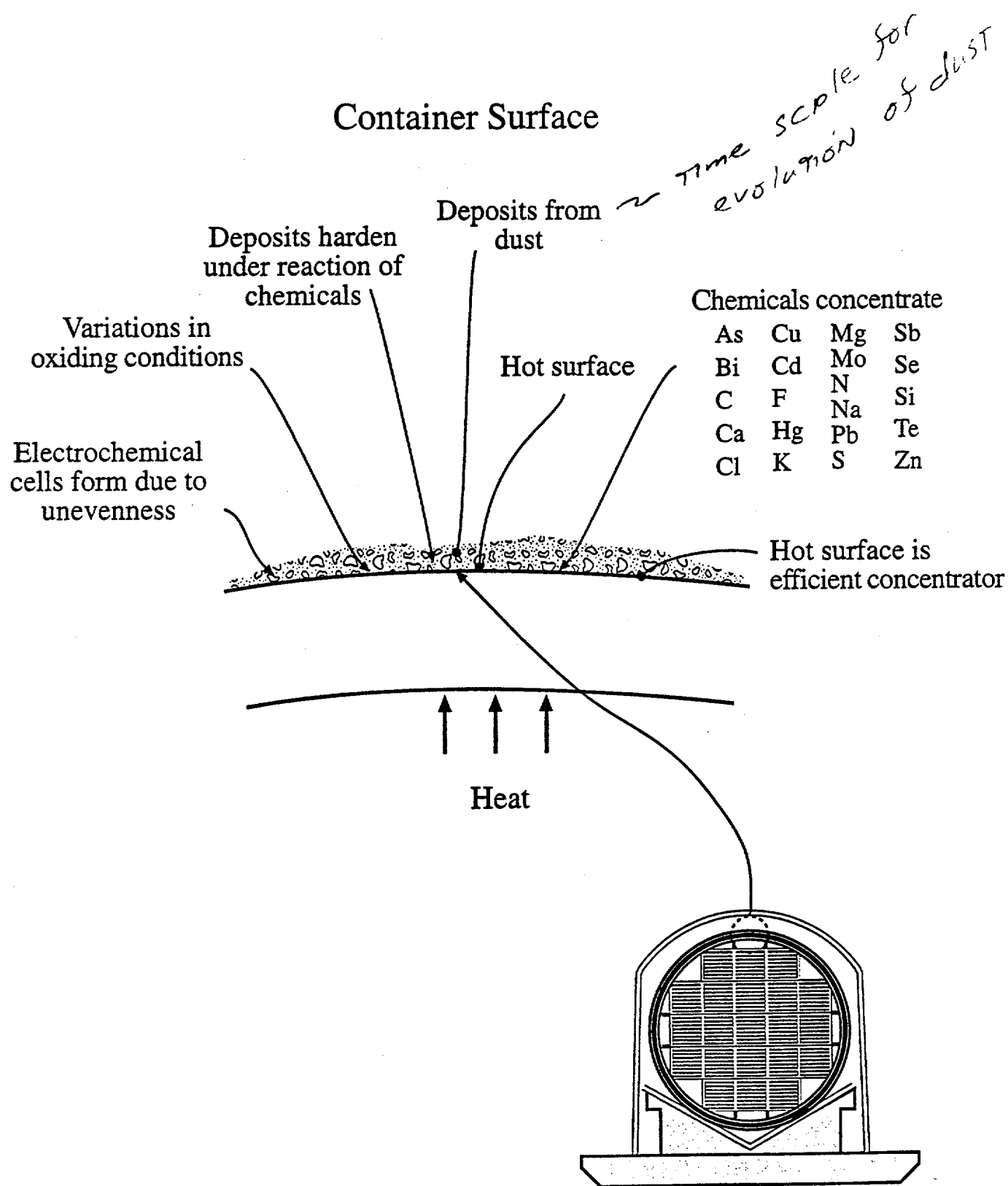
Container Surface

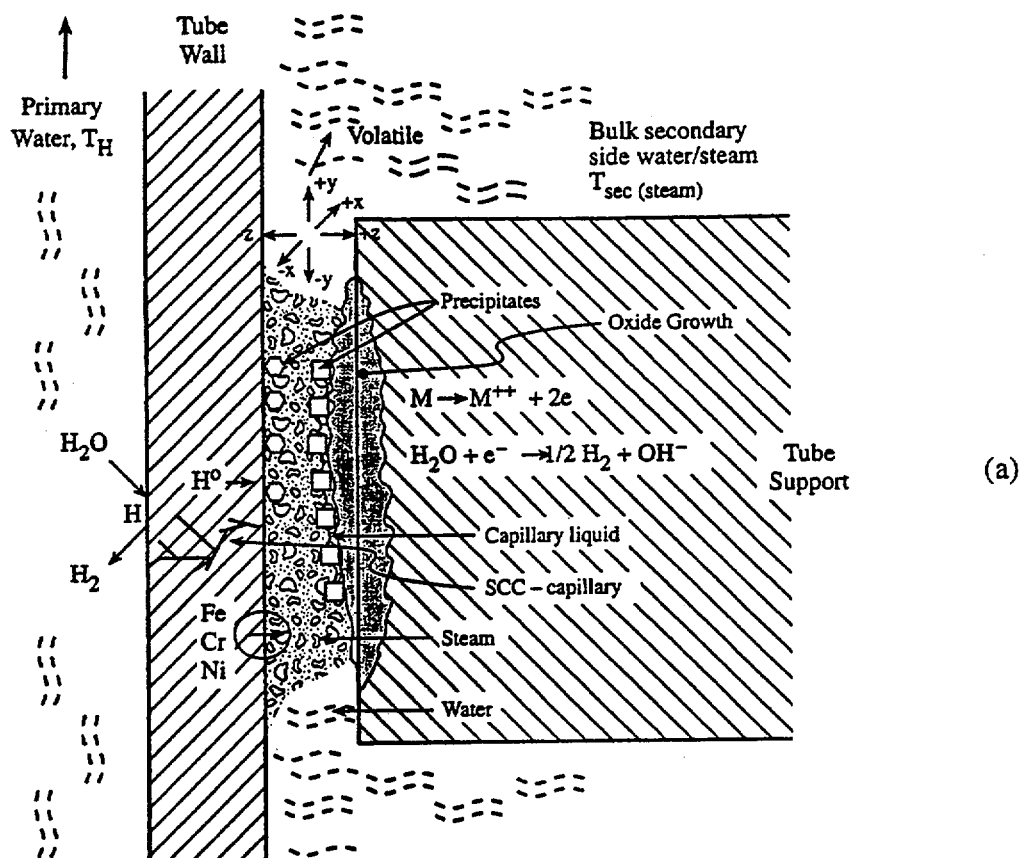


*These are heavily
assumption
a place to
start.*

CBDA: Environ Definition #2, Heated Surfaces of Waste Container,-- Applied to YM

- 1. Paradigm is heated surfaces on secondary side of PWR steam generators**
- 2. Very efficient concentrators even when solids are in range of tens of ppb.**
- 3. Local steam phases possible**
- 4. Change in local oxidizing condition to negligible oxygen at some locations**
- 5. Unevenness produces cells**
- 6. "Everything" seems to end up on heated surfaces: full chemistry of Yucca Mountain is accessible**
- 7. Water currents when rock is heated produces different chemistry access**
- 8. Dust deposits increase thermal resistance; also leads to gradients inside waste package**
 - Rate of dust deposition**
 - Chemistry of dust**
- 9. Detailed chemistry of backfill**

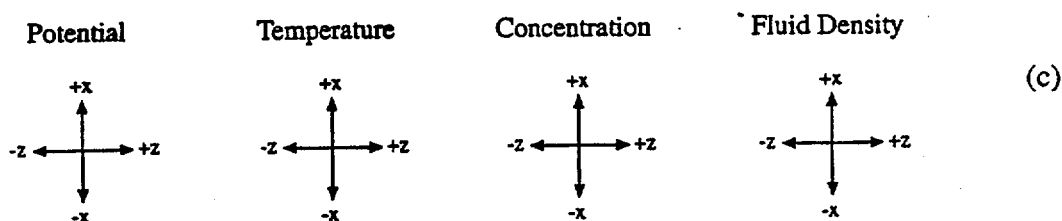




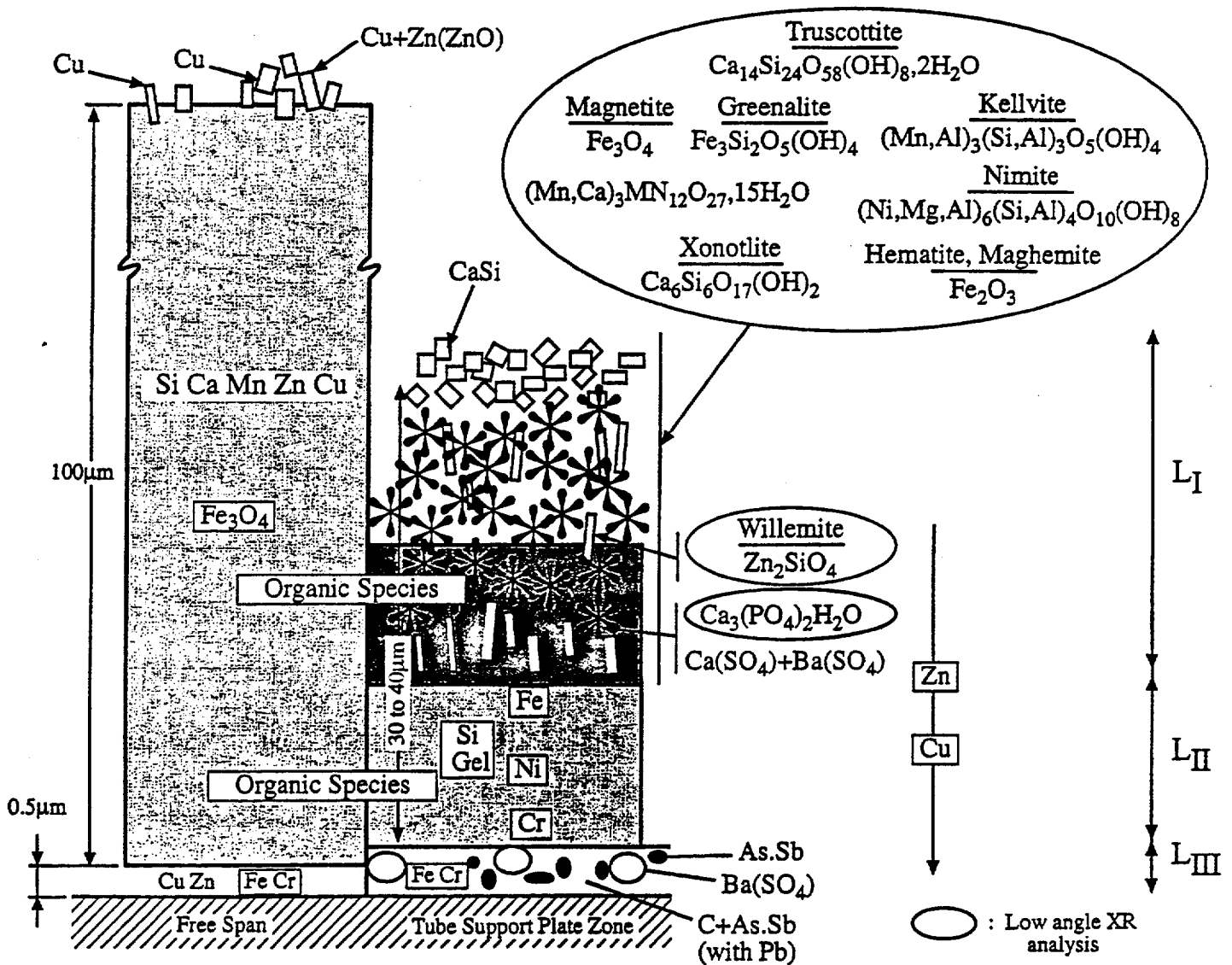
Cl	(Cl ⁻ , HCl)	B, Ti, Zn	(inhibitors)
SO _x	(S ⁺⁶ → S ⁺⁴ → S ⁺² → S ⁰ → S ⁻)	O ₂	(H ₂ O, compounds)
SiO _x	(SiO ₂ , complex compounds)	H ₂	(H ⁺)
AlO _x	(Al ₂ O ₃ , complex compounds)	N ₂ H ₄	(NH ₃ , N ₂)
Cu	(Cu ⁰ , Cu ⁺⁺ , CuO)	C	(CO ₃ ⁼ , organic)
Pb	(Pb ⁰ , PbO _x)	N	(NO _x , organic)
Na, Ca, Mg	(complex compounds)	Fe, Cr, Ni	(Fe ⁺² , Cr ⁺³ , Ni ⁺² , complex compounds)
Na ₂ HPO ₄	(retrograde compounds plus H ₃ PO ₄)		

(b)

Gradients



Schematic illustration of chemical processes which can occur in heat transfer crevices at the intersection of tubes and tube supports on the secondary side of steam generators used in pressurized water nuclear reactors. (a) The crevice geometry occurs between a tube with hotter water than the secondary side and a tube support which is cooler. (b) Chemicals concentrate and react in the sequestered geometry. Typical species of products are shown. (c) Inside the crevice, gradients in potential, temperature, concentration and density occur; these cause movements, further concentrations, and electrochemical cells.



Sketch of deposits and surface films observed on IGA affected tubes pulled from a French plant with copper alloy condenser and cooled by Loire river.

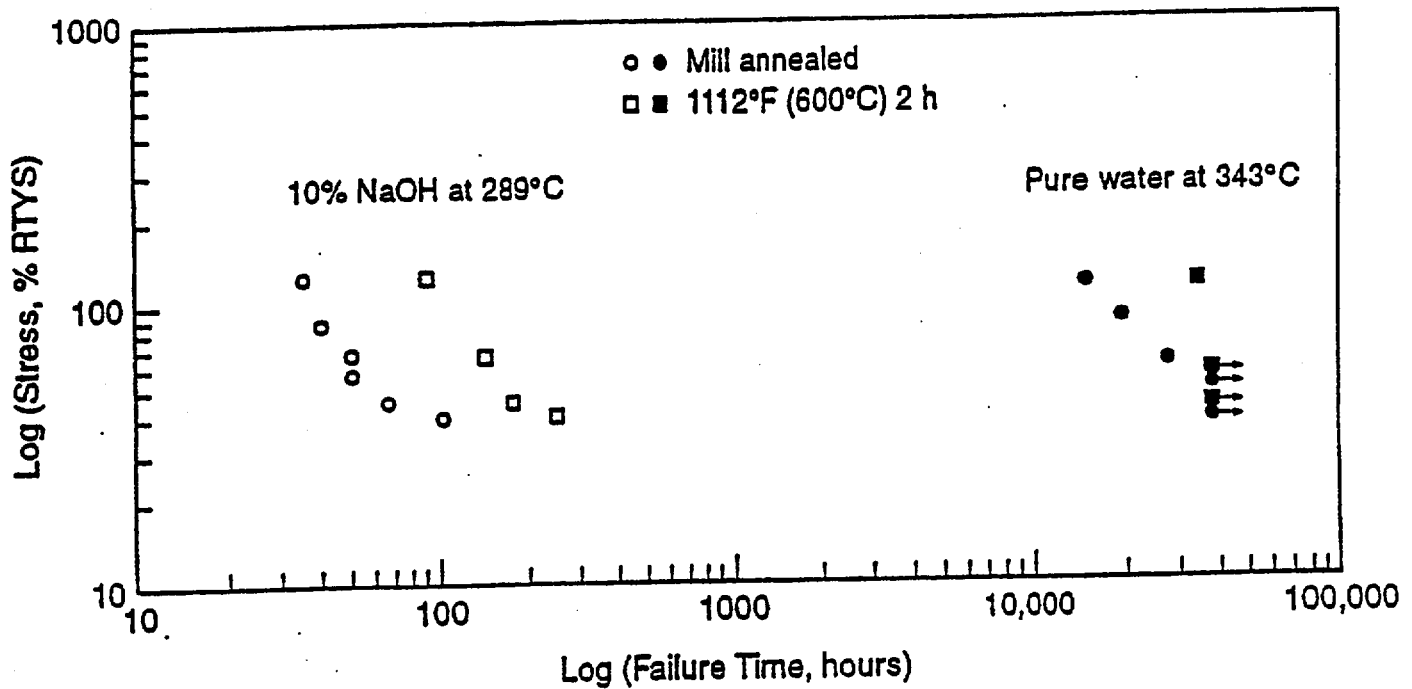
B. Sala, P. Combrade, A. Gelpi, M. Dupin, "The Use of Tube Examinations and Laboratory Simulations to Improve the Knowledge of Local Environments and Surface Reactions TSPs," in *Control of Corrosion on the Secondary Side of Steam Generators*, Proceedings of meeting held in Airlie, VA, October 9-13, 1995. NACE International, Houston, 1996.

CBDA: Environ Definition #3, Heated Surfaces of Drip Shield,-- Applied to YM

- 1. Impurities in backfill**
- 2. Moderately heated surface**
- 3. Crevices due to construction**
- 4. Residual stresses from fabrication**
- 5. Access to mountain chemistry**

CBDA: Environ Definition #4, Stresses,-- Applied to YM

- 1. Internal heating produces tensile thermal stresses on outside heated surface.**
- 2. Residual stresses from fabrication adequate to produce SCC anywhere on outside surface--welds are not only sources of stress. SCC of SG tubing at tube supports is example**



Effect of stress on time-to-failure for Alloy 600 in (a) pure water at 343°C and (b) 10% NaOH at 289°C. Adapted from work by Theus.⁶⁸

68. G. J. Theus, "Summary of the Babcock and Wilcox Company's Stress Corrosion Cracking Tests of Alloy 600," EPRI WS-80-136, EPRI Workshop on Cracking of Alloy 600 U-Bend Tubes in Steam Generators, Denver, August, 1980.

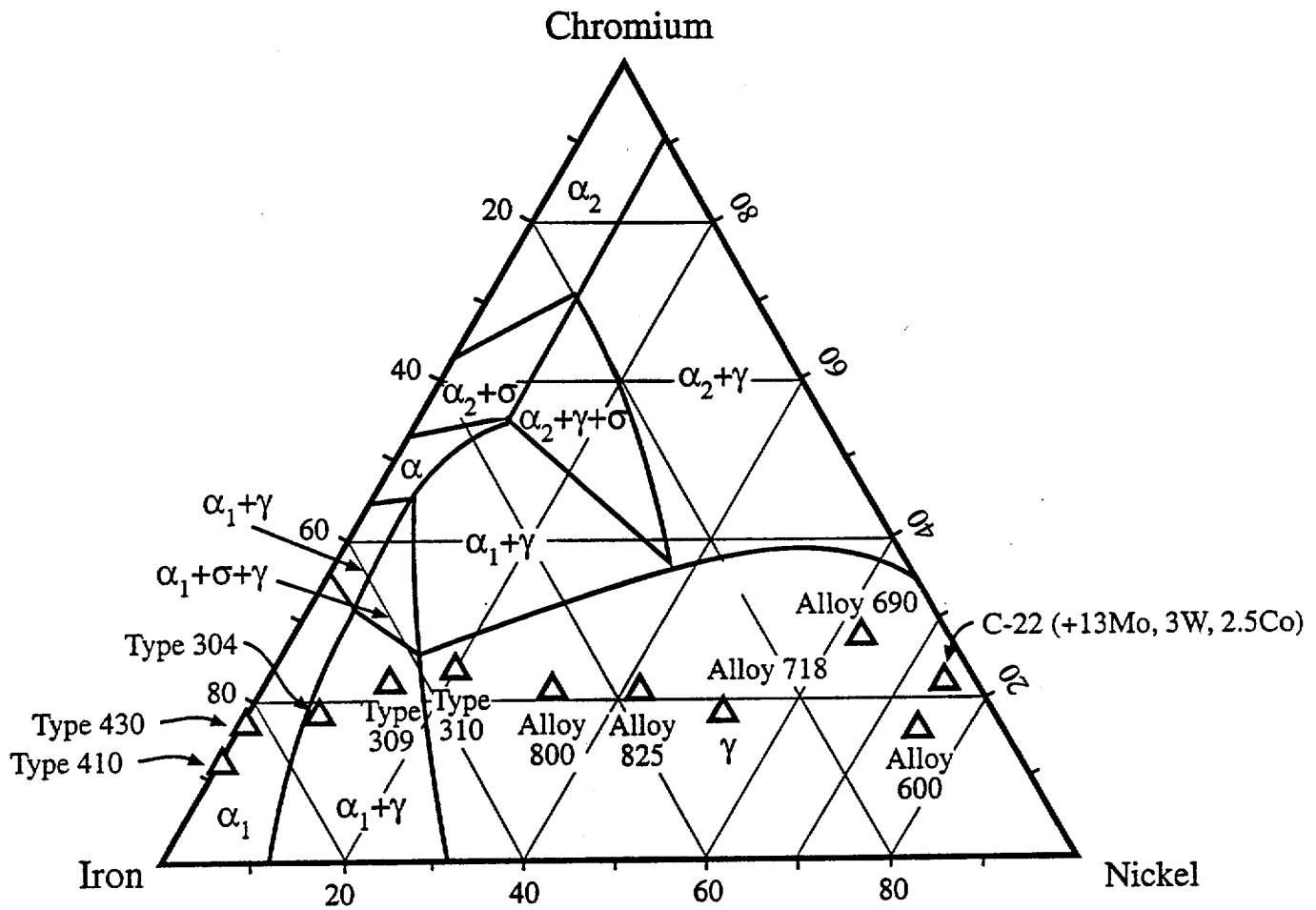
Main groups of residual stress	Sub groups
Machining residual stresses	Grinding Turning Milling Planing Drilling } Residual stresses
Joining residual stresses	Welding Soldering Brazing Adhering } Residual stresses
Forming residual stresses	Rolling Drawing Forging Pressing Spinning Shot peening } Residual stresses
Heat-treating residual stresses	Quenching Transformation Hardening Case hardening Nitriding } Residual stresses
Coating residual stresses	Cladding Spraying Electroplating Plating Galvanizing } Residual stresses

Origins and types of residual stresses. Adapted from Macherauch.⁴⁶

R.W. Staehle, "Combining Design and Corrosion for Predicting Life," presented as a plenary lecture at Life Prediction of Corrodible Structures, Conference held in Kauai, Hawaii, November 1991, NACE International, Houston, 1994, p. 138 - 291.

CBDA: Material Definition for C-22 -- Applied to YM

- 1. Essence of C-22: alloy is prone to be less stable in neutral and alkaline environments due to high solubility of chromium, molybdenum and tungsten alloying elements with increasing pH.**
- 2. C-22 is much like Alloy 600; in the absence of much data for C-22, the Alloy 600 data should be carefully considered.**
- 3. Recall range of effects of metallurgical structure in Alloy 600:**
 - a. Large difference in proneness to all submodes of SCC**
 - b. Testing of high susceptibility and low susceptibility heats provides misleading results.**
- 4. If global stress relief used, will change structure and proneness to corrosion**
- 5. Grain boundary composition as function of heat treatment affects SCC and IGC**
- 6. Prototype fabrication is required to determine real conditions of residual stresses, material structures due to fabrication**



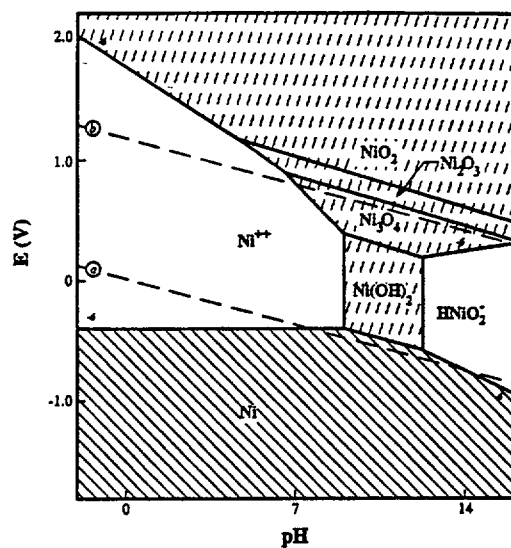
Notes:

- Ternary phase diagram for Fe-Cr-Ni Alloys at 400°C
- Compositions of commercial alloys show only Fe, Cr, Ni

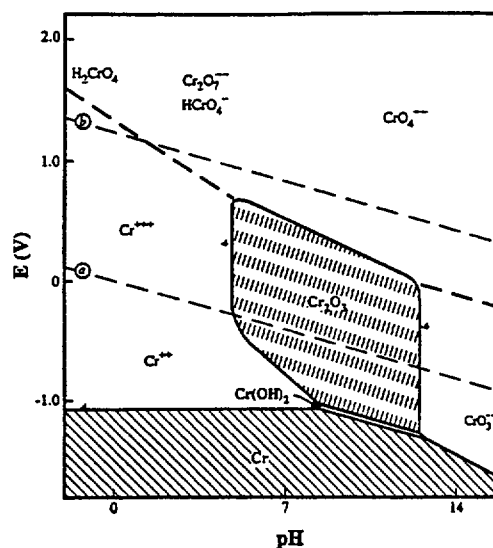
Potential pH Diagrams for Alloying Elements in C-22

- Diagrams at 25°C
- Solubilities are at 10^{-6} M concentrations

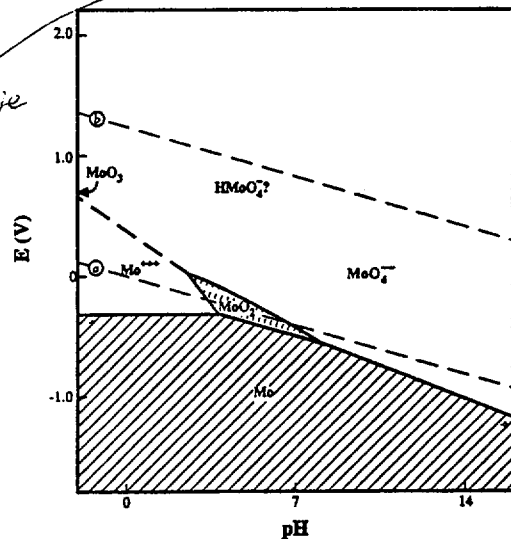
Ni - 56.5%



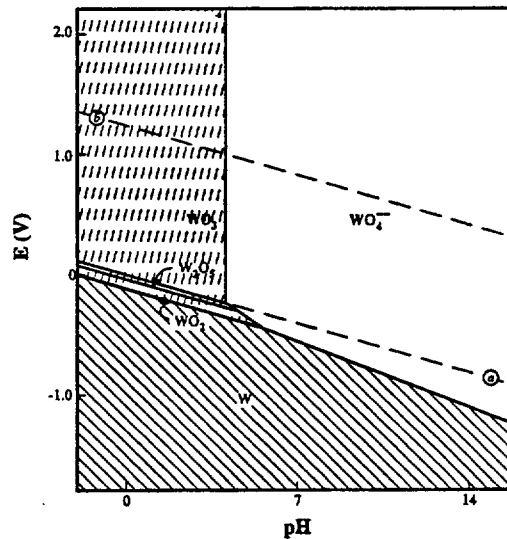
Cr - 21%



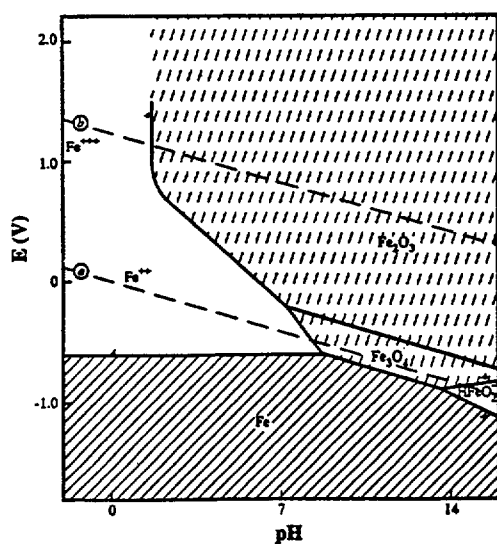
Mo - 13.5%



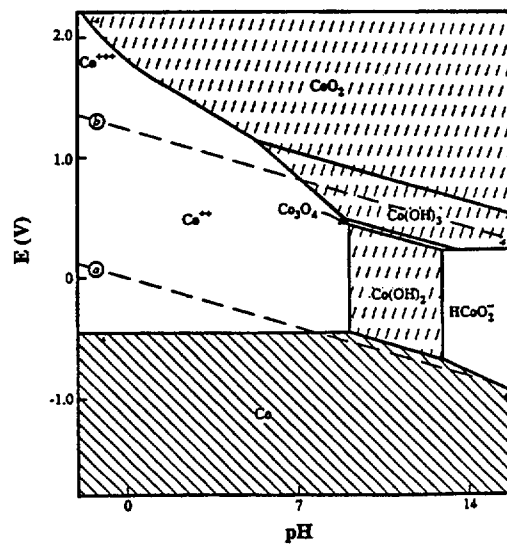
W - 3.0%

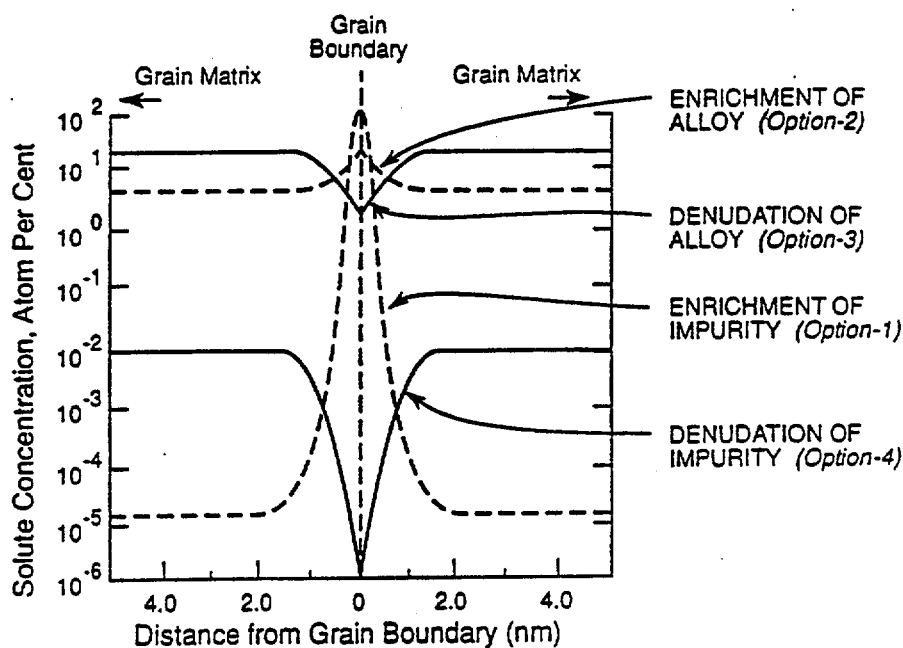


Fe - 4.0%

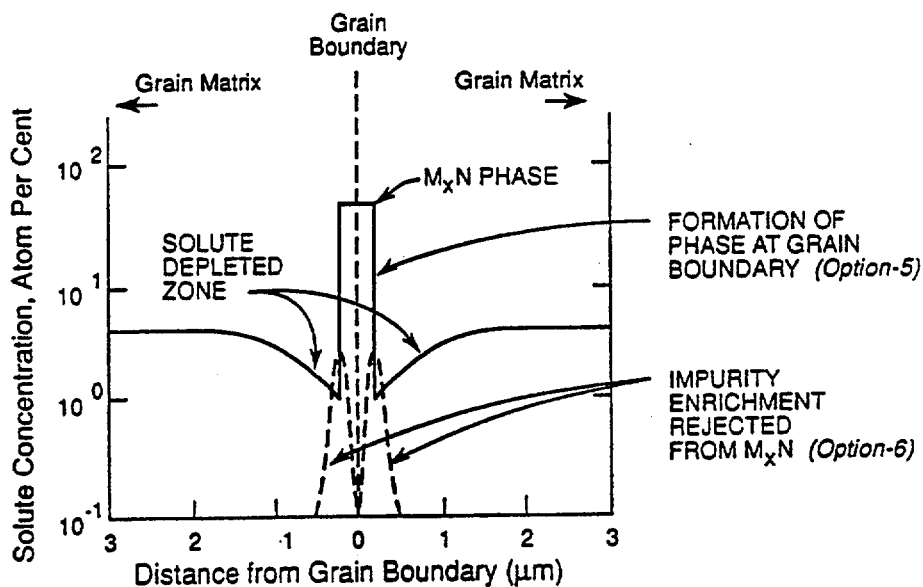


Co - 2.0%





(a)



(b)

Distribution of chemical species at grain boundaries for the case of adsorption (a) and precipitate formation. (b) Various options for distributions of species are identified.

R.W. Staehle, "Understanding 'Situation-Dependent Strength': A Fundamental Objective in Assessing the History of Stress Corrosion Cracking," Environment Induced Cracking of Metals, Proceedings of the First International Conference on Environment-Induced Cracking of Metals, October 2-7, 1988, Kohler, Wisconsin, NACE-10, National Association of Corrosion Engineers, Houston, Texas, 1990, pp. 561-612.

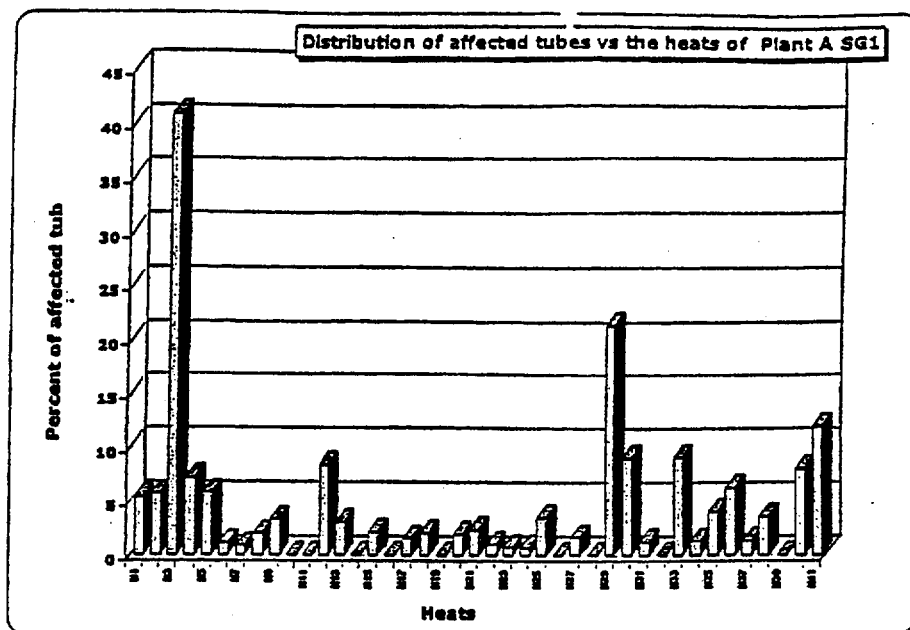


Figure 4: Histogram of fraction of tubes of each heat of alloy 600 affected by IGSCC on the primary side of the roll transitions in a steam generator tube bundle after ~40,000 hours in service.

P.M. Scott, "Stress Corrosion Cracking in PWRs— Interpretation, Modeling and Remedies," Speller Award Lecture, CORROSION 2000, NACE International, Houston, 2000.

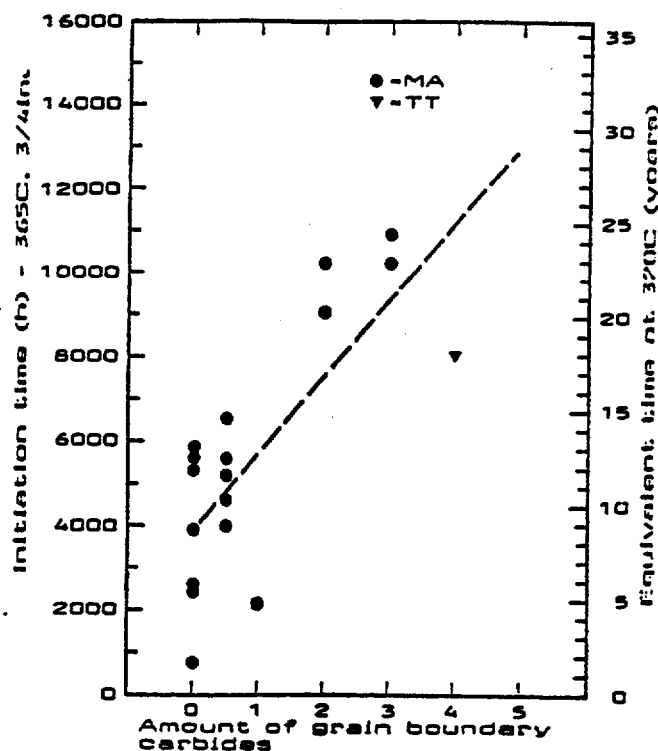
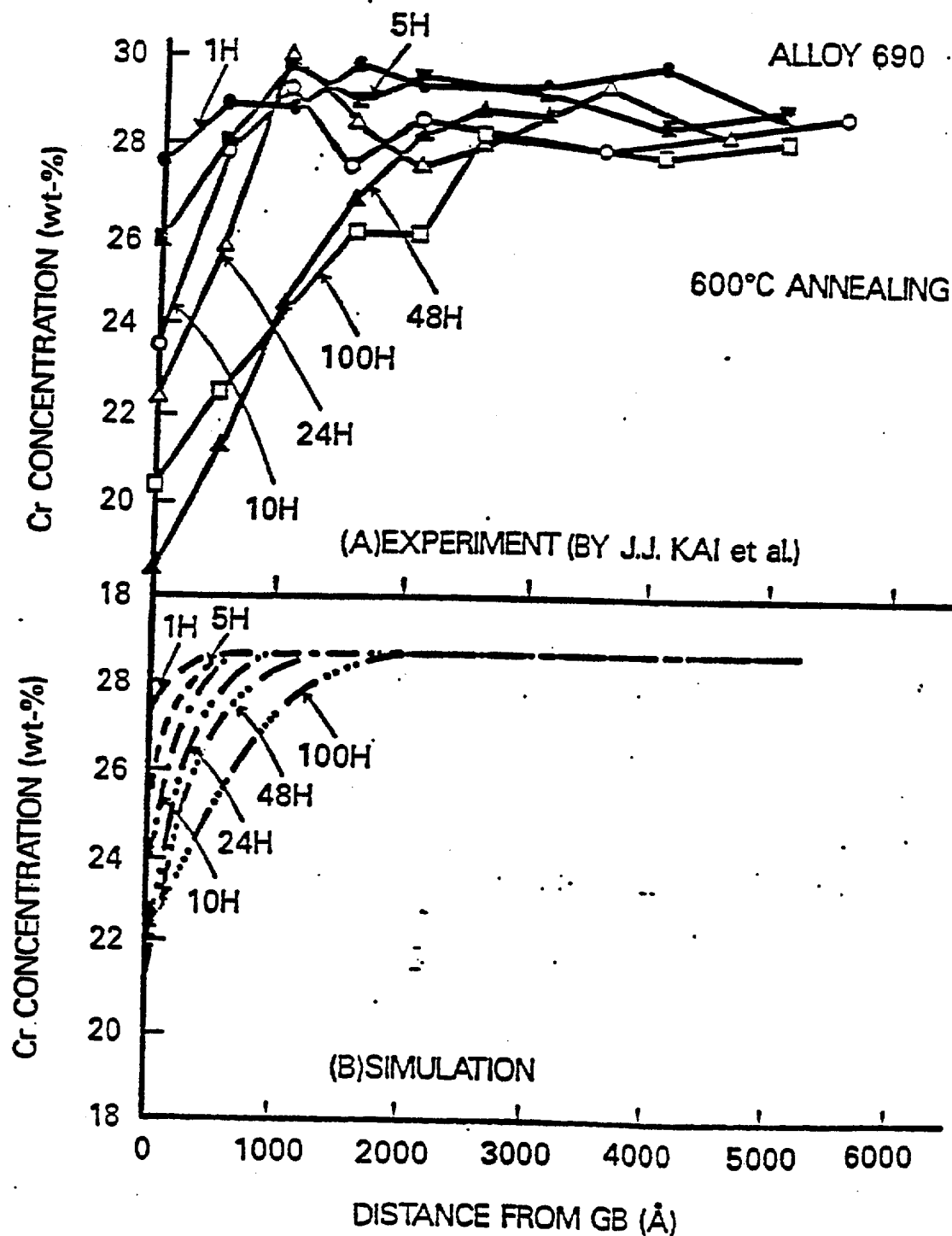


Figure 8 - Influence of grain boundary carbides on the crack initiation time (0 = no carbides at all; 5 = the grain boundaries are completely covered with carbides).

K. Norring, J. Engstrom and P. Norberg, "Intergranular Stress Corrosion Cracking in Steam Generator Tubing. Testing of Alloy 690 and Alloy 600 Tubes," *Environmental Degradation of Materials in Nuclear Power Systems— Water Reactors*. G.J. Theus and J.R. Weeks, Eds., The Metallurgical Society, Warrendale, PA. 1988.



Experimental Measurements of GB Chromium
Depletion for Alloy 690 at 600°C.

Simulation Results.

C.F. Lo, W.E. Mayo, and S. Weissmann, "Computer Simulation of Grain Boundary Depletion in Alloys 600 and 690," Presented at EPRI Workshop on Alloy 690, New Orleans, LA. April 12-14, 1989.

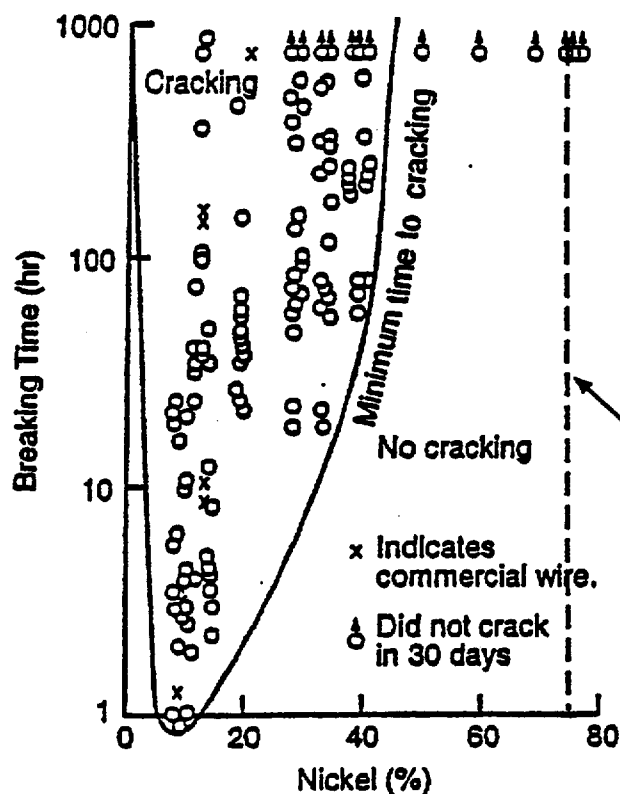
CBDA: Material Definition for Ti-Gr7 -- Applied to YM

- 1. Essence of Ti-Gr7 is the presence of 0.1-0.25% Pd. This produces persistently higher open circuit potentials owing to the high exchange current density on net Pd surface.**
- 2. This alloy has been used generally in chemical environments for corrosion and hydride resistance. However, its general SCC behavior relevant to YM is not established.**
- 3. The presence of the Pd surface will greatly accelerate any reduction of oxygen or water as well as any other species in a highly oxidized state. This tendency will place the alloy in a range of potentials that are not common to other titanium alloys.**
- 4. The metallurgy of this alloy is not well defined.**

**CBDA: Material Definition: Applicable
Material Selection: Examples of Problems--
Applied to YM**

1. SCC of Fe-Cr-Ni alloys in boiling MgCl_2 as function of Ni concentration was basis for Alloy 600 and assumed immunity to all corrosion:
 - a. Alloy 600 sustains SCC under mild conditions in chloride environments
 - b. Failures of alloy 600 occurred without presence of chloride in many environments in service--non-chloride
2. Alloy 690 was initially selected based on (a) resistance to SCC in lead and (b) resistance to SCC in oxidizing crevices, both criteria were erroneous:
 - a. Alloy 690 sustains severe SCC in low concentrations of lead in liquid and vapor
 - b. Alloy 690 sustains severe SCC in oxidizing acidic environments

INITIAL DATA FROM COPSON (1957-59)



BERGE & DONATI
1981
Show Cl SCC of Alloy 600

Effects of alloy composition on the stress corrosion cracking of Fe-Cr-Ni alloys exposed to boiling 42% MgCl_2 . (Adapted from the work of Copson [17])

ALSO

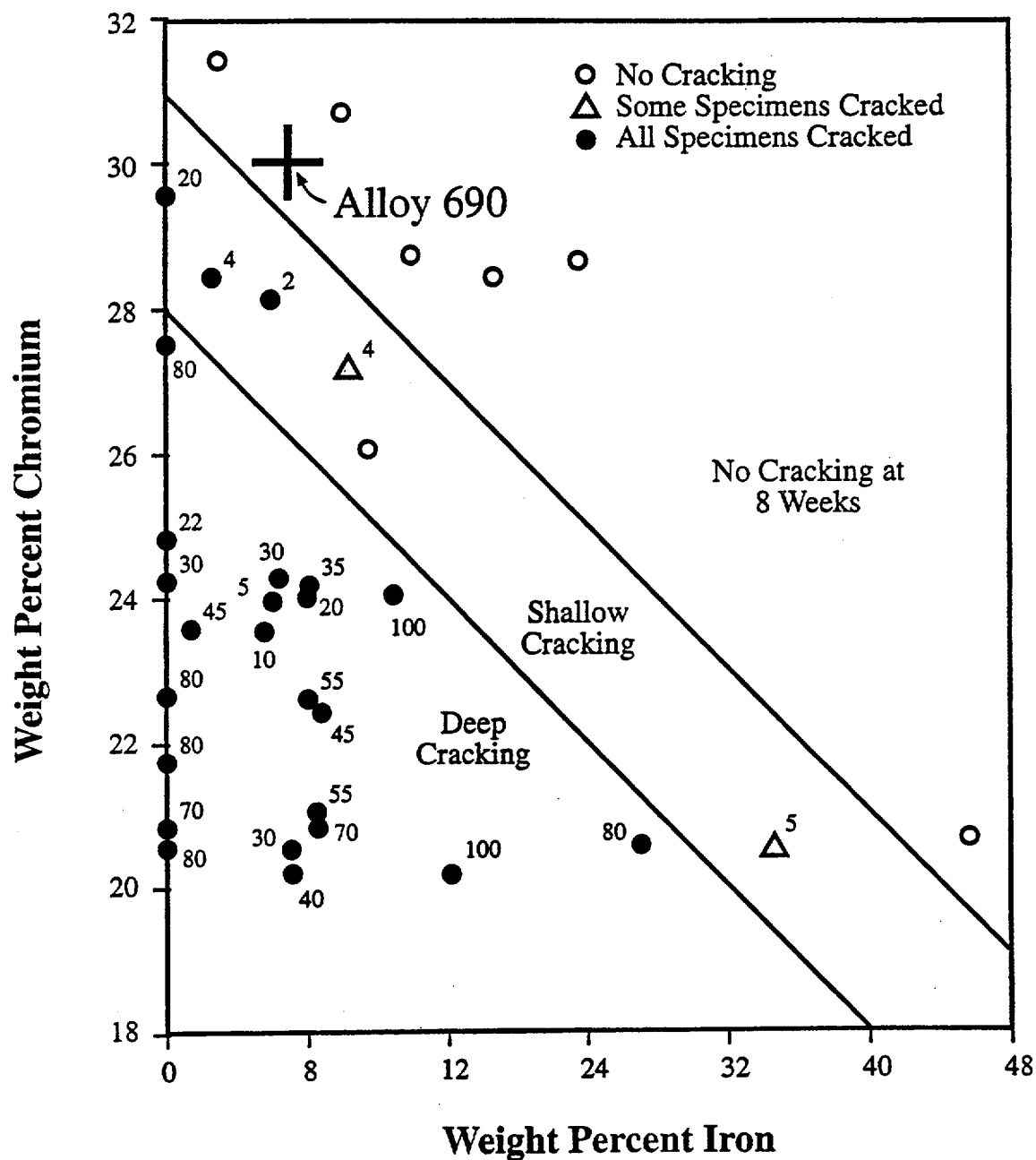
- Alkaline SCC
- Acid SCC
- Lead SCC
- Low Potential SCC
- Copper SCC
- Low Valence Sulfur SCC

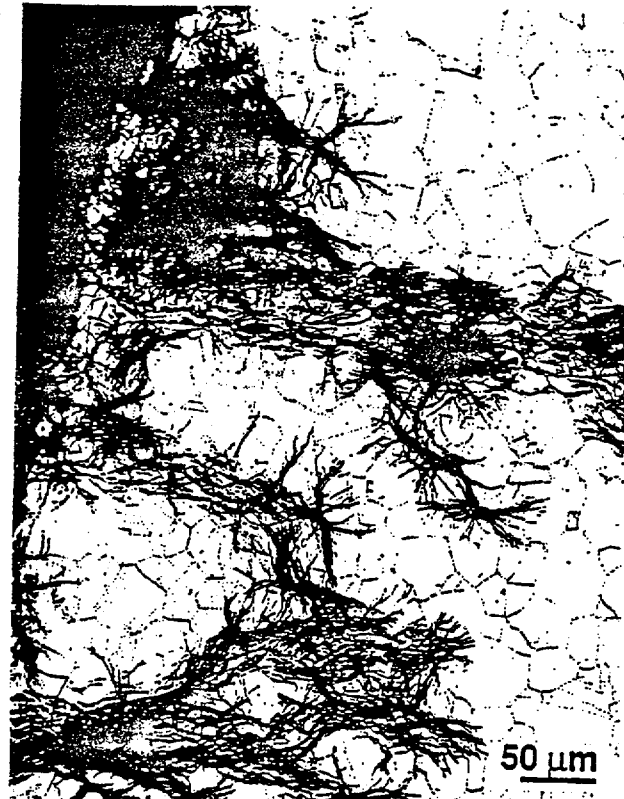


Stress corrosion cracking of Alloy 600 at 100°C in a solution containing boric acid (50 g/l boron) and chloride (2 g/l Cl^-). U-bend specimen after 800 h.

Alloy 600
not a Cr-Ni
problem

**Maximum Depth of Cracking (in mils)
of Ni-Cr-Fe Alloys after 8 Weeks in
Deaerated Water + Pb**



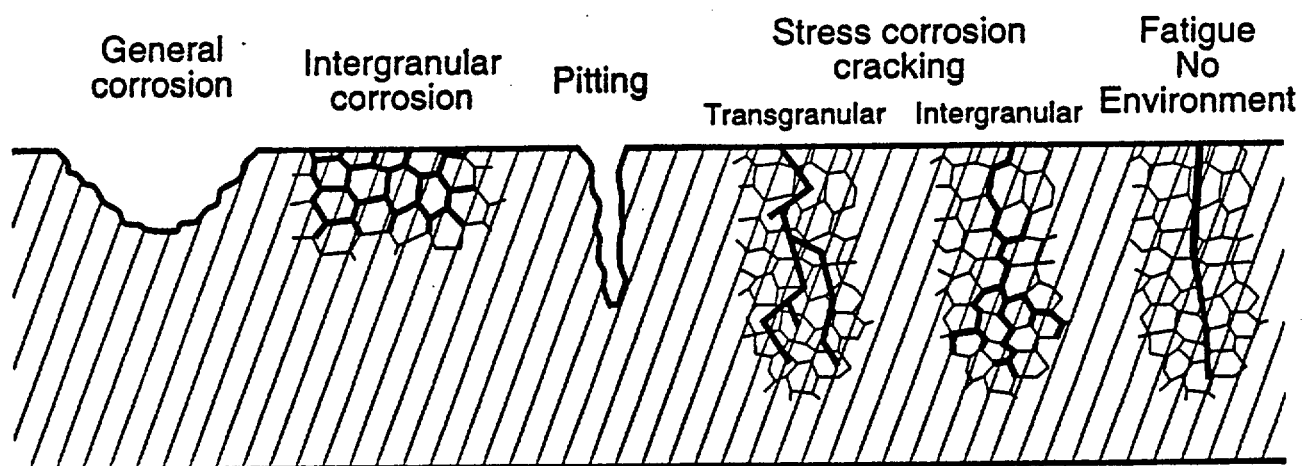


C-ring 8-196, Alloy 690, Heat 752469, TT, after 4073 hrs in vapor of Canister 9 (1.0m NaOH + 0.1m PbO); left photos unetched.

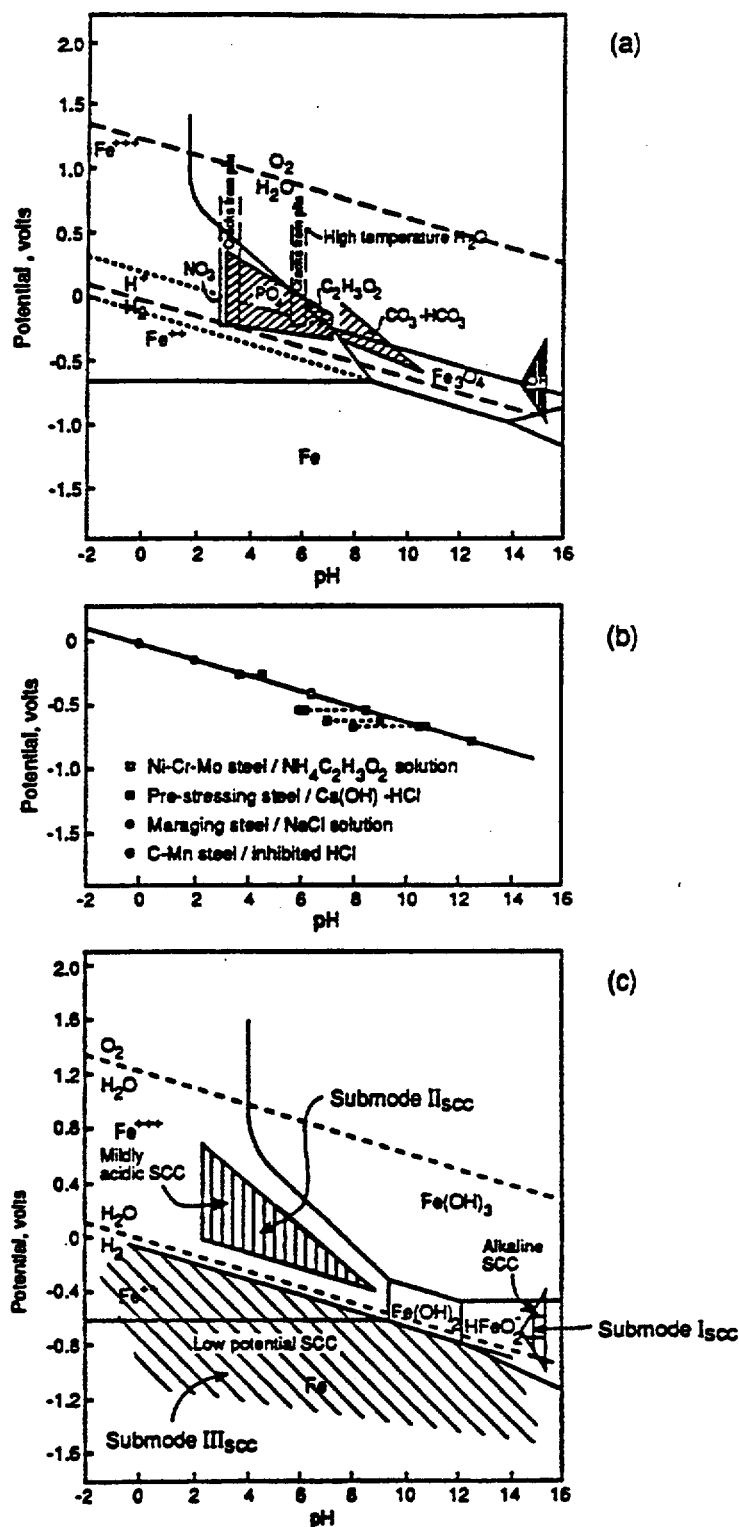
CBDA: Mode Definition--Applied to YM

- 1. Modes of corrosion includes general, pitting, IGC, SCC, CF**
- 2. Submodes of e.g. SCC include same modes with different dependencies upon principal variables.**
- 3. Defining regions in which corrosion (mainly SCC here) occurs that can be compared with possible environments.**
- 4. Defining dependencies on principal variables: potential, pH, species, alloy composition, alloy structure, temperature, stress.**
- 5. Specifying differences between initiation and propagation dependencies.**
- 6. Occurrences of submodes of SCC are generally orderly and can be "guessed at" and determined on an orderly and rapid basis.**
- 7. Correlation of submodes with locations on mode diagram provides qualitative insights to dependencies.**

X



Intrinsic modes of corrosion. (From Staehle [15].)

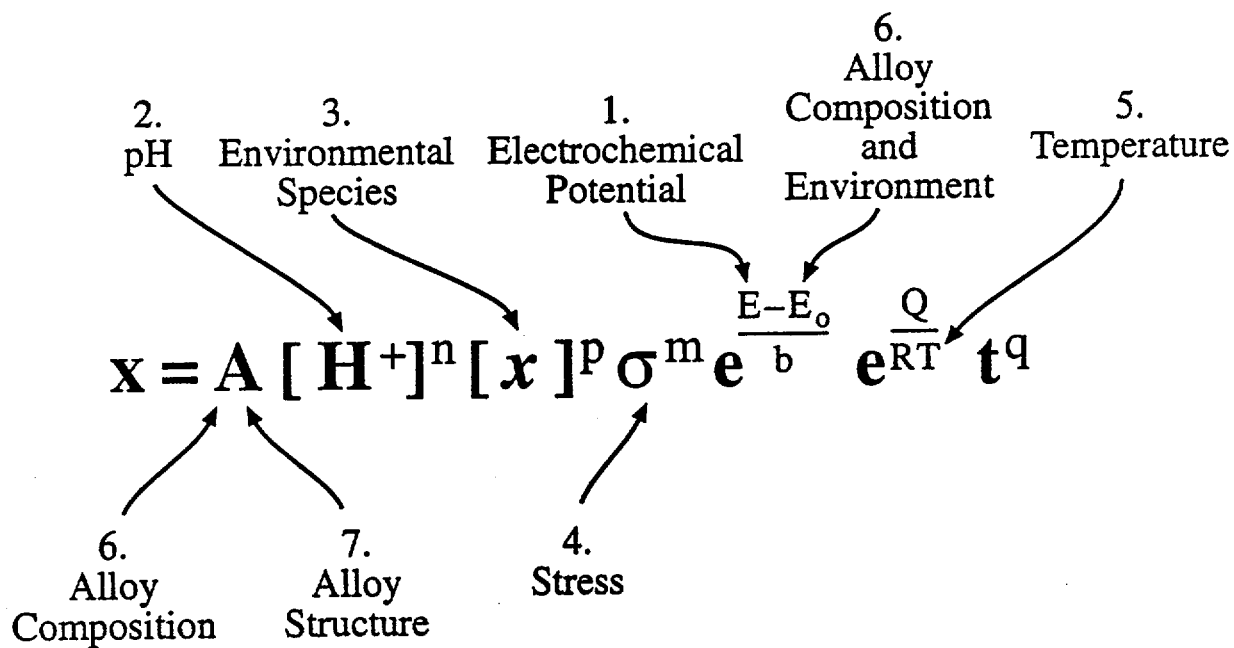
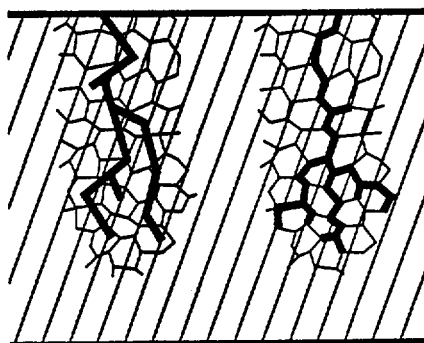


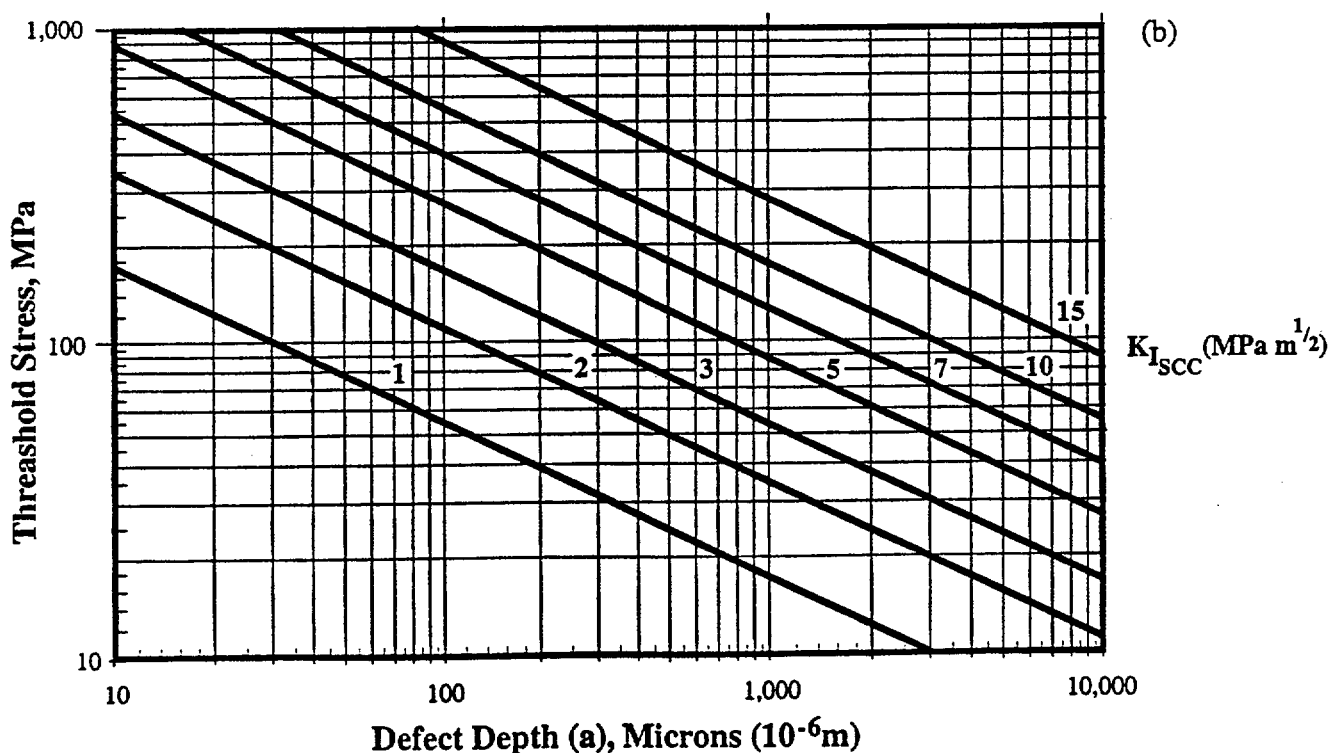
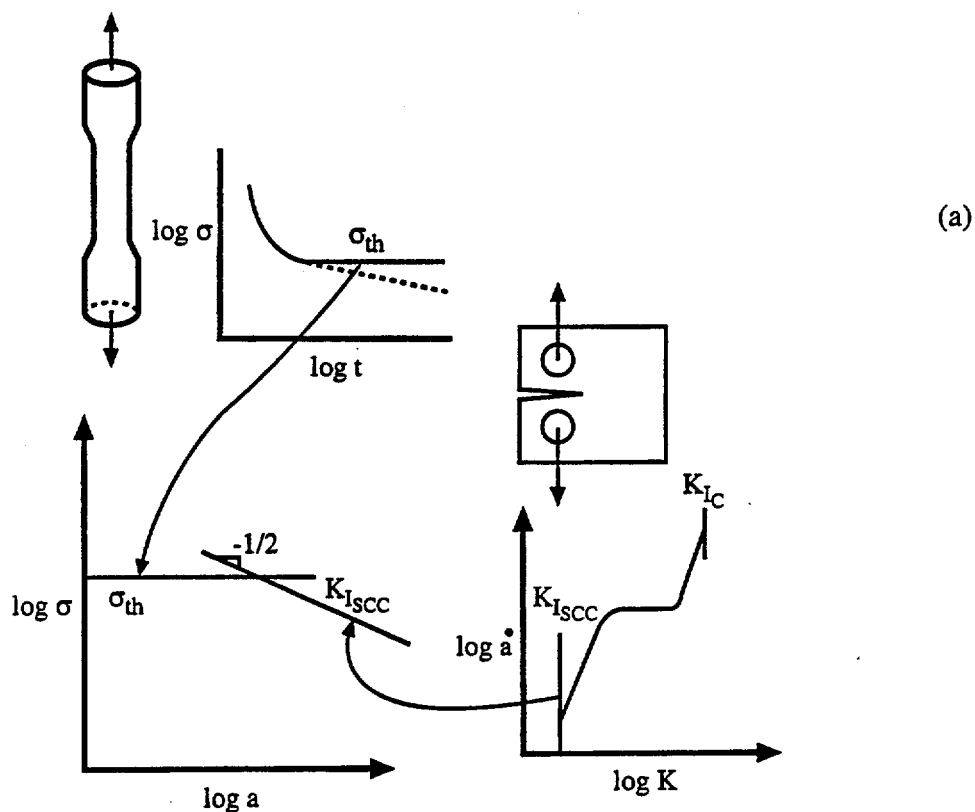
Regions of occurrence for different modes of SCC for low alloy steels exposed to aqueous solutions mostly at room temperature. Work shown is taken from studies in different environments and for different alloys. (a) Shaded areas show regions where SCC occurs. Adapted from Congleton *et al.*¹⁴³ (b) Line shows the potential below which hydrogen related SCC occurs. Adapted from Parkins.¹⁴⁴ (c) Schematic synthesis showing three submodes of SCC based on (a) and (b).

Principal Variables Affecting Modes and Submodes of SCC

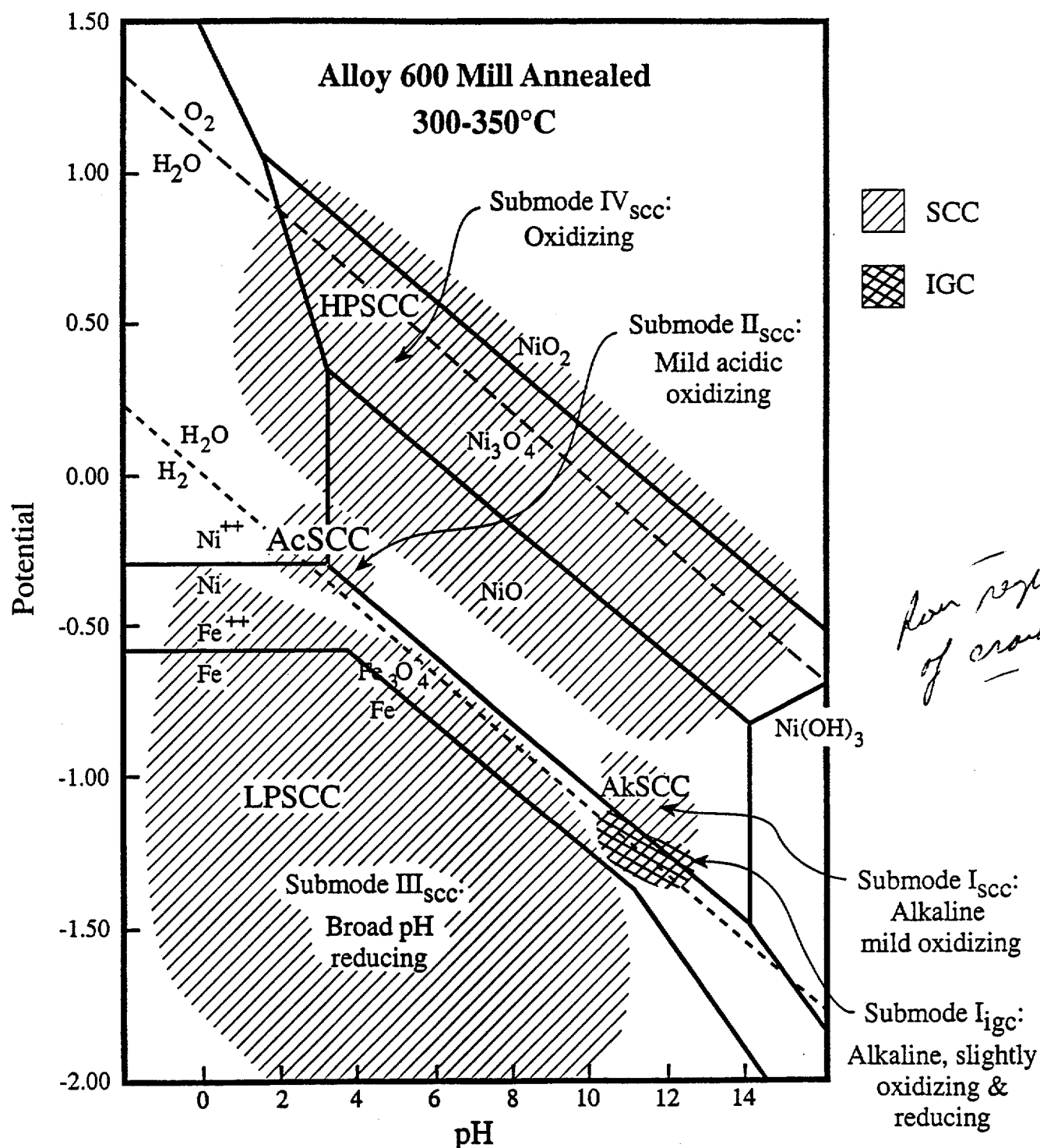
Stress corrosion
cracking

Transgranular Intergranular

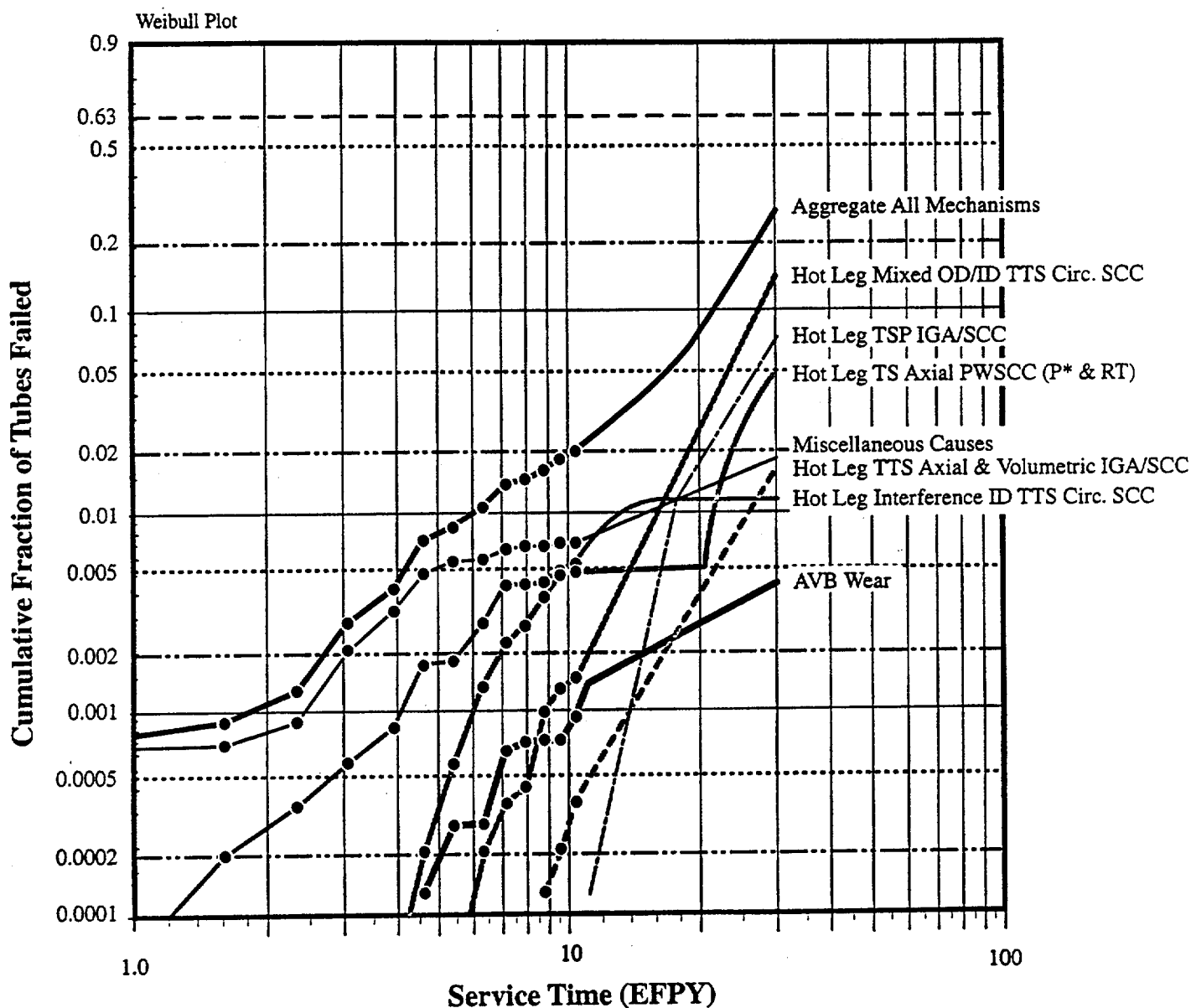




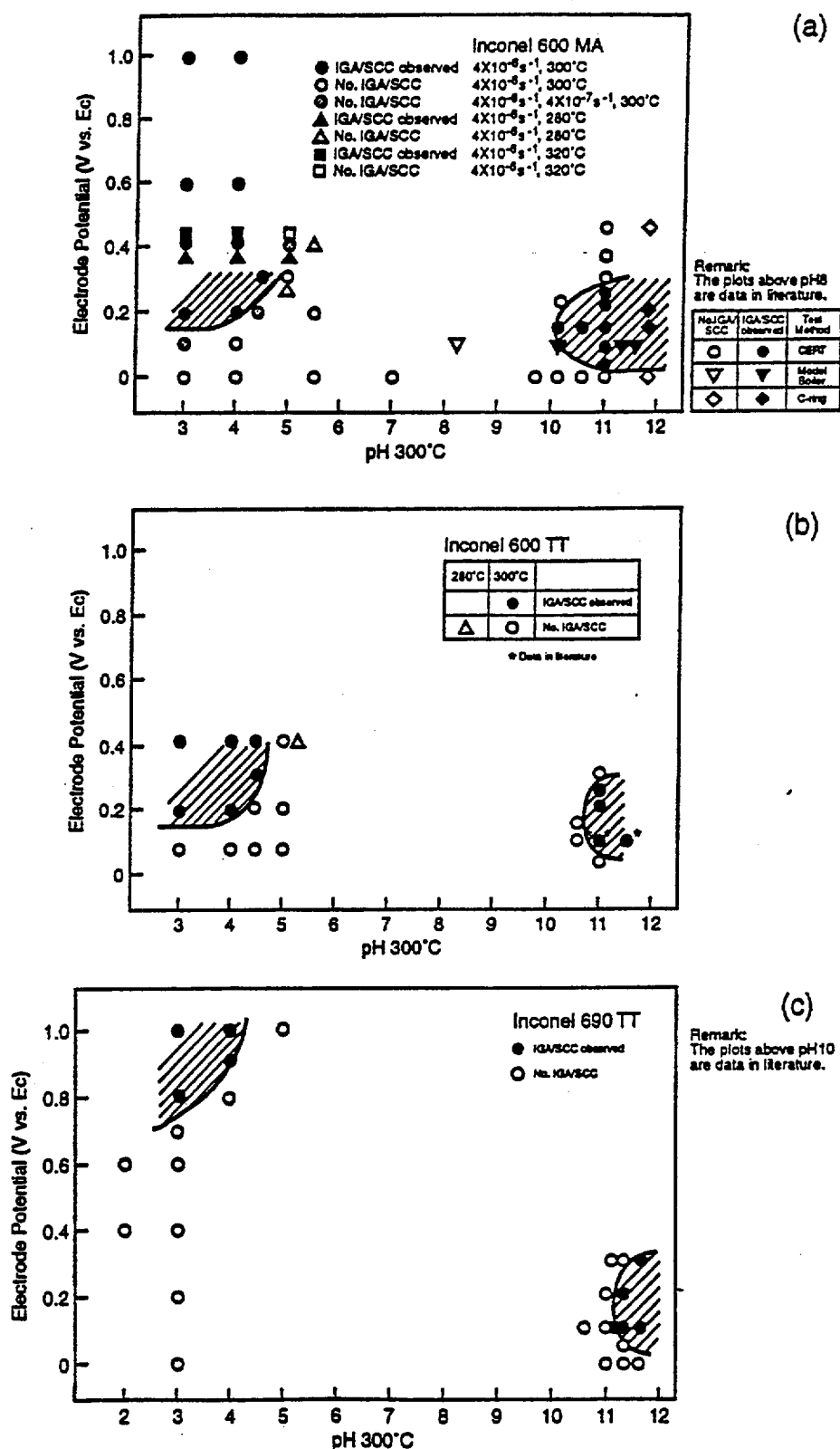
Distinguishing between initiation and propagation. (a) Schematic view of log stress versus log of defect depth for the cases of initiation stress as determined from smooth surface and SCC growth as determined from a pre-cracked specimen. (After Staehle²) (b) Log-log plots of parametric values of threshold stress (horizontal lines) and $K_{I_{SCC}}$ ($-1/2$ slope).



Occurrence of major modes, MD_j, and submodes, SD_j, of SCC and IGC for mill annealed Alloy 600 in the range of 300-350°C plotted with respect to aqueous equilibria for nickel and iron. Submodes included are alkaline SCC, acidic SCC, low potential SCC, high potential SCC. (Diagram originally from Staehle and Gorman [20] and modified in Staehle [13].)

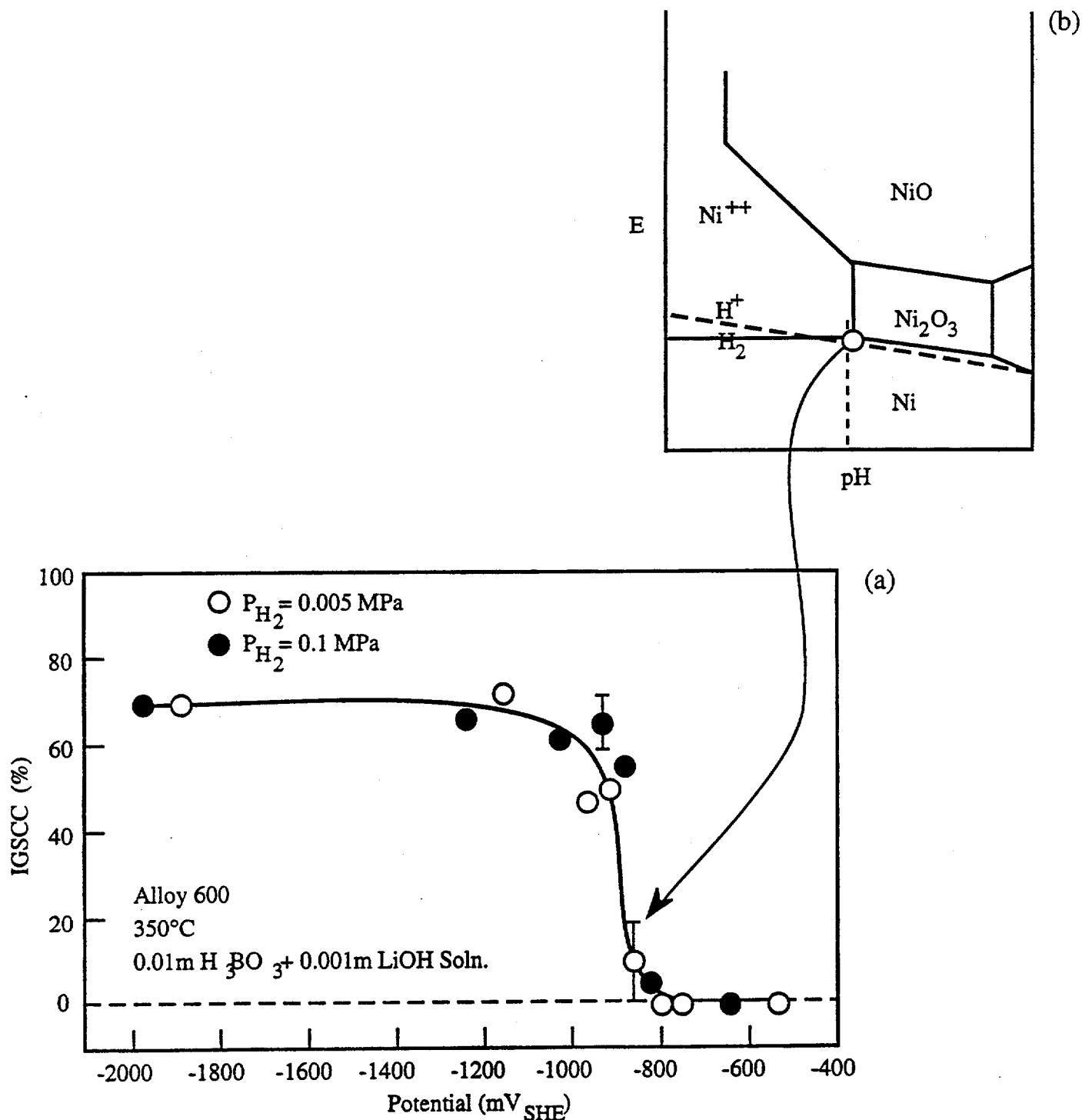


Cumulative fraction of tubes failed versus service time in EFPY (Equivalent Full Power Years) for seven mode-location cases from the set of steam generators in the Ringhals 4 pressurized water nuclear plant. "TTS" refers to "Top of Tube Sheet." "TS" refers to "Tubesheet." "Circ. SCC" refers to "Circumferential SCC." "P*" refers to a special location where SCC may not be serious. "RT" refers to SCC at the "Roll Transition" location. "AVB" refers to "Anti-Vibration Bars" (At top of steam generator to stabilize the tops of the U-bends.) (Unpublished data provided by L. Bjornkvist of Vattenfall and J. Gorman of Dominion Engineering.)



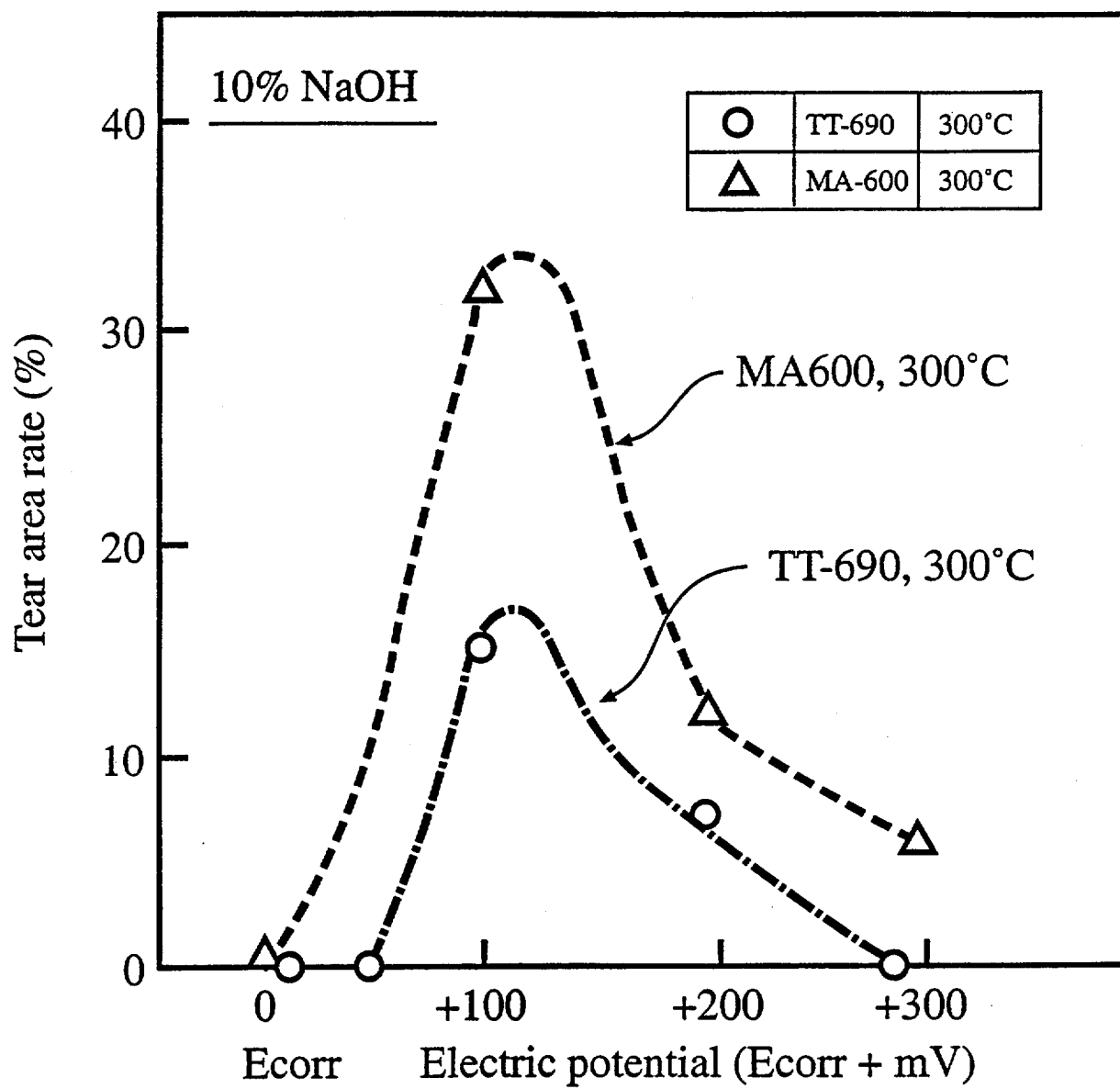
IGA/SCC tests results in the range of 280 to 320°C range as a function of electrode potential and pH taken at 300°C for (a) Alloy 600MA, (b) Alloy 600TT, (c) Alloy 690TT. From Ohsaki et al.⁴³

43. I. Ohsaki, K. Onishi, Y. Ohkubo, T. Hattori, and S. Tokunaga, "Study of the Improvement of Steam Generator Tubing and Tube Support Plate Materials," presented at the 2nd International Steam Generator and Heat Exchanger Conference, June 1994, Toronto.



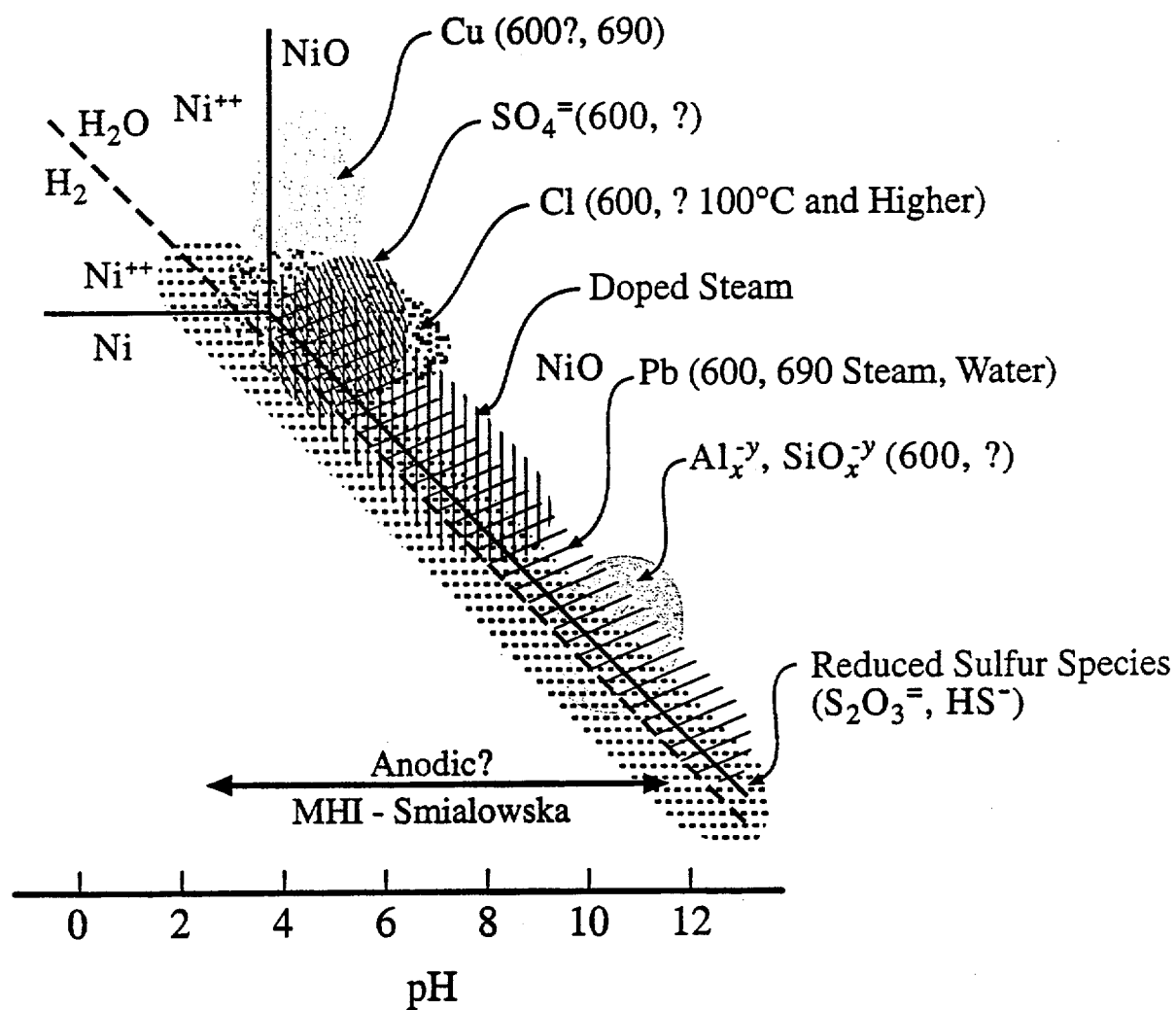
(a) Percent of fracture surface with IGSCC as a function of applied potential for Alloy 600 tested at 350°C using SSRT for two pressures of hydrogen. The open circuit potential is compared with the E-pH diagram for nickel in water in (b). Data from Totsuka and Smialowska.

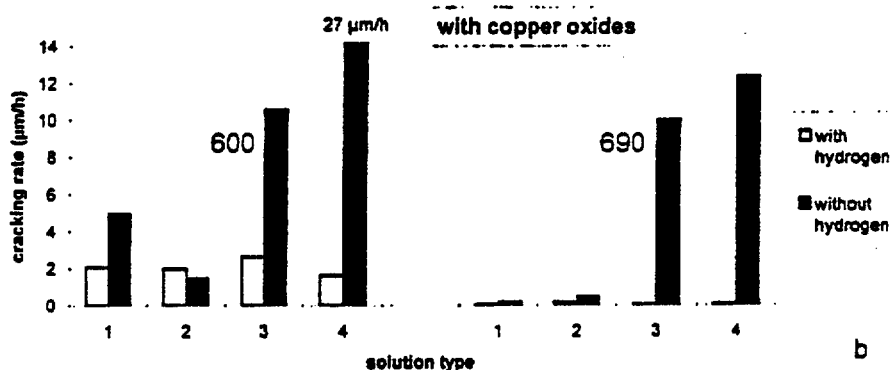
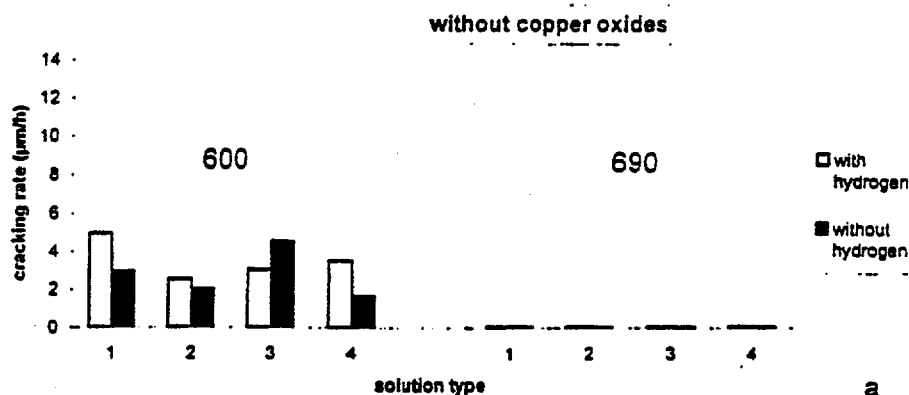
N. Totsuka and S. Smialowska, Proceedings of the Third International Symposium on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, Eds. G.J. Theus, J.R. Weeks, New York, AIME, 1988, p. 691.



Alloy 600, 690

Minor Submodes, Applied to Temperature Range of 288-350°C





Maximum cracking rates obtained with solutions 1 to 4 for alloy 600 (lots 9831 and 9649) and for alloy 690 (lot 7430).

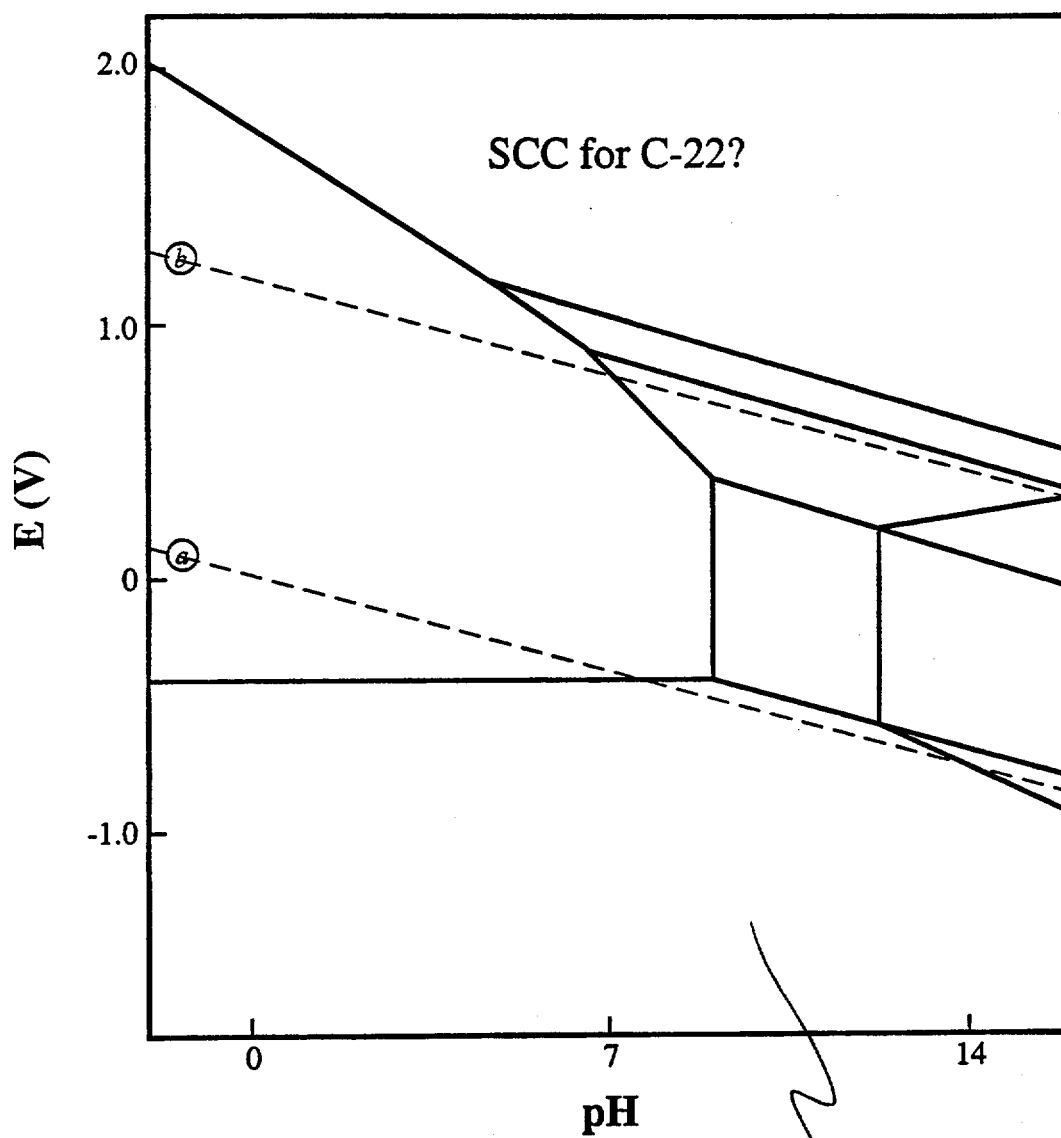
Table 1. Composition and pH calculated at 320°C (MULTEQ calculation) of the test solutions

Solution	Composition	pH
1	0.082m Na ₂ SiO ₃ , 0.3m Fe ₃ O ₄ , 170g/l cationic resins	2.6
2	0.082m Na ₂ SiO ₃ , 0.3m Fe ₃ O ₄ , 170g/l cationic resins, 0.012m Pb	2.6
3	0.75m Na ₂ SO ₄ , 0.25m FeSO ₄	4.4
4	0.75m Na ₂ SO ₄ , 0.25m FeSO ₄ , 0.1m PbO	4.8

CBDA: Mode Definition--Applied to YM. Mode Definition Applied to C-22

- 1. Analogy to Alloy 600 of major and minor submodes is good place to start**
- 2. All of the Fe-Cr-Ni alloys exhibit about the same general features in their proneness to SCC**
- 3. Sensitizing heat treatments change regions of proneness to SCC:**
 - a. Sulfur species**
 - b. Low temperature proneness**
- 4. So far there is no definition of SCC modes for C-22.**

Mode Diagram for C-22 (Based on Nickel Background)



CBDA: Mode Definition--Applied to YM. Mode Definition Applied to Ti-Gr7

- 1. Presence of Pd produces a persistently high potential**
- 2. Some features of Ti SCC submodes generally are known**
 - Propagation in sea water**
 - Acidic oxidizing conditions**
 - Alcohol s**
 - Iodine**
- 3. Generally, the submodes relevant to YM are not well established.**

CBDA: Mode Definition for SCC--Applied to YM. Problems with Dependence on Methods A and B

1. The K_{ISCC} determined for C-22 is relevant to only a limited set of conditions and most likely not to the concentrated chemistry expected on a heated surface. e.g. the K_{ISCC} for Alloy 600 in alkaline environments is in the range of 10 Ksi in^{1/2}.

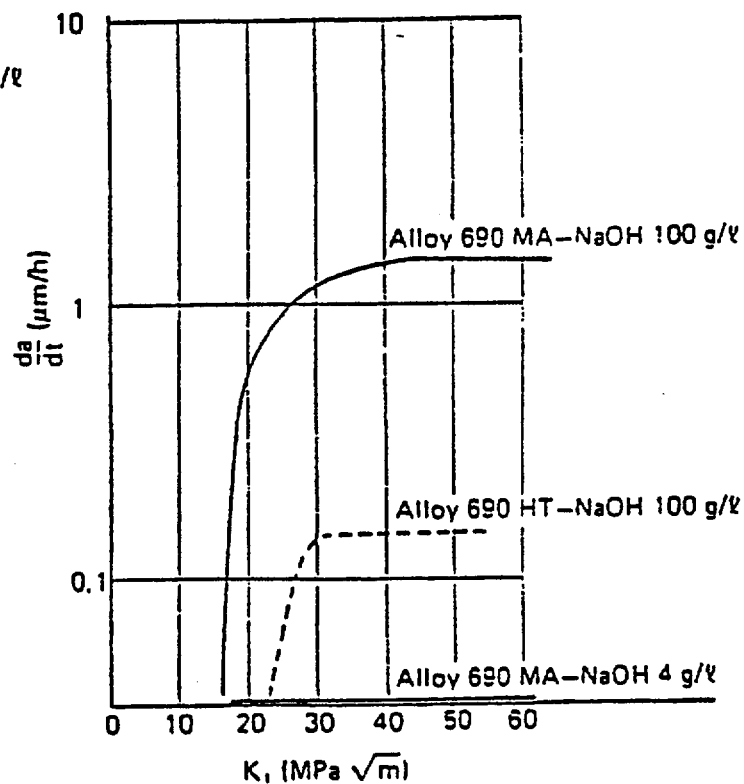
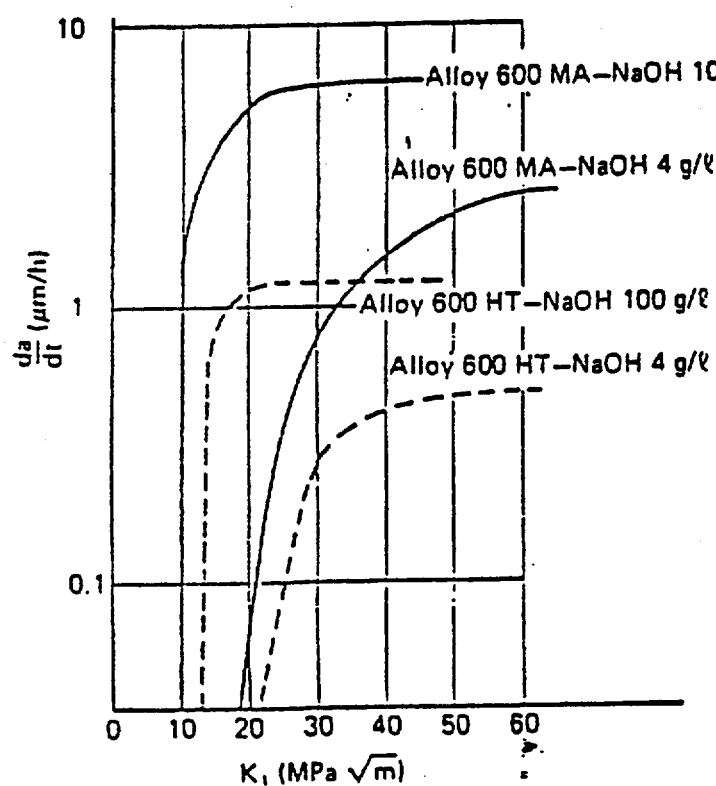
2. The relationship

$$V_t = A \left(\dot{\epsilon}_{ct} \right)^n$$

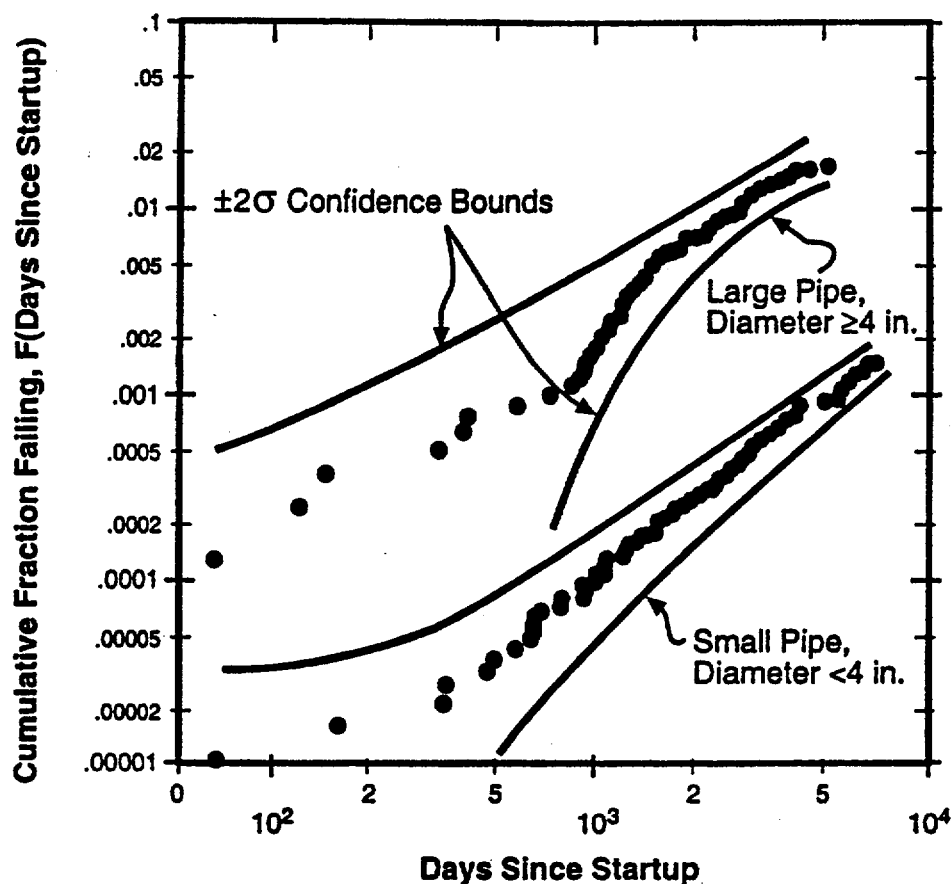
does not predict anything. It only correlates data and does not apply nor distinguish readily the many submodes of SCC observed on the secondary side of steam generators.

3. These relationships do not interpret the actual occurrence of SCC in BWRs in the statistical array as occur in the field.

350°C WOL-TYPE SPECIMENS



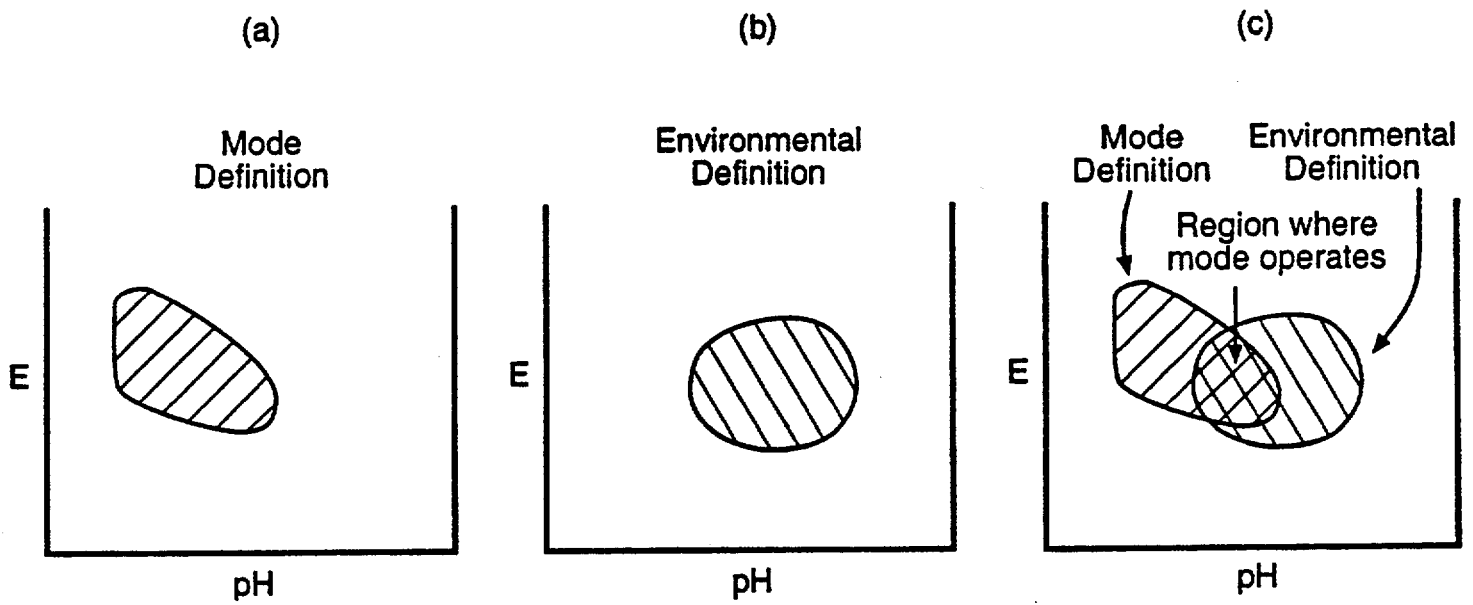
Stress corrosion tests in deaerated sodium hydroxide at 350°C on fracture mechanics-type specimens: comparison of Alloys 600 and 690 behavior. Effect of heat treatment at 700°C for 16 h.



Cumulative fraction failed versus time for piping of two ranges of diameters exposed in boiling water nuclear reactors where the environments are pure water. The larger diameter pipes include only IGSCC, and the smaller pipes include all failure modes although they are mainly IGSCC. The Weibull characteristics, θ , and slopes, b , are 144 years and 1.2 and 1675 years and 1.4, respectively, for the large and small pipes. (Adapted from Eason and Shusto [27].)

CBDA: Superposition--Applied to YM.

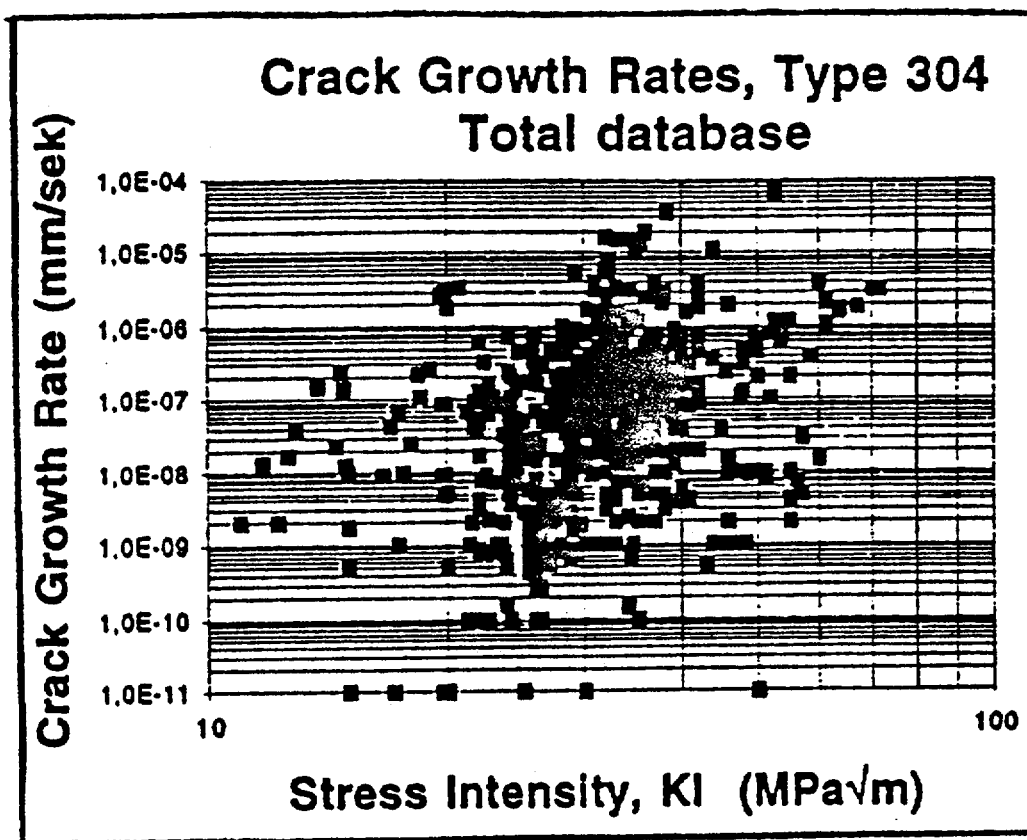
- 1. Superposition involves comparing environmental definition with mode definition for a specifically defined material**
- 2. Require thorough definitions of SCC (and other corrosion) submodes.**
- 3. Require thorough definition of environments**



(a) Mode definition, (b) environmental definition, and (c) overlap shown schematically in the coordinates of potential and pH. (From Staehle [21].)

CBDA: Accelerated Corrosion Testing—Applied to YM

- 1. Accelerated testing must be responsive to the following for container and drip shield:**
 - a. real conditions of hot surfaces including deposits**
 - b. complicated chemistry of the YM**
 - c. diversity of metallurgy**
- 2. Isothermal testing is not adequate for heated surface condition; adequate if it considers environments on heated surfaces.**
- 3. Analogy of model boiler (in the commercial reactor world) necessary to study integrated corroding systems.**
- 4. Prototype of “unit cell” in YM required to model full environmental conditions of YM as they affect one cell.**
- 5. Real manufactured containers required for realistic testing.**

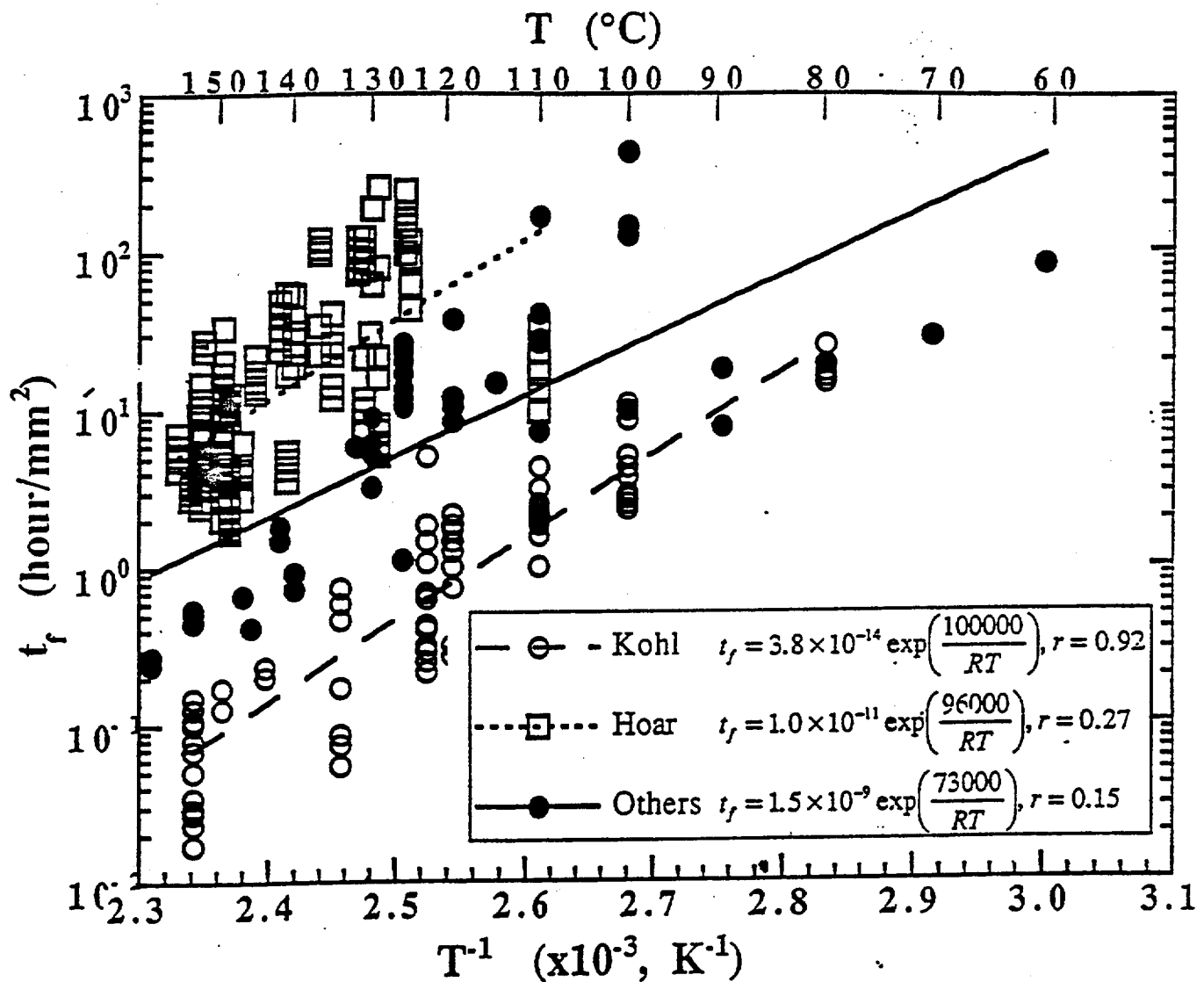


**Fig 1 All available CGR data in the database for
Type 304 in various BWR environments**

Note –

- Data not censored
- Multiple test methods, some of questionable validity

C. Jansson and U. Morin, "Assessment of Crack Growth Rates in Austenitic Stainless Steels in Operating BWRs." *Proceedings: Eighth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors*, Eds. A.R. McIlree and S.M. Bruemmer, American Nuclear Society, La Grange Park, Illinois, 1997.



Times-to-failure versus temperature for the 23 sets of data measured for stainless steels in boiling 35-42% MgCl₂ solutions at open circuit potentials. Data from Table 2.