

Analysis of Alloy 600 Stress Corrosion Cracking with an Artificial Neural Network.

M.J. Pattison, S. Belsito, S. Banerjee
MetaHeuristics LLC, Santa Barbara, CA 93105

W.H. Cullen
Nuclear Regulatory Commission, Rockville, MD 20852

Contents

1. Available models
2. Approach taken – why neural networks?
3. ANN model developed
4. Results and comparison with data
5. Relative importance of variables

Existing Models

Scott (1991) model:

$$CGR = 2.8 \times 10^{-11} (K - 9)^{1.16}$$

Ford (1987), Ford et al. (1997)

$$CGR = 7.8 \times 10^{-3} n^{3.6} (4.1 \times 10^{-14} K^4)^n$$

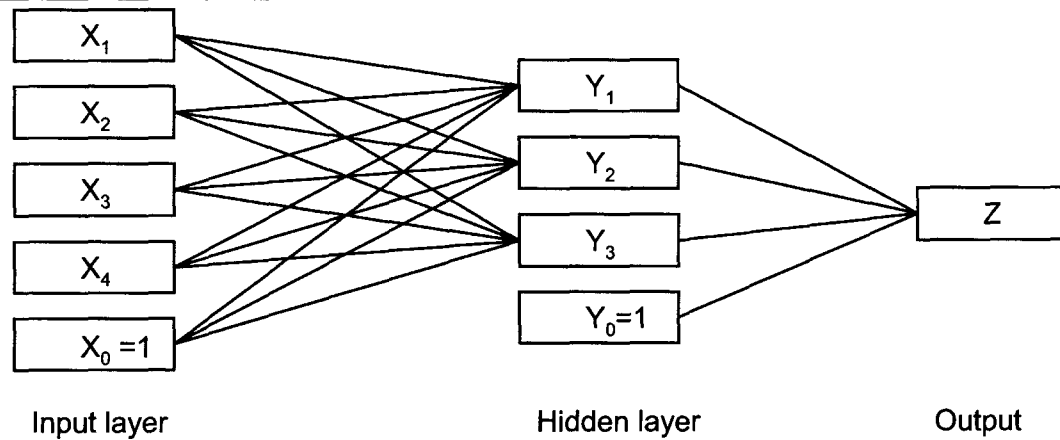
Model temperature dependence as:

$$CGR \sim \exp(-E / kT)$$

Principal Variables

- Applied stress
- Temperature
- Solution chemistry
 - Impurities and additives, e.g. lithium, boron, sulphates
 - pH
 - Dissolved gases: hydrogen, oxygen
- Alloy properties
 - Composition
 - Grain size
 - Cold/hot work - affects structure and yield strength
 - Grain carbide coverage
 - Carbides present

Diagram of Neural Network



$$Y_j = f\left(w_{0j} + \sum_{i=1}^{i=m} w_{ij} X_i\right)$$

$$f(x) = \tanh(x)$$

$$Z = f\left(w_0^h + \sum_{i=1}^{j=n} w_j^h Y_i\right)$$

Training of Neural Network

Objective: Calculate weights, $\mathbf{w}$, so as to minimise the energy function:

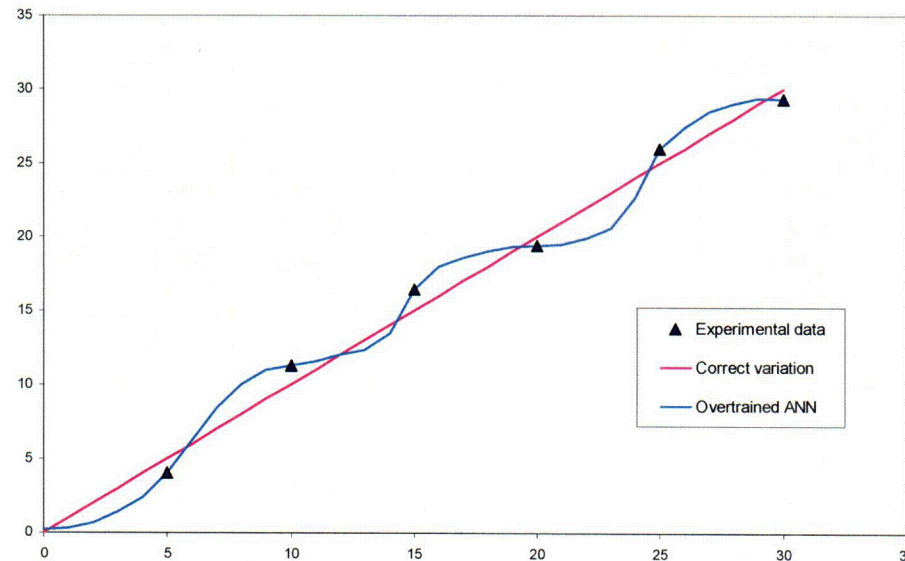
$$e(\mathbf{w}, \mathbf{x}, m) = \sum_{k=1}^n (z - z_p)^2$$

The MetaSolve algorithm uses a novel, computationally efficient, iterative approach using ODEs to determine the weights

Verification of Solution

- Danger of overtraining – with sufficient hidden nodes, the neural net can fit the data to any degree of accuracy
- With an overtrained net, data used for training can be reproduced well, but poor performance will be obtained for other data
- Usual to split the database into two parts – one for training and one for testing

Validation of Model

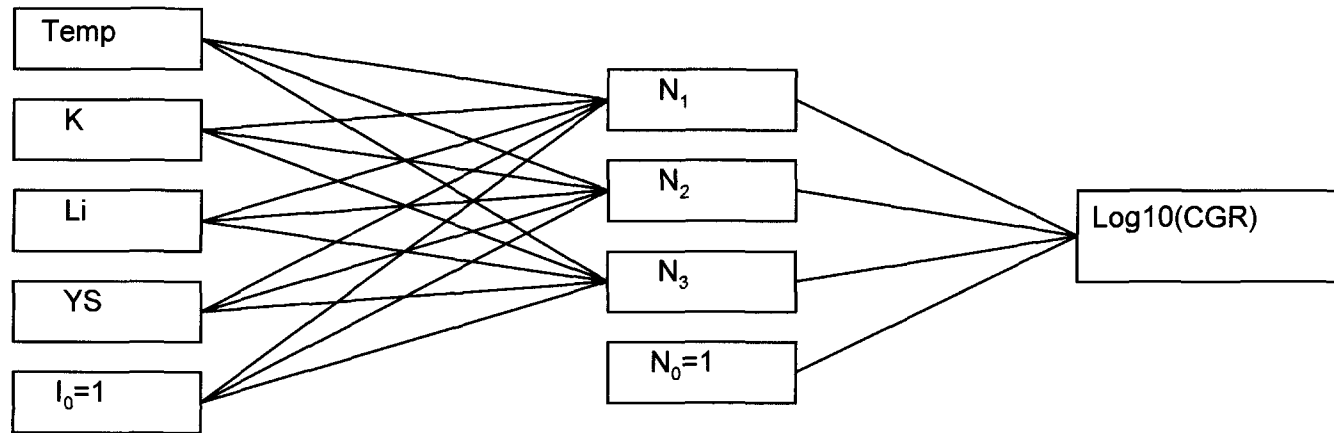


- Overtraining can happen if too many nodes used for number of data
- Split database to check for this:
 - 75% for training, 25% for testing

Database Available

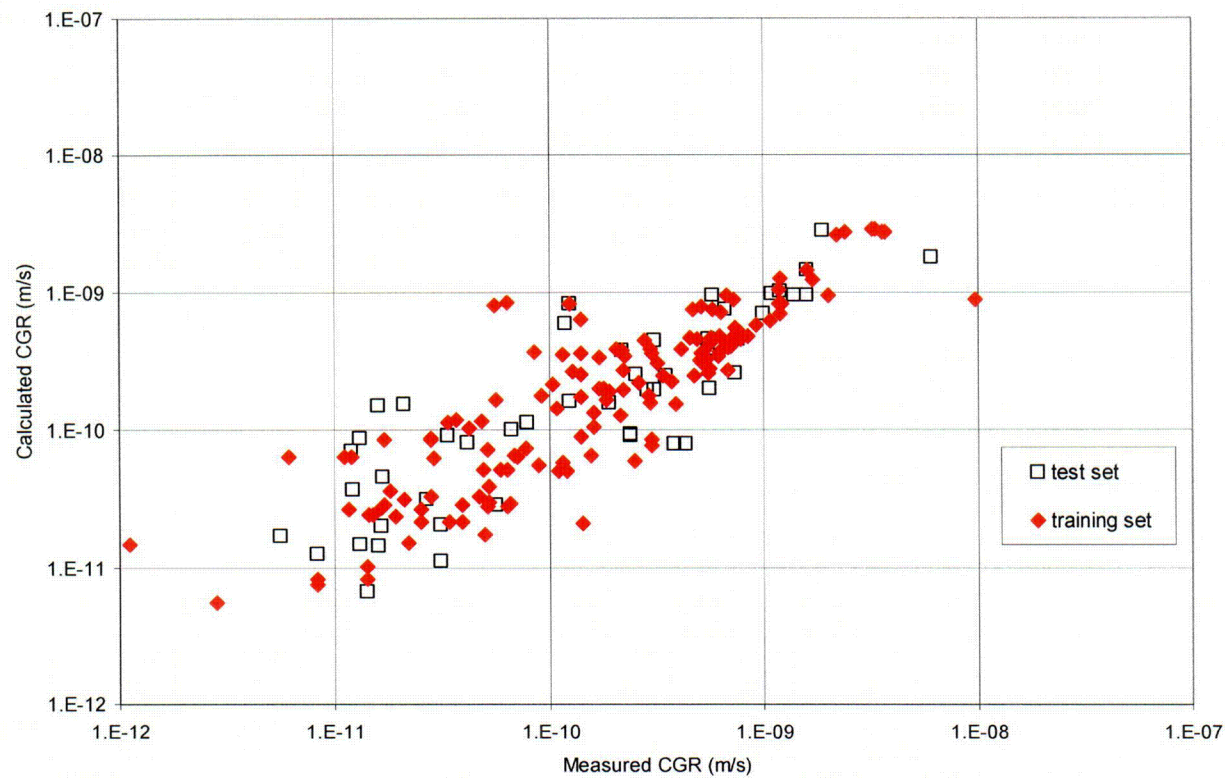
- ~200 experimental measurements of crack growth rates (CGRs)
- Data cover a wide range of applied stress, temperature, and water chemistries
- Number of different specimens used
- Conditions similar to those in a PWR
- Split database 75% for training, 25 for testing

Network Derived

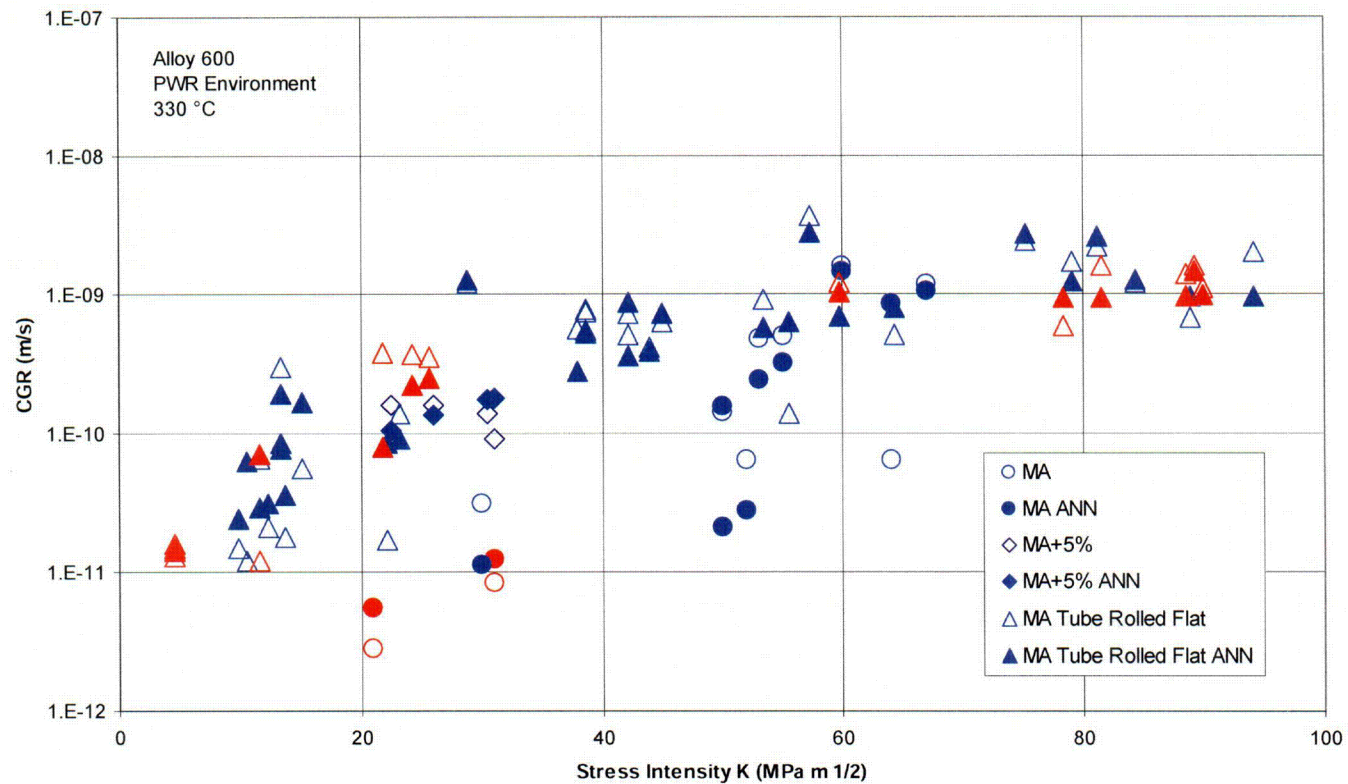


	Node 0	Node 1	Node 2	Node 3
Temperature		-0.19699	-0.27891	-0.2595
Stress		-0.26174	-1.948	-0.39729
Li conc.		-0.07173	2.20143	-0.07249
Yield strength		0.91762	-2.62216	1.57788
I0		-1.34723	-1.59432	-1.38374
Log10(CGR)	-11.364	-0.83189	5.31381	-5.89371

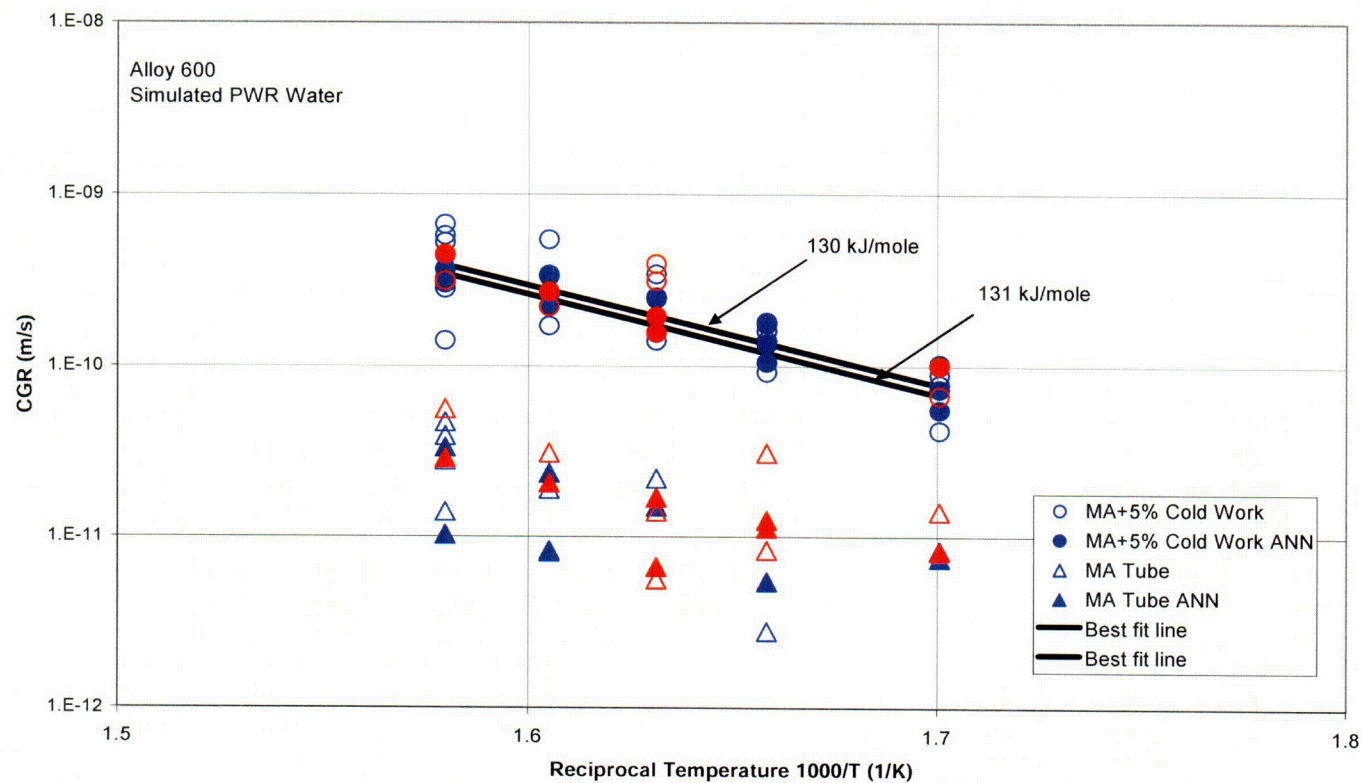
Comparison of Measured and Predicted Data



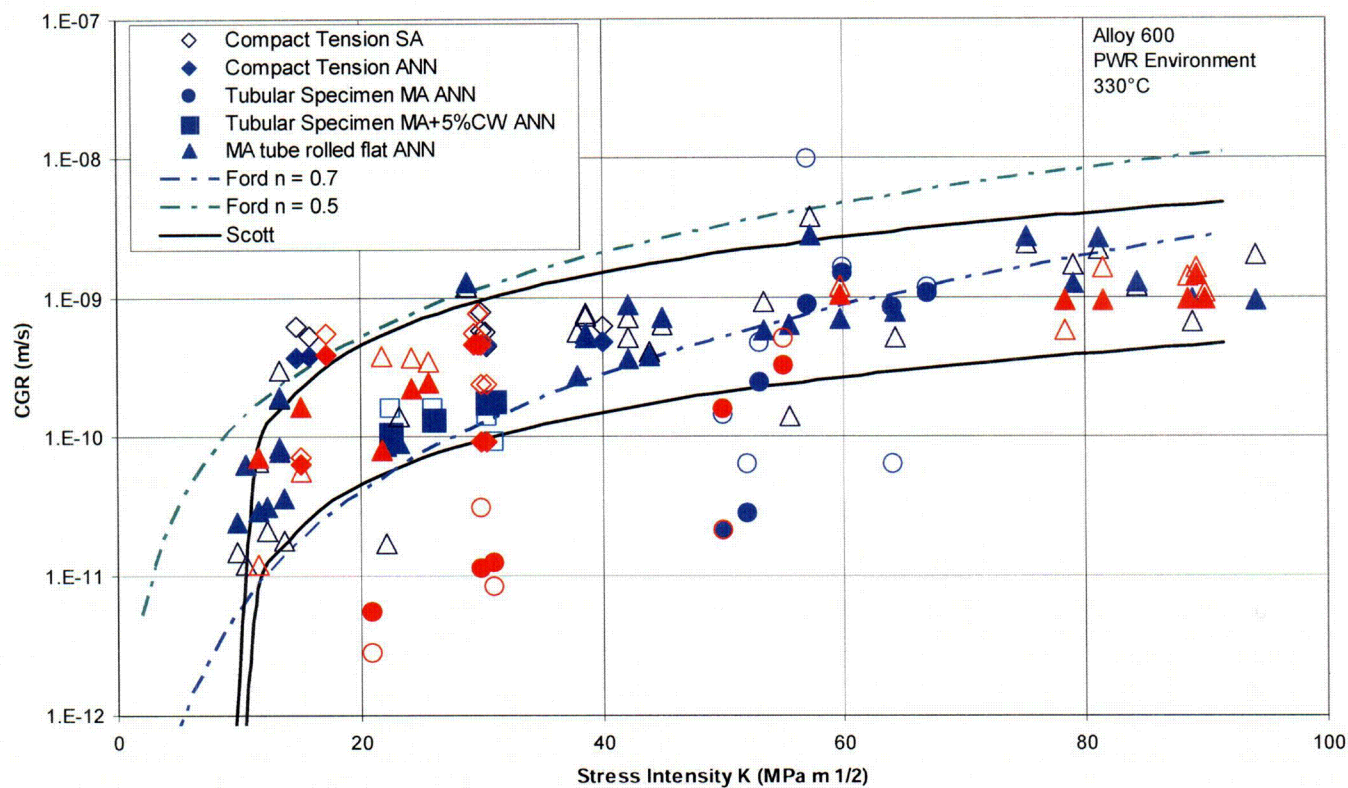
CGR vs. Applied Stress



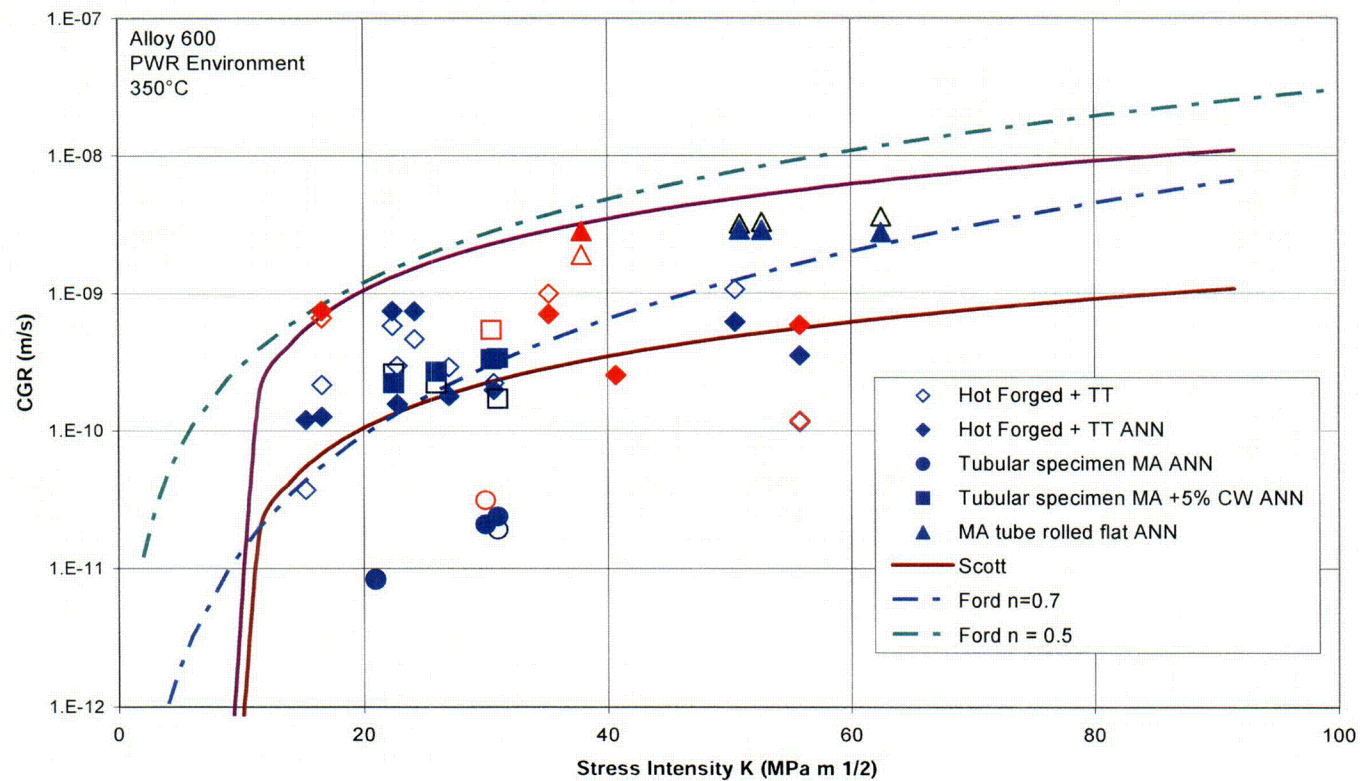
CGR vs. Temperature



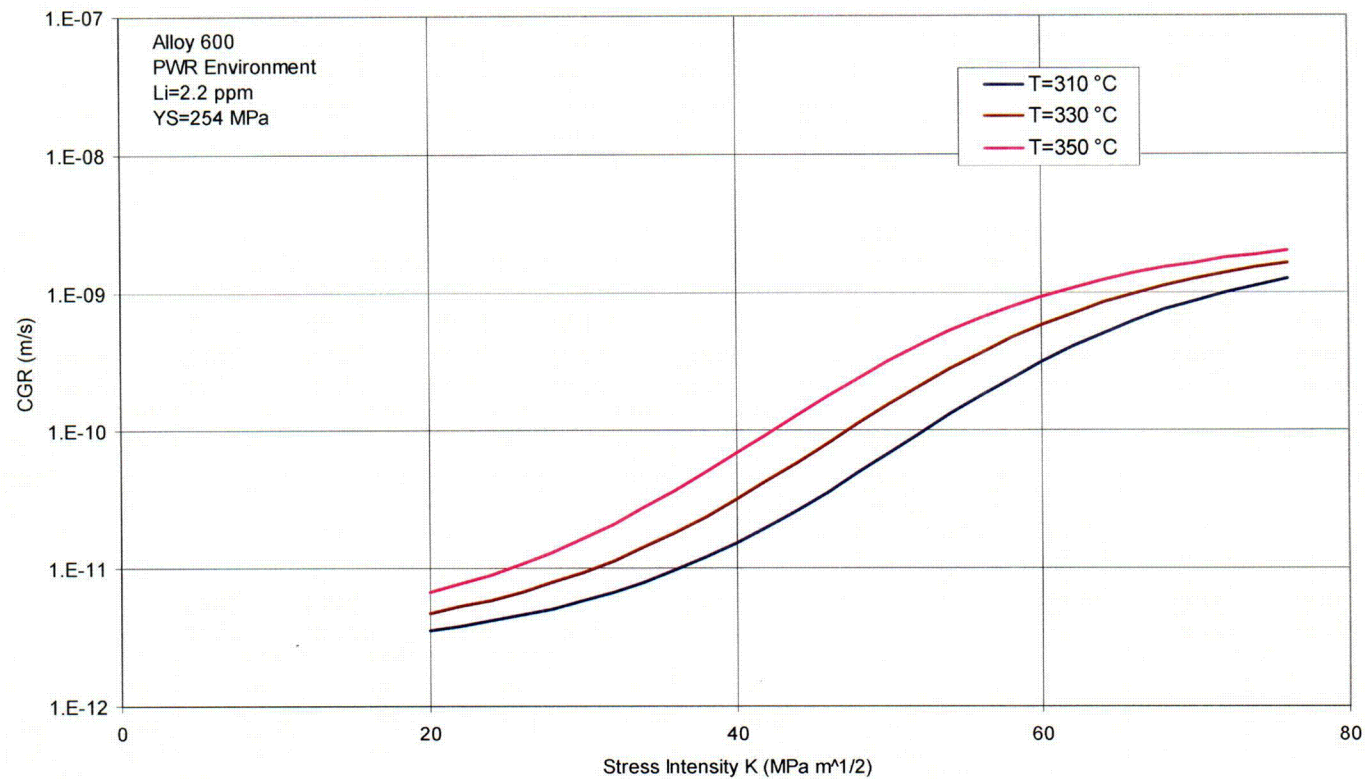
Comparison with Correlations - 330°C



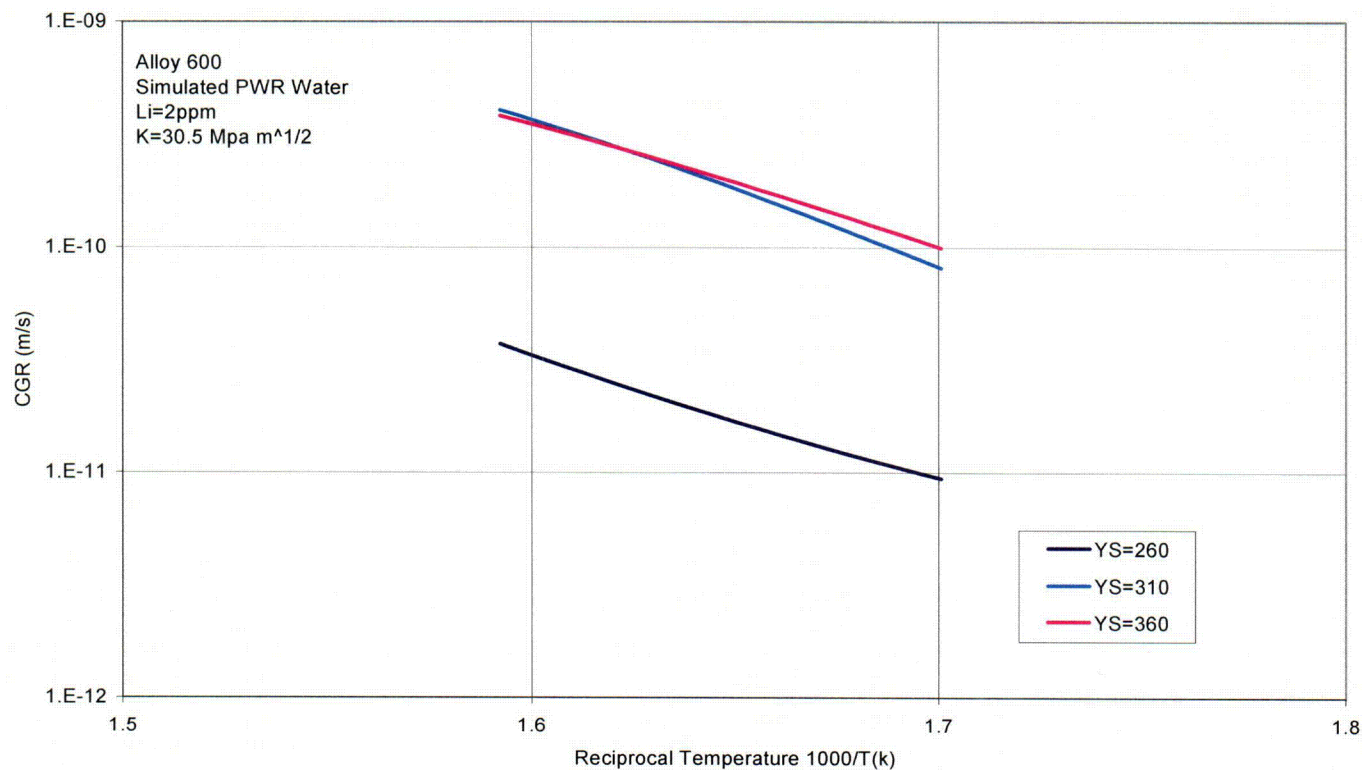
Comparison with Correlations - 350°C



Variation of CGR with Stress for Different Temperatures



Variation of CGR with Temperature for Different Yield Strengths



Relative Effect of Variables

Parameter	Variation [decades]	Range	Direction	Notes
Temperature	0.5 (factor of 3)	310 – 350°C	CGR decreases with temperature	Few data were available for lower temperatures. An activation energy of 130kJ/mol predicts a variation of about 0.75 decades over this range.
Lithium concn.	1 (factor of 10)	0-10 ppm	CGR increases with Li concn.	Most records in database had a conc. of ~2ppm. Comprehensive data for a range of concns. were only available for specimens with a yield strength of ~500 MPa
Applied stress	1 to 2.5 (factor of 10 to 300)	20–60MPam ^{1/2}	CGR increases with applied stress	The CGR was much more sensitive to this parameter for specimens with a low yield strength
Yield strength	1.5 (factor of 30)	200-500MPa	CGR increases with yield strength	Yield strength correlates strongly with amount of cold work



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**CONFERENCE ON VESSEL HEAD PENETRATION
INSPECTION, CRACKING AND REPAIRS
Gaithersburg, MD – Sept. 29-Oct. 2, 2003**

**Results of Accelerated SCC Testing of Alloy
82, Alloy 182 and Alloy 52M Weld Metals**

R. J. Jacko, R. E. Gold, G. V. Rao,
A. Kroes [Westinghouse Electric] and K.
Koyama** [MHI]



Presentation Content

- Background
- Experimental Program and Approach
 - Materials
 - Test Environments
- Results of Corrosion Testing
- Conclusions

Background

- Increased incidences of environmental degradation (PWSCC) of Alloy 600 and the corresponding weld metals have emphasized the need for expanding the corrosion test database.
- The research reported here was conducted to examine:
 - Crack initiation in Alloy 52M (and controls of Alloy 182 and Alloy 600), used for recent weld metal repairs at Ringhals 3 and 4,
 - Crack initiation in Alloy 82 and Alloy 182 weld metal specimens removed from the V.C. Summer RV nozzle safe-end that cracked in service in 2000, and
 - Crack growth rates in the V.C. Summer Alloy 82 and Alloy 182 safe-end weld metals.

Overall Test Matrix

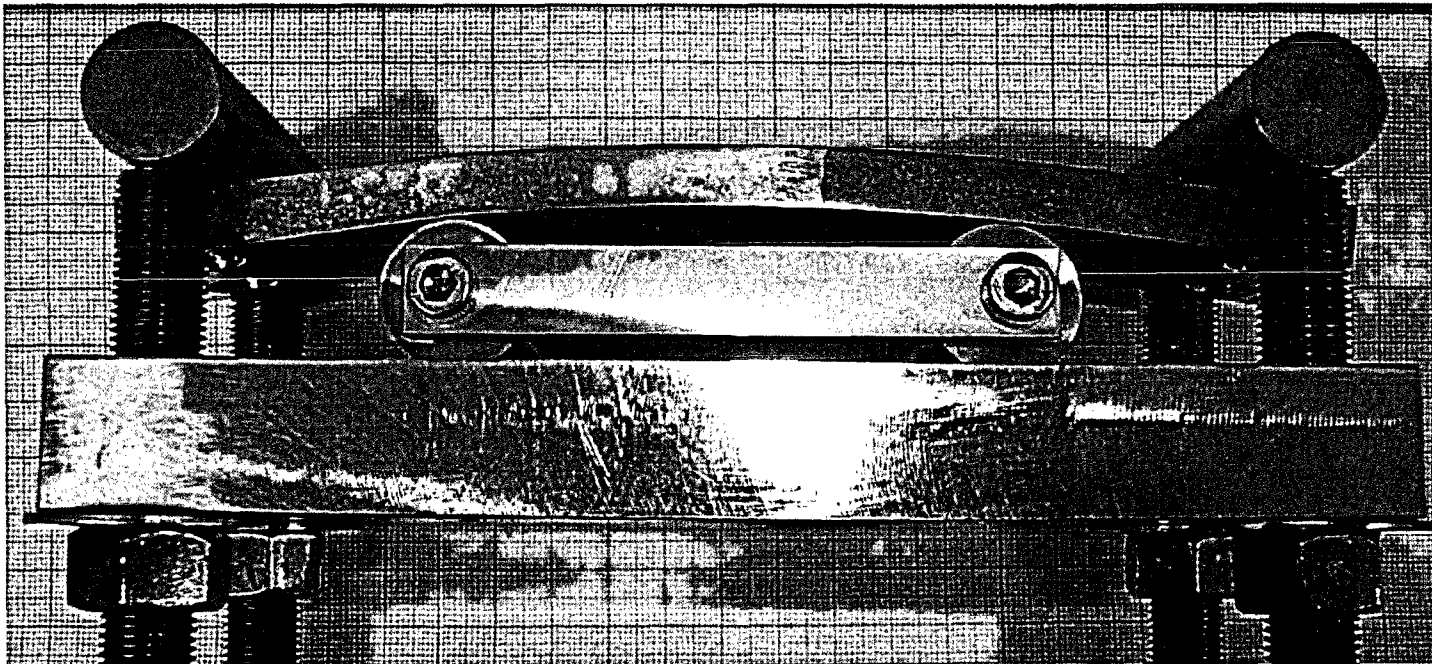
	CRACK INITIATION	CRACK INITIATION	CGR TESTS 0.5T-CT
MATERIAL	400°C	360°C	325°C
Alloy 82	--	X	X
Alloy 182	X	X	X
Alloy 52M	X	--	--
Alloy 600	X	--	--
Approx. Stress	500 MPa (73 ksi)	500 MPa (73 ksi)	--
Levels	360 MPa (52 ksi)	400 MPa (58 ksi)--	--
Stress Intensity	--	--	20, 35 MPavm

Experimental Program – Crack Initiation Tests

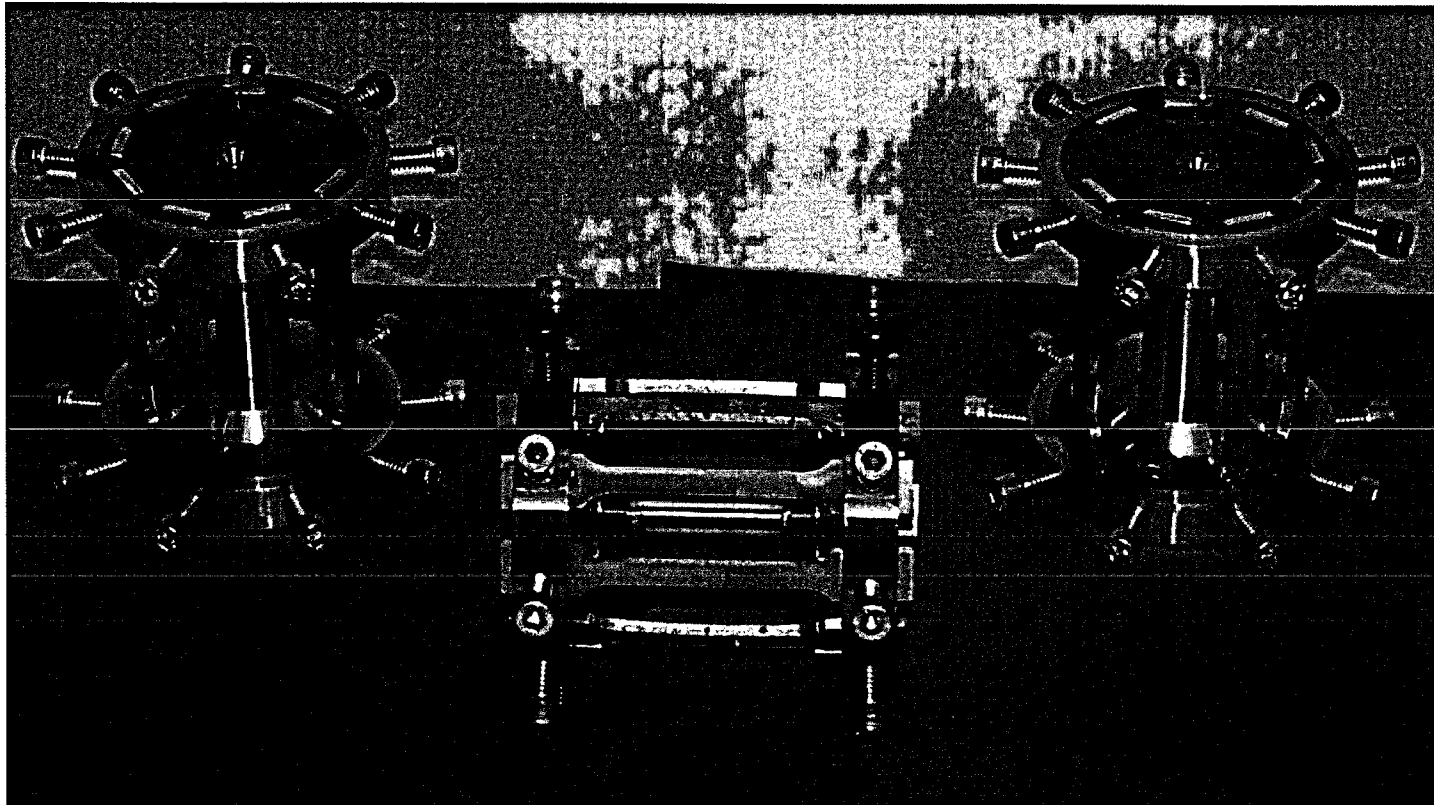
- Four-point bent-beam specimens of Alloy 52M and Alloy 182 weld metal were tested at strains of 0.35 and 1.0 % in a 400°C doped steam environment for periods equivalent to more than forty years at normal operating temperatures.
 - Alloy 600 specimens from archived sections of a CRDM nozzle were included as controls.
- Four-point bent-beam specimens of the V.C. Summer Alloys 82 and 182 weld metals were exposed for 3522 hours in a 360°C (680°F) simulated primary water environment with applied loads equivalent to surface stresses of 400 and 500 MPa.

Test Configuration – 400°C Steam Tests Alloy 52M / Alloy 182 welds – 4 point Bending

Welds for Ringhals 3 and 4 tests are 9 mm thick,
Specimens machined from pre-repair qualification welds



Photos of Alloy 82/182 VC Summer Weld Specimens Accelerated testing in 360°C Primary Water



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Experimental Program – Crack Growth Rate Tests

- Crack growth rate tests were performed on 0.5T-compact tension specimens of the V.C. Summer Alloy 82 and Alloy 182 weld metals.
- Testing was performed in 325°C (617°F) simulated primary water; 3.5 ppm Li, 1800 ppm B, 32 cm³ (STP)H₂/kg H₂O.
- Specimens were actively loaded to nominal stress intensities of 20 and 35 MPa√m.
- Specimens were periodically unloaded to 0.7 initial load
 - Unloading period 1000 s / 9000 s / or constant load
- Crack growth was monitored using reverse DC potential

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Crack Initiation Test Results – Alloy 52M, Alloy 182 and Alloy 600 in 400°C Doped Steam

- Alloy 52M is a modified version of Alloy 52 and is used for GTA welding of Alloy 690 [30% Cr compared to 14-16% Cr typical for Alloy 600 and Alloy 182].
- The doped steam-plus-hydrogen environment, containing
 - 30 ppm of F^- , Cl^- , and SO_4^{2-} and
 - 75 kPa of hydrogen in 20 MPa steam,
 - provides an acceleration factor estimated as 195 relative to corrosion at the 322.8°C Ringhals 3 & 4 RV outlet temperature.
- Weld specimen test articles were 180 mm x 40 mm x 9 mm
Alloy 600 specimens were 102 mm x 19 mm x 3.8 mm.

Crack Initiation Test Results – Alloy 52M, Alloy 182 and Alloy 600 in 400°C Doped Steam (cont'd.)

- The 4-point bent-beam specimens were loaded to either
 - 0.35% strain or
 - 1.0% tensile surface strains;
 - the strains were monitored by strain gages.
- The stresses were “stabilized” by 16 to 19-hour exposures at 400°C, after which the specimens were unloaded and reloaded
- These strains corresponded to residual stresses in the range
 - 320 to 400 MPa [46.4 to 58.0 ksi] for 0.35% strain and
 - 440 to 560 MPa [63.8 to 81.2 ksi] for 1.0% strain.

Crack Initiation Test Results – Alloy 52M, Alloy 182 and Alloy 600 in 400°C Doped Steam (cont'd.)

- Interim inspections were performed at intervals varying from 120 hours (early) to 450 hours; at 418 hours, the strains were “verified” by unload-reload.
- After 2051 hours (equiv. to 45.7 efpy), crack initiation was not observed in the Alloy 52M specimens.
- For Alloy 182, cracking occurred in the high-stress specimens after 214 hours [4.8 equiv. efpy], and in the low-stress specimens after 450 hours [10 equiv. efpy].
- Alloy 600 controls cracked only at the high-stress condition in times from 450 to 598 hours [10 to 13.3 equiv. efpy]. This heat of Alloy 600 exhibits generally good resistance to PWSCC.

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Crack Initiation Test Results – V.C. Summer Alloy 82 and Alloy 182 in 360°C Primary Water

- Specimens were pre-strained to permit testing at 400 and 500 MPa [58.0 and 72.5 ksi] as four-point bent-beams.
- The test environment was 2.0 ppm Li, 500 ppm B and 25-35 cm³ (STP) H₂/kg water at 360°C (680°F).
- After a total exposure time of 3522 hours, crack initiation was not observed in careful post-test examinations.
- Time equivalent to 5.9 efpy in VC Summer Nozzle
 - Cracking detected at VC Summer after 13.1 efpy in 2000

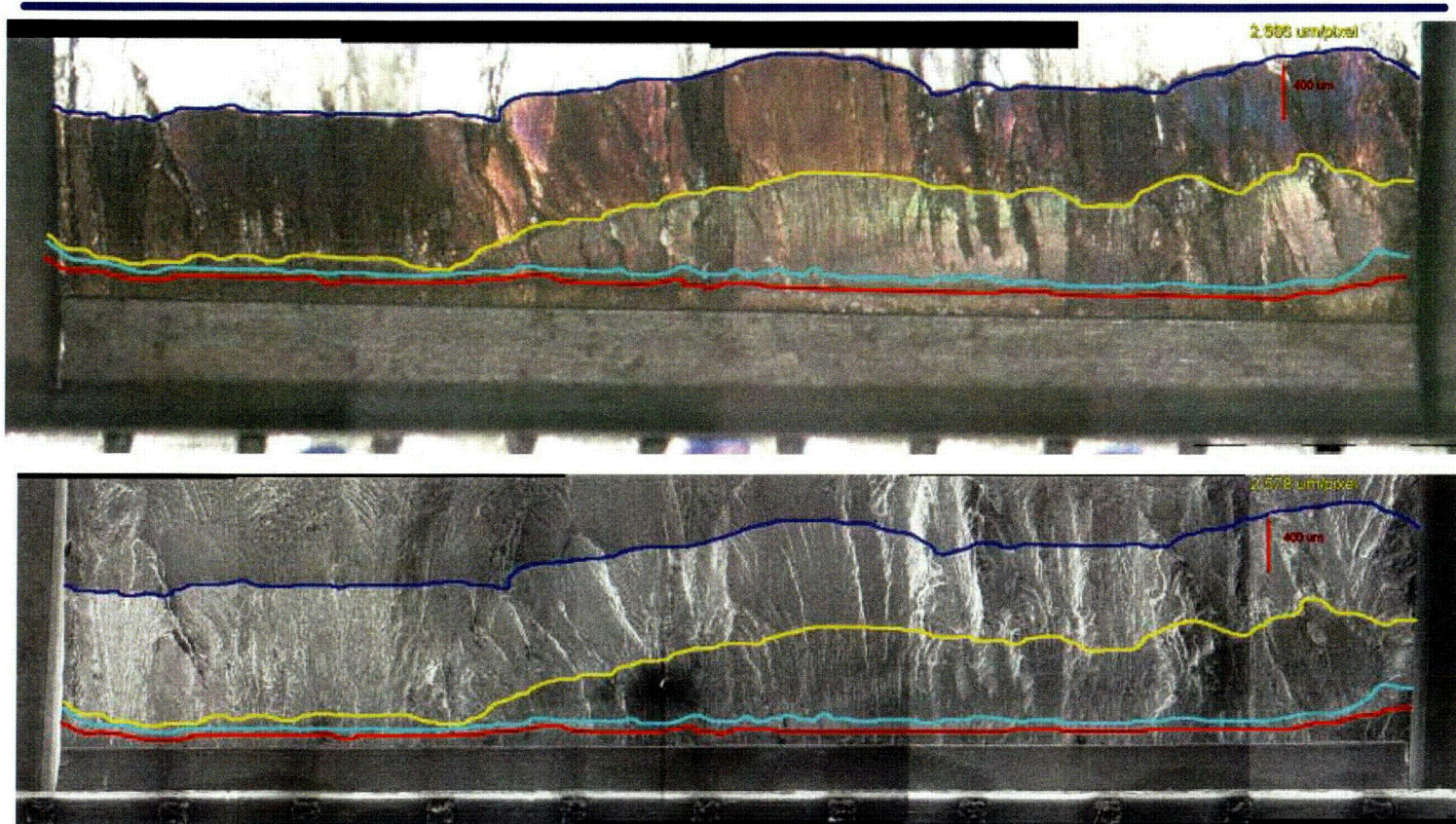
Crack Growth Rate Test Results – V.C. Summer Alloy 82 and Alloy 182 in 325°C Primary Water

- 0.5T-compact tension specimens of the V.C. Summer weld metals were tested at stress intensities of 20 and 35 MPa√m.
- The test environment consisted of 3.5 ppm Li, 1800 ppm B and 30-35 cm³ (STP) H₂/kg water at 325°C (617°F).
- Specimens were fatigue pre-cracked in air at a stress intensity less than 15 MPa√m.
- Specimens were periodically unloaded to 0.7 initial load.
- Reverse DC potential drop was used to monitor crack growth

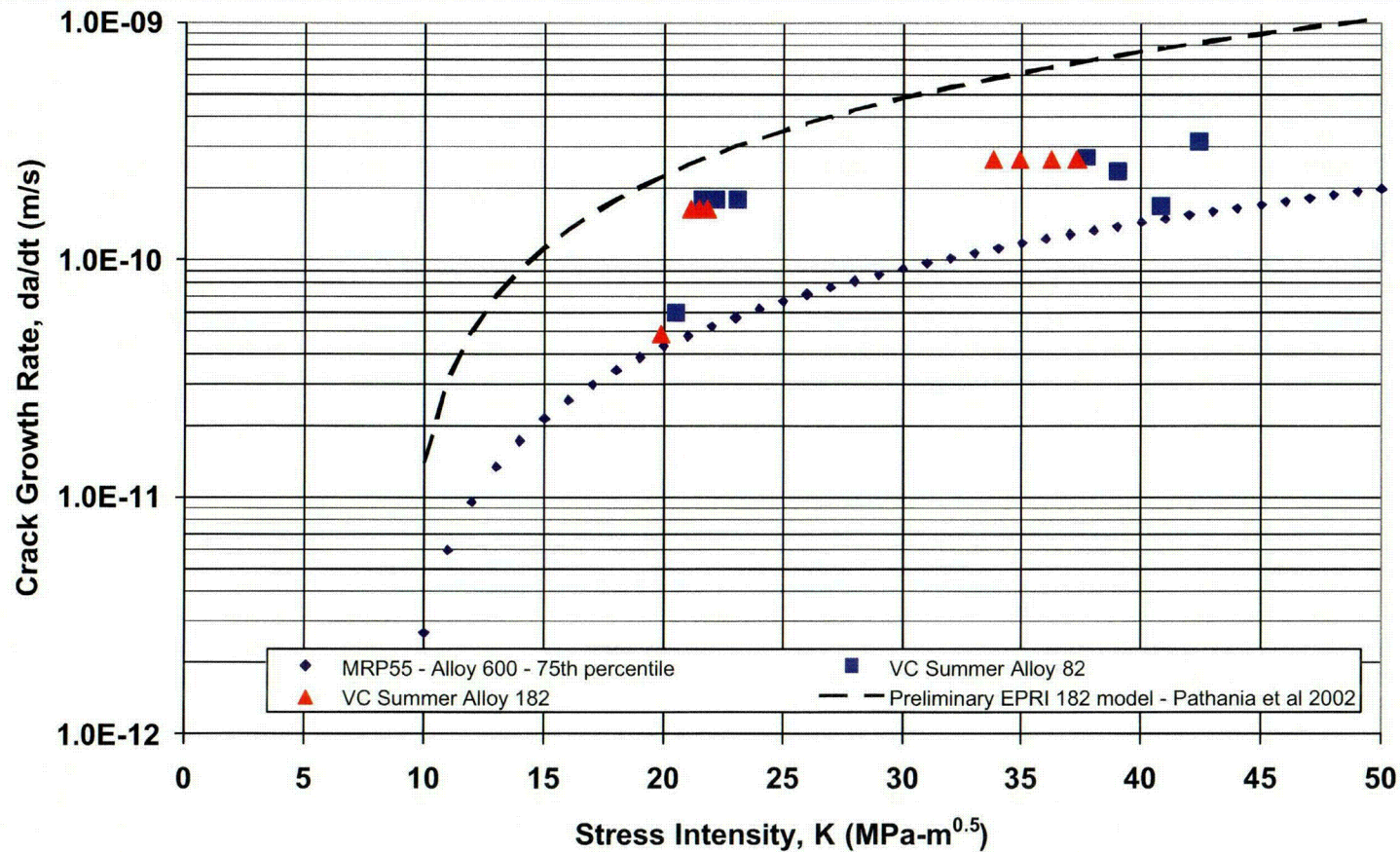
Crack Growth Rate Test Results – V.C. Summer Alloy 82 & Alloy 182 in 325°C Primary Water (cont'd.)

- Only relatively small differences were observed in the crack growth rates in the Alloy 82 and Alloy 182 specimens.
- The crack growth rates were measured to be between the 75th percentile curve for Alloy 600 (EPRI-MRP) and the curve presently proposed in a preliminary EPRI model for Alloy 182 (PWR MRP-21; TR-1000037).

Fractographs – Optical and SEM of 182



Comparison of VC Summer Alloys 82 and 182 Results with EPRI Models



Summary - 400°C Doped Steam Crack Initiation Tests for Ringhals 3 and 4

- Alloy 52M exhibited complete resistance to crack initiation under conditions of high stress (strain)
 - for exposures equivalent to more than 45 years of [322.8°C] operating experience.
- Crack initiation occurred in Alloy 182 and Alloy 600 specimens in shorter periods
 - Alloy 182 equivalent to 5 – 10 efpy
 - Alloy 600 equivalent to 6 – 13 efpy in service.

Summary - 360°C Primary Water Initiation Tests VC Summer Weld Material

- V.C. Summer Alloy 82 and Alloy 182 nozzle safe-end weld metal specimens, strain-hardened and stressed to 400 and 500 MPa, resisted crack initiation for 3522 hour exposures in primary water
- Equivalent to > 5 efpy at 320°C (608°F) [approximate nozzle outlet temperature].

Summary - 325°C Primary Water Growth Rate Tests VC Summer Material

- Crack growth rates measured for Alloy 82 and Alloy 182 RV nozzle safe-end weld metals at stress intensities of 20 and 35 MPa√m were similar
- Growth rates obtained were between the 75th percentile curve for Alloy 600 and a preliminary Alloy 182 curve proposed by EPRI.

Conclusions

- Cracking did not initiate in Alloy 52M under extremely aggressive and accelerated test conditions
- Under similar conditions, crack initiation occurred in Alloy 182 weld metal and Alloy 600 CRDM nozzle material
- The V.C. Summer Alloy 82 and Alloy 182 weld metals exhibited fairly good resistance to crack initiation; measured crack growth rates were consistent with the general industry database.



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**CONFERENCE ON VESSEL HEAD PENETRATION
INSPECTION, CRACKING AND REPAIRS
Gaithersburg, MD – Sept. 29-Oct. 2, 2003**

**Metallurgical Investigation and Root
Cause Assessment of the Reactor Vessel
Head Penetration Alloy 182/82 J-Groove
Weld Cracking in Two Rotterdam Vessels**

**GUTTI RAO¹, GORAN EMBRING³, JIM BENNETCH²,
and WAYNE GAHWILLER¹**

¹Westinghouse Electric Company, Pittsburgh, PA;

²Dominion Generation; ³Vattenfall AB

Objective

- To establish the Mechanism and Root Cause of the CRDM Alloy 182/82 J-Weld Cracking in Rotterdam Vessels

Investigation Centered on J-Groove Weld Indications

- Ringhals 2 CRDM Penetration 62
- North Anna 2 CRDM Penetration 62

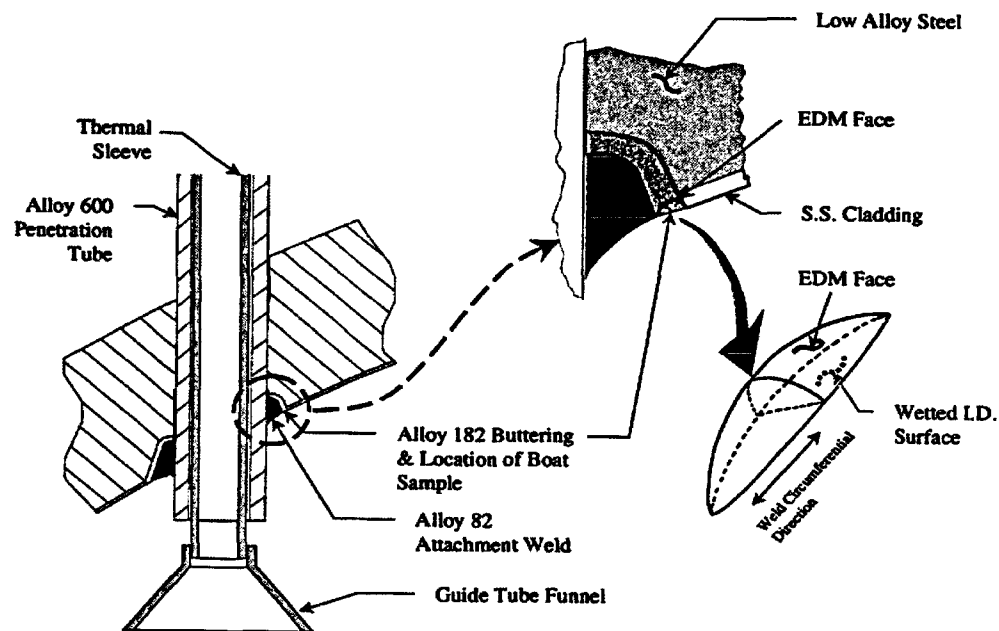
Summary of Hot Cell Investigations

- Surface Examinations
 - Metallographic Examination of the boat Sections
 - Fractographic Examination of the freshly opened cracks
 - Chemistry Assessment of the weld metal regions and fracture surface by:
 - ◆ Energy Dispersive X-Ray Analysis
 - ◆ Microprobe Analysis
 - ◆ X-Ray Diffraction Analyses Techniques
 - Review of the original Fabrication Records
 - Mechanistic and Root Cause Assessments
-

NORTH ANNA 2 - BACKGROUND

- Fall 2001 Outer Surface Inspections of the RV Head revealed Boric Acid Crystals encircling three (Nos. 51, 62 and 63) of the 69 Penetrations
- Subsequent inspection of the Bottom ID Surface of the Vessel Head revealed crack-like indications in the vicinity of the J-Groove weld/butter region of the three penetrations
- An 0.5 inches wide, 2 inch long boat sample, circumferentially positioned in the butter region of the weld and containing the affected region, was removed for investigation
- Hot Cell investigation was conducted at Westinghouse Pittsburgh Laboratories

NORTH ANNA BOAT SAMPLE



Schematic Representation of the Boat Sample Location in North Anna 2
Reactor Vessel Head Penetration J-Groove Weld

SUMMARY OF NORTH ANNA 2 BOAT SAMPLE

- Examinations confirmed extensive hot cracking in the buttering adjacent to the low alloy steel and stainless steel interfaces
- Few of the hot cracks extended to the wetted ID surface of the buttering
- The propensity of hot cracking in the buttering decreased as we moved away from low alloy steel interface

NORTH ANNA 2 BOAT SAMPLE

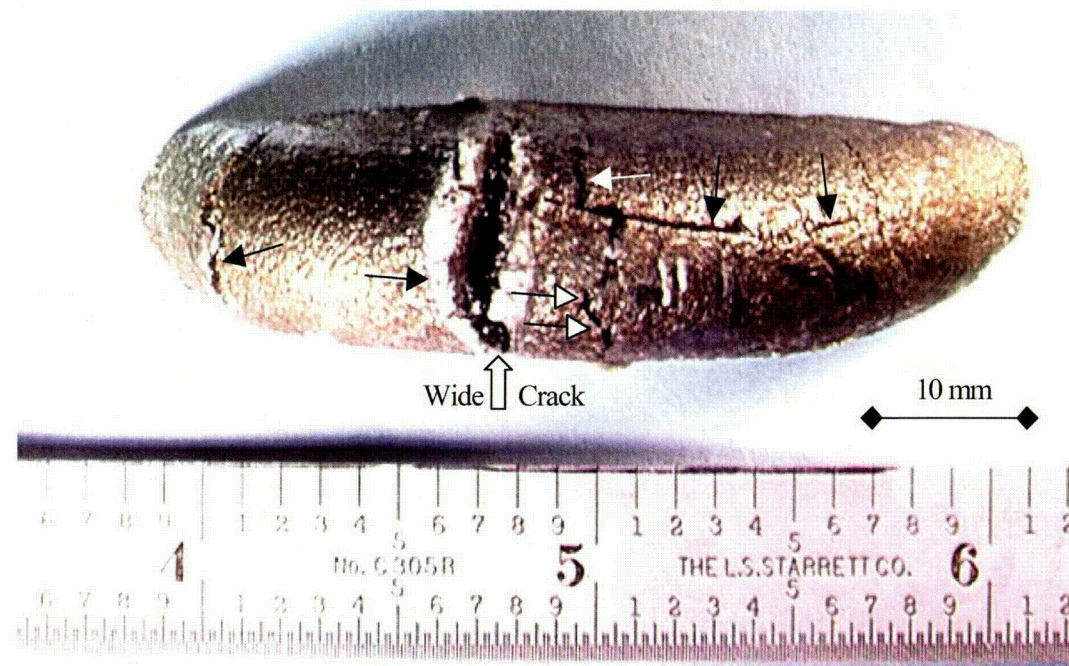
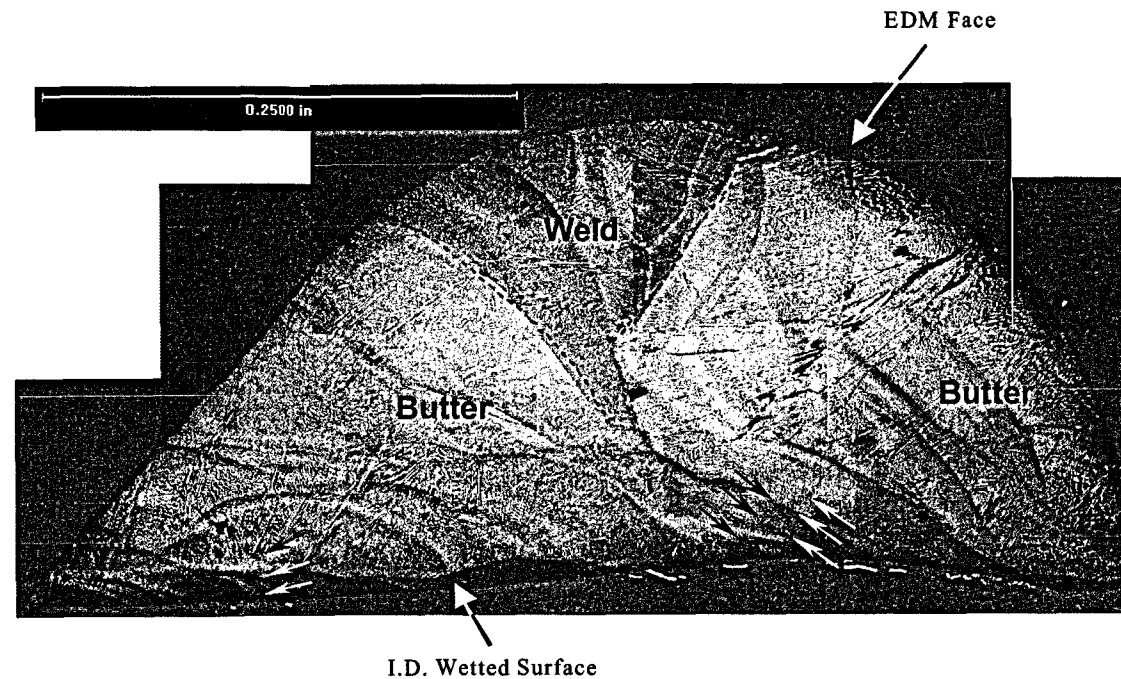


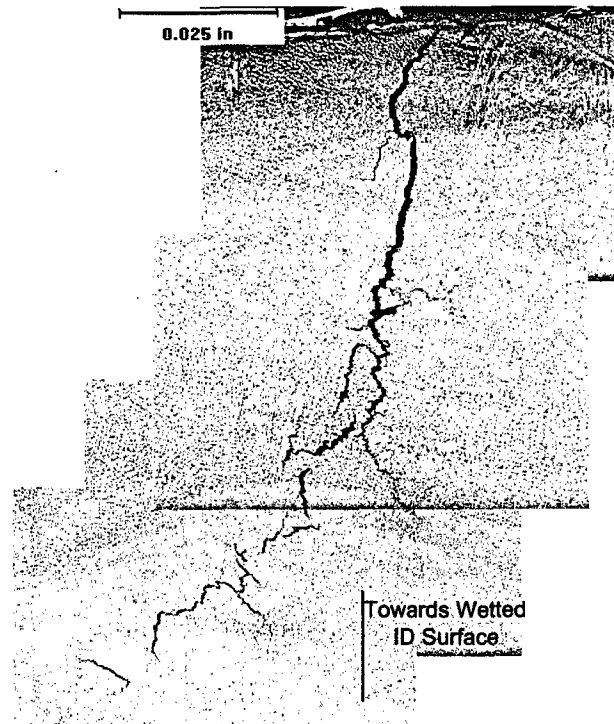
Illustration of the EDM Cut Face
North Anna 2 Boat

NORTH ANNA 2 BOAT SAMPLE



**Metallography with Identified Butter and Weld Regions
By EDAX Analysis, North Anna 2 Boat**

NORTH ANNA 2 BOAT SAMPLE



**Axial Section of North Anna 2 Boat, Showing PWSCC Crack
Progressing from EDM Cut Fact to the Wetted ID Face of RVH**

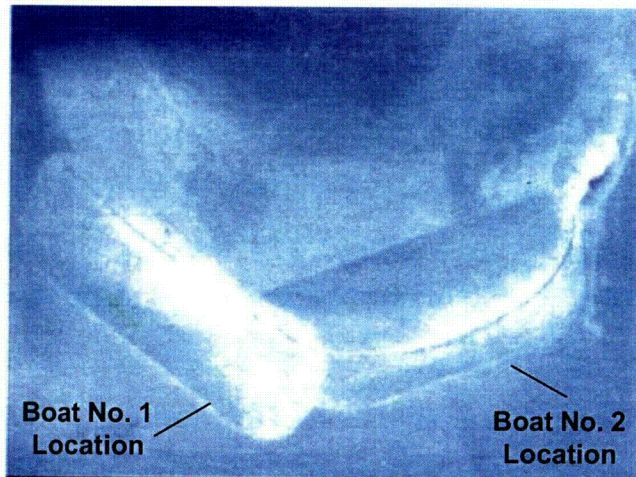
RINGHALS 2 - BACKGROUND

- 1993 outage inspections revealed a 7-inch (18 cm) long circumferentially-oriented surface indication in the J-weld of Penetration No. 62
- Investigations centered on:
 - ◆ Two small boats – 1 inch diameter and 0.1 inch thick
 - ◆ Two large boats – 2.75 inches long, 0.8 inch deep
- Hot Cell investigations were conducted at:
 - ◆ Studsvik Laboratory in Sweden
 - ◆ Westinghouse Laboratories in Pittsburgh, USA

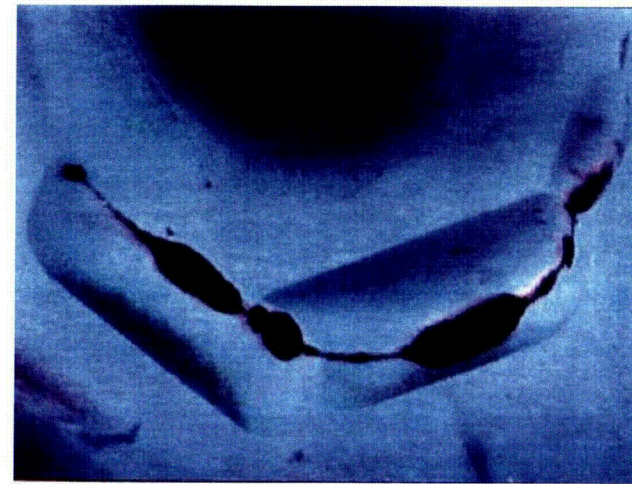
SUMMARY OF RINGHALS 2 BOAT SAMPLES

- Evidence of 0.02 inch-wide crack between low alloy steel and Alloy 182 buttering running along the entire boat length
 - The crack was arrested and blunted as it extended into the Type 309 stainless steel cladding
 - The crack appeared wider at the EDM cut face and it narrowed down as it approached cladding
 - Incomplete wetting (fusion) of the first layer of buttering resulting in “lack of fusion” defects at the interface
 - Significant carbide precipitation in the fusion zone
 - The interconnected microfissures provided access of primary water to the weld interface and contributed to:
 - ◆ Microscopic wastage of low alloy steel interface
 - ◆ Secondary crack extension of the weld defects by PWSCC
-

RINGHALS 2 BOAT SAMPLE



Before PT

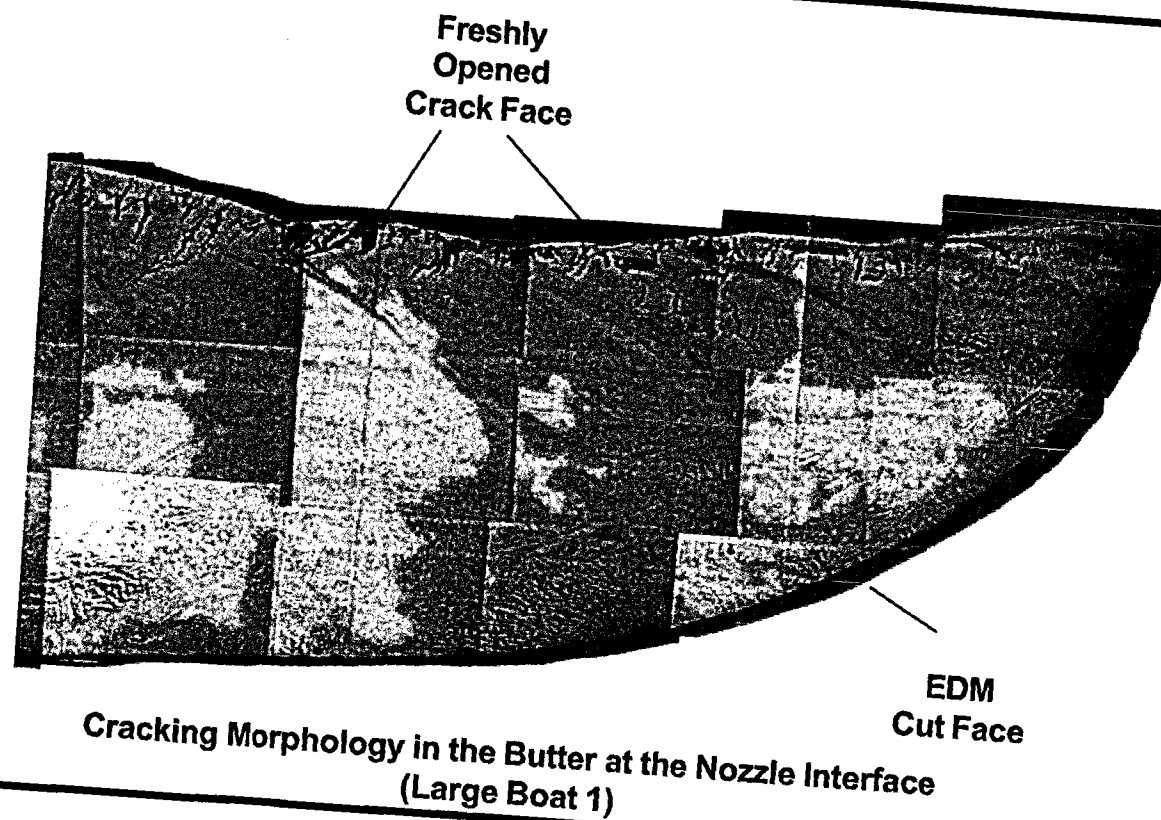


PT Results

Appearance of Crack at the Bottom of Divots
(Ringhals 2 Penetration 62)

RINGHALS 2 BOAT SAMPLE

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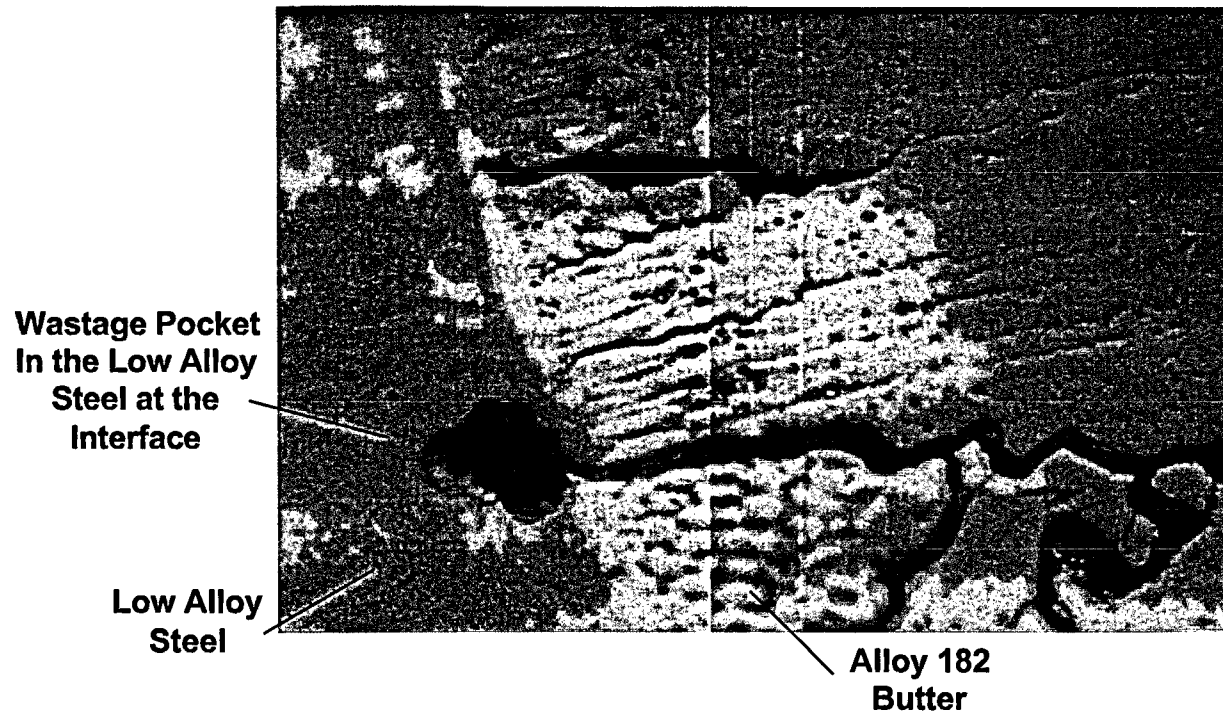
RINGHALS 2 BOAT SAMPLE



Crack Termination at the Cladding

RINGHALS 2 BOAT SAMPLE

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Evidence of Carbon Steel Wastage at the Butter Interface

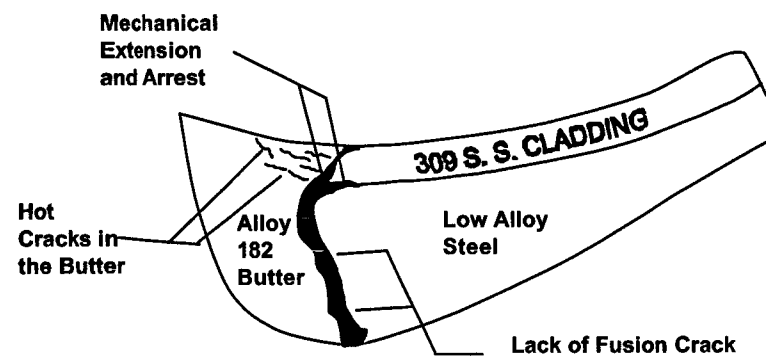
ROOT CAUSE CONSIDERATIONS AND POSTULATED MECHANISM

- The J-Weld preparation by Air Arc Gouging Technique left an oxide layer and carbon residue on the low alloy steel surface
- Inadequate cleaning prior to welding left oxide, carbon and moisture on the surface
- The surface condition contributed to a non-wetting and lack of fusion bonding during the deposition of the first layer of buttering at the low alloy steel interface

ROOT CAUSE CONSIDERATIONS AND POSTULATED MECHANISM (continued)

- Attempt to repair this during subsequent depositions was unsuccessful, leaving presence of heavy carbides, slag inclusions and poor bonding at the interface
- A thin initial layer of buttering and non-uniform temperatures may have led to the de-bonding of the weld interface under the influence of thermal stresses even while the top (ID surface) layers of the weld metal were being deposited
- The movement of the crack faces and the crevice condition of the crack created a strain field at the crack tip during the fusion of the top layers of the weld inducing microfissures due to hot cracking of the weld metal

RINGHALS 2 BOAT SAMPLE



Ringhals 2 Boat Sample (Transverse Section)

CONCLUSIONS

- North Anna and Ringhals Boat Samples showed similar characteristics
 - The investigation results of the CRDM Penetration cracking at Ringhals 2 and North Anna 2 units supports that the observed cracking originated from the original fabrication of the J-Weld buttering
 - The microfissuring of the final layers of weld metal buttering occurred by a “hot cracking” mechanism. Excessive strains caused by the occurrence of a sub-surface larger lack-of-fusion crack at the weld metal to low alloy steel interface most likely contributed to the cracking in the Ringhals weld.
-

CONCLUSIONS (continued)

- The occurrence of the main crack at the weld interface and the microfissuring of the weld metal are both caused by the inadequate surface preparation of the J-Groove prior to the welding and/or weld repair
 - The root cause of the cracking in the Ringhals and North Anna vessels examined here is believed to be lack of fusion at the Low Alloy Steel Interface
 - Primary water accessed to the area of lack of fusion through exposed hot cracks at the wetted surface provided potential for additional cracking by PWSCC
-



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French Regulatory Experience and Views on Nickel-Base Alloys PWSCC Prevention & Treatment

by

Guy TURLUER, Gérard CATTIAUX, Bernard MONNOT
(IRSN/DES, Fontenay-aux-Roses, France)

*Institute for Radiological Protection & Nuclear Safety **
Department of Safety Evaluation

and

David EMOND , Jacques REUCHET, Philippe CHARTIER,
(DGSNR/BCCN, Dijon, France)

*General Directorate for Nuclear Safety and Radiological Protection ***
Nuclear Steam Supply System Inspectorate

* <http://www.irsn.fr/> guy.turluer@irsn.fr , fax: + 33 1 47 46 10 14

** <http://www.asn.gouv.fr/> david.emond@asn.minefi.gouv.fr , fax: + 33 3 80 29 40 88

French Nuclear Safety Bodies Presentation Outline

- Context & objectives of a presentation by French Nuclear Safety Bodies
- Specific features of French nuclear organizations and practices
- An all PWR fleet prone to « generic effects » illustrated by the Inconel Zones
- Features , Principles and Evolution of French Regulatory Rules
- Specific Features of Alloy 600 PWSCC
- « Inconel Zones Review », A Proactive Approach to maintenance vs PWSCC
 - background
 - objectives
- Treatment of Inconel Zones
- Use of PWSCC initiation models (Interest and limitations)
- Involvement of ASN / IRSN in the implementation and follow-up of a comprehensive In Service Inspection (ISI) Program
- Status of Vessel Head Inspection and Replacement
- Status and Prospects for Bottom Vessel Head Penetrations in France
- Future Prospects and Investigation Needs
- French Nuclear Safety Authority (ASN) & IRSN CONCLUSIONS

Context & Purpose of the IRSN/DGSNR Presentation in this Conference

Presentation of the French Nuclear Safety Organizations & their role

EDF the French sole Nuclear Operator in France, in the first place, responsible for the Nuclear Safety of a fleet of 58 PWRs: It has:

- **A large expertise in terms of R/D, failed components investigation capabilities,**
- **International activities and is an active EPRI member,**
- **Structured and comprehensive maintenance programs and central support staffs to anticipate problems and instruct an important experience feedback,**
- **Units and staffs devoted to manage safety, set doctrines & audit their implementation.**
- **been PROACTIVE with regard to the Inconel vessel penetrations since 1991**

The vigilance and positions of the French Safety Bodies may have played a crucial role in the early strategies and steady follow up of the Inconel Saga.

Hence the objectives of the IRSN/DGSNR (ASN) presentations:

- **Recall the main specific aspects of the French situation vs. the Inconel zones,**
- **Recall the main regulatory features and their evolutions in France,**
- **Present the « PROACTIVE Inconel Zones » return of experience », as perceived by the Safety Bodies from the technical and regulatory stand point,**
- **Explain the reasons for the technical and regulatory positions of DGSNR/IRSN on the now 13 years old « Inconel Zones Review » in France,**
- **Bring some Testimony in the USA, in the wake of the**
« Davis Besse Lessons Learned Issue »

Specific features of French Nuclear Organizations & Practices

- One Nuclear Power Operator of a fleet of 58 PWRs EDF
- One Power Reactor Manufacturer Framatome-ANP
- One Scientific Organization in charge of Nuclear R&D CEA
- One Regulatory Body for Nuclear Safety & Rad Protection (ASN) ⇔ DGSNR
 - Central Staff (150 members) + regional offices (100 members)
- One Body for Nuclear Safety and Radiological Protection, (staff 1500) IRSN
 - performing Research mainly in accident studies, radiological protection...
 - & Technical Support to DGSNR, (staff : 350), some specialists following Materials, Components, NDE, R&D issues, with some limited confirmatory or exploratory Research
- No License Renewal in FRANCE,
- Importance of Decennial Complete Visits for: (DCV = 10 yearly outage)
 - Comprehensive Components Condition Investigations, Repairs , Replacements
 - and for Safety Reassessment, & Implementation of Safety improvements
- Decennial Complete Visits (DCV) including regulatory hydro test for primary circuit
 - CP 0 (900 MWe) Second DCV, nearing Third (BUGEY 3 CRDM Leak at 1st DCV)
 - CP1-CP2 (900 MWe) first DCV, some Second DCV
 - P4-P'4 (1300 MWe) first DCV
 - Latest French Design N4 series (4 Units) , commissioned in 1996-99

An All PWR Fleet of 58 Reactors, where Alloys 600/182-82 extensively used

- An important all PWR fleet (63 GWe- 80 % of French electricity)
- Standardized in 4 PWR series constructed and commissioned in a crash program,
- Sensitivity to generic effects,
- Advantage for the return of experience.

Some differences with the use of alloys 600, 600 TT, 690 , Stainless Steel within the series

SERIES	Loops/MWe	N° of units	Date of Commission	Main Specific initial features, as commissioned
CPO	3 /900	6	1977-79	Hot Plenum, Bugey 3 (1978)
CP1-CP2	3 /900	28	1981-87	Cold Plenum, Blayais 1, (1981) some SG tubing in 600 TT
P4 –P'4	4 /1300	20	1984-93	Hot Plenum, Alloy 600 TT for SG Alloy 600 for PZR nozzles, Cat. 2 (1987)
N4	4 /1450	4	1996-99	Alloy 690 for SG, CRDM (4 units) Alloy 690 for BMI (2 units) 3 last Units with Vessel/Primary loop Alloy /82 DMW (600°C stress relieved)

Specific Features of Nickel base Alloys PWSCC

PWSCC may be considered as a major contributor to degradation & aging in PWRs, particularly difficult to assess since:

- The degradation mechanisms are not yet fully established neither understood,
- Characterized by incubation times (crack initiation) which can be very long, ex: Fessenheim 2 CRDM first incipient penetration crack detected after some 130 000 h., to be compared to some units like Cattenom (30 000 h.) or Blayais (80 000 h).
- Inconel PWSCC crack initiation times t_i are not only governed in a deterministic manner by various parameters difficult to assess , quantify, and weigh, i. e. :
 - Actual Wall Temperature and temperature dependence (activation energy)
 - Bulk and Surface Residual + Operational Stresses (σ) $\Rightarrow 1/t_i \propto \sigma^n$, $n=4\pm?$
 - Material composition (C content) & microstructure (grain boundary Chromium Carbide relative coverage) and other metallurgical unknowns,
- Inconel PWSCC crack initiation times are also governed by stochastic processes and characterized by a large scatter (large distribution of time to initiation for identically stressed carefully controlled identical Inconel specimen even in the laboratory tests,
- Stress Assessment : actual residual stress fields, bulk, surface, static and some dynamic operation cycling or transients may strongly govern in a complex manner both Crack Initiation (CI) & Crack Propagation Rates (CGR).

Features, Principles and Evolution of French Regulatory Rules to Ensure Integrity of the Main Primary Circuit (1/3)

Evolution of French Regulatory Practices:

- **Ministerial order 1974** : concerning the Main Primary Circuit (manufacturing and operation),
- **Ministerial order 1999** : concerning the surveillance in operation for Main Primary and Secondary Circuits,
- **RCCM code** (last edition June 2000),
(Rules for Conception, Construction of PWR Mechanical components):
compiled by EDF (utility) and Framatome (designer/manufacturer);
- **RSEM code** (first edition 1997) :
 - Rules of Surveillance in Operation for PWR Mechanical components, compiled by EDF
 - and accepted by French Safety Authority (ASN)
- **Regulatory decisions since 2000**: ASN may write and publish decisions (web site),
 - with requests about important technical problems,
 - for example the decision for Inconel Zones (IZ) in March 2001.

Features, Principles of French Regulatory Rules to Ensure Integrity of the Main Primary Circuit *(continued, 2/3)*

- **Preclude (avoid and prevent leak) any leak in the main primary circuit**
- **Make sure that no flaws would lead to a leak during operation**
- **Methodology pertaining to the so called « Sensitive Zones »(SZ)**
 - **Search for possible degradations through:**
 - Design files (Stress analysis reports),
 - Fabrication files (repairs, deviation from procedures),
 - Complex loads such as mixing fluids, possible synergetic effects of cyclic loads on SCC,
 - **Sensitivity analysis $\Rightarrow$ zones ranking regarding their sensitivity to some likely degradation mechanisms (such as corrosion, SCC, Fatigue, Corrosion-fatigue..),**
 - **$\Rightarrow$ Determination of Sensitive Zones (SZ),**
 - **In SZ, knowledge and characterization of the Degradation mechanism(s) anticipated,**
 - **In SZ, determination of flaw critical size (with security margins),**
- **Methodology for In Service Program (ISI)**
 - **Definition of an ISI program as preventive, and capable to detect flaws prior to reaching critical size,**

Features, Principles of French Regulatory Rules to Ensure Integrity of the Main Primary Circuit *(continued 3/3)*

- **Coverage of Inconel Zones Families would be possibly achieved by inspection of several precursor SZ among all the SZs:**
 - Precursor should be truly representative of SZ (i.e.: same degradation mechanism), provided it is truly demonstrated as a forerunner for initiation, and exhibits a faster degradation propagation rate (CGR),
 - ⇒ requires the definition of extension rules in ISI program.
- **Methodology of NDE qualification:**
 - Ensure flaw detection before reaching critical size,
 - ⇒ choice of NDE method & performances and a qualification process,
 - In SZ ⇒ flaw detection demonstration:
 - When flaws have already been detected in components,
 - ⇒ »specific» qualification,
 - When flaws are « feared » but not yet detected,
 - ⇒ »general» qualification,
 - In Non SZ ⇒ only a description of methods performances is required,
 - For each NDE method, the nature, the objective & NDE intervals should be specified.

INCONEL ZONE REVIEW for the French FLEET of 58 PWRs (Background which entailed a Strong PROACTIVE PROJECT)

- 1959, by CORIOU et. al. in CEA/Saclay first Laboratory Discovery of Alloy 600 propensity to crack by SCC in PURE WATER at 350 °C,
- 1959-1975, confirmation of Alloy 600 SCC in Pure & in nominal Primary Water (hence the acronym PWSCC, PW for Pure or Primary Water), then ⇒
- Alloy 600 and Nickel base alloys prone to PWSCC in nominal Primary Water (hydrogenated HT water ⇒ places Ni base alloys in the unfavorable SCC susceptibility range close to Ni/NiO transition).
 - ⇒ Generic problem on highly stressed Nickel base alloy components,
 - ⇒ Hence a source of primary components failures and primary water leaks for which anticipation methodologies may be limited*.
- In 1989, in addition to many SG tubing problems, 2 fast PWSCC degradations could occur in France within the first fuel cycle on 1300 MWe units (Nogent 1)
 - Circumferential through wall Cracking on new alloy 600TT, SG tubing on top of TS,
 - Leaks on PZR instrumentation nozzles of 1300 MWe units (made from alloy 600).
- 1989, Initiation of the “Inconel Zones Review” by EDF & Framatome, at the “strong request of ASN, i.e. more than 1 year before the Bugey 3 CRDM leak.

* refer to : « status of alloy 600 components degradation by PWSCC in France; incentives & limitations of life predictions as viewed by a Nuclear Safety Body », by G. TURLUER, IPSN/DES/SAMS, Fontenay-aux Roses, France, Proc. of Intern. Symposium on Plant Aging & Life Prediction of Corrodible Structures, May 15-18, 1995, Sapporo, Japan

PROACTIVE « Inconel Zones Review » in France: Objectives and Tasks

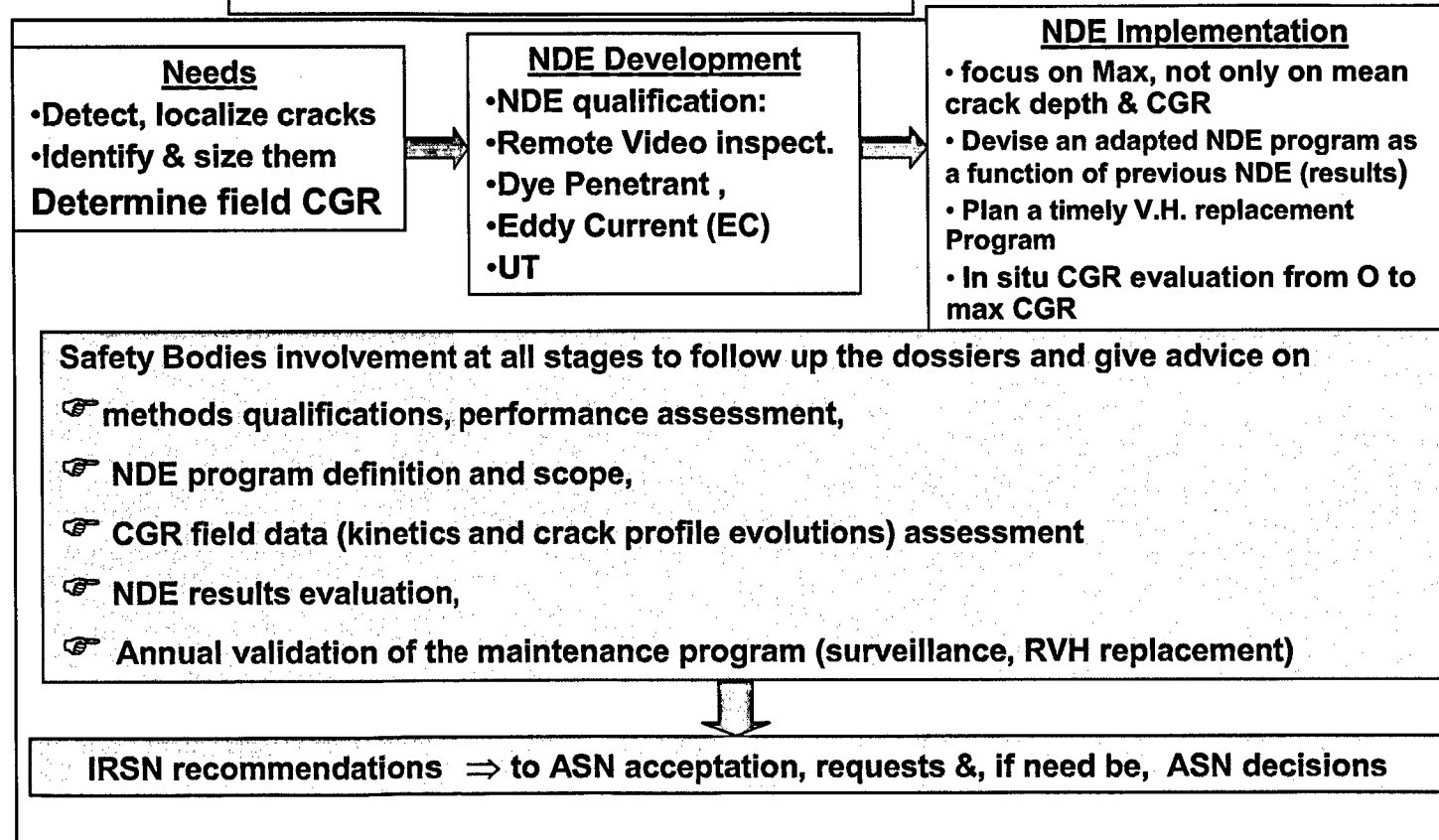
- Review for all « Inconel Zones (IZ) Potential PWSCC Occurrence,
- Assess all IZ fitness for service,
- Develop NDE inspections techniques & tooling,
- Implement NDE Program for the most PWSCC prone IZ,
- Justify the IZ Review by a comprehensive R&D Program,
- Refine an empirical PWSCC initiation model for ranking purposes,
- Verify the postulated IZ, time to cracking by a sufficiently large NDE program:
 - Either full scale, (100 %)
 - Or on significant sampling rate,
- Perform a Safety assessment for each IZ, postulating worse consequences:
 - From Leaks, which, in many instances of un-sustained leak, may lead to dry boric acid/salts deposits, with no measurable general corrosion, BUT:
 - small concealed low leak rates may entail penetration OD SCC (Bugey 3, Occonee)
 - to higher leak rates $\Rightarrow$ corrosion/flow accelerated corrosion to low alloy steel,
 - From a possible Break, including Control rod ejection.
- Prepare for mitigation techniques, including repair or replacement

Use of PWSCC Initiation deterministic (empirical) Models as a Predictive Tool for PWSCC Occurrence in Plants ?

- Crude Temperature/time models(?), ignoring paramount effects of stress, metallurgical factors, & batch to batch variations, are irrelevant, (misleading?)
- More sophisticated models such as those developed in France, either expressed in terms of relative sensitivity of Inconel Zones or estimated time to initiation :
 - Need a sufficient validation with NDE findings in the field,
 - Then may be used with caution for ranking purposes (precursor determination),
 - CANNOT be used to predict the time to macroscopic crack initiation (ti) for a given component, since :
 - Intrinsic material sensitivity to PWSCC can only be qualitatively estimated,
 - Effective Stress, including surface CW, residual Surface Stress due to assembly, machining, grinding or final surface finish (Sigma to the power 4 $\pm$ x) cannot be estimated everywhere exactly on as fabricated components,
 - Uncertainty brackets cannot easily be estimated (in terms of index or time ti).
- IRSN & DGSNR accepted only the empirical models only for
 - comparing and integrating Inconel zones data,
 - Ranking purposes to set inspections priorities,
- IRSN/DGSNR did not accept any absolute time to initiation prediction of the kind «no cracking anticipated before 30years of operation » for a given zone,
- Hence the request to proceed to NDE at least on a sampling basis

Implementation of a comprehensive In Service Inspection (ISI) Program IRSN & ASN involvements (1/2)

Vessel Head CRDM Penetrations



Implementation of a comprehensive In Service Inspection (ISI) Program IRSN & ASN involvements (2/2)

Other Inconel Zones :

**R.V. Bottom Mounted Instrument (BMI) Penetrations
Local Vessel under clad defect repairs with Inconel 182**

Nuclear Safety Bodies examine

- ☛ Maintenance & NDE doctrines, including the analysis of possible «Inconel Zones» degradation, potentially prone to PWSCC or to other types of degradations,
- ☛ NDE objectives definition files (*technical requirements,..*)
- ☛ Methods qualification results (performances,..)
- ☛ Procedures,
- ☛ NDE Results,
- ☛ NDE « maintenance » programs,
- ☛ Miscellaneous : Mitigation and repair files, ..



**IRSN specialists issue recommendations to ASN leading either to EDF proposal acceptance
or to further requests or possible ASN decisions*. (*Published on ASN web site)**

Status of Vessel Head Penetration Inspection and Replacement (as of 07/03)

- **After 12 years of Inconel Zone Policy implementation in France:**
 - 42 vessel heads replaced, out of 54 units initially fitted with alloy 600 CRDM
⇒ 46 units in operation with alloy 690 CRDM & vent penetrations,
- **On 11 out of 42 retired VH, CRDM J groove welds have been inspected in details, by remote high resolution video inspection**
 - No PWSCC crack initiations were ever found
- **3 replacement vessel heads with penetrations in alloy 690 have been successfully inspected after some 10 years of operation,**
- **Vessel head replacement planning for the future would normally depend on regular NDE results, on remaining un-replaced VH,**
- **but in many instances, replacement is made by anticipation,**
- **Would the VH replacement planning in France be affected by the sudden surge of urgent vessel replacement needs in the USA ?**

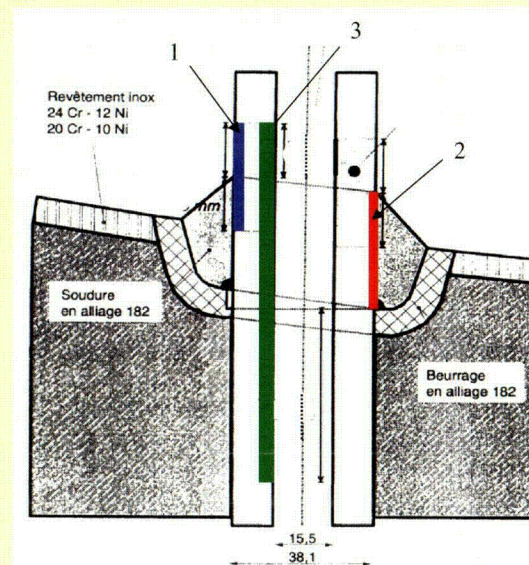
Present Status of the Inconel Zone Treatment in France (as of 07/03)

- Focus on Reactor bottom head penetrations (BMI) assessment and inspection
 - Normally, BMI are stress relieved with the vessel (600 °C), after welding into the vessel,
 - Some repaired or straightened penetrations **after** the in shop vessel stress relief,

- So far, 12 units successfully inspected for BMI penetrations integrity, **(including Bugey 3 inspected 3 times).**

Schematic representation of BMI zones ⇒ inspected by NDE

- 1 search zone for OD cracks
- **2 search of interfacial defects**
- 3 search zone for ID cracks



- Steam Generator Partition Plate and its welded zones: (in progress),
- Other zones ...(in progress).

Future Prospects and Needs (to better analyze World Wide Experience)

- **Focus in the future On Weld Metal Behavior, in the Field & Lab,**
- **Need to better assess initiation & CGR dependence on Temperature,**
- **Provide enough accurate data on:**
 - **Actual IZ wall temperature**
 - **Account for variations of PWSCC Sensitivity of Inconel components as a function of process, & fabrication variables & metallurgical state,**
 - **Improve the evaluation of residual AND Operational Stresses,**
 - **Take into account the final surface state resulting from machining, grinding, or other surface finish,**
 - **NDE performances and resolution,**
- **Express and use CGR in terms of maximum rate, or CGR brackets and not only by « mean values »,**
- **Take into account possible synergistic effects of various forms of mechanical stresses or strains other than residual ones (ex. low f cyclic ripple or load transients),**
- **Last but not least, review & refine crack initiation anticipation methodology, in order to mitigate early enough leak consequences.**

ASN/IRSN French Experience: CONCLUSIONS

(1/2)

- **PRECLUDING LEAKAGE: Successful strategy,**
since Bugey 3, no other CRDM leak
- **Importance of regulatory hydro-test at 1.2 times the design pressure**
as an in depth defense measure, with «bare metal Surface access» for leak detection,
not as an « NDE method of detecting flaws »,
- **Recourse to extensive ISI,**
 - **First 100% to assess the whole fleet condition with regard to PWSCC for CRDM penetrations,**
 - **Then flexible re-inspection schedule for PWSCC affected un-replaced vessel heads,**
 - **NDE inspection & re-inspection of BMI on an oriented sampling basis,**
with a priority to units comprising repaired or straightened up BMI after vessel stress relief treatment,
 - **ASN allowed maintaining some medium size PWSCC cracks for
«in the field CGR» assessment by UT.**

ASN/IRSN French Experience: CONCLUSIONS

(2/2)

- Considerable R&D by EDF and Framatome to constitute & improve:
 - Crack initiation data base from Lab & Field NDE detection,
 - Propagation data bases : Max CGR derived from Lab & Field,
 - Comparisons should be made with international data ,
 ⇒ looking for clear, fair & «CONSERVATIVE SCREENING CRITERIA»
 - reported regularly to ASN & IRSN,
- Timely replacement of the most PWSCC affected vessel heads
- Only 3 young units (N4) with stress relieved alloy 82 DMW on Vessel/Primary loops junctions,
 Now in France, no Inconel parts linked to the Pressurizer,
- Now, continued focus on BMI & other Inconel Zones,
- Interest to follow up closely worldwide experience feedback
 for weld materials where PWSCC initiation and propagation were observed,
 since weld cracking by PWSCC hardly experienced in France. Why?
- So far, so good..., in France, but .. let us keep vigilance as plants age!
 One example of precaution : 3 full NDE inspections of replacement Vessel Heads with Inconel 690 penetrations after some 10 years of operation.

Section 6:
**Session 5: Mitigation of Nickel-base Alloy Degradation
and Foreign Experience**



Belgian activities on alloys 600 and 182 issues

R.Gerard

Ph.Daoust

NRC-ANL conference, Gaythersburg, MD, Sept.29-Oct-2, 2003

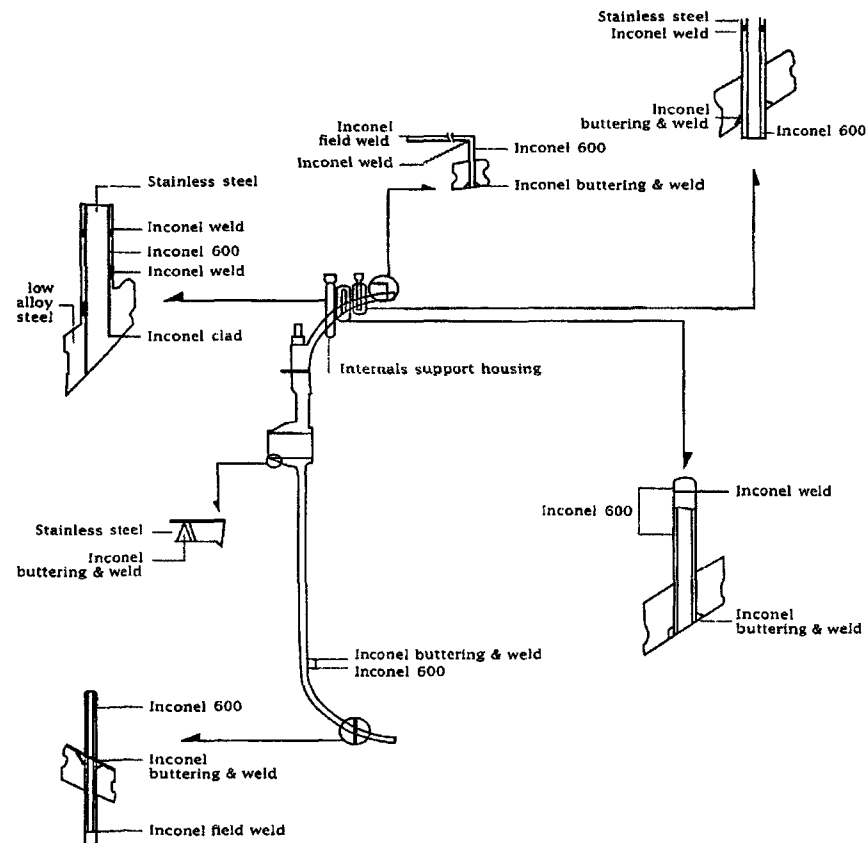
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Belgian Nuclear Units operated by Electrabel

Unit	Capacity MWe,netto	First Operation	NSSS designer
Tihange 1	962	1975	Westinghouse
Tihange 2	1008	1983	Framatome
Tihange 3	1015	1985	Westinghouse
Doel 1	392.5	1974	Westinghouse
Doel 2	392.5	1975	Westinghouse
Doel 3	1006	1982	Framatome
Doel 4	985	1985	Westinghouse

RV Alloy 600 components

figure 1



Alloy 600 – Base material Inspection status in Belgium (2003)

Head Penetrations

Inspection date	Unit	Age*	EFP* (hours)	T° (°C)	Inspector	Inspected penetrations	Inspection method	Results
Oct. 92	Tihange 1	17	123 000	318	ABB-R	65	ET	no crack (1 indication)
March 98	Tihange 1	23	163 000	318	FRA	65 + 1	ET + UT	Several cracks (1 heat)
October 99	Tihange 1	24	RPV head replaced					
Oct. 93	Tihange 2	10	81 000	287	ABB-R	65 + 1	ET	no crack
March 00	Tihange 2	17	131 000	287	ABB-R	65 + 1	ET	no crack
March 93	Tihange 3	8	59 000	318	ABB-R	65 + 2 + 3	ET	no crack
Dec. 96	Tihange 3	11	87 000	318	ABB-R	65 + 2 + 3	ET	1 indication
June 98	Tihange 3	13	99 000	318	ABB-R	65 + 2 + 3	ET	1 indication
September 01	Tihange 3	16	124 000	318	W-R(3)	65 + 2 + 3	ET	1 indication no propagation

* At the inspection date

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Alloy 600 – Inspection status in Belgium (2003)

Inspection date	Unit	Age*	EFP* (hours)	T° (°C)	Inspector	Inspected penetrations		Results
Head Penetrations								
Sept. 93	Doel 1	19	137 000	307	W	49	ET	no crack (1 indication)
August 98	Doel 1	24	174 000	307	ABB-R	49 + 1	ET + UT	Several indications (small cracks)
August 99	Doel 1	25	182 000	307	ABB-R	11	ET + UT	small cracks
August 01	Doel 1	27	198 000	307	W-R(3)	36	ET + 4UT	small cracks propagation
Sept.03	Doel 1	29	215 000	307	FRA	49	UT+visual (welds)	
May 94	Doel 2	19	125 000	307	W	49	ET + UT	no crack(2)
May 00	Doel 2	25	170 000	307	W-R	49 + 1	ET + UT	small cracks
May 03	Doel 2	28	194 000	307	FRA	49	UT+visual (welds)	small scratches (no longer characterized as cracks)

* At the inspection date

(1) Intercontrôle (IC) and AIB-Vinçotte

(2) Indications of original defects in the weld due to lack of fusion

(3) ex ABB-R

Alloy 600 – Inspection status in Belgium (2003)

Inspection date	Unit	Age*	EFP* (hours)	T° (°C)	Inspector	Inspected penetrations	Results	
Head Penetrations								
June 93	Doel 3	10	82 000	287	ABB-R	65 + 1	ET	no crack
April 00	Doel 3	17	134 000	287	ABB-R	65 + 1	ET	no crack
April 94	Doel 4	9	66 000	314	ABB-R	65 + 2 + 3	ET	no crack
June 99	Doel 4	14	100 000	318	ABB-R	65 + 2 + 3	ET	no crack

* At the inspection date

(1) Intercontrôle (IC) and AIB-Vinçotte

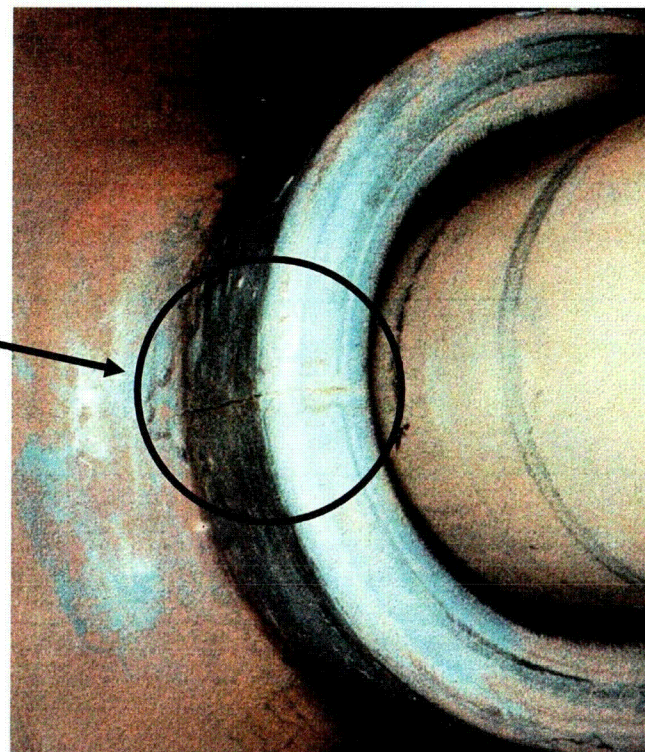
(2) Indications of original defects in the weld due to lack of fusion

(3) ex ABB-R

Tihange 1 RPV head – Cracking in 03/1998

Long axial through-wall crack below weld

Operation justified for one additional cycle (17 months) before replacement



Stress corrosion crack growth

- Different crack growth rates in depth and in length directions often seen in field experience
- MRP law conservative for CGR in depth direction; could underestimates CGR in length (based on simple analysis with constant stress level)
- Difference too big to be explained by non uniform stress distribution (especially since stresses could be expected to decrease away from the weld)
- Power law with 1.16 exponent probably overconservative at high K_I (plateau-like behavior?)

Equivalent Degradation Years

Unit	Temp (°C)	EDY
Tihange 2 - Doel 3	287	1.9
Doel 1-2	307	12.7 – 11.6
Tihange 3 – Doel 4	318	18.3 – 17.6
Tihange 1 (RPV head replaced 1999)	318	24
Tihange 1 new head	318	4

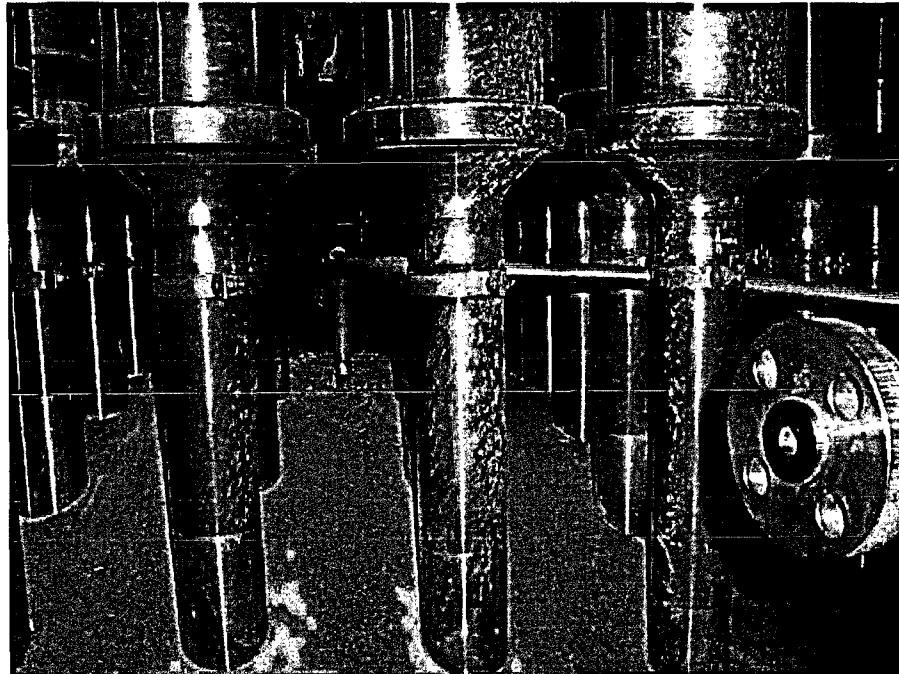
EDY: equivalent years at the reference temperature of 316°C (Arrhenius law with activation energy 50 kcal/mole)

Bare metal visual inspections

5 units inspected 2002
(some only partially)

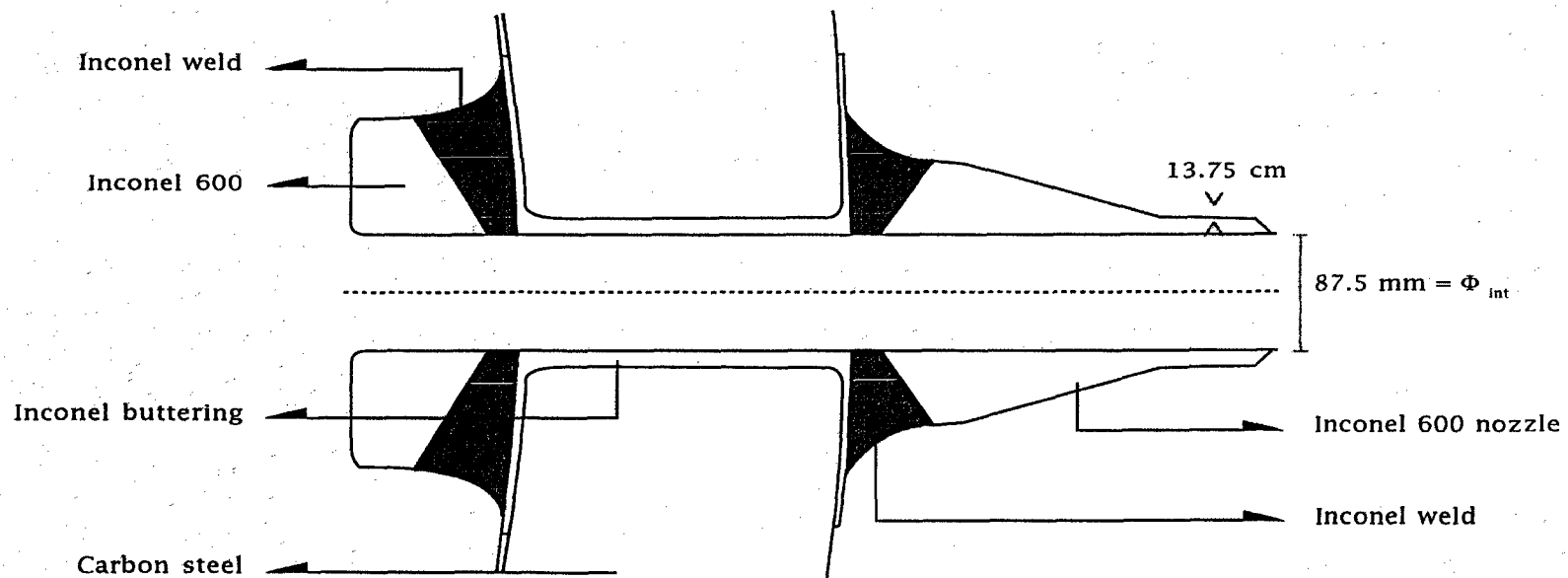
“Clean” heads with locally
some rusty streaks and
boric acid traces,
attributed to canopy seals
leaks

No evidence of RPV head
corrosion



Safety injection nozzles

(Doel 1-2) figure 3



Alloy 600 – Inspection status in Belgium (end 2002)

Inspection date	Unit	Age*	EFP* (hours)	T° (°C)	Inspector	Inspected penetrations	Results
BMI Penetrations							
May 95	Doel 2	20	132 000	287	TRC	13	ET + UT no crack(2)
May 00	Doel 2	25	175 000	287	W-TRC	13	ET + UT no crack(2)
SI Nozzles							
Oct. 95	Doel 1	21	160 000	287	(1)	2	UT no crack(2)
August 99	Doel 1	25	188 000	287	IC	2	ET + UT small surface indication + (2)
May 00	Doel 2	25	175 000	287	IC	2	ET + UT small surface indication + (2)

* At the inspection date

(1) Intercontrôle (IC) and AIB-Vinçotte

(2) Indications of original defects in the weld due to lack of fusion

Alloy 600/82/182 – Weld and buttering parts

<u>Component</u>	<u>Part</u>	<u>Base material</u>	<u>Weld</u>	<u>Buttering</u>	<u>Cladding</u>	<u>Units</u>
Pressurizer	Safe ends welds		✓	✓		D3/T2/D4/T3
Steam Generator	Partition plate	✓	✓	✓		D1/D2
	Tube	✓	✓			D1/D2
	Tubesheet				✓	D3/D4/T3
	Drain Nozzle safe ends welds		✓ ✓(82)	✓		D4/T3 T1
Vessel	Safe ends welds		✓	✓		D3/T2/D4/T3
	BMI	✓	✓	✓		ALL
	CSB	✓	✓	✓		ALL
	SIN	✓	✓	✓		D1/D2
Vessel Head	Penetrations	✓	✓	✓		ALL except T1

Alloy 82/182 – PWSCC Inspection Result

<u>Component</u>	<u>Part</u>	<u>Inspection type</u>	<u>Result (PWSCC)</u>
Pressurizer	Safe ends welds	External UT, PT, VT2	Surface indications (Ti 2)
Vessel	Safe ends welds	Internal UT	Nothing to report (NTR)
		External PT, VT2	
	CSB	Internal VT3	NTR
	BMI	External VT2	NTR
		Internal VT3	NTR
Vessel Head	SIN	Internal UT, ET	Surface indications (*)
		External PT, VT2	
Vessel Head	Penetrations	External PT, VT2	NTR
		Visual internal	NTR

SAFE ENDS : Alloy 182 status

- ⌘ Alloy 182 present on Reactor Pressure Vessel and Pressurizer Nozzles (D3/T2/D4/T3).
- ⌘ Inventory available including fabrication process (material, welding, repair, stress-relieving, surface finish and inspection results).
- ⌘ Alloy 182 welds on RPV were submitted to the final stress relief heat treatment of the vessel (8h at 610°C), but not the pressurizer welds
- ⌘ Higher temperature makes pressurizer welds more sensitive

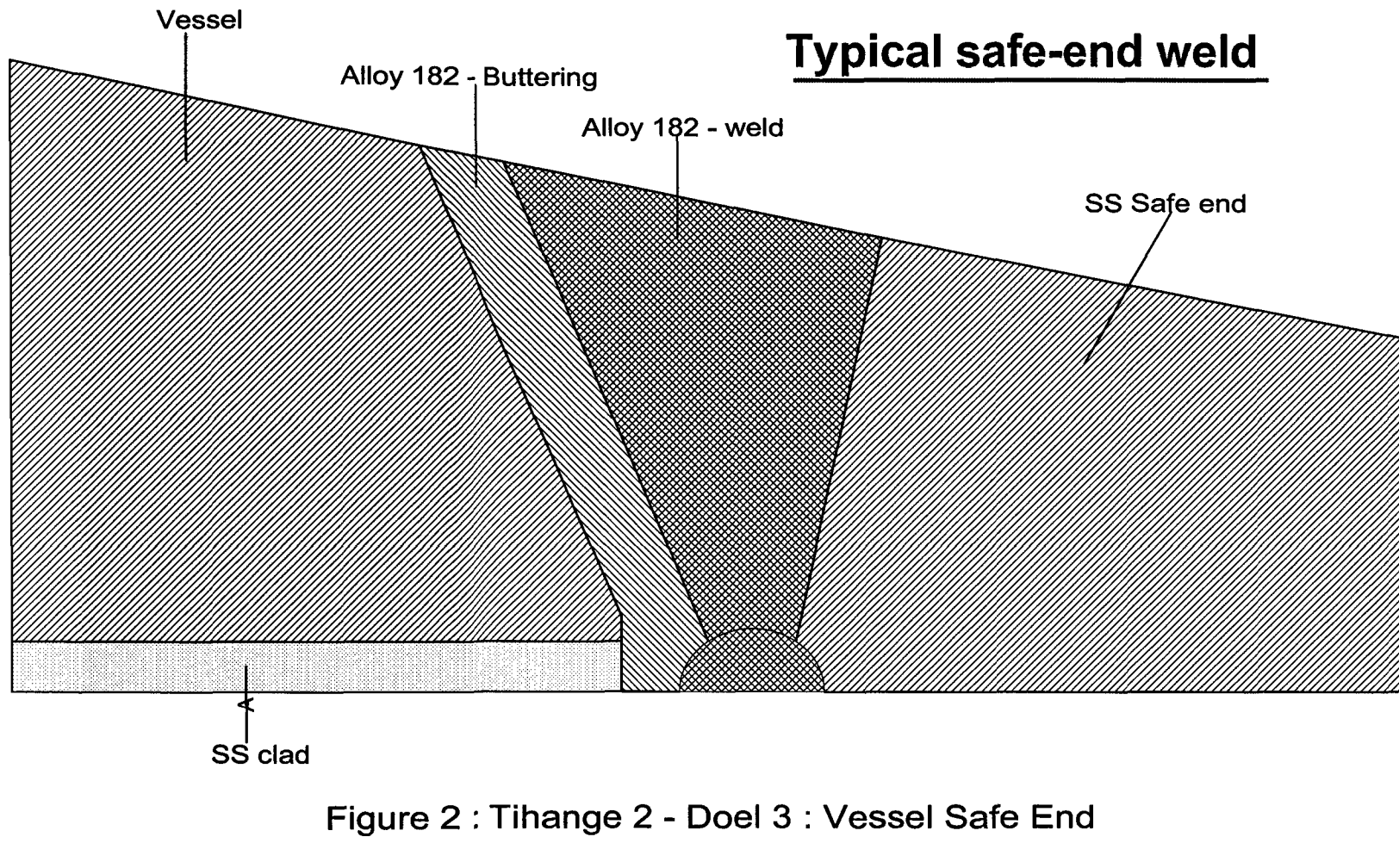
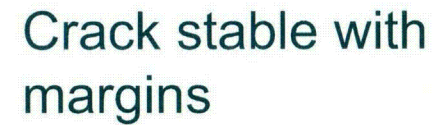


Figure 2 : Tihange 2 - Doel 3 : Vessel Safe End

Stress and fracture mechanics analyses – RPV outlet

- ⌘ Normal operating stresses at RPV outlet nozzle to safe end weld are maximum 220 MPa, well below threshold for initiation (≈ 350 MPa).
- ⌘ Axial stresses much lower than circumferential stresses → axial crack more likely
- ⌘ If initial defect is postulated, Defect Tolerance Analysis (Vessel Outlet Nozzles) indicates high crack growth rate. Confirms that axial defect is more critical than circumferential defect.

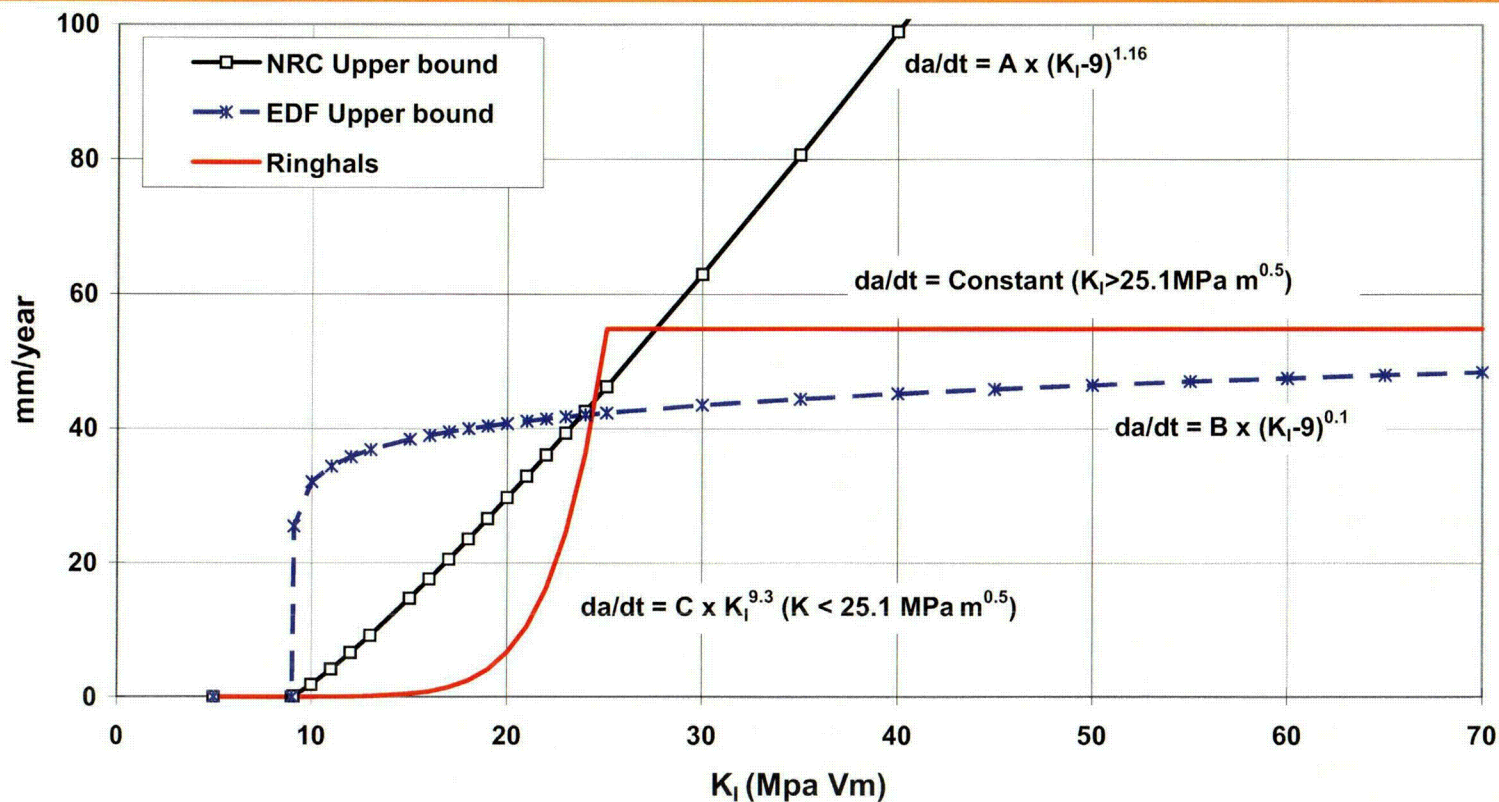


Very small leak
rate (2 - 5 kg/h)

Stress and fracture mechanics analyses – Pressurizer surge nozzle to safe-end weld

- ⌘ Normal operating hoop stresses 300 to 350 MPa at inside surface, close to threshold for initiation (≈ 350 MPa).
- ⌘ High contribution of postulated residual hoop stresses
- ⌘ Axial stresses much lower than circumferential stresses → axial crack more likely
- ⌘ Operating temperature 345°C
- ⌘ Most critical location based on semi-empirical ranking (based on stress, temperature, PWHT, fabrication repairs, consequences)

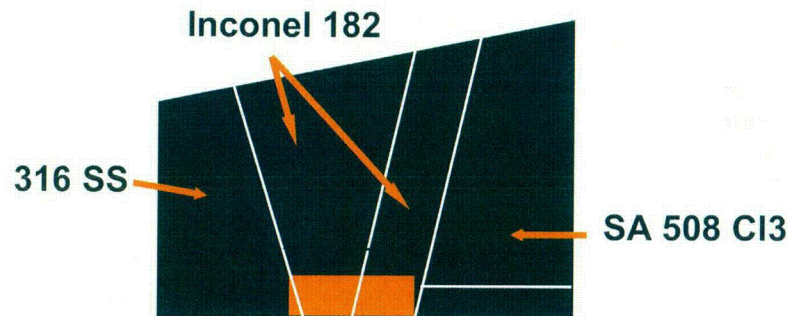
Crack growth rates - Inconel 182 at 345°C (Arrhenius with Q=130 kJ/mole)



Stress and fracture mechanics analyses – Pressurizer surge nozzle to safe-end weld

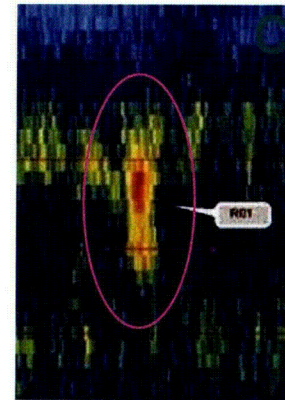
- If initial defect is postulated, Defect Tolerance Analysis indicate very high crack growth rate.
- Not possible to base an inspection plan on such crack growth rates (or inspect every 2 months!)
- Lack of data of high K_I , leading to significant differences in extrapolations from existing data
- Increased inspection frequency recommended, using qualified technique

Pressurizer surge nozzle to safe-end weld Tihange 2 – Oct. 2002 inspection



- Axial indication
- Close to fabrication repair
- Could be exposed to primary water
- Flaw dimension $\approx 4 \times 26$ mm

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Pressurizer surge nozzle to safe-end weld

- Defense in-depth analysis of through-wall axial crack (limited to the weld) shows it should remain stable
- Estimated leak rate at the limit of detectability with existing systems; local systems added (humidity sensor + infrared camera)
- Restart authorized for 6 months
- Validation of MSIP (Mechanical Stress Improvement Process, AEA patent) on surge line geometry (conical safe-end)

Pressurizer surge nozzle to safe-end weld

- Principle of MSIP:
 - ⌘ Mechanically contract the pipe on one side of weldment
 - ⌘ Replace residual tensile stresses with compressive stresses
- MSIP: Specific stress analysis and qualification on mock-up with Tihange 2 exact geometry
- Evaluation of potential repair techniques
- Reinspection in May 2003 – No crack growth
- Next inspection scheduled October 2003

Alloy 600 / Alloy 182 – Belgian strategy

Alloy 600 Components	Strategy
RVH Penetrations	Follow cracks D1/D2 Crack growth analysis Reinspect other heads Evaluate repair/replacement options
BMI/CSB/SIN	Follow ASME ISI program Reevaluate following STP1 event

Alloy 600 / Alloy 182 – Belgian strategy

Alloy 182 components	Strategy
RPV / pressurizer safe-ends welds	Perform Defect Tolerance Analysis Anticipate and enhance inspections Residual stress analysis Validate MSIP on surge line nozzle
RVHP welds	Visual inspections (internal + external) Evaluate other surface inspection techniques
Others	Follow ASME ISI program

Conclusions

- RPV head penetration program in place since 1992
- Significant cracking detected in Tihange 1 in 1998; head replaced in 1999
- Small indications in other units followed by regular inspections; slow propagation
- Program on Inconel 182 safe-end welds started after VC Summer event
- Fracture mechanics analysis + ranking critical locations + increased inspections

Conclusions (continued)

- Analyses show pressurizer safe end welds most critical location (not stress relieved, high residual stresses, high temperature)
- Increased inspections implemented on these welds
- Small indication in Tihange 2 surge line weld, suspected to be PWSCC, to be followed. Potential solutions: MSIP or repair.
- The proactive inspection and justification strategy followed in Belgium made it possible to detect flaws well before they could cause leaks in the primary pressure boundary.

A FRAMATOME ANP

Conference on Vessel Head Penetration Inspection, Cracking and Repairs

German Experience with RPV Head Penetrations

**Klaus Degmayr
Framatome ANP GmbH, Erlangen, Germany
Oct 2nd, 2003**

AL: N

Goods labeled with "AL not equal to N" are subject to European or German export authorization when being exported out of the EU. Goods labeled with "ECCN not equal to N" are subject to US reexport authorization. Even without a label or with label "AL:N" or "ECCN:N" authorization may be required due to the final whereabouts and purpose for which the goods are to be used.

ECCN: N

Content (1)

- > *NPPs with PWR built by Siemens/KWU *)*
- > *The NPP Obrigheim RPV Head Design*
 - *Operation Data*
 - *Design of Penetration Nozzles*
 - *Characteristic Features of the Obrigheim Design*
 - *KWO Manufacturing Sequence*
 - *Evaluation of PWHT with Respect to PWSCC*
 - *Integrity Evaluation of the KWO RPV Head*
 - *Investigations, Inspections Measurements in KWO*
 - *Non Destructive Examination*
 - *Leakage Detection, Global and Local*
 - *Design of Flange*
 - *In-Service Experience of NPP KWO*

**) name of predecessor company of Framatome ANP GmbH, Germany*

Content (2)

- > *The current Siemens/KWU Design of RPV Head Nozzles since NPP Stade*
 - *Characteristic Features of the Siemens/KWU Design*
 - *The Current Siemens/KWU Flange Design*
 - *In-Service Experience of All Other German Plants*
- > *Summary and Conclusions*

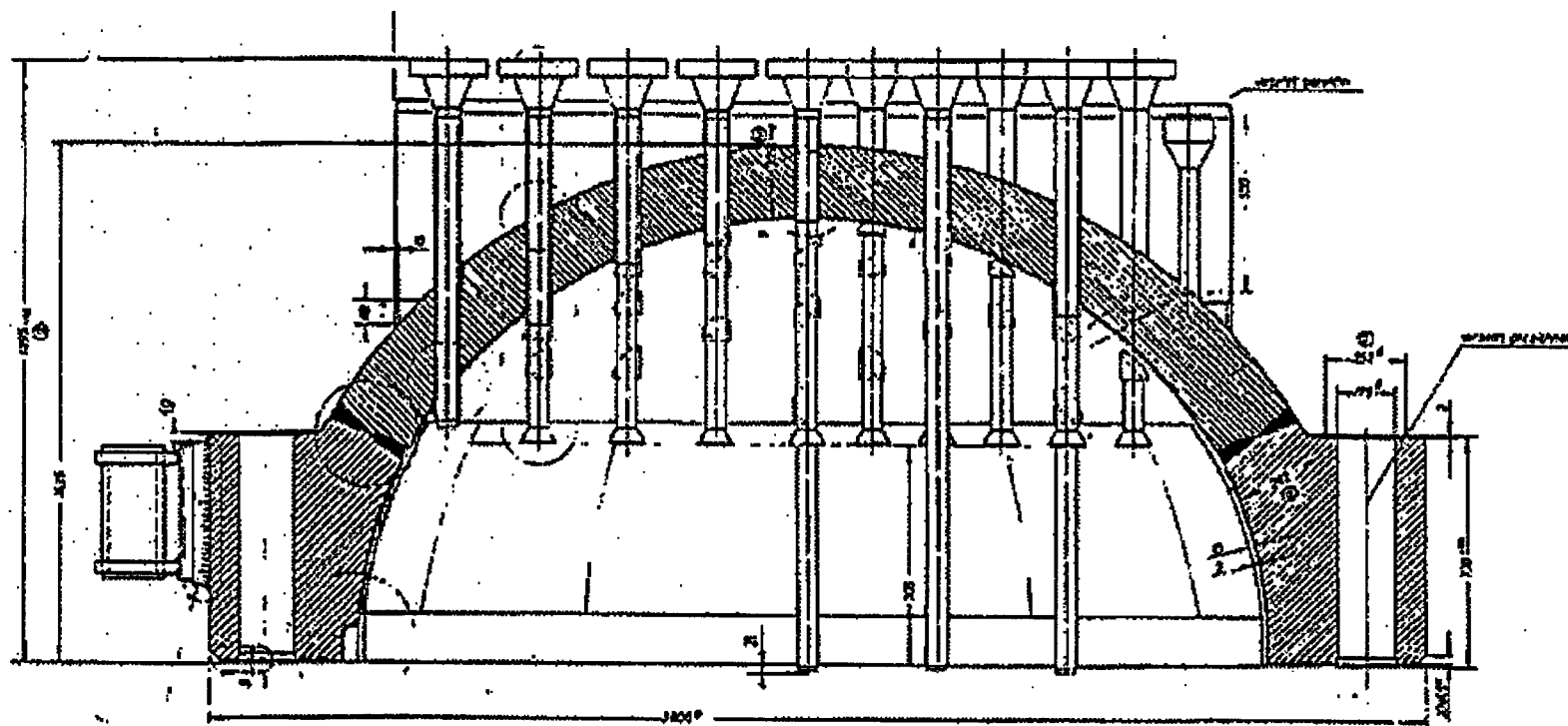
NPPs with PWRs and Year of Start-Ups built by Siemens/KWU

<i>PWR plant</i>	<i>Country</i>	<i>Year of Start up</i>	<i>MWe cross/net</i>
<i>Obrigheim</i>	<i>GER</i>	<i>1968</i>	<i>357 / 340</i>
<i>Stade</i>	<i>GER</i>	<i>1972</i>	<i>672 / 640</i>
<i>Biblis A</i>	<i>GER</i>	<i>1974</i>	<i>1204 / 1146</i>
<i>Biblis B</i>	<i>GER</i>	<i>1976</i>	<i>1300 / 1240</i>
<i>Neckar 1</i>	<i>GER</i>	<i>1976</i>	<i>840 / 785</i>
<i>Unterweser</i>	<i>GER</i>	<i>1978</i>	<i>1300 / 1230</i>
<i>Grafenrheinfeld</i>	<i>GER</i>	<i>1981</i>	<i>1300 / 1235</i>
<i>Grohnde</i>	<i>GER</i>	<i>1984</i>	<i>1395 / 1325</i>
<i>Philippsburg 2</i>	<i>GER</i>	<i>1984</i>	<i>1349 / 1268</i>
<i>Brokdorf</i>	<i>GER</i>	<i>1986</i>	<i>1395 / 1326</i>
<i>Isar 2</i>	<i>GER</i>	<i>1988</i>	<i>1400 / 1320</i>
<i>Emsland</i>	<i>GER</i>	<i>1988</i>	<i>1341 / 1270</i>
<i>Neckar 2</i>	<i>GER</i>	<i>1989</i>	<i>1360 / 1225</i>
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<i>Atucha 1</i>	<i>ARG</i>	<i>1974</i>	<i>357 / 335</i>
<i>Gösgen</i>	<i>CH</i>	<i>1979</i>	<i>1020 / 970</i>
<i>Trillo</i>	<i>ES</i>	<i>1988</i>	<i>1066 / 1000</i>
<i>Angra 2</i>	<i>BRA</i>	<i>2000</i>	<i>1309 / 1229</i>

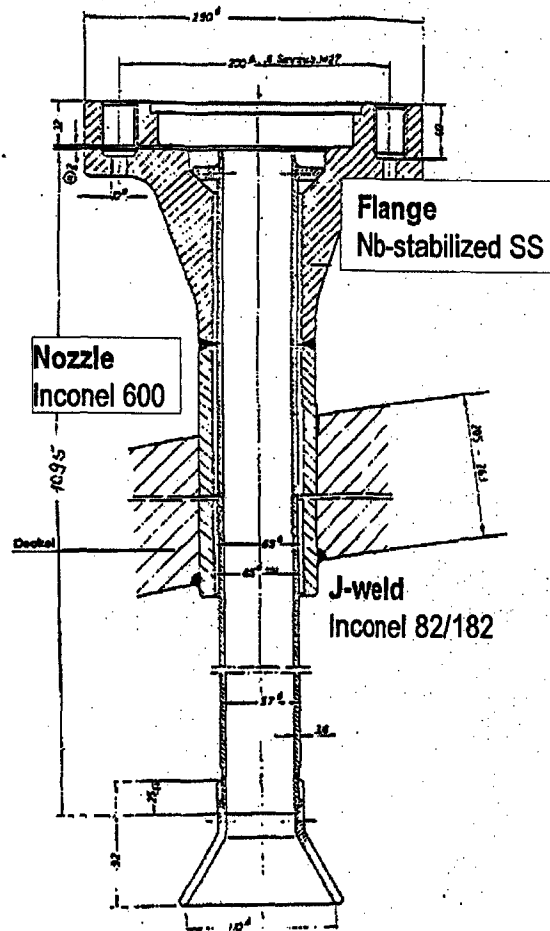
KWO Operating Data

- > *Operation Time until 2003:* *approx. 240,000 hours*
- > *Pressure:* *approx. 145 bar*
- > *Operation Temperature*
 - *RPV inlet* *279 ° C*
 - *RPV outlet* *308.5 ° C*
 - *upper plenum* *306.8 ° C*
 - *head outside* *282,2 ° C*
 - *nozzle weld inside* *284 – 295 ° C*

The NPP Obrigheim RPV Head Design



Design of Penetration Nozzle



> material

- nozzle: Inconel 600
- flange: Nb-stabilized SS
- J-weld: Inconel 82/182

> dimensions

- inner diameter: 85 mm
- outer diameter: 105 mm

> connection

- shrink fitted, welded into RPV head

Characteristic Features of the Obrigheim Design (1)

> Material

- *RPV closure head:* *22 NiMoCr 37*
- *RPV head inner surface:* *Austenitic SS cladding*
- *Head penetration nozzles:* *Inconel 600*

> Weld

- *J-groove weld without buttering of the head*
- *weld material:* *Inconel 82/182*

> Heat treatment (PWHT):

- *stress relief annealing of entire RPV closure head*
600 ° C ≥ 10 hours

Characteristic Features of the Obrigheim Design (2)

> Manufacturing

- *seamless pipe, hot formed*

- *solution annealing:* 1000 – 1050 ° C

- *roughness:* outside max. 5 µm
inside max. 80 µm

> Chem. composition:

low C-content

> Mech. properties:

low yield strength (227 – 257 N/mm²)

KWO Manufacturing Sequence (1)

- > fitting in of tubes into the RPV closure head***
 - *cooling down tubes, head at ambient temperature*
 - *shrinking of tubes into the head shell*

- > Welding***
 - *preheating of the head up to 150 ° C for welding*
 - *shielded Metal Arc Welding (SMAW)*
 - *welding sequence: starting with the center nozzle, followed by nozzles on outer circumference in a circular manner*
 - *delayed cooling*

KWO Manufacturing Sequence (2)

> non destructive examination (NDE)

- *grinding of each layer*
- *surface of weld layer by Liquid Penetrant Testing*
- *final surface by Liquid Penetrant Testing*

> Post weld heat treatment (PWHT)

- *540 ° C / 8 hours + 600 ° C / 10 hours*

RPV Head KWO Evaluation of PWHT with Respect to PWSCC

- > Susceptibility of Inconel 600 to PWSCC is reduced by PWHT:*
 - magnitude of residual stresses is reduced down to a level not high enough for initiating PWSCC*
 - due to carbide precipitation during heat treatment the PWSCC resistance is increased (TT condition vs. MA condition)*
- > Effect is confirmed by several extensive investigations on „thermally treated“ Inconel 600 and 690 material*

RPV head KWO Integrity Evaluation

- > *Susceptibility of KWO head penetrations to PWSCC is considered low, since***
 - *operational loading (incl. residual stresses) is low;
Typical stresses in nozzle end are less than 2/3 of the yield strength at operation temperature.*
 - *Consequently, secondary effects (like cracking in circumferential direction) can be excluded (confirmed by UT of 4 nozzles without internals)*

- > *Safety margin is ensured by***
 - *special leakage detection system: sensory (electrical) cable*
 - *general leakage detection systems: activity, condensate, environmental temperature, relative humidity, sump water*
 - *shut down capability is available in case of nozzle rupture*

Investigations, Inspections, Measurements in KWO

> Non Destructive Testing of Penetrations and RPV head

- *ultrasonic testing (UT)*
- *liquid penetrant testing (LPT)*
- *eddy current (EC)*

> Leakage Detection at KWO

- *global leakage detection*
- *local leakage detection*

> Visual Inspection of RPV closure head

Non Destructive Examination of Penetrations and RPV Closure Head

Testing Procedure	Extent of Testing	Inspection Year	Intervals
UT	4 penetrations w/o internals, entire length of penetration, longitudinal and circumferential indications	1992 extra inspection	-
LPT	4 penetrations w/o internals, entire length of penetration, including flange weld	1992 extra inspection	-
Eddy Current	24 + 4 outer penetrations, rotating probe, entire length (4), narrow gap probe up to 250 mm (24)	1992 extra inspection	-
Eddy Current	All penetrations over entire length including flange weld, longitudinal and circumferential indications	1994 2000	8 years
Specific visual in- spection with cam	Internal head surface including penetration and weld	2000	4 years
UT of closure head ligament	All closure head ligaments, volume between penetrations, faults originating from bore	1976, 1980, 1983, 1987, 1992, 1996, 2000	4 years

Source: KWO

Leakage Detection at KWO

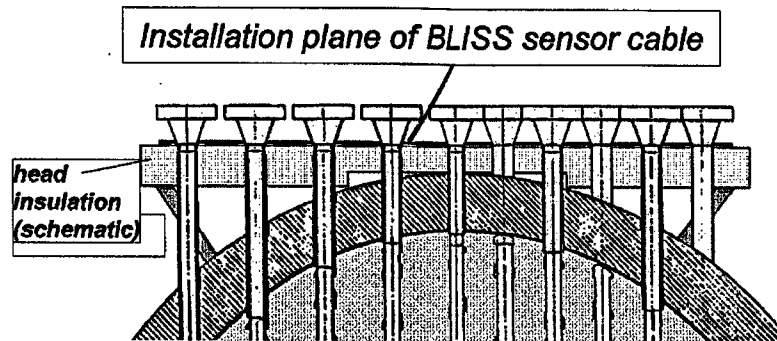
> Global Leakage Detection (Plant Environment)

- inert gas measurement of plant environment from approx. 10 l/h
- condensate measurement in air circulation cooler from approx. 10 l/h
- temperature in air circulation cooler from approx. 2 – 3 l/h
- relative humidity in air circulation cooler from approx. 2 – 3 l/h
- sump water collection of building TF 01
- sampling exhaust air inner plant environment from approx. 10 – 15 l/day

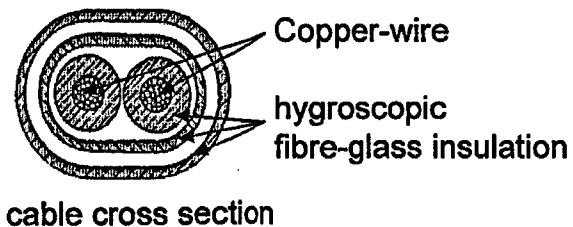
> Local Leakage Detection (RPV Head)

- leakage detection system (BLISS) humidity yes/no
- humidity control system (FLÜS) < 1 l/h

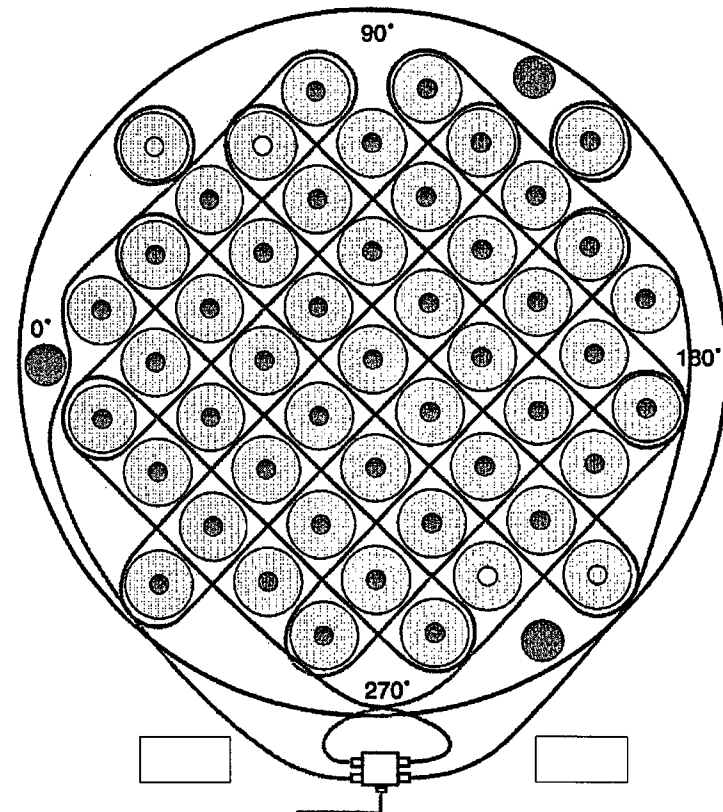
Local Leakage Detection BLISS



**Leakage detection system BLISS
in area of penetration flange,
monitoring of flange connection
YA01 M001 (sensor-cable)**



Bartec Leakage Indication Sensor System



source: KWO

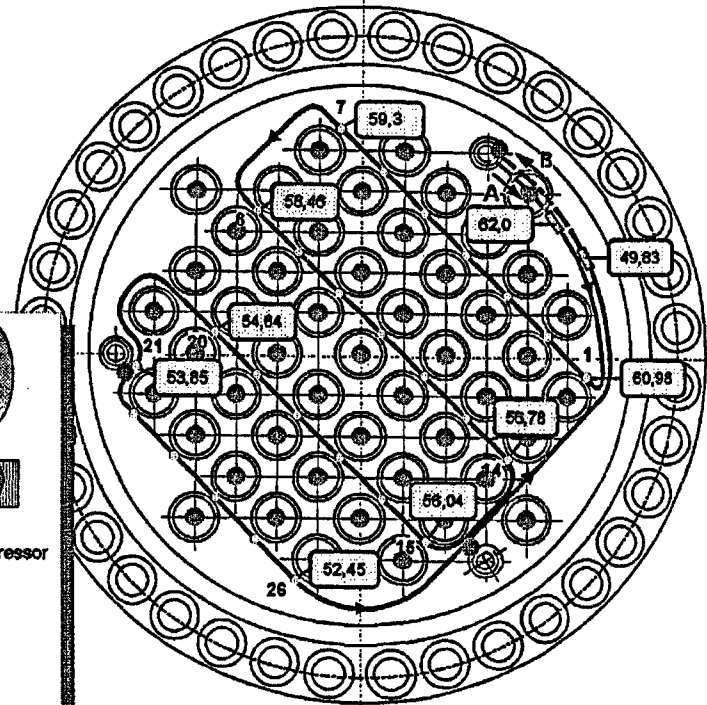
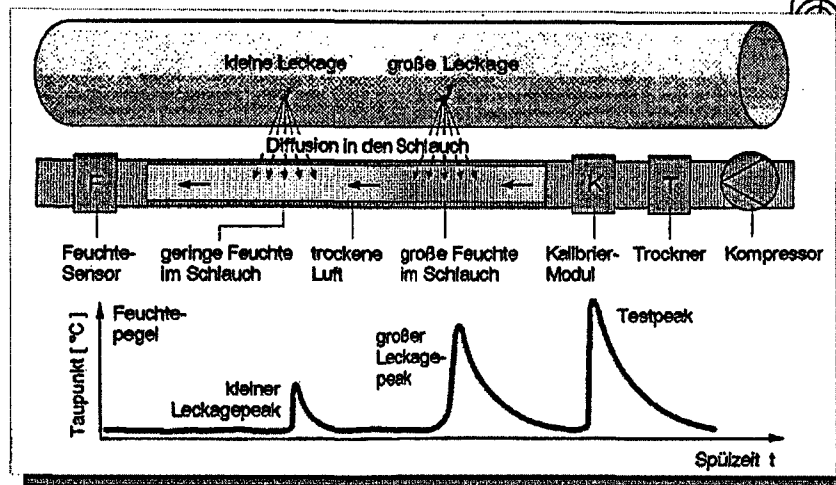
Visual Inspection of RPV Closure Head during Revision in 2002



source: KWO

Local Leakage Detection System in RPV Head FLÜS

Humidity control system FLÜS
in area of RPV penetrations
YA01 M010 (sensor-hose)



- leakage-simulation point 1/2/3
- Ni-sinter tablet (diffusion point)
- coupling
- distance in m

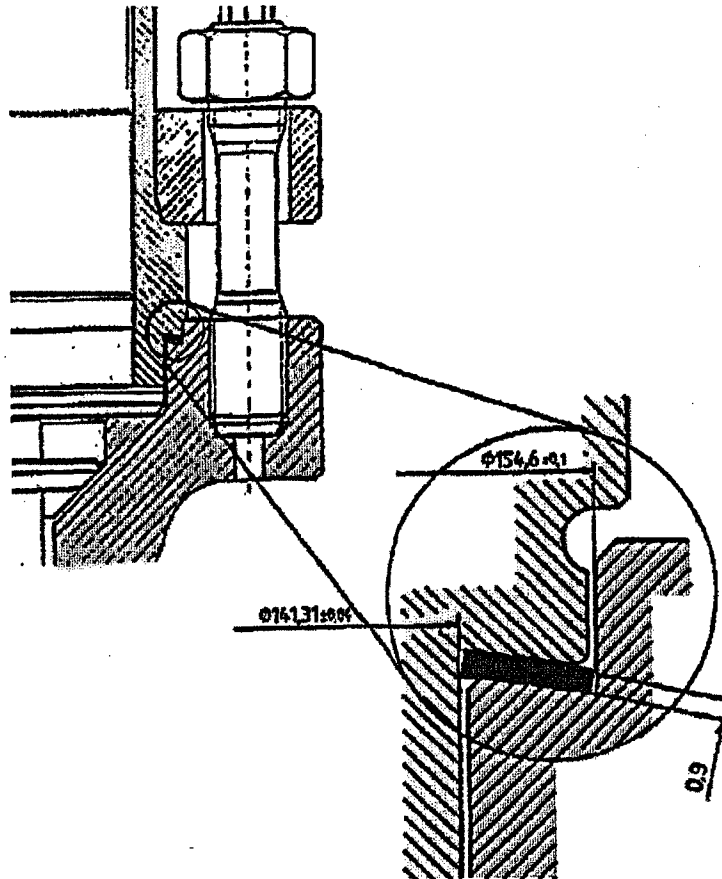
source: KWO

Visual Inspection of RPV Closure Head during Revision in 2002



source: KWO

NPP KWO Flange Design



Gasket: material X10Cr13

***In period from 1980 to 1994
4 minor leakage incidents, which
were detected immediately***

***1996 total gasket change,
followed by Helium leakage test***

source: KWO

In-Service Experience of NPP KWO

> *The structural integrity of head penetrations at the NPP KWO is considered sound due to the following facts:*

- *heat treatment history of head penetration material included a solution and stress relief annealing resulting in a low level of residual stresses and minor susceptible microstructure*
- *good access allowing regular visual and comprehensive non-destructive inspections*
- *sensitive leakage detection systems on a local and a global scale*

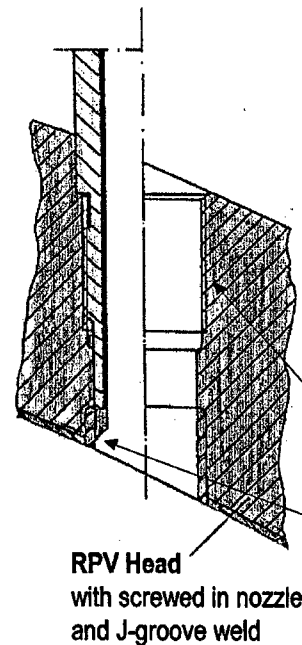


Cracking is not expected

NPPs with PWRs and Year of Start-Ups Built by Siemens/KWU

PWR plant	Country	Year of Start up	MWe cross/net
Obrigheim	GER	1968	357 / 340
Stade	GER	1972	672 / 640
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Grohnde	GER	1984	1395 / 1325
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Brokdorf	GER	1986	1395 / 1326
Isar 2	GER	1988	1400 / 1320
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Atucha 1	ARG	1974	357 / 335
Gösgen	CH	1979	1020 / 970
Trillo	ES	1988	1066 / 1000
Angra 2	BRA	2000	1309 / 1229

987



**J-groove weld with
Nb-stabilized SS,**

Characteristic Features of the Siemens/KWU Design

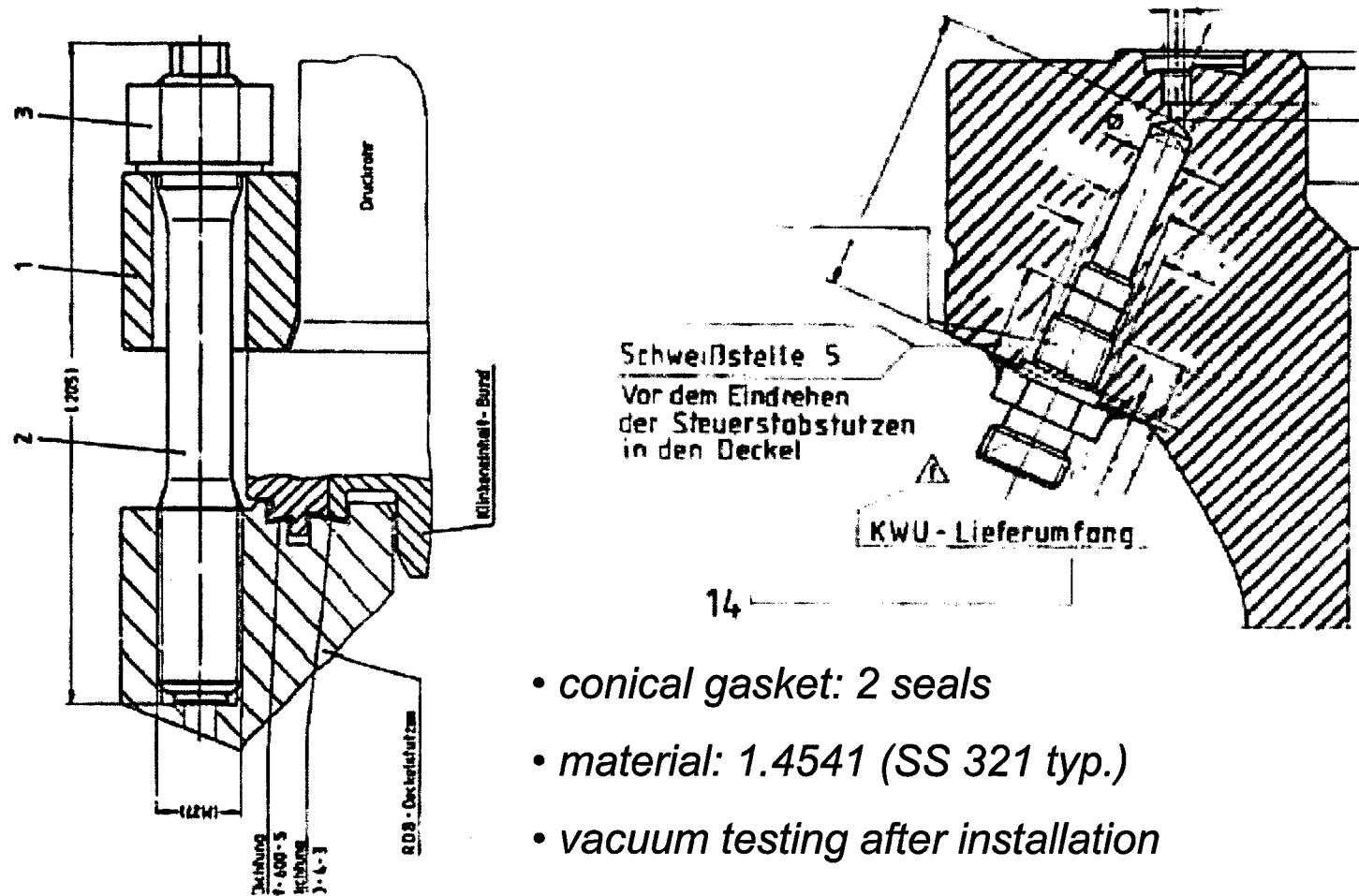
> material

- *RPV head:* 22 NiMoCr 37/ 20 MnMoNi 55
- *RPV surface cladding:* Austenitic SS cladding (Nb stabilized)
- *head penetration nozzles:* compound tube made of St 52.4/1.4550
end of nozzle buttered with
Austenitic SS cladding (Nb stabilized)
- *CRDM flange* Nb stabilized SS

> design

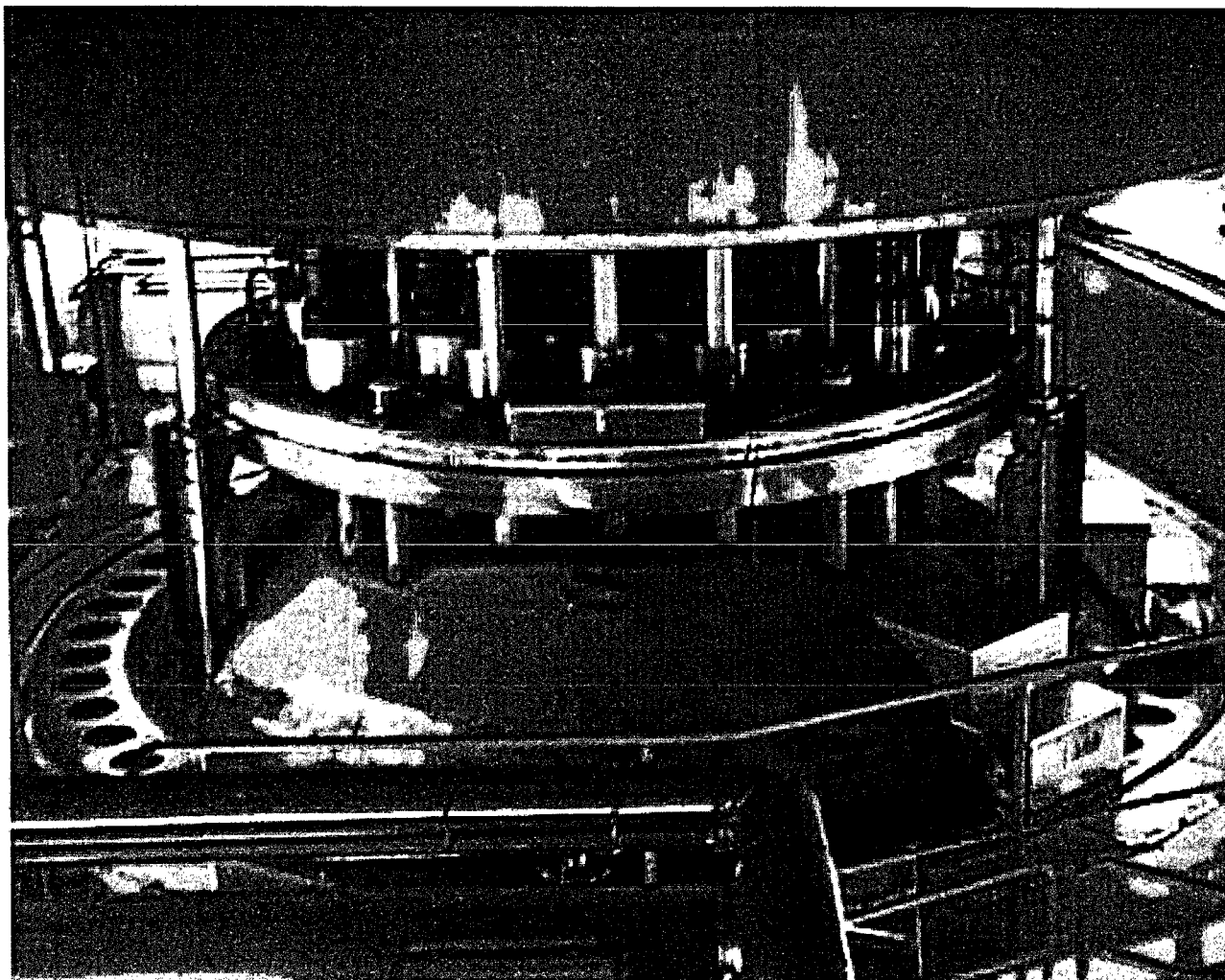
- *trapezoidal screw thread for load bearing*
- *J-groove weld with Nb stabilized SS*

The Current Siemens/KWU Flange Design

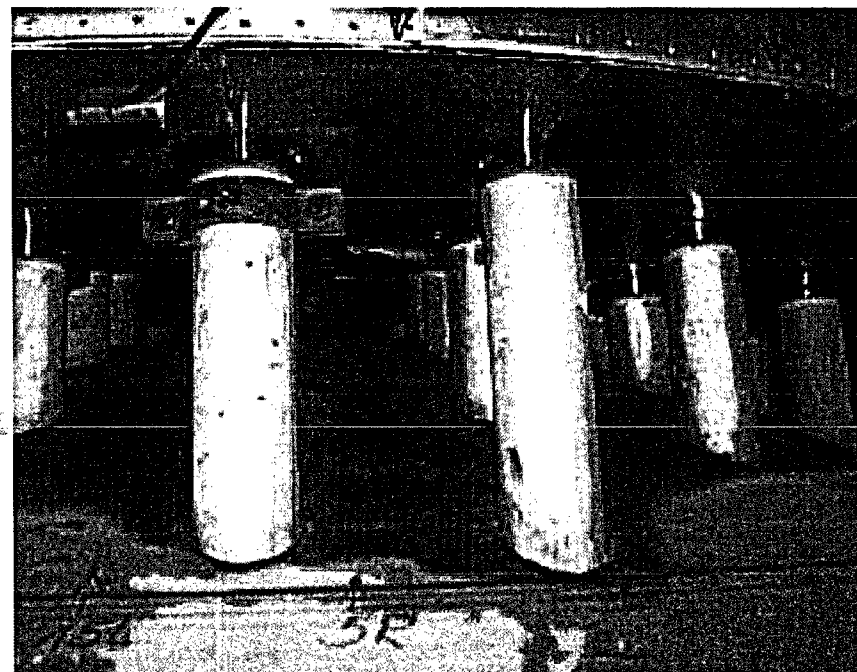
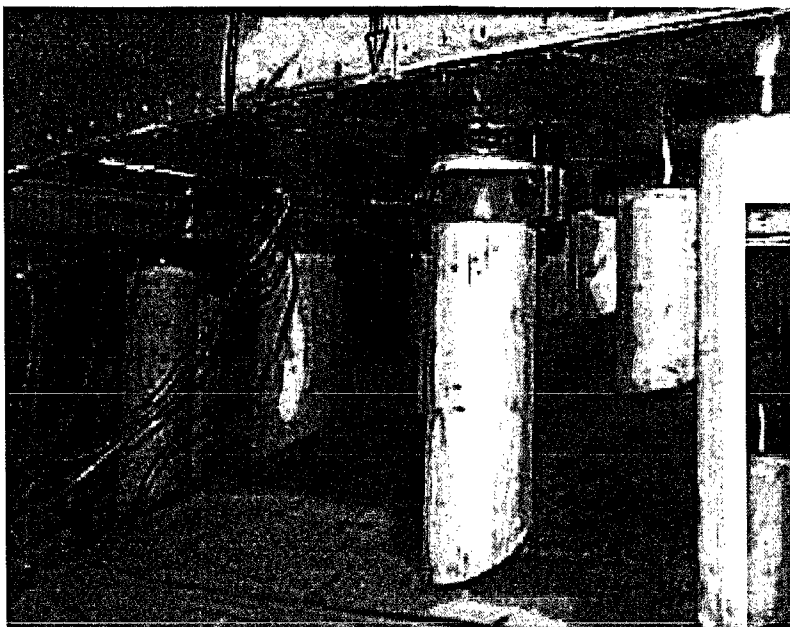


- conical gasket: 2 seals
- material: 1.4541 (SS 321 typ.)
- vacuum testing after installation
- test pipe used for leak detection

RPV Head after Removal from the Vessel



Visual Inspection



Easy Access to RPV Head and Penetrations in German PWRs

In-Service Experience of All Other German Plants

- > *Different design and materials of head penetrations greatly reduce the risk of cracking.*
- > *access and ISI of head penetrations and RPV head enable:*
 - *visual Inspection during every outage*
 - *UT inspection of closure head ligaments (outer and inner surface and volume inspection) every 4 and 5 years resp. to KTA 3201.4*
- > *Leak detection system including:*
 - *humidity measurements*
 - *measurement of the condensate rate at the air recirculation system coolers*
 - *measurement of accumulated sump water*

Summary and Conclusions

Two Different Designs Found in German Plants

> KWO similar to abroad design

- *special treatment during manufacturing and*

- *very effective in-service control systems*

ensure to have and to get no problems

> current design (Stade – Neckar 2)

- *choice and combination of material reliable over years*

- *optimized conditions by separating the function load bearing and sealing*

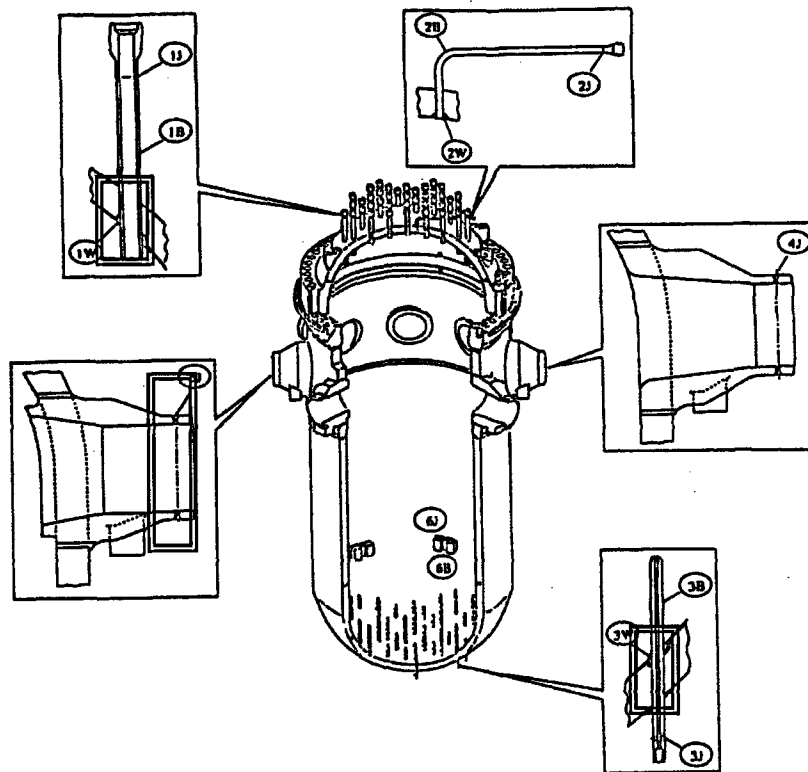
- *optimized welding design and welding process*

eop

Activities on Alloy 600 Cracking of PWRs in Japan

Masahiko Toyoda, Seiji Asada and Nobuyuki Hori
Mitsubishi Heavy Industries, Ltd.
Kobe Shipyard and Machinery Works

Activities on Alloy 600 Cracking of PWRs in Japan



**Maintenance Programs
on PWSCC of Alloy 600
in Japan are discussed,
specially for**

- RVH Penetration Nozzle
- BMI Nozzle
- Hot Leg Nozzle

Activities on Alloy 600 Cracking of PWRs in Japan

		RVH Penetration Nozzle		BMI Nozzle		Hot Leg Nozzle
		Base metal	J - weld	Base metal	J - weld	
Cracking	Japan	Takahama #2 (<1mm)	No Indication in Inspected	Takahama #1 (<1mm?)	No Indication in Inspected	No Indication in Inspected
	US & Europe	Many	More than 10 plants	South Texas 1 (under investigation)	No report	V.C.Summer Ringhals
PWSCC Assessment	Stress	Tension ($> \sigma_y$)	Tension ($> \sigma_y$) (Surface: Compression)	Tension ($> \sigma_y$)	Tension ($> \sigma_y$) (Surface: Compression)	Nearly equal to σ_y
	Temperature	Converted from T-hot to T-cold		T-cold		T-hot
	Susceptibility	Moderate	Low	Moderate	Low	Moderate
Inspection	Technique	ECT UT	VT ECT	ECT UT	VT ECT	UT ECT
	Application	17 plants	Not yet	6 plants	Not yet	5 plants
Mitigation		Done (T-cold conversion)		WJP (5plants)	WJP	WJP
Counter Measure or Contingency		RVH Replacement (11plants)		Emergency Repair Method BMI Nozzle Replacement		690 Cladding
						Spool-piece Replacement

RVH Penetration Nozzle

- RVHs for 11 plants have adopted alloy 690 penetration nozzle (Replaced).
- T-cold modification as mitigation measurement has been adopted in 11 relatively new plants leaving alloy 600 nozzles.
- NDIs (ECT for nozzles) were carried out for 6 plants in 1993 and 1994, no indications were detected.

RVH Penetration Nozzle

- **No official request of specific inspection against VHP nozzles has been issued by government.**
- **Some of T-cold modification plants are scheduled to inspect VHP nozzle and J-weld in the future.**

Activities on Alloy 600 Cracking of PWRs in Japan

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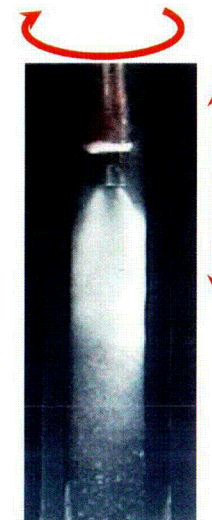
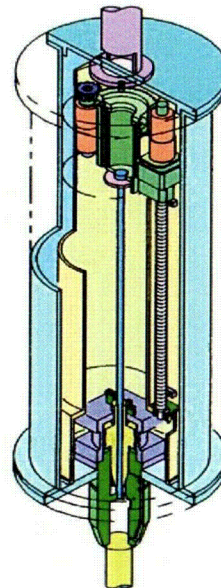
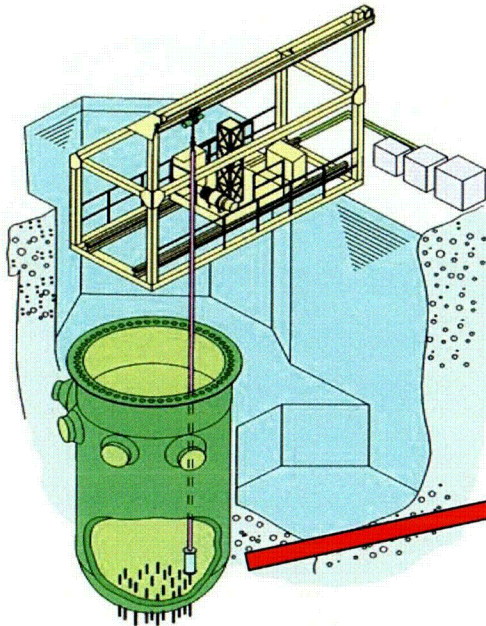
BMI Nozzle

- **Based on recent PWSCC assessment, BMI nozzles are suspected to have cracking and mitigation measurement is recommended.**
- **ECT and water jet peening (WJP) technology for BMI nozzles have been developed by MHI as mitigation measurement in accordance with PWSCC assessment.**

BMI Nozzle

Concept of WJP Technology for Field Application

Field work image



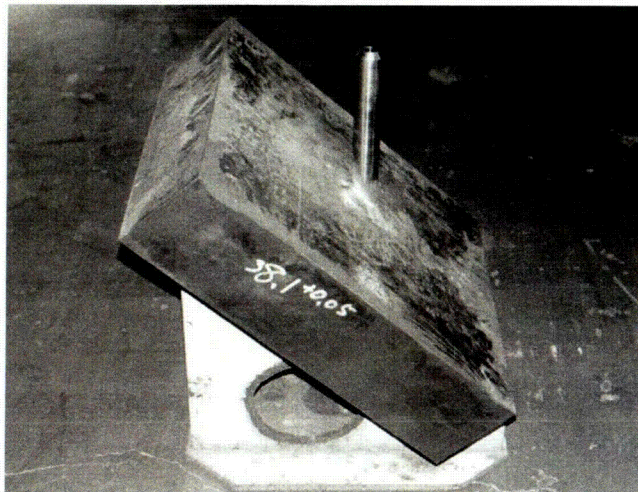
WJP equipment

State of WJP
in small diameter pipe

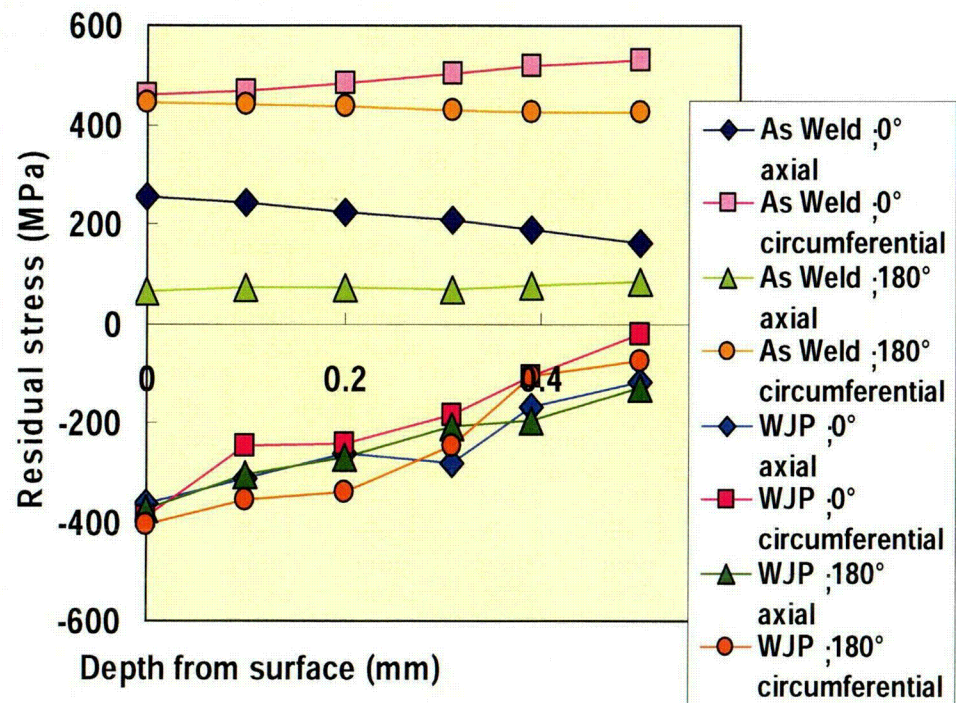
Mitsubishi Heavy Industries, Ltd.

BMI Nozzle

Improvement of Residual Stress by WJP Technology



Mock-up of BMI

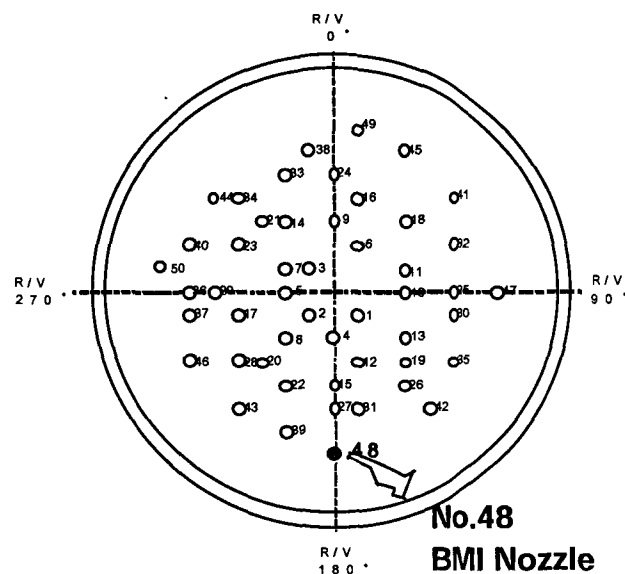


Result of residual stress measurement

BMI Nozzle

- **Kansai Electric Power Co. planned to perform WJP to all (50) BMI nozzles as preventive measure against PWSCC.**
- **Before WJP, ECT was performed on inner surface of the BMIs to conform soundness of the surface.**
- **An indication was found at BMI nozzle in Takahama unit1.**

BMI Nozzle



**No.48
BMI Nozzle**

ECT Probe

11.4mm approx.
thickness

**Location of Indication
(Inside surface of BMI)
Length : 32 mm approx.
Depth : less than 1 mm**

BMI Nozzle

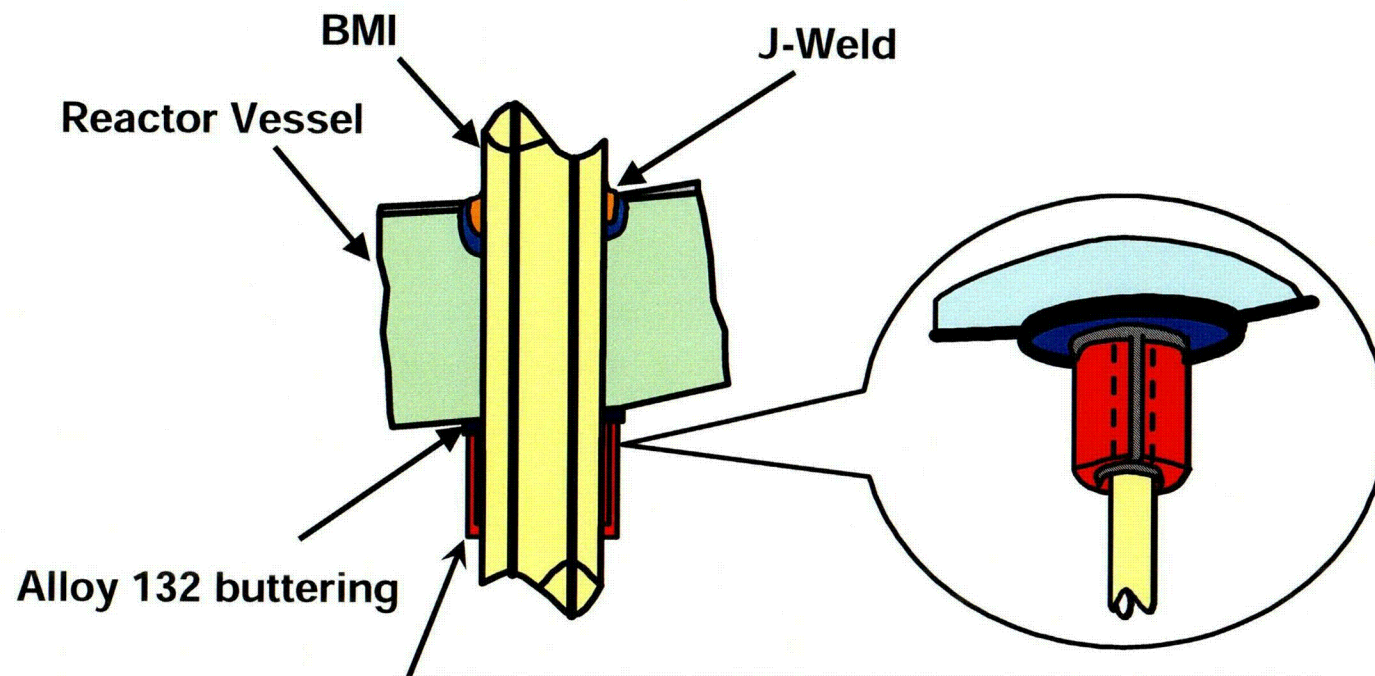
- The indication is not identified as PWSCC.
- The indication will be left as it is.
- Additional inspection will be performed after a few cycles.

BMI Nozzle

- **Inspection and WJP technology for J-Weld is under development.**
- **Emergency repair method and replacement technology have been developed for the case of encountering the leakage from BMI nozzles.**

BMI Nozzle

Concept of Emergency Repair Method



The leakage can be repaired with the cap.

Mitsubishi Heavy Industries, Ltd.

Activities on Alloy 600 Cracking of PWRs in Japan

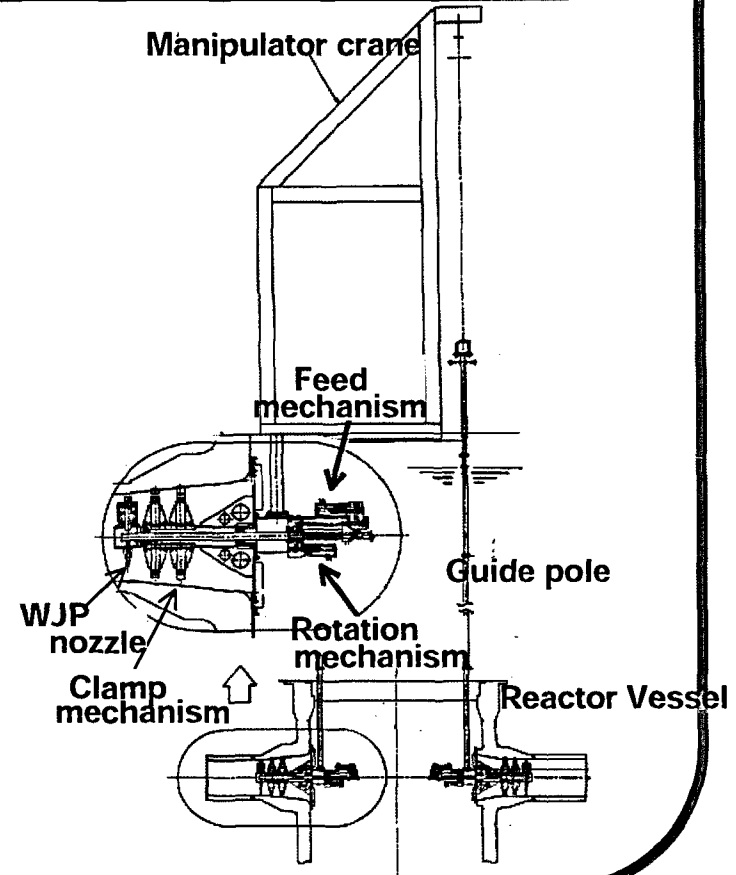
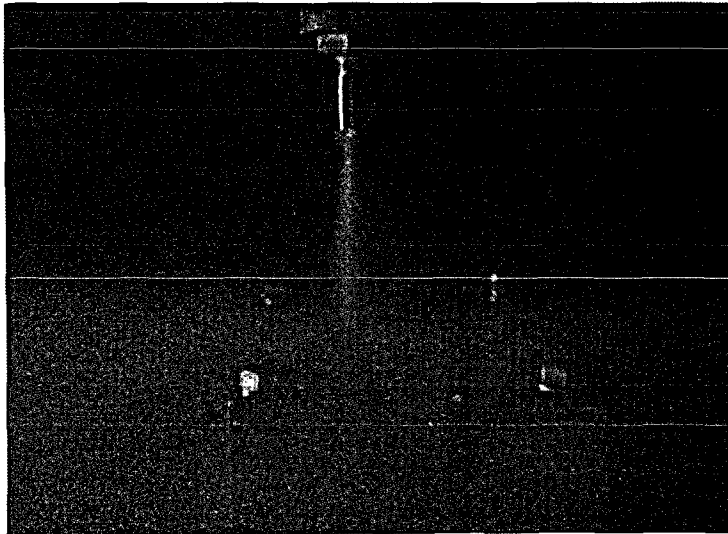
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						Spool-piece Replacement

Hot Leg Nozzle

- **UT from inside or outside of hot leg nozzles have been performed and no indications have been reported.**
- **In case of emergency, spool piece replacement technology and equipment have been developed.**
- **WJP technology as mitigation measurement is under development.**

Hot Leg Nozzle

Concept of WJP for Hot Leg Nozzle



Mitsubishi Heavy Industries, Ltd.

Activities on Alloy 600 Cracking of PWRs in Japan

- PWSCC in alloy 600 is recognized as important common issue for PWR plant operation.
- PWSCC assessment and countermeasure for J-Weld and dissimilar weld are important.
- In order to maintain plant operation, it is necessary to implement inspection and preventive maintenance in accordance with PWSCC assessment.

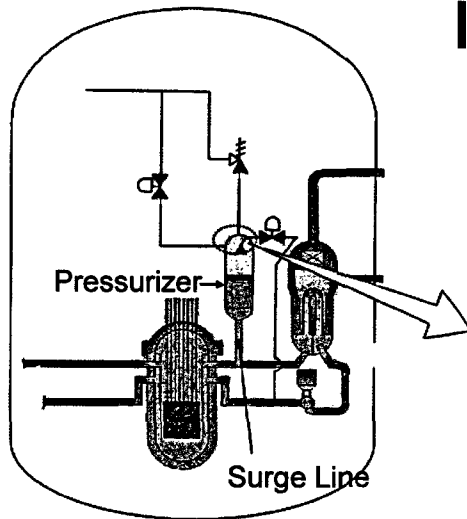
**Tsuruga Unit-2 Pressurizer
Leakage from the Dissimilar Weld
(Alloy 600) of the Relief Nozzle**

The Japan Atomic Power Company

Tsuruga Unit-2

- Start of Operation : February, 1987
 - Power : 1,160 MWe
 - Type : 4-loop
 - Fabricator : Mitsubishi Heavy Industries
-
- This Outage (found leakage) : #13
 - Accumulated operating time: about 120,000 H

Inspection Results

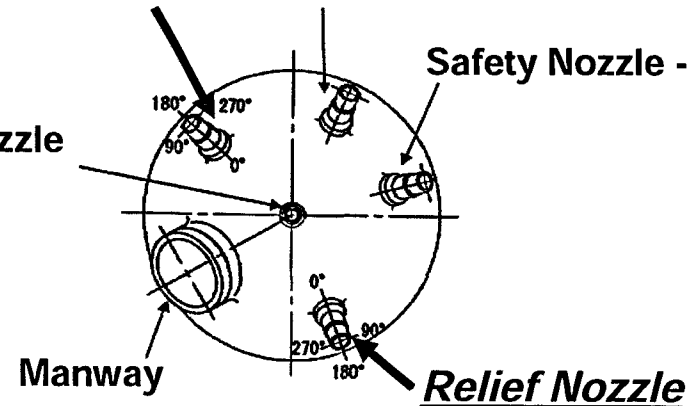


Safety Nozzle - A

Safety Nozzle - B

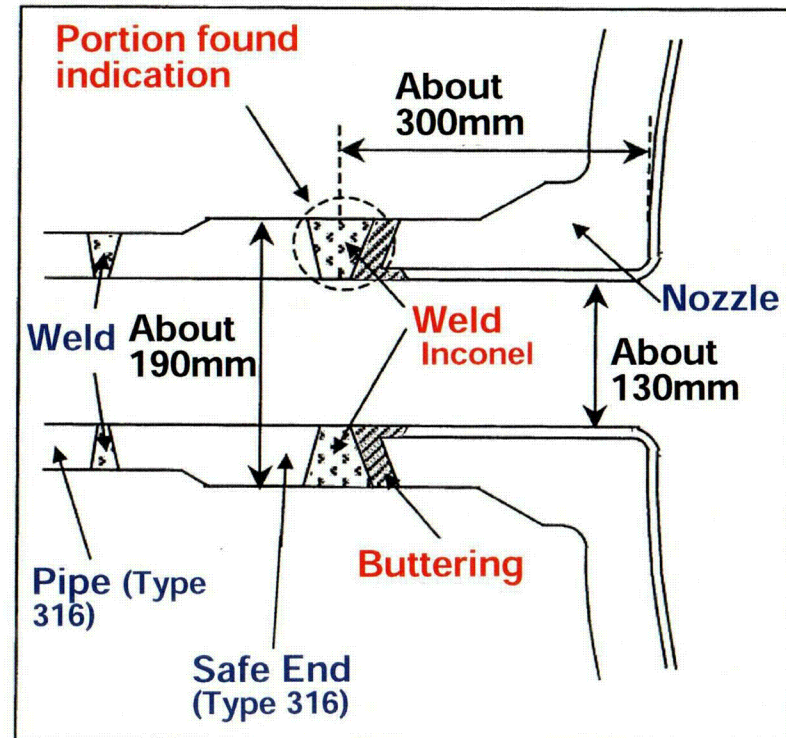
Safety Nozzle - C

Spray Line Nozzle

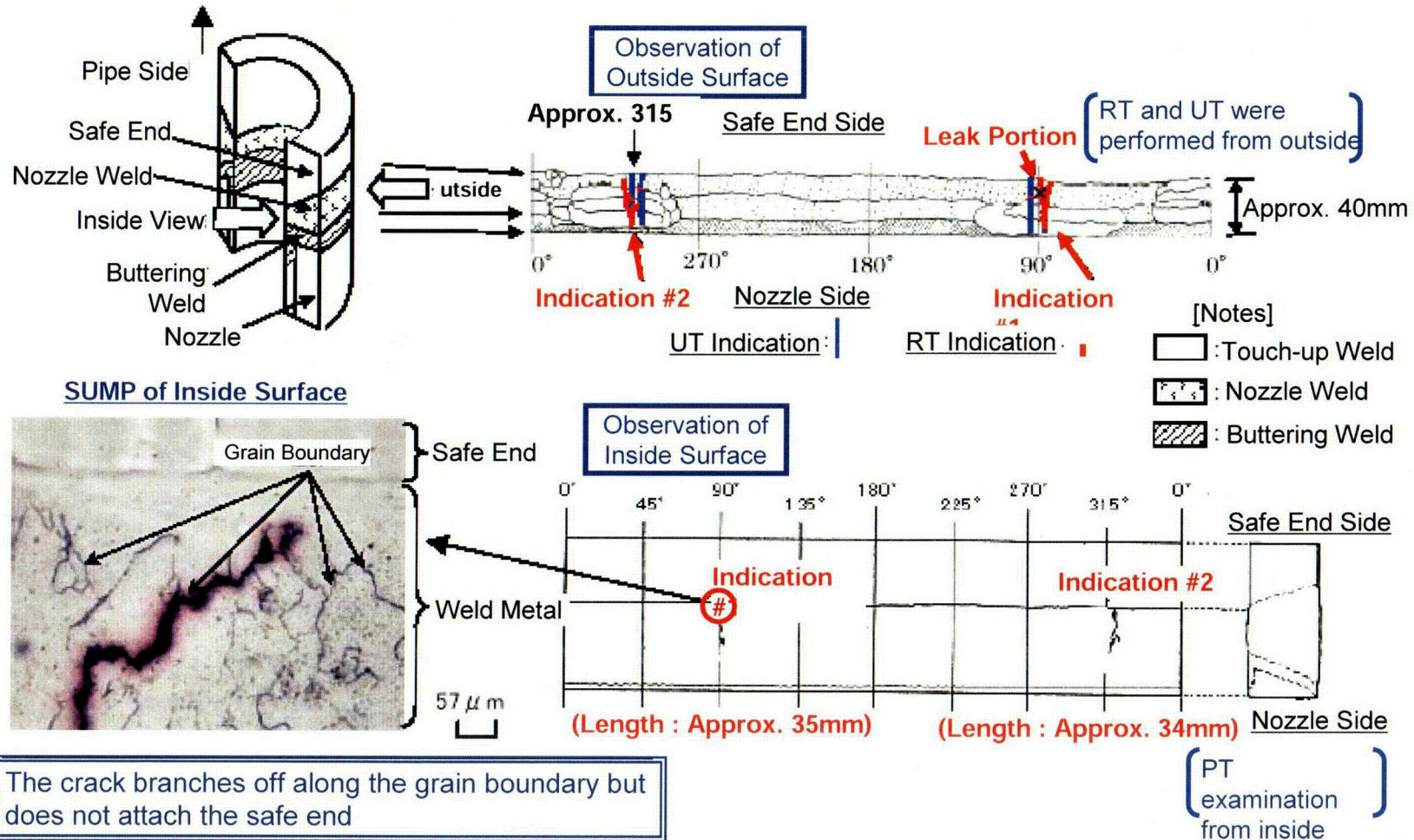


	Indication	Position	Number	Max. Length	Notes
Relief Nozzle	Found	90	2	About 40mm	- Boric acid deposit - UT, RT
	Found	315	3	About 40mm	-UT, RT
Safety Nozzle-A	Found	35	2	About 50mm	-UT, RT
Safety Nozzle-B	No				-UT
Safety Nozzle-C	No				-UT
Spray Line Nozzle	No				-UT

1016



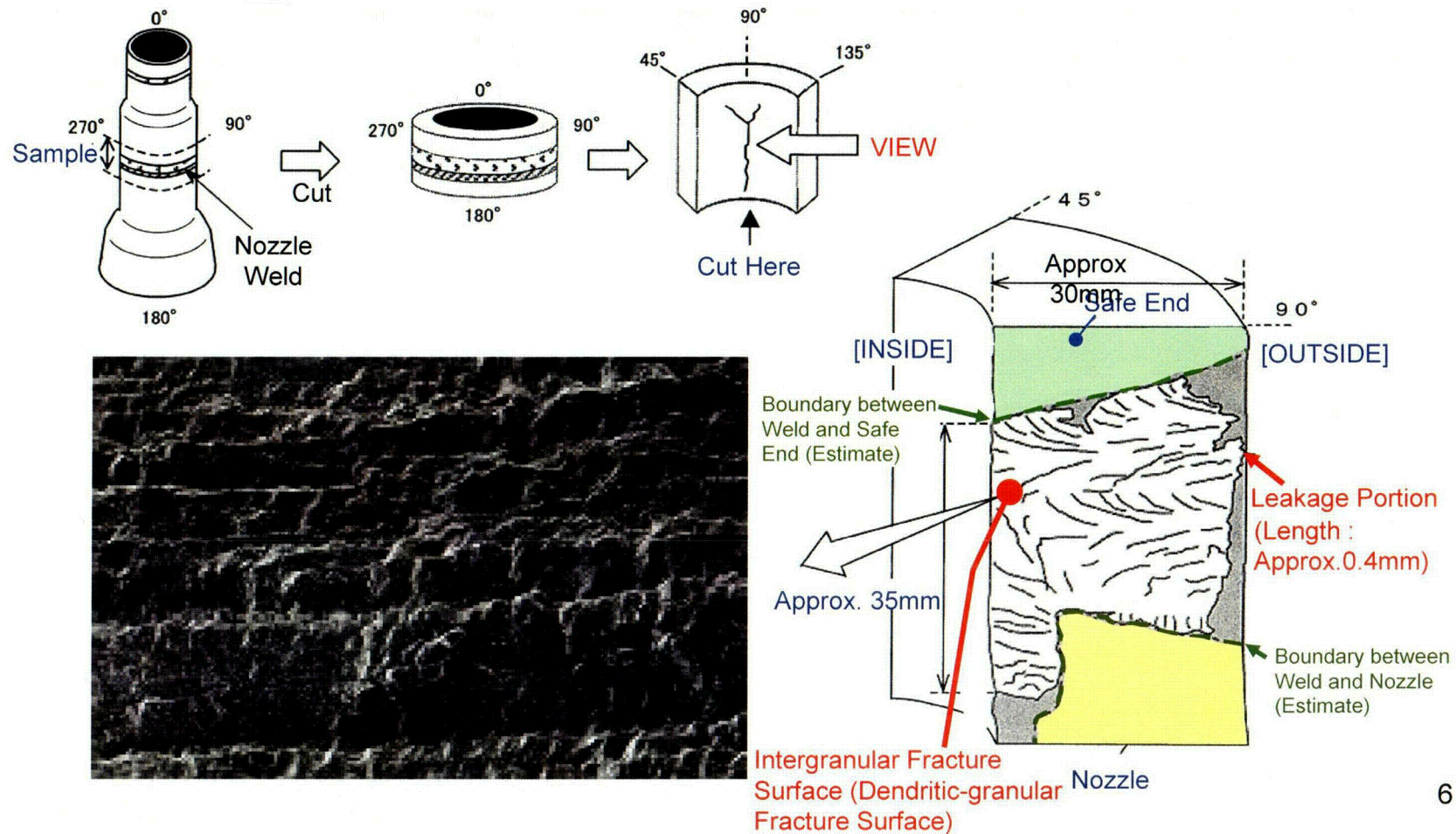
Observation of Inside & Outside Surface



The crack branches off along the grain boundary but does not attach the safe end

Observation of Fracture Surface

■ Indication #1 at 90°



**If you want to look at more clear
picture, please access to web-site
of [http: www.japc.co.jp](http://www.japc.co.jp)**

**If you have more additional questions, please
contact to Mr. Hoshio.
His E-Mail Address is
tomohiko-hoshino@japc.co.jp**

RPV Heads: Inspection vs. Replacement Strategies for Ringhals- PWR

Pål Efsing - Ringhals AB

Christer Jansson - SwedPower AB

*Presentation made at "Vessel Head Penetration"-meeting in Washington
DC. September 29 - October 2 2003*

Ringhals at a glance

- **PWR:**
 - 3 Westinghouse (US) units
 - Ringhals 2 870 MW
 - » Comm. 1975
 - Ringhals 3 920 MW
 - » Comm. 1981
 - Ringhals 4 915 MW
 - » Comm. 1983
- **BWR:**
 - 2 Westinghouse Atom units
 - Ringhals 1 835 MW
 - » Comm. 1976
 - Barsebäck 2 615 MW
 - » Comm. 1977

Approximately 1500 employees

20% of the Swedish production capacity

Majority owned by Vattenfall, Minority owner: Sydkraft

Background

Previous control order

By “the rule of thumb”/Augmented inspections:

No shorter inspection intervals than 3 years

Inspections with “validated inspection system”

Introduction of a more rigid control order with the release of the “new” regulatory guide: SKIFs 1994:1

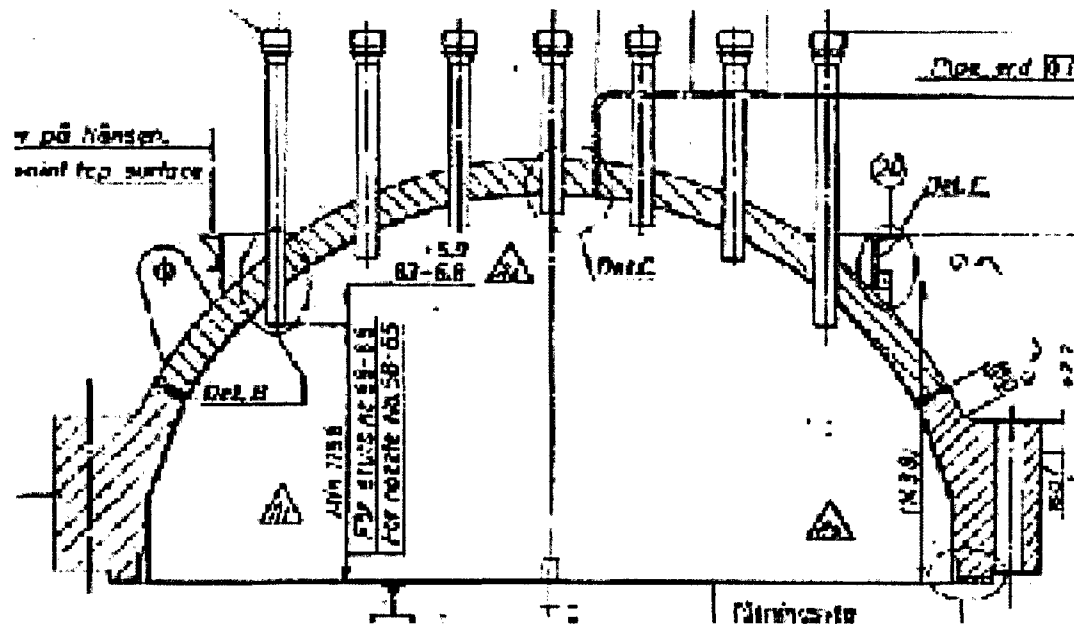
Qualification of inspection systems

Swedish Qualification body, SQC

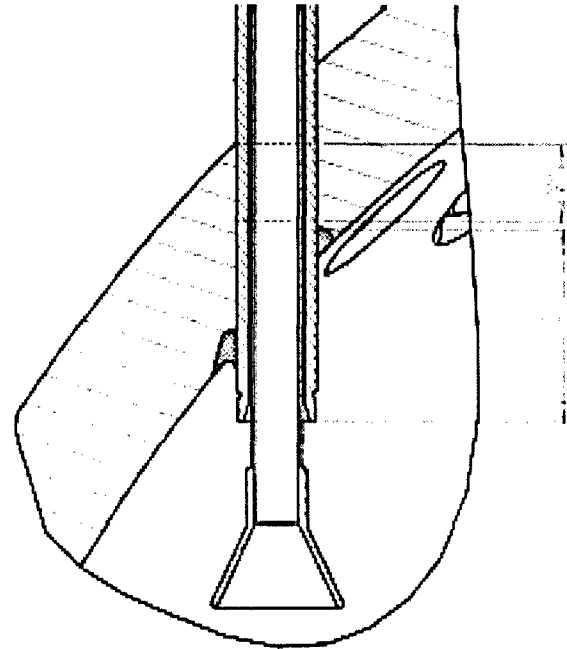
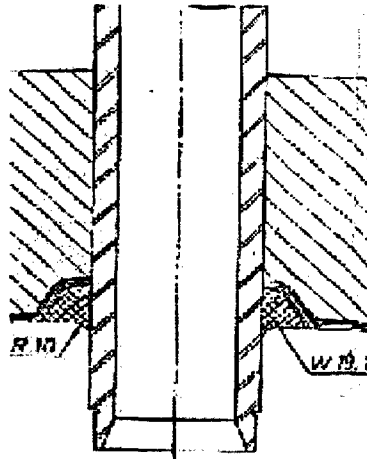
Introduction of “accredited third party body”

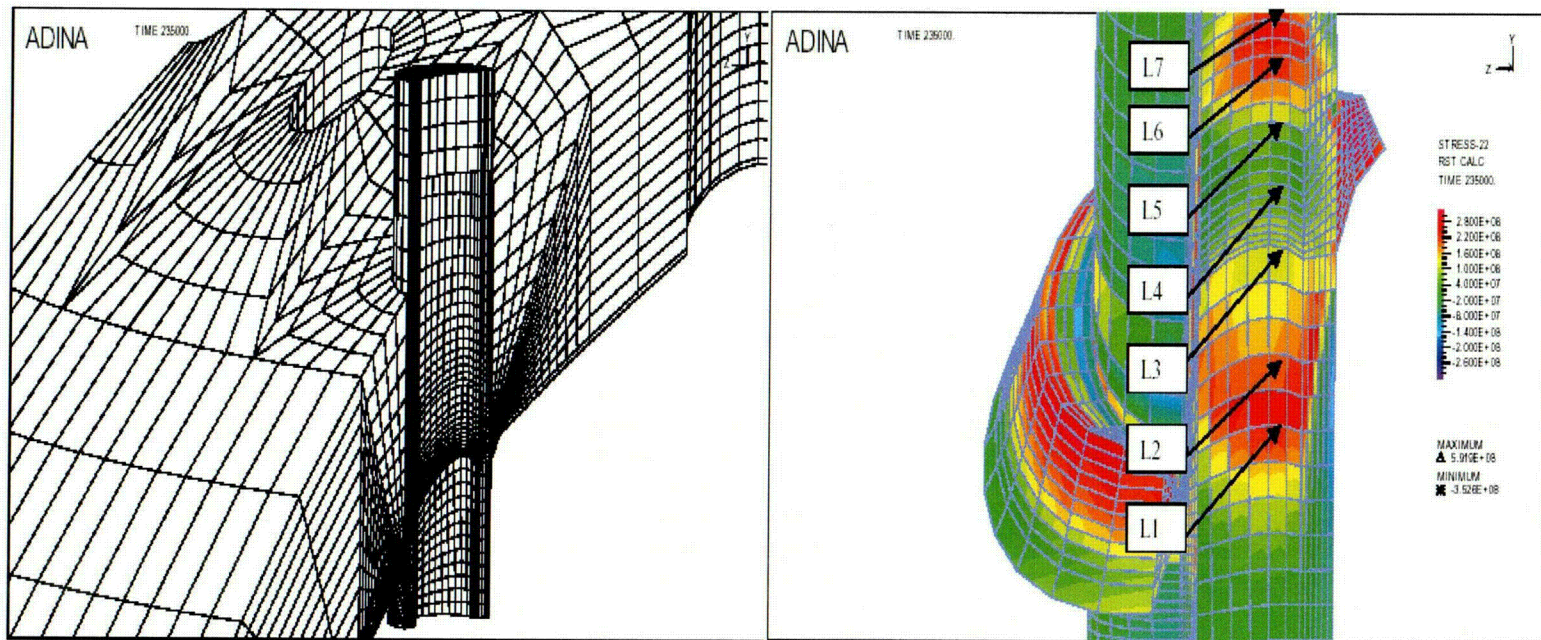
*Strengthening of the control program to be reviewed by the
3rd party body*

RPV Head Ringhals 3 and 4



Vessel head penetrations





Qualification of an inspection system

DaD - Damage and Defect analysis

- To ensure correct inspection means
- To evaluate residual risks

WCD - MSIT - Worst Case Defect with Minimum Suggested Inspection Technique

- To capture the most intriguing inspection task for the suggested technique

Defect Tolerance analysis

- To give correct inspection interval and detection targets
- To give “risk ranking”

Defect tolerance analysis

Current praxis:

According to ASME XI and/or R6-methodology to assess critical and acceptable defect sizes

To:

Establish a detection target
Establish an inspection interval

How:

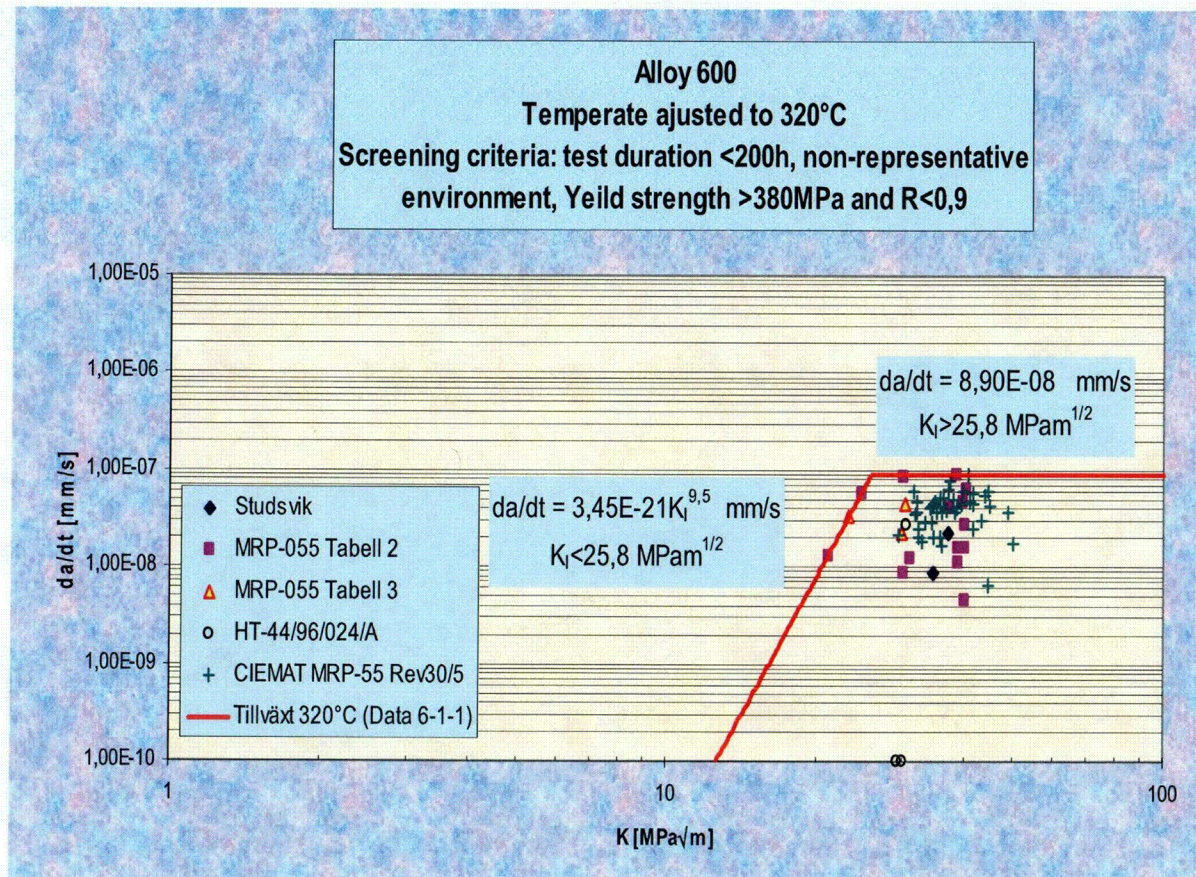
“Inverse crack growth calculation”

- **Inspection interval and detection target dependent on estimated crack growth:**
 - Other parameters are code and practice dependent
 - Single determining parameter assuming other input are fixed
 - Some guidance in regulatory guide
 - Some guidance from third party body
- **Thus: Critical issue to assess crack growth within needs of both reactor safety and reactor economy!**
- **All work in this area review by independent 3rd party body:**
 - Including assessment of crack growth rates

Assessment procedure

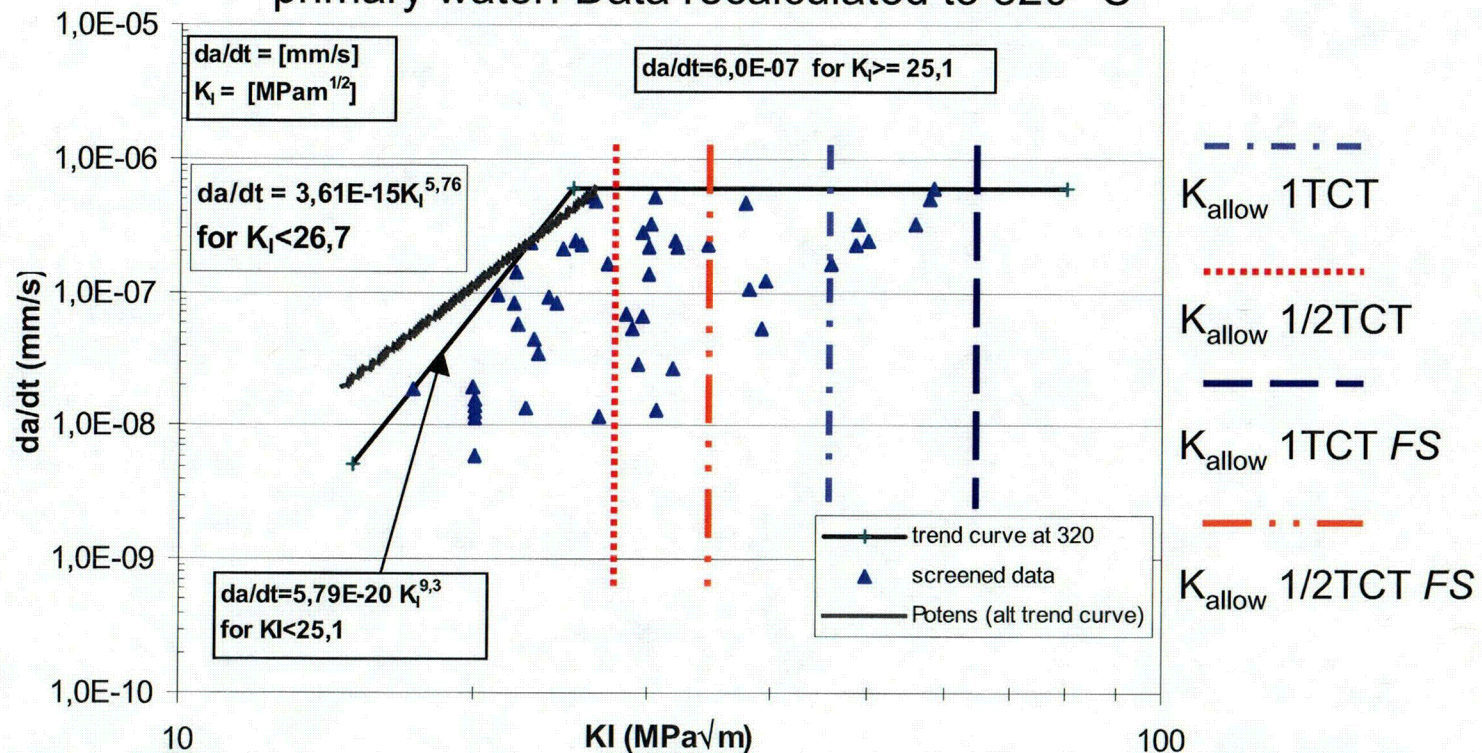
- **Assuming a reviewed data base with sufficient data**
 - “Aggressive screening”
- **Several filters included in the screening procedure:**
 - **Test procedures / Administrative issues**
 - » Constant load testing!
 - » Hold time / cycling of specimen
 - **Environmental issues**
 - » Constant monitoring
 - **Mechanical issues**
 - » Yield strength / R-value / Pre-fatigue /
 - » Temperature dependence

Assessment of crack growth rate



Assessment of crack growth rate

Screened data and bounding curves for Alloy 182 crack growth in PWR primary water. Data recalculated to 320 °C

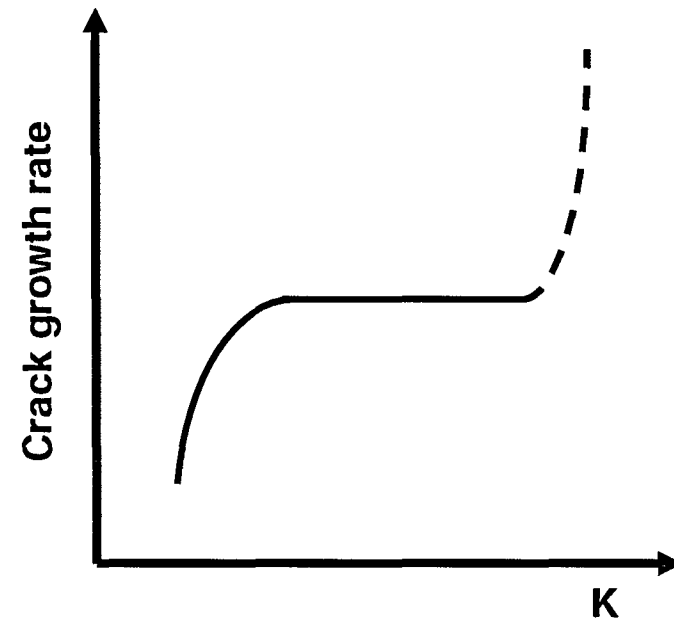


Available data does:

Give sufficient evidence to formulate K-dependent part of CGR-curve for most technically interesting materials

Indicate the need for valid high-K data

- Obvious objective to clearly demonstrate K-independence at higher K-levels
- General trend indicated here found in many systems



Indicate the need to enhance data base to be statistically significant at low to medium high K-levels

Reactions from the reviewer:

3rd Party Body

- Database: Accepted
- Acceptance standards of specimen sizes, geometrical issues, flow stress vs. Yield stress etc
- No acceptance on temperature recalculation using Weibull curve and relating SCC to thermally activated processes
- No acceptance of plateau value from our definition
 - » Wanted to tie the plateau value to a specific K-value rather than the data base

Regulatory Body

- Non-solvable issues with 3rd party body
- Assumed responsibility for theoretical issues outside competence of 3rd party body
- Acceptance of temperature recalculation using Weibull curve and relating SCC to thermally activated processes
- No general acceptance of plateau value but open for discussion on specific issues given sufficient evidence

Inspection results

- **Surface breaking defects found in 26 penetrations between 2000 and 2002**
 - Depth less than 2 mm (lower bound inspection capability)
 - » Measurements on samples: < 1mm!
 - lengths varying from less than 4 mm to 18 mm
 - Defect clusters found in 16 penetrations, “Crackled surface”

The situation:

Despite good quality data:

*Rapid crack growth - small detection targets -
complicated qualification of NDT - short inspection
interval*

Easy to come to the conclusion that replacement or
exchange is the “solver” for most issues

*As long as EAC/operationally induced defects are
an issue it is “efficient” both with respect to reactor
safety issues and plant economics issues, to consider
replacement*

Demands on Engineering Department at power
plants

Defend Cost efficiency and Availability

Current technology vs. Future

- **Produced in:**

- Penetrations in Alloy 600
- Welded with Alloy 82/182
- Butt welds in RPV head

- Known situation

- Penetrations in Alloy 690
- Welded with Alloy 52
- No butt welds in RPV head, single forging possible

- New situation

Decision making

- Effort to estimate cost for inspections, including qualification costs
- Costs of replacement heads fairly well known
- Largest estimated individual cost - forced outages to repairs or prolonged outages due or inspections of penetrations

Thus:

- **Replacement head ordered for delivery in 2004 and 2005**
 - Single forging
 - Penetrations in Alloy 690
 - Nozzle welds made in Alloy 52
- **Foreseen actions to establish a better situation:**
 - Data collection from other RPVH and focused crack growth experiments
 - » 10 year inspection interval possible if further evidence is provided that supports the indications from previous experience and initiation studies

Pros and Cons

- Known fracture toughness of both the weld metal and the base metal
- Good field experience with some replacements
- Documented resistance to crack initiation due to EAC
- Insufficient “good quality data” on crack growth
- Few reactor years in total operated compared to 600/182/82
- Possible that thermal fatigue plays role in initiation portion of the issue
 - Possible that we will be back in same situation again!

Still judged that the new RPVHs are less susceptible to crack initiation and environmental degradation than the current ones - thus it is a correct step to ensure future safe and economical production, for the remainder of the expected technical life

Conclusions

Despite good quality data:

- Rapid crack growth - small detection targets - complicated qualification of NDT - short inspection interval

Easy to come to the conclusion that replacement or exchange is the “solver” for most issues

As long as EAC/operationally induced defects are an issue it is “efficient” both with respect to reactor safety issues and plant economics issues, to consider replacement

Demands on Engineering Department at power plants

Defend Cost efficiency and Availability

Only possible decision : replace RPVH

Alloy 600 PWSCC Mitigation: Past, Present, and Future

***S. Fyfitch
Framatome ANP, Inc.***

***U.S. NRC and ANL Conference
on Vessel Head Penetration Inspection, Cracking, and Repair
Marriott Washingtonian Center, Gaithersburg, MD***

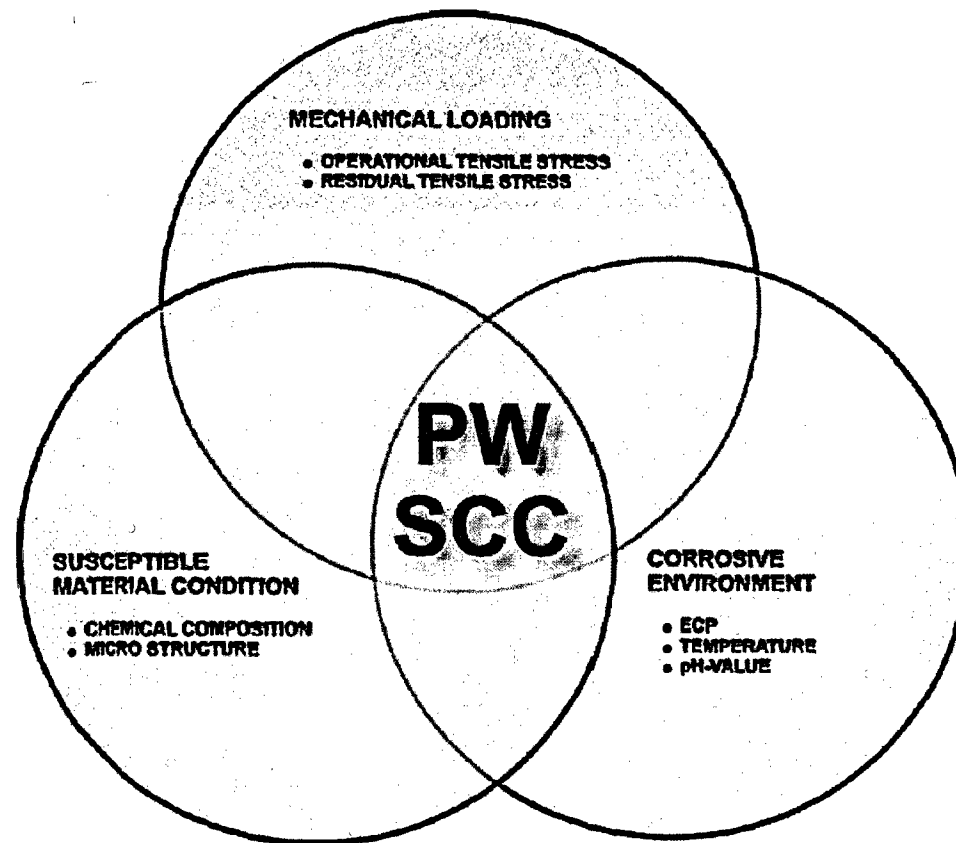
Outline

- > ***Main Factors That Cause PWSCC***
- > ***Brief History of Alloy 600/182/82 PWSCC***
- > ***Previous PWSCC Mitigation Techniques***
- > ***Present PWSCC Mitigation Techniques***
- > ***Potential Future Mitigation Techniques***
- > ***Closing Remarks***

Main Factors That Cause PWSCC

- > PWSCC is cracking of Alloy 600/182/82 material under the combined action of stress and corrosion***
- > Three main factors necessary to initiate PWSCC***
 - ♦ Mechanical loading***
 - ♦ Corrosive environment***
 - ♦ Susceptible material***

Main Factors That Cause PWSCC



Alloy 600/182/82 PWSCC Experience in Commercial PWRs

Component Item	Date PWSCC Initially Observed	Service Life ^a (Calendar Years)
Steam Generator Hot Leg Tubes and Plugs	~1973	~2
Pressurizer Instrument Nozzles	1986	2
Steam Generator Cold Leg Tubes	1986	18
Pressurizer Heaters and Sleeves	1987	5
Steam Generator Channel Head Drain Pipes	1988	1
Control Rod Drive Mechanism Nozzles	1991	12
Hot Leg Instrument Nozzles	1991	5
Power Operated Relief Valve Safe End	1993	22
Pressurizer Nozzle Welds	1994	1
Cold Leg Piping Instrument Nozzles ^b	1997	13
Reactor Vessel Hot Leg Nozzle Buttering/Piping Welds	2000	17
Control Rod Drive Mechanism Nozzle/RV Head Welds	2000	27
Surge Line Nozzle Welds ^c	2002	21
Reactor Vessel Lower Head In-Core Instrumentation Nozzles/Welds ^c	2003	14

PWSCC Mitigation Techniques

> Categories of Mitigation Techniques

- ♦ ***Mechanical surface enhancement (MSE)***
 - *Shot peening*
 - *Electropolishing*
- ♦ ***Environmental Barriers or Coatings***
 - *Nickel plating*
 - *Weld deposit overlay*
- ♦ ***Electrochemical corrosion potential (ECP) control***
 - *Zinc addition*
 - *Modified water chemistry*

Previous PWSCC Mitigation Techniques

MSE Techniques

- > Shot Peening***
- > Flapper Wheel Grinding***
- > Electrical-Discharge Machining***
- > Stress Relief Heat Treatment***
- > Electropolishing***

Objectives:

Reduce tensile stress and/or induce compressive residual stress on exposed surface

Extend crack initiation time and reduce crack propagation rate

Previous PWSCC Mitigation Techniques

ECP Technique

> Temperature Reduction

Objective:

Extend crack initiation time and reduce crack propagation rate

Present PWSCC Mitigation Techniques

MSE Techniques

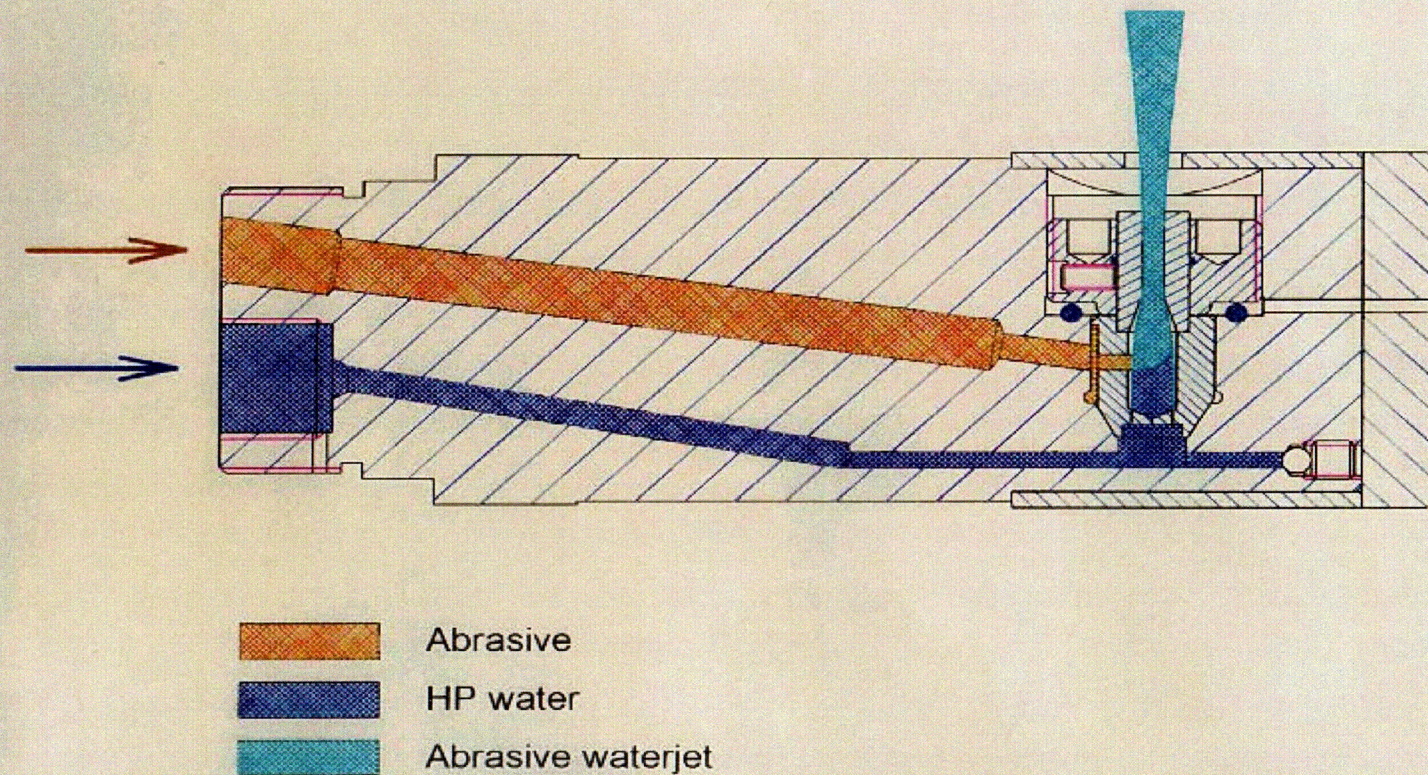
- > Abrasive Water Jet Conditioning***
- > Mechanical Stress Improvement Process (MSIP)***

Objective:

Reduce tensile stress and/or induce compressive residual stress on exposed surface

Abrasive Water Jet Conditioning

Water Jet Nozzle



1052

C96

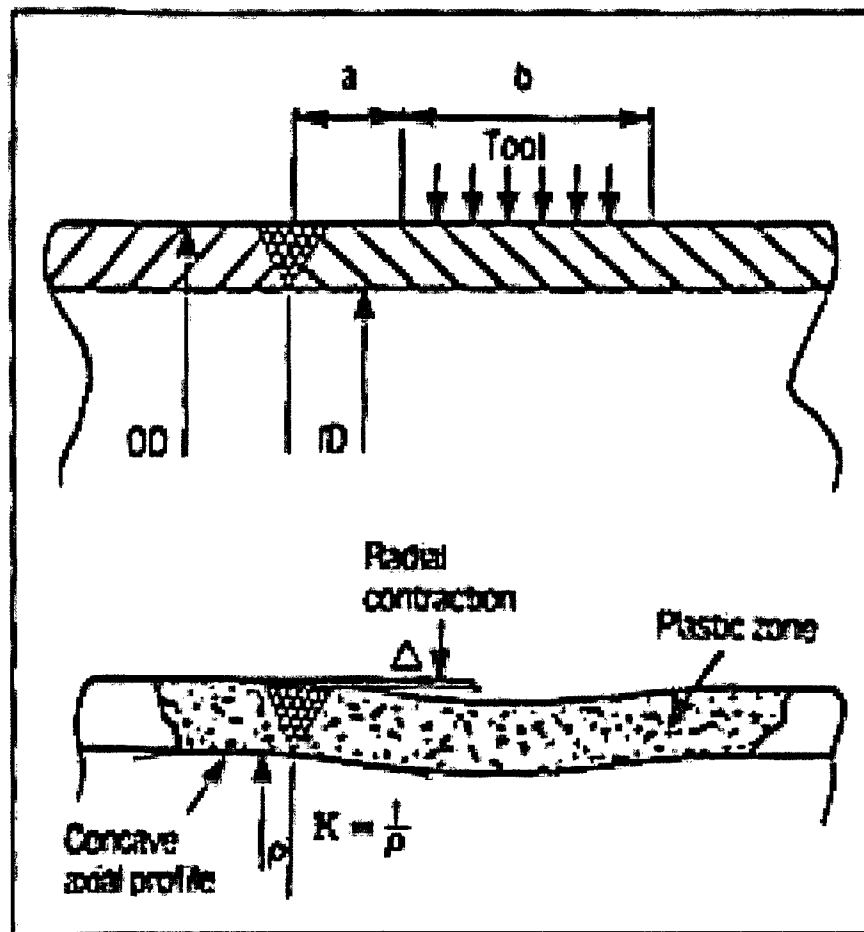


FIGURE 2 TOOL LOCATION AND DEFORMATION CONTOUR AFTER APPLYING MSIP

MSIP

A
FRAMATOME ANP

Present PWSCC Mitigation Techniques

Environmental Barrier or Coating Techniques

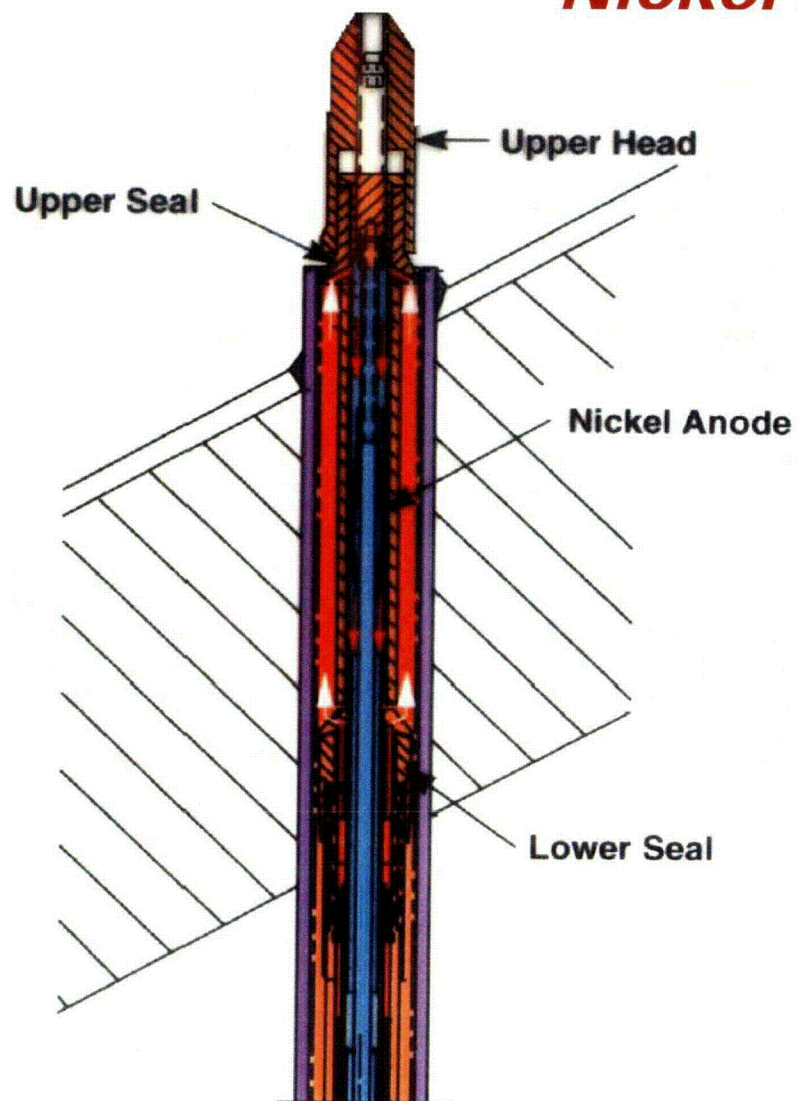
- > Nickel Plating***
- > Weld Deposit Overlay***
- > Electroless Nickel Plating***
- > Laser Weld Deposit/Cladding***

Objectives:

Eliminates the environment that may cause PWSCC
Stops existing cracks from propagating

End Effector

Nickel Plating



Present PWSCC Mitigation Techniques

ECP Control Technique

> Zinc Addition

Objectives:

Inhibits PWSCC initiation

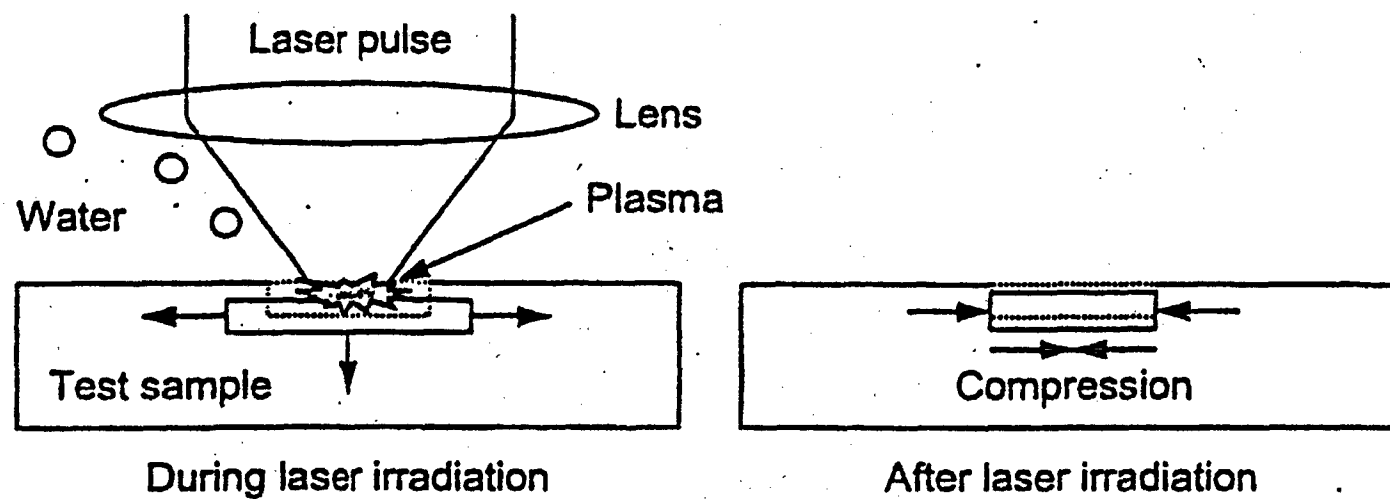
Potentially reduces crack propagation

Potential Future Mitigation Techniques

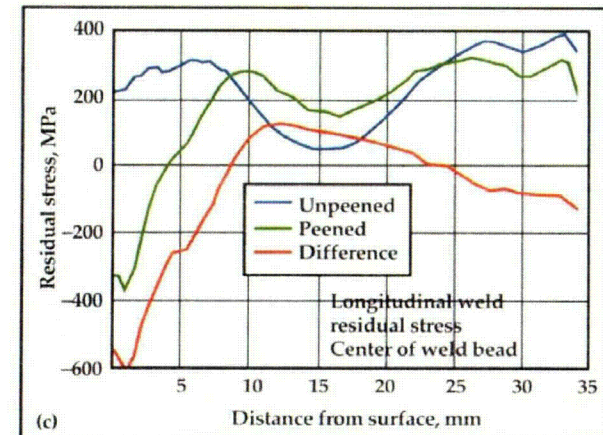
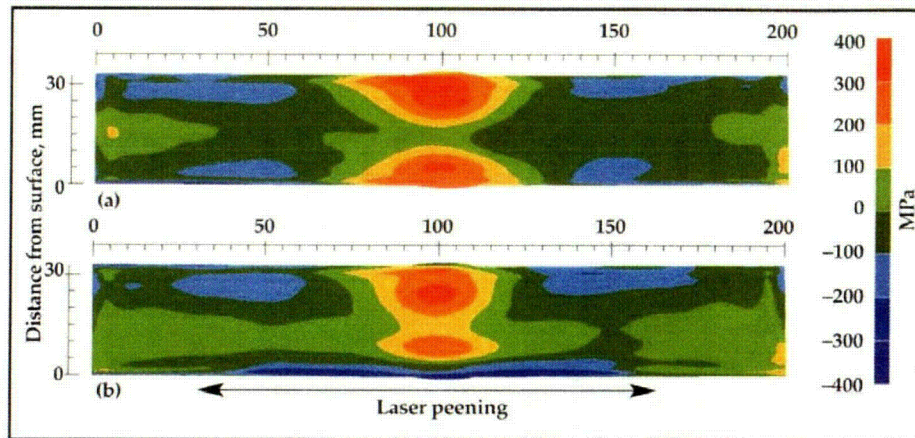
MSE Techniques

- > Laser Shock Peening*
- > Low Plasticity Burnishing*
- > Heat Sink Welding*
- > Induction Heating Stress Improvement (IHSI)*

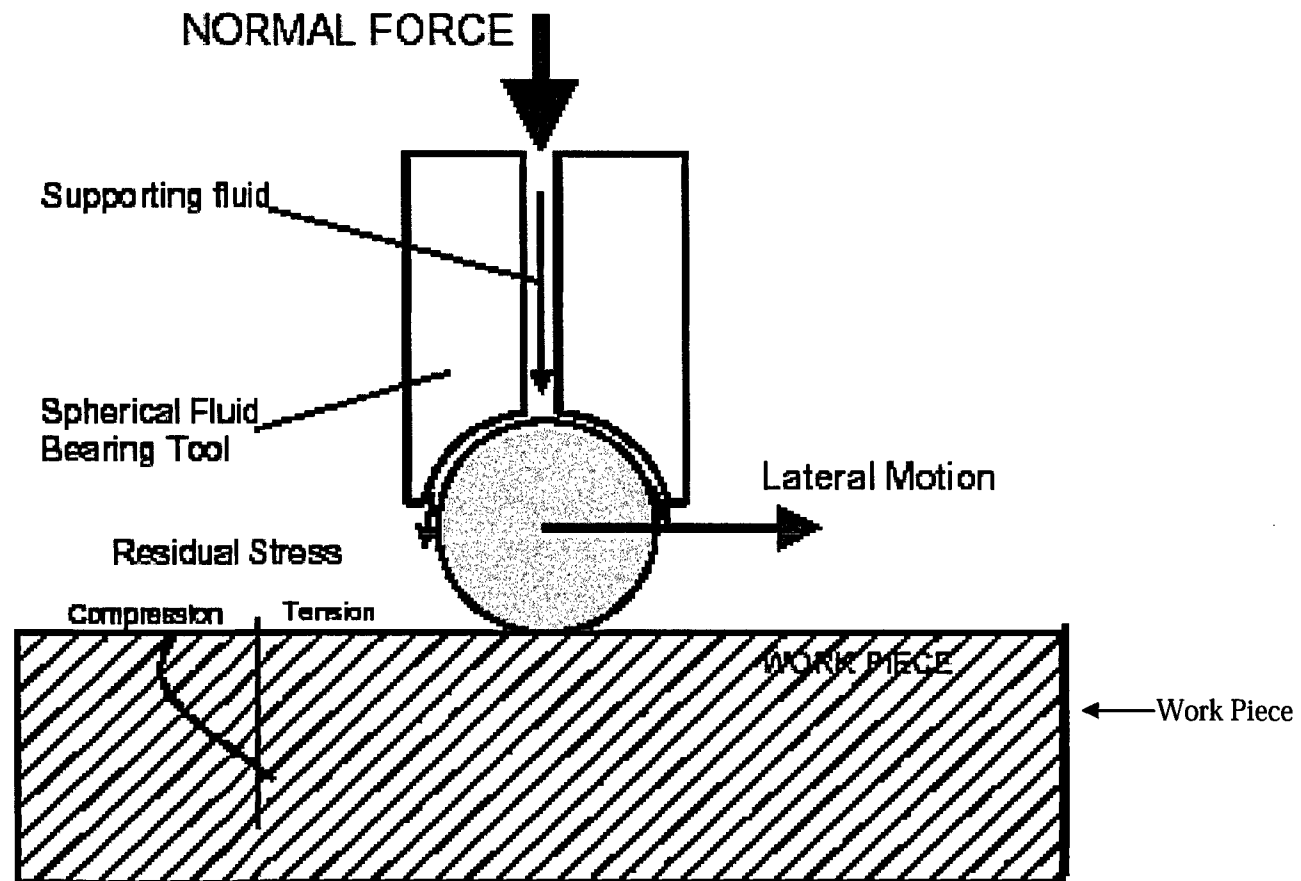
Laser Peening



Laser Peening Residual Stresses

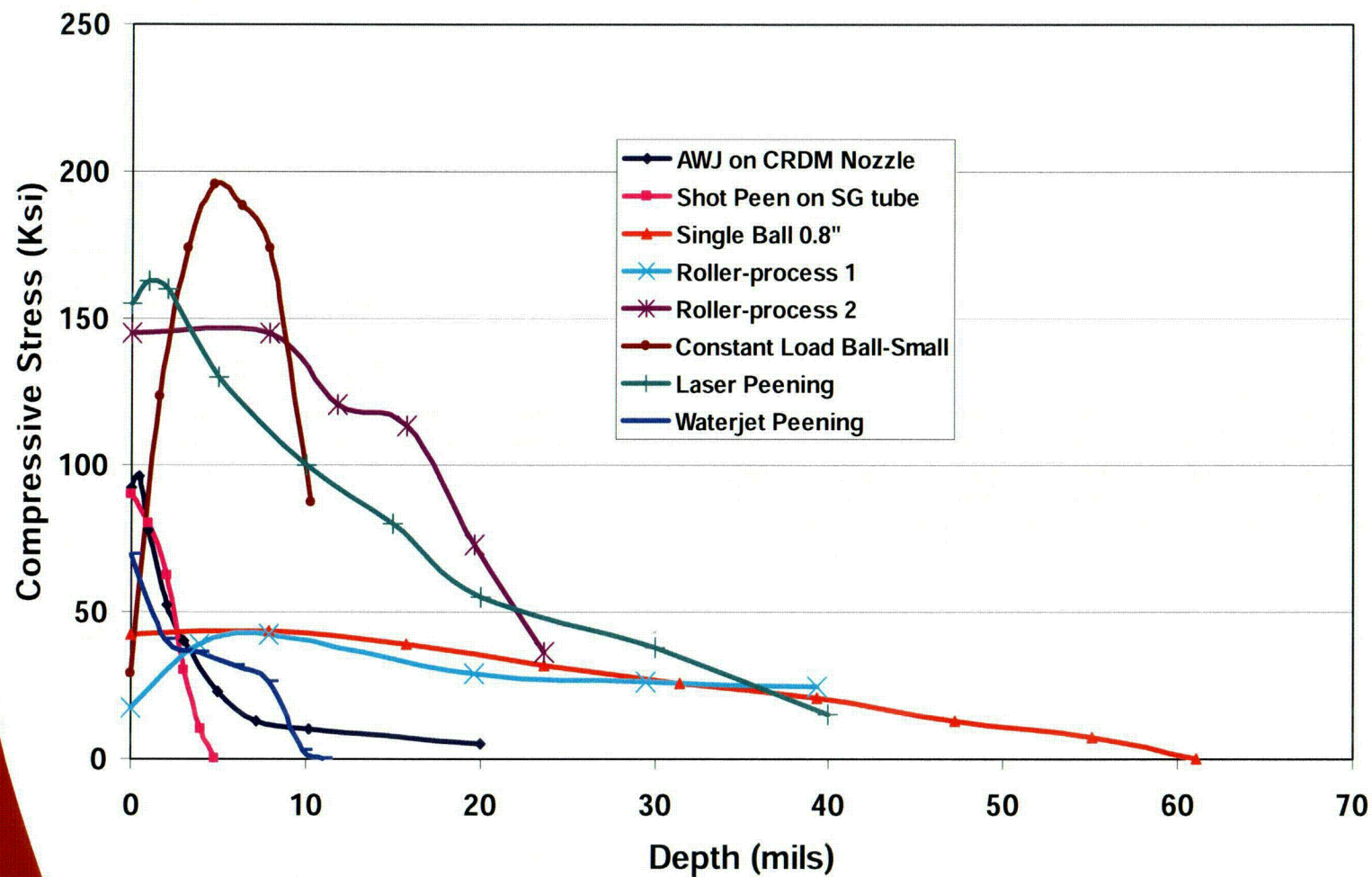


Low Plasticity Burnishing



1060

Comparison of Potential Remediation Techniques



Potential Future Mitigation Techniques

Environmental Barrier or Coating Techniques

- > Ion Implantation and Ion Beam Enhanced Coatings***
- > Thermal Spraying***

Potential Future Mitigation Techniques

ECP Control Techniques

- > Modified Primary Water Chemistry Control*
- > Other Chemical Additions*
- > Anodic Protection*

Closing Remarks

- > PWSCC of Alloy 600/182/82 should be a major concern for most utilities***
- > Replacement with less susceptible material is the obvious alternative***
 - ♦ Alloy 690/152/52 materials mostly utilized***
 - ♦ Not considered remedial***
- > Mitigative techniques very geometry dependent***
- > Many techniques not effective if crack already initiated***
- > Future NDE requirements must be considered***
- > Most techniques require further developmental efforts***

Closing Remarks

- > Utilities need to evaluate a variety of techniques
 - ♦ *One mitigative technique not applicable to all locations**
- > Cost-benefit analyses need to be performed*
- > Utilities should consider developing site-specific Alloy 600 aging management programs
 - ♦ *For current license attainment*
 - ♦ *For license renewal**

A Reactor Vessel Upper Head Temperature Reduction Program to Prevent and Mitigate Alloy 600 Cracking

David R. Forsyth, Pat L. Strauch and Paul J. Kreitman
Westinghouse Electric Company LLC

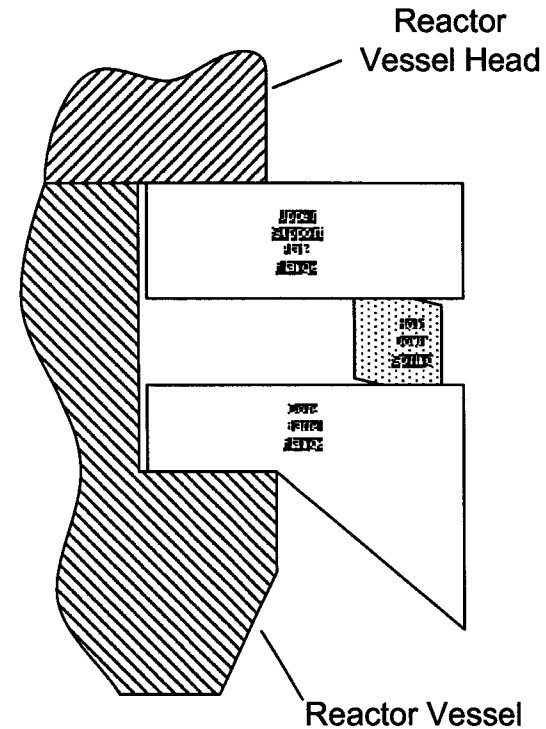
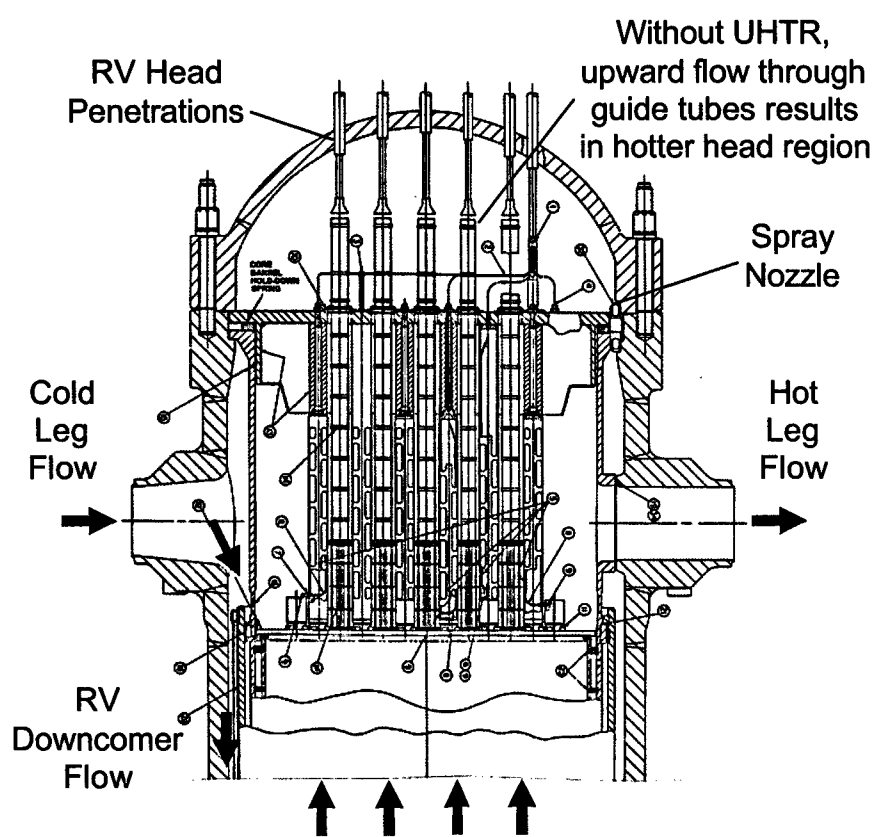
Outline

- What is an Upper Head Temperature Reduction (UHTR) Program
- Benefits
- Effects of Temperature on Cracking
- Westinghouse Fleet Experience

Upper Head Temperature Reduction (UHTR) is a Field Modification Performed on the Reactor Vessel (RV) Internals Structures

- Increases the bypass flow from the RV downcomer region (which is at cold leg temperature) into the upper head region
- Lowers the bulk fluid average temperature underneath the closure head to the cold leg temperature
- This lowers the RV head penetration temperatures

Upper Internals Components



Detail of Components where UHTR Modification is Implemented (by providing a flow path to the upper head region)

1070

Benefits of UHTR

- Significant reduction in effective degradation years (EDY) accumulation rate
 - Can lead to reduced number of required inspections of either a new closure head or an existing closure head
- Reduces the risk associated with head penetration cracking
 - significantly increases time for crack initiation
 - significantly reduces rate of crack propagation
- Significantly increases Peak Clad Temperature margin for large break LOCA
 - provides margin to support an increase in power output
- Slightly increases RCS flow
 - increases steam generator tube plugging margin

Effect of Temperature on Cracking

Effective Degradation Years:

$$EDY_{600^{\circ}\text{F}} = \sum_{j=1}^n \left\{ \Delta EFPY_j \exp \left[-\frac{Q_i}{R} \left(\frac{1}{T_{\text{head},j}} - \frac{1}{T_{\text{ref}}} \right) \right] \right\}$$

where:

$EDY_{600^{\circ}\text{F}}$ = total effective degradation years, normalized to a reference temperature of 600F

$\Delta EFPY_j$ = effective full power years accumulated during time period j

n = number of time periods with distinct 100% power head temperatures

Q_i = activation energy for crack initiation (50 kcal/mole)

R = universal gas constant (1.103×10^{-3} kcal/mole-R)

$T_{\text{head},j}$ = 100% power head temperature during time period j ($R = F + 459.67$)

T_{ref} = reference temperature (600F = 1059.67R)

Effect of Temperature on Cracking

Crack Growth:

$$\dot{a} = \exp \left[-\frac{Q_g}{R} \left(\frac{1}{T} - \frac{1}{T_{ref}} \right) \right] \alpha (K - K_{th})^\beta$$

where:

$\dot{a}$ = crack growth rate at temperature T (inches/year)

α = crack growth amplitude (3.69×10^{-3})

Q_g = activation energy for crack growth (31 kcal/mole)

K = crack tip stress intensity factor (ksi vinch)

R = universal gas constant (1.103×10^{-3} kcal/mole-R)

K_{th} = stress intensity factor threshold (8.19 ksi vinch)

T = absolute operating temp. at location of crack (R)

β = exponent (1.16)

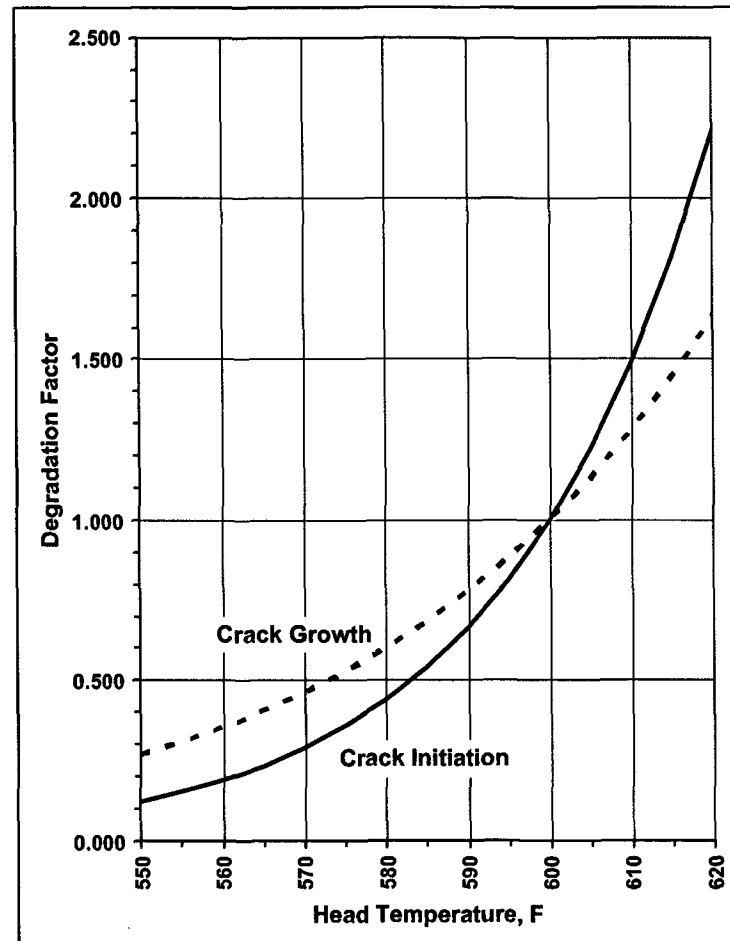
T_{ref} = absolute reference temperature to normalize data

Effect of Temperature on Cracking

<u>Temp</u>	<u>Degradation Factors*</u>	
	<u>Initiation</u>	<u>Growth</u>
600F	1.00	1.00
550F	0.12	0.27

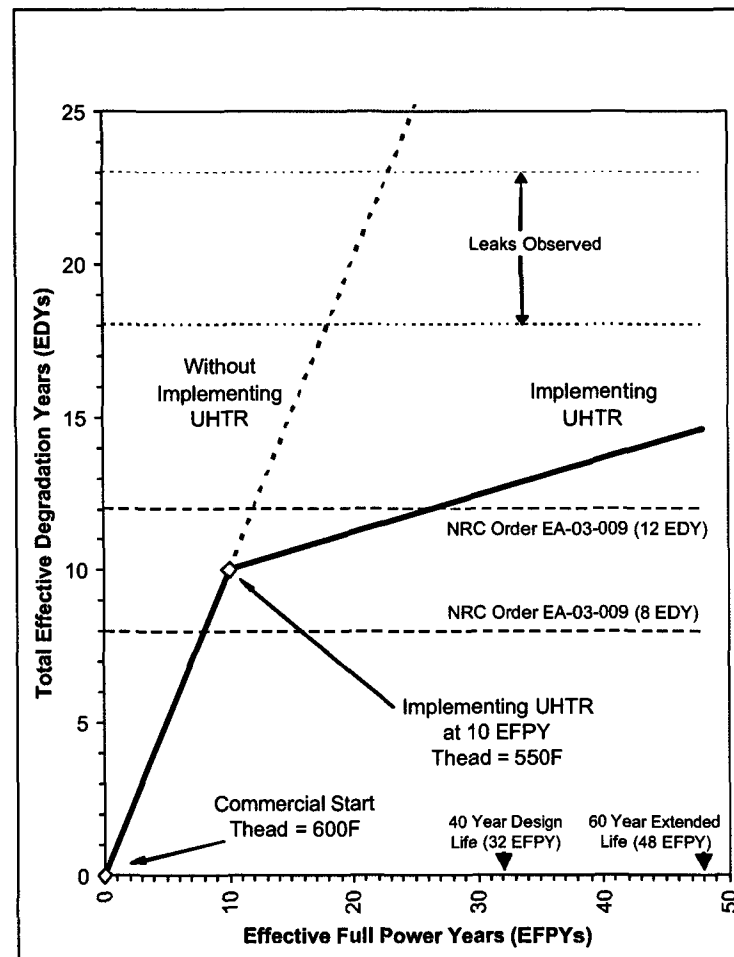
i.e., crack initiation and growth rates at 550F are 12% and 27%, respectively, of their rates at 600F

*Exponential terms in Equations on previous two pages



Example of UHTR Effectiveness for a Unit Approaching the 8 EDY Limit, with Respect to NRC Order

- Early UHTR implementation results in most favorable results
- May extend life into license renewal period



Domestic Plant Ranking vs. EDY

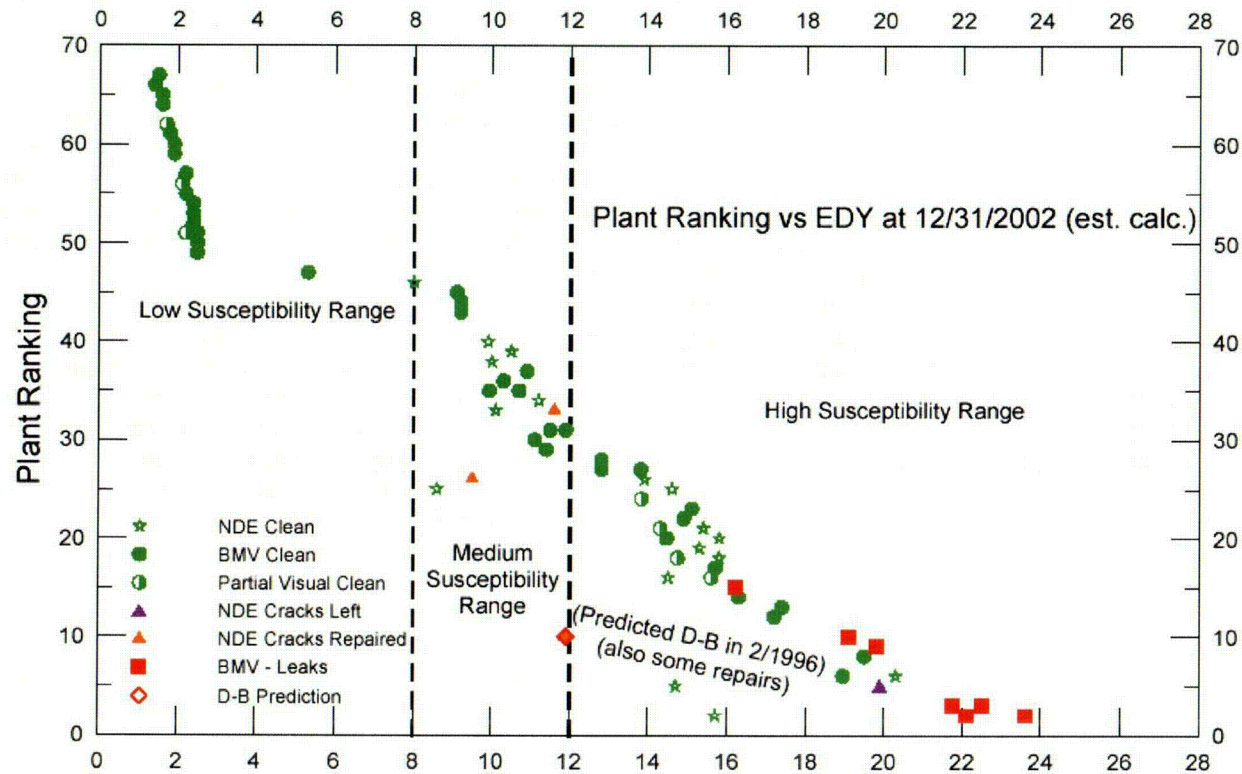


Figure 1. Ranking of domestic plants according to the EDY formula, showing results of inspections, evidence of leakage, and repairs. Many plants are shown with multiple symbols, indicating a "clean" inspection at inspection opportunity, followed by a different finding at a subsequent inspection (e.g., Oconee 2: clean NDE @ EDY=15.7, leaks and circ. flaws @ 22.1)

Westinghouse Fleet Status

- Approximately Half (30) of the Westinghouse Units were Designed and are Operated with Upper Head Fluid at Cold Leg Temperature
- Westinghouse has an Improved Process to Implement UHTR for the Remaining Units
 - Requires no machining in core barrel flange
 - Does not require removal of lower internals package from RV
 - Modifications performed off-critical path (outage time unaffected)

Westinghouse UHTR Field Modification Experience

- One European unit in 1992
 - Maintain LOCA margin
- Two domestic units in 2000 and 2002
 - Reduce core flow
 - Lower susceptibility to PWSCC
- A second European unit in 2003
 - Lower the risk associated with head penetration cracking
 - Provide margin to support an increase in power output
- A third European unit is scheduled for early 2004

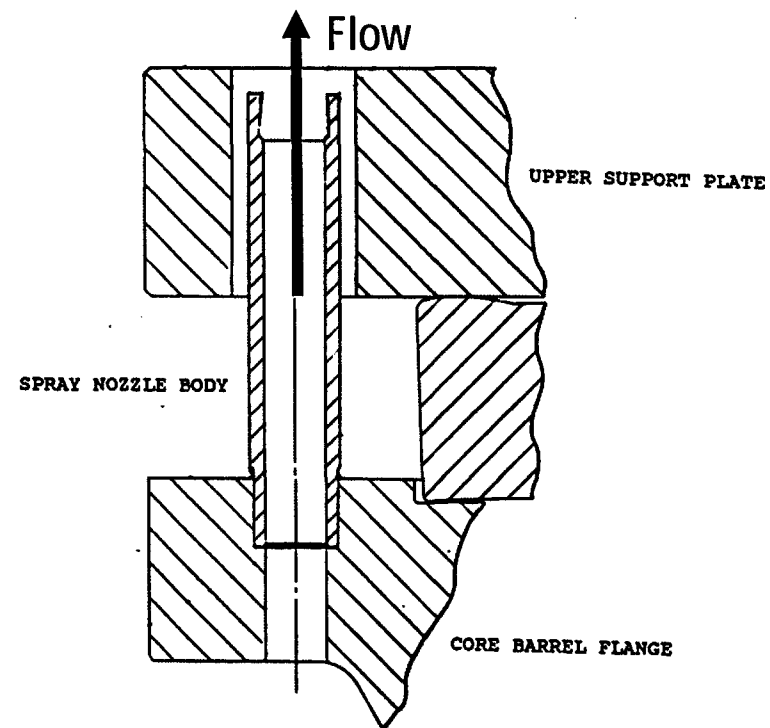
Westinghouse Implementation Designs: Spray Nozzle Plug Removal (3 Units)

Remove specified plugs from existing flow nozzles on the core barrel flange that protrude through holes on the upper support plate flange

Actual Implementation Data:

Schedule: 10 hours

Exposure: 10 mR



Westinghouse Implementation Designs: Upper Support Plate Modification (1 Unit)

Remove a selected number of the irradiated specimen access plugs to expose specimen access holes

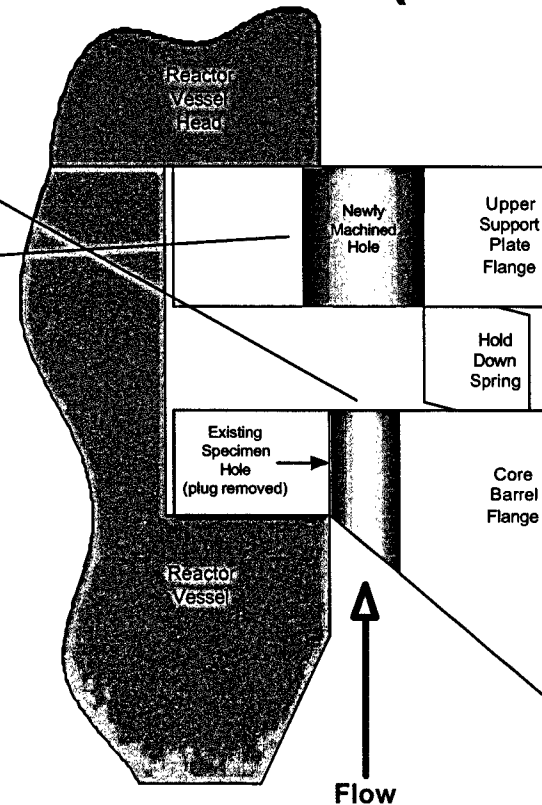
Electric Discharge Machine (EDM) large holes in the upper support plate above each specimen access hole location

Multiple work stations are utilized

Actual Implementation Data:

Schedule: 4 days

Exposure: 637 mR





Status report on the effect of zinc additions on mitigation of PWSCC in Alloy 600

John Hickling

Technical Leader – Materials Issues

Nuclear Power - Science & Technology
Department, Palo Alto, CA

NRC/ANL Conference on Vessel Head
Penetration Inspection, Cracking and
Repairs; Gaithersburg MD, 10/2/2003



Acknowledgements

- Thanks to Bob Gold (Westinghouse) for carrying out the detailed review (documented in MRP-78) upon which this presentation is primarily based
- Key contributions from the following EPRI colleagues are also gratefully acknowledged:
 - Keith Fruzzetti
 - Raj Pathania
 - Chris Wood
- Appreciation is expressed to John Wilson (Exelon), Rick Eaker (Duke Power) and various members of the MRP Expert Panel on PWSCC for their assistance in designing a new test program on chemical mitigation to be funded by the MRP Alloy 600 ITG Mitigation WG



Background to PWR Zinc Addition Studies

- Zinc injection used at most BWRs to control radiation fields, but also helps to inhibit IGSCC (mainly of stainless steels)
- Lab data and German PWR experience indicated similar potential benefit for PWRs
- The objective of the field program in the USA was:
 - To evaluate the long-term effect of Zn addition in mitigating radiation fields and Alloy 600 PWSCC
 - To ensure that zinc does not have an adverse effect on fuel performance and other components
- Zinc addition demonstrations were conducted at Farley (from 1994) and Diablo Canyon (from 1998)
- Palisades uses depleted zinc to reduce radiation fields



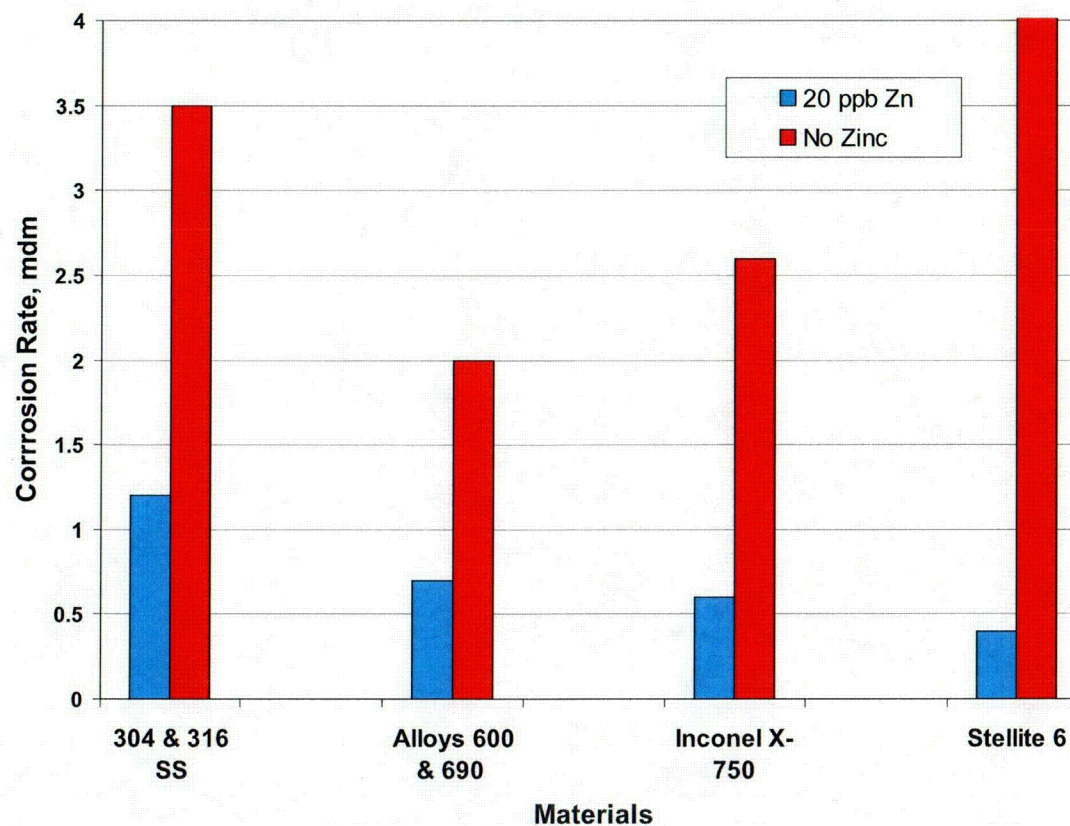
Interaction of Zn with corrosion films on Ni-based alloys in PWR primary water

- Long-term exposure without Zn leads to duplex oxide film:
 - inner layer is chromite spinel $(\text{Fe,Ni,Co})\text{Cr}_2\text{O}_4$ with enriched Cr and Fe and forms by corrosion of metal
 - outer layer grows from solution and typically consists of inverse spinel ferrites such as $(\text{Ni,Co})\text{Fe}_2\text{O}_4$
- Zn displaces Co, Ni and other cations from the normal inner spinel oxides because of its higher site preference energy
- Auger spectroscopy confirms that a large fraction of near-surface tetrahedral sites become occupied by Zn
- Concentration at surface and penetration depth appear to correlate more with exposure time than with coolant Zn level

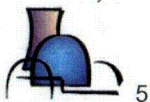


Effect of Zinc on Corrosion Rates

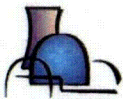
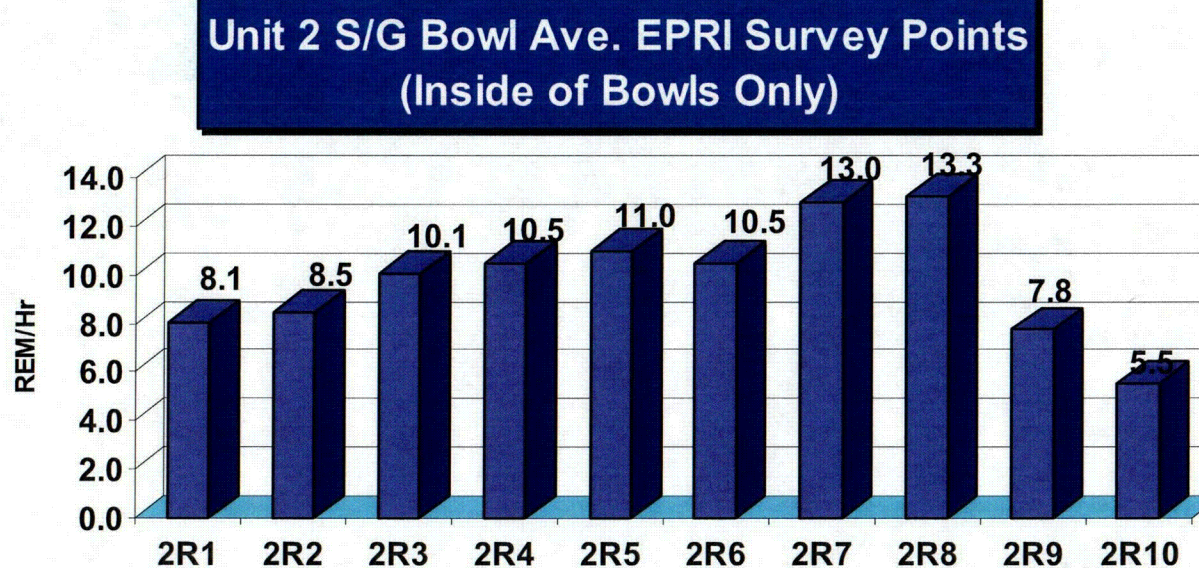
Corrosion Rate at 3.5 Months for Various Alloys



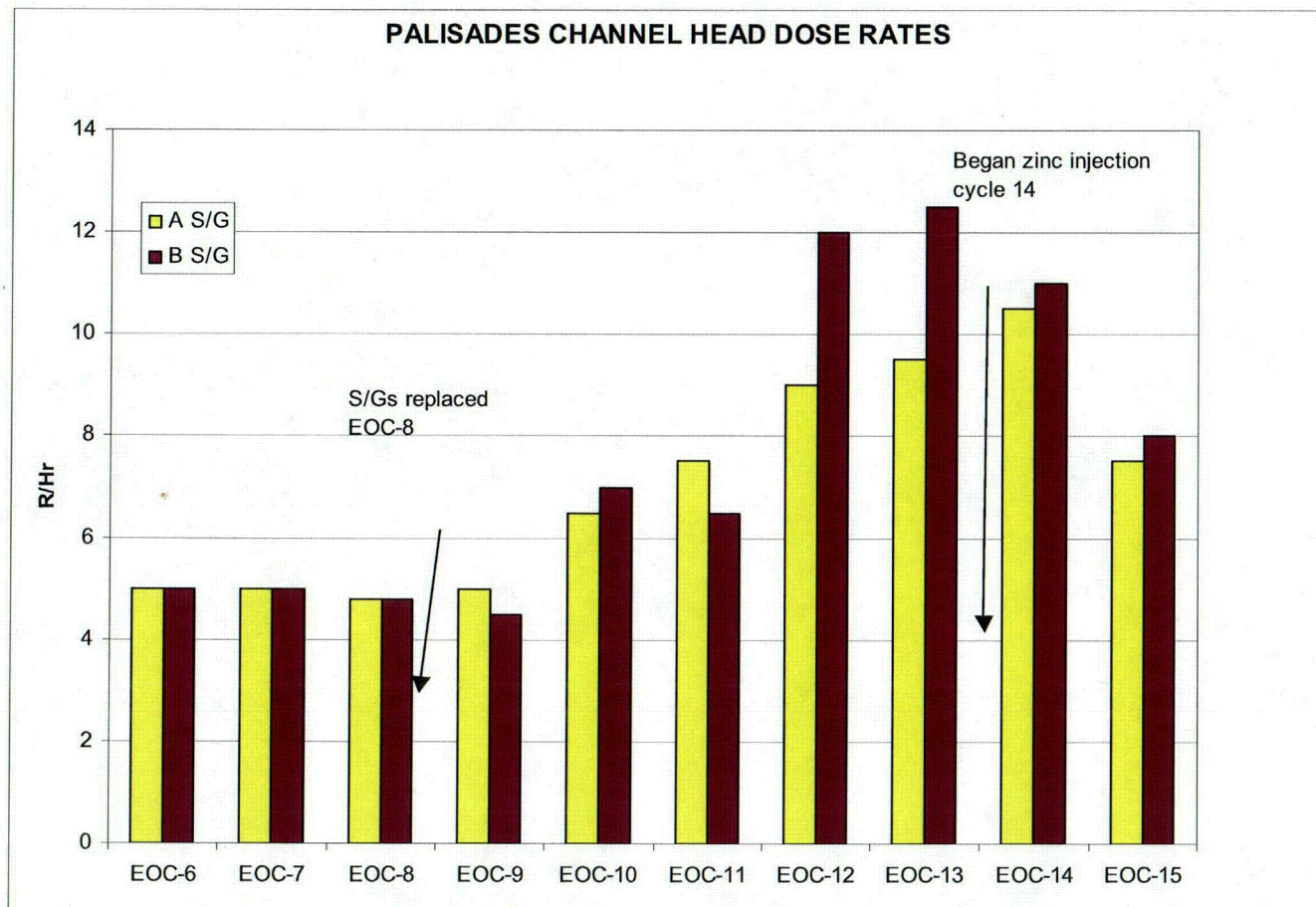
(from Esposito, et. al., Proceedings of the fifth Symposium on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, August 1991)



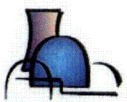
Post Zinc Dose Rate Trends: Diablo Canyon 2 (first additions during cycle 9; range 15 to 30 ppb)



Post Zinc Dose Rate Trends: Palisades (levels up to 10 ppb)



1087



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EPRI

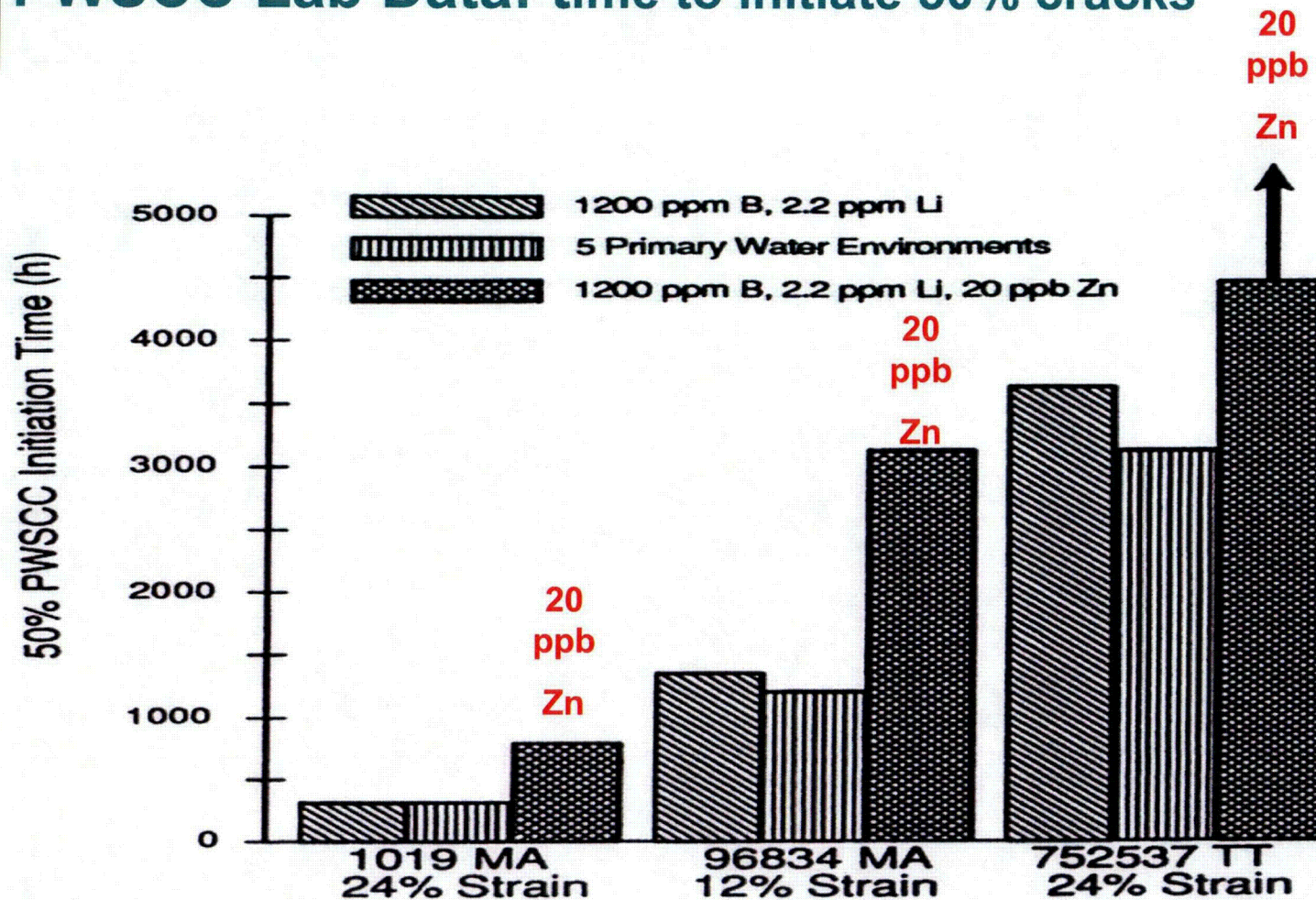
C103

PWR Primary Water Stress Corrosion Cracking of Nickel-based Alloys (600/182/82)

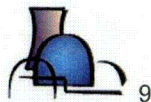
- Main factors affecting PWSCC are materials, material condition, stress and temperature
- Water chemistry in the normal operating range has a relatively small effect:
 - Lithium, boron, pH (minimal effect on initiation or growth)
 - Dissolved hydrogen (minor effect over current field levels but important influence on CGR shown in laboratory studies)
- Zinc injection has potentially significant mitigation benefit
- Laboratory data will be considered for time to initiate cracks and for growth rate of pre-existing cracks
- EPRI Materials Reliability Program (MRP) is starting additional CGR measurements in the near future to examine all of the above chemistry issues using advanced testing techniques



PWSCC Lab Data: time to initiate 50% cracks



1089



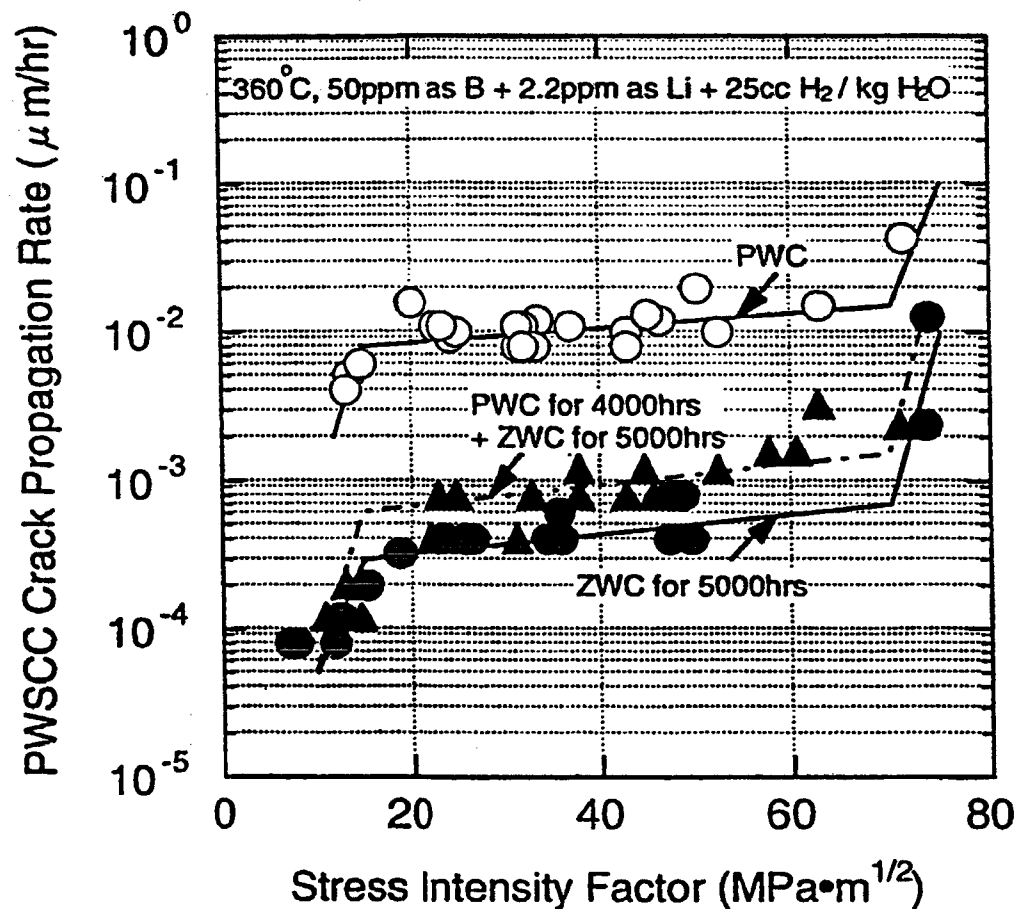
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EPRI

C104

PWSCC Lab Data on CGR with and without Zn addition (10 ppb) to primary water



Kawamura
et al. (1998) using
DCB specimens
from plate material

SSRT also
showed a beneficial
effect of Zn
additions (factor of ~
2x on PWSCC depth)



Other PWSCC Lab Data on CGR in fracture mechanics specimens is less conclusive

- In a test at 330C, Gold et al. (1994) found that 20 ppb Zn lowered the CGR of a pre-cracked SG tube specimen under dead-weight loading at high K by a factor of $\sim 3x$
- In further tests on CRDM material at lower K values, no crack growth was found when Zn (50-250 ppb) was present
- Airey et al. (1996) found no apparent effect of 40 ppb Zn in extended tests at high K levels using WOL & CT specimens
- Further tests in the same program, reported in 1999, gave the same result at lower K levels
- Tests by Morton et al. (1997) also failed to show a beneficial effect of Zn, even when added at high levels (~ 100 ppb)



Possible explanation for apparent lack of beneficial effect from Zn in CGR testing

- Morton et al. found Zn had been absorbed into the chromite spinel films on the free surfaces but was NOT present at the crack tip, where they reported mainly cubic NiO present
- In contrast, Kawamura et al. report finding the spinel at the crack tips in their work, which would be consistent with the beneficial effect observed
- Recent high-resolution ATEM studies indicate that crack tip oxides in Ni-based alloys are complex and may vary both according to the environment and the crack growth rate
- Possible that effective introduction of Zn into the crack tip films requires more time than is often allowed in testing
- Would be consistent with the work of Andresen on factors affecting Zn incorporation in Alloy 600 cracks in BWR water

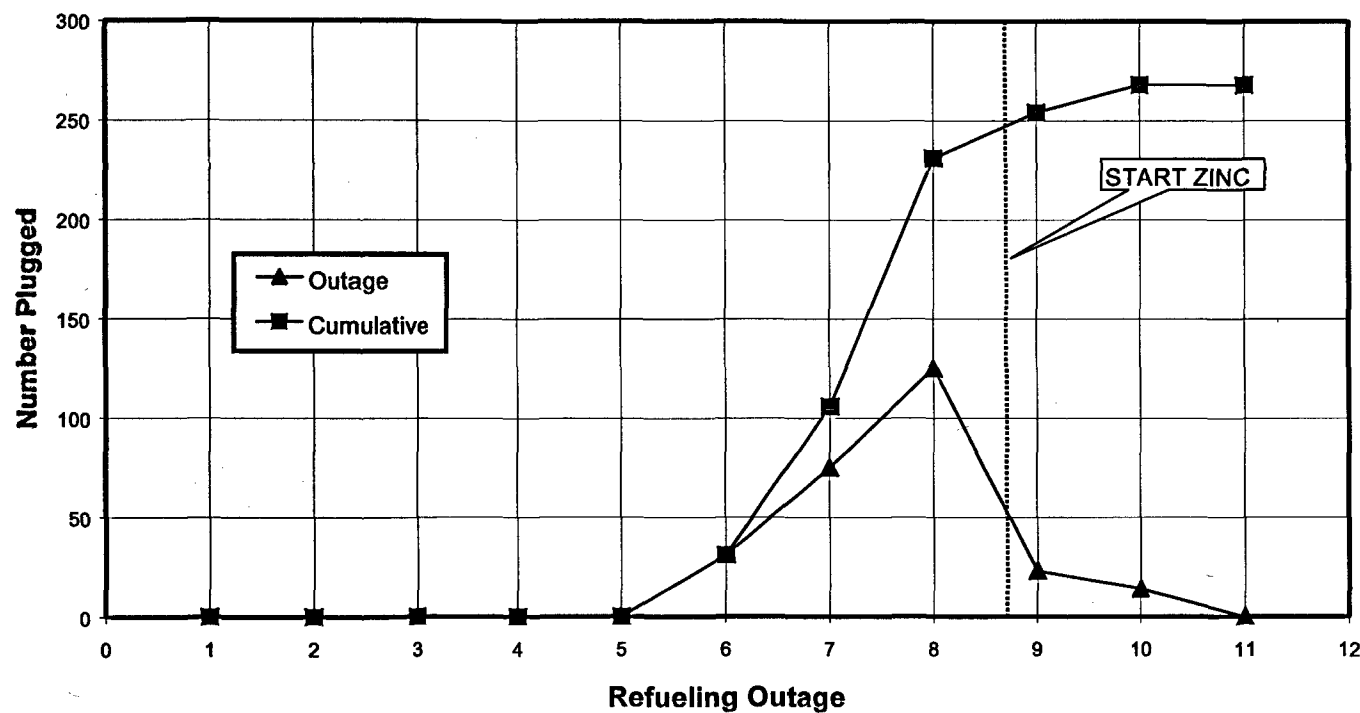


US field data with regard to Zn and PWSCC

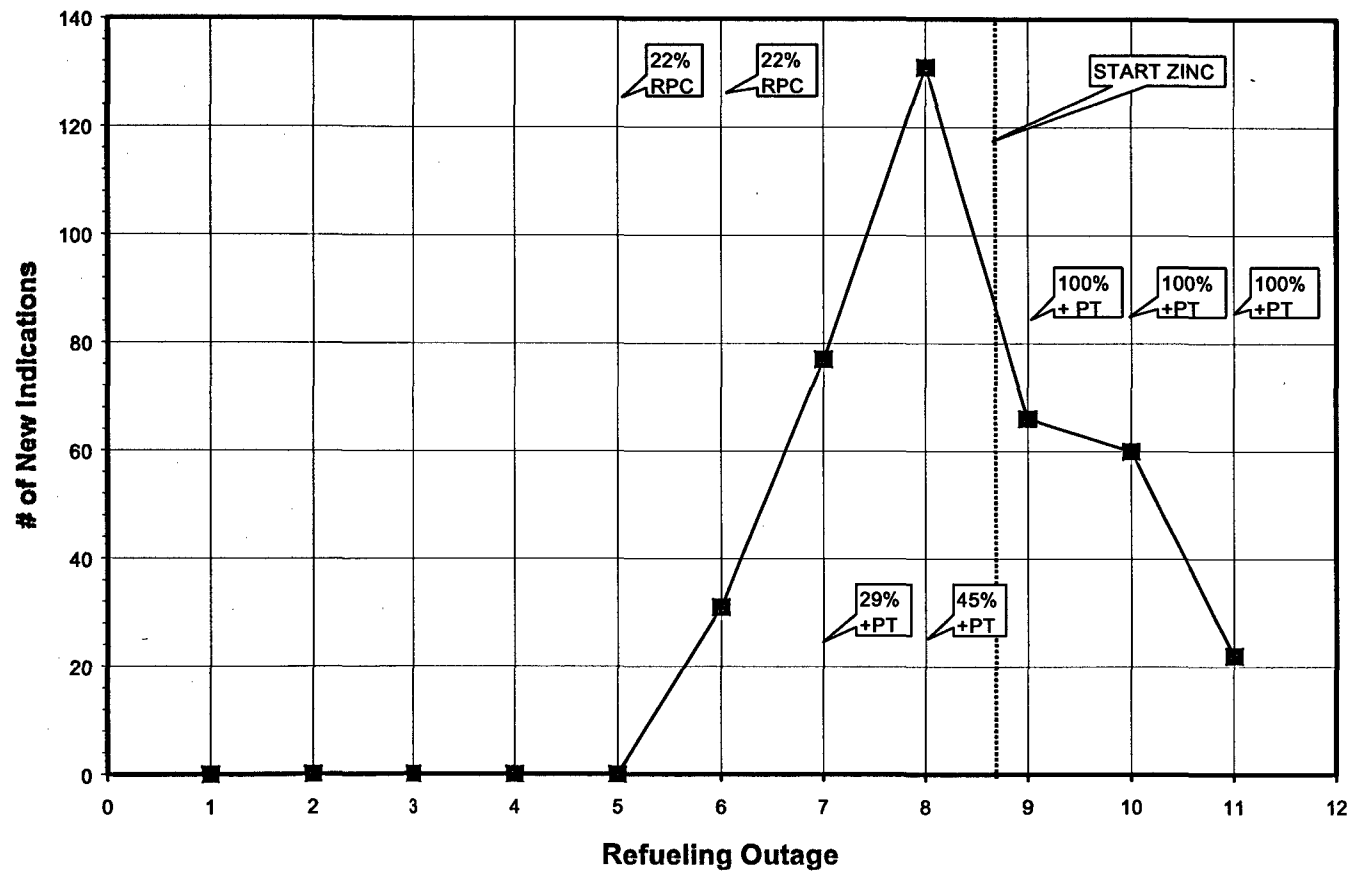
- Diablo Canyon Units 1 & 2 provide the best opportunity to assess the effect of Zn additions on PWSCC (of SG tubing)
- Plugging/repair actions at the TTS locations have become manageable over recent cycles and do not appear to represent a threat to SG reliability
- Trends at the tube/TSP locations are also encouraging, particularly the decrease in the # of new indications
- It is tempting to interpret this as a Zn effect!
- May be correct, but the data are ambiguous because of a number of factors, such as changes in inspection practice and equipment, limited and intermittent periods of zinc injections, modified plugging criteria, etc.



Example for Diablo Canyon Unit 1: SG tube plugging for PWSCC at TSP locations



Example for Diablo Canyon Unit 1: new indications of PWSCC at TSP locations



Zinc Effects on PWSCC: Summary

- Strong laboratory evidence exists to support the position that zinc inhibits the *initiation* of PWSCC in Alloy 600
- Less conclusive laboratory evidence suggests zinc may be effective in inhibiting the *propagation* of PWSCC
- Zinc incorporated in corrosion films on Alloy 600 tubing
 - Too early to assess effect on PWSCC in plants because of complications involving NDE data
- More field eddy current inspection data needed to confirm Zn injection mitigates PWSCC crack initiation and/or growth
- Continuous injection of 20-35 ppb of zinc acetate is currently the most promising chemistry mitigation technique



Zinc – Fuels Issues

- Increase in Zircaloy fuel cladding oxidation measured at Farley 2 after cycle 10
 - Detailed root cause analysis showed higher oxidation caused by higher thermal duty and measurement bias
- Subsequent oxide measurements at Farley 2 showed lower values on once- and twice-burned fuel
 - Confirms no effect of zinc
- Recent scrapes at Palisades showed no evidence of zinc silicates, following operation with Zn ~ 9 ppb & silicates up to 2.5 ppm



Overall conclusions on adding Zinc in PWRs

- Farley, Diablo Canyon and Palisades show significant reductions in PWR shutdown radiation fields with Zn additions
- No adverse effects of Zn additions observed on Zircaloy or ZIRLO fuel cladding corrosion
- Need to resolve potential issues associated with Zn injection on fuel performance in high duty plants
- Latest Chemistry Guidelines (June 2003) recommend PWRs should consider implementing 5-10ppb Zinc
 - reduce radiation buildup
 - prepare plant to gain benefits of zinc to mitigate PWSCC, if this is confirmed to be effective
- New MRP crack growth measurement program to start soon





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**CONFERENCE ON VESSEL HEAD PENETRATION
INSPECTION, CRACKING AND REPAIRS
Gaithersburg, MD – Sept. 29-Oct. 2, 2003**

**An Assessment of MSIP for PWSCC
Mitigation of PWR Thick Wall Piping Welds
by Instrumented Monitoring of Full-Scale
Mock-up Test**

**GUTTI RAO¹, MANU BADLANI², EDWARD RAY¹,
and THOMAS DAMICO²**

¹Westinghouse Electric Company, LLC

²AEA Technology

OBJECTIVES

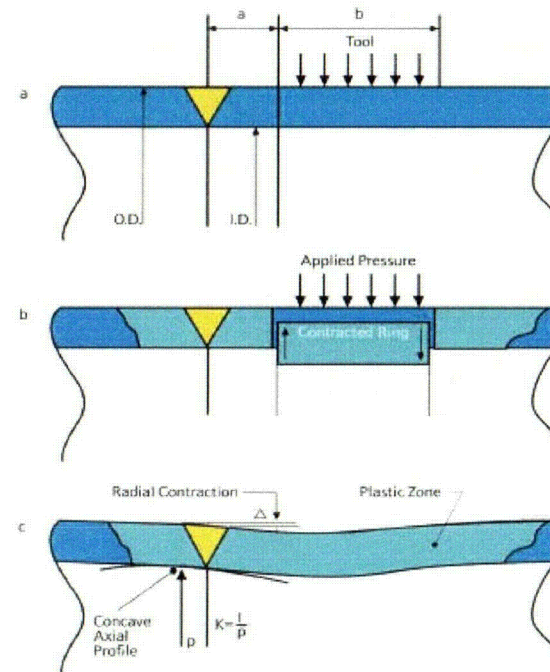
- To validate analysis and confirm applicability of MSIP for thick wall PWR piping
 - ◆ Verify that the desired MSIP load locations and range of radial contractions achieve permanent compressive residual stresses at the nozzle ID surface at the nozzle-to-safe-end weld
- To verify post-MSIP OD surface profile satisfies inspection acceptability

QUALIFICATION PROCEDURES

- Detailed qualification procedures were developed for:
 - ◆ The MSIP tooling, calibration, testing, data recording and documentation
 - ◆ Strain gauge instrumented monitoring of the MSIP testing, including strain gauge positioning and mounting procedures, strain gauge calibration and data recording, and documentation

MSIP TECHNOLOGY

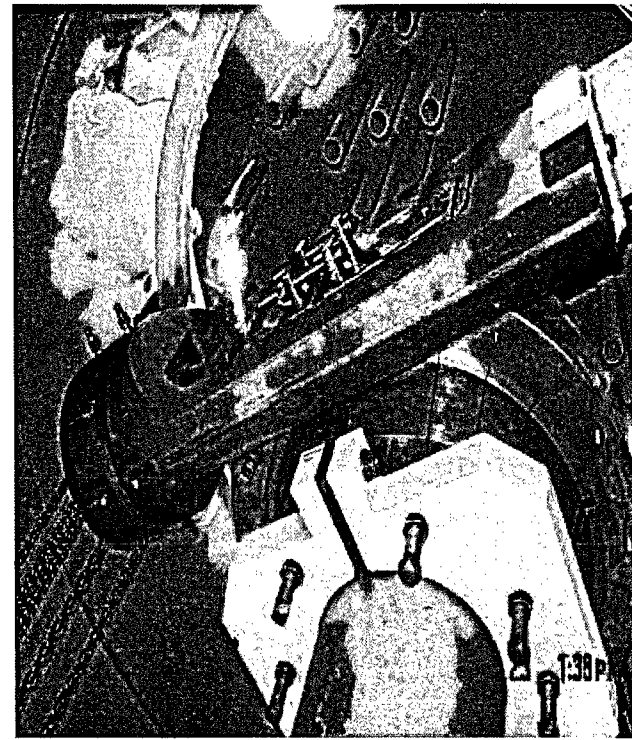
- **Patented (AEA) process that prevents/mitigates SCC in piping and nozzle weld joints**
- **MSIP**
 - ◆ Mechanically contracts the pipe on one side of weldment
 - ◆ Replaces residual tensile stresses with compressive stresses
- **Verified by Argonne National Laboratory & EPRI**
- **Accepted by the NRC (NUREG 0313, Rev. 2)**



MSIP VERIFICATION TESTS

- The MSIP loading (pipe squeezing) of the mockup nozzle weld region was accomplished by the application of hydraulic pressure through the MSIP tool clamp rings, mounted on the OD surface at predetermined positions
 - A planned sequence of two pipe squeezes were applied to obtain the desired data and accomplish the desired radial displacements and the ID surface strains
 - ◆ The maximum pressure generated by the MSIP tool was increased to obtain minimum specified contraction and generate acceptable residual stress redistribution in the nozzle-to-safe-end weld region upon unloading
 - ◆ Additional loading of the tool was applied to reach the maximum specified contraction and achieve the desired condition in the weld region following removal of the tool
 - Post-MSIP OD profile was measured
-

PRESURIZER SURGE NOZZLE MOCK-UP FOR TIHANGE 2

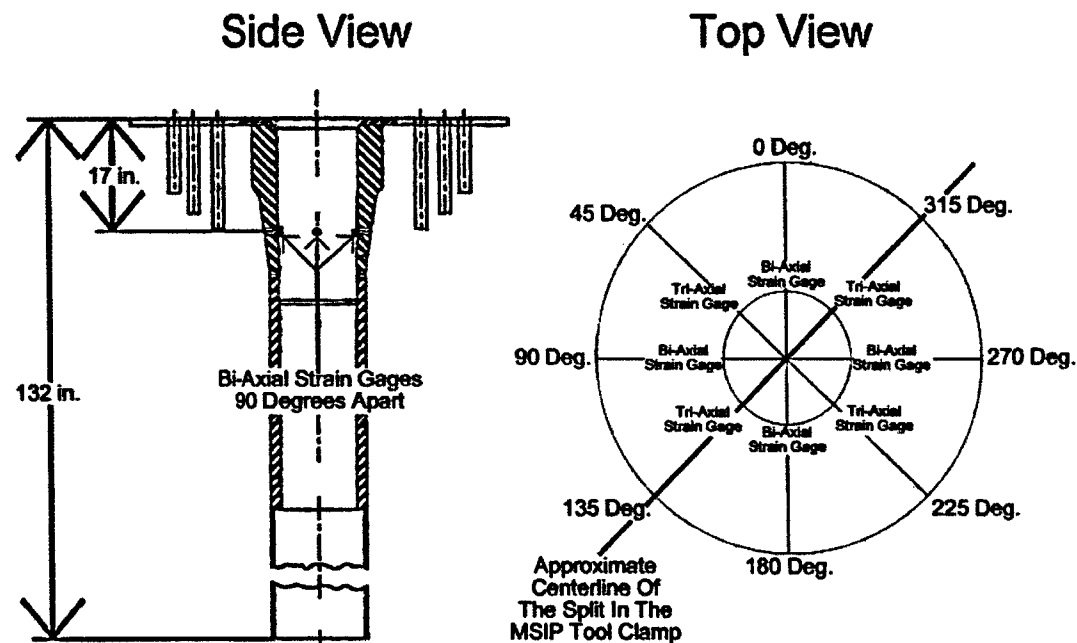


Pressurizer Surge Nozzle Mock-up for Tihange 2

STRAIN GAUGING

- ID strains at the weld were monitored by employing:
 - ◆ Single electrical resistance strain gauges applied at each of the eight measurement locations situated 45 degrees apart on the ID surface at the weld
 - ◆ Bi-axial strain gauges were applied at the 0, 90, 180 and 270 degree positions with the grids aligned in the hoop and axial directions. Strain gauge rosettes were applied to the 45, 135, 225 and 315 degree positions.

SCHEMATIC ILLUSTRATION OF POSITIONS OF BI-AXIAL AND TRI-AXIAL STRAIN GAUGES NEAR WELD REGION AT THE ID SURFACE



Schematic Illustration of the Positions of Bi-axial and Tri-axial (Rosette) Strain Gauges Near the Weld Region at the ID Surface

ILLUSTRATION OF INSTALLED STRAIN GAUGES AND STRAIN MEASURING INSTRUMENTATION AT GIRARD SITE PRIOR TO MSIP LOAD TEST



Illustration of the Installed Strain Gauges and the Strain Measuring
Instrumentation at the Girard Site, Prior to MSIP Load Test

ILLUSTRATION OF INSTRUMENTED STRAIN GAUGES INSTALLED ON ID SURFACE NEAR WELD LOCATION OF MOCK-UP PRESSURIZER NOZZLE

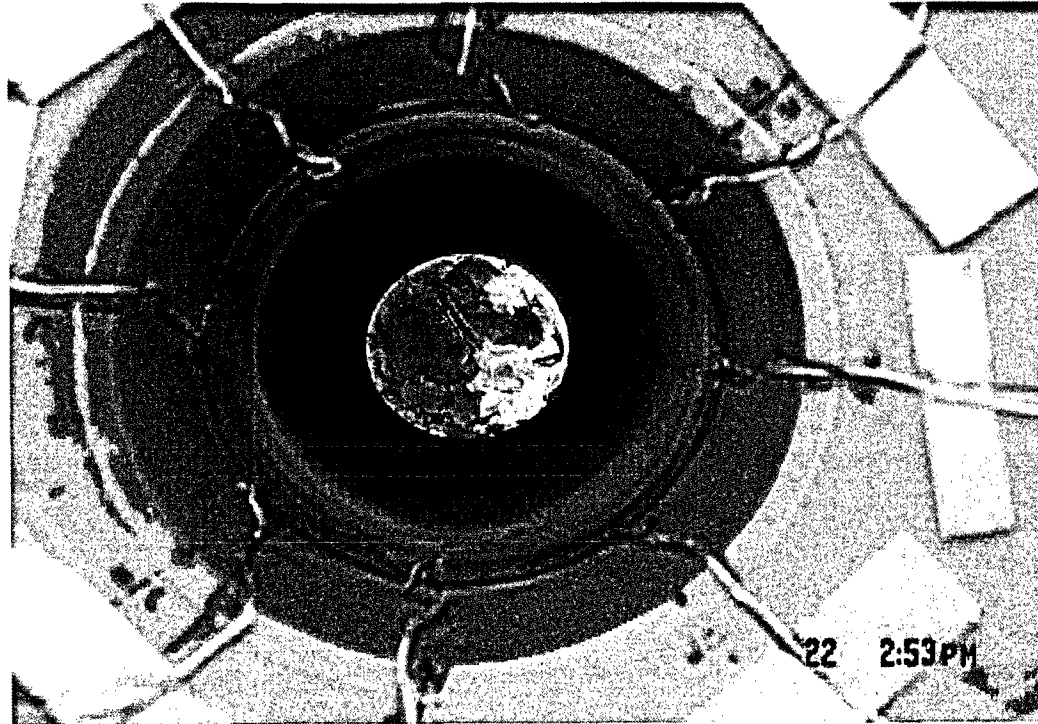
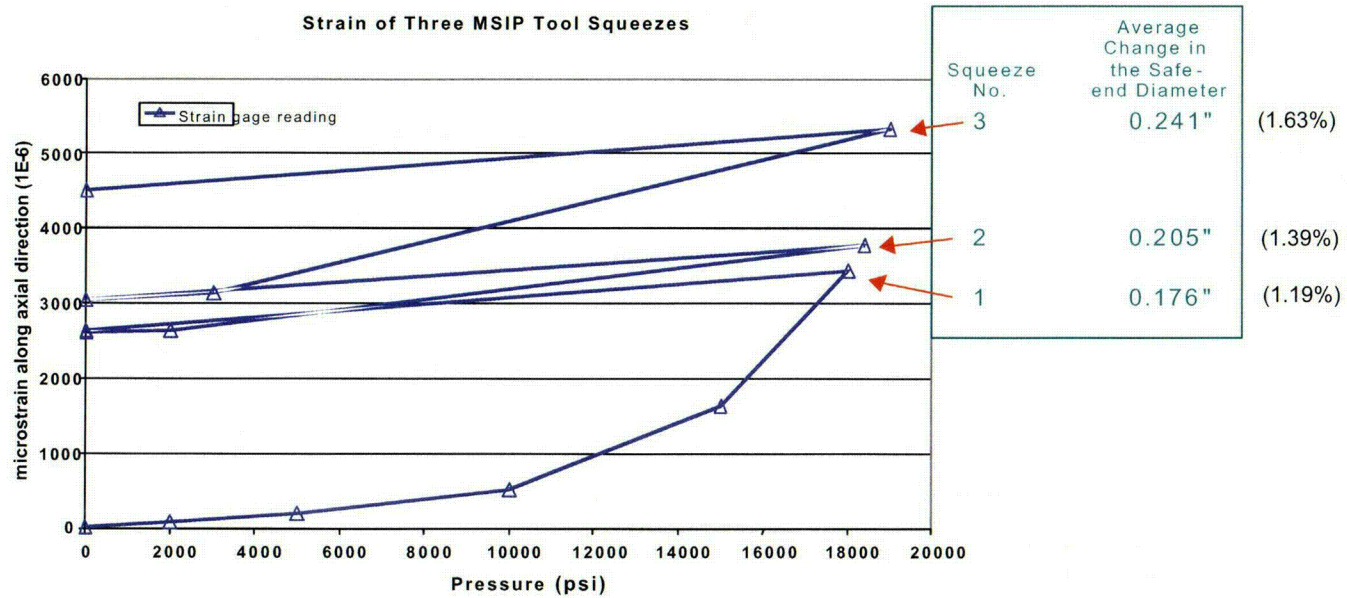


Illustration of the Instrumented Strain Gauges Installed on the ID Surface
Near the Weld Location of the Mockup Pressurizer Nozzle

STRAIN GAUGE RESULTS

- MSIP generated desired compressive strains in inner weld region
- Hoop strains were fairly axisymmetrical
- Axial strains were fairly axisymmetric except for the 135 and 270 degree positions which showed significantly higher magnitudes of compressive strain
- Compression maintained throughout MSIP application

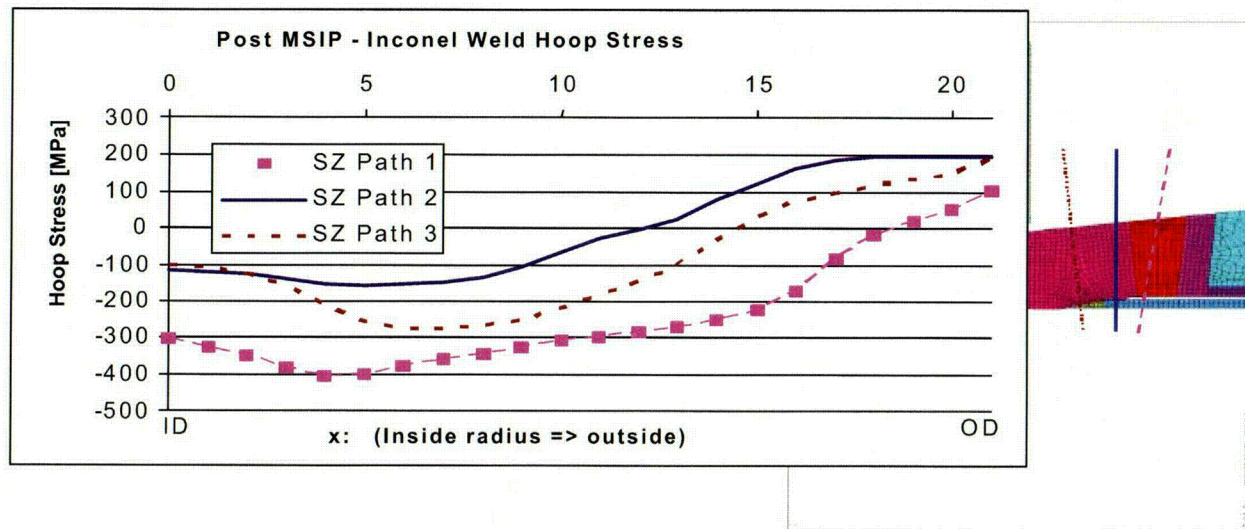
SAFE-END DIAMETER CHANGES ASSOCIATED WITH THREE MSIP SQUEEZES



Safe-end Diameter Changes Associated with the Three MSIP Squeezes

POST MSIP-THROUGH WALL HOOP STRESS

Analytical Results



Post MSIP-Through Wall Hoop Stress

CONCLUSIONS

- Tihange 2 MSIP qualification program demonstrated that the MSIP process was very effective in generating compression at the weld location
 - Demonstrated that the MSIP process works well in thick-walled PWR applications
 - Demonstrated that the post-MSIP OD profiles are acceptable for in-service inspections
 - MSIP can be an effective part of a proactive Alloy 600 mitigation program
-



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Section 7:

Session Summaries



United States Nuclear Regulatory Commission

CONFERENCE ON VESSEL HEAD PENETRATION INSPECTION, CRACKING, AND REPAIRS

Sponsored by

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Session I: Inspection Techniques, Results, and Future Developments

Chairpersons:

S. Doctor, Pacific Northwest National Laboratory

D. Jackson, U.S. Nuclear Regulatory Commission



United States Nuclear Regulatory Commission

NDE of Austenitic Materials - A Review of Progress and Challenges Frank V. Ammirato, EPRI NDE Center

- ☐ Based on recent events, presented industry's progress on addressing PWSCC
- ☐ Provided a status of development of mockups and performance demonstrations
- ☐ Highlighted advanced NDE technology to improve inspection reliability
 - UT Phased Array
 - ET Arrays

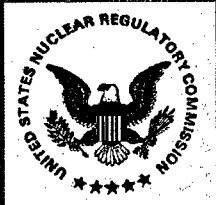


United States Nuclear Regulatory Commission

Inspection Reliability of Reactor Vessel Head Penetrations

Steven R. Doctor, PNNL

- ☐ PWSCC failure in Inconel Alloy 600\182\82 is a generic problem
- ☐ NDE programs should have goal of preventing leaks, not finding leakage
- ☐ There are a number of studies, nationally and internationally, that are addressing issues of NDE reliability
 - NRC
 - EPRI/MRP
 - JRC/Petten
 - Finland

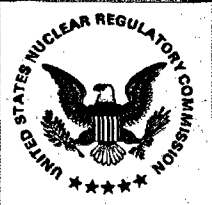


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The Evolution of Inspection and Repair Approaches for Reactor Vessel Head Penetrations

Dan M. Schlader, Framatome ANP, Inc.

- ☐ Presented overview of evolving and advanced technology to facilitate improved and faster NDE inspections, identifying VT robotic system and scanners
- ☐ Discussed remote repair methods



United States Nuclear Regulatory Commission

Inspection Techniques, Results and Future Developments, Summary of U.S. PWR Reactor Vessel Head Nozzle Inspection Results Glenn White, Dominion Engineering, Inc.

- ☐ Presented a summary of a large amount of inspection data
- ☐ Discussed findings from a statistical analysis of the inspection data
- ☐ Identified significant factors
 - Time at temperature
 - Head fabricator
 - Nozzle material supplier



United States Nuclear Regulatory Commission

Inspection Technology for In-Core Penetrations **Michael Lashley, STP Nuclear Operating Company**

- ☐ Provided an overview of the many NDE technologies that were rapidly deployed to assess the integrity of the BMI issue
- ☐ Discussed the benefit of each NDE technology for the BMI inspections



United States Nuclear Regulatory Commission

EPRI MRP Alloy 600 RPV Head Penetration Inspection Demonstration Program

C. Thomas Alley, Duke Energy Cooperation

- ☐ Reviewed industry's program (MRP) that was developed to build test specimens and to demonstrate inspection technology as new failure sites were found
 - ☐ Flaws in tubes
 - ☐ Flaws in J-groove weld
 - ☐ BMI nozzle



United States Nuclear Regulatory Commission

Production of Realistic Flaw in Alloy 600 Qualification Purposes

Mika O. Kenppainen, Trueflaw Ltd.

- ☐ Presented advanced flaw production method of representative service induced cracks
- ☐ The method is a thermal fatigue cracking process
- ☐ Provided research results of the cracking method and the applicability to alloy 600
- ☐ Flaws can be introduced into full-scale components



United States Nuclear Regulatory Commission

Generic Guidance for an Effective Boric Acid Inspection Program for Pressurized Water Reactors **T. R. Satyan Sharma, American Electric Power Co.**

- ☐ Provided information on how industry's boric acid corrosion control programs can be updated to take advantage of industry experience to better manage this degradation process
- ☐ This guidance does not apply to the reactor vessel heads which is covered under MRP-75



United States Nuclear Regulatory Commission

Risk-Informed Evaluation of PWR Reactor Vessel Head Penetration Inspection Intervals Glenn White, Dominion Engineering, Inc.

- ☐ Used risk-informed evaluation to determine ISI re-inspection frequency of the vessel head penetrations
- ☐ Re-inspection every second or third operating cycle
- ☐ Issue raised during question session regarding whether risk measures should be CDF or avoiding leakage



United States Nuclear Regulatory Commission

Reactor Vessel Head Penetration Inspection Technology, Past, Present and Future

John P. Lareau, Westinghouse Electric Co. LLC

- ☐ Describes the evolution of NDE technology for the inspection of vessel head penetration to speed up these inspections and make them more reliable
 - ☐ UT
 - ☐ ET
 - ☐ J-groove weld scanner



United States Nuclear Regulatory Commission

Summary

- ☐ PWSCC and Inconel is a complex problem
- ☐ Generic to the entire industry
- ☐ Rapid evolution of NDE technology and systems
- ☐ Reactionary response to events as opposed to a proactive comprehensive program
- ☐ Progress is being made but additional work is still required to address the issue of NDE reliability for VHP

CONFERENCE ON VESSEL HEAD PENETRATION INSPECTION, CRACKING, AND REPAIRS

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Session II: Continued Plant Operation

Chairpersons: A. Hiser, Jr., U.S. Nuclear Regulatory Commission
 W. Bamford, Westinghouse Electric Company, LLC

Continued Plant Operation

- These were the best presentations of the meeting!
- Analytical and Repair Approaches to allow continued operation
- Also actual application at South Texas

Evaluation Methods

- Now developed for upper head penetrations
- To appear in 2004 edition of Sect. XI, and also a code case
- NRC has endorsed this methodology in a letter of April 2003

French Maintenance Strategy

- ☐ Excellent Summary
- ☐ French programs are strongly proactive

Strategic Planning for Operation after Repair or Mitigation

- A methodology was developed to compare various options for VHP
- Comparison included repair costs, down time, and is based on net present value
- Optimum Solution was head temperature reduction
- The next best solution was NDE every other outage, with BMV every outage

South Texas BMI Issue

- Excellent summary of the incident, and utility response to it
- STP had help and advice from a number of other utilities
- Repair is now complete, and the plant is back at power
- The evaluation of the boat sample showed that the cracking started in the Weld (in the considered opinion of the author)
 - ▶ large lack of fusion area
 - ▶ ductile failure of a small ligament to the surface
 - ▶ water invasion of the lack of fusion
 - ▶ cracking of the BMI tube from the OD

Embedded Flaw Repair - VHP

- Originally developed in 1993
- First implemental at DC Cook 2 in 1996, and ID
- Good service experience after 6-7 years
- Technique now adapted for OD and J-groove welds
- NRC endorsed with SER in 2003

Weld Overlay on Pipe Welds

- Looked at thickness and lengths needed to establish compressive Stresses
- Similar idea to the BWR Weld overlay technique
- PWR pipes are much thicker



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CONFERENCE ON VESSEL HEAD PENETRATION INSPECTION, CRACKING, AND REPAIRS

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Session III: Structural Analysis and Fracture Mechanics Issues

Chairman: G. Wilkowski, Engineering Mechanics Corporation of Columbus



United States Nuclear Regulatory Commission

No Information Available

Session Summary

IV: Crack Growth Rate Studies for the Disposition of Flaws - total 12 presentations-

Tetsuo Shoji

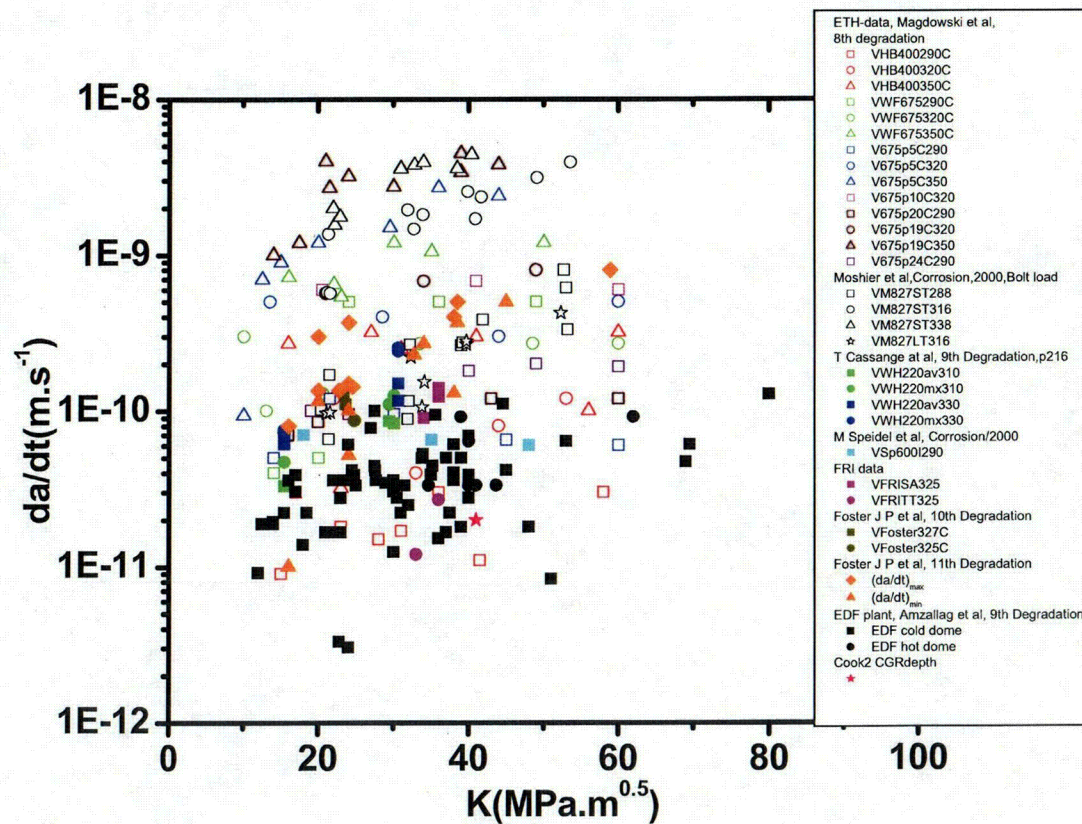
Regulatory Experience and Prognosis on Nickel-Base Alloy PWSCC in VHP and RPV Head Degradation

- Allan Hiser, Jr(NRC) gave a historical review of the axial and circumferential cracking in the US plants and NRC Bulletins and Orders.
 - Order EA-03-009-February 2003
 - Mandates inspection for all PWRs
 - Possible modifications based upon a technical basis
 - Other Consideration
 - Avoid significant events
 - Leakage from thermocouple nozzle(Alloy 690 plug and 152 weld)
 - Bulletin 2003-02:Information Request(LHP)

- Guy Turluer(IRSND/DES) presented French approach for PWSCC prevention and treatment.
 - Recognition of Generic effects - Inconel Zone Review
 - Specific features
 - French Nuclear Organizations & Practices
 - Effectiveness of Decennial Complete Visits(DCV)
 - Specific features of Nickel base Alloys PWSCC
 - Crack initiation can be stochastic processes
 - Uncertainties in stress assessment, residual stress, transients and cycling etc.
 - Proactive program to preclude any leak in the main primary circuit-no other CRDM leak after Bugey 3.
 - Regulatory hydro-test at 1.2 times the design pressure
 - Extensive ISI
 - Conservative Screening Criteria

Literature Survey

Existing CGR Data-Laboratories & Plants



CGRs of Alloy 600
in PWR environments

- Lab. data:
 - thick plate material
 - fracture mechanics specimen
- Plant data:
 - EDF & Cook 2

>Huge scatter of the
data in da/dt vs K

SCCGRs -New testing methodology

- Steven Attanasio (Lockheed Martin Co.)
 - Compliant Self-Loaded CT specimens
 - Qualified with data
- Tetsuo Shoji(Tohoku University)
 - Accelerated tests suggested from the mechanism with an clearly defined acceleration factor
 - Increase σ_y or hardness, or decrease in n , strain hardening coefficient
 - Higher dK/dt condition-specimen design or Rising Load SCC tests
 - Smaller m , slow passivation or oxide growth rate (Increase in crack tip oxidation rate constant, k_a

SCCGRs –Evaluation Procedures

- Steven Attanasio (Lockheed Martin Co.)
 - Maximum or Average SCCGR?
 - Correlation between Max./Ave. ratio(R)
 - SCCGR data can be reasonably reported as $SCCGR_{ave} + R$
- Toshio Yonezawa(MHI)
 - Examination of periodic unloading for crack tip activation
 - Effective to start crack grow but not so for straight crack front

SCCGRs

-alloys 182, 152, 132, 82, 52 comparison-

- Steven Attanasio (Lockheed Martin Co.)
 - Alloy 182 SCCGRs > Alloy 82 SCCGRs
- Toshio Yonezawa (MHI)
 - Alloy 132 SCCGRs ~ Alloy 182 SDCCGRs
 - SCCGRs in TS and LS specimens X3~10 > LT
- George Young (Lockheed Martin Co.)
 - In Alloy 600, SCCGRs in HAZ X30 >> Base plate
 - Due to loss of grain boundary Cr carbides
 - Residual local plastic strain from welding
 - DH effects is ~2.8X > base plate

SCCGRs

-alloys 182, 152, 132, 82, 52 comparison-

- Richard Jacko(WH)
 - Alloy 52M showed no crack initiation even under an aggressive and accelerated condition
 - Crack initiation occurred
 - Alloy 182 equivalent to 5-10 EFPY
 - Alloy 600 equivalent to 6-13 EFPY
 - The V.C. Summer Alloy 82 and 182 showed a similar SCCGRs to the general industry database.

SCCGRs

-alloys 182, 152, 132, 82, 52 comparison-

- Gutti Rao(WH)
 - CRDM Penetration crack at Alloy 182/82 J-Weld at Ringhals 2 and North Anna 2 originated from the original fabrication of the J-Weld buttering and lack of fusion at the Low Alloy Steel Interface is a main contribution to cracking.
 - There was a Wastage Pocket in the Low Alloy Steel at the interface

SCCGRs –DH effects

- Steven Attanasio (Lockheed Martin Co.)
 - Max. SCCGR at Ni/NiO by CER
 - X750 HTH, Alloy 600
- George Young (Lockheed Martin Co.)
 - In Alloy 600, SCCGRs in HAZ X30 >> Base plate
 - DH effects is ~2.8X > base plate
- Il Soon Hwang (Seoul National University)
 - In-situ Raman Spectroscopy system developed and successfully applied to oxide analysis in PWR
 - Ni/NiO equilibrium agreed with CER data by Attanasio et al.

SCCGRs –Temperature effects

- Yoshito Nishikawa (INSS)
 - Alloy 132(SMAW) and 82(TIG)
 - Alloy 600/132 HAZ and Alloy 600/82 HAZ
 - Accelerated SSRT
 - Activation Energy
 - 179-188 kJ/mol for weld metals
 - 148-156 kJ/mol for HAZs
- George Young(Lockheed Martin Co.)
 - In Alloy 600, SCCGRs in HAZ X30 >> Base metal
 - Activation energy for Alloy 600 HAZ ~ Base metal
 - 125 kJ/mol +_47kJ/mol for HAZ & 145+_18kJ/mol for BM

SCCGRs –Models

- Steven Attanasio (Lockheed Martin Co.)
 - Three empirical models seem reasonable($R^2=0.55$).
 - MRP without threshold, K dependence not fixed
 - MRP with threshold, K dependence not fixed
 - MRP with threshold, K dependence
- Tetsuo Shoji(Tohoku University)
 - Proposal of theoretical formulation based upon crack tip mechanics and oxidation kinetics
 - Significance of σ_y and dK/dt and other parameters
 - K dependence depends upon σ_y and m, oxidation kinetics parameter

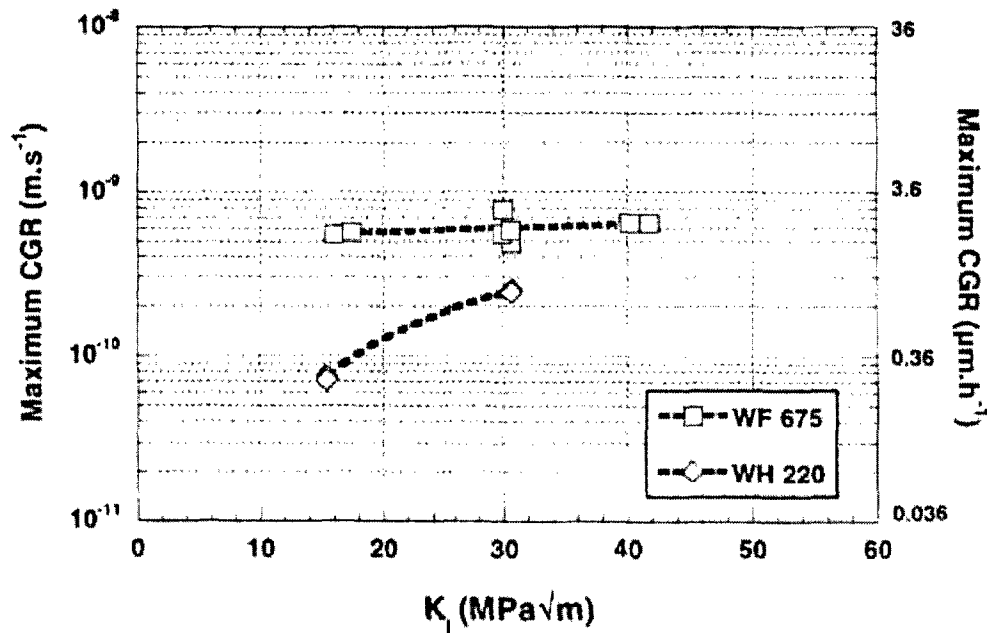
SCCGRs –Models

- Michael Hall, Jr (Bettis APL)
 - Hydrogen Assisted Fracture Model
 - Describe a sensitivities of Alloy 600 to K, T, C% and σ_y
 - Suggesting a comprehensive data sets obtained on single heats of Alloy 600 required
 - Important dependence of CGR on crack growth orientation

SCCGRs –Models

- Martin Pattison(MetaHeuristics LLC)
 - Data analysis by an Artificial Neural Network
 - Relative Effect of Variables
 - Temperature(factor of 3)
 - Lithium concentration(factor of 10)
 - Applied stress intensity factor, K(factor 10~300)
 - Yield strength(factor 30)
 - CGR was much more sensitive to K for the specimens with a low yield strength(Agree with FRI model)

Different K dependence



T. Cassagne, et al
9th Degradation,
PWR, 330°C

Two types of CGR-K curves

- WF 675, CGR plateau, $YS(\text{WF675}) = 468\text{MPa}$
- WH 220, moderate increase of CGR with K, $YS(\text{WH220}) = 394\text{MPa}$

SCCGRs –Lifetime Prediction

- Tetsuo Shoji(Tohoku University)
 - Possible crack growth retardation under the condition of negative dK/dt , which might be relevant in crack growth under compressive residual stress field
- George Young(Lockheed Martin Co.)
 - Need to consider PWSCC of the HAZ separately from the base metal and weld metal
 - Other Nickel-base alloys which rely on grain boundary Cr-rich precipitates for PWSCC resistance(e.g.A690) may show increased susceptibility to PWSCC in the HAZ

SCCGRs –Lifetime Prediction

- Il Soon Hwang(Seoul National University)
 - Fluctuation of DH in PWR may weaken oxide integrity and accelerate PWSCC
 - Stabilize and/or lower DH may provide a mitigation in PWSCC

Summary

- **Hardening is harmful not only initiation but also in propagation**
 - Surface finish, fabrication strain, weld strain, weld shrinkage strain etc.
 - No data on resistant materials such as Alloy690, 52 etc
- **Resistant microstructure might be altered in HAZ and may show a susceptibility**

- **Need qualified acceleration tests with a quantitative acceleration factor**
 - Data on resistant materials
 - Easy to back calculate the SCCGRs for realistic condition and plant application
 - Need qualification by Regulatory Authorities
- **Physical or Mechano-chemical models provide a tool for sorting out complex crack growth characteristics and provide a basis for development of higher confidence Disposition Curves of Flaws.**



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CONFERENCE ON VESSEL HEAD PENETRATION INSPECTION, CRACKING, AND REPAIRS

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Session V: Mitigation of Nickel-base Alloy Degradation and Foreign Experience

Chairmen:

**S. Fyitch, Framatome ANP, USA
P. Scott, Framatome ANP, France**



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Foreign Experience

- ☐ Belgian Activities on Alloys 600 and 182 Issues
R. Gérard and Ph. Daoust, Tractebel Engineering, Brussels, Belgium
- ☐ German Experience with Vessel Head Penetrations
K. Degmayr, Framatome ANP, Erlangen, Germany
- ☐ Activities on Alloy 600 Cracking of PWRs in Japan
M. Toyoda, S. Asada, and N. Hori, Kobe Shipyard and Machinery Works, Mitsubishi Heavy Industries, Ltd, Japan
- ☐ RPV Heads: Inspection vs. Exchange Strategies for Ringhals PWR Units 3 and 4
P. Efsing, Ringhals AB, Sweden



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Session V: Foreign Experience Summary

- ❑ Proactive approach being taken at Belgium reactors to inspect all Alloy 600/182/82 locations and repair, mitigate, or replace components as needed before leakage occurs
- ❑ German RPV heads
 - Obrigheim only RPV head with Alloy 600 nozzles; stress relieved with RPV head; expected to have low susceptibility
 - All other RPV heads contain different design with carbon steel nozzles clad with Nb-stabilized SS
 - Leak detection systems in place to identify any leakage should it occur

[Note: French experience and approach summarized in Session IV]



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Session V: Foreign Experience Summary

- ❑ **Japanese RPV Alloy 600 activities:**
 - RPV head nozzles: inspections performed on 17 plants; T_{cold} conversion performed on newer plants; older plants replaced RPV head
 - BMI nozzles: inspections performed on 6 plants; minor indication found at Takahama #1 (to be inspected again); WJP performed on 5 plants
 - Hot leg nozzle welds: inspections performed on 5 plants; use of WJP or Alloy 690 cladding (under development)
- ❑ **Ringhals RPV Head Activities:**
 - Inspections performed; some indications identified; defect tolerance evaluated; conclusion: replace RPV heads



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Session V: Mitigation of Nickel-base Alloy Degradation Summary

- ☐ Alloy 600 PWSCC Mitigation: Past, Present, and Future
S. Fyitch, Framatome ANP, Inc., Lynchburg, VA
- ☐ A Reactor Vessel UPPER Head Temperature Reduction Program to Prevent and Mitigate Alloy 600 Cracking
D. R. Forsyth and P. L. Strauch, Westinghouse Electric Company LLC
- ☐ Status Report on the Effect of Zinc Additions on Mitigation of PWSCC in Alloy 600
J. Hickling, R. Pathania and C. Wood, EPRI, Palo Alto, CA
- ☐ An Assessment of MSIP as a PWSCC Mitigative Technique by Instrumented Monitoring of ID Strains During the Full Scale Mock Up Demonstration Test of Pressurizer Nozzle Weld at Tihange Unit 2 Station
G. Rao, Westinghouse Electric Company, Pittsburgh, PA



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Summary Mitigation of Nickel-base Alloy Degradation

- ❑ Replacement with Alloys 690/52/152 mostly used today
- ❑ Three categories of mitigation techniques: mechanical surface enhancement (MSE), environmental barriers or coatings, and chemical or corrosion potential (ECP) control
- ❑ Very geometry dependent, many techniques not effective if cracking present, utilities need to evaluate a variety of techniques, one is rarely applicable to all locations, cost-benefit analyses need to be performed, most techniques require further developmental efforts



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Summary Mitigation of Nickel-base Alloy Degradation

- ❑ Many cold head design plants in operation in W-fleet (30); upper head temperature reduction performed at three additional; two others planned
 - Benefits: reduced accumulation rate of EDY and possibly number of required inspections; reduced risk of cracking; increases peak clad temperature margin; slightly increases RCS flow and increases SG tube plugging margin; early implementation may extend life into license renewal



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Summary Mitigation of Nickel-base Alloy Degradation

☐ Zinc additions:

- Favorable experience with zinc controlling radiation fields
- Field tests in USA to evaluate long term effects on mitigating PWR radiation fields, evaluating effect on PWSCC, and ensuring no adverse effect on fuel or other components
- Mitigation of radiation fields demonstrated
- Worthwhile favorable influence on lab PWSCC initiation times
- PWSCC lab data on CGR in fracture mechanics specimens is less conclusive; field data ambiguous
- No adverse effects observed on fuel cladding corrosion but need to resolve potential issues associated with high duty plants

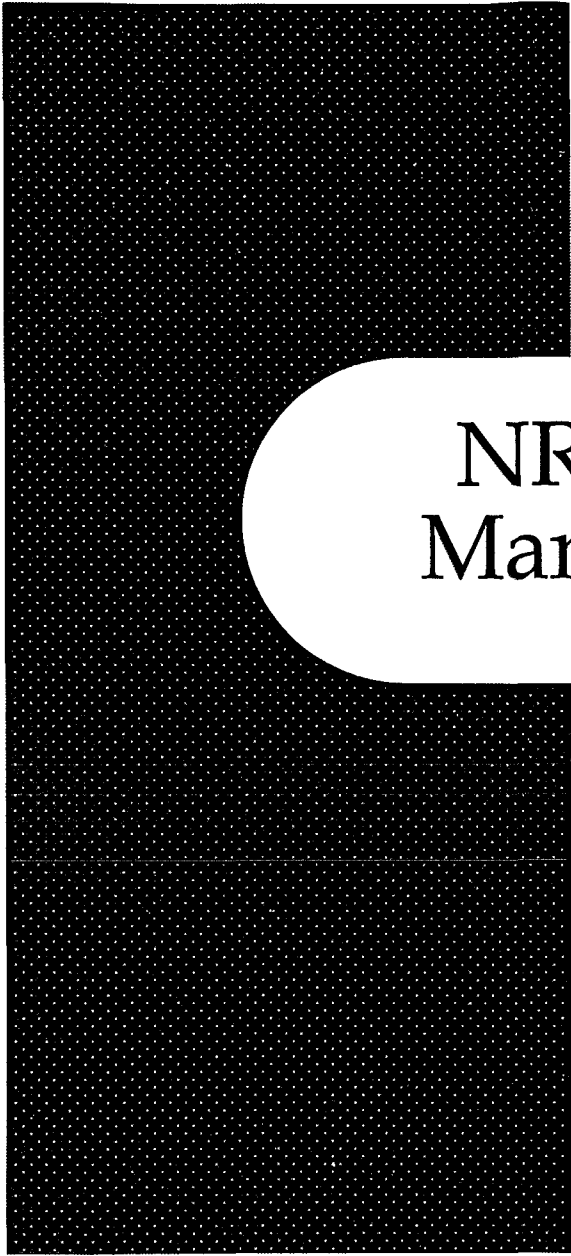


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Summary Mitigation of Nickel-base Alloy Degradation

- ☐ Program performed to confirm applicability of MSIP to thick wall PWR piping, verify analysis and inspectability
- ☐ Qualification testing with mockup of Tihange 2 pressurizer surge line nozzle
- ☐ MSIP generated required compressive strains in inner weld region
- ☐ Post MSIP profiles were acceptable for in-service inspections
- ☐ MSIP can be a potential part of a proactive Alloy 600 mitigation program

Section 8: Panel Discussion



NRC Perspective on the Management of Materials Degradation



Dr. Richard Barrett, Director
Division of Engineering
Office of Nuclear Reactor Regulation
Nuclear Regulatory Commission
October 2, 2003

ALLOY 600 ISSUES

- Cracking frequently identified and repaired in pressurizer heater sleeves and instrument nozzles
- Hot leg weld cracking – V.C. Summer
- Upper head nozzle cracking – ANO, Oconee, etc.
- Upper head wastage – Davis-Besse
- Lower head nozzle cracking – South Texas Unit 1



October 2, 2003

RECENT NRC ACTIONS

- **Bulletin 2001-01: Upper head inspections for high-susceptibility plants**
- **Bulletin 2002-01: Adequacy of boric acid corrosion control programs**
- **Bulletin 2002-02: Bare metal visual and non-destructive examinations of upper heads**
- **NRC Order EA-03-009**
- **Bulletin 2003-02: Lower vessel head inspections**



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FUTURE NRC NEEDS

- **More complete and realistic technical basis for inspections and repairs**
 - ◆ **Crack initiation and growth rates**
 - ◆ **Susceptibility models**
 - ◆ **Alloy 600 and 690**
- **Continued progress on inspection methods**
- **Regulatory requirements that accommodate materials differences, evolving technical information, and emerging inspection methods**



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SUMMARY

- Frequency and significance of materials degradation issues are growing
- Research community must continue to develop technical basis for inspections and repairs
- Industry must be prepared to provide comprehensive approaches in a timely manner
- NRC will continue in its regulatory role and will take necessary actions based on its evaluation of the available information



October 2, 2003



INTEGRATED INSPECTION MODEL FOR MANAGING MATERIALS ISSUES

- Inspection Scope
- Inspection Method
- Acceptance Criteria
- Inspection Frequency

Integrated Inspection Model (con't)

- Inspection Scope
 - How Many Components to Look at
 - How Much of Each Component to Look at
 - Expansion Criteria
 - *Based on statistical evaluations to provide the reliability necessary to maintain desired level of component reliability and an acceptable level of overall risk*

Integrated Inspection Model (con't)

- Inspection Method
 - Inspection Technology (e.g., VT, PT, ECT, UT,)
 - Technique and Personnel Qualification (Detection and Sizing)
 - *Based on performance demonstration with defined level of reliability*

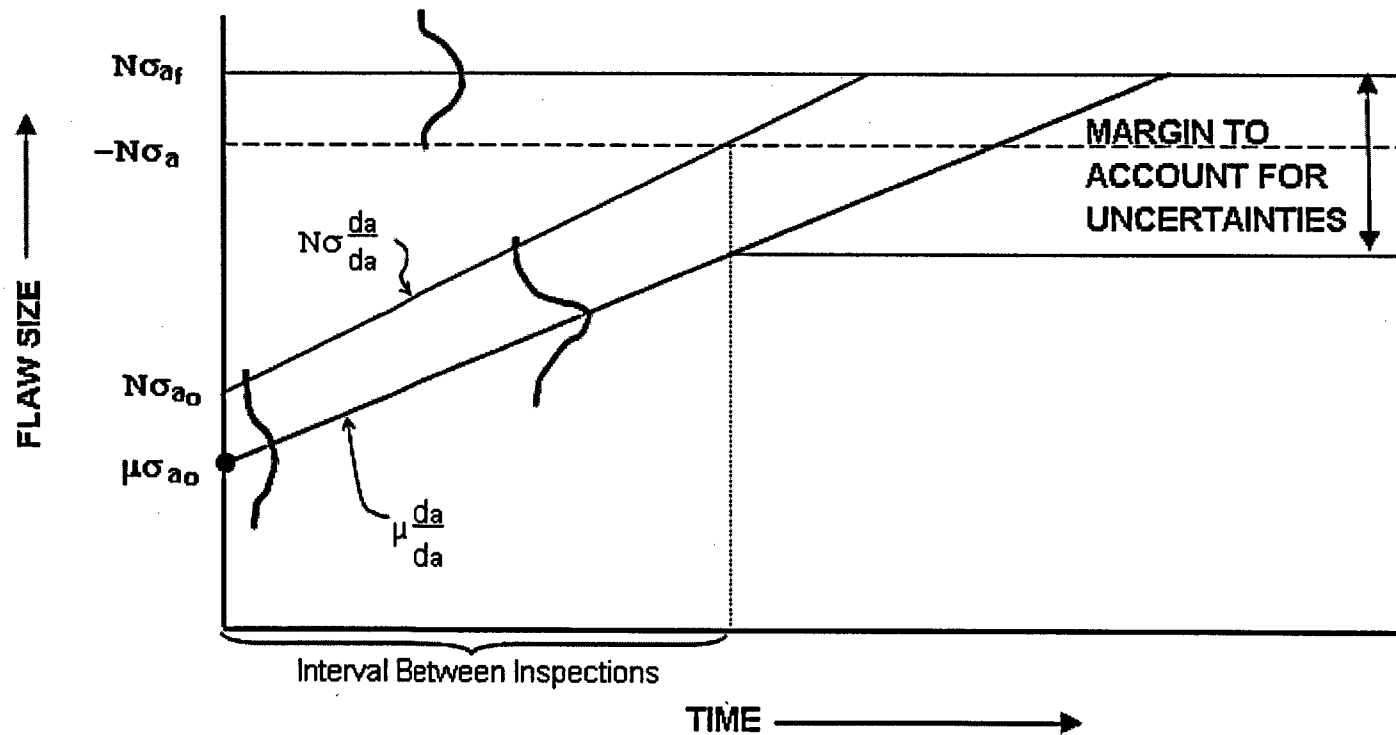
Integrated Inspection Model (con't)

- Acceptance Criteria
 - Defined Failure Point
 - Applicable Margins
 - *Margins account for uncertainties e.g., in inspection methods, degradation rates, failure criteria*

Integrated Inspection Model (con't)

- Inspection Frequency
 - Degradation Rates
 - Performance Based?
 - *Requires integration of reliability of inspection method, degradation rates and acceptance criteria to maintain desired level of component reliability*

INTEGRATED INSPECTION MODEL



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IMPORTANCE OF IMPLEMENTATION

- The Best Research and Technical Work Will Be for Naught If:
 - Results Are Not Put Into an Implementable Format (e.g., Code or Guidance Document)
 - Implementation Is Not Monitored to Ensure Effectiveness

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

NUREG/CP-0191

2. TITLE AND SUBTITLE

Proceedings of the Vessel Penetration Conference on Inspection, Crack Growth and Repair;
Volume 1: Manuscripts
Proceedings of the Vessel Penetration Conference on Inspection, Crack Growth and Repair;
Volume 2: Presentations

3. DATE REPORT PUBLISHED

MONTH

YEAR

September

2005

4. FIN OR GRANT NUMBER

5. AUTHOR(S)

Compiled and edited by T. S. Mintz and W. H. Cullen, Jr.

6. TYPE OF REPORT

Conference Proceedings

7. PERIOD COVERED (Inclusive Dates)

8. PERFORMING ORGANIZATION - NAME AND ADDRESS (If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)

Division of Engineering Technology
Office of Regulatory Research
U. S. Nuclear Regulatory Commission
Washington, DC 20555-0001

9. SPONSORING ORGANIZATION - NAME AND ADDRESS (If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)

Same as above

10. SUPPLEMENTARY NOTES

Conference held September 29 - October 2, 2003 in Gaithersburg, Maryland, USA

11. ABSTRACT (200 words or less)

These two volumes of proceedings contain the visual projections (in Volume I), and the contributed manuscripts (in Volume II) from the Conference on Vessel Head Penetration, Crack Growth and Repair, held at the Gaithersburg Marriott at Washingtonian Center on September 29 - October 2, 2003. The conference was co-sponsored by the U. S. Nuclear Regulatory Commission and Argonne National Laboratory. Over two hundred attendees were provided with 45 presentations, divided into five sessions: (I) Inspection Techniques, Results, and Future Developments, (II) Continued Plant Operation, (III) Structural Analysis and Fracture Mechanics Issues, (IV) Crack Growth Rate Studies for the Disposition of Flaws, and (V) Mitigation of Nickel-Base Alloy Degradation and Foreign Experience. The conference opened with a plenary session including presentations giving the overview from the NRC Office of Regulatory Research, and an overview of nickel-base alloy cracking issues worldwide. The conference closed with a panel session consisting of industry representatives and NRC management discussing the prognosis for future issues in this area of concern.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

Stress corrosion cracking
Non-destructive inspection
Ultrasonic inspection
Eddy Current inspection
Alloy 600
Alloy 182
Alloy 690
Alloy 152

13. AVAILABILITY STATEMENT

unlimited

14. SECURITY CLASSIFICATION

(This Page)

unclassified

(This Report)

unclassified

15. NUMBER OF PAGES

16. PRICE

NUREG/CP-0191
Vol. 2, Part 2

**PROCEEDINGS OF THE CONFERENCE ON VESSEL PENETRATION INSPECTION,
CRACK GROWTH AND REPAIR**

SEPTEMBER 2005