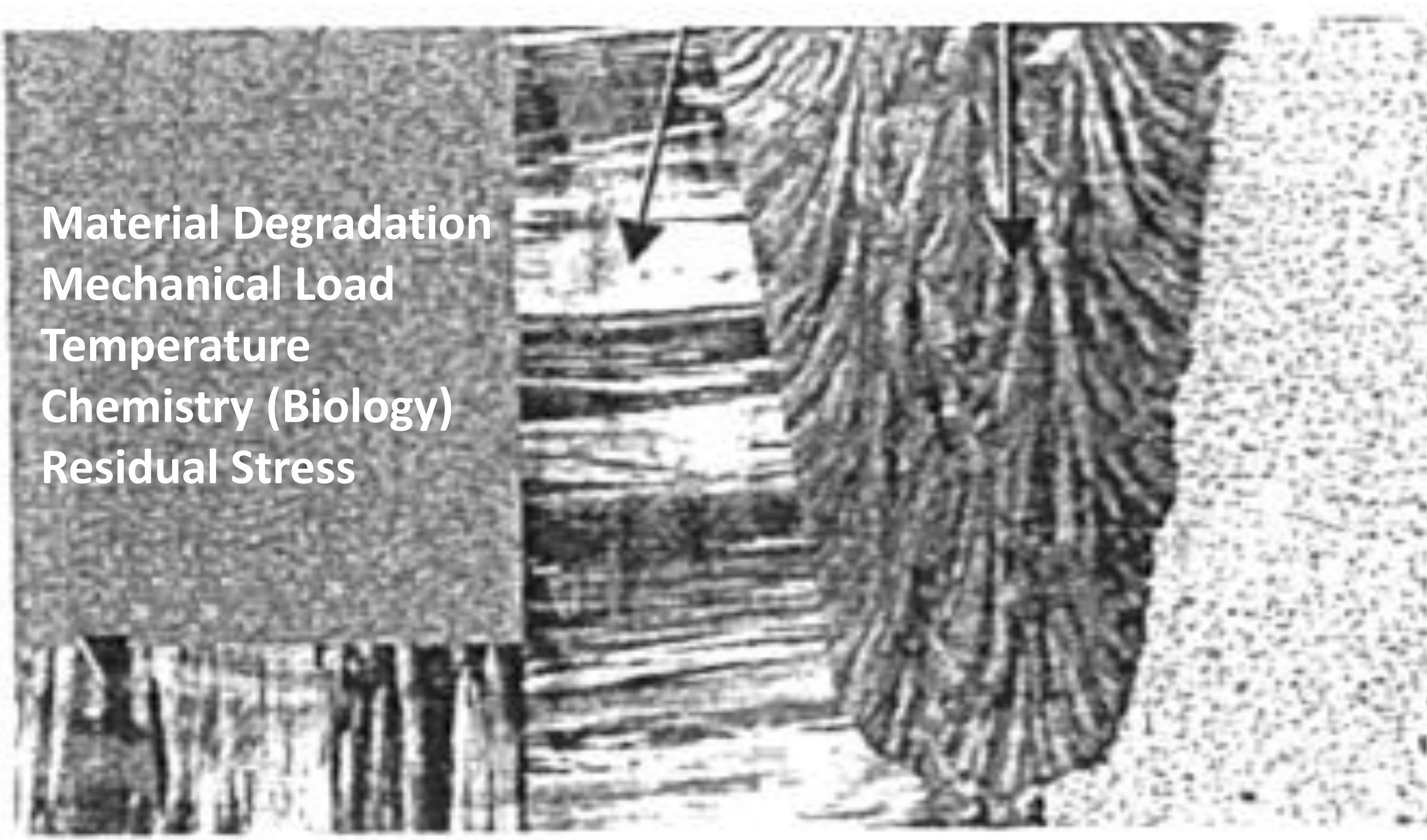
Degradation of nuclear structures during operation

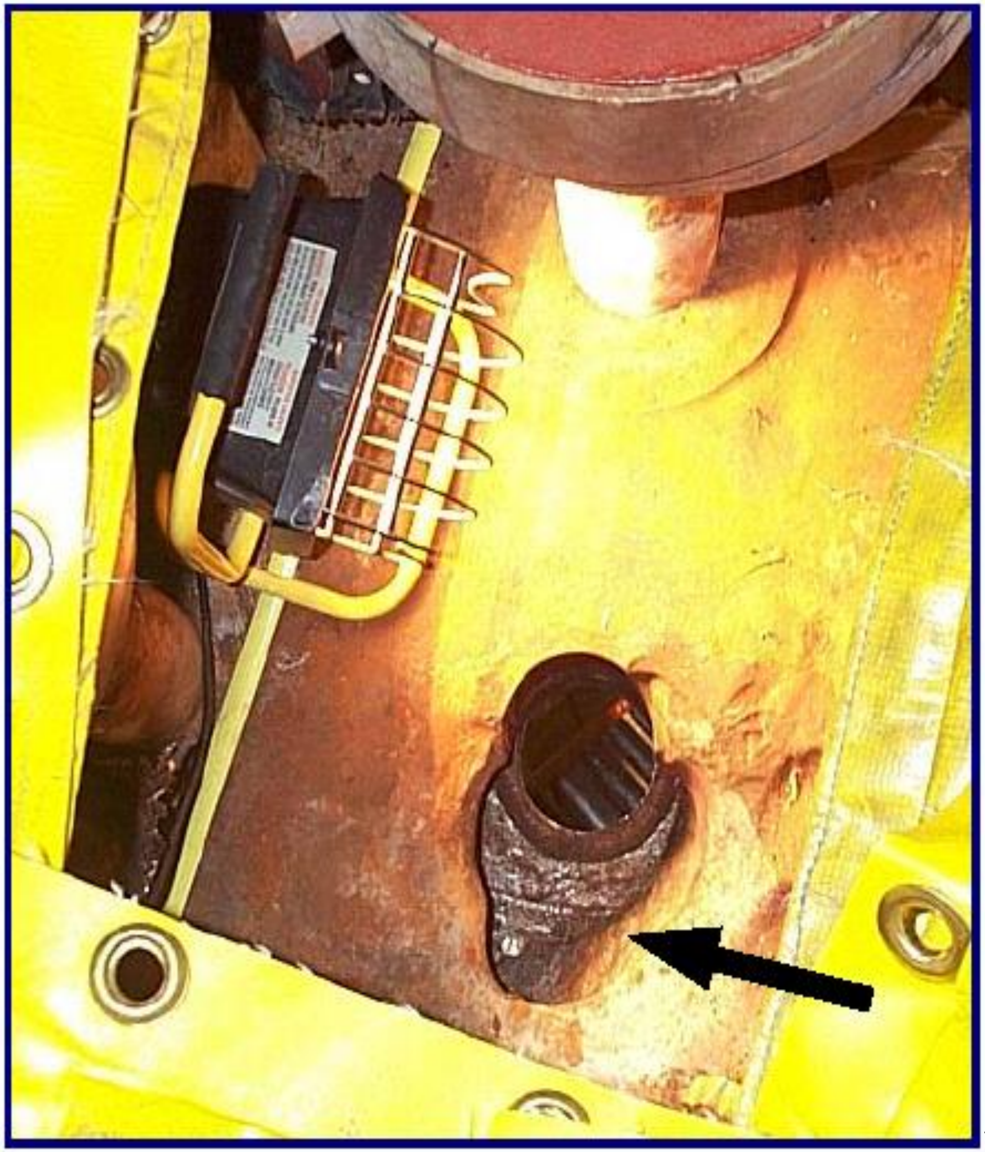


Material Degradation
Mechanical Load
Temperature
Chemistry (Biology)
Residual Stress

Intergranular PWSCC
in Inconel weld material

2.	Degradation of nuclear structures during operation
2.1.	Aging, Neutron Embrittlement, Structural Material Parameters
2.2.	**Stress Corrosion Cracking**
2.3.	Fatigue
2.4.	(Unexpected events)

RPV Closure Head / Boric Acid Corrosion



as Concequence of CRDM-Nozzle Cracking (Inconel 600)

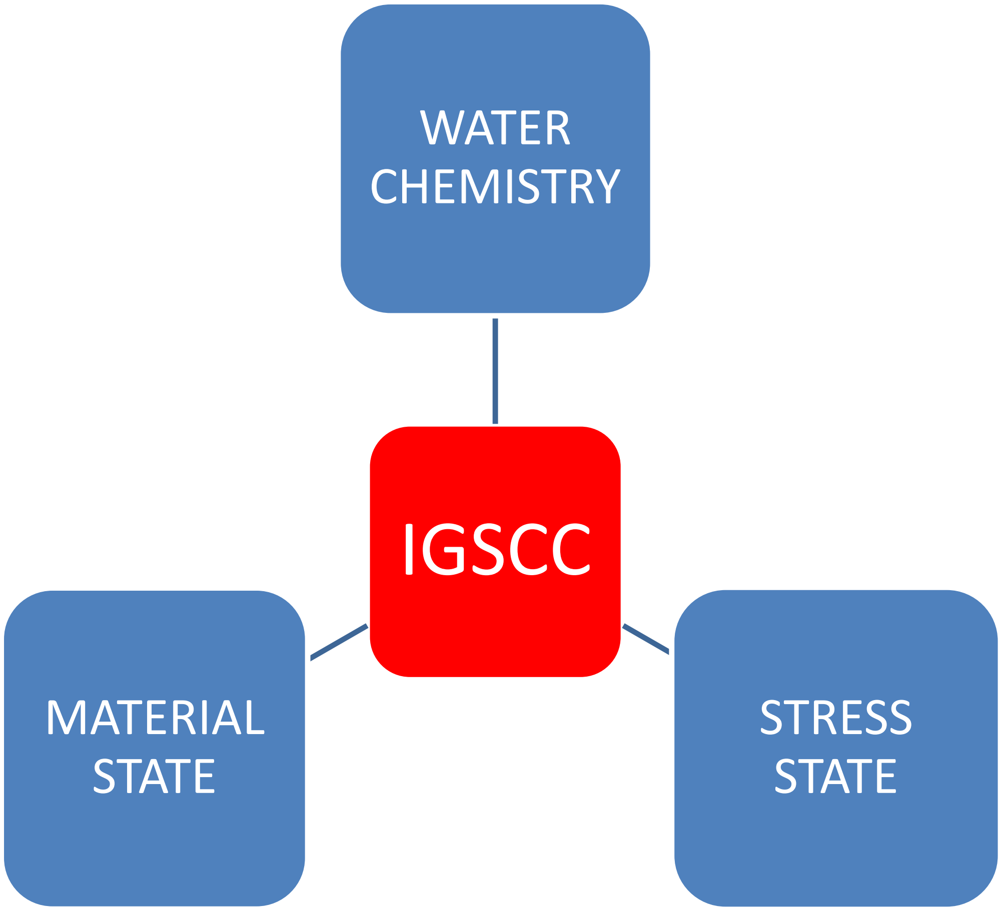
Source: NRC home page

Stress Corrosion Cracking

This is a close-up picture of Nozzle #3 and the cavity area, as seen on page 1.

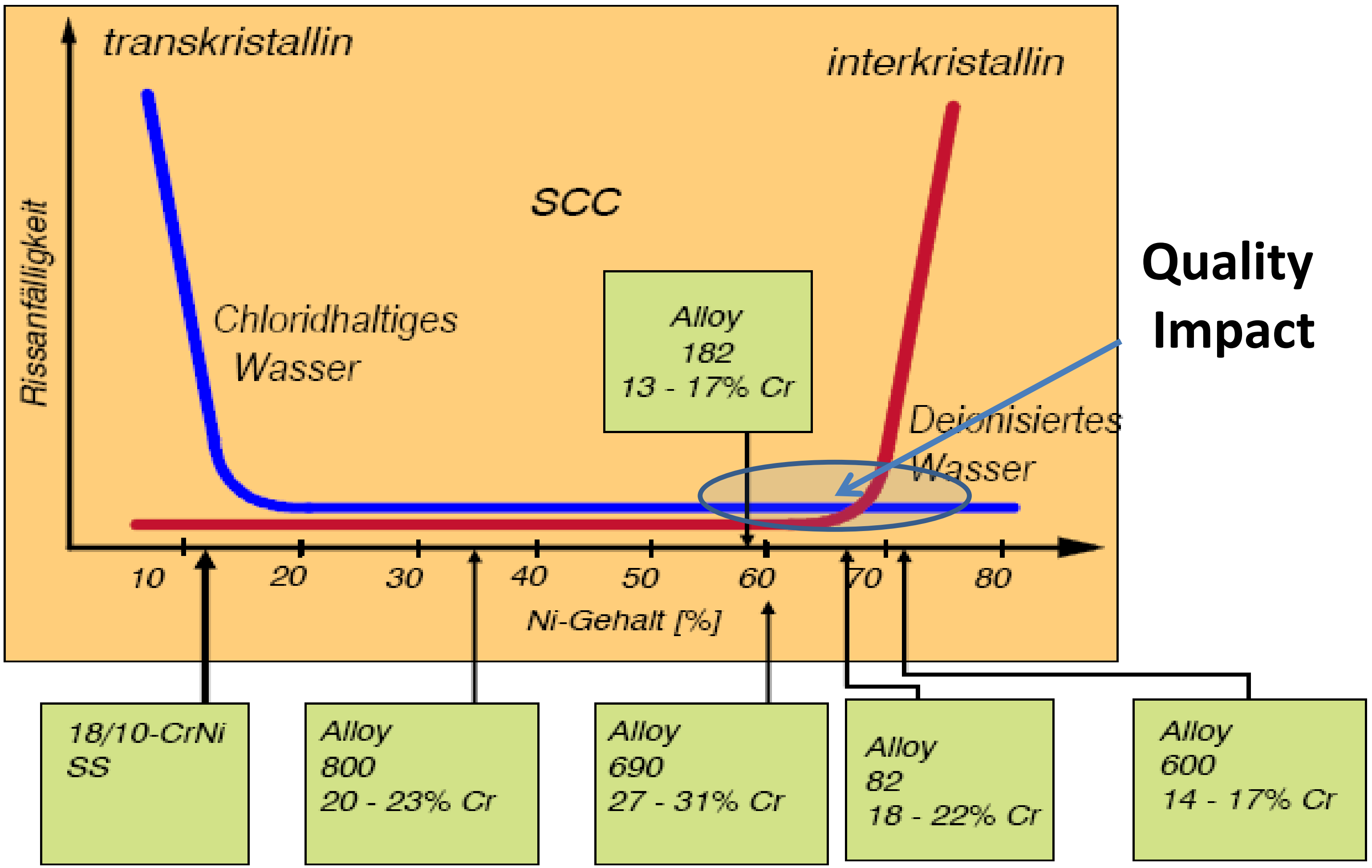
Stress Corrosion Cracking

IGSCC: caused by three factors simultaneously affecting the structure

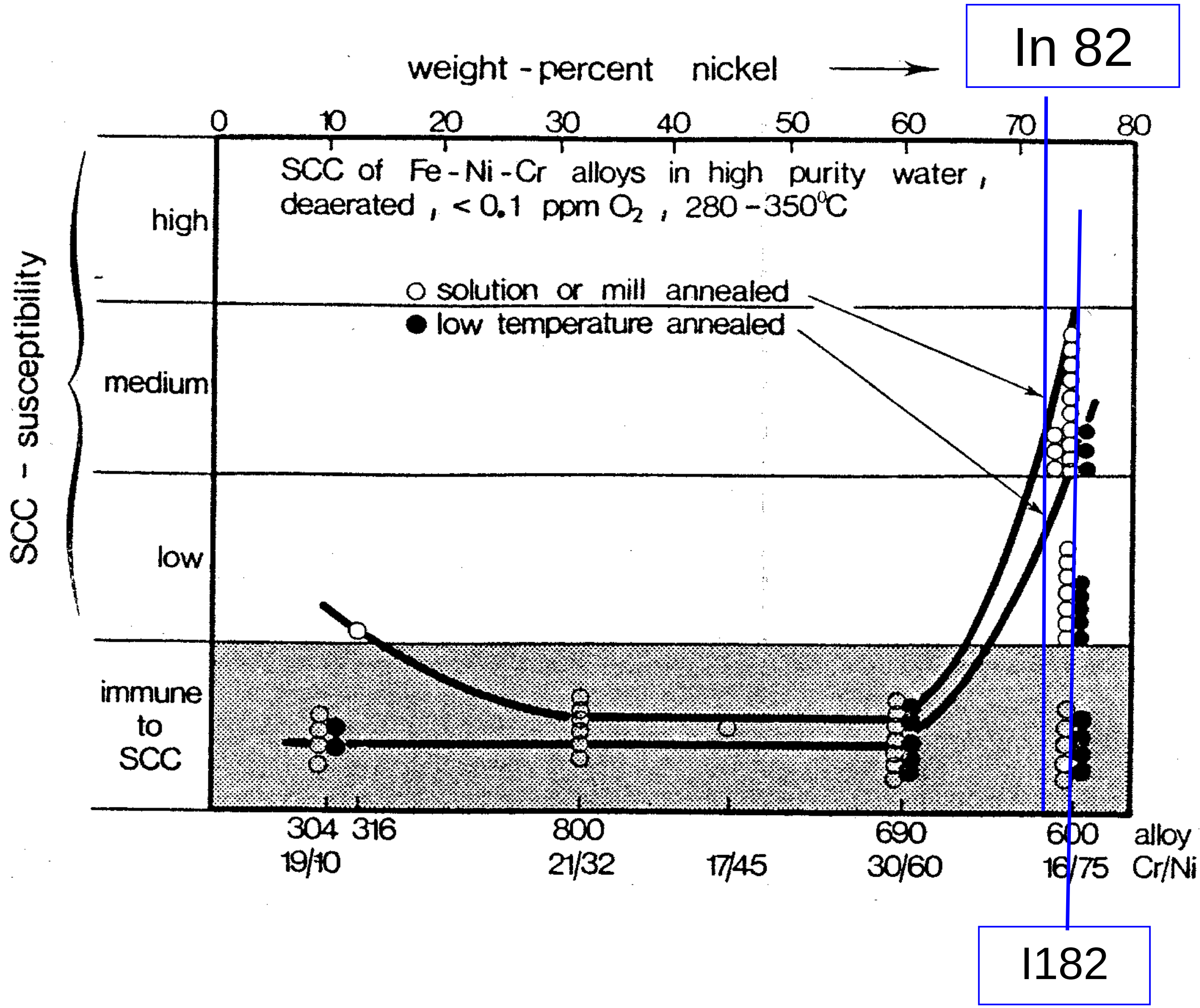


INSPECTION WITH CAUSE

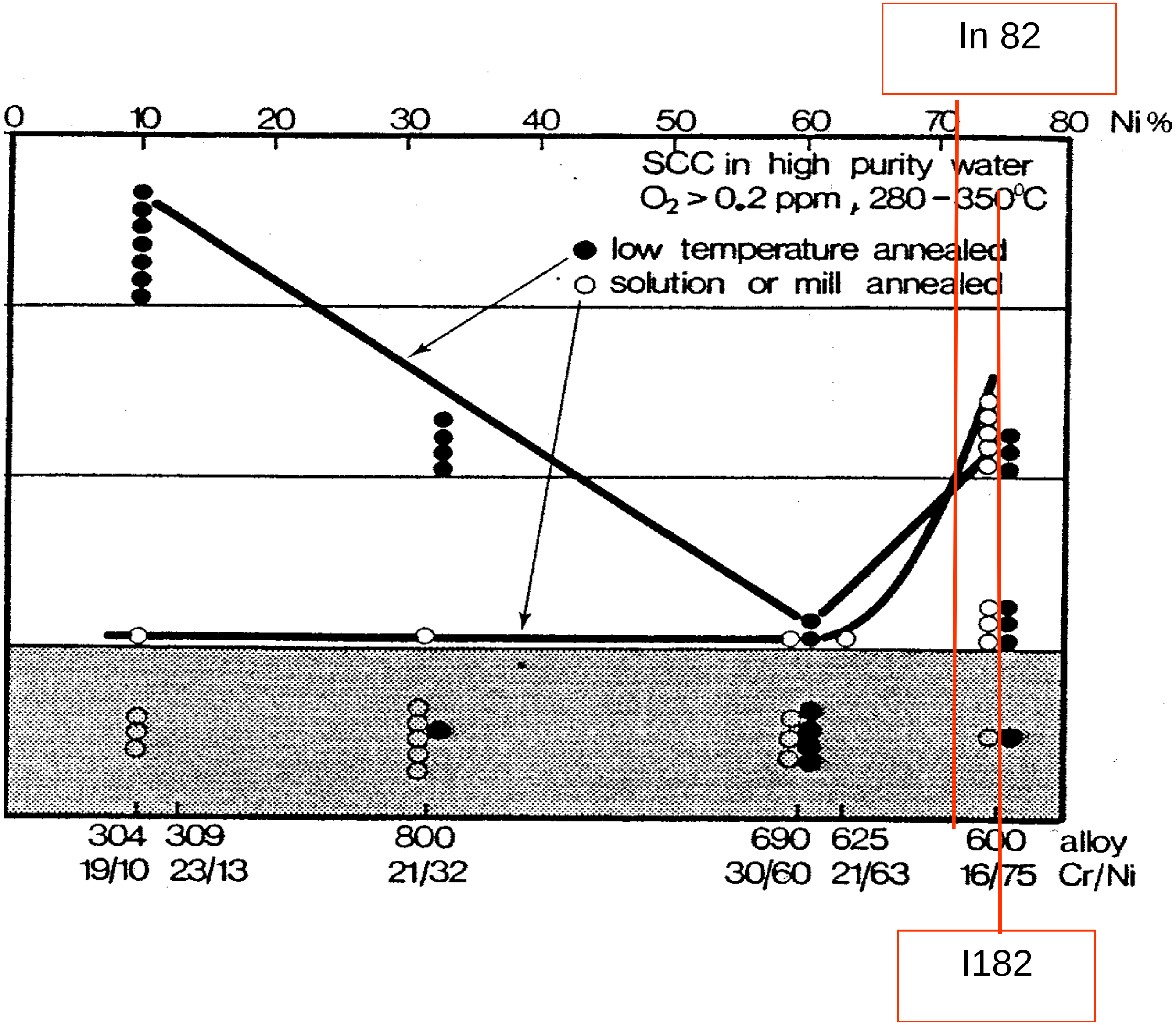
Primary Water Stress Corrosion Cracking - PWSCC



Effect of Nickel Content on IGSCC Susceptibility in High Temperature Water



Effect of Nickel Content on IGSCC Susceptibility: O_2 > 0,2ppm



INTERGRANULAR STRESS COROSION CRACKING
IGSCC

A serious concern for safe and profitable NPP operation

CAUSE FOR INTERNATIONAL COOPERATION

IAEA Extrabudgetary Programme
on Mitigation of Intergranular Stress Corrosion Cracking in RBMK Reactors

INTERGRANULAR STRESS COROSION CRACKING
IGSCC

There is painful evidence for IGSCC

(*see also*: **IGSCC IN AUSTENITIC STAINLESS STEEL PIPING OF RBMK REACTORS REPORT OF THE SAFETY ASSESSMENT GROUP***:* IAEA-EBP-IGSCC-P03 Vienna, 99)

Cause for great international cooperation
The IAEA Programme

The Programme relied on extrabudgetary funding from Japan, Spain, UK and the USA, as well as in-kind contributions from Finland, Germany, Lithuania, Russia, Sweden and the Ukraine. Major input was provided through related national or bi-lateral activities, such as the Swedish International Project Nuclear Safety (SIP) and the US Department of Energy International Nuclear Safety Program (INSP).

IGSCC: IAEA Program
Cause

IGSCC of chromium nickel stainless steel piping in BWRs has had a major impact on plant availability since the early seventies. Cracks in BWR piping have occurred mainly in the sensitized heat affected zones of welds subject to relatively high residual tensile stress due to welding processes and water chemistry.

In 1997, a similar cracking phenomenon has been revealed on a number of RMBK reactor pipings in Lithuania, Russia and Ukraine. Early in 1998, the Agency initiated activities to assist the countries operating RBMK reactors to address the issue.

In May 2000, the Agency started an Extrabudgetary Programme to assist countries operating RBMK reactors to mitigate effectively IGSCC in austenitic stainless steel piping. This Programme was completed mid-2002.

IAEA Program Implementation

The activities of the Program were conducted in four Working Groups, which focus on:

- **Improvements to in-service inspection (performance and qualification);**
- ***Comprehensive assessment techniques;***
- **Qualification of repair techniques;**
- **Water chemistry and decontamination techniques.**

IAEA Training Program

- Risk based inspection;
- Advanced ultrasonic training seminar for
  IGSCC detection and flaw sizing
  characterization and repair of IGSCC
  weld overlay examination (including transfer of respective procedures);
- Advanced ultrasonic training course for
  detection and characterization of IGSCC in stainless steel piping;
- Weld overlay ultrasonic testing techniques;
- Advanced ultrasonic sizing seminar;
- Automated IGSCC ultrasonic inspection seminar;

- GTAW welding and repair methods;
- Water chemistry monitoring (Gundremmingen and Philippsburg NPPs);
- Seminar on risk based inspection pilot study for Ignalina NPP.

Main Root Causes of IGSCC: stainless steel 08X18H10T (RBMK):

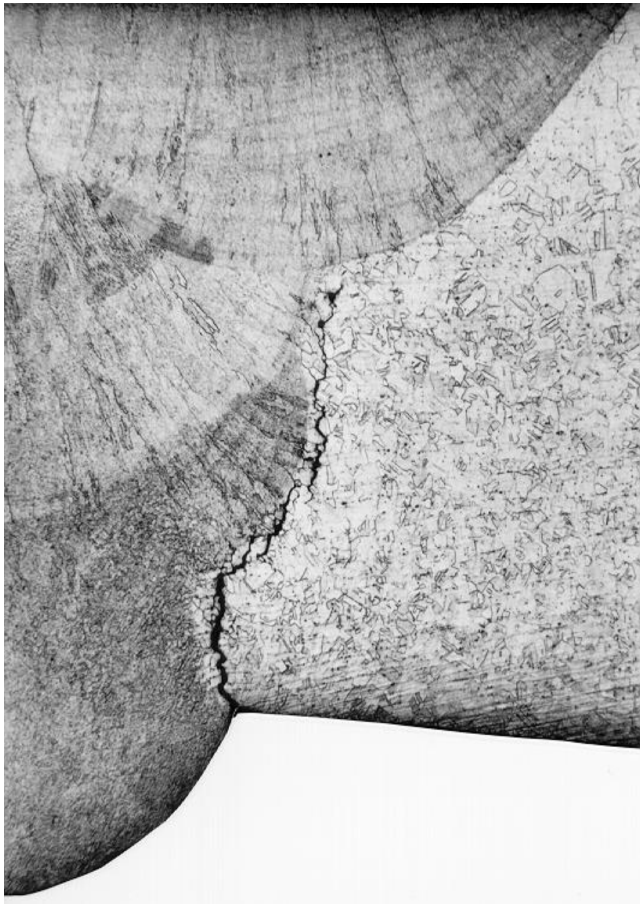
- **Sensitization caused by** high degree of free carbon, low stabilization ratio in the material, and high heat input during welding;
- **Deformation** of the pipe inner surface due to weld preparation;
- **Geometrical weld imperfections** accelerating crack initiation;
- **Material Deformation** in the heat affected zone (HAZ) due to weld shrinkage;
- **High tensile stresses** (residual and/or operational), indicated by a large opening of the cracks;

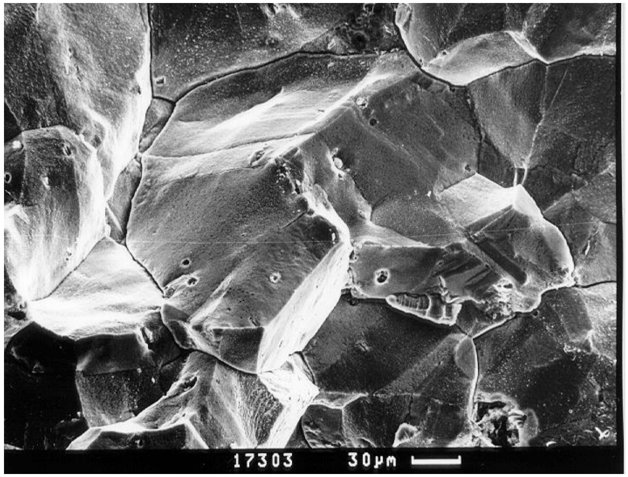
Main Root Causes of IGSCC: stainless steel 08X18H10T (RBMK):

- **Environmental parameters**, indicated by chlorides on the fracture surface, known condenser leakage incidents, possible sulphate intrusions, which cannot be ruled out, water impurities and the oxidizing power of the water;
- **Operational fluctuating stresses**, indicated by observation of fatigue striations on the fracture surfaces.

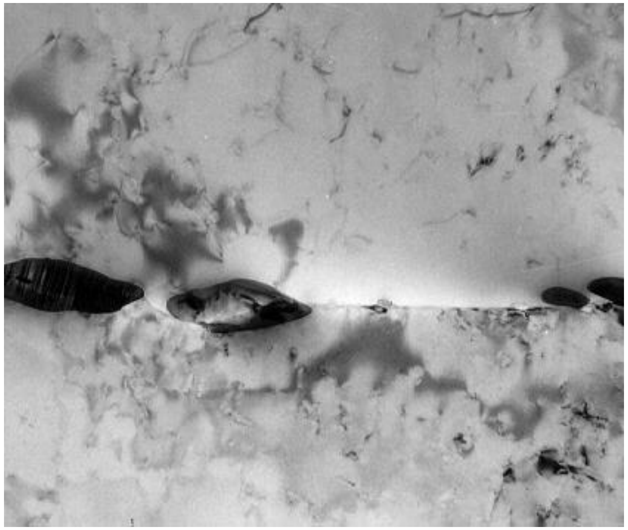
Stress Corrosion Cracking

Austenitic Stainless Steels in HT-Water
IGSCC due to Sensitization by Chromium Depletion



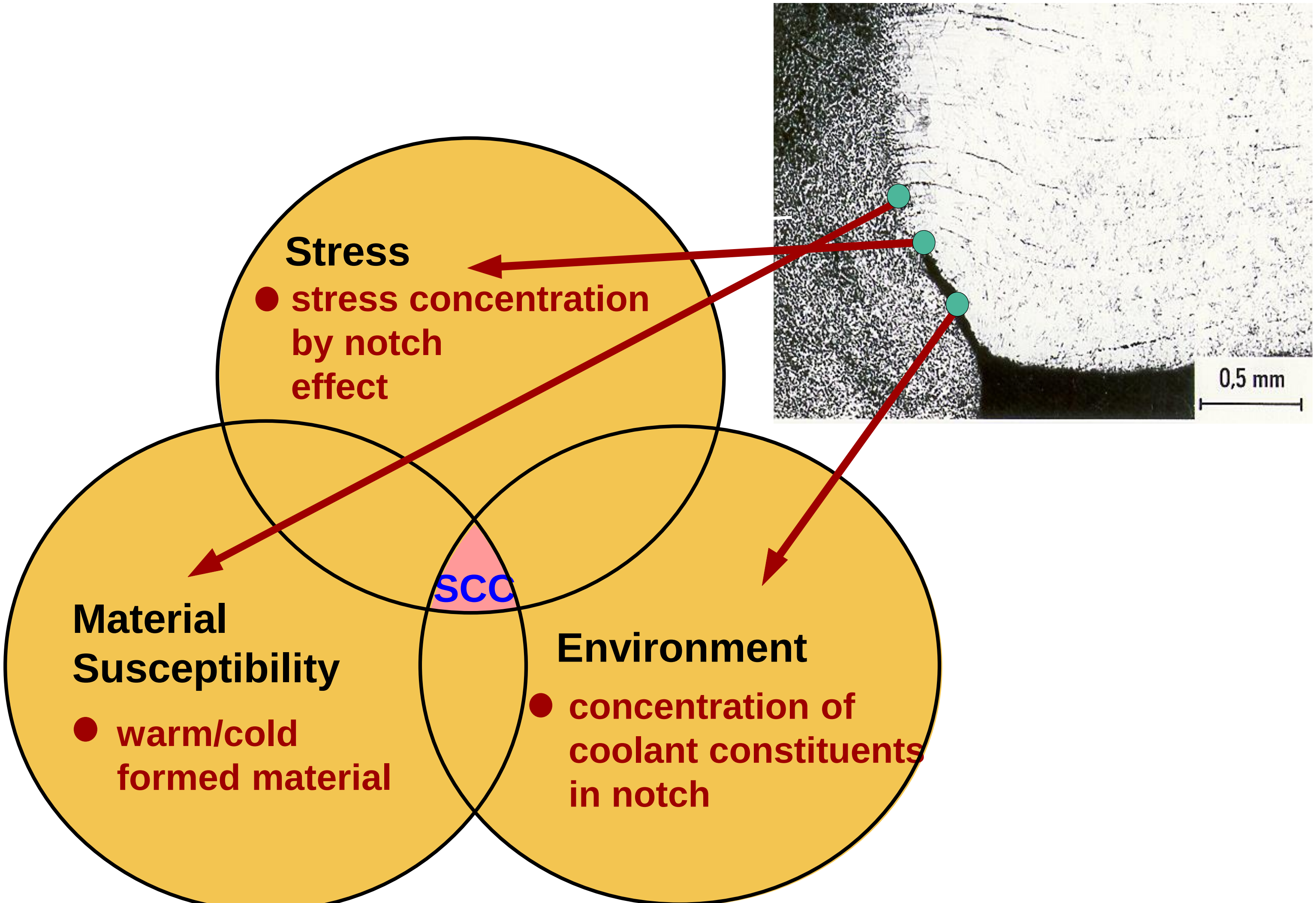


SEM



TEM

Cracking in Austenitic Stainless Steel Piping
Importance of Root Formation during Welding Process



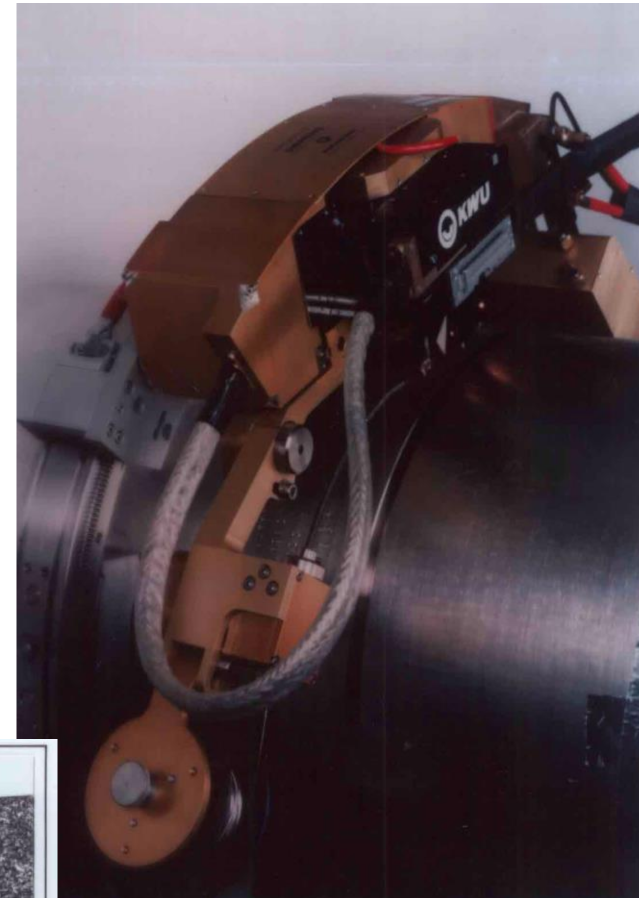
IGSCC in Austenitic Steel 304 Grade

Standard Weld Design

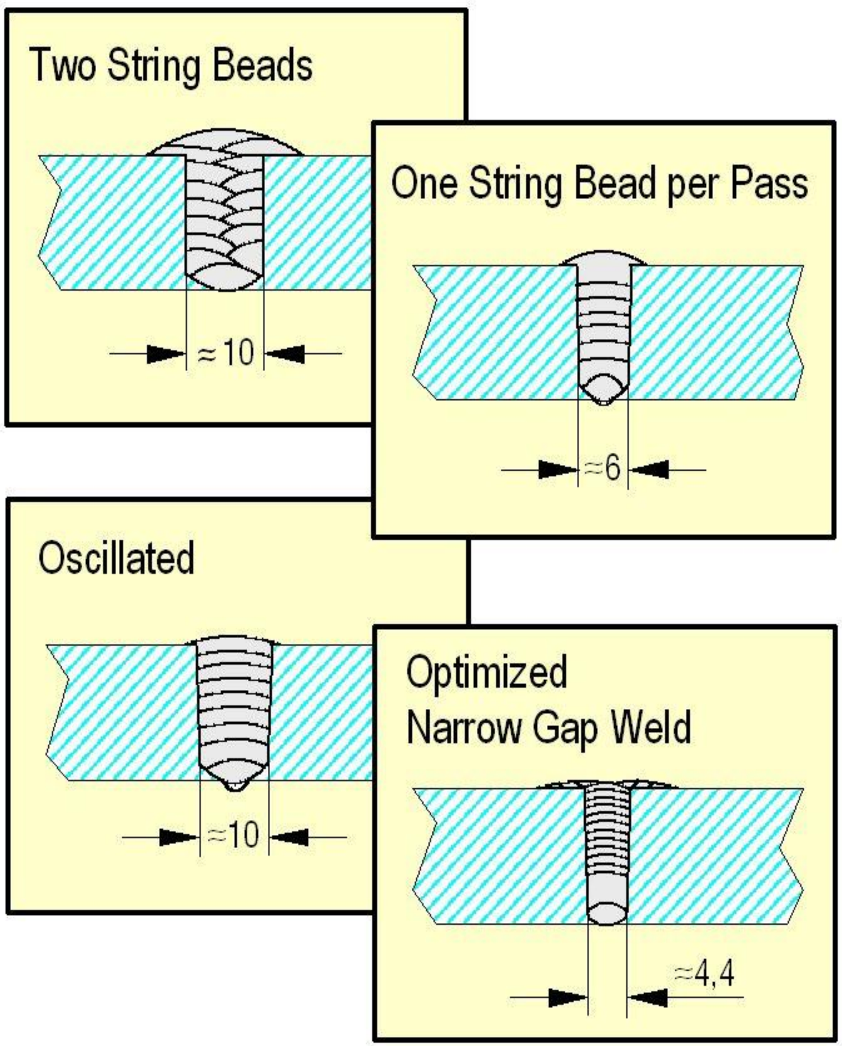
Narrow Gap Welding

MITIGATION STRATEGIES: Welding Technology

Pipe Welding with Orbital Welding Head (TIG)

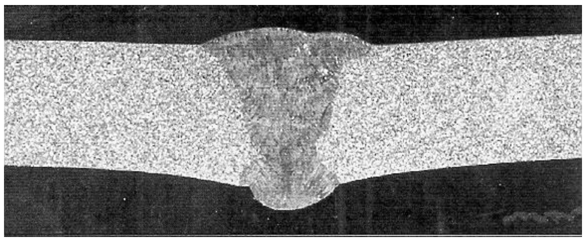


Comparison of GTA Welds



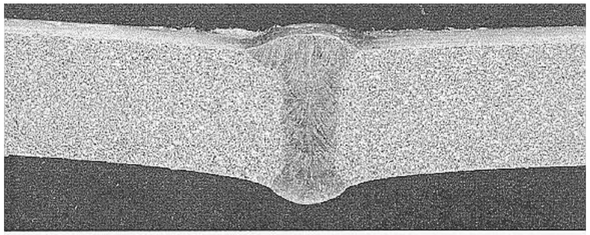
Manual Weld

Material: Austenit Thickness: 12 mm



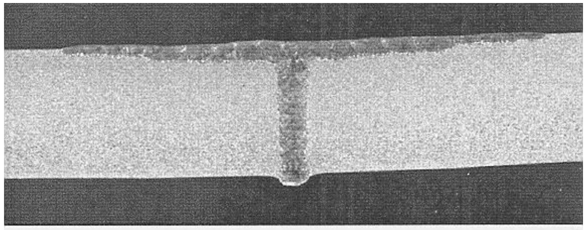
Former Narrow Gap Weld

Material: Austenit Thickness: 12 mm

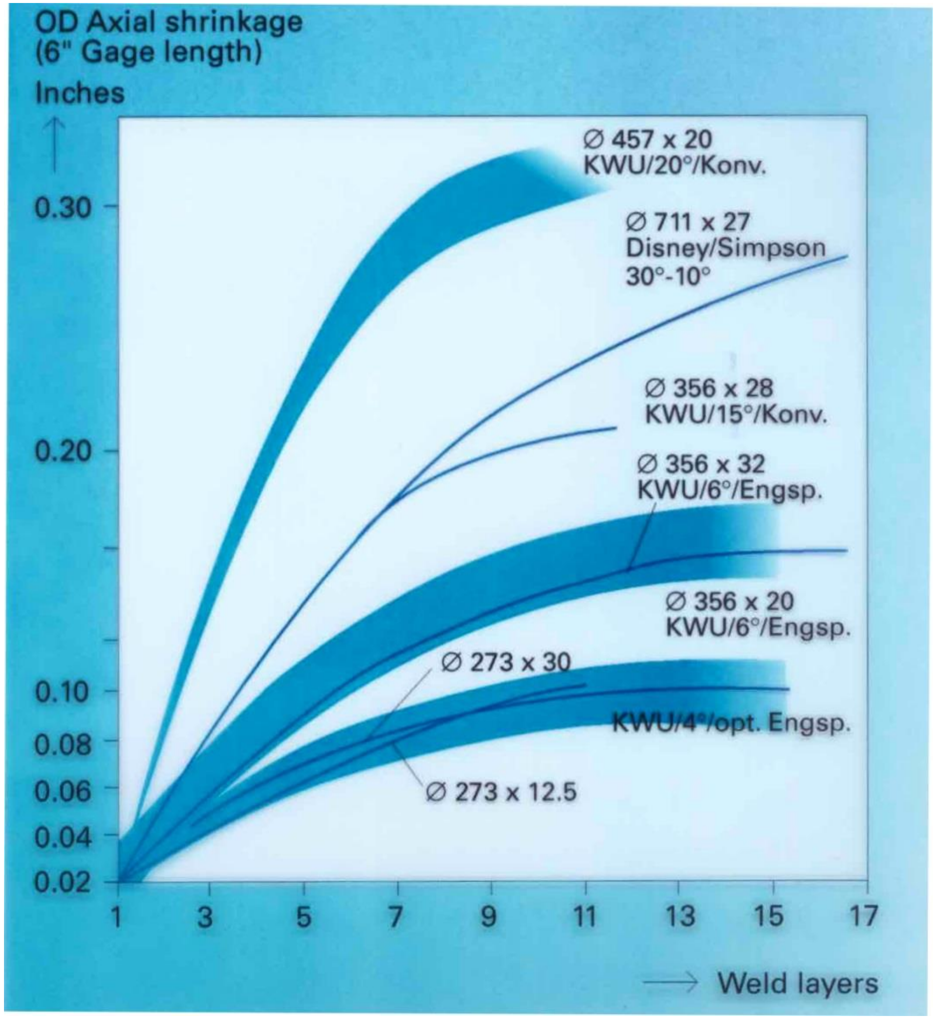


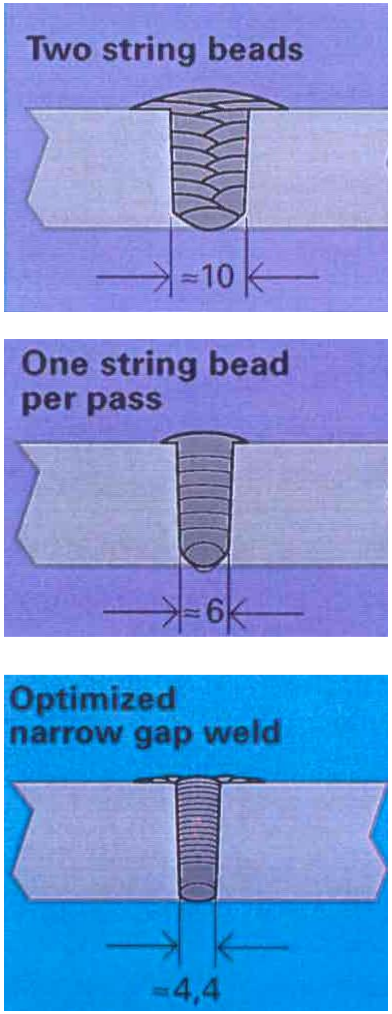
Optimized Narrow Gap Weld

Material: Austenit Thickness: 12 mm

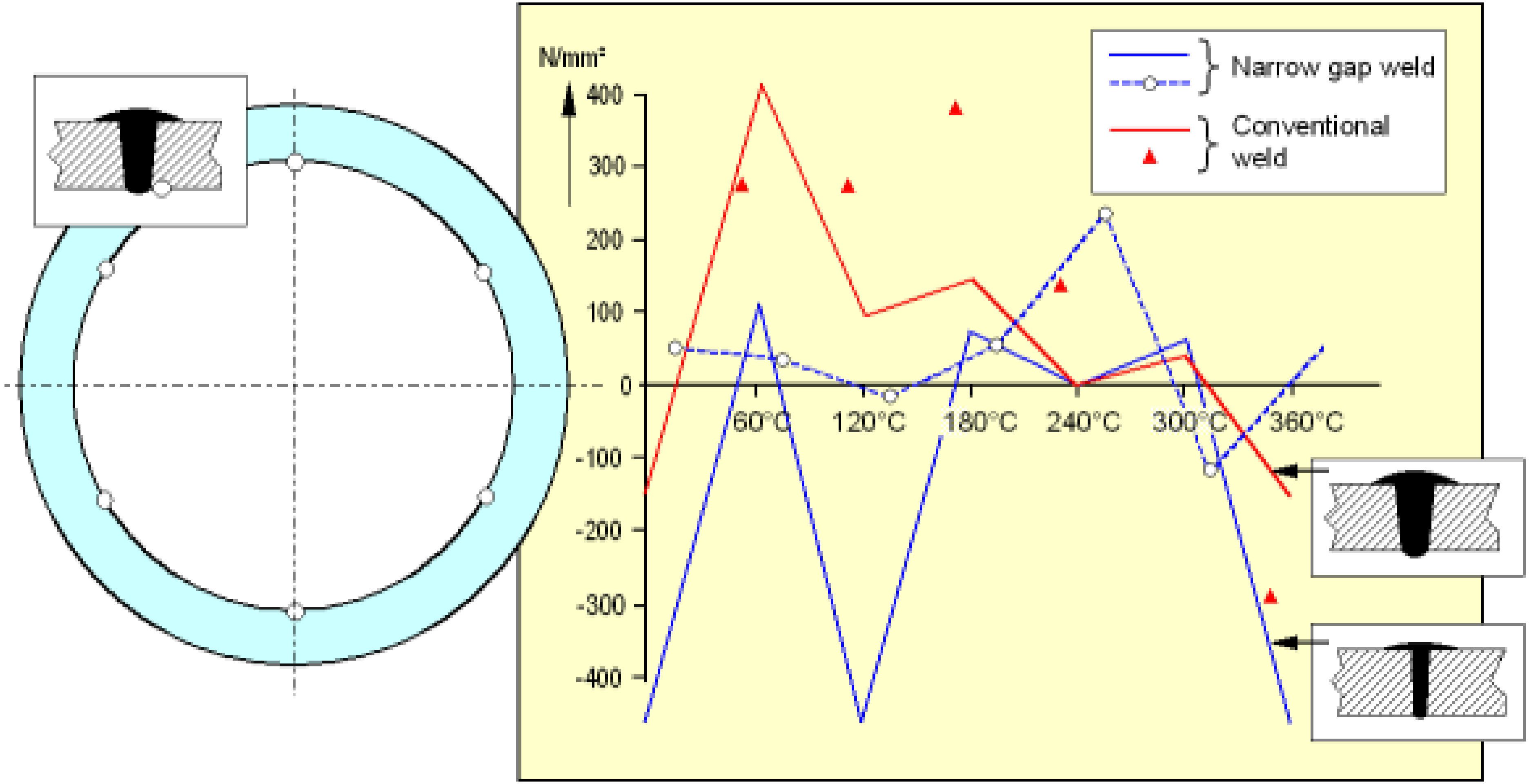


Shrinkage in TIG-Orbital Welding (Conventional Gap - Optimized Narrow Gap)



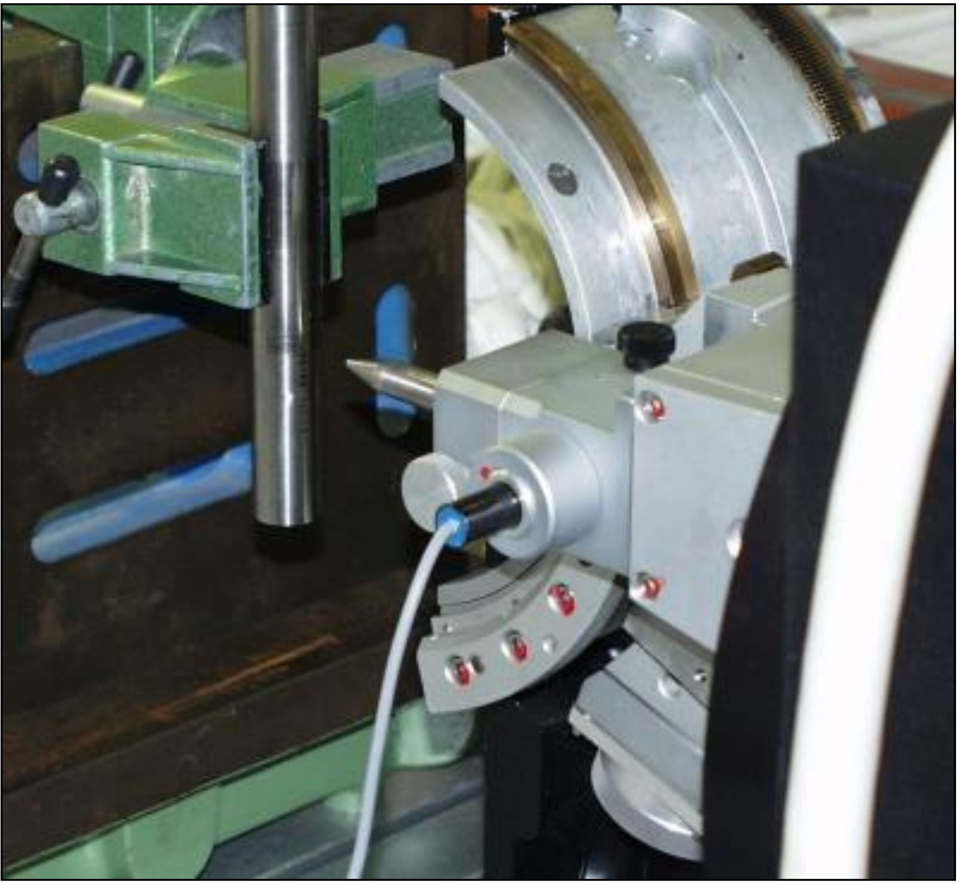


Residual Stress State

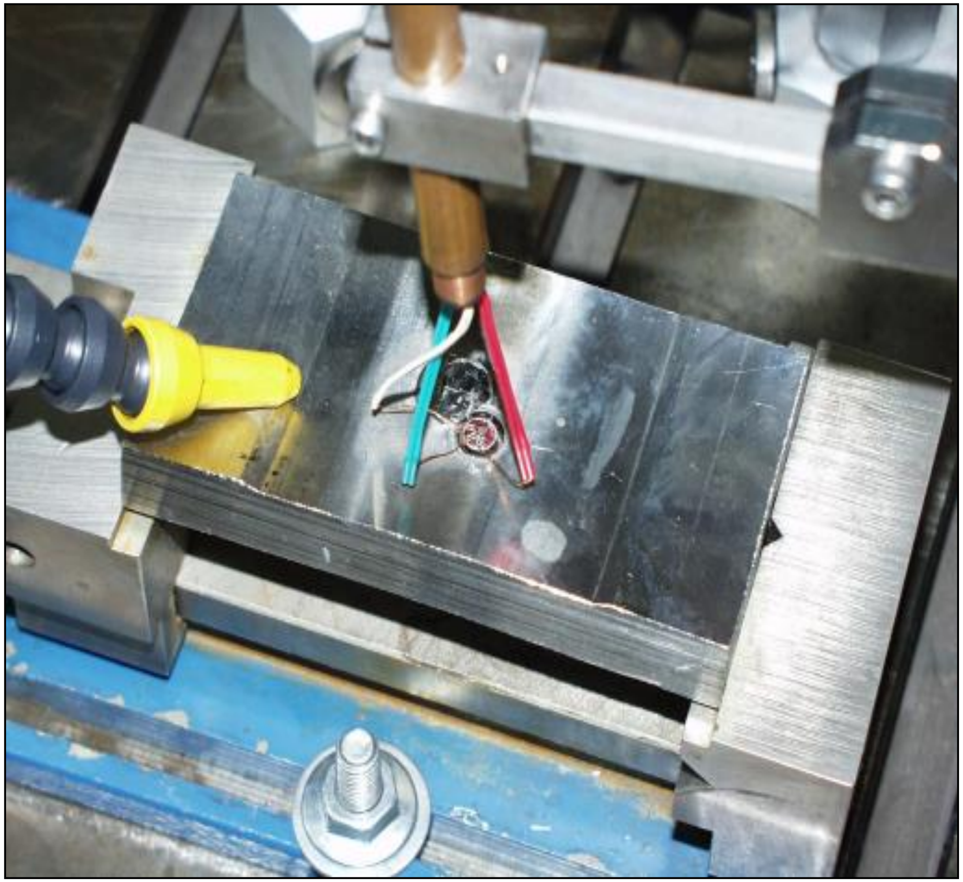


Residual Stress State Measurement Techniques

X-Ray Diffraction Method

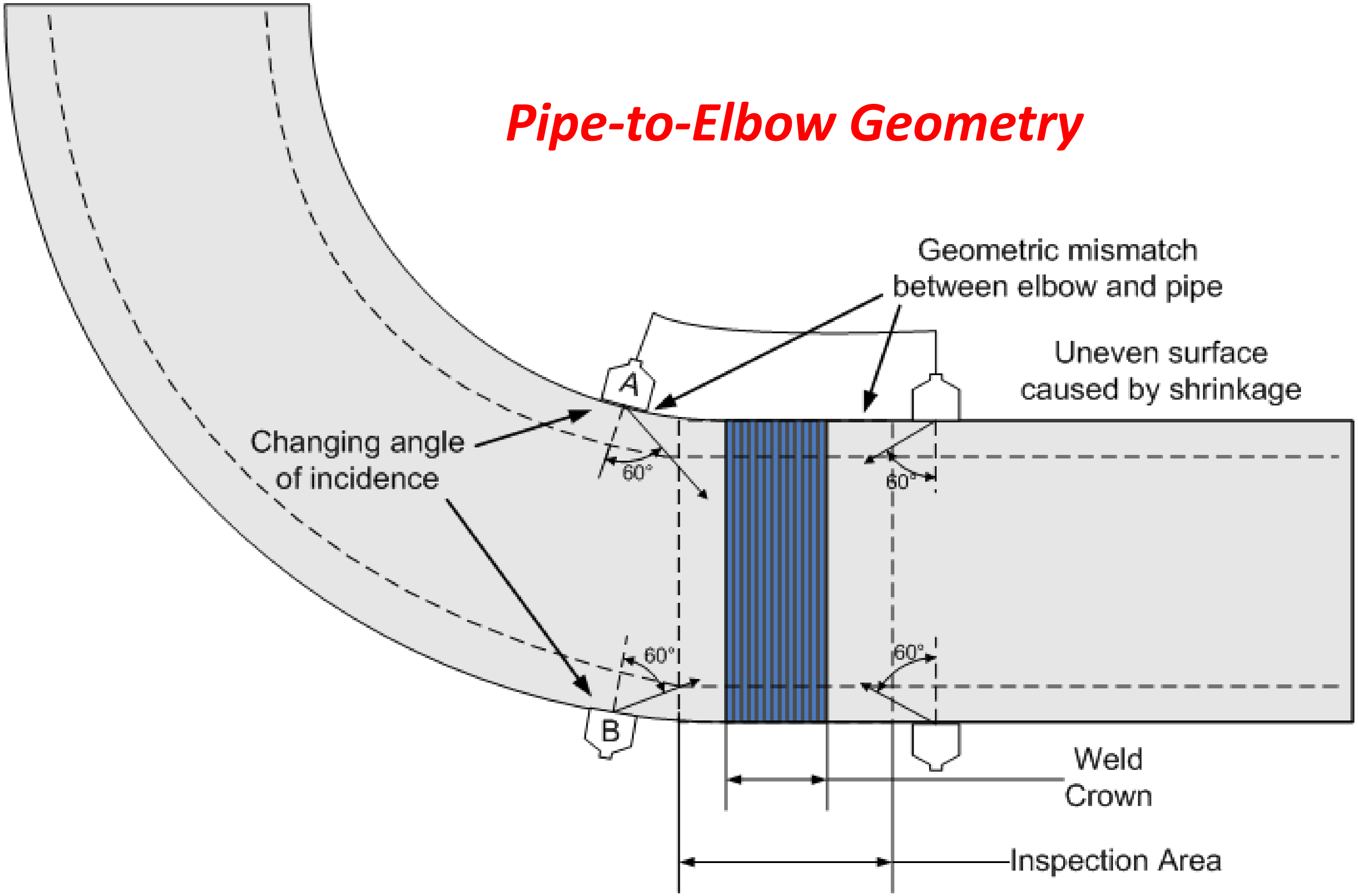


Ring-Core-Method

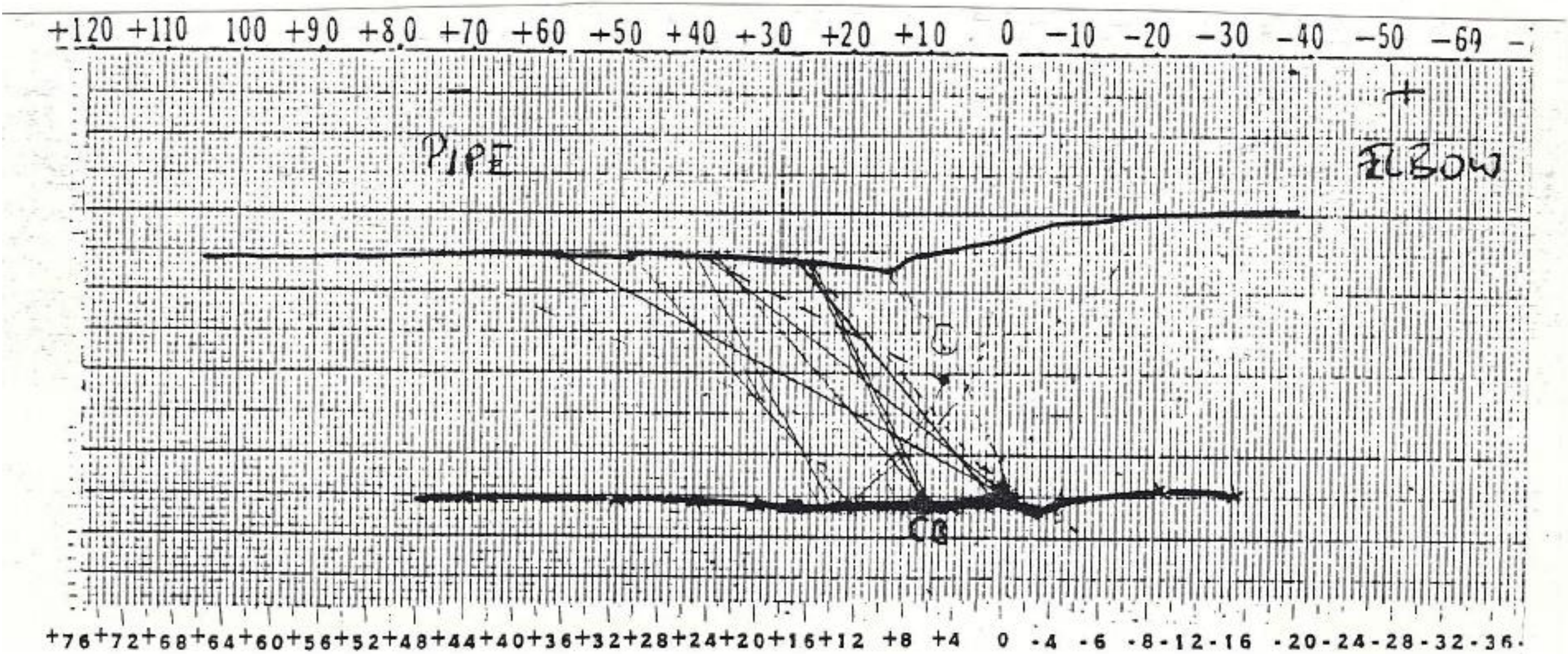


IGSCC in Austenitic Steel 304 Grade

Pipe-to-Elbow Geometry

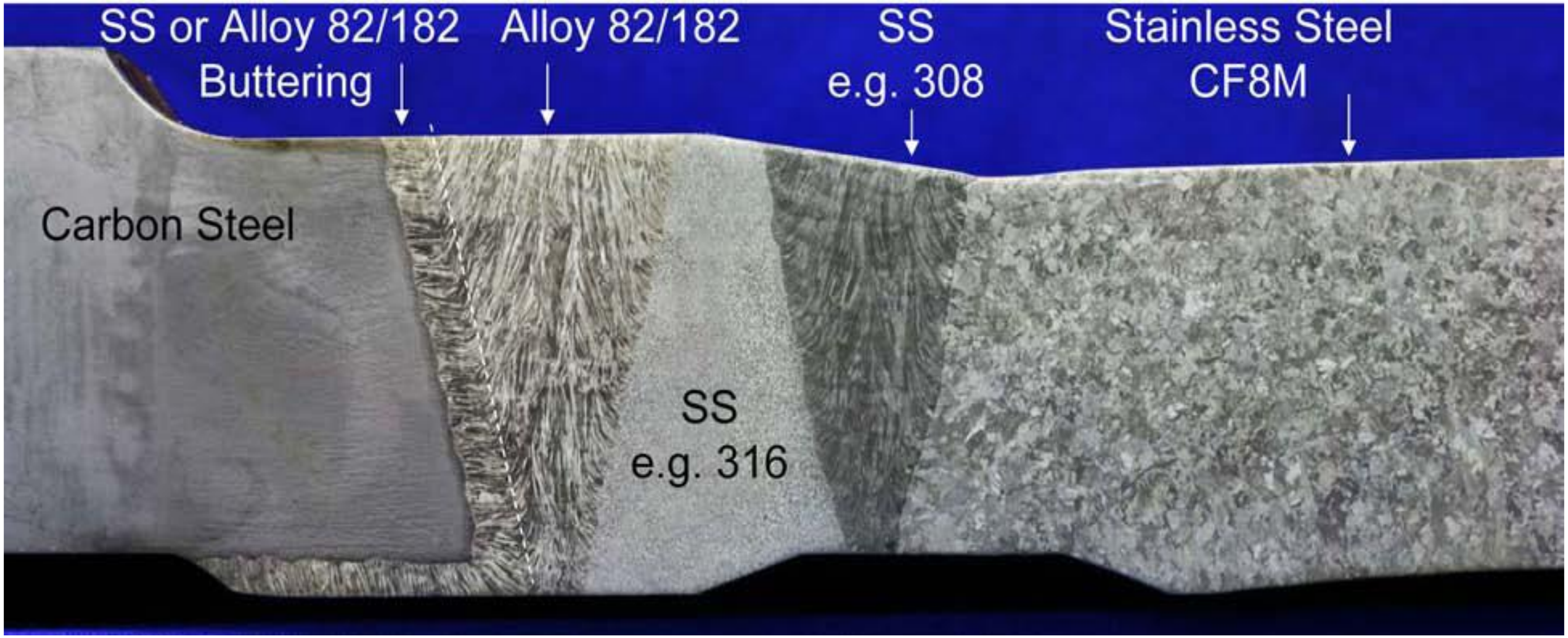


MITIGATION STRATEGIES: Component Geometry



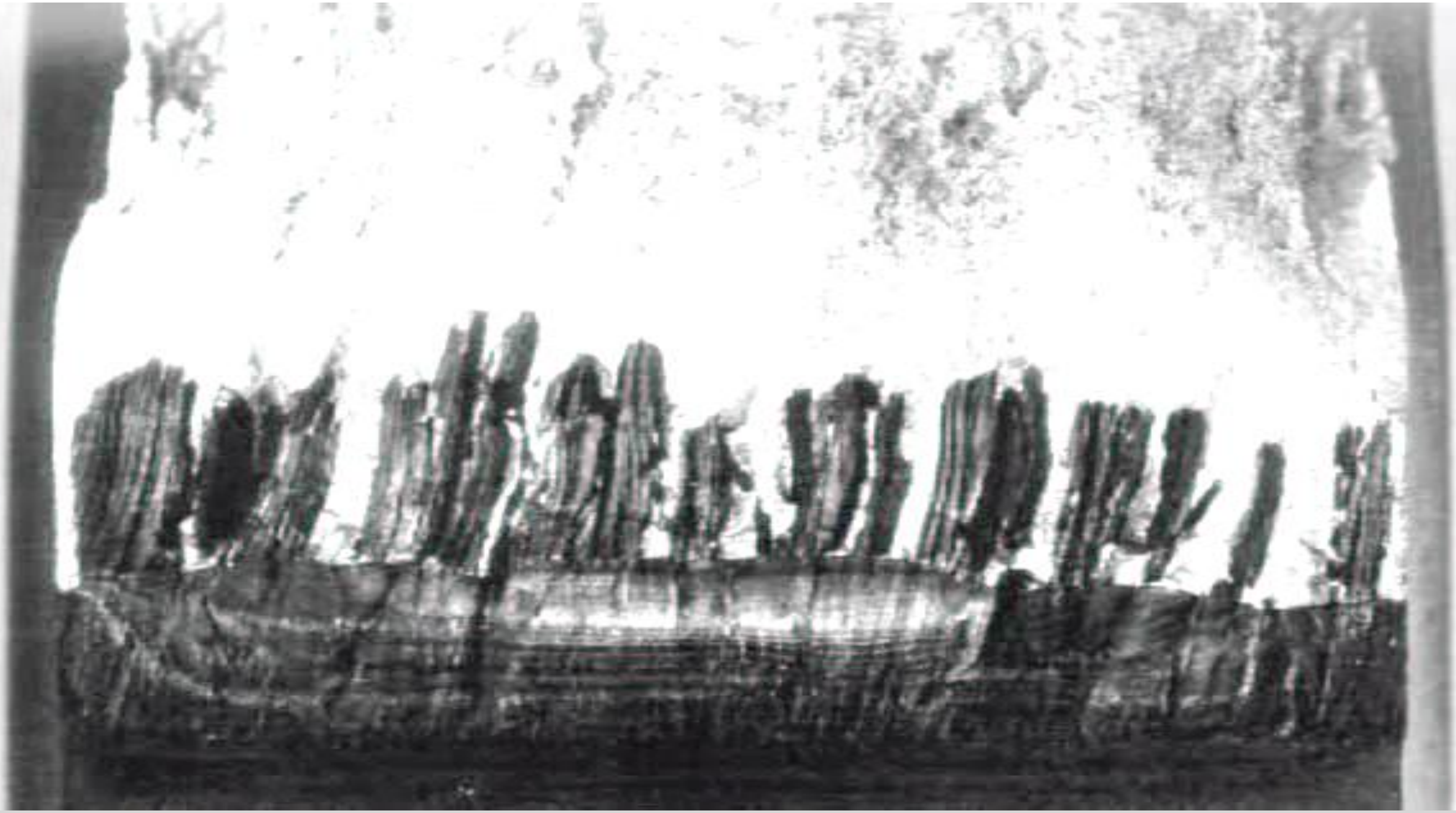
Surface Contour of Pipe to Elbow Weld

MITIGATION STRATEGIES: Component Geometry



Standard PWR Steam Generator Nozzle DMW

Primary Water Stress Corrosion Cracking Inconel 600



Stainless Steels and Ni-Base Alloys in HT-Water
Intergranular Stress Corrosion Cracking (IGSCC)

Laboratory experiments

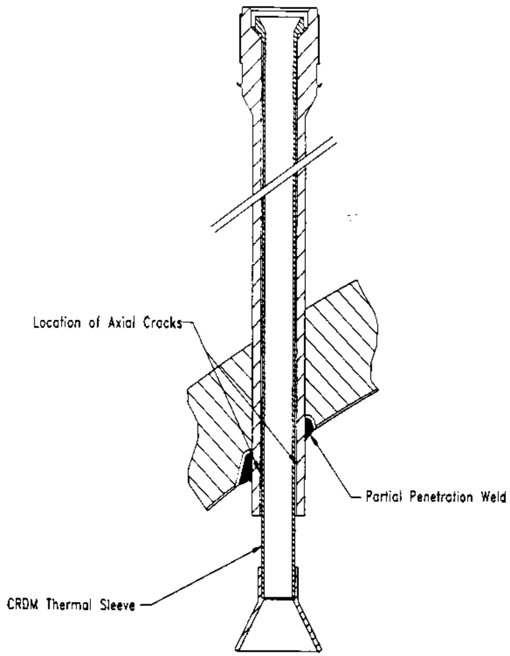
Pure Water Cracking (PWR)

- Incoloy 800 mod. and Inconel 690TT are immune
- Inconel 600
  - can be preceded by an extremely long incubation periode
  - susceptibility increases with T
  - stresses near or above $Rp_{0,2}$
  - H_2 increases susceptibility (DWR)
  - Immunity cannot be achieved by heat treatment (thermal treatment TT)
- Inconel X750 shows similar behaviour like Inconel 600

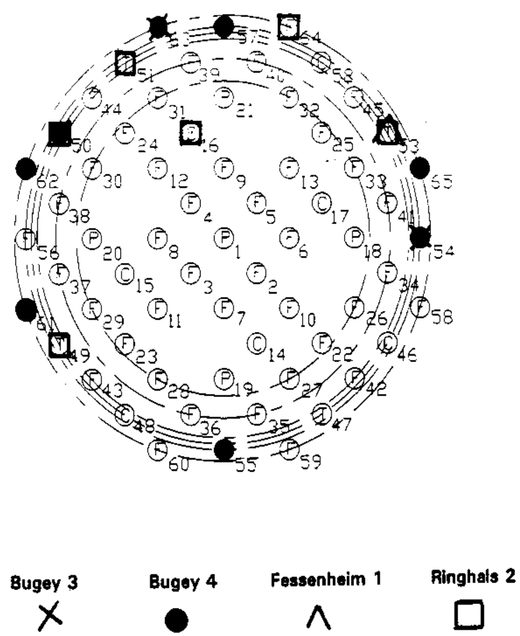
Pure Water Cracking (BWR)

- Inconel 690 seems to be immune
- Inconel 82 more resistant than Inconel 182
- Inconel 182 shows similar behaviour like Inconel 600
- creviced conditions plays an important role

Inconel 600 CRDM Nozzles



Axial Cracks



Position of cracks in RPV CRDM nozzles

Estimated percentage of defected RPV penetrations

South Africa
France
Sweden
Switzerland
USA
Belgium

Acc. to W. Bamford, Westinghouse, Status as of 2001

Stress Corrosion Cracking

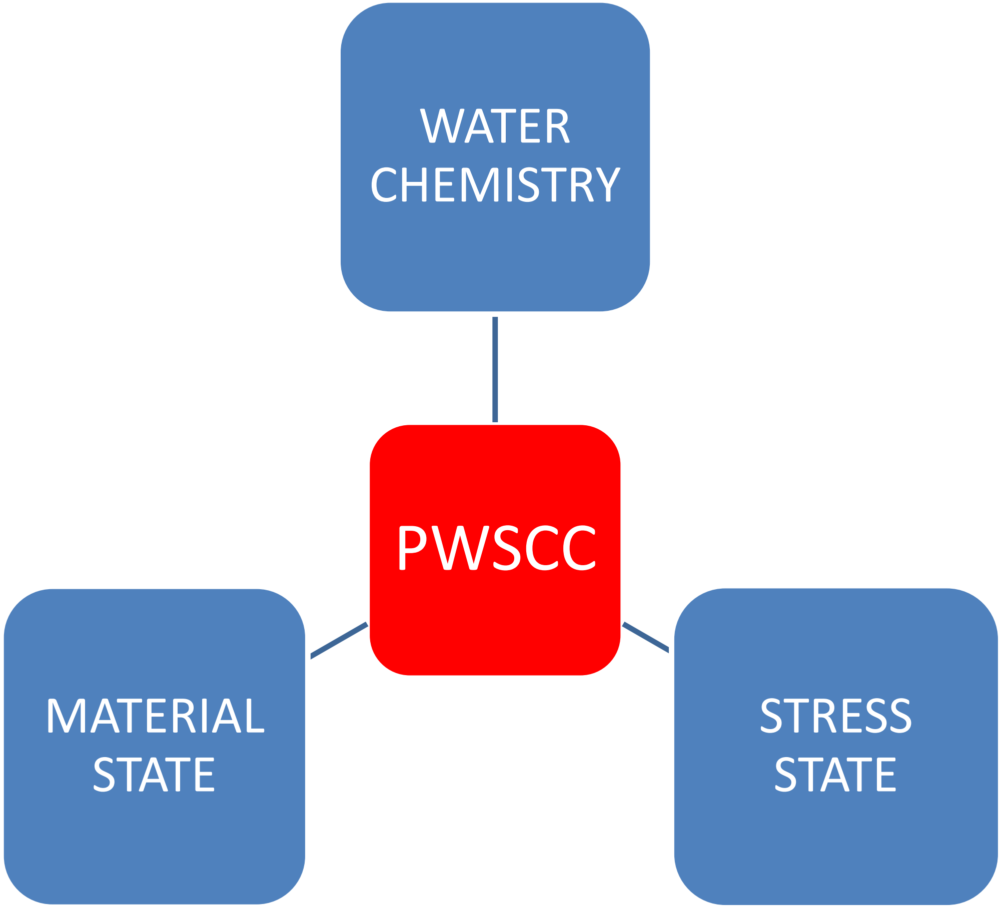
INSPECTION BY CAUSE

Primary Water Stress Corrosion Cracking - PWSCC

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	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	2002	21
Reactor Vessel Lower Head In-Core Instrumentation Nozzles/Welds	2003	14

Alloy 600 PWSCC Experience in Commercial PWRs
Crack Initiation Times

INSPECTION BY CAUSE
Primary Water Stress Corrosion Cracking - PWSCC



INSPECTION BY CAUSE

Primary Water Stress Corrosion Cracking - PWSCC

The generic IGSCC of the nickel-based Alloy 600 … in PWR has been studied extensively. Despite considerable experimental efforts, ***no consensus exists*** *as to the nature of the cracking mechanism, and life modeling and remedial measures have had to rely on empirical, phenomenological correlations. By contrast, its counterpart in BWR, in terms of extent and cost of remedial measures, of IGSCC of sensitized, austenitic materials, benefits from a solid basis of fundamental understanding of the cracking mechanism for life modeling and repair remedies.*

2000 F.N. Speller Award Lecture by P.M. Scott, Framatome.

INSPECTION BY CAUSE

Primary Water Stress Corrosion Cracking - PWSCC

WATER CHEMISTRY

Main Parameters

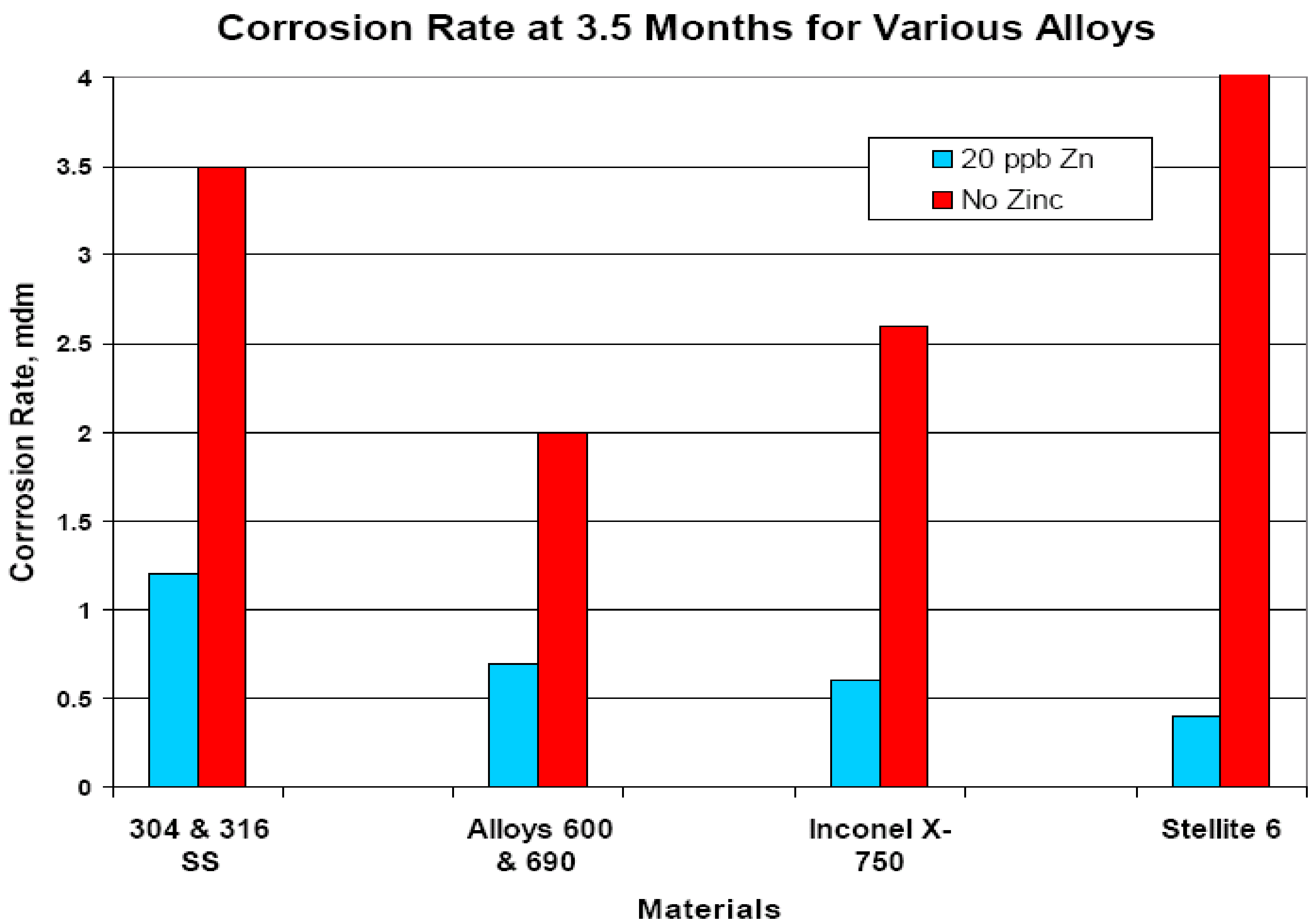
- *hydrogen partial pressure (or corrosion potential)*
- *temperature*

Mitigation Potential

- *zinc additions to the reactor coolant system (Reduction of general corrosion)*
- *temperature reduction (thermally-activated mechanism)*

INSPECTION BY CAUSE

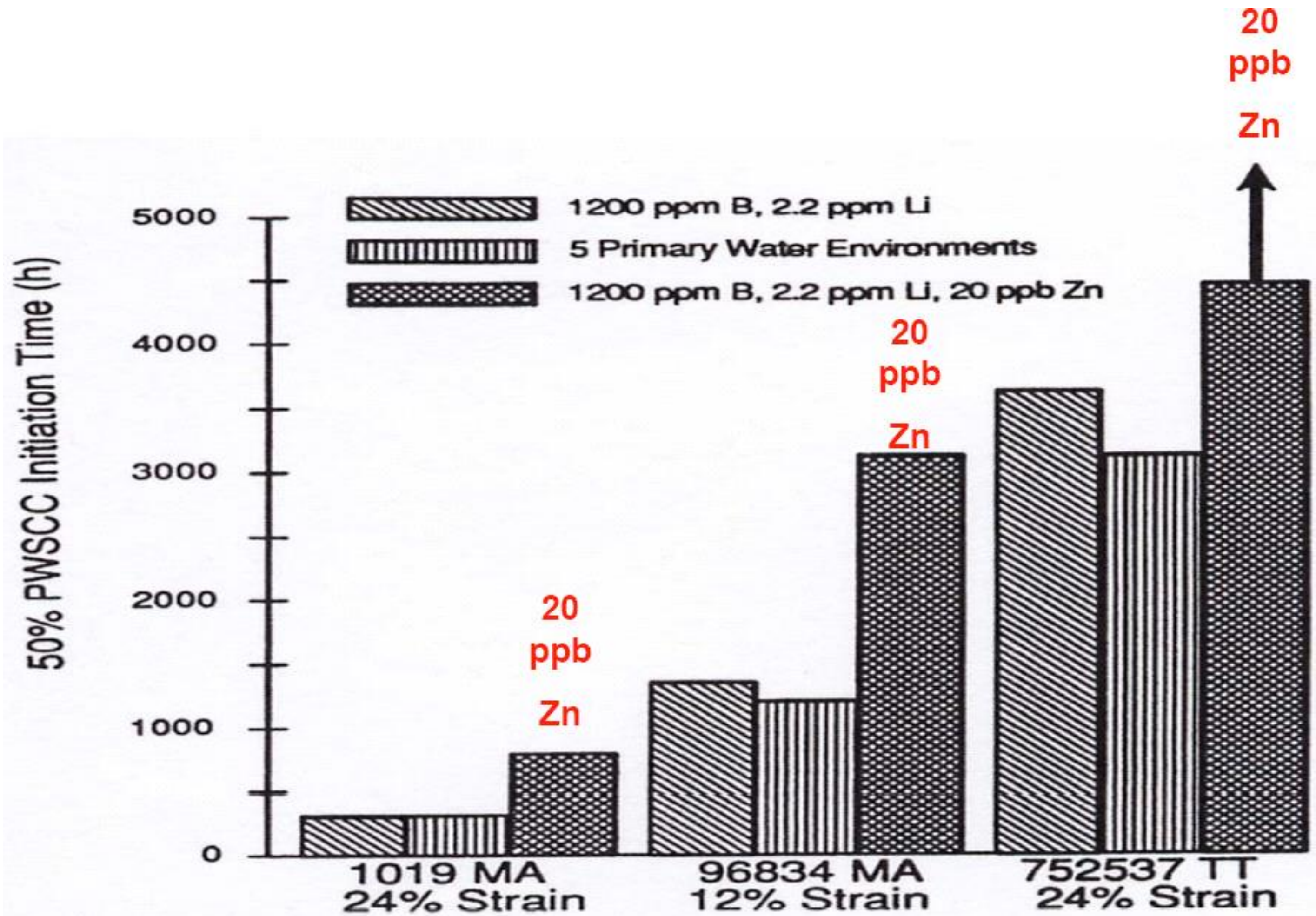
Primary Water Stress Corrosion Cracking - PWSCC



Effect of zinc on corrosion rates of various alloys in laboratory tests (after Esposito et al.**)**

INSPECTION BY CAUSE

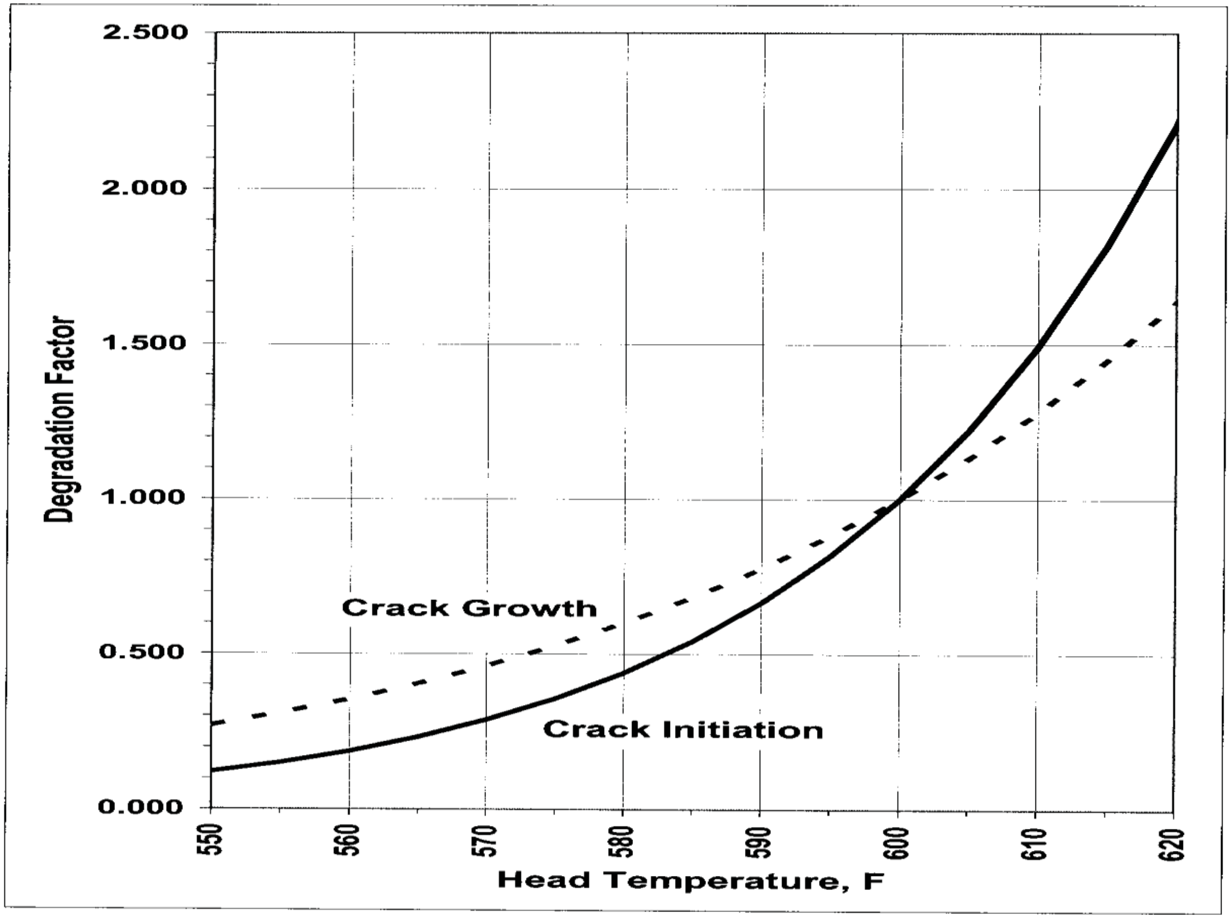
Primary Water Stress Corrosion Cracking - PWSCC



Example for the effect of zinc on time to initiate PWSCC in laboratory tests (Esposito et al. 1991**)**

INSPECTION BY CAUSE

Primary Water Stress Corrosion Cracking - PWSCC



Degradation Factor as a Function of Temperature

(ref. (David R. Forsyth, 2005)**)**

INSPECTION BY CAUSE
Primary Water Stress Corrosion Cracking - PWSCC

STRESS STATE

Main Parameters

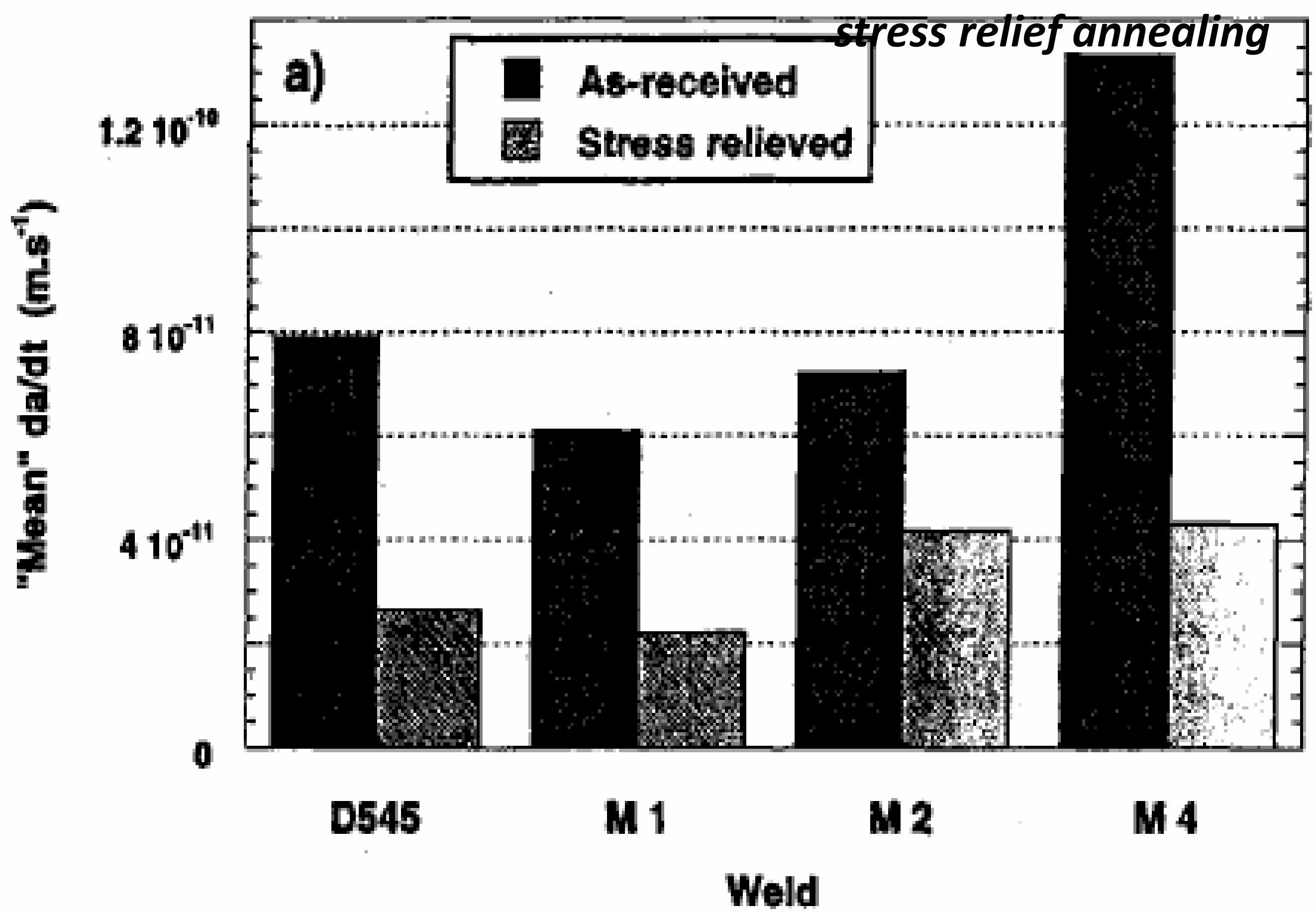
- *welding procedure*
- *heat treatment*

Mitigation Potential

- *Mechanical Surface Enhancement (MSE)*
- *stress relief heat treatment*

INSPECTION BY CAUSE

Primary Water Stress Corrosion Cracking - PWSCC



Effects of heat treatment on SCC susceptibility of Alloy 182

Mechanical Surface Enhancement (MSE):

shot peening
flapper wheel grinding
electrical-discharge machining
electro-polishing
abrasive water jet conditioning
mechanical stress improvement process

INSPECTION BY CAUSE
Primary Water Stress Corrosion Cracking - PWSCC

MATERIAL STATE

Main Parameters

- *material and weld microstructure*
- *weld defects*

  (relatively large and sharp defects, lack of fusion areas, promote PWSCC by acting as stress concentrators)

Mitigation Potential

- *metals with 30% chromium*

  (threshold for PWSCC resistance: between 22 and 30% chromium)
- *quality assessment*

  (no repair, weld bead size, heat treatment, weld design)

INSPECTION BY CAUSE

Primary Water Stress Corrosion Cracking - PWSCC

Assessment of Dissimilar Welds: „Risk for PWSCC"

Monitored Subject: „Nickel-Base Weld Metal"

(1 = no risk up to 4 = higher risk)

Design Layout	**1**	**2**	**3**	**4**
- Nickel-base root	no	yes	yes	yes
- One sided welding	yes	yes	yes	no
- ID repair	no	no	no	yes
- OD repair	no	yes	yes	yes
- Shop weld	n.r.	n.r.	?	no
- E manual/mechanized	n.r.	n.r.	?	manual
- Alloy 182/82	n.r.	n.r.	?	182
- with/without buffer	n.r.	without	?	with
- with/without annealing	n.r.	n.r.	?	with
- ISI yes/no	n.r.	n.r.	?	?
Suspect for PWSCC	**no**	**no**	**?**	**Yes**
NDT recommended	**no**	**no**	**yes**	**yes**

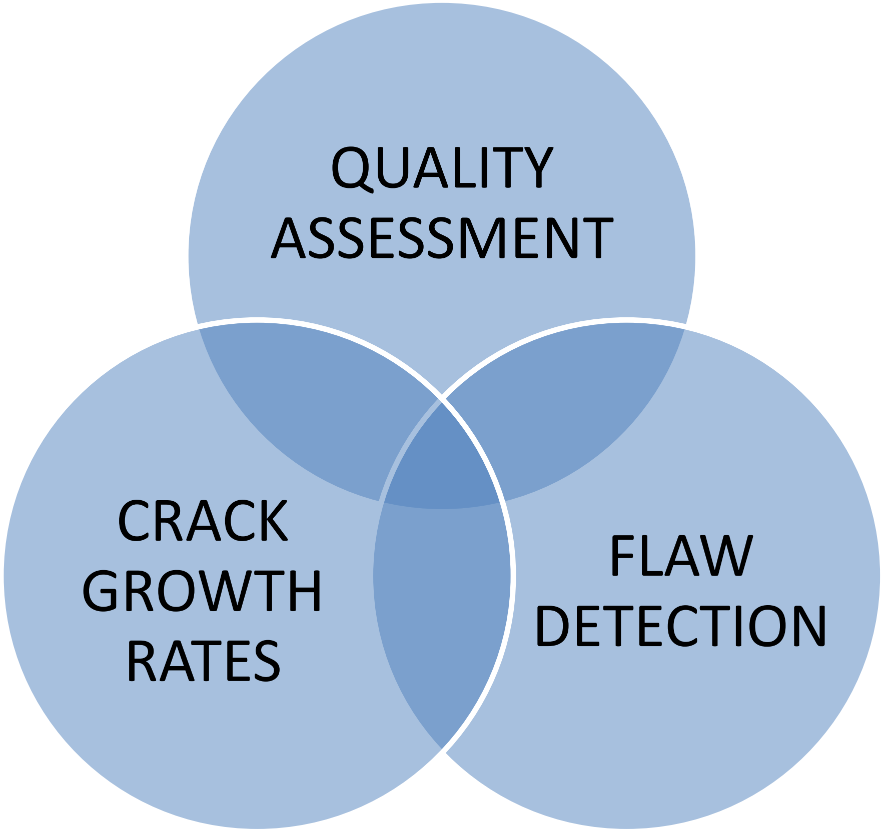
n.r. = nonrelevant ? = unknown

Assessment of Dissimilar Welds: "Risk for PWSCC"

INSPECTION BY CAUSE
Primary Water Stress Corrosion Cracking - PWSCC

The risk for PWSCC in alloy 600 components and its weld metal alloy 128/28 is low when best craftsmanship, optimized design, manufacturing and fabrication can be certified by documentation. Under these conditions, both the stress resp. strain state and the material's microstructure state of the critical component area are on a level to ascertain a low susceptibility to PWSCC.

INSPECTION BY CAUSE
Primary Water Stress Corrosion Cracking - PWSCC

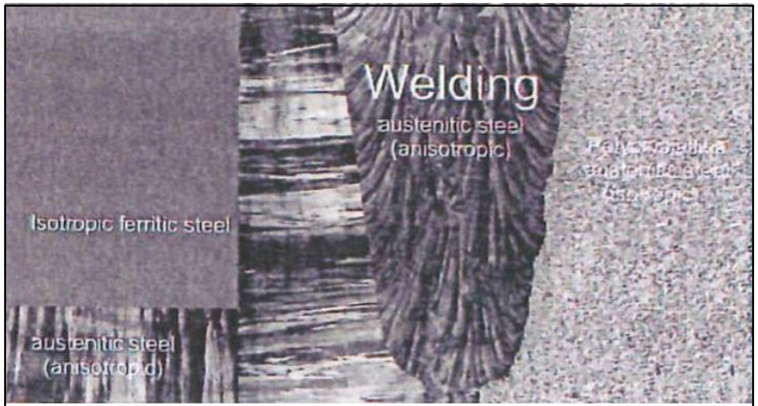


NDT SUPPORTED MITIGATION CONCEPT

INSPECTION PROBLEM
Acoustic Anisotropy

a - standard pipe to pipe weld

b - narrow gap weld



c - dissimilar weld

PHOTOMICROGRAPHS
of
WELD SECTIONS

Literature

IAEA Training Materials and Reports on IGSCC

IAEA-EBP-IGSCC-31: Risk based inspection (IRBIS) Workshop
IAEA-EBP-IGSCC-32: Advanced ultrasonic training seminar for detection, characterization and repair of IGSCC, IGSCC flaw sizing and weld overlay examination (including transfer of respective procedures) - Training Materials
IAEA-EBP-IGSCC-33: Advanced ultrasonic training seminar for detection, characterization and repair of IGSCC, IGSCC flaw sizing and weld overlay examination (including transfer of respective procedures) - Training Course report
IAEA-EBP-IGSCC-34: Advanced ultrasonic training course for detection and characterization of IGSCC in stainless steel piping - Training materials
IAEA-EBP-IGSCC-35: Advanced ultrasonic training course for detection and characterization of IGSCC in stainless steel piping - Training Course report
IAEA-EBP-IGSCC-36: Automated IGSCC ultrasonic inspection seminar
IAEA-EBP-IGSCC-37: Advanced ultrasonic sizing seminar - Training materials
IAEA-EBP-IGSCC-38: Advanced ultrasonic sizing seminar - Report
IAEA-EBP-IGSCC-39: Workshop on GTAW welding and repair methods
IAEA-EBP-IGSCC-40: Workshop on Water chemistry monitoring (Gundermingen and Philipsburg NPPs)

Literature

1. Steve Bruemmer, Peter Ford, Gary Was (eds*): Proceedings of the Ninth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors,* The Minerals, Metals, and Materials Society, Warrendale, Pennsylvania, ISBN Number 0-87339-475-5, 1999