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

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Tractebel Engineering

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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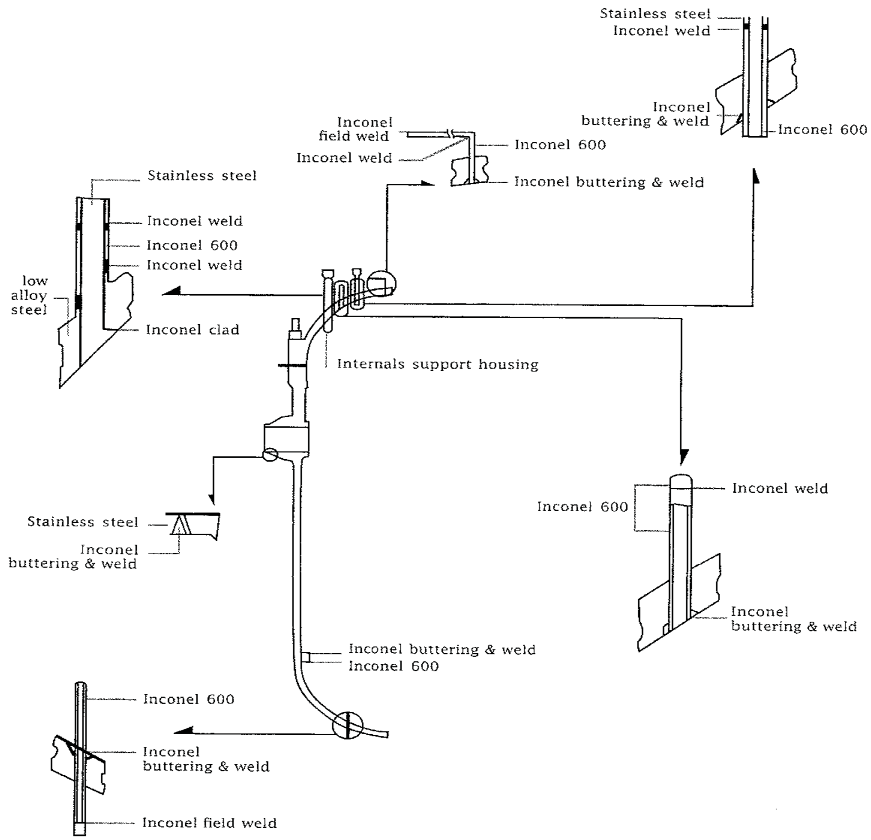
Belgian Nuclear Units operated by Electrabel

Unit	Capacity	First	NSSS
	MWe,netto	Operation	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

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

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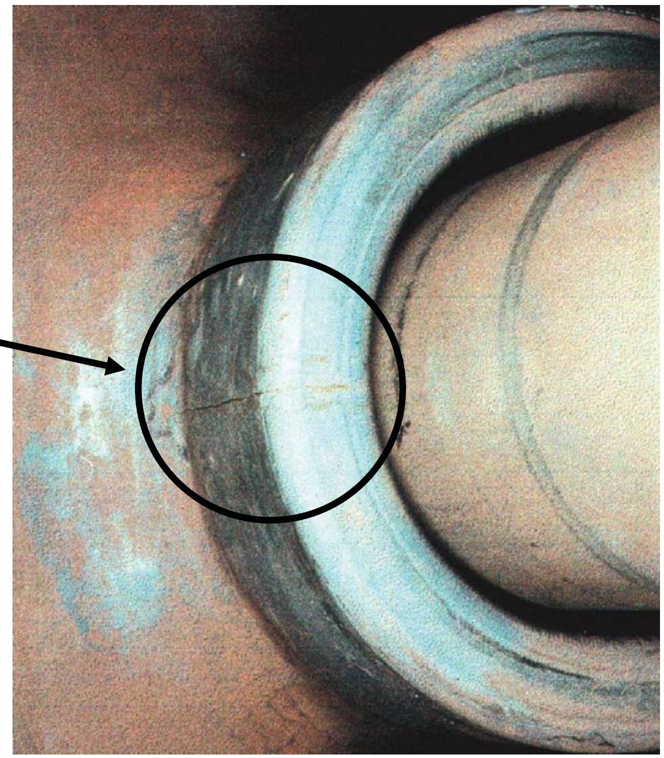
Alloy 600 – Inspection status in Belgium (2003)

Inspection date	Unit	Age*	EFP* (hours)	T° (°C)	Inspector	Inspected penetrations		Results
Head Penetrations								
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?)

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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) Tihange 1 new head	318 318	24 4

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

Bare metal visual inspections

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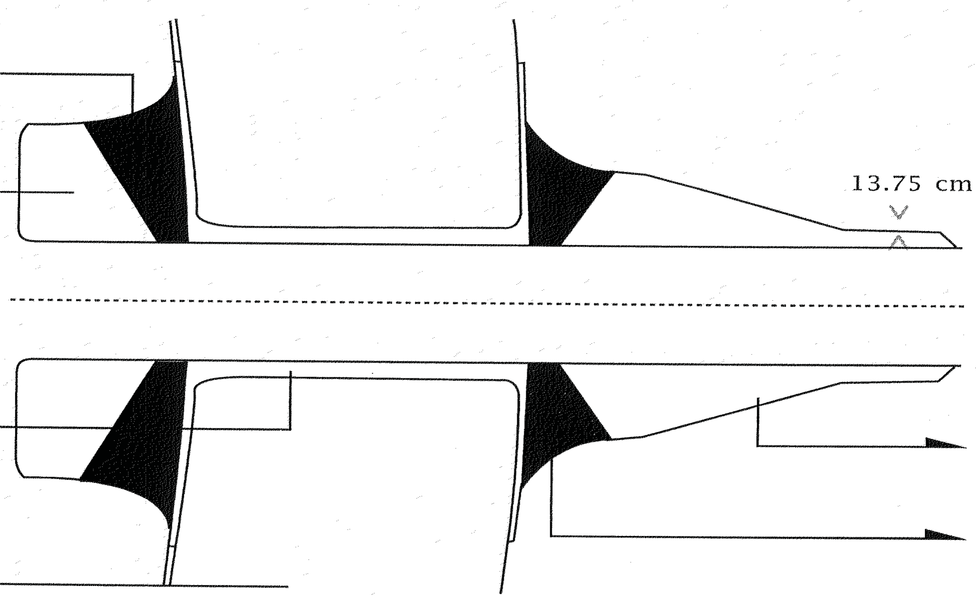
5 units inspected 2002 (some only partially)

"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

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Alloy 600/82/182 – Weld and buttering parts

Component	Part	Base material	Weld	Buttering	Cladding	Units
Pressurizer	Safe ends welds		✓	✓		D3/T2/D4/T3
Steam Generator	Partition plate	✓	✓	✓		D1/D2
	Tube	✓	✓			D1/D2
	Tubesheet				✓	D3/D4/T3
	Drain		✓	✓		D4/T3
	Nozzle safe ends welds		✓(82)			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

Component	Part	Inspection type	Result (PWSCC)
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
	SIN	Internal UT, ET	Surface indications (*)
		External PT, VT2	
Vessel Head	Penetrations	External PT, VT2	NTR
		Visual internal	NTR

(*) unknown origin

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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

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Typical safe-end weld

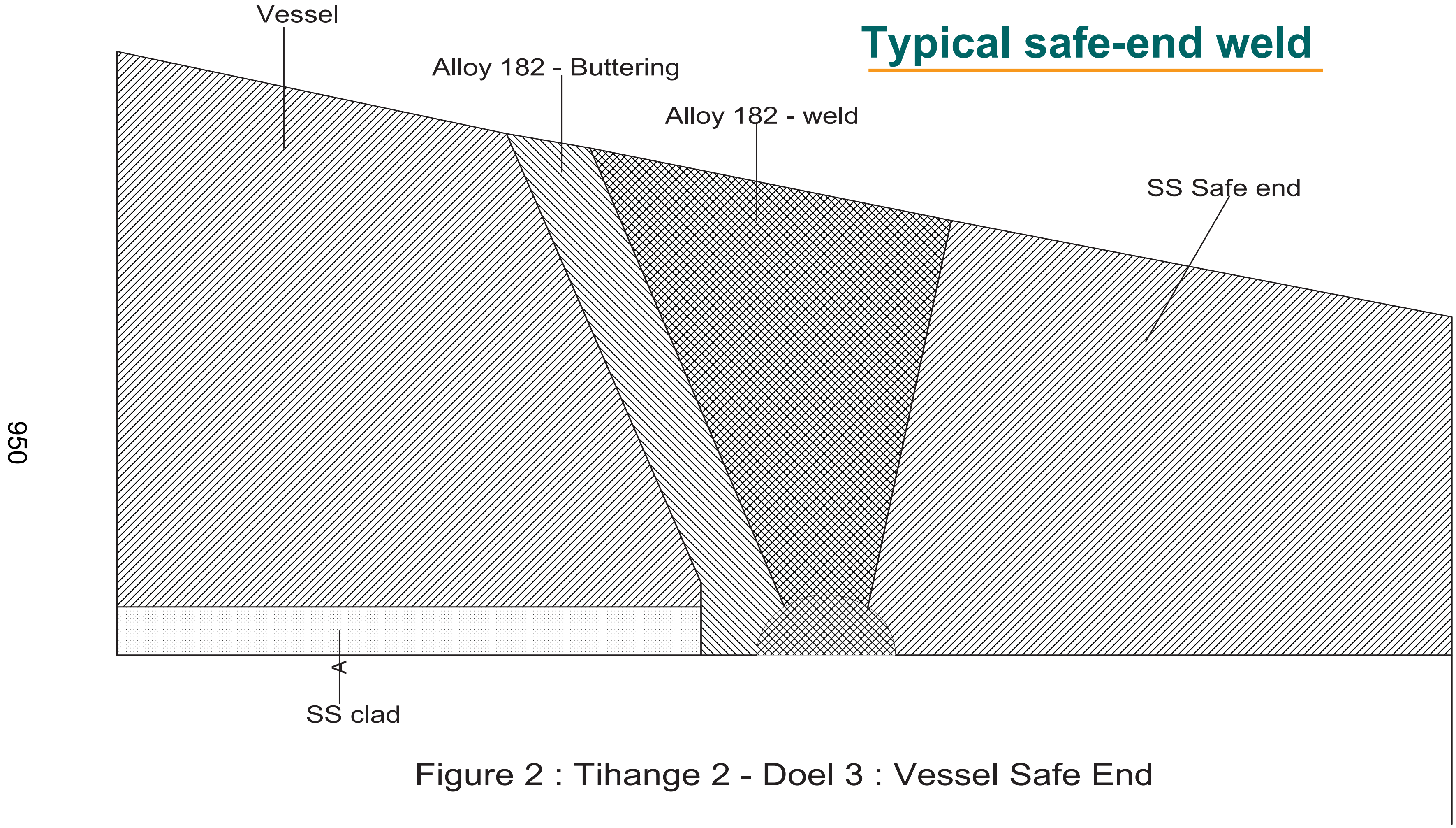

Figure 2 : Tihange 2 - Doel 3 : Vessel Safe End

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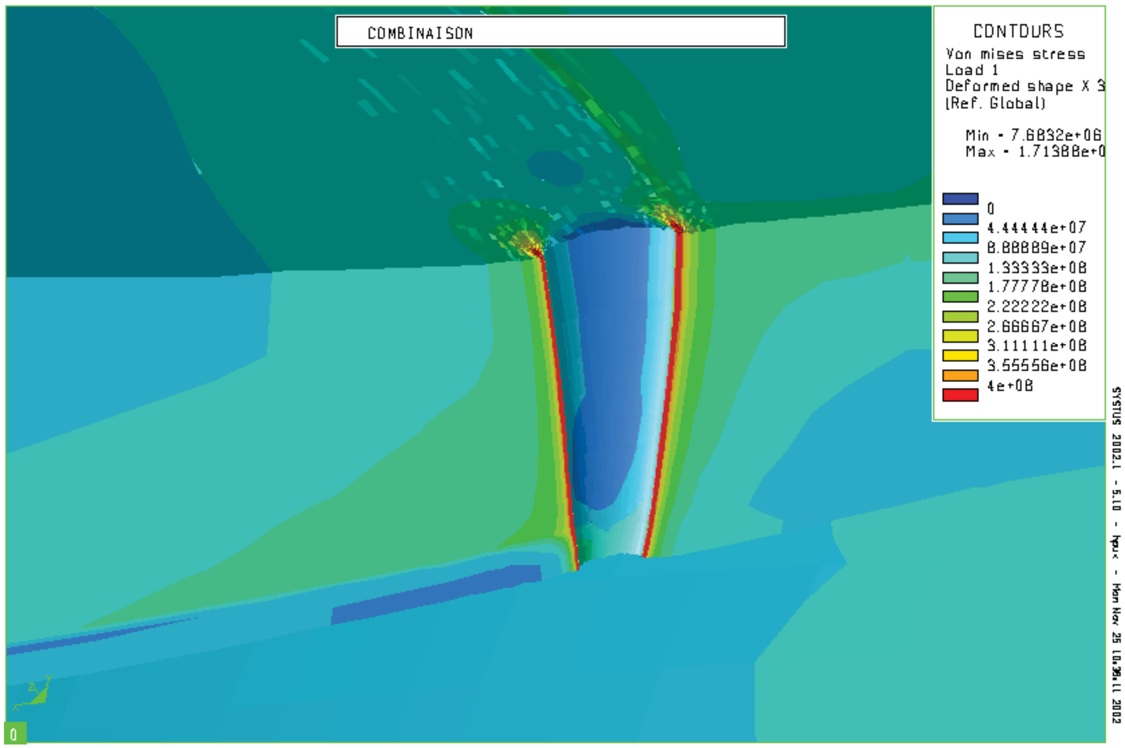
Stress and fracture mechanics analyses – RPV outlet

- 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.

Through-wall defect analysis in RPV inlet nozzle (weld repaired in fabrication after stress relief in one unit)



Crack stable with margins

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

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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)

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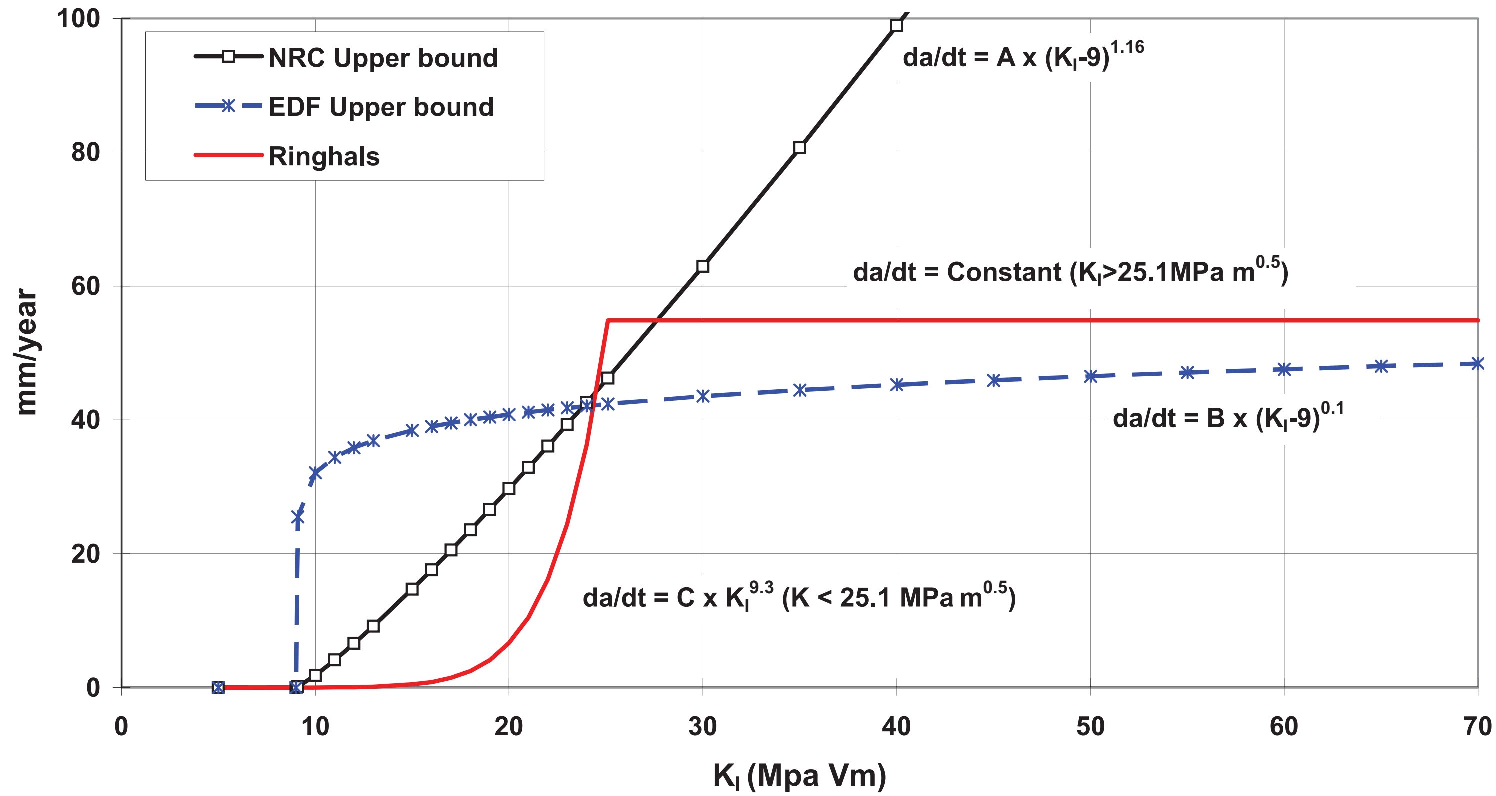
Crack growth rates - Inconel 182 at 345°C (Arrhenius with Q=130 kJ/mole)



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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

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

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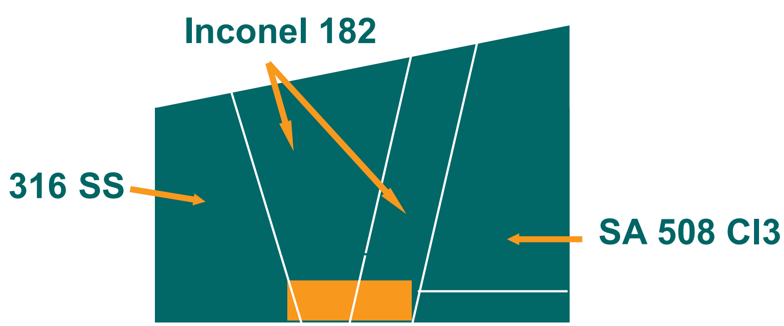

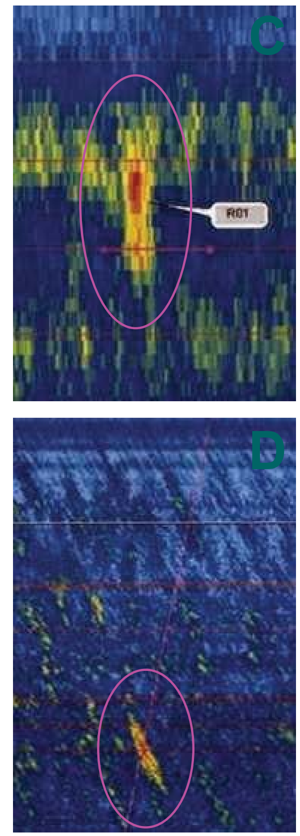

- Axial indication
- Close to fabrication repair
- Could be exposed to primary water
- Flaw dimension ≈ 4 x 26 mm

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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

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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

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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

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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.

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

FRAMATOME ANP

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

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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
Biblis A	GER	1974	1204/ 1146
Biblis B	GER	1976	1300 / 1240
Neckar 1	GER	1976	840 / 785
Unterweser	GER	1978	1300 / 1230
Grafenrheinfeld	GER	1981	1300 / 1235
Grohnde	GER	1984	1395 / 1325
Philippsburg 2	GER	1984	1349 / 1268
Brokdorf	GER	1986	1395 / 1326
Isar 2	GER	1988	1400 / 1320
Emsland	GER	1988	1341 / 1270
Neckar 2	GER	1989	1360 / 1225
Borssele	NL	1973	481 / 449
Atucha 1	ARG	1974	357 / 335
Gösgen	CH	1979	1020 / 970
Trillo	ES	1988	1066 / 1000
Angra 2	BRA	2000	1309 / 1229

KWO Operating Data

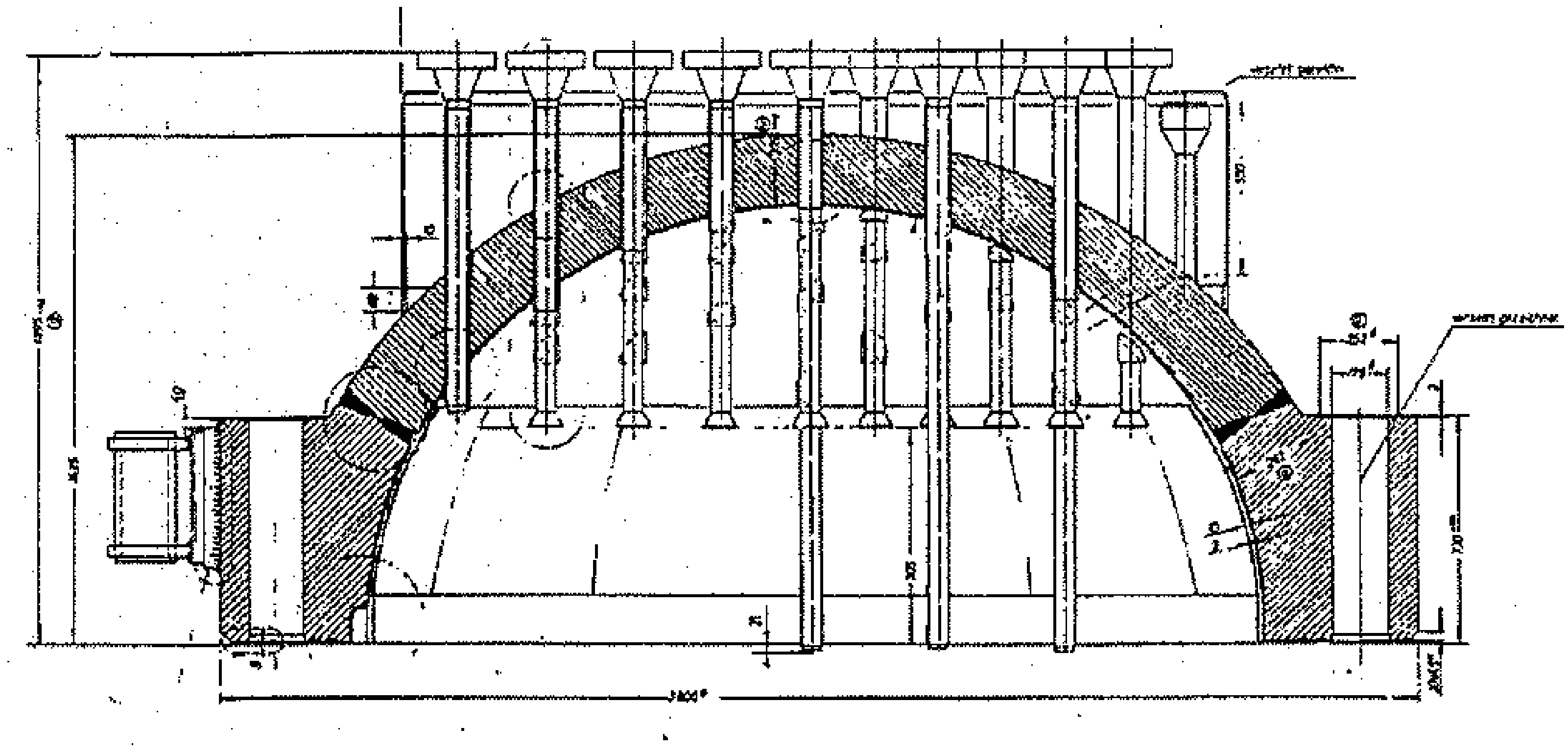
> Operation Time until 2003: approx. 240,000 hours

> Pressure: approx. 145 bar

> Operation Temperature

RPV inlet	279 º C
RPV outlet	308.5 º C
upper plenum	306.8 º C
head outside	282,2 º C
nozzle weld inside	284 – 295 º C

The NPP Obrigheim RPV Head Design



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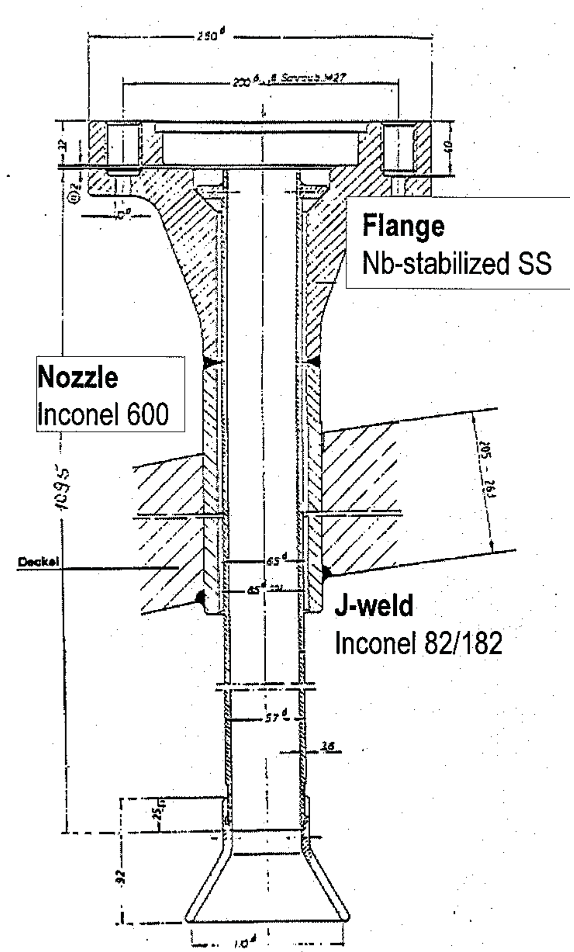
Design of Penetration Nozzle



> 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 º C ≥ 10 hours

Characteristic Features of the Obrigheim Design (2)

> Manufacturing
- seamless pipe, hot formed
- solution annealing: 1000 – 1050 º C
- roughness: outside max. 5 µm
  inside max. 80 µm

> Chem. composion: 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 condidered 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 pentrations 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 cosure 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
■ condesate measurement in air circulation cooler	from approx. 10 l/h
■ termperature 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

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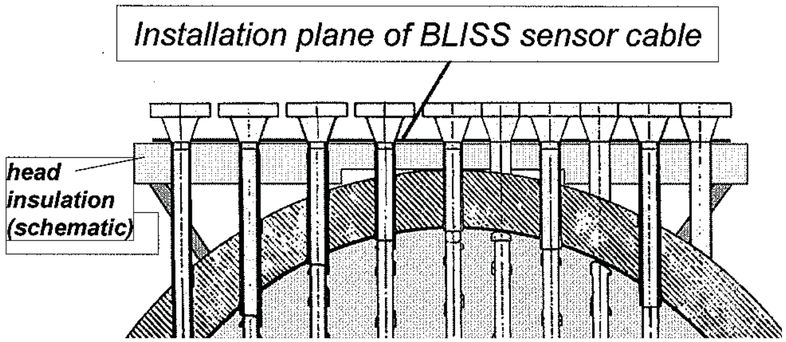
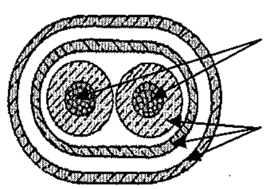
Local Leakage Detection BLISS

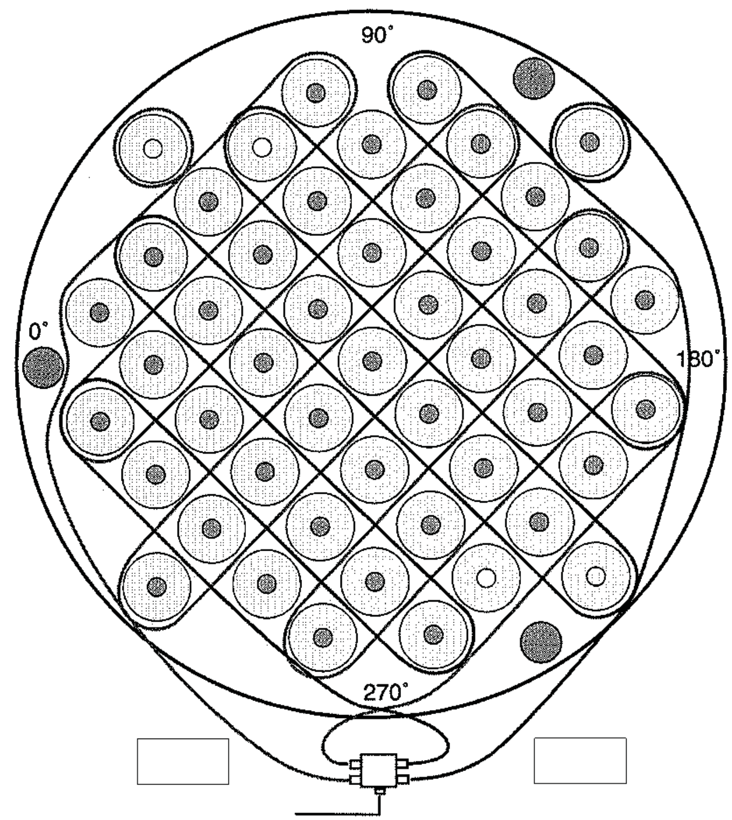


Leakage detection system BLISS in area of penetration flange, monitoring of flange connection YA01 M001 (sensor-cable)



cable cross section

Bartec Leakage Indication Sensor System



source: KWO

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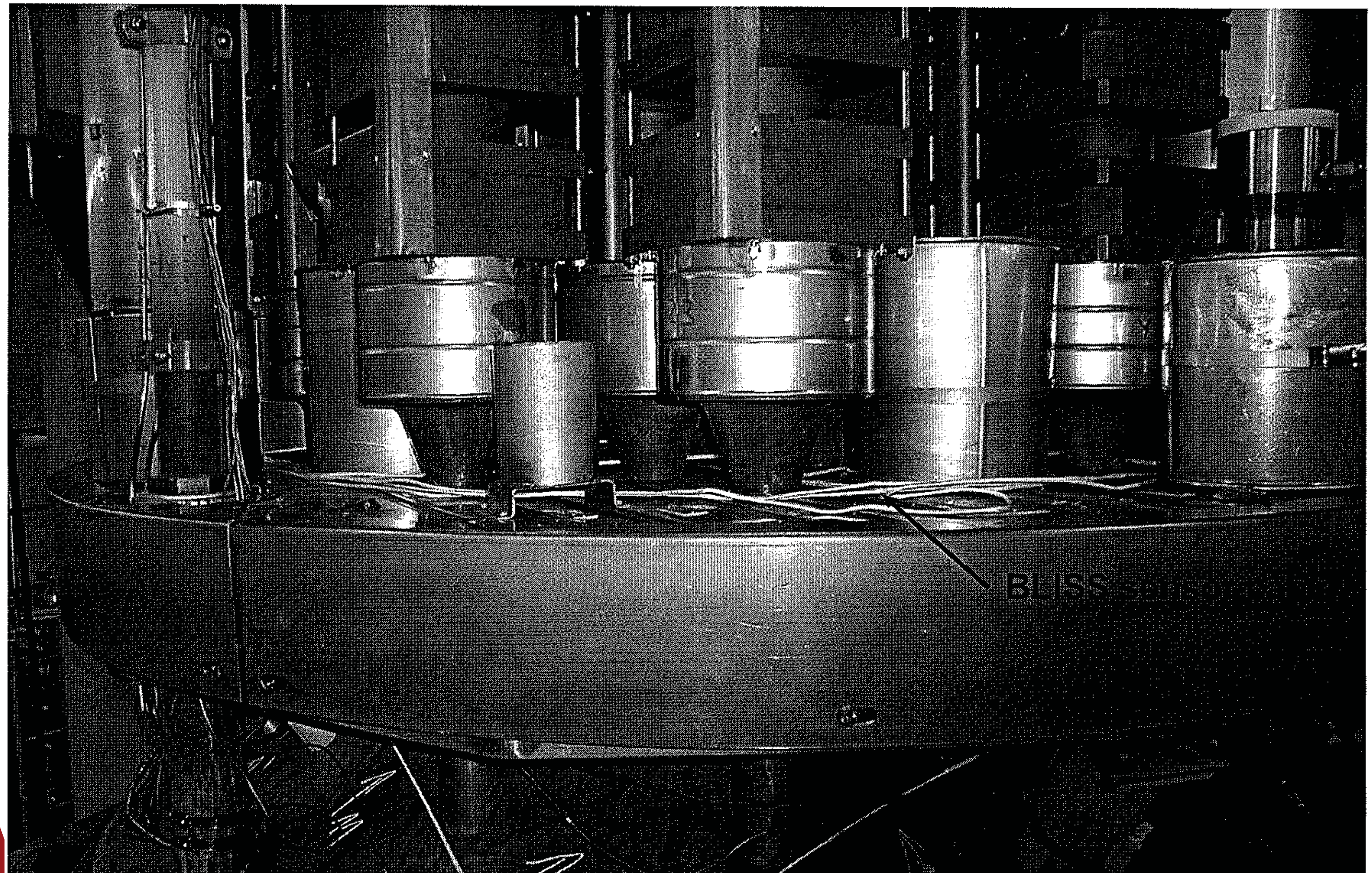
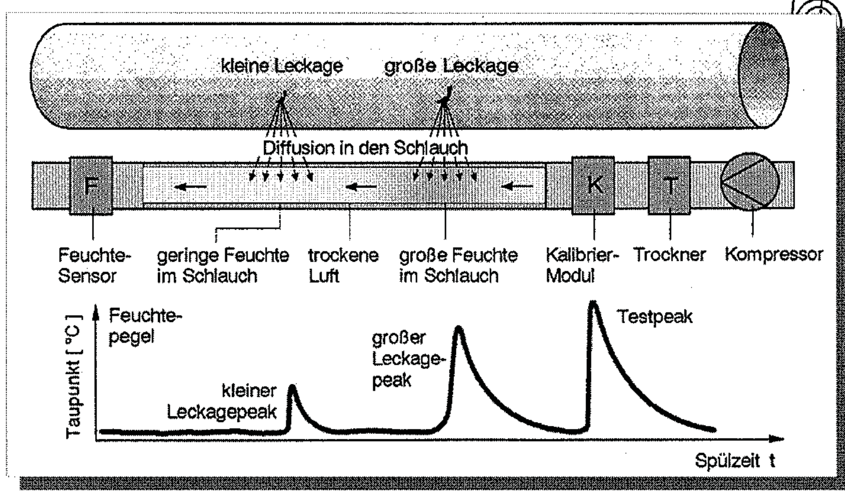
Visual Inspection of RPV Closure Head during Revision in 2002

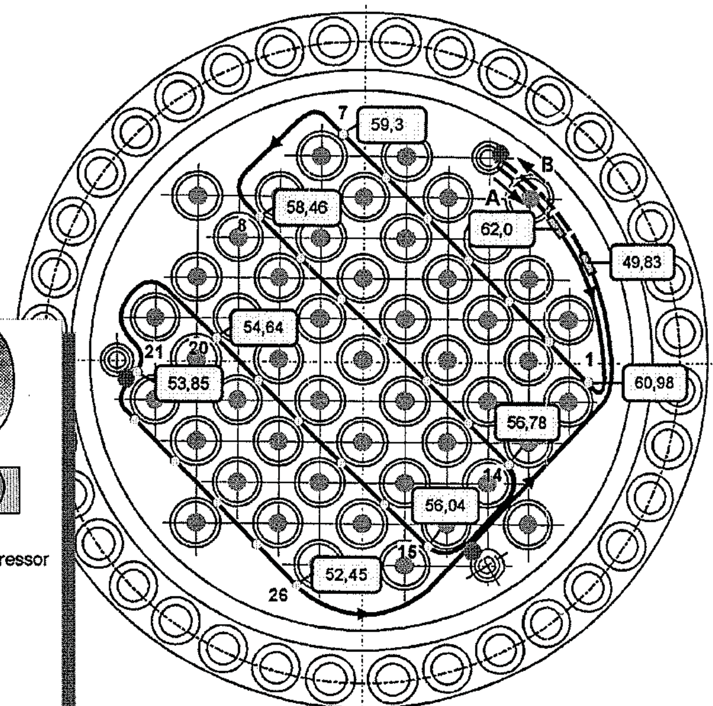


source: KWO

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

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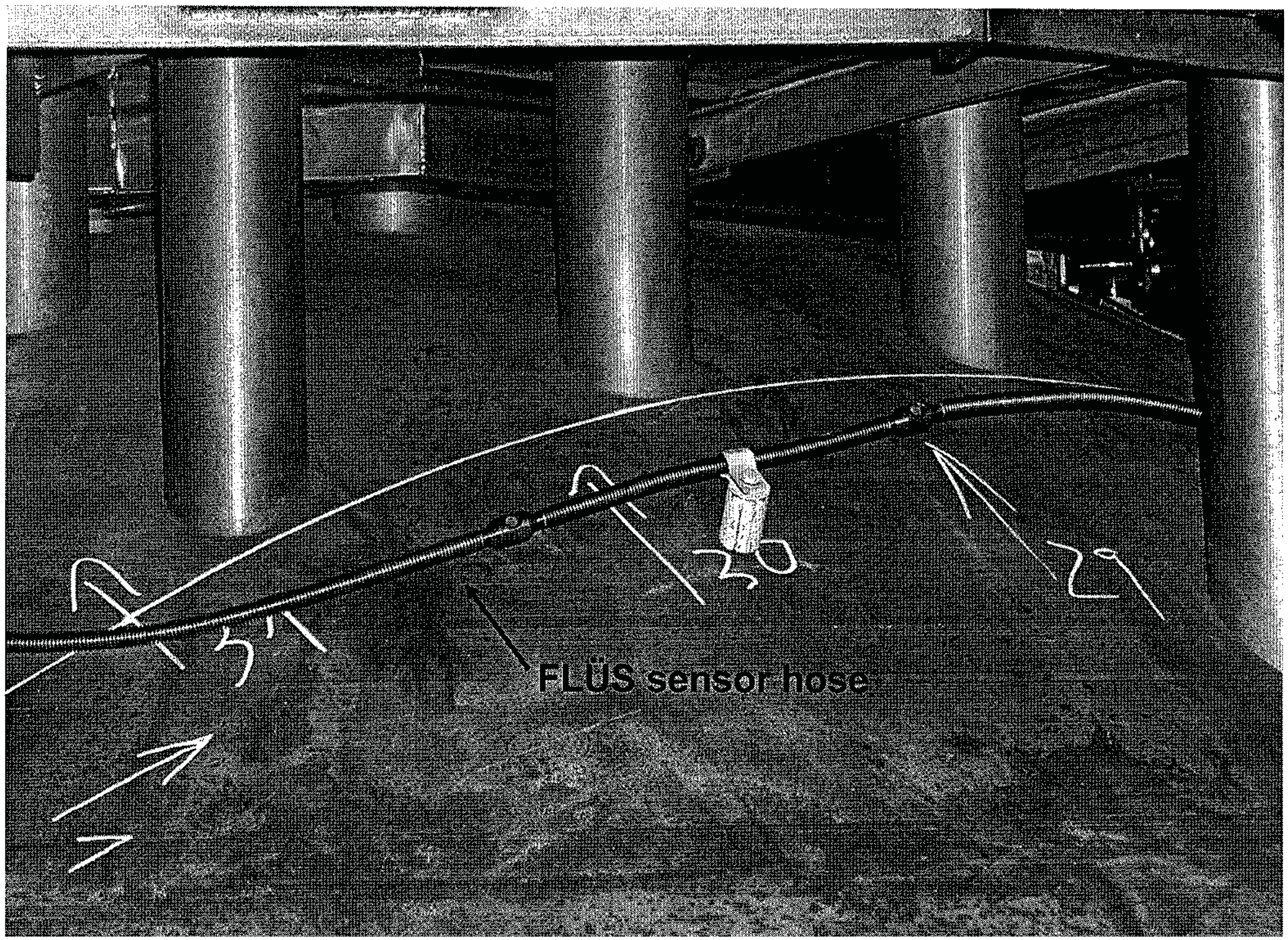
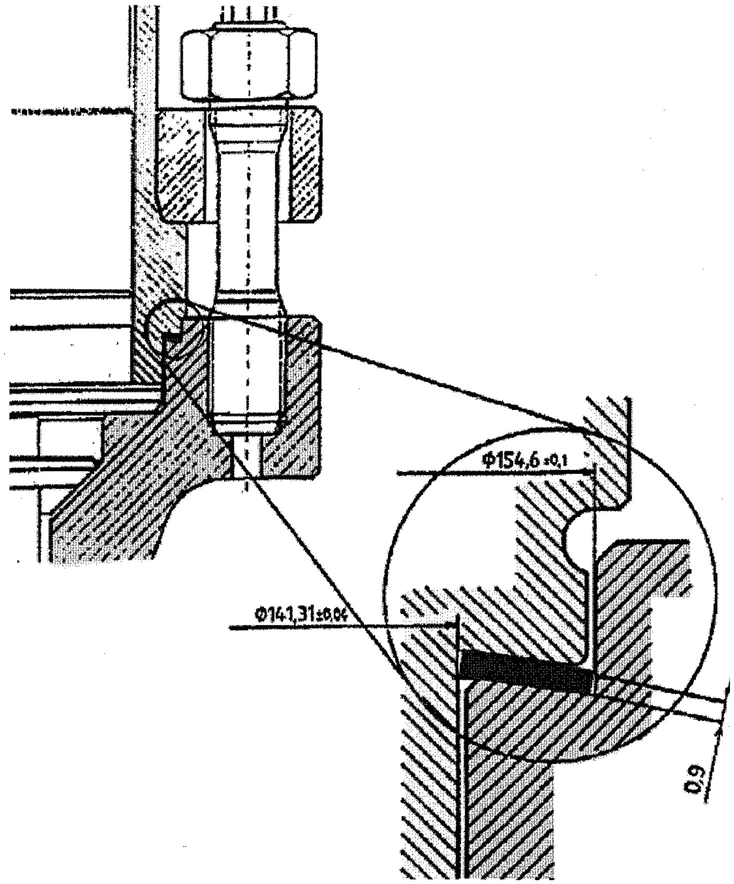
Visual Inspection of RPV Closure Head during Revision in 2002



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:*

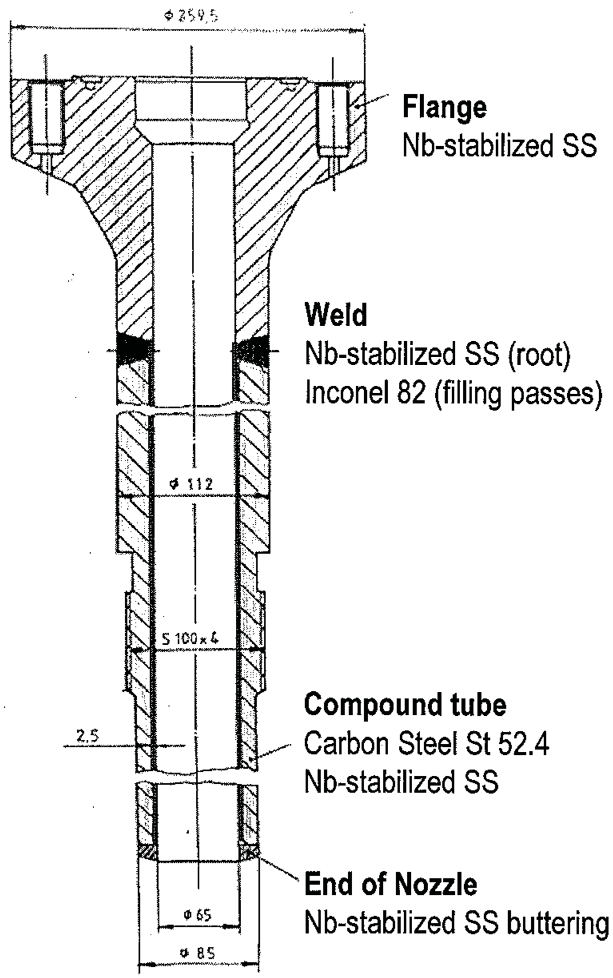
- *heat treatment history of head penetration material included a solution and stress relief annealing resulting in a low level of residual stresses and minor susceptible microstructure*
- *good access allowing regular visual and comprehensive non-destructive inspections*
- *sensitive leakage detection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

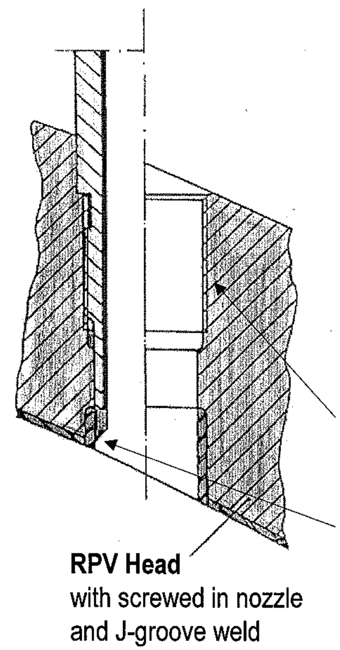
⇨ ***Cracking is not expected***

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
Biblis A	GER	1974	1204/ 1146
Biblis B	GER	1976	1300 / 1240
Neckar 1	GER	1976	840 / 785
Unterweser	GER	1978	1300 / 1230
Grafenrheinfeld	GER	1981	1300 / 1235
Grohnde	GER	1984	1395 / 1325
Philippsburg 2	GER	1984	1349 / 1268
Brokdorf	GER	1986	1395 / 1326
Isar 2	GER	1988	1400 / 1320
Emsland	GER	1988	1341 / 1270
Neckar 2	GER	1989	1360 / 1225
Borssele	NL	1973	481 / 449
Atucha 1	ARG	1974	357 / 335
Gösgen	CH	1979	1020 / 970
Trillo	ES	1988	1066 / 1000
Angra 2	BRA	2000	1309 / 1229

The Current Siemens/KWU Design of RPV CRDM Nozzles (since Stade)





RPV Head:
22 NiMoCr 37/20MnMoNi55

RPV head inner surface:
Austenitic SS cladding

Head Penetration Nozzles:
Compound tube St 52.4/1.4550
End of nozzle buttered with Nb-stabilized austenitic SS

Separation of tasks:

Main loading:
Trapezoidal screw thread

Sealing:
J-groove weld with Nb-stabilized SS,

Characteristic Features of the Siemens/KWU Design

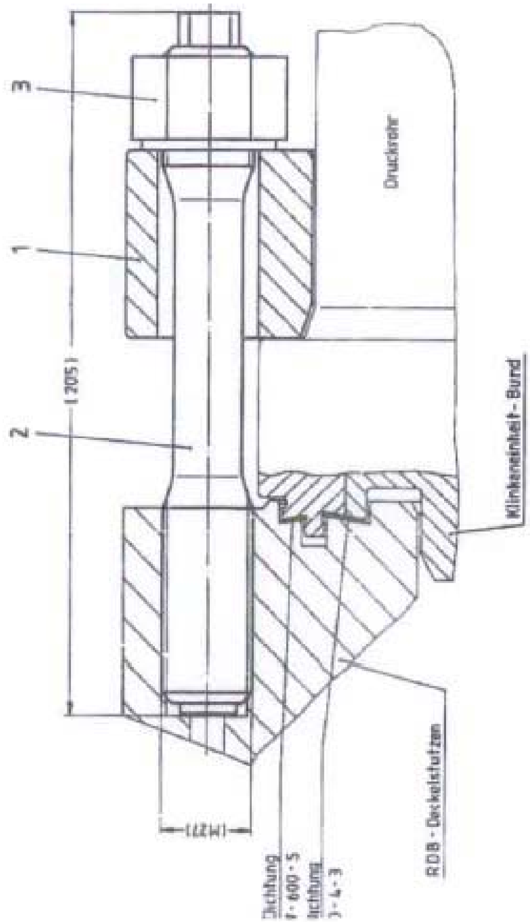
> material

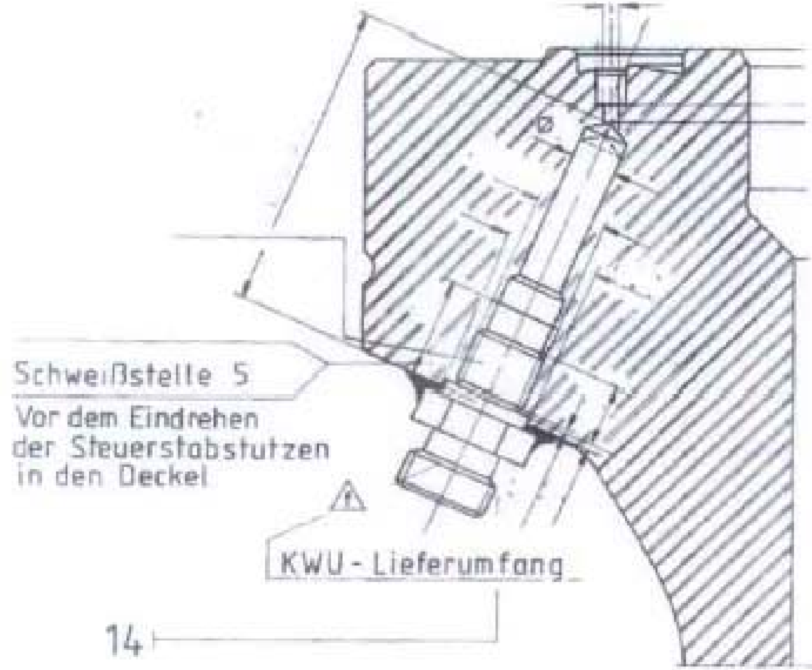
- RPV head: 22 NiMoCr 37/ 20 MnMoNi 55
- RPV surface cladding: Austenitic SS cladding (Nb stabilized)
- head penetration nozzles: compound tube made of St 52.4/1.4550
  end of nozzle buttered with
  Austenitic SS cladding (Nb stabilized)
- CRDM flange: Nb stabilized SS

> 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 condesate 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)

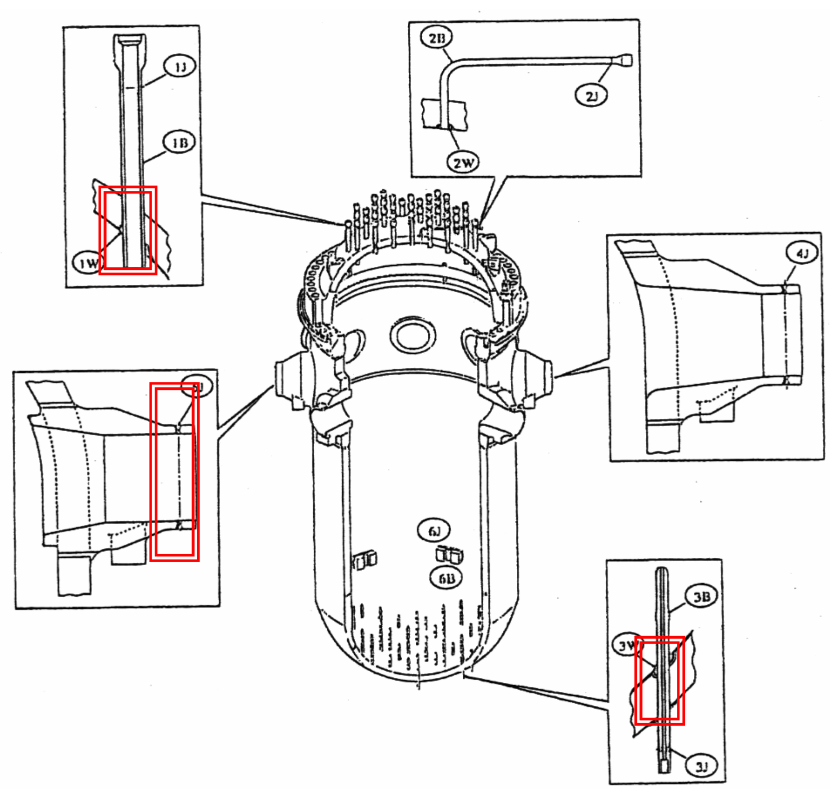
- choice and combination of material reliable over years
- optimized conditions by separating the function load bearing and sealing
- optimized welding design and welding process

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

: Ready for field application : Under development		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 ($\leq$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 (> σ_y)	Tension (> σ_y) (Surface: Compression)	Tension (> σ_y)	Tension (> σ_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

1000

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Counter Measure or Contingency		RVH Replacement (11plants)		Emergency Repair Method BMI Nozzle Replacement		690 Cladding Spool-piece Replacement

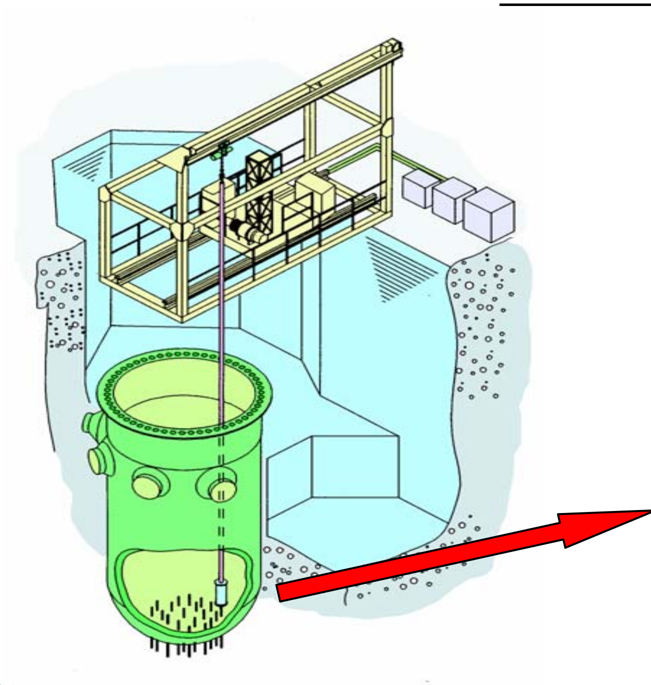
BMI Nozzle

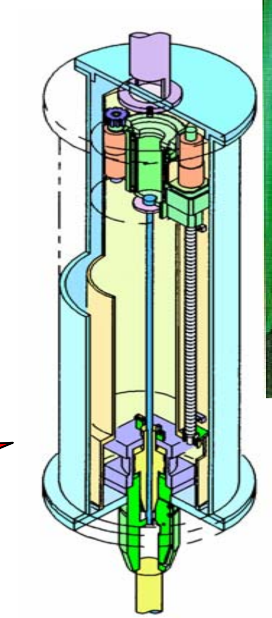
- **Based on recent PWSCC assessment, BMI nozzles are suspected to have cracking and mitigation measurement is recommended.**
- **ECT and water jet peening (WJP) technology for BMI nozzles have been developed by MHI as mitigation measurement in accordance with PWSCC assessment.**

BMI Nozzle

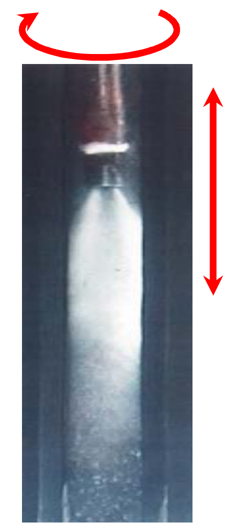
Concept of WJP Technology for Field Application

Field work image





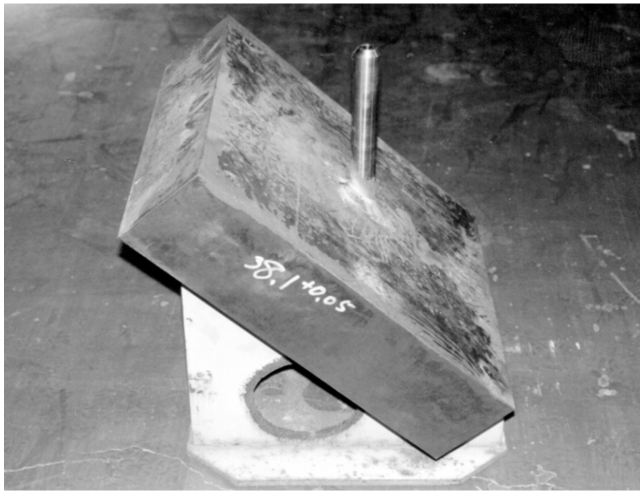
WJP equipment



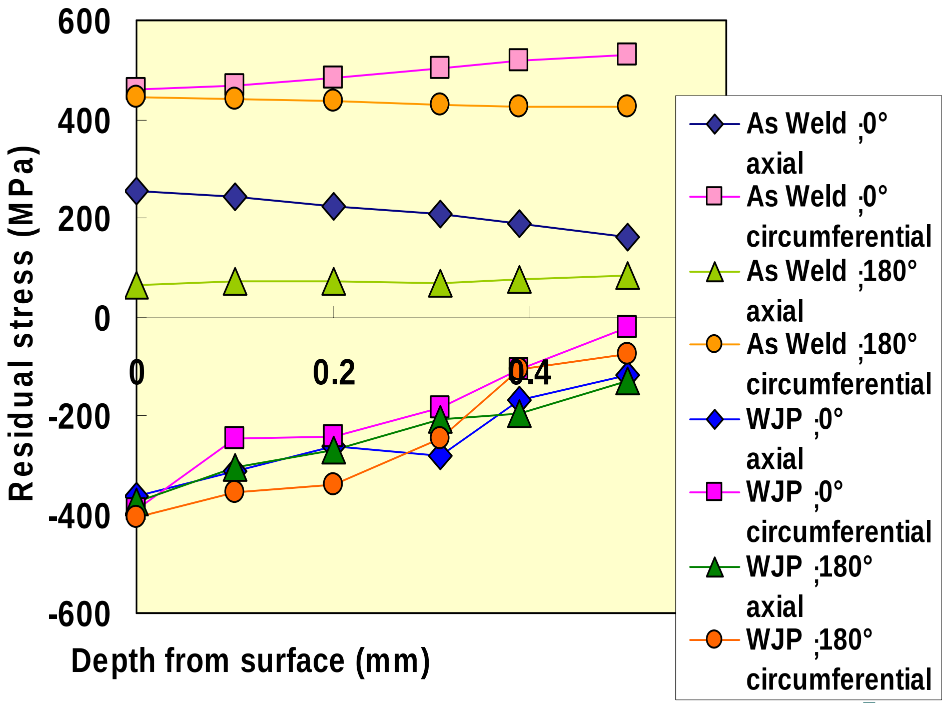
State of WJP
in small diameter pipe

BMI Nozzle

Improvement of Residual Stress by WJP Technology



Mock-up of BMI



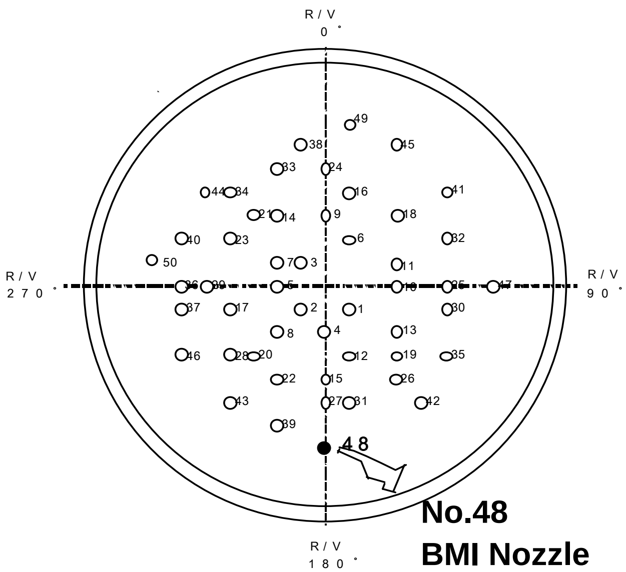
Result of residual stress measurement

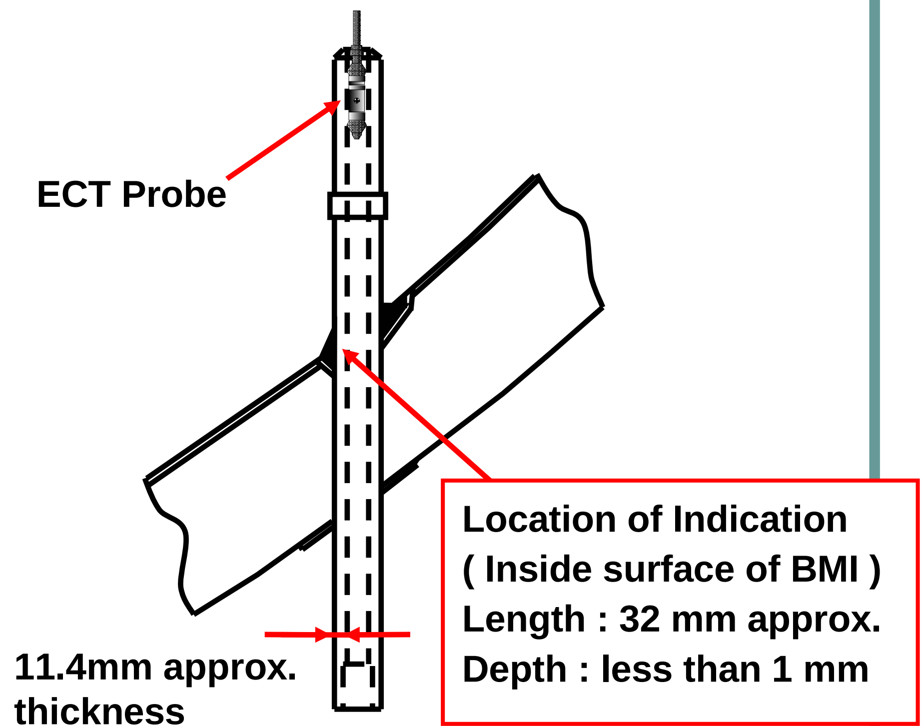
1003

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





1005

1006

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.**

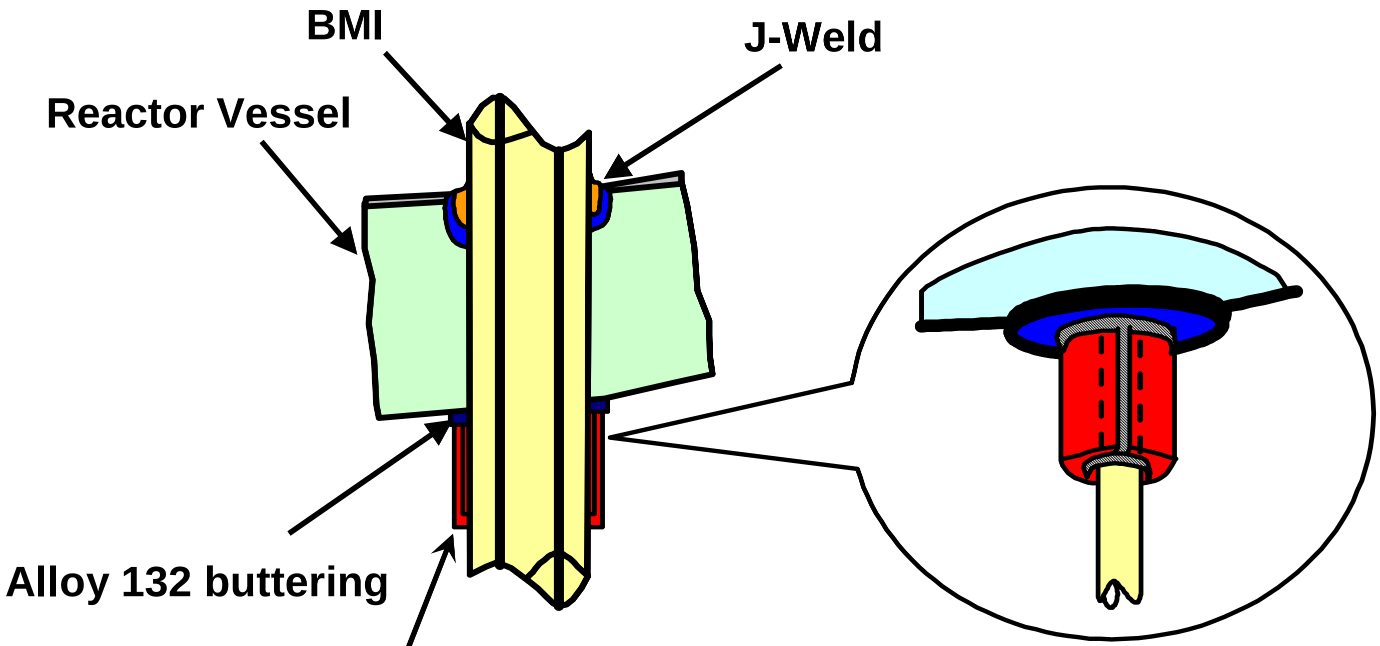
BMI Nozzle

- **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.

1008

Activities on Alloy 600 Cracking of PWRs in Japan

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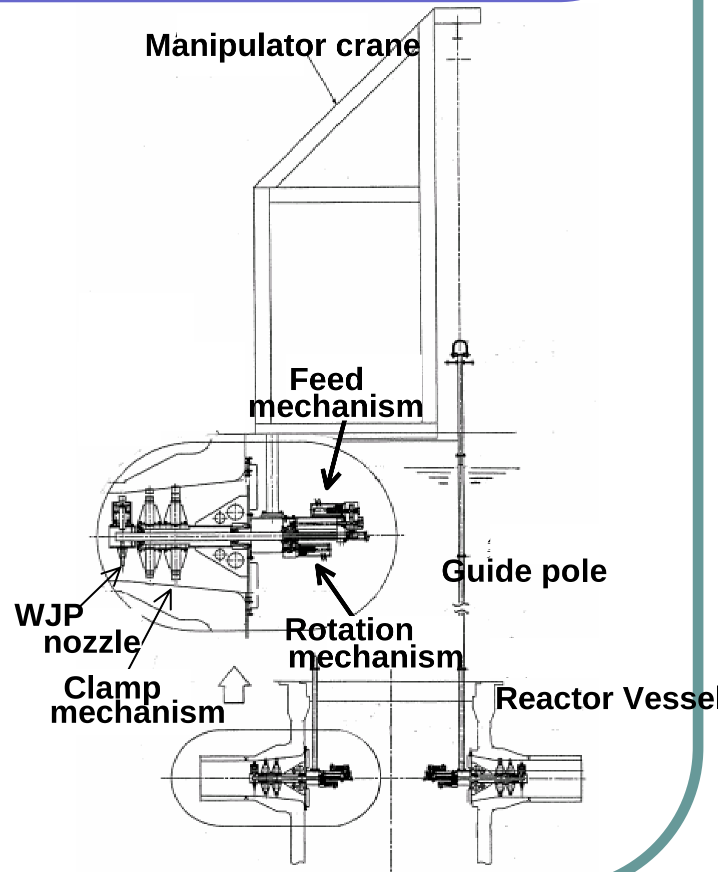
Counter Measure or Contingency		RVH Replacement (11plants)		Emergency Repair Method BMI Nozzle Replacement		690 Cladding Spool-piece Replacement

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



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.**

1013

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

The Japan Atomic Power Company

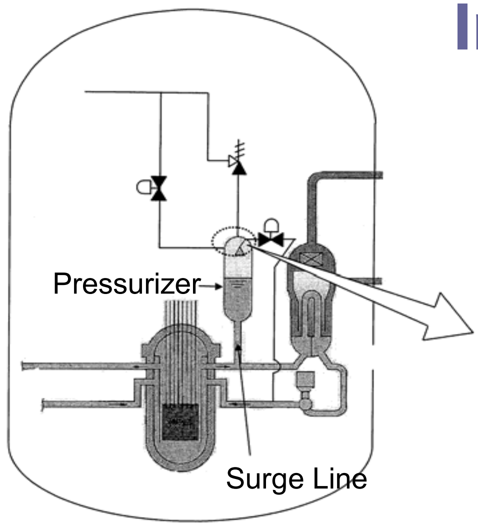
Tsuruga Unit-2

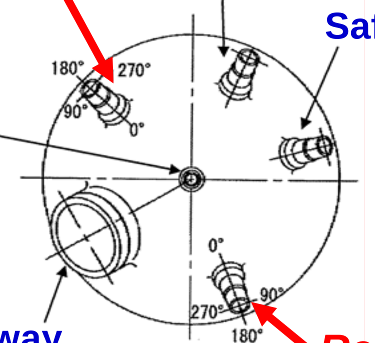
- Start of Operation : February, 1987
- Power : 1,160 MWe
- Type : 4-loop
- Fabricator : Mitsubishi Heavy Industries

1014

- This Outage (found leakage) : #13
- Accumulated operating time: about 120,000 H

Inspection Results



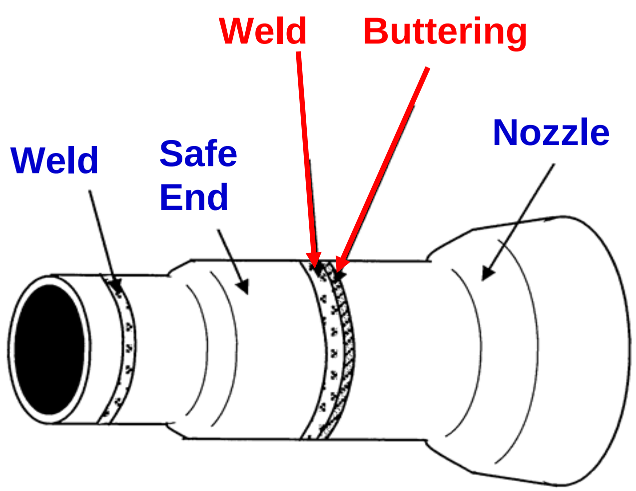


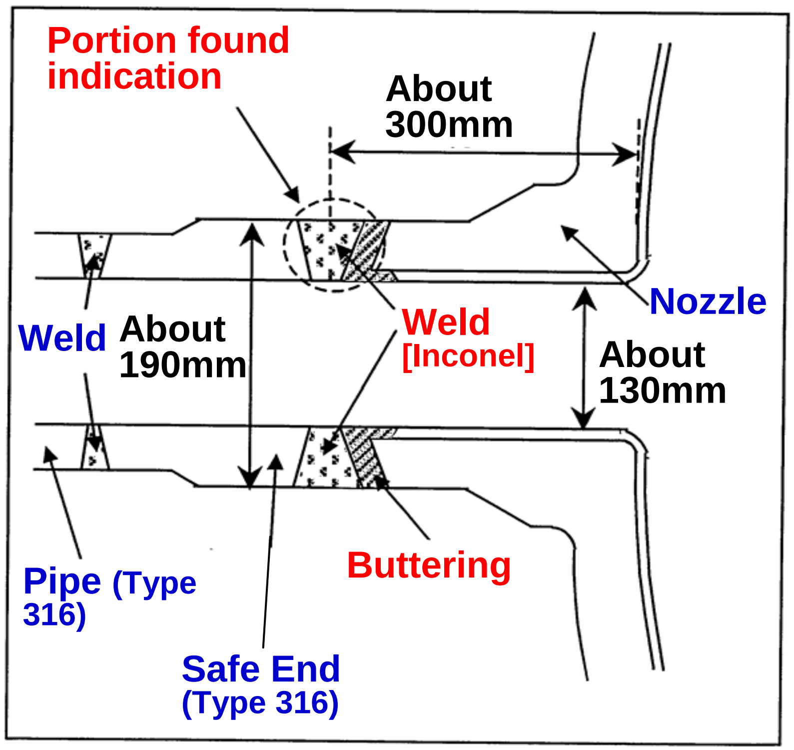
1015

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

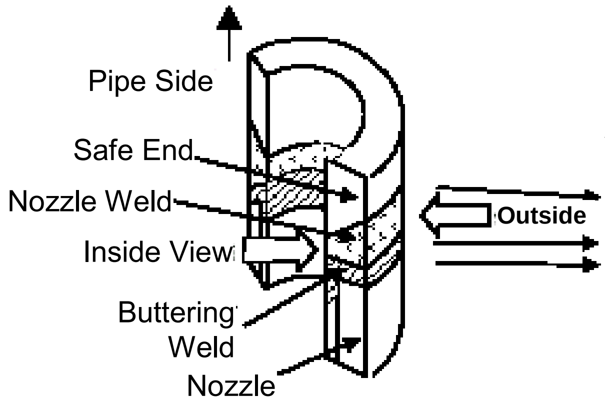
Safety Nozzle & Relief Nozzle (Same Size)

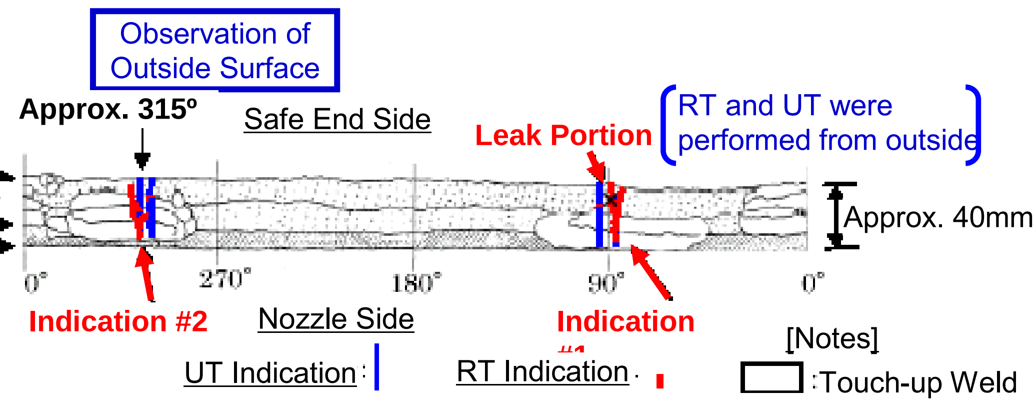
1016





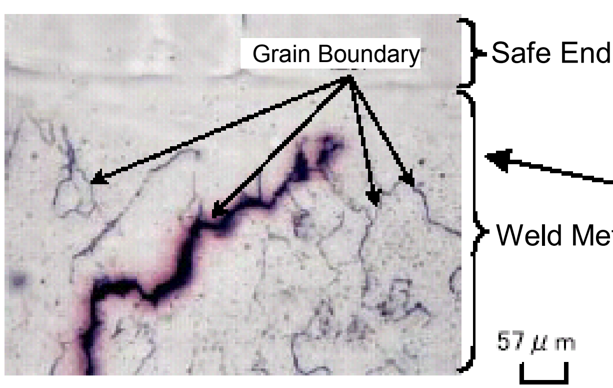
Observation of Inside & Outside Surface

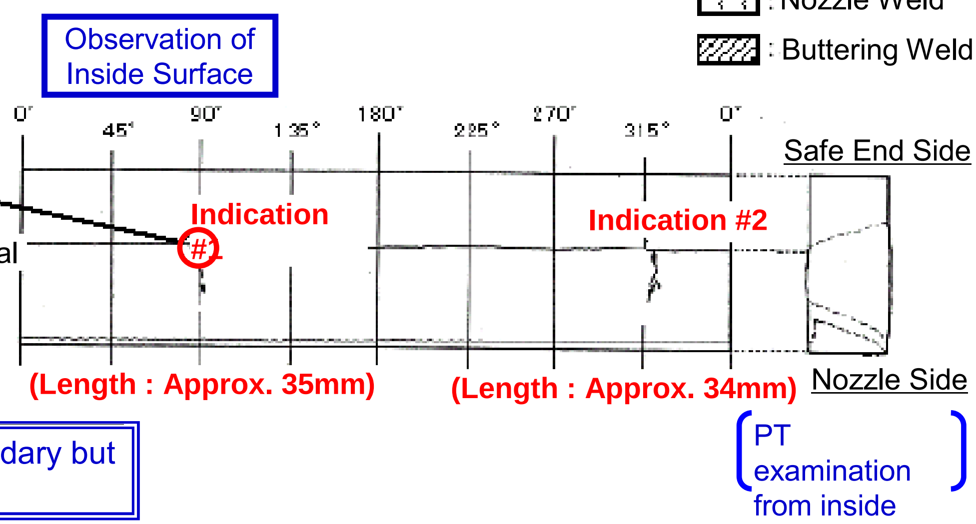




1017

SUMP of Inside Surface



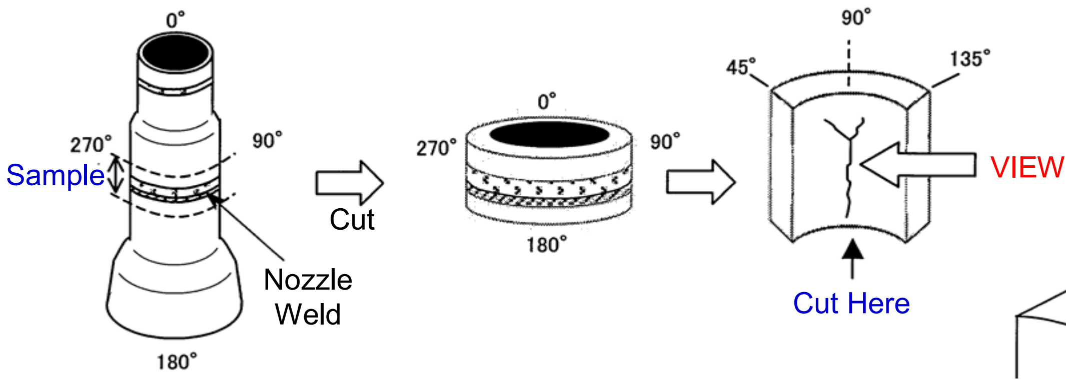


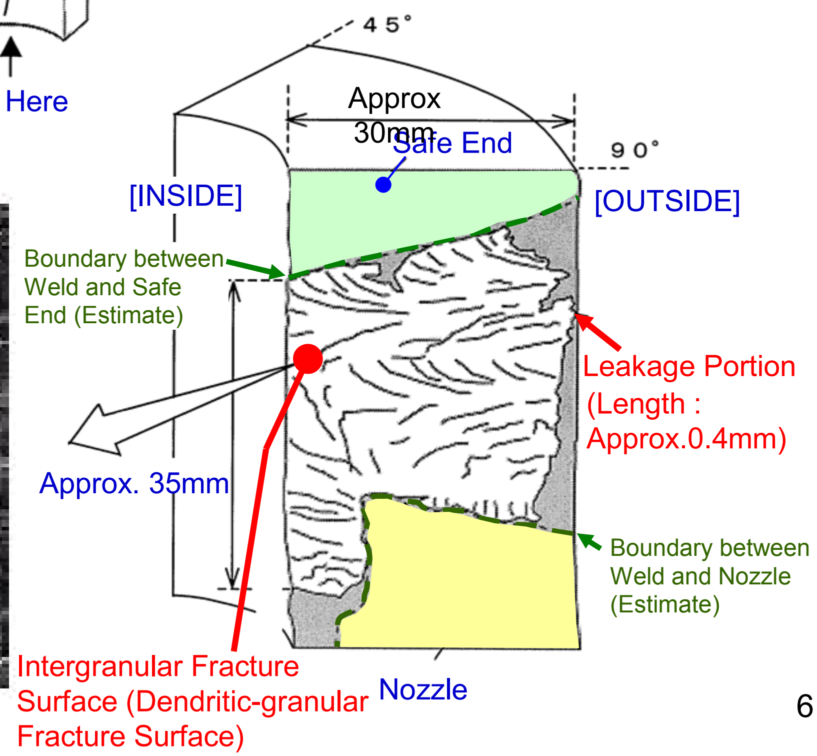
The crack branches off along the grain boundary but does not attach the safe end

Observation of Fracture Surface

- Indication #1 at **90º**

1018





If you want to look at more clear picture, please access to web-site of 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

1021

Pål Efsing - Ringhals AB

Christer Jansson - SwedPower AB

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

Ringhals

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*

Ringhals

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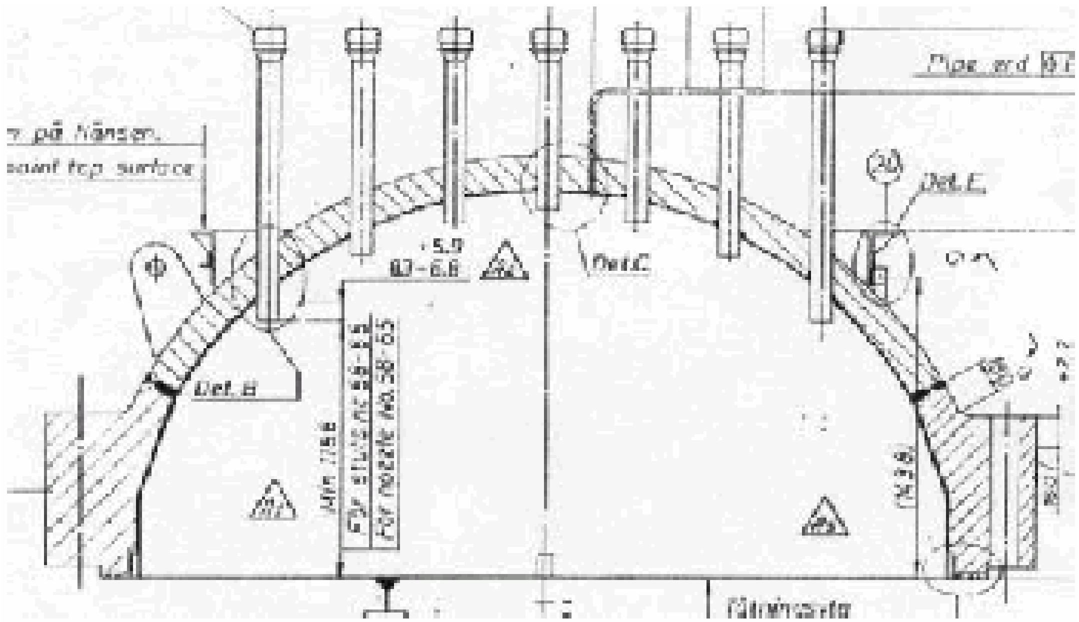
RPV Head Ringhals 3 and 4



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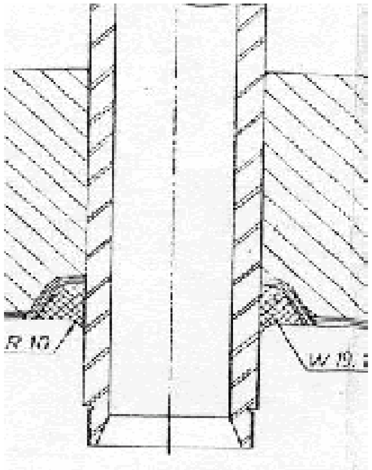
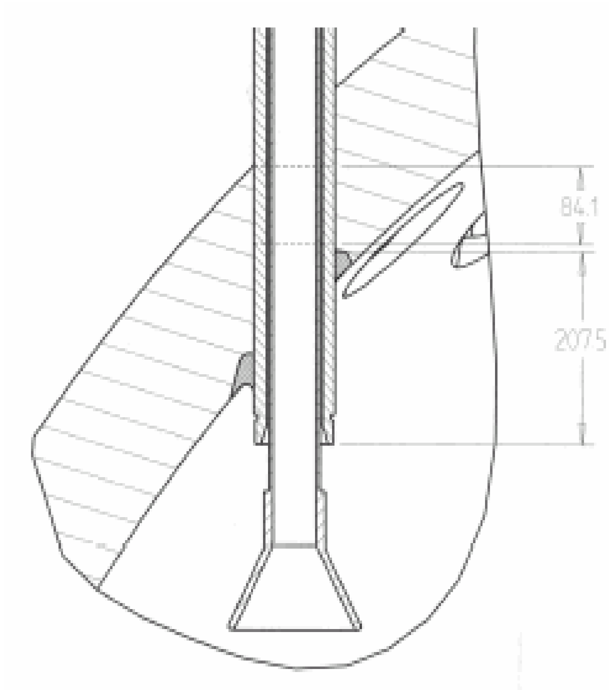
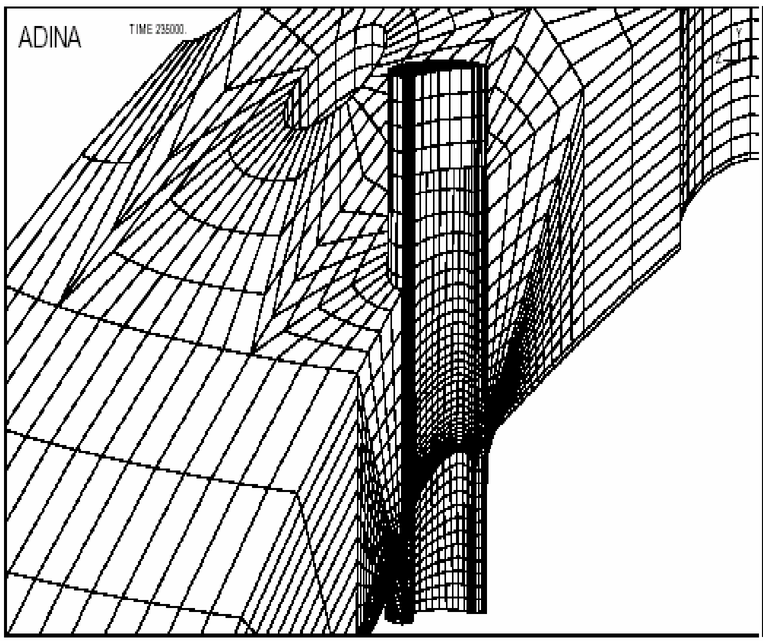
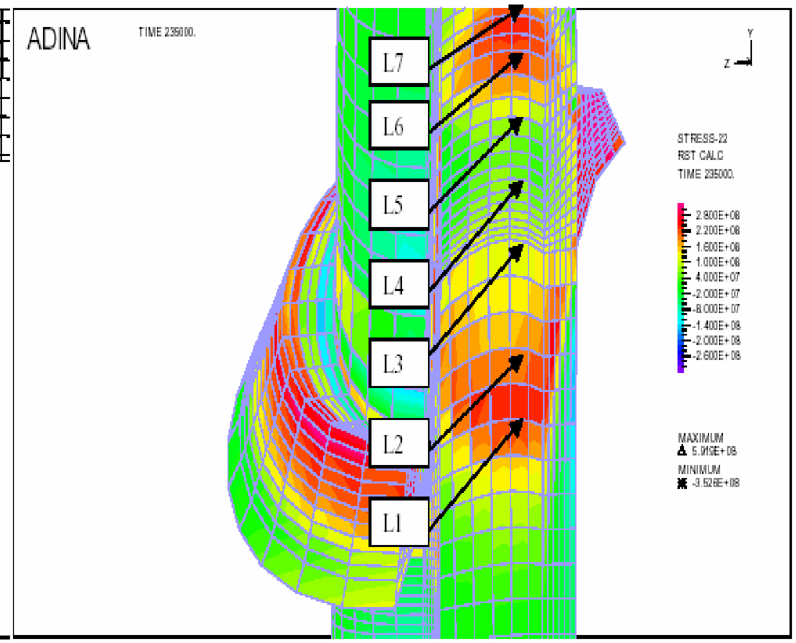
Vessel head penetrations






ADINA
TIME 235000.


ADINA
TIME 235000.
L7
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L2
L1
Y
Z
STRESS-22
RST CALC
TIME 235000.
2.800E+08
2.200E+08
1.600E+08
1.000E+08
4.000E+07
-2.000E+07
-8.000E+07
-1.400E+08
-2.000E+08
-2.600E+08
MAXIMUM
5.919E+08
MINIMUM
-3.526E+08

Ringhals

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:

1028

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**

Ringhals

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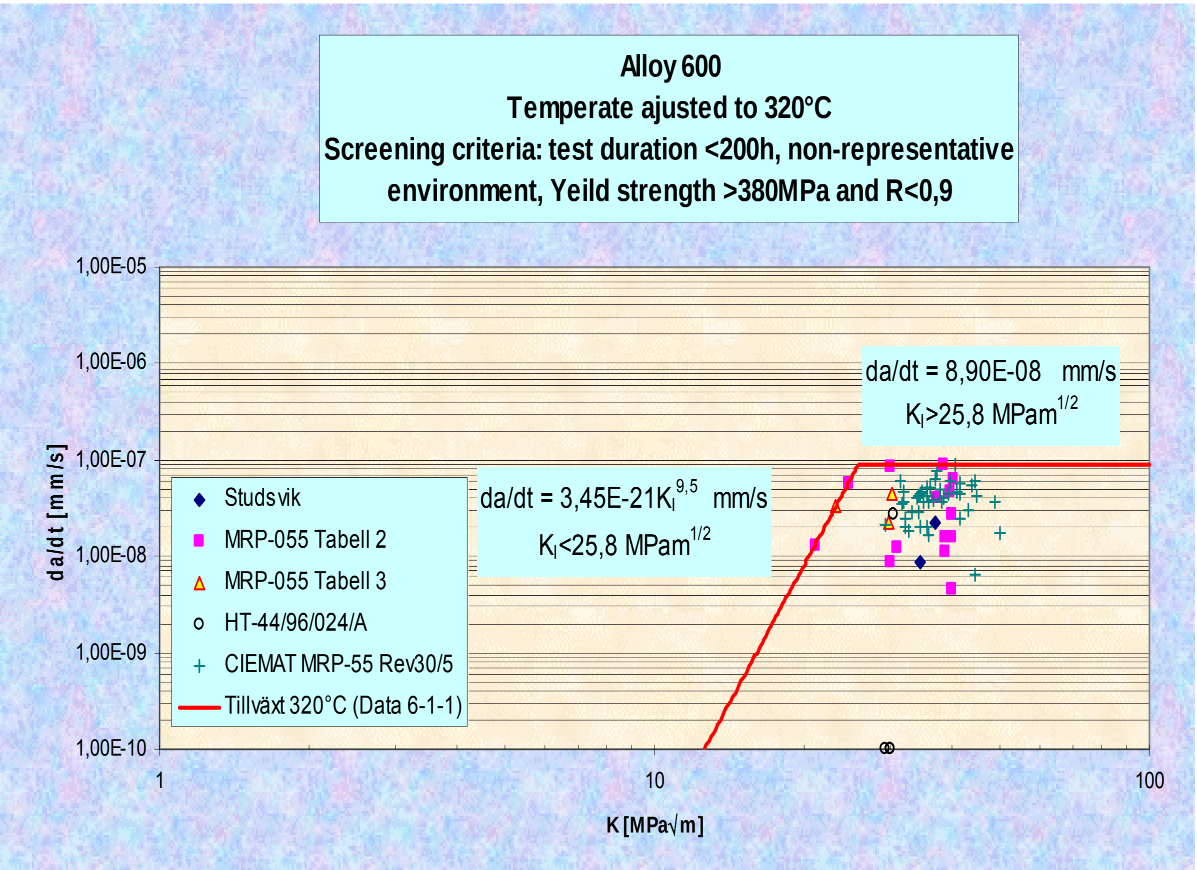
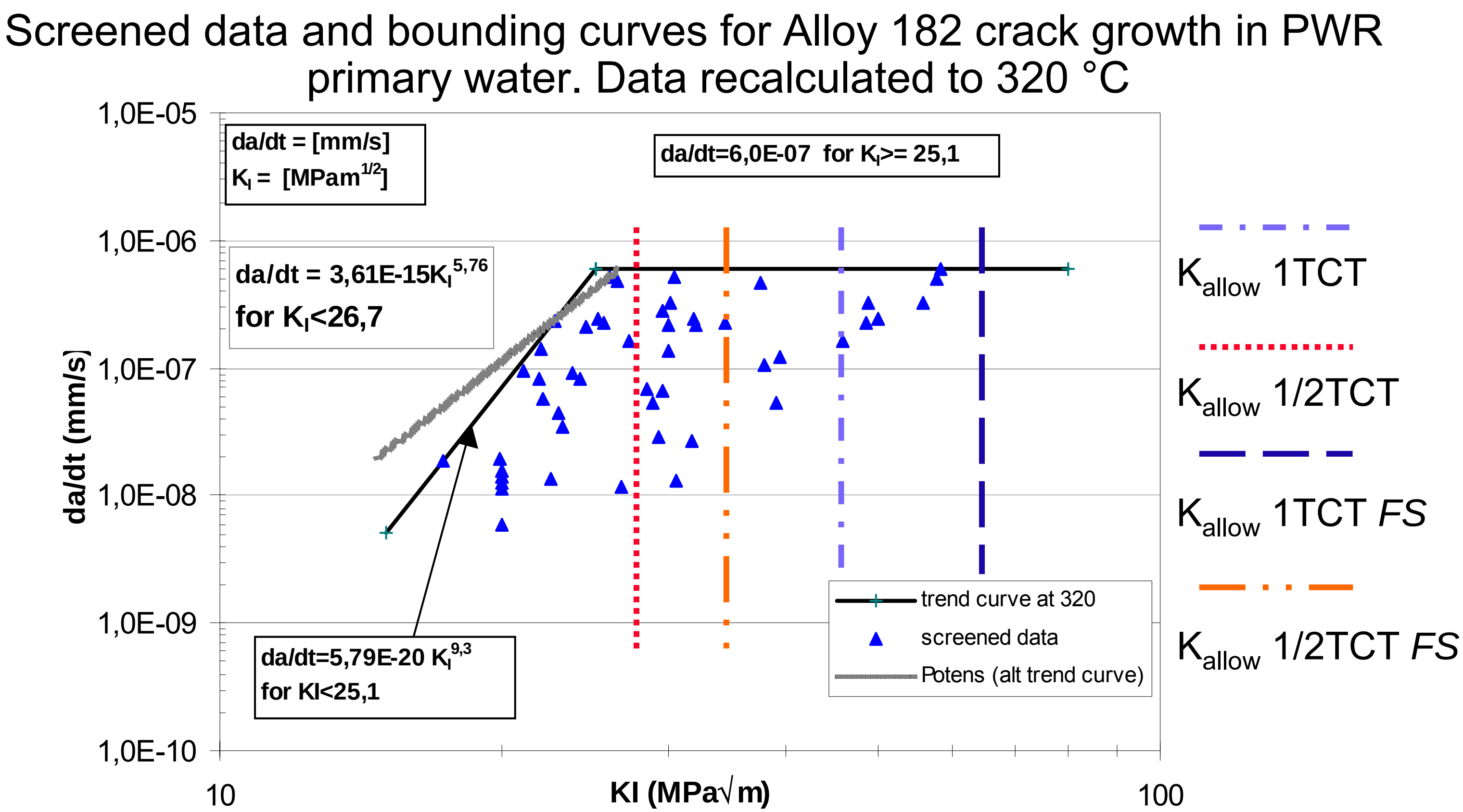
Assessment procedure

- **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

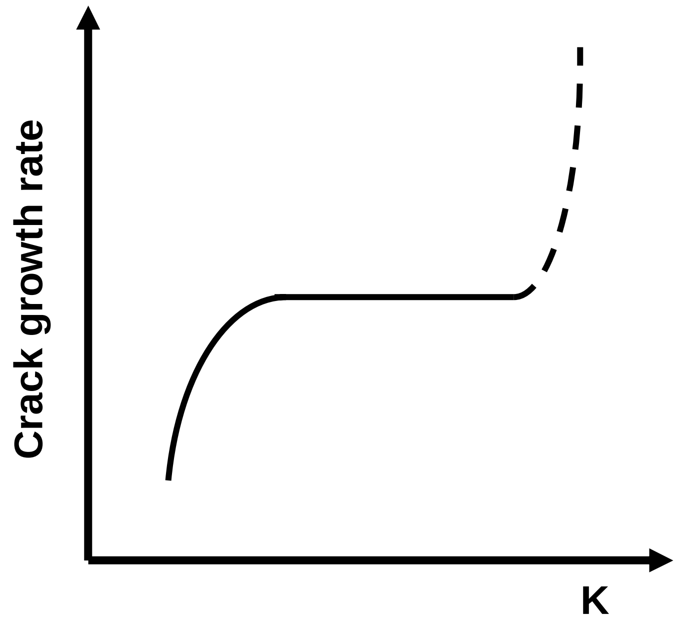


Available data does:

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

Ringhals

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

1043

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

1044

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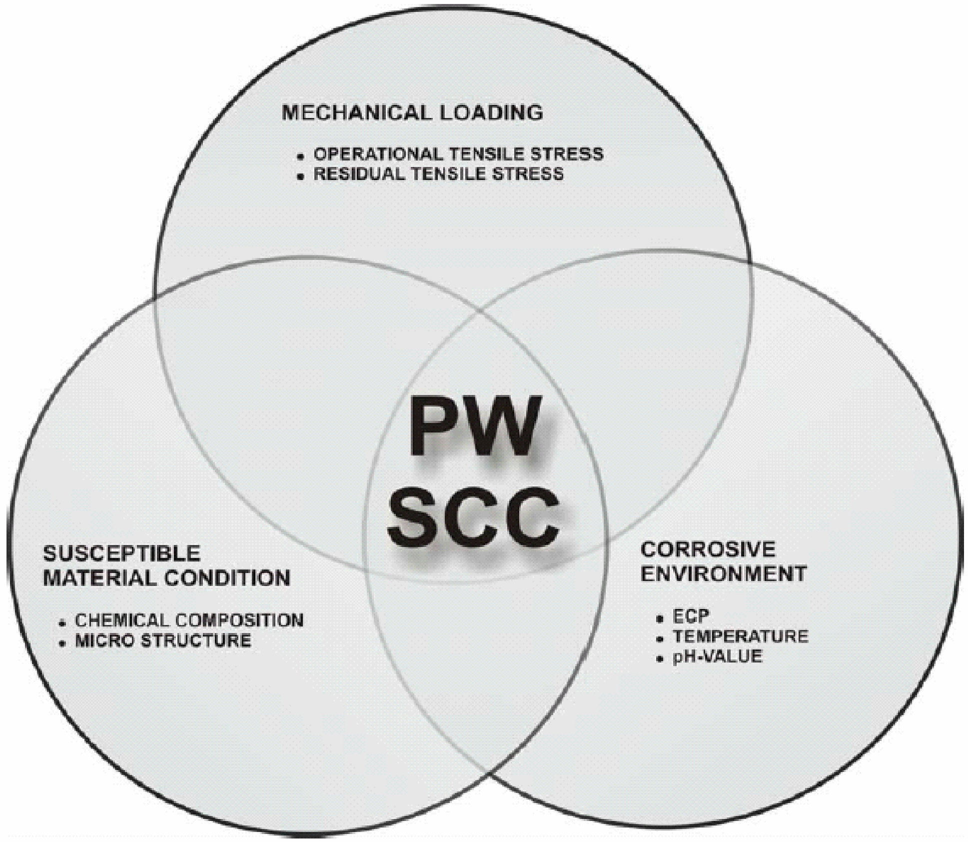
Main Factors That Cause PWSCC

- > ***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

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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

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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*

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Objective:

Extend crack initiation time and reduce crack propagation rate

Present PWSCC Mitigation Techniques

MSE Techniques

> *Abrasive Water Jet Conditioning*

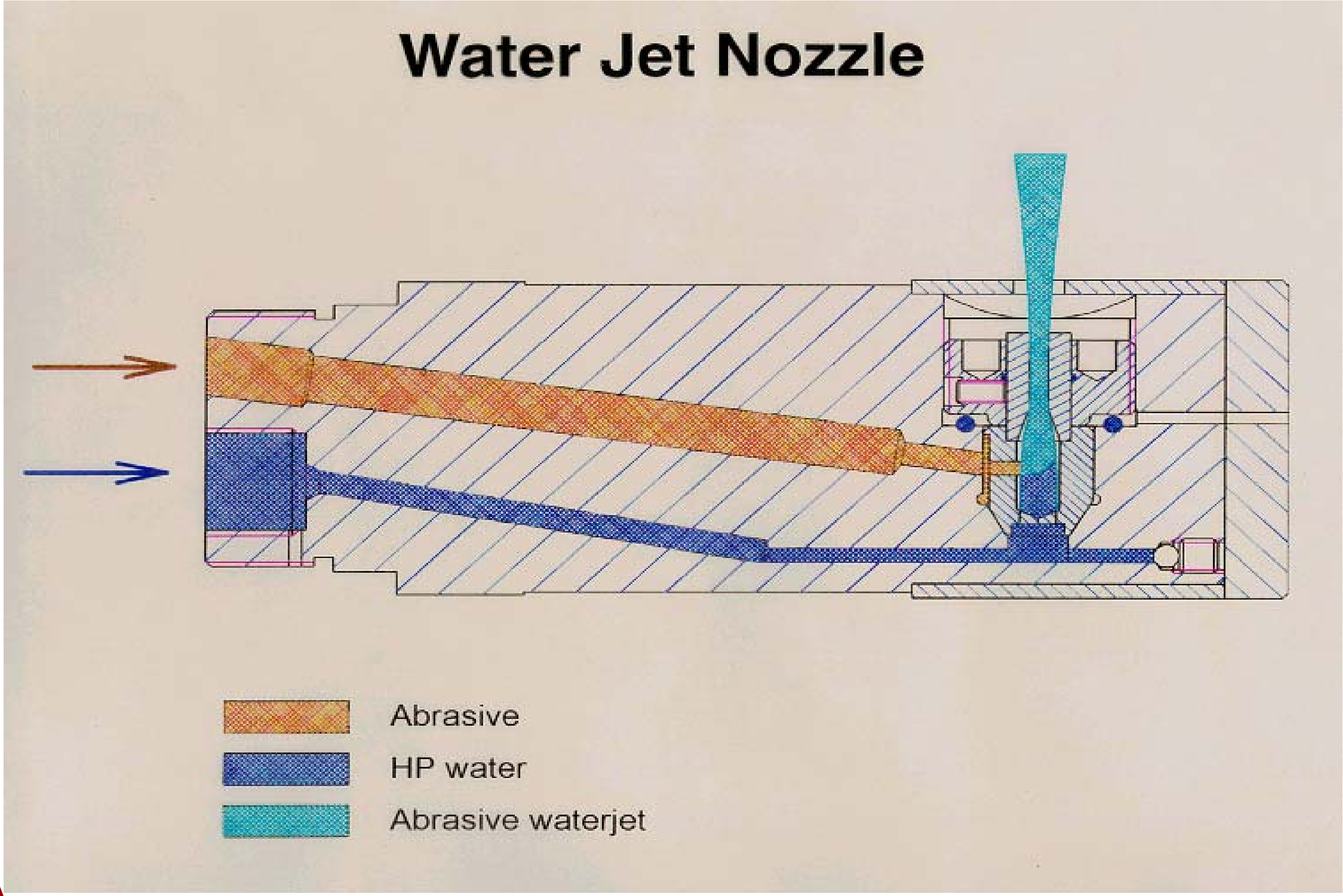
> *Mechanical Stress Improvement Process (MSIP)*

1051

Objective:

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

Abrasive Water Jet Conditioning



MSIP

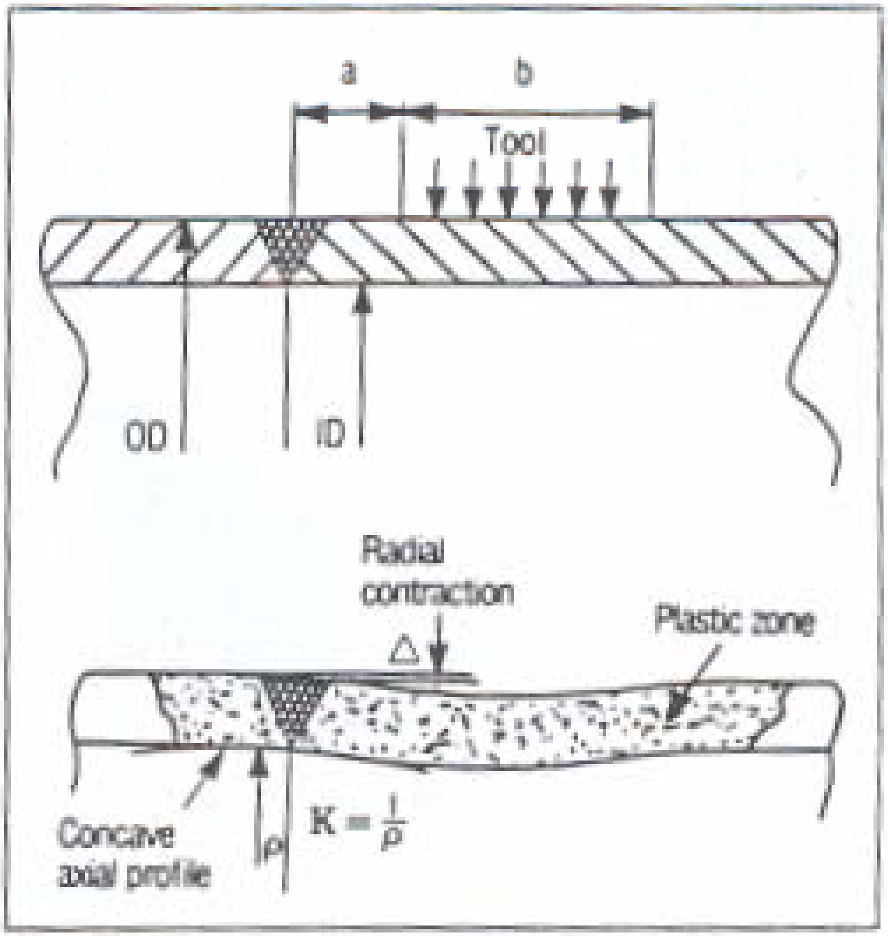


FIGURE 2 TOOL LOCATION AND DEFORMATION CONTOUR AFTER APPLYING MSIP

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1054

Present PWSCC Mitigation Techniques

Environmental Barrier or Coating Techniques

> Nickel Plating

> Weld Deposit Overlay

> Electroless Nickel Plating

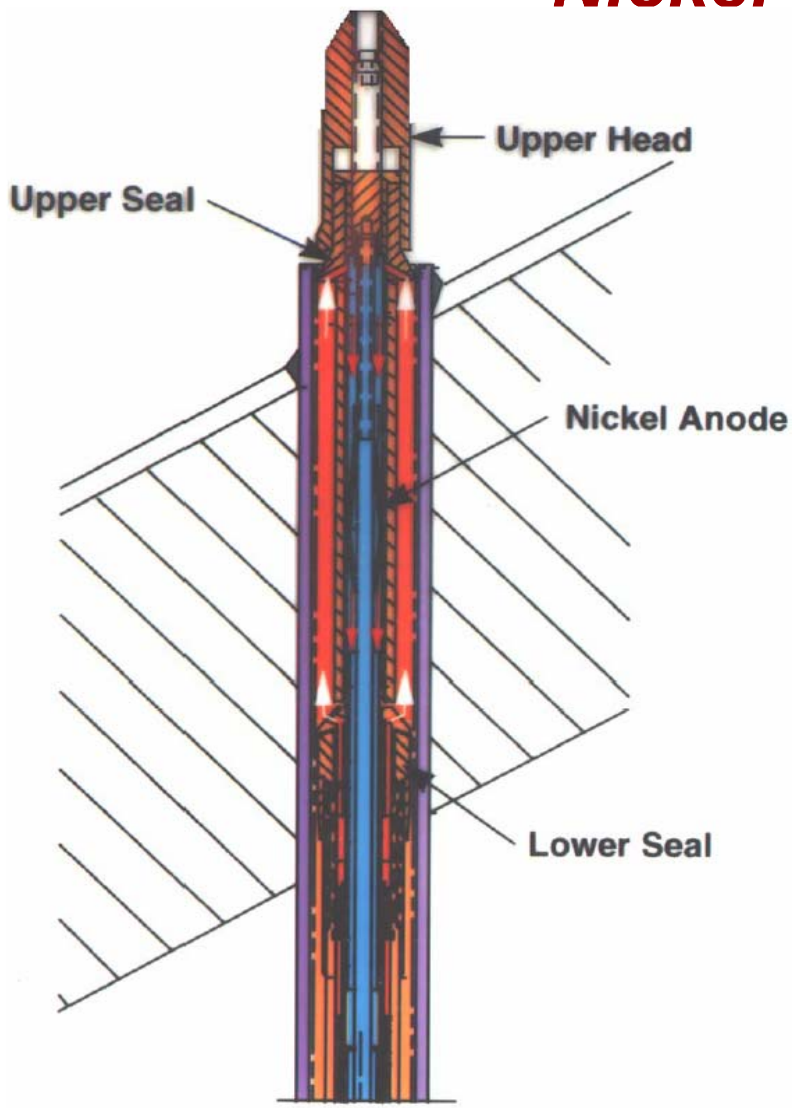
> Laser Weld Deposit/Cladding

Objectives:

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

Nickel Plating

End Effector



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Present PWSCC Mitigation Techniques

ECP Control Technique

> ***Zinc Addition***

Objectives:

Inhibits PWSCC initiation
Potentially reduces crack propagation

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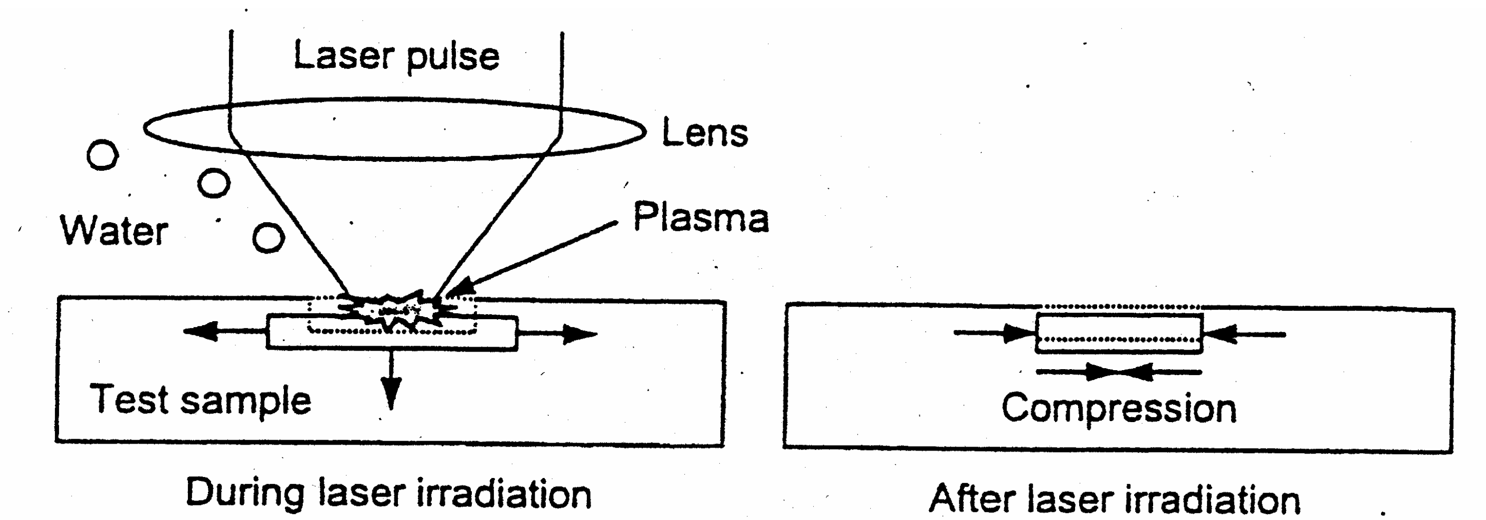
Potential Future Mitigation Techniques

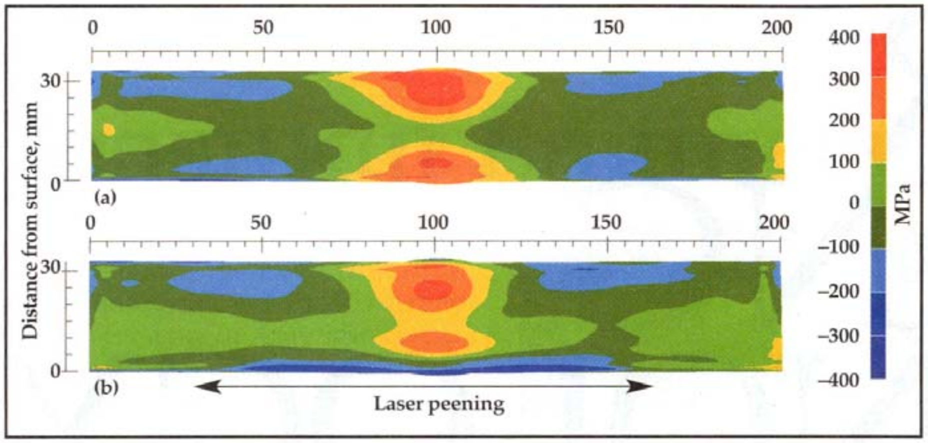
MSE Techniques

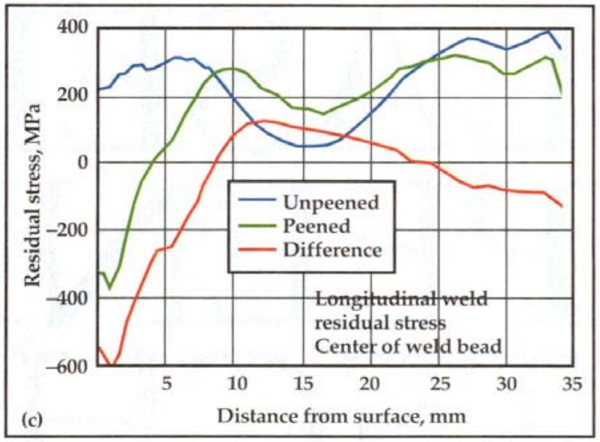
> Laser Shock Peening
> Low Plasticity Burnishing
> Heat Sink Welding
> Induction Heating Stress Improvement (IHSI)

Laser Peening



Laser Peening Residual Stresses





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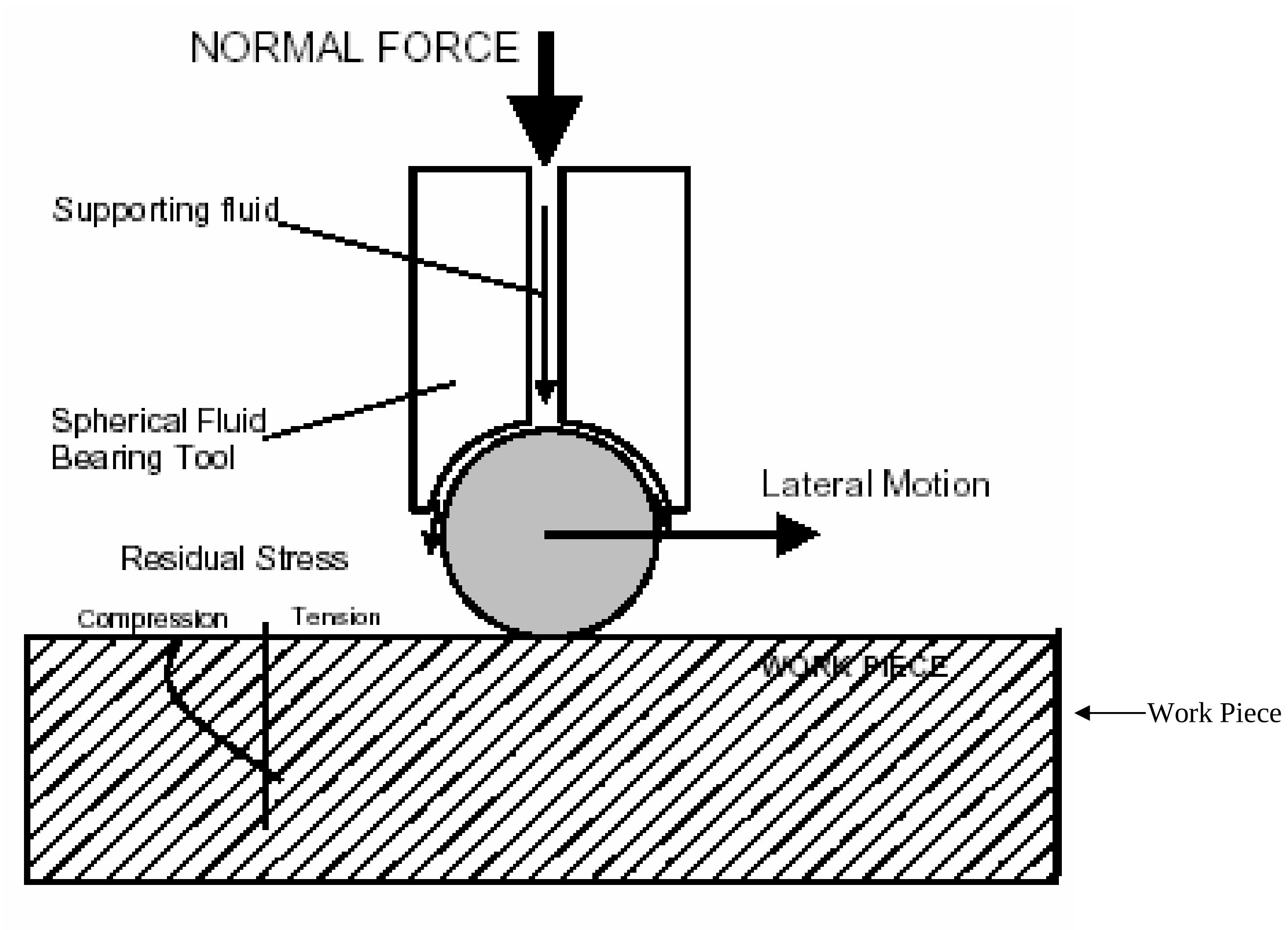
Low Plasticity Burnishing



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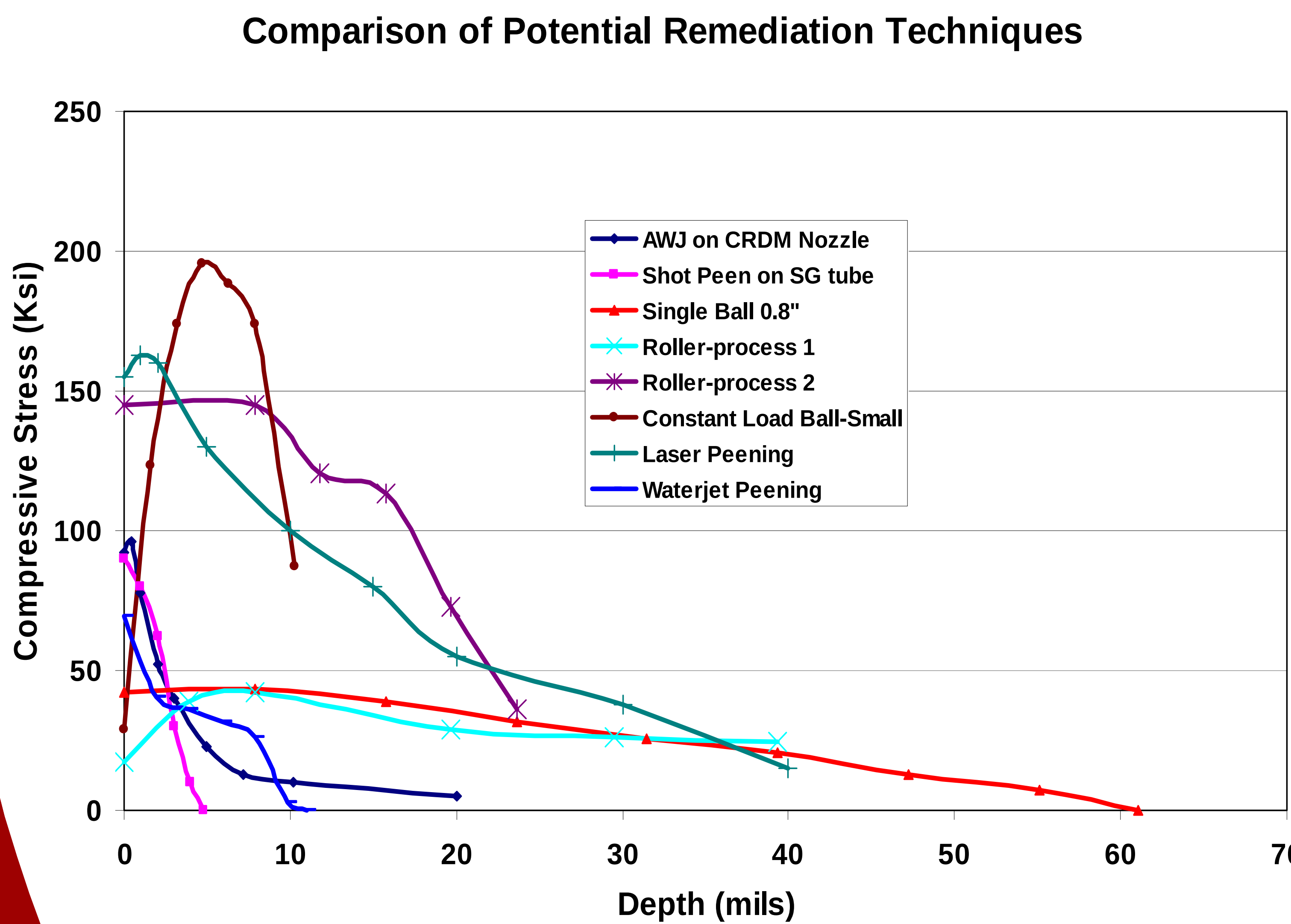

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Potential Future Mitigation Techniques

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***

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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*

1064

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

1067

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

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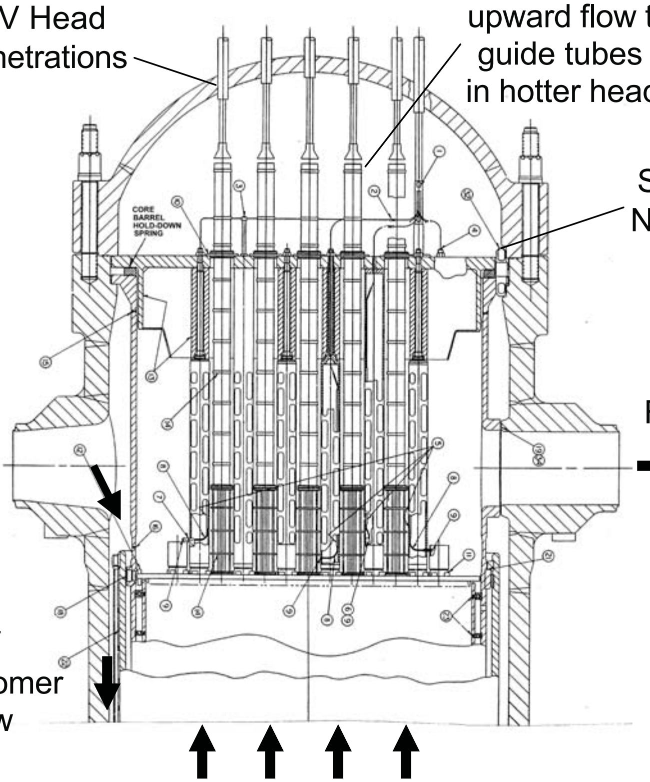
Upper Head Temperature Reduction (UHTR) is a Field Modification Performed on the Reactor Vessel (RV) Internals Structures

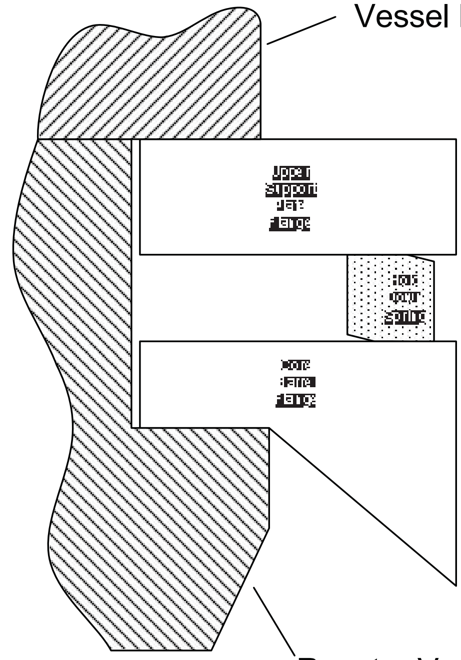
1069

- 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

1070

Upper Internals Components





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

1071

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

1072

Effect of Temperature on Cracking

Effective Degradation Years:

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

where:

EDY_{600F} = 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)

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

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

1073

Effect of Temperature on Cracking

Crack Growth:

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

where:

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

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

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

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

T_{ref} = absolute reference temperature to normalize data

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

K = crack tip stress intensity factor (ksi vinch)

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

β = exponent (1.16)

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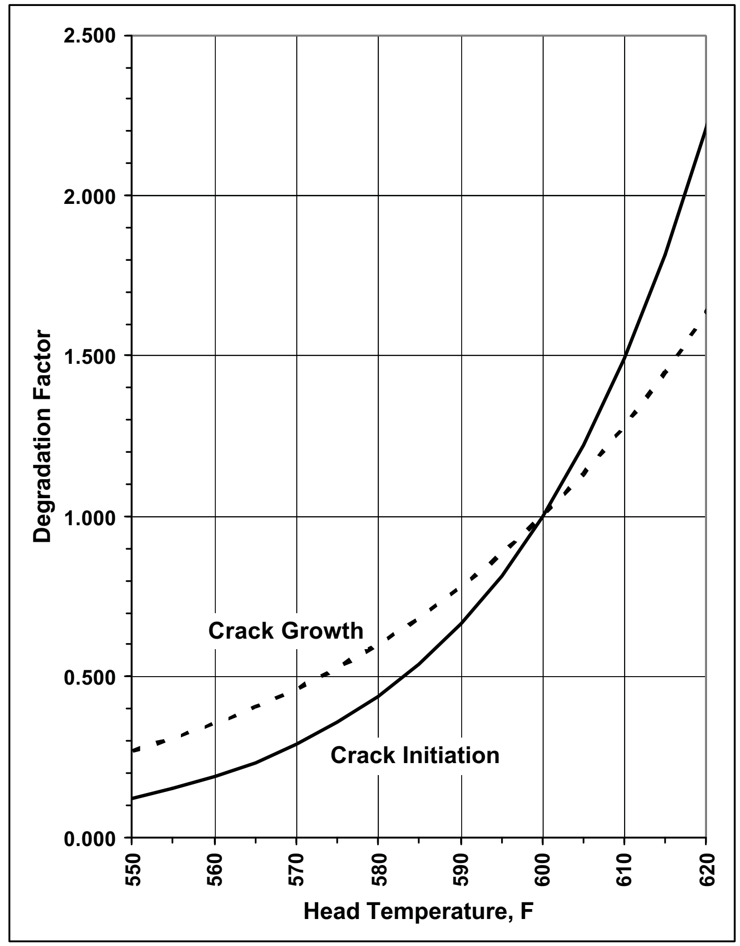
Effect of Temperature on Cracking

Temp	Degradation Factors* Initiation	Growth
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



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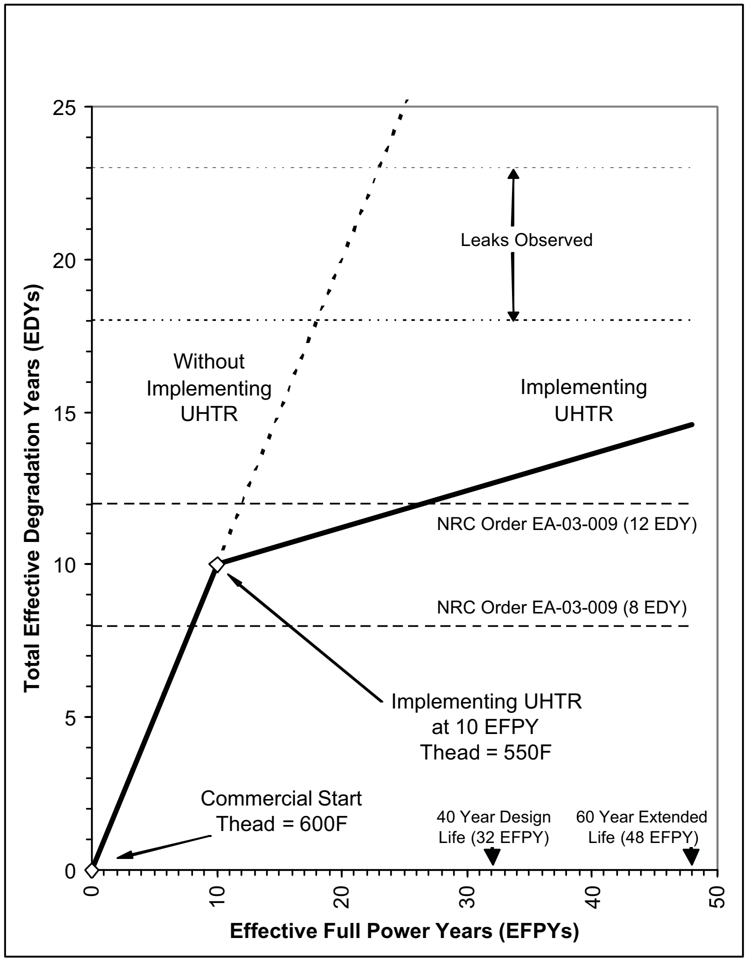
Example of UHTR Effectiveness for a Unit Approaching the 8 EDY Limit, with Respect to NRC Order

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



Domestic Plant Ranking vs. EDY

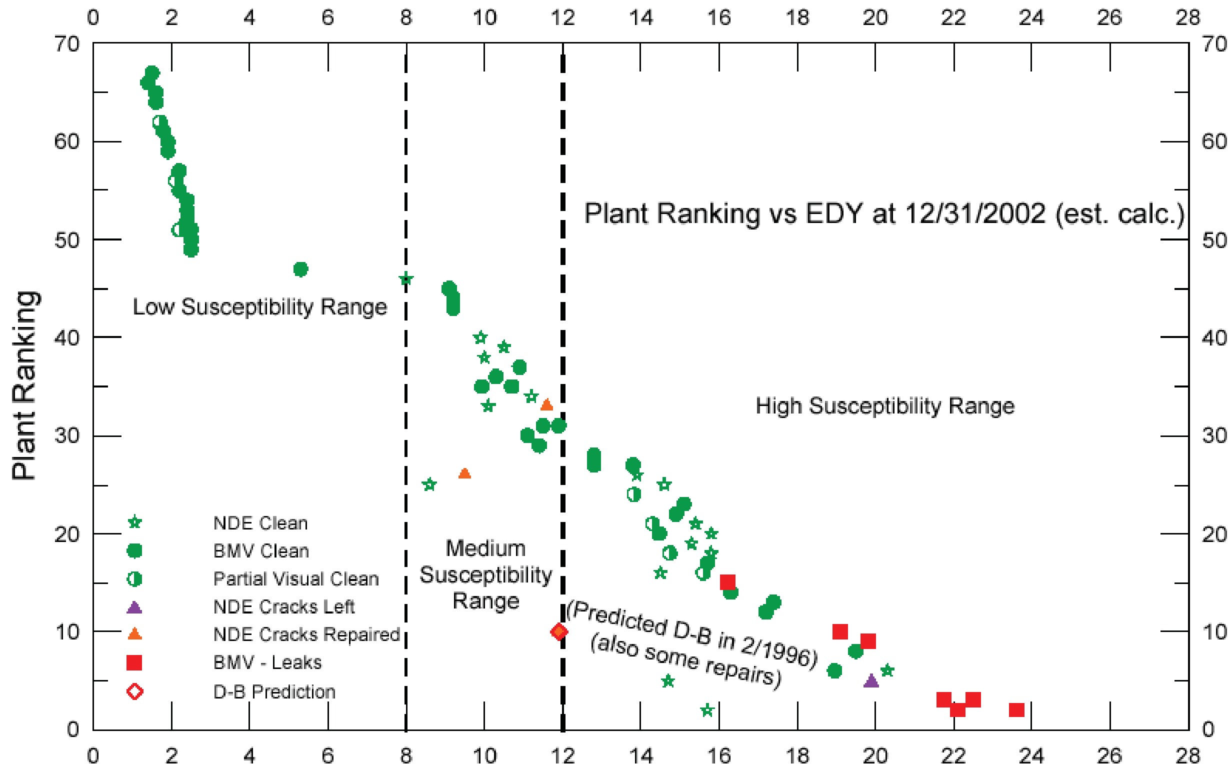


Figure 1. Ranking of domestic plants according to the EDY formula, showing results of inspections, evidence of leakage, and repairs. Many plants are shown with multiple symbols, indicating a "clean" inspection at inspection opportunity, followed by a different finding at a subsequent inspection (e.g.,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

Westinghouse Fleet Status

1077

- 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)

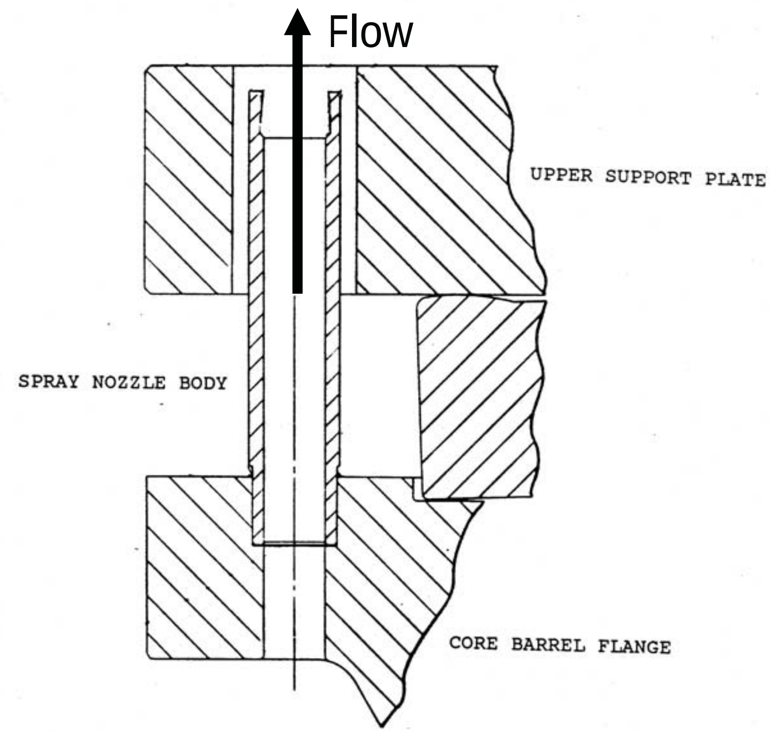
Westinghouse UHTR
Field Modification Experience

- 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

1078

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



<u>Actual Implementation Data:</u>

Schedule: 10 hours

Exposure: 10 mR

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

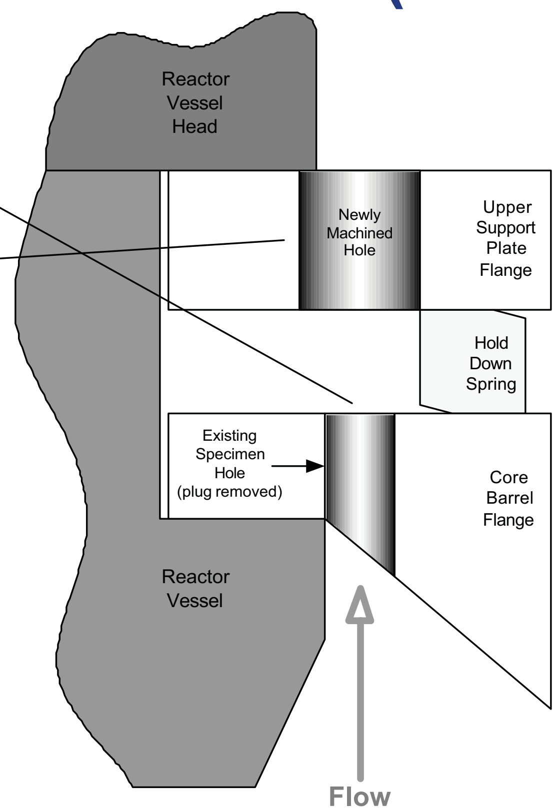
1080

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

<u>Actual Implementation Data:</u>
Schedule: 4 days
Exposure: 637 mR



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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

EPRI

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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

EPRI

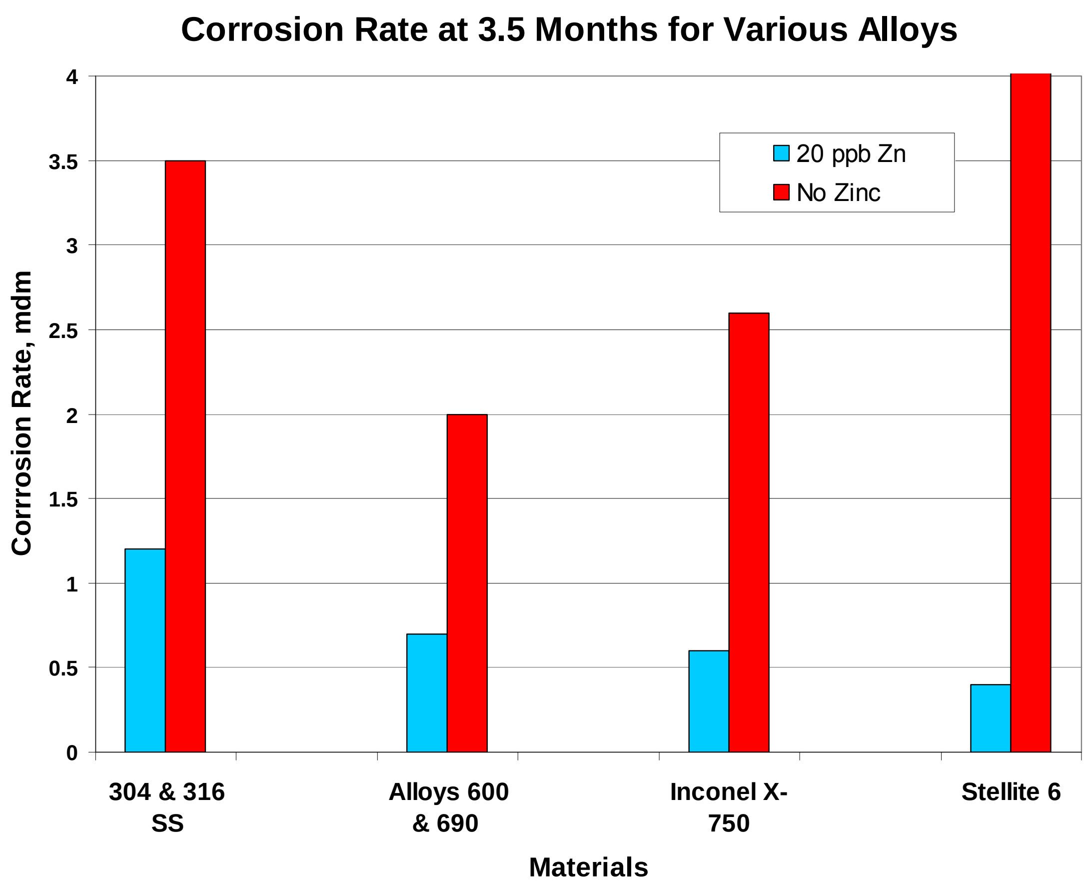
Background to PWR Zinc Addition Studies

- 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 (Fe,Ni,Co)Cr_2O_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 (Ni,Co)Fe_2O_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

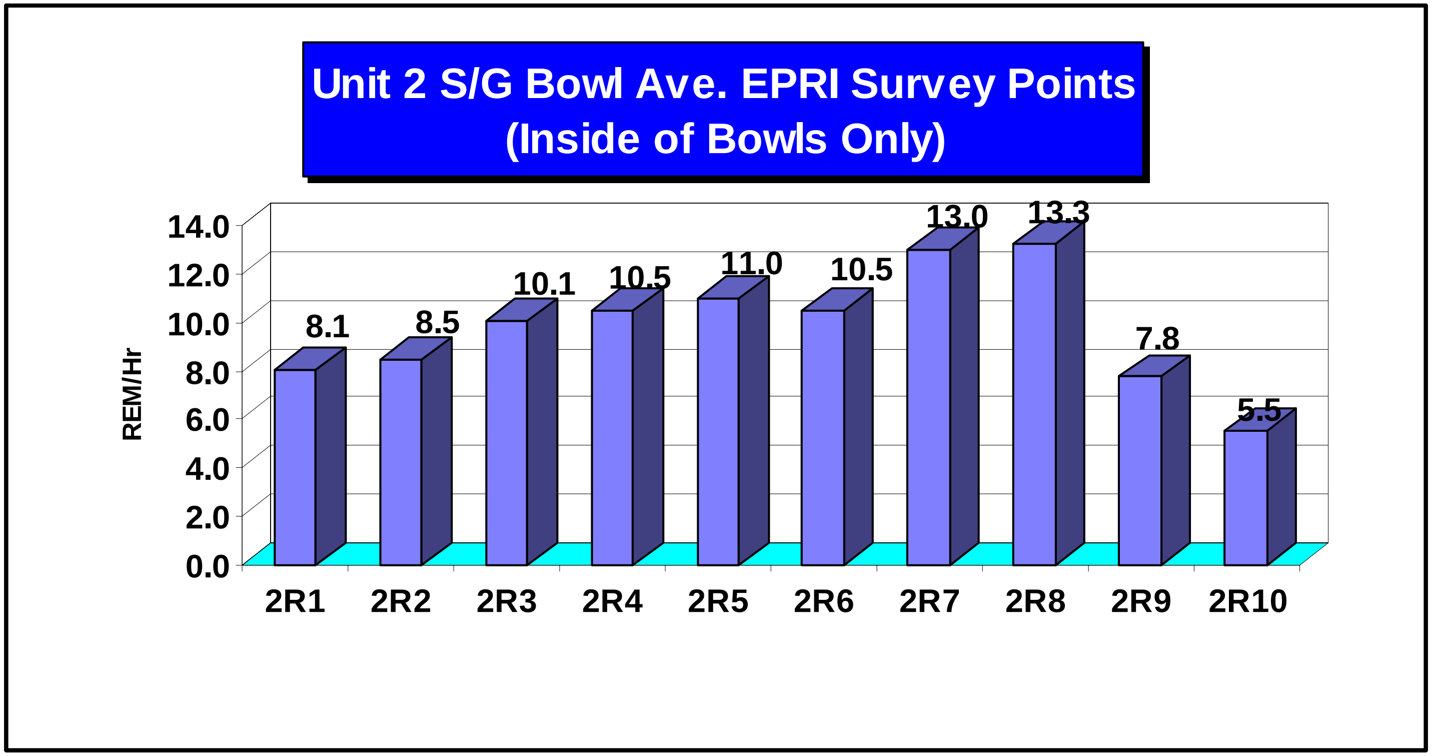
Effect of Zinc on Corrosion Rates



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

1086

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



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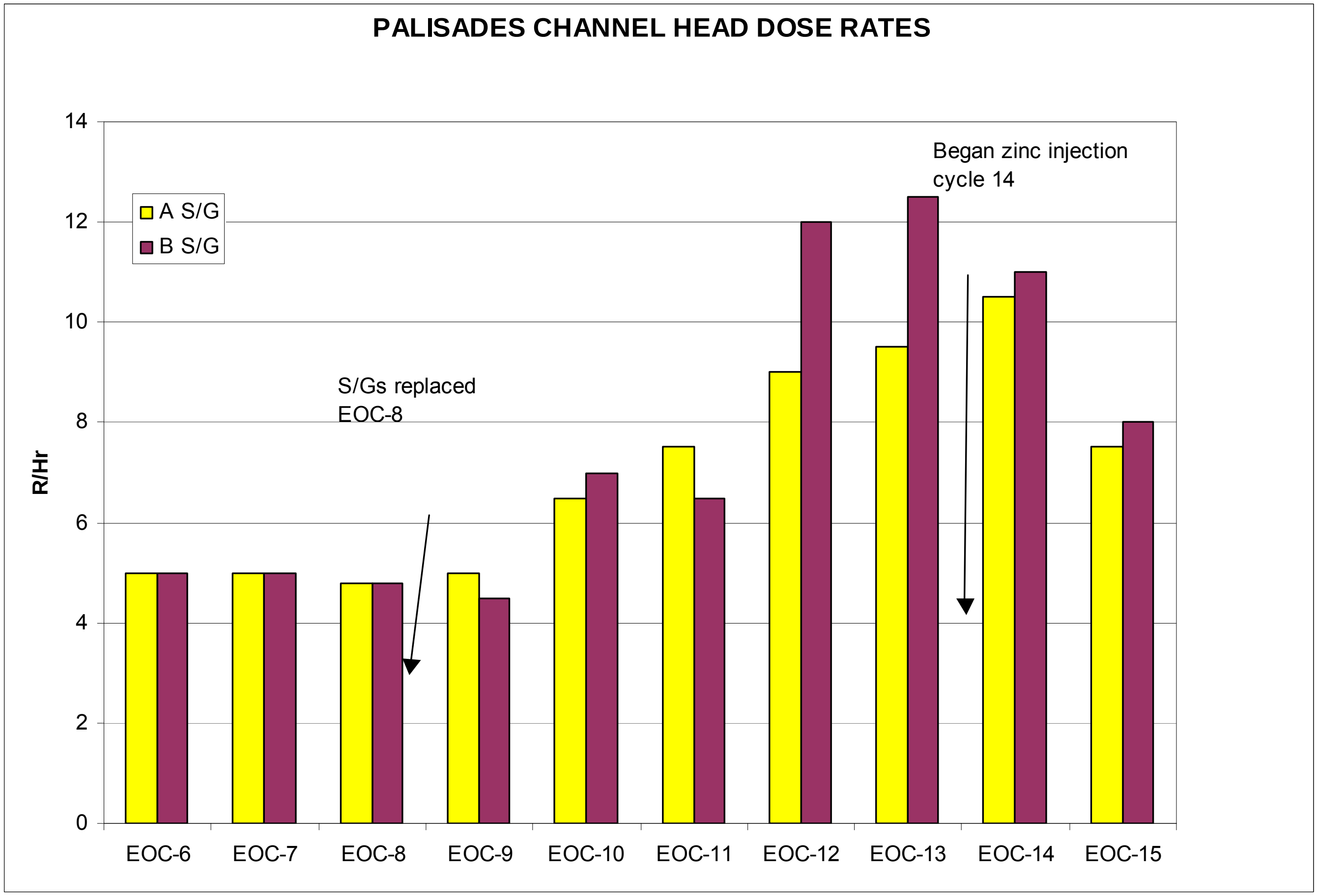
Post Zinc Dose Rate Trends: Palisades
(levels up to 10 ppb)



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

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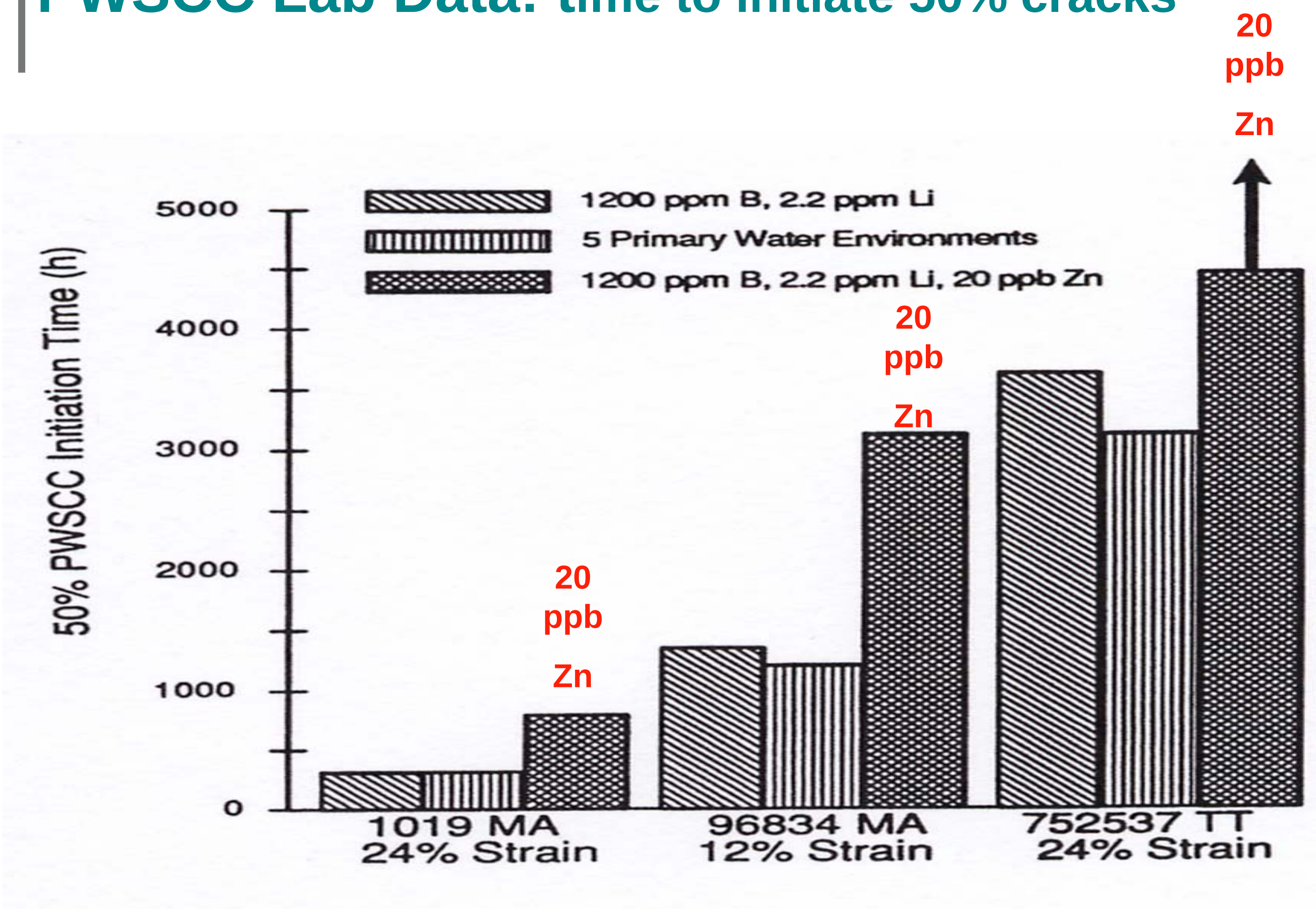
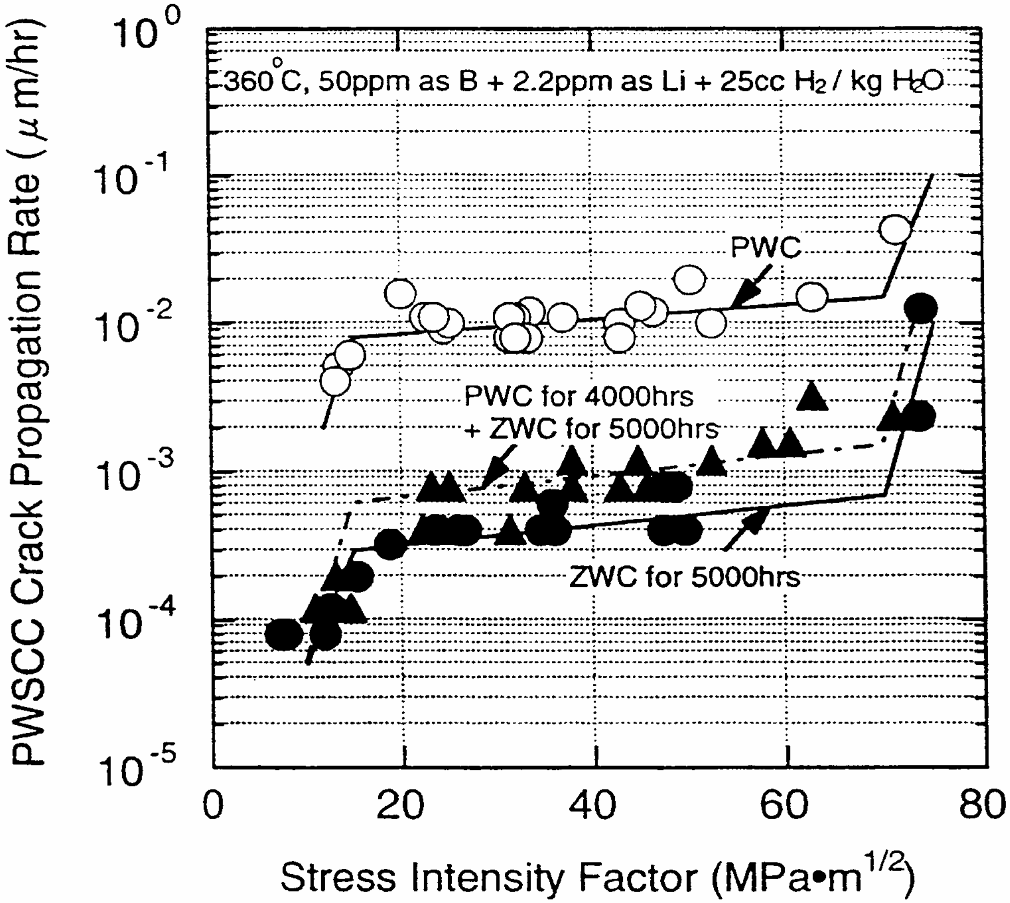
PWSCC Lab Data: time to initiate 50% cracks



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



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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)

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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 ~ 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

1092

- 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 of a number of factors, such as changes in inspection practice and equipment, limited and intermittent periods of zinc injections, modified plugging criteria, etc.

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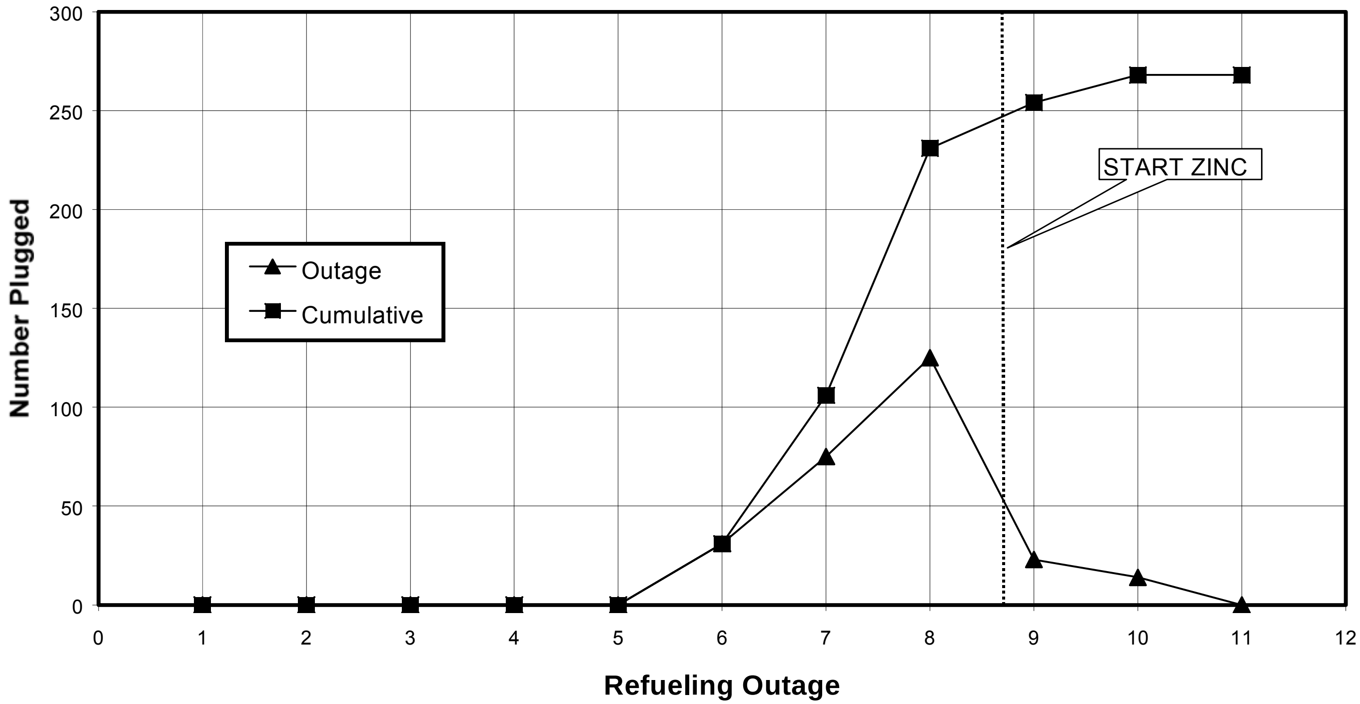
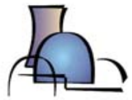
Example for Diablo Canyon Unit 1: SG tube plugging for PWSCC at TSP locations





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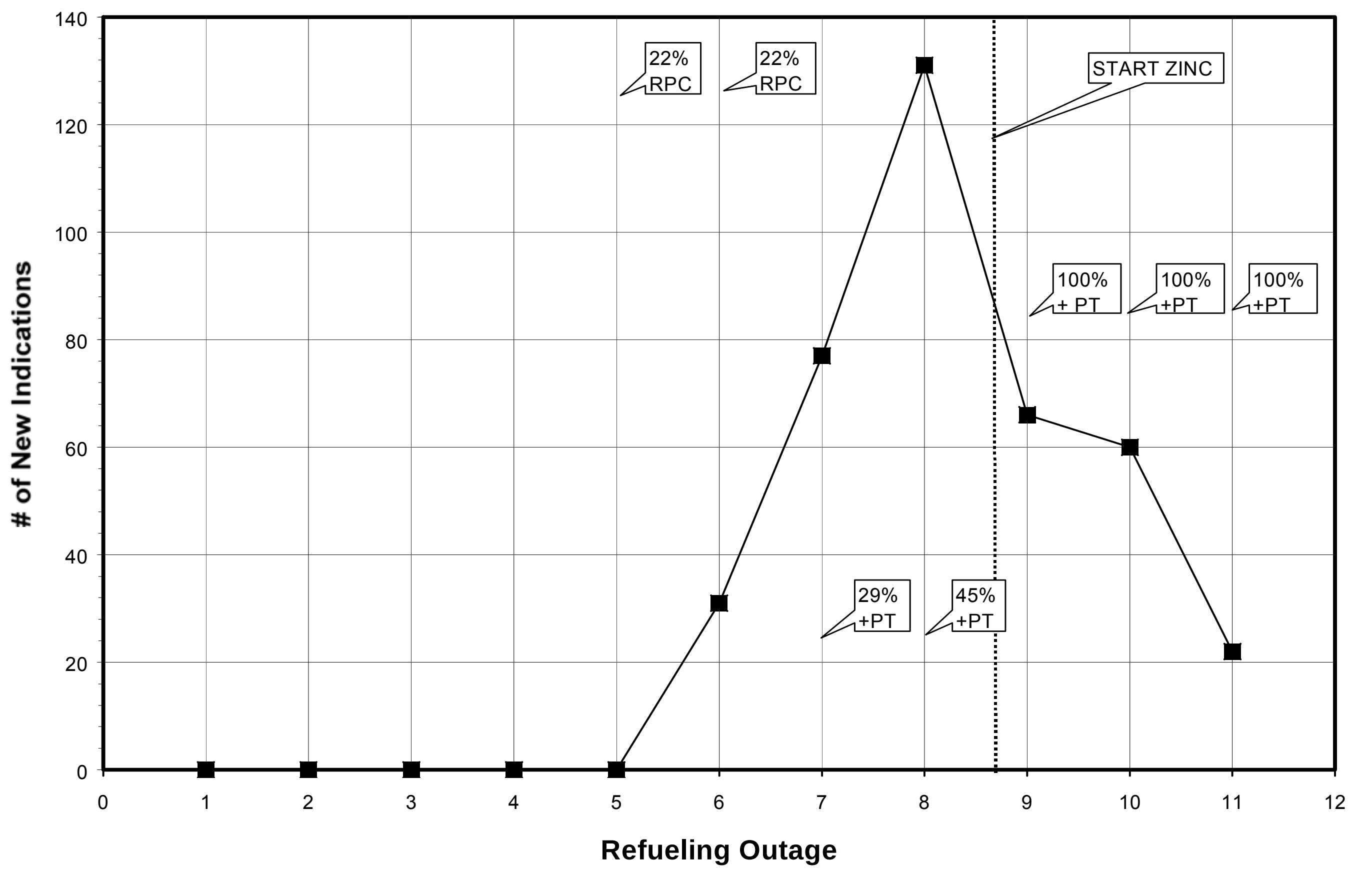
Example for Diablo Canyon Unit 1: new indications of PWSCC at TSP locations



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

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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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Westinghouse

A BNFL Group Company

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

1100

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

GUTTI RAO[1], MANU BADLANI[2], EDWARD RAY[1], and THOMAS DAMICO[2]

[1]Westinghouse Electric Company, LLC
[2]AEA Technology

BNFL   Westinghouse

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

1101

QUALIFICATION PROCEDURES

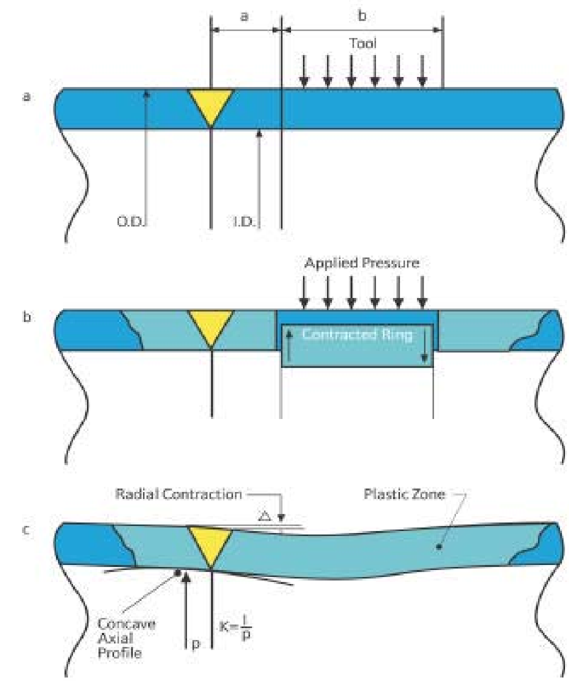
- Detailed qualification procedures were developed for:
  - The MSIP tooling, calibration, testing, data recording and documentation
  - Strain gauge instrumented monitoring of the MSIP testing, including strain gauge positioning and mounting procedures, strain gauge calibration and data recording, and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

1102

1103

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

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PRESURIZER SURGE NOZZLE MOCK-UP FOR TIHANGE 2

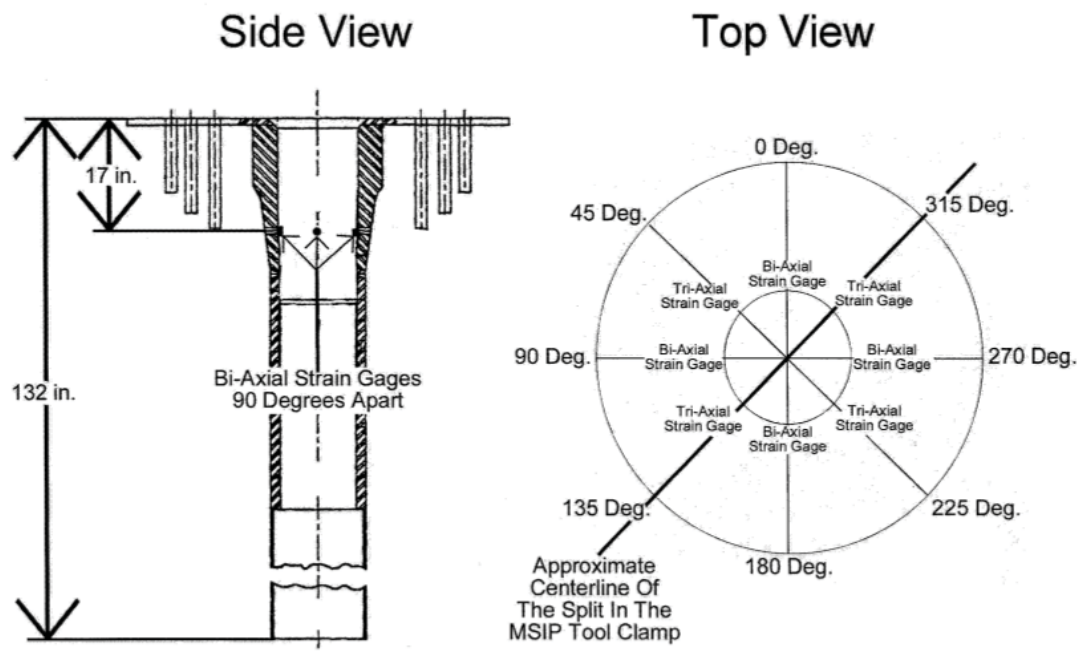
Pressurizer Surge Nozzle Mock-up for Tihange 2

STRAIN GAUGING

1106

- 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

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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

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

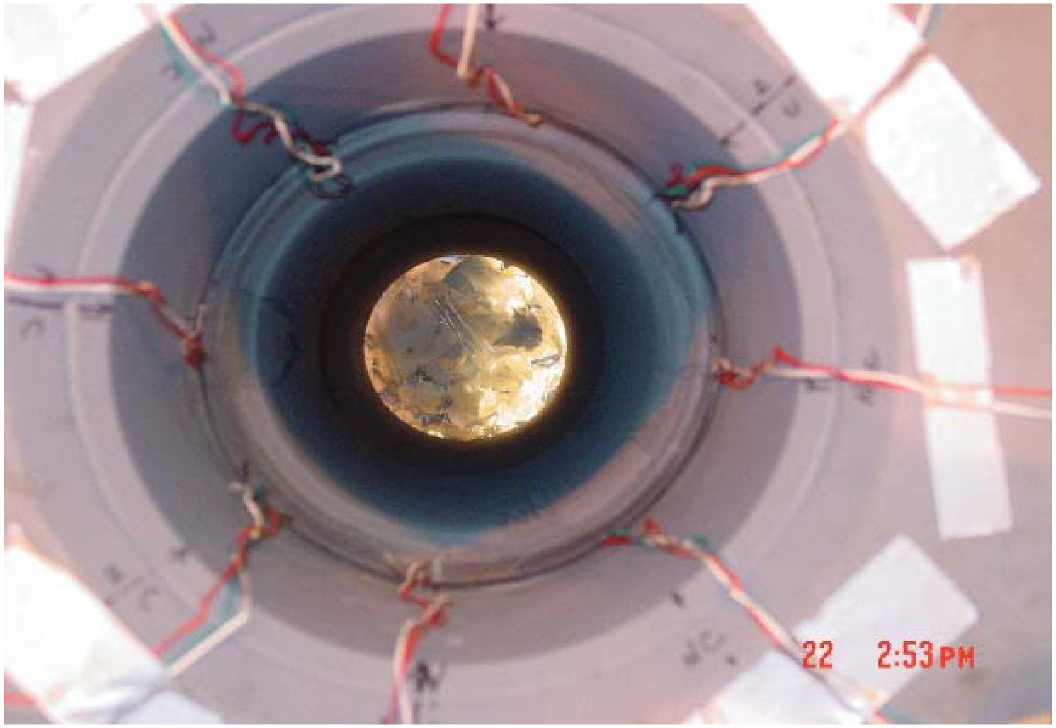
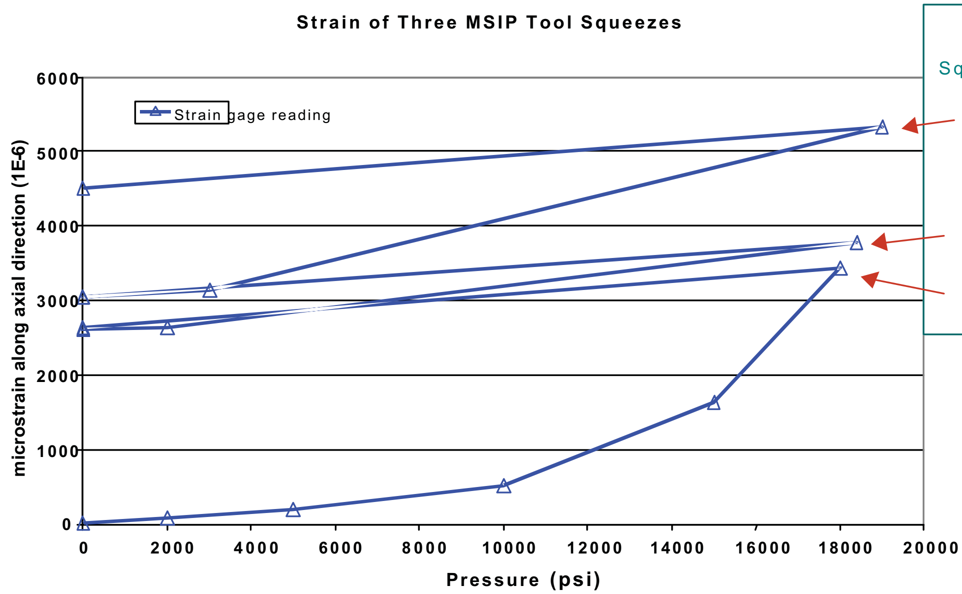


Illustration of the Instrumented Strain Gauges Installed on the ID Surface Near the Weld Location of the Mockup Pressurizer Nozzle

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



Squeeze No.	Average Change in the Safe-end Diameter	
3	0.241"	(1.63%)
2	0.205"	(1.39%)
1	0.176"	(1.19%)

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Safe-end Diameter Changes Associated with the Three MSIP Squeezes

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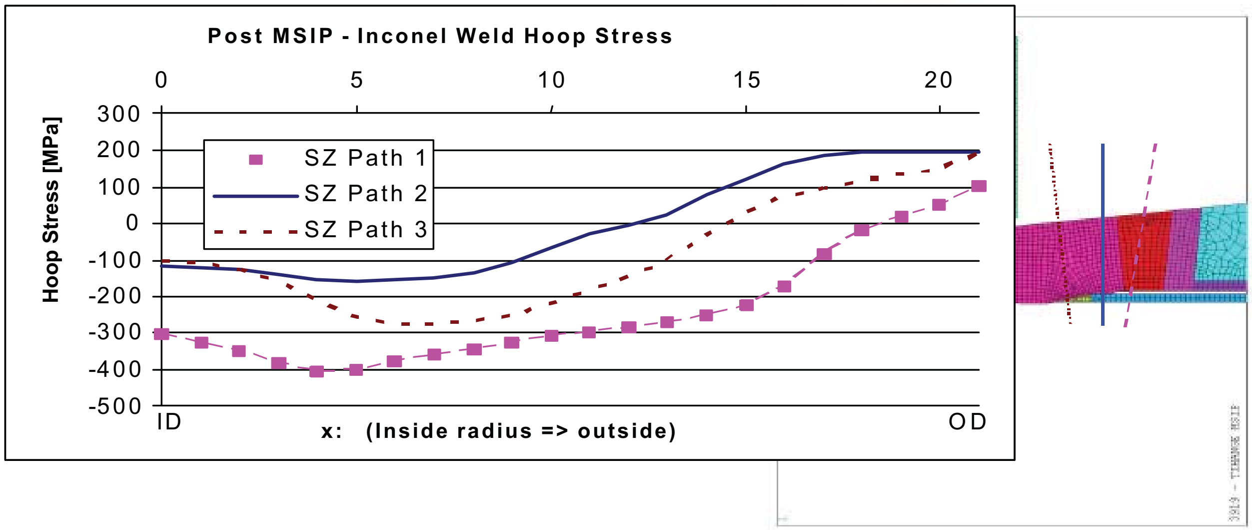
POST MSIP-THROUGH WALL HOOP STRESS

Analytical Results



Post MSIP-Through Wall Hoop Stress

CONCLUSIONS

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- 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

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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

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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**

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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

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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

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

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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

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No Information Available

Session Summary

IV: Crack Growth Rate Studies for the Disposition of Flaws

- total 12 presentations-

Tetsuo Shoji

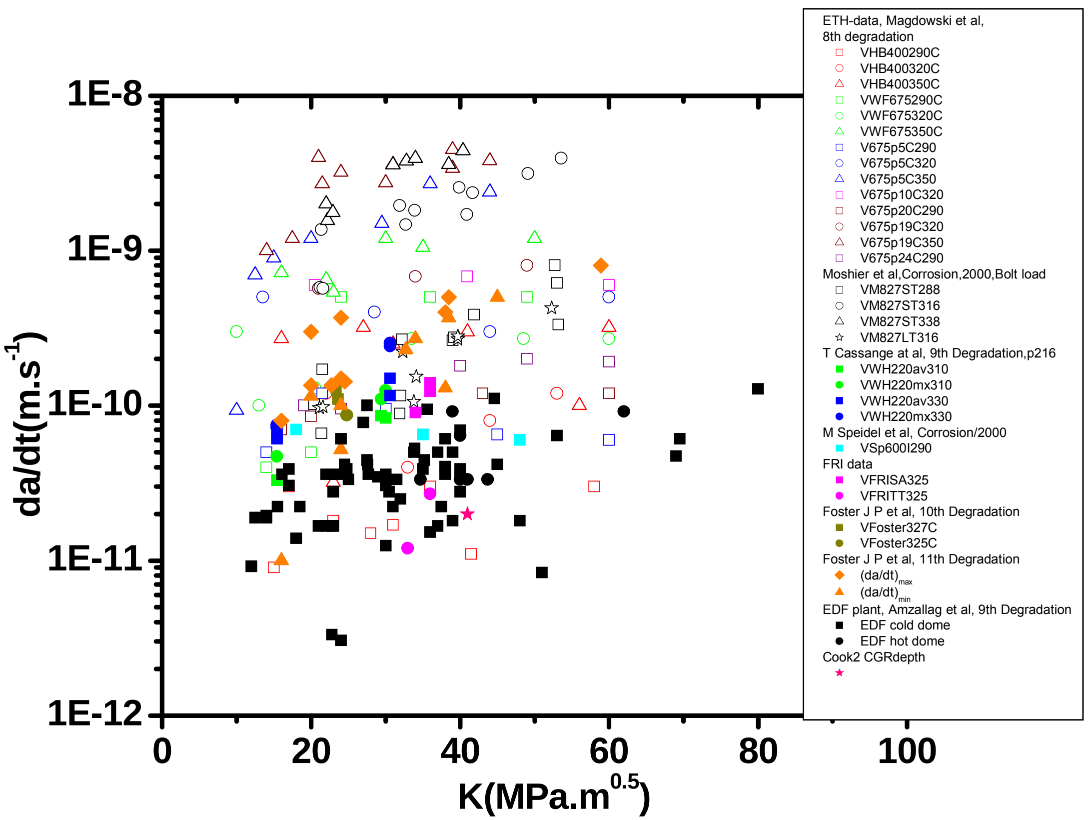
Regulatory Experience and Prognosis on Nickel-Base Alloy PWSCC in VHP and RPV Head Degradation

- 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(IRSN/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 σy 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, κa

SCCGRs –Evaluation Procudures

- Steven Attanasio (Lockheed Martin Co.)
  - Maximum or Average SCCGR?
    - Correlation between Max./Ave. ratio(R)
    - SCCGR data can be reasonably reported as SCCGRave + 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
-alloys182,152,132,82,52 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
-alloys182,152,132,82,52 comparison-

- Richard Jacko(WH)
  - Alloy 52M showed no crack initiation even under an aggressive and accelerated cocndition
  - 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.

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SCCGRs
-alloys182,152,132,82,52 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

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- 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 kineics
    - Significance of σy and dK/dt and other parameters
    - K dependence depends upon σy and m,oxidation kinetics parameter

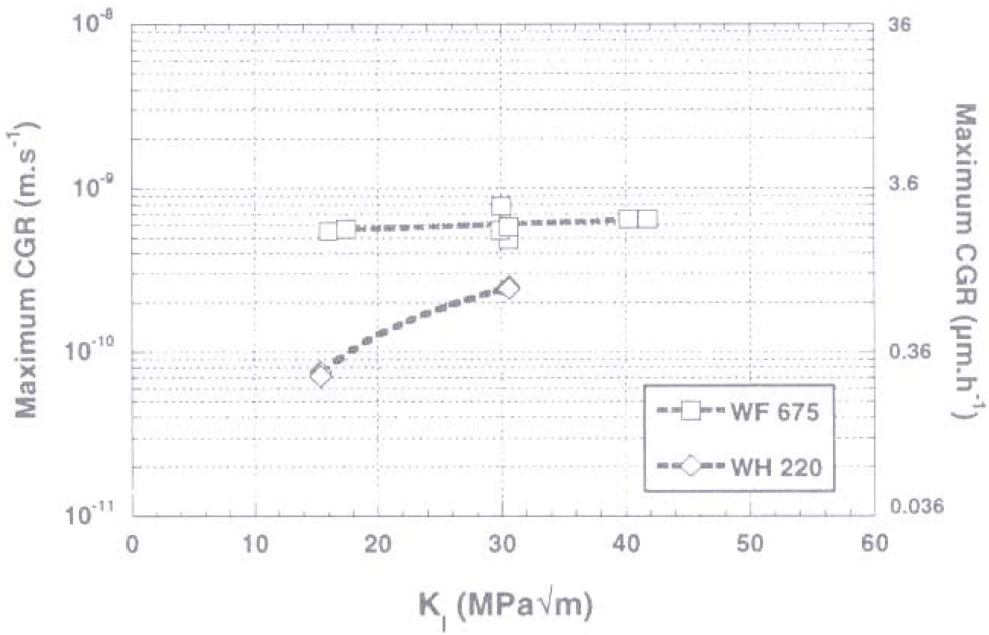
SCCGRs –Models

- Michael Hall, Jr (Bettis APL)
  - Hydrogen Assisted Fracture Model
  - Describe a sensitivities of Alloy 600 to K, T, C% and σy
  - Suggesting a comprehensive dfata 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
9^{th} Degradation,
PWR, 330^{0}C

Two types of CGR-K curves
- WF 675, CGR plateau, YS(WF675)= 468MPa
- WH 220, moderate increase of CGR with K, YS(WH220)= 394MPa

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.**

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. Fyfitch, 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

Session V: Mitigation of Nickel-base Alloy Degradation Summary

- Alloy 600 PWSCC Mitigation: Past, Present, and Future
  S. Fyfitch, 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**

Summary Mitigation of Nickel-base Alloy Degradation

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- **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