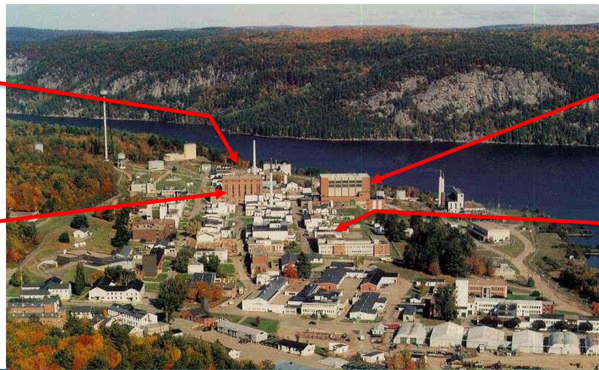


Neutron Beams for Lifetime Prediction, Failure Analysis, Informed Inspection, Qualification…

R.B. Rogge

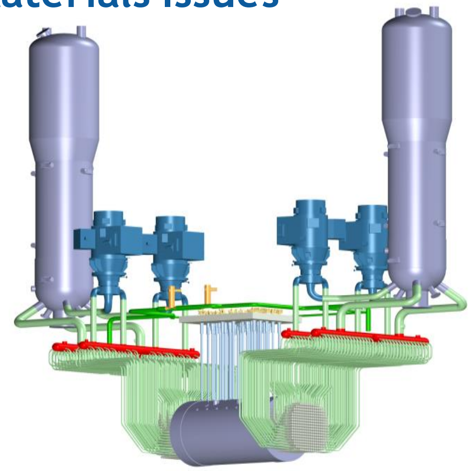
Joint ICTP/IAEA Workshop, 2017 November 6-10

Introduction

Chalk River is the nucleation point of the Canadian nuclear industry—natural outcome was that much of the neutron beam work was on nuclear materials

- Reactors present a wide range of materials issues
- Why use neutrons?
- Present several examples:
  - In-core materials and ex-core (BoP) materials
  - Failure analysis, fitness for service / qualification, component lifetime prediction, inspection protocol, fuel development, waste/storage…

Nuclear Industry
Scope of Materials Issues



Nuclear Industry
Scope of Materials Issues

- In-core components
  - pressure vessels and tubes
  - calandria & calandria tubes
  - spacers
  - rolled joints and welds
- Fuels
  - compositional analysis
  - poisons
  - cladding
- Ex-core components
  - feeder circuits
  - joints and welds
  - steam generator components
  - turbine components
- Nuclear Waste Disposal
- Performance
  - component lifetime
  - irradiation effects
- Failure analysis
  - understanding failure
  - regulator concerns
- Qualifying changes in process
  - validating designed performance predictions
  - validating FEM
  - new material/supplier
  - radical new design
  - maintain quality standards

The Neutron's Unique Properties

- Wavelength, λ, comparable to interatomic spacing
- Energies comparable to *excitations*
- Magnetic moment
- Scatters coherently and incoherently, or is absorbed
- Cross sections are of same order of magnitude for all nuclei (*e.g.* can 'see' Mg about as well as Fe or Au)
- Cross sections vary irregularly across periodic table (*e.g.* Fe about 10x Co)
- Highly penetrating (no charge, interacts with nucleus)

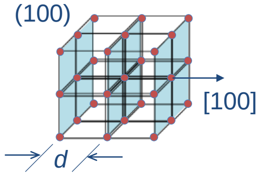
Bottom Line:
Neutrons and X-Rays do many of the same things. Neutrons are sometimes flux-limited in comparison, but some things only neutrons can do.

Crystal Structure

Crystal Planes

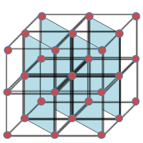
Periodic arrangement forms *planes of atoms*

(100)



- Families of plans are described using the *Miller Indices* (*hkl*) and (*hkil*)
- [*hkl*] denotes the direction perpendicular to the (*hkl*) planes
- *d* is the perpendicular spacing between these planes of atoms

(110)



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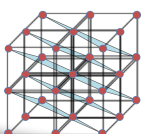
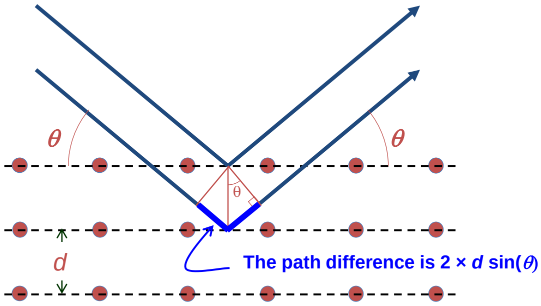


Bragg's Law

A Matter of Constructive Interference

$$n\lambda = 2d\sin(\theta)$$

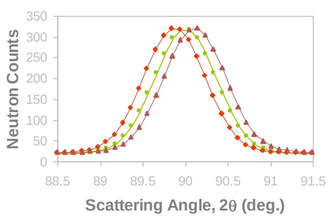
Constructive interference when the path difference between rays reflected by adjacent planes is an integer number of wavelengths, $n\lambda$

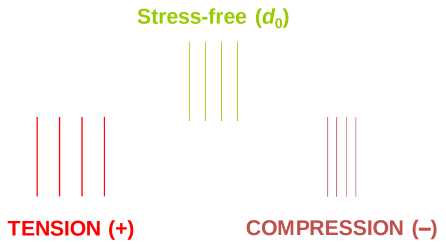


Measuring Strain by Diffraction

$$\varepsilon \equiv \frac{d - d_0}{d_0}$$

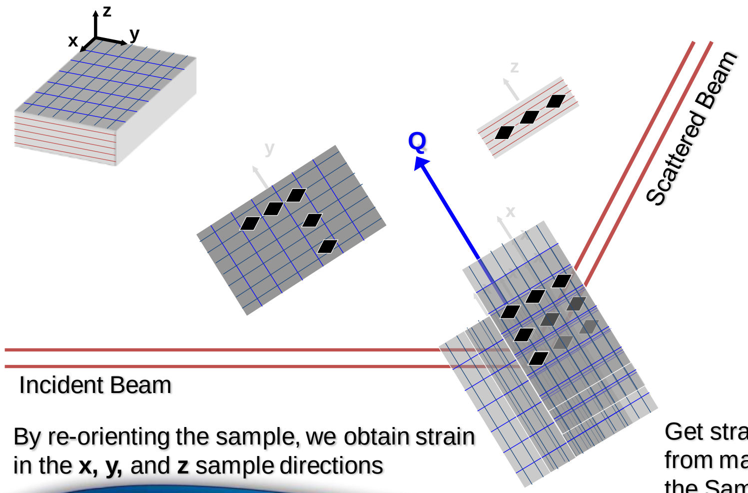
$$\lambda = 2d\sin(\theta)$$





Mapping Stress at Depth

Usually we need 3 components



By re-orienting the sample, we obtain strain in the **x, y,** and **z** sample directions

Get strain data only from material inside the Sampling Volume

Getting Stress from Strain

Usually we need 3 components

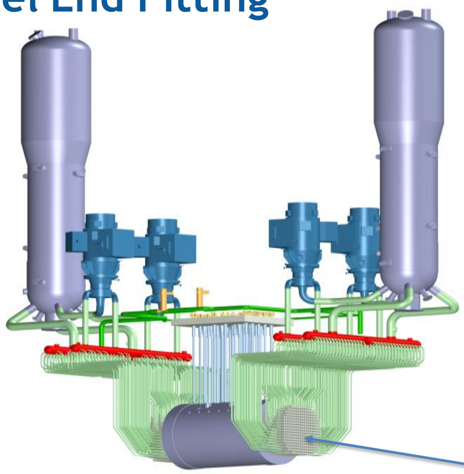
If the *Principal Stress* directions are known, we can measure just those 3 strain components

Then we can calculate the 3 *Principal Stresses* from the 3 strains using the Generalized Hooke's Law, *viz.*

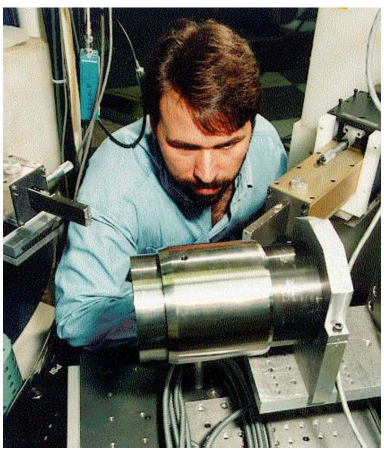
$$\sigma_\alpha = \frac{E}{1+\nu}\left[\varepsilon_\alpha + \frac{\nu}{1-2\nu}\left(\varepsilon_x + \varepsilon_y + \varepsilon_z\right)\right], \alpha = (x, y, z)$$

If the *Principal Stress Directions* are not known, we need to measure enough strain components to determine the full *strain tensor* $\Rightarrow$ *stress tensor*

Nuclear Industry
Fuel Channel End Fitting



Predicting Performance
Life-Time Stress Relaxation Stresses in a Rolled Joint



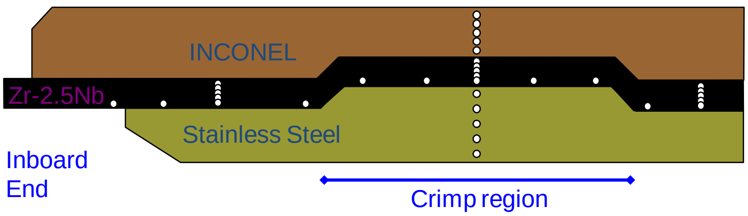
Will the residual stresses relax over the projected 30-yr lifetime of the reactor?

- Map residual stresses in as-rolled joints.
- Heat-treat at elevated temperature (350 C vs. 288 C) to accelerate stress relaxation (30 h ⇨ 1 yr, 635 h ⇨ 30 yr).
- Re-evaluate residual stresses at identical locations after each heat treatment.

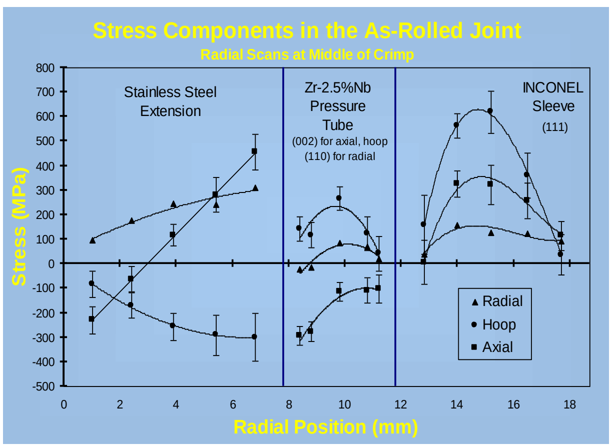
M. Hayashi *et al.* Proceedings of the 14th Int'l Conf. of Non-Destructive Evaluation, Nuclear and Pressure Vessel Industries, Stockholm, Sweden (1997).

Locations for Repeated Scans

- Through-thickness scans in each component
- Track at constant depth in Zr-2.5Nb pressure tube material
- Edges of crimp region
- Free end



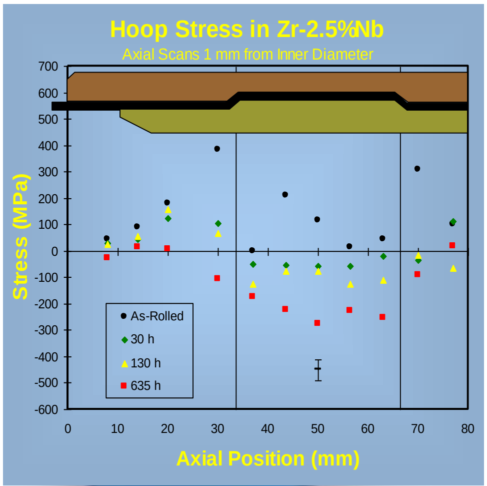
Stresses in As-Rolled Condition



- Significant variations in stress across each component
- Overall trend from compressive hoop stresses in steel extension to tension in INCONEL sleeve
- Axial stresses balance near interfaces

Hoop Stress After Heat Treatments

Action is in the Zr-2.5Nb

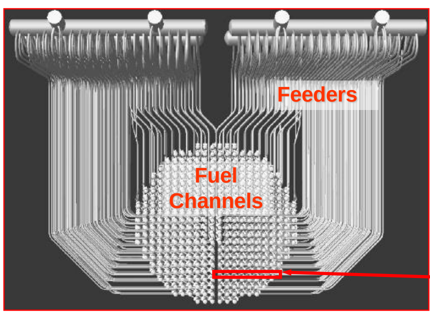


- Continuous change as heat treatments proceed
- Outside of crimp stresses tend to relax
- Over crimp region stresses shifted from tensile to compressive
- Is cycling an issue?

Over the proposed 30-year lifetime, stresses will relax in the sleeve and extension and become compressive (favourable) in the Zr-2.5Nb

Failure Analysis

An *Ordinary* Bent Steel Pipe in the Heat Transport System

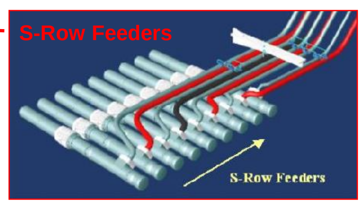


A CANDU plant has 380 to 480 fuel channels

⇒ 760 to 960 feeder pipes

Scale of the problem is potentially huge

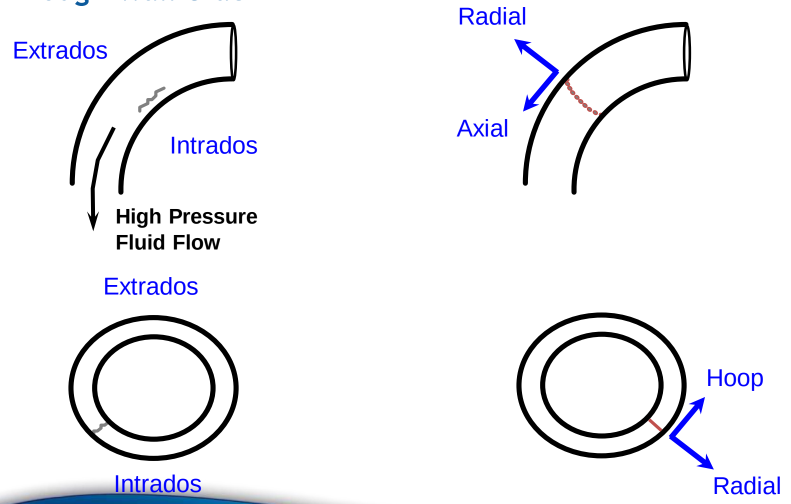
⇒ rapid response essential



Images courtesy of AECL

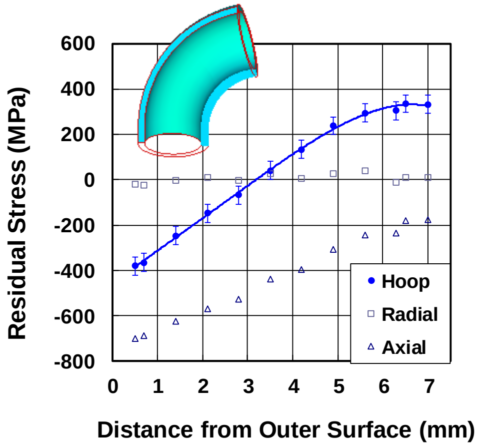
Bent Steel Pipe

Axial Through-Wall Crack



Bent Feeder Pipe

Through Wall Stress



- Tensile hoop stresses near the inside surface of the pipe are at yield point of the material.
- These stresses tend to accelerate growth of axial, through-wall cracks.

Residual stress has a significant role in these failures.

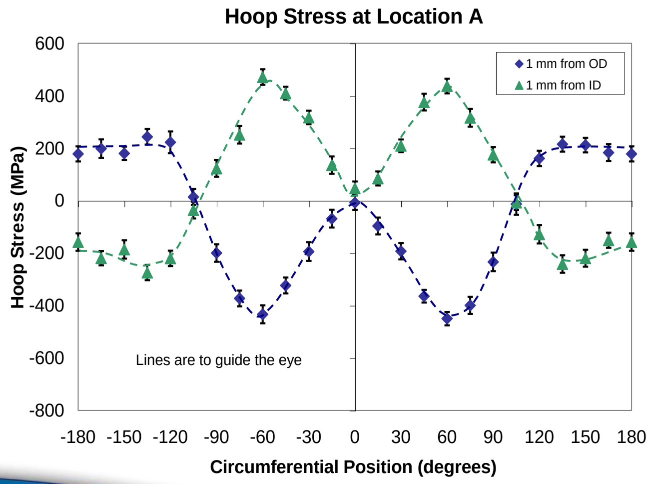
Bent Feeder Pipe

Initial Hoop Stress Variation

Technique is non-destructive, so safe to examine archive pieces

Failure analysis was on a post-service sample, so radioactive*

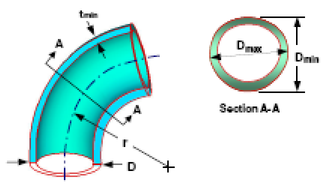
Confirms that initially the stress distribution was symmetric

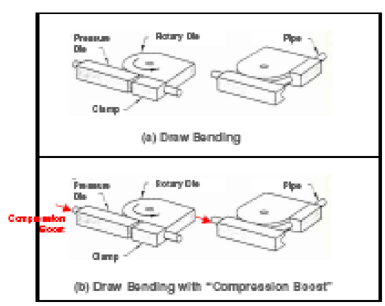


* < 1 R/h (10 Sv/h) can handle with remote tooling an barriers

Why the hoop stress?

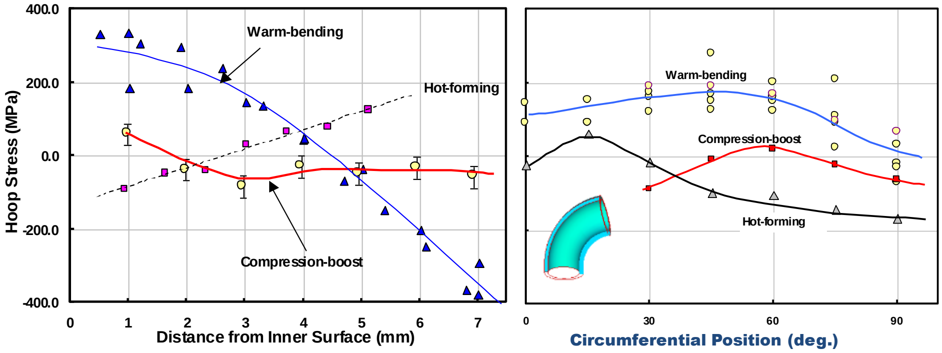
- Bending implies primary stress is axial
- Axial stress at location is compressive and a tensile axial stress would not produce an axial crack
- Plant design requires tight radius bend, r/D = 1.5, 73°
- Cold bends recommended to have r/D ≥ 3
- Special techniques required





Graphics courtesy of AECL

Bent Feeder Pipe
Effect of *Different* Manufacturing Processes



- **All pipes meet the same dimensional specifications**
- **Stresses are very different (magnitude and shape)**
- **Only *one* type cracks**

Yetisir, Rogge & Donaberger, Proceedings of PVP2005, 2005 ASME Pressure Vessels and Piping Division Conference, July 17-21, 2005, Denver

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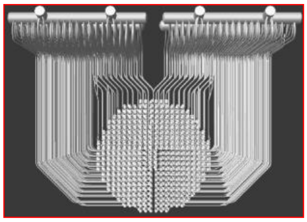
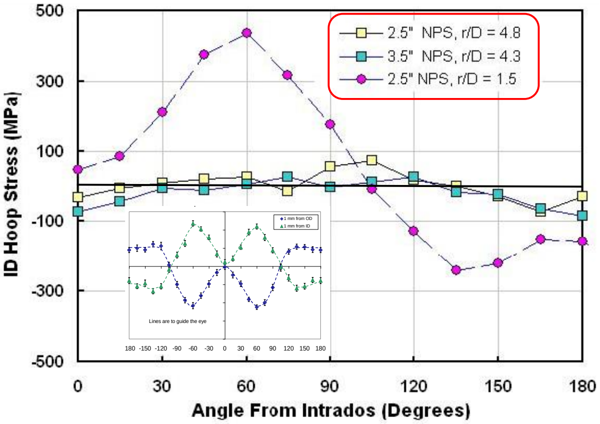
Bent Feeder Pipe
Inspection Protocol: Bend Radius

- Many feeders, need to rank inspection
- Various pipe diameters
- Tight bends
- Large bends
- Welds





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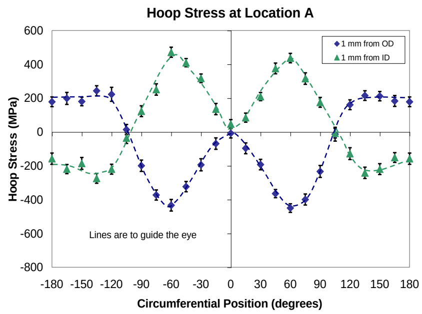
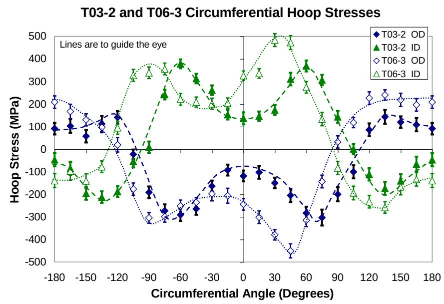
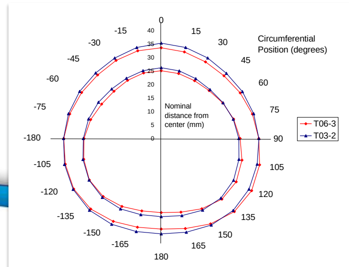
Yetisir, Rogge & Donaberger, Proc. of PVP2006, ASME Pressure Vessels and Piping Division Conference, July 23-27, 2006.

Bent Steel Pipe

Effect of *Change in* Manufacturing Process



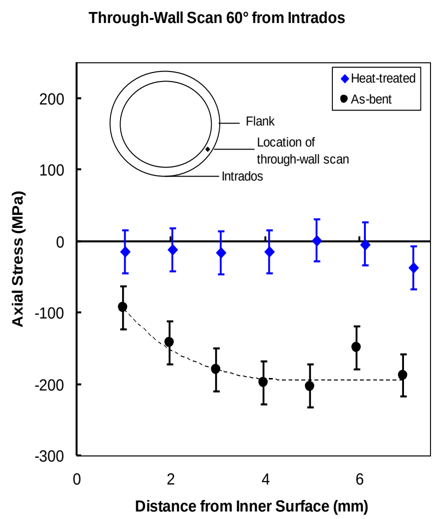




Bent Feeder Pipe

Change Specifications

Specifications now include manufacturing process:
compression boost and heat treatment



What We Have Done

- Initial failure examination that confirmed stress plays a role in the failure
- Feeder Bends from various power plants
  - Evaluate condition
  - Compare manufacturing processes
- Preproduction work for new reactor
  - Confirm the undesirable stress condition is avoided
  - Evaluate change in specifications
- Data beyond stress
  - Wall thickness data (stress bonus data)
  - Tomography

What *More* We Have Done

- Evaluate wall thinning
- Evaluate effect of small changes in fabrication
- Examine 1st and 2nd bends (different radii of curvature)
- Evaluate weld stresses
- Measure stress in larger diameter pipe
- Weld and weld repair stresses
- Evaluate relationship between stress and cross section
- Evaluate strain field around crack tip

Yetisir, Rogge & Donaberger, Proceedings of PVP2006, 2006 ASME Pressure Vessels and Piping Division Conference, July 23-27, 2006, Vancouver

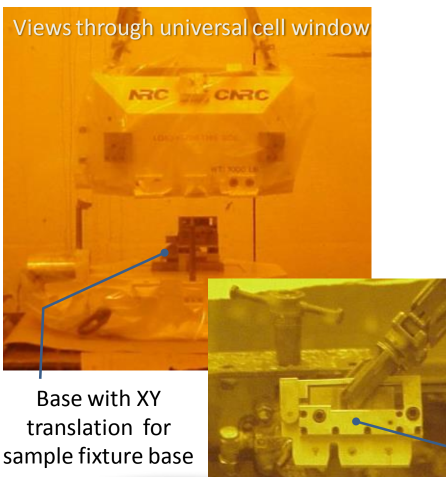
Radiation Induced Stress Relief

- Various in-core components are welded
- Most welds have stresses, often large; a concern for stress corrosion cracking
- Will stresses be relieved over lifetime due to irradiation?
- Two bead-on-plate studies
  - 304 Stainless Steel[1]
  - 316L Stainless Steel[2]

1. M. Obata, *et al.*, J. ASTM Int. **3** (1) (2006) JAI12348.
2. Y. Ishiyama , R.B. Rogge and M. Obata, J. of Nuc. Mat. **408** (2011) .

Dealing With Radioactive Samples

Access to CRL On-site Hot Cells



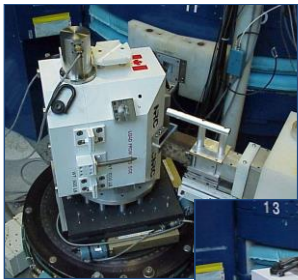
Base with XY translation for sample fixture base

Specimen and holder

- Used AECL expertise in handling and shipping radioactive components
- Made extensive use of AECL hot cells
- CNBC staff designed and constructed shielded container
- Specimen holder designed for ease of handling in hot cell
- Specimen and holder keyed to reliably define specimen orientation in container

Stress Changes Due to Fast Neutron Irradiation

Need Three Sample Orientations to Determine Stress



Longitudinal

Capability unique to Chalk River

Transverse

- Sample, main source is ^{60}Co
- 200 Sv/h (20 000 R/h) on contact
- Analysis gave 1.4 TBq on most active sample

- Min. 12.7 cm (5”) Pb path
- Weight, 682 kg (1,500 lbs)
- Shield, 20-40 μSv/h (2-4 mR/h) near contact
- Through ports, 2-10 mSv/h (0.2-1 R/h) at exit
- No impact on ^{3}He detector

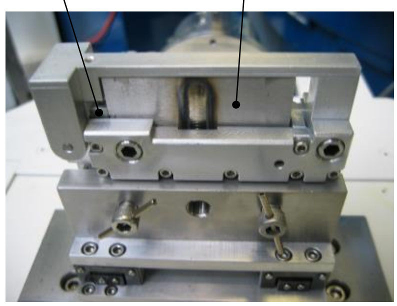
Experiment Plan

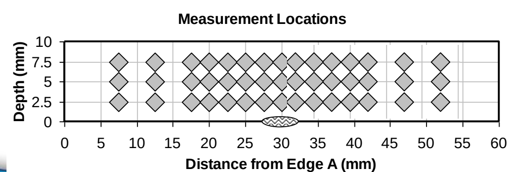
304 Stainless Steel

- Samples were paired
  - Bead on plate weldment
  - Reference cube
- Four pairs studied
  - As welded
  - 3 irradiated
- Data were obtained as paired sets (the reference and weldment have same thermal/irradiation history)
  - Changes only due to relaxation

Reference

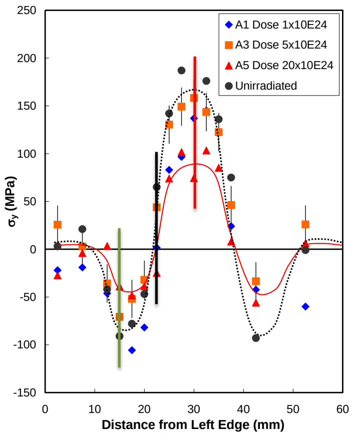
Side A

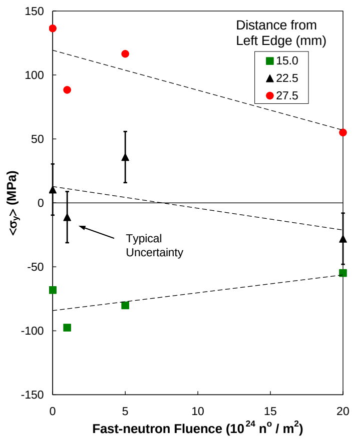




Stress Data vs. nº Fluence

304 Stainless Steel



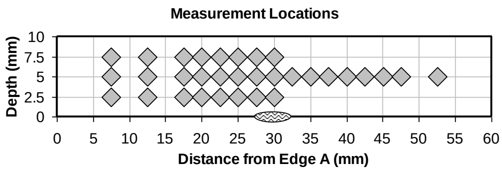


M.Obata *et al.*, Proc. 22nd Symp. on Effects of Radiation on Materials, ASTM, Boston (2004)

Experiment Plan

316L Stainless Steel

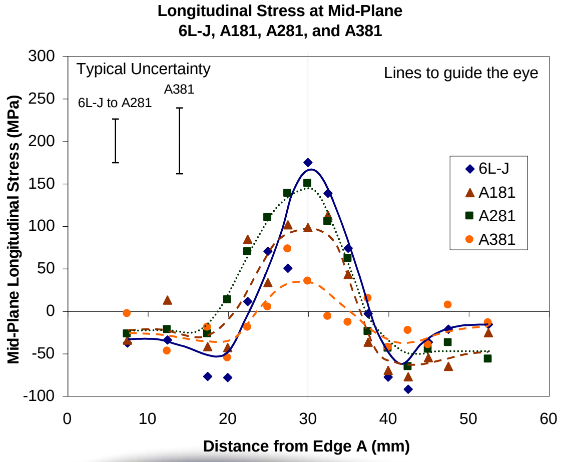
- Samples were *not* paired
  - Bead on plate weldment
  - Reference cube
- Four weldments studied
  - As welded
  - 3 irradiated

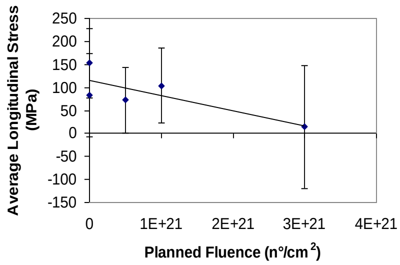


- For each sample there are data taken before irradiation, but not by us → compared baselines
- Data were obtained using unirradiated reference the reference and weldment *do not* have same thermal/irradiation history
  - Changes can be a mixture of irradiation & relaxation

Effect of Irradiation

316L Stainless





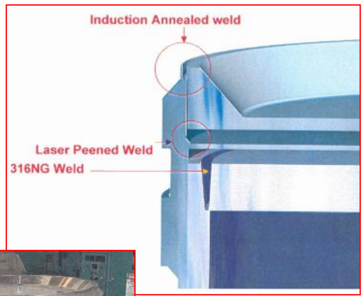
0.9, 1.9 and 4.1 dpa

Stress Changes Due to Fast Neutron Irradiation

Summary

- Neutron diffraction stress mapping on irradiated bead-on-plate stainless weldments revealed:
  - 304 and 316L stainless steels show similar stress relief
  - Stress relief appears nominally linear with fluence
  - Best to have reference sample-weldment pairs that follow same irradiation history

Ensuring Longevity
Weld Stress Mitigation



- Stress can assist corrosion
- Client has *challenging* corrosion avoidance requirements
- Welding generally produces unfavourable tensile stress
- Stress mitigation:
  - Heat treatment
  - Stress modification

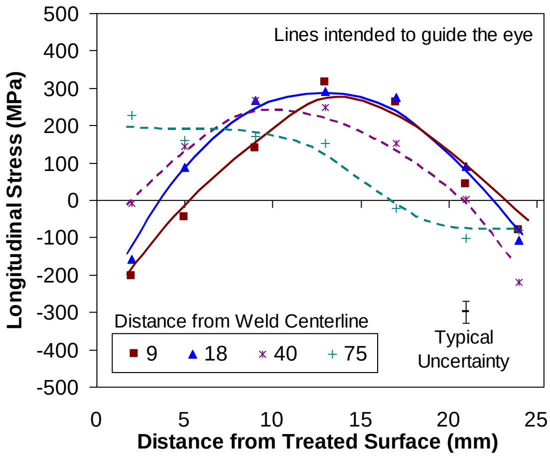
Laser peening or low plasticity burnishing are only practical (robotic) options, but…
Are they effective?

Ensuring Longevity
Weld Stress Mitigation

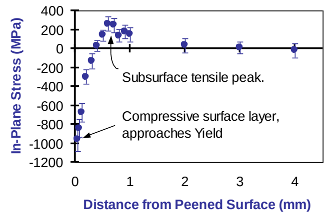
- Examined 9.5 mm and 25 mm thick plate
- Measured stress on as-welded plates
- Welding followed by application of stress mitigation process:
  - Low plasticity burnishing
  - Laser shot peening

Stress Mitigation

Low Plasticity Burnishing



- LPB has significantly modified stress distribution
  - +480 MPa ⇨ –200 MPa
  - 0 MPa ⇨ +200 MPa
- Compressive zone of LPB is very deep
- Similar profile over the LPB zone



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25 mm Ni alloy plate

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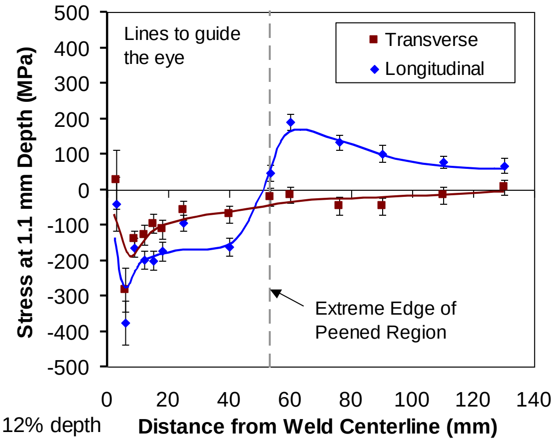
Stress Mitigation

Laser Shot Peening



12% depth

- LSP also significantly modified stress distribution
- Compressive zone also very deep
- Profile also similar over most of the LSP zone
- Sharp transition at the edge of the zone
- Outside LSP zone high tensile stresses

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9.5 mm Ni alloy plate

UNRESTRICTED / ILLIMITÉ -38-

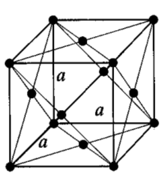
Crystallographic Texture

Why it can be important

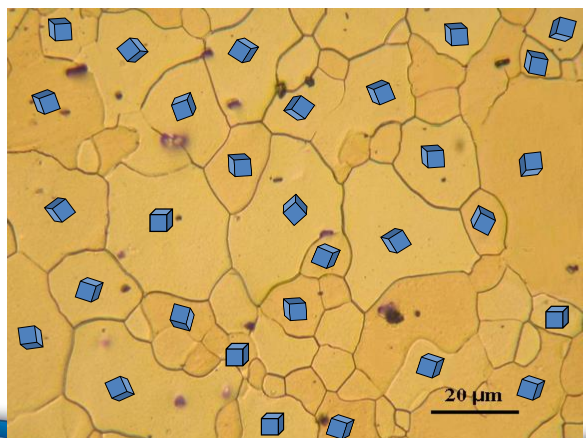
- Single crystals can have anisotropic mechanical properties
- If the crystallites tends to take on specific orientations, the anisotropy of the crystals is inherited by the polycrystalline material
- Texture can affect performance of industrial components
  - Strength
  - Creep resistance
  - Formability

What is Texture

Most engineering materials comprise a collection of crystallites (grains), each characterized by the orientation of the unit cell.



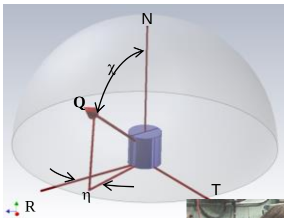
The distribution of orientations is referred to as the *texture* of the material.

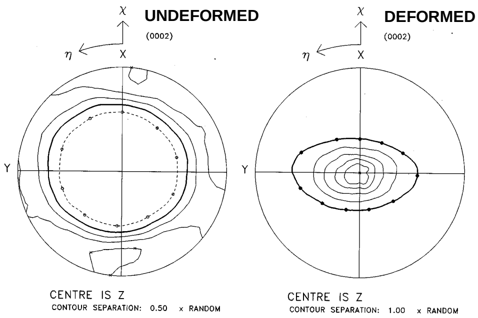


Measuring Texture

Measure the Distribution of Crystallographic Orientations

Rotate the sample over a hemisphere of orientations to map the distribution of grain orientations: *pole figure*





Texture of Pressure Tube

(0002) Pole Figures

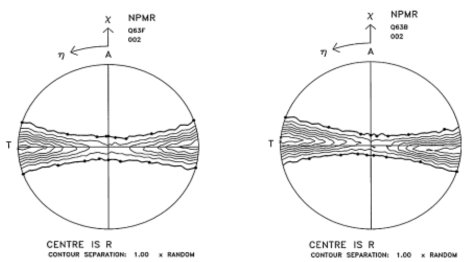


Fig. 6. (0002) pole figures determined by neutron diffraction for Tubes 63F and 63B.

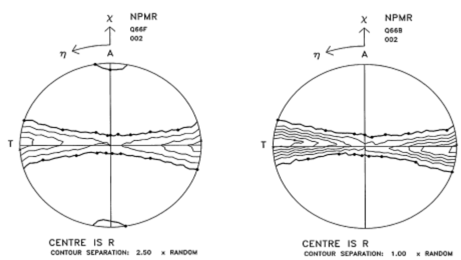


Fig. 7. (0002) pole figures determined by neutron diffraction for Tubes 66F and 66B.

T = 1090 K 10.07:1 Quench

T = 1090 K 10.0:1 Slow cool

Y. Li, R.B. Rogge & R.A. Holt, Mat. Sci. Eng. A, **437,** p 10-20 (2006)

Texture of Pressure Tube

(0002) Pole Figures

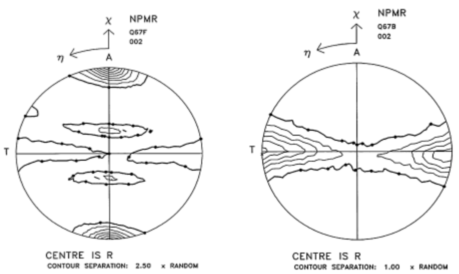


Fig. 9. (0002) pole figures determined by neutron diffraction for Tubes 67F and 67B.

T = 1250 K   10.0:1   Slow cool

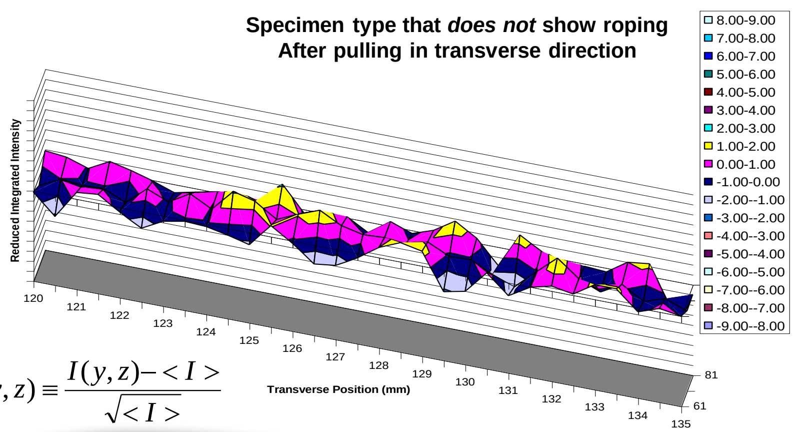
Resolved fraction of basal poles

Tube ID	F_R	F_T	F_A	F_R/F_T
62F	0.50	0.41	0.09	1.24
62B	0.43	0.50	0.07	0.85
63F	0.36	0.58	0.06	0.61
63B	0.36	0.58	0.06	0.63
64F	0.30	0.40	0.30	0.75
64B	0.33	0.55	0.13	0.60
65F	0.44	0.50	0.07	0.88
65B	0.46	0.48	0.07	0.96
66F	0.33	0.56	0.11	0.59
66B	0.35	0.53	0.12	0.67
67F	0.27	0.29	0.44	0.93
67B	0.33	0.54	0.13	0.61

Extrusion ratio and pre-heat temperature were manipulated to generate various textures in Zr-2.5Nb thereby imparting favourable mechanical properties to the pressure tube

Roping in Aluminum Sheet

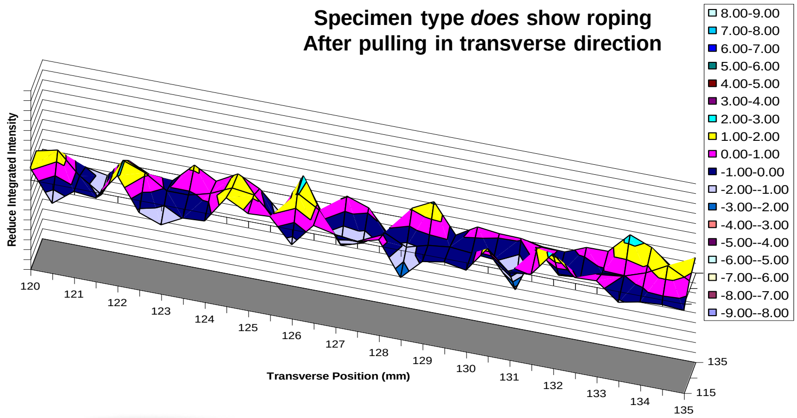
Alcan-McGill



$$i(y,z) \equiv \frac{I(y,z) - \langle I \rangle}{\sqrt{\langle I \rangle}}$$

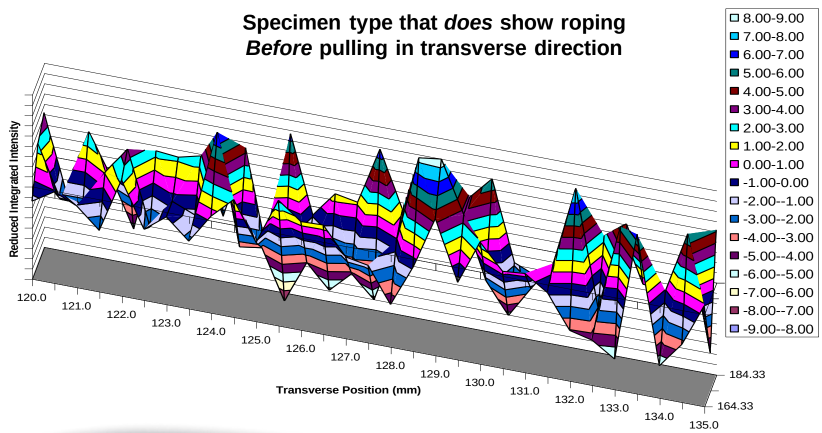
Roping in Aluminum Sheet

Alcan-McGill



Alcan-McGill

Roping in Aluminum Sheet



Nuclear Industry
How We Have Contributed

- ✓In-core components
  - ✓pressure vessels and tubes
  - ✓calandria & calandria tubes
  - ✓spacers
  - ✓rolled joints and welds
- ✓Fuels
  - ✓compositional analysis
  - ✓poisons
  - ✓cladding
- ✓Ex-core components
  - ✓feeder circuits
  - ✓joints and welds
  - ✓steam generator components
  - ✓turbine components
- ✓Nuclear Waste Disposal
- ✓Performance
  - ✓component lifetime
  - ✓irradiation effects
- ✓Failure analysis
  - ✓understanding failure
  - ✓regulator concerns
- ✓Qualifying changes in process route
  - ✓validating designed performance predictions
  - ✓validating FEM
  - ✓new material/supplier
  - ✓radical new design
  - ✓maintain quality standards

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Summary

- Materials for reactors—power and research—is a topic area rich for the materials researcher
  - Materials face challenging and unique applications
  - Some of the materials complex in behaviour
  - Some systems are challenging
- The unique properties of neutrons often make neutron scattering the technique of choice
- In some cases, neutrons are the only choice
- The Chalk River environment has provided opportunity to employ neutron scattering to study these materials for:
  - Failure Analysis
  - Fitness for Service
  - Performance/Lifetime Prediction
  - Fundamental Materials Studies

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