Implication of Potential Quasi-Laminar Indications in USA Reactor Pressure Vessel Shell Ring Forgings

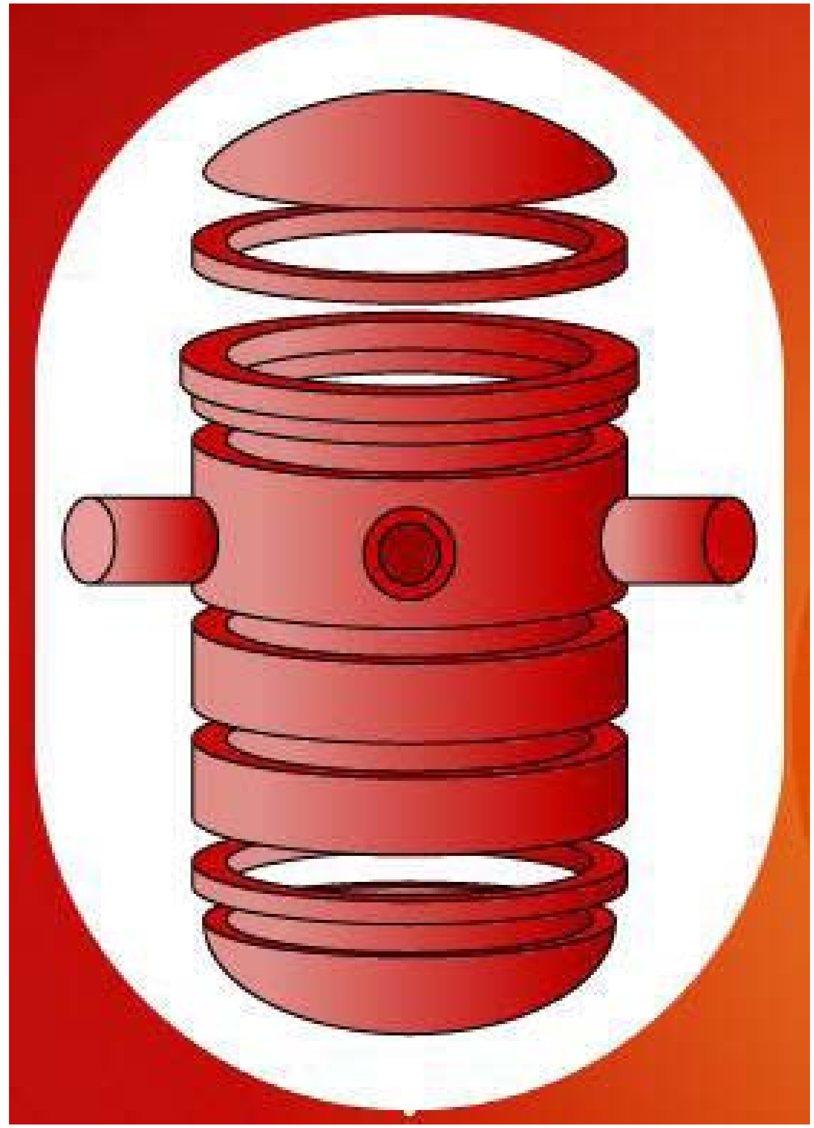
Name	Office	Role / Topic
Robert Hardies	NRR	Coordinator
Carol Nove	RES	Nondestructive Examination
Jeff Poehler	NRR	Metallurgy
Mark Kirk	RES	Structural Integrity

Public Meeting
USNRC Headquarters, Rockville, Maryland
March 5th 2013

Overview

Indications in Reactor Pressure Vessel (RPV) Ring Forgings

- Summer 2012
  - > 8000 quasi laminar indications discovered in Doel 3 NPP
  - ≈10 mm disks
  - ≈10° off-laminar
- September 2012
  - Tihange >2000



Overview

Belgian Regulatory Context & Source of Info

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

- Belgian Regulator: Federal Agency for Nuclear Control (FANC)
  - Uses American Society of Mechanical Engineers (ASME) design and inservice inspection code
- FANC website is a wealth of information:
  - http://www.fanc.fgov.be/nl/page/dossier-pressure-vessel-doel-3-tihange-2/1488.aspx?LG=2
  - Sampling of Documents
    - Doel 3 and Tihange 2 Reactor Pressure Vessels Provisional Evaluation Report, 30 January 2013
    - Safety Case Report, Doel 3 Reactor Pressure Vessel Assessment, 5 December 2012
    - Safety Case Report, Tihange 2 Reactor Pressure Vessel Assessment, 5 December 2012

Overview

RPV Design Basis

- From a design perspective, failure of the reactor pressure vessel is not considered a credible event
  – No mitigating systems
  – 10 CFR part 50, Appendix A
    - Criterion 14 – Extremely low probability of gross rupture
    - Criteria 30, 31, 32 – Quality, Fracture Prevention and Inspection

Overview
Status in USA

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- Current understanding
  - All of the indications identified in Doel 3 and Tihange 2 are of a size, shape and nature that they would have been acceptable according to the ASME Code, Section III
  - All of the indications in Doel 3 and Tihange 2 are structurally insignificant
- NRC Staff continues to collect information to validate our understanding of the implications for U.S. plants

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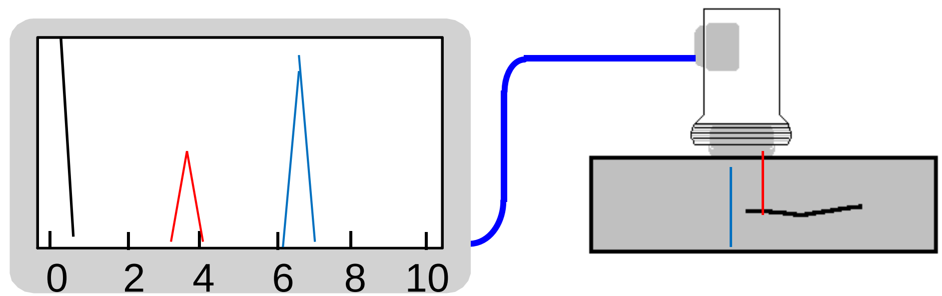
NONDESTRUCTIVE EXAMINATION (NDE)

Ultrasonic Testing (UT) Basics

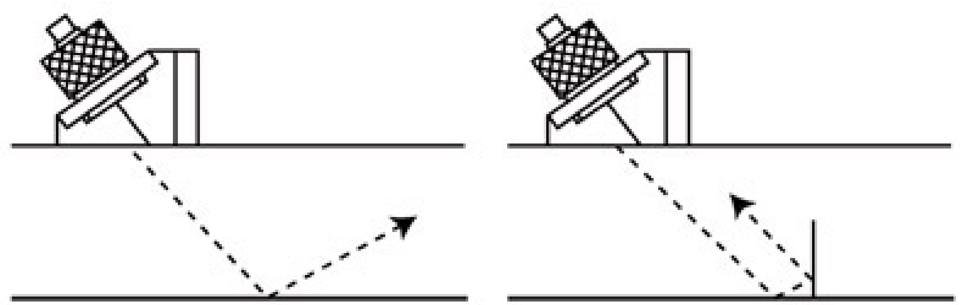
- High frequency sound waves are introduced into a material and are reflected back from interfaces such as surfaces or flaws.
- Reflected sound energy is displayed versus time, and inspector can visualize a cross section of the specimen showing the depth of features that reflect sound.

"Straight beam" (i.e., 0°) exams



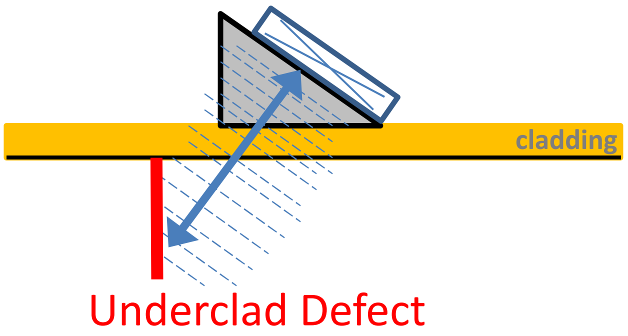
Oscilloscope, or flaw detector screen

"Angle beam" (i.e., greater than 0°) exams



2012 UT In-service Inspections (ISI) in Belgium

- June 2012: UT exam to detect underclad cracks at Doel 3
  - Covered first 30 mm in depth of the core shells from inside diameter
  - Found no underclad defects
  - Detected a high number of indications in RPV base metal

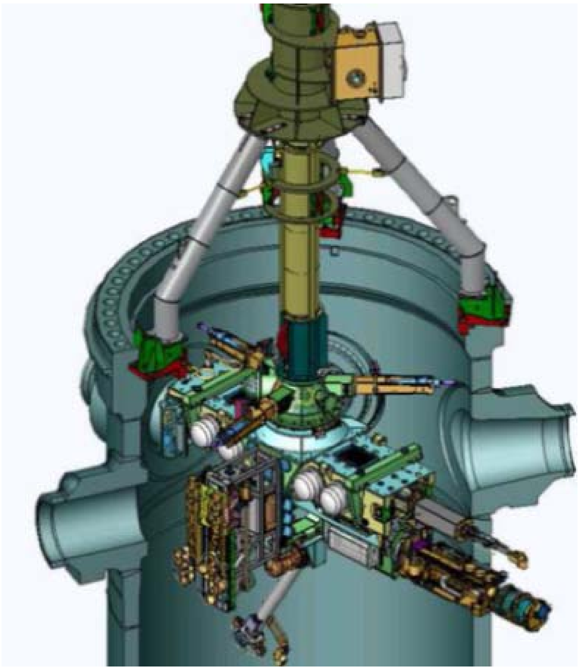


- July 2012: 2nd round of exams at Doel 3
  - Covered entire thickness of RPV
  - Included vessel flange, welds, nozzle shell, upper and lower core shells, & transition ring
  - UT method formally qualified for weld exams only

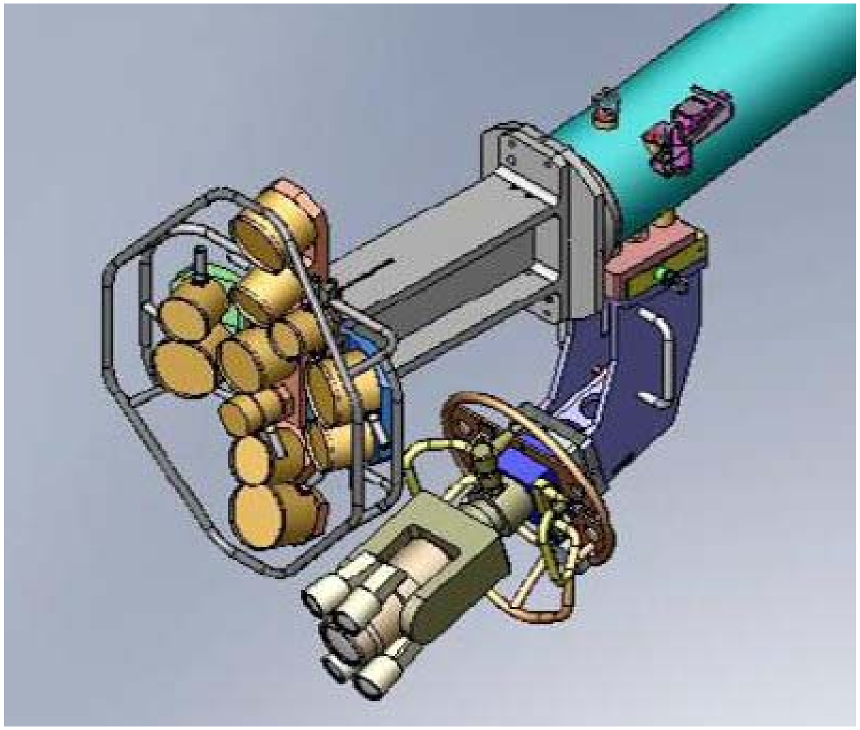
- September 2012: Tihange 2 examined in using same method as in July 2012 Doel 3

Automated MIS-B Equipment used for ISI

ENIQ qualified for weld exams



- MIS-B equipment shown inside the vessel
- The vessel thickness is divided into three depth ranges which requires three different sets of ultrasonic transducers to scan entire thickness range



- A sophisticated tool that holds the three sets of probes (one 0° and four 45°per set)
- A standard sizing method (6 dB drop) was used to measure indication dimension

2012 UT ISI

Summary for Doel & Tihange

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RPV Component	Number of flaw indications in RPV	
	Doel 3	Tihange 2
Vessel head flange	3	5
Vessel flange	2	19
Nozzle shell	11	0
Upper core shell	**857**	**1,931**
Lower core shell	**7,205**	**80**
Transition ring	71*	0

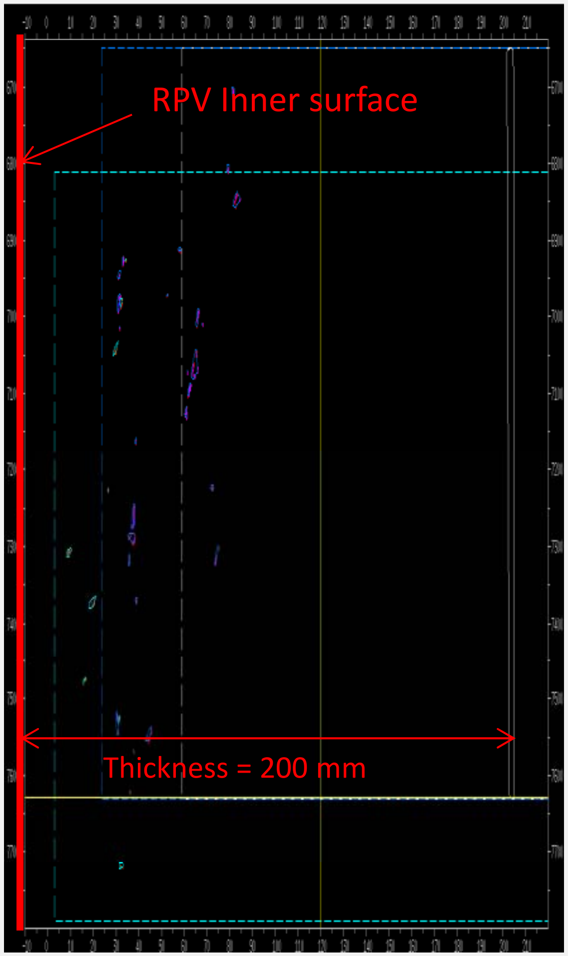
* Flaws are laminar but not clustered

- Flaws in the core shells observed up to a depth of 100 mm from the ID; however, most of the flaws are located between 20-70 mm (first half of shell thickness)
- Flaws are circular discs with a typical diameter of 10 mm

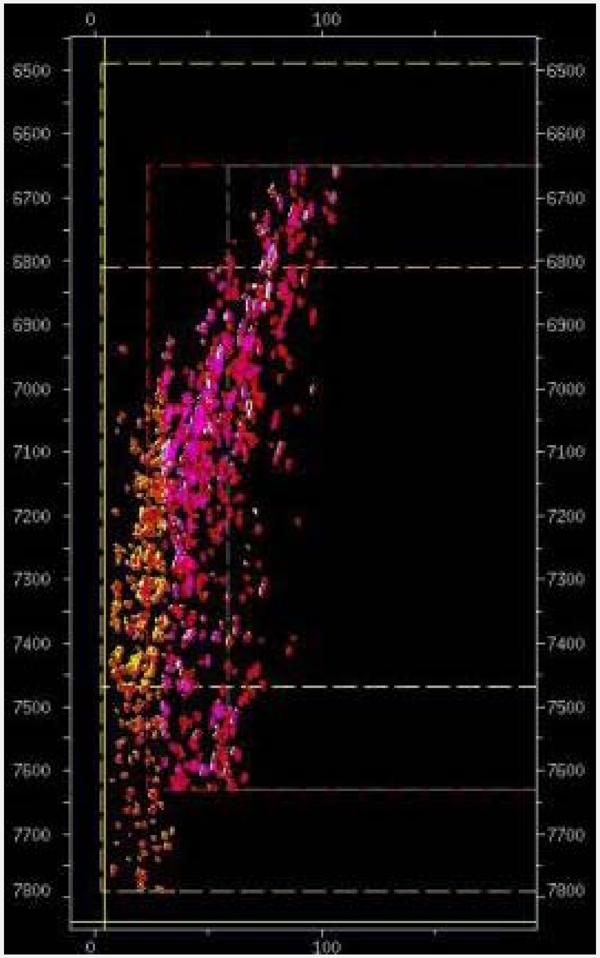
Doel 3 Lower Core Shell

Example UT Data

Typical single plane



Accumulation of all planes in 20° axial sector



Indications appear to be nearly laminar and form a cluster sinking with increasing altitude, from the inner surface up to a depth of about 120 mm.

Doel 3 RPV Flaw Depth Distribution

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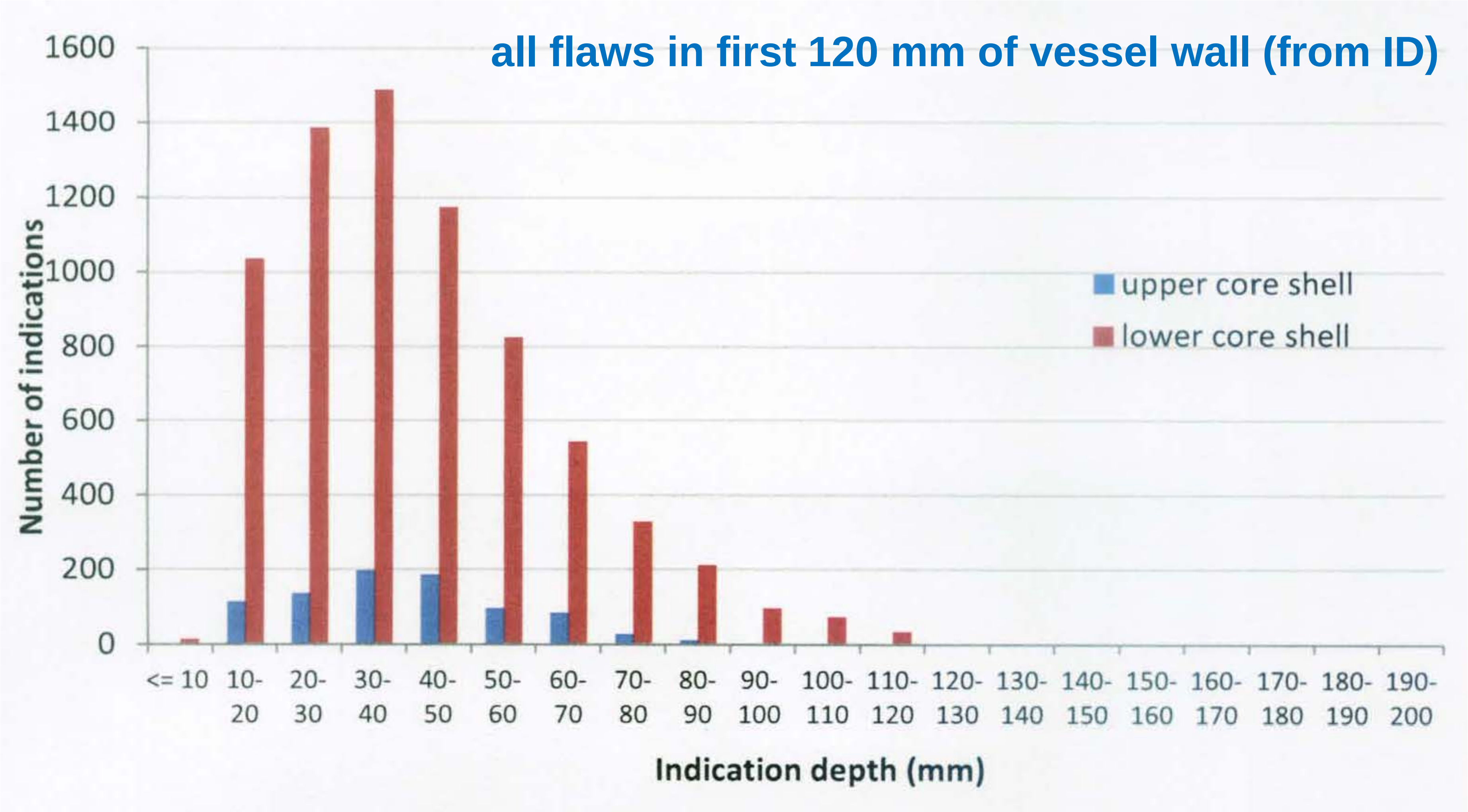

Tihange 2 Upper Core Shell

Example UT Data

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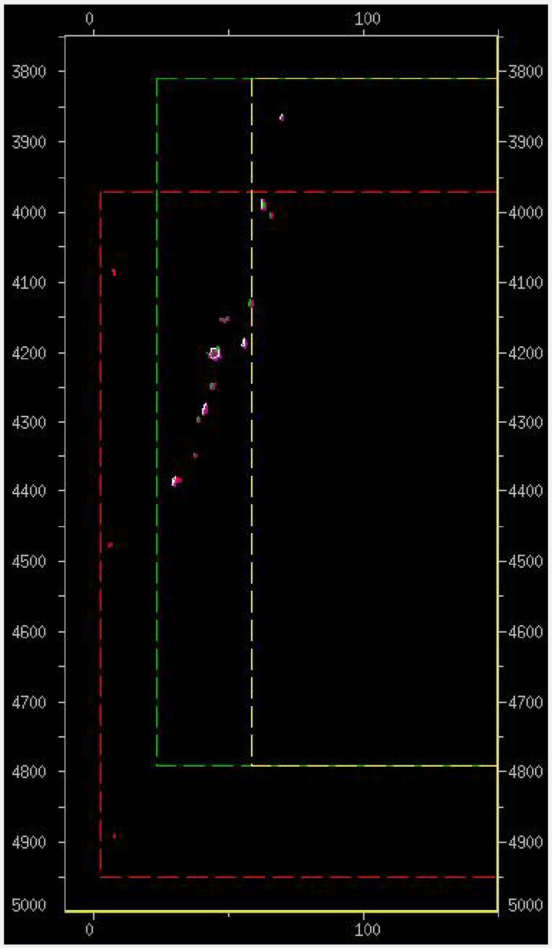
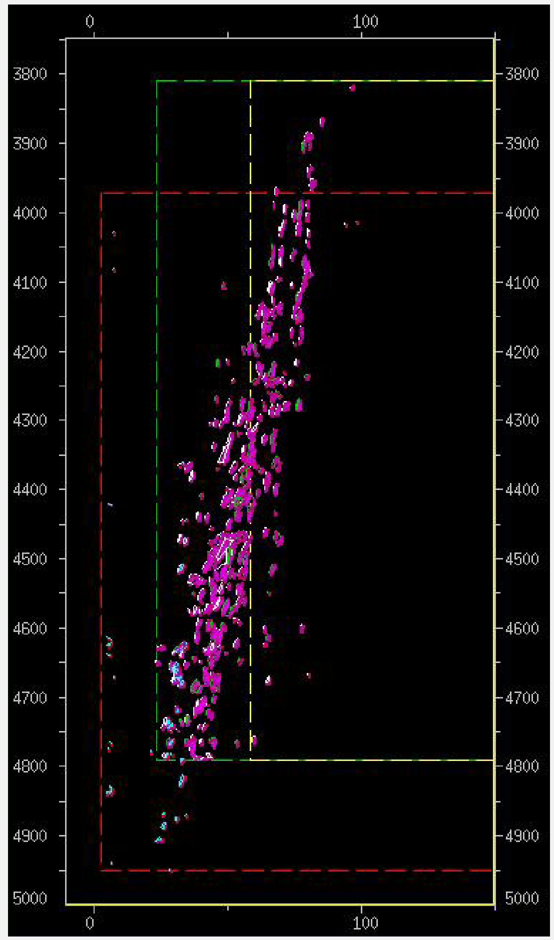
A less affected 20° axial sector



One of the most affected 20° axial sectors



Indications appear to be nearly laminar and form a cluster sinking with increasing altitude, from the inner surface up to a depth of about 120 mm.

Tihange 2 RPV Flaw Depth Distribution

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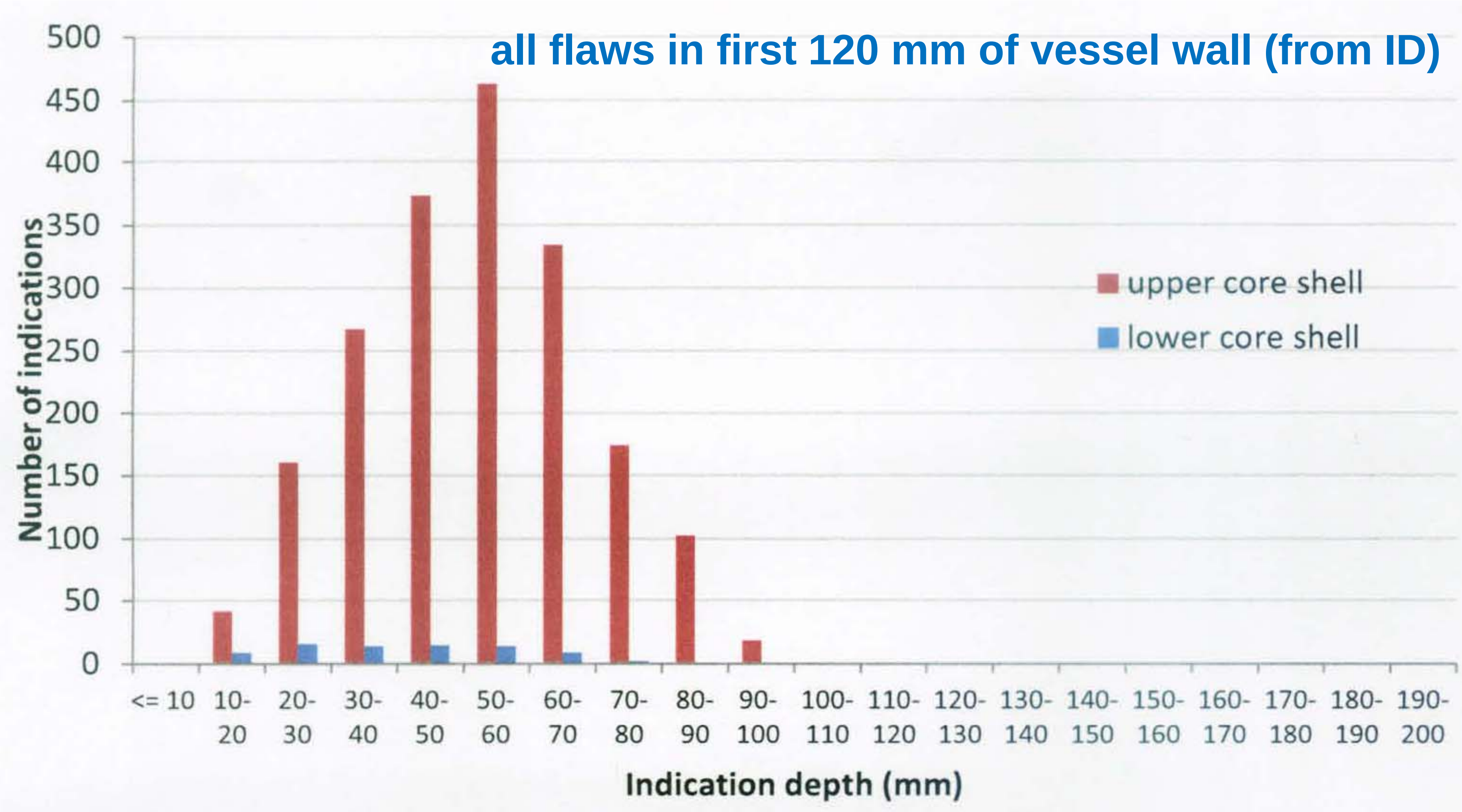

Manufacturing UT Inspections

Methodology

- Manufacturer's examination uses the acceptance criteria of ASME III NB 2542, 1974 Edition, which states that a defect is unacceptable if it leads to complete loss of back wall echo.
- Straight beam, manual examinations were performed from the outside diameter of the vessel.
- The sensitivity level for manufacturing exams was based on the UT response of an infinite reflector (the backwall).

Manufacturing UT Inspections

Information from Belgian Licensee

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- No indications found in lower core shells of Doel 3 and Tihange 2 and the nozzle of Doel 3.
- Some indications found in the upper core shell of Doel 3, and the transition rings.
  - For upper core shell of Doel 3, all indications found to be within acceptance criteria, thus component was accepted.
  - The transition ring of Tihange 2 had unacceptable indications due to hydrogen flaking. Component rejected.

Differences between Manufacturing and In-Service NDE Exams

	Manufacturing Exams	ISI Exams
Technique	Manual from OD	Encoded/automated from ID
Sensitivity based on	Response to infinite reflector (i.e., loss of backwall response)	Response to 2 mm side drilled hole (SDH)
Key Concepts	1. Relatively large reflector required to generate flaw signal and reduce backwall echo 2. Flaws far from probe	1. Small reflectors on order of size of reference reflector cause gain of signal 2. Flaws closer to probe 3. Focused sound beams further enabled detection of smaller flaws

Manufacturing Ultrasonic Inspections

- Expert working group assessment of RDM UT procedures used at time of manufacturing found that the flaws detected in 2012 should have been detectable and reported during manufacturing examinations.

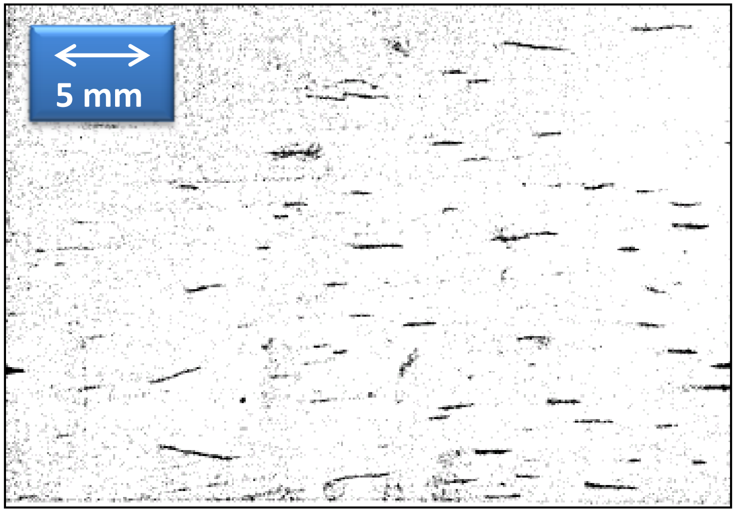
- The reasons why the flaws were not reported during the manufacturing process is not clear, and uncertainty remains about the quality of the UT performed during manufacturing.

METALLURGY

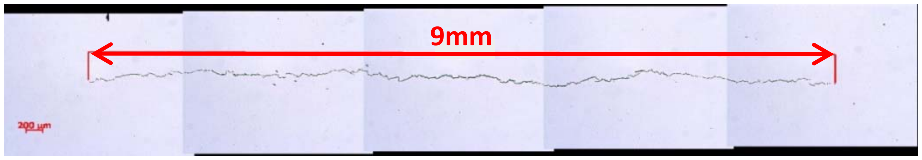
Hydrogen Flaking

- FANC and owner determined the most likely origin of the indications is hydrogen flaking
- Hydrogen flakes are flat, discontinuous internal fissures caused by stresses and decreased solubility of hydrogen during cooling
- Generally numerous and found in bands near the center of a forging, not close to surfaces

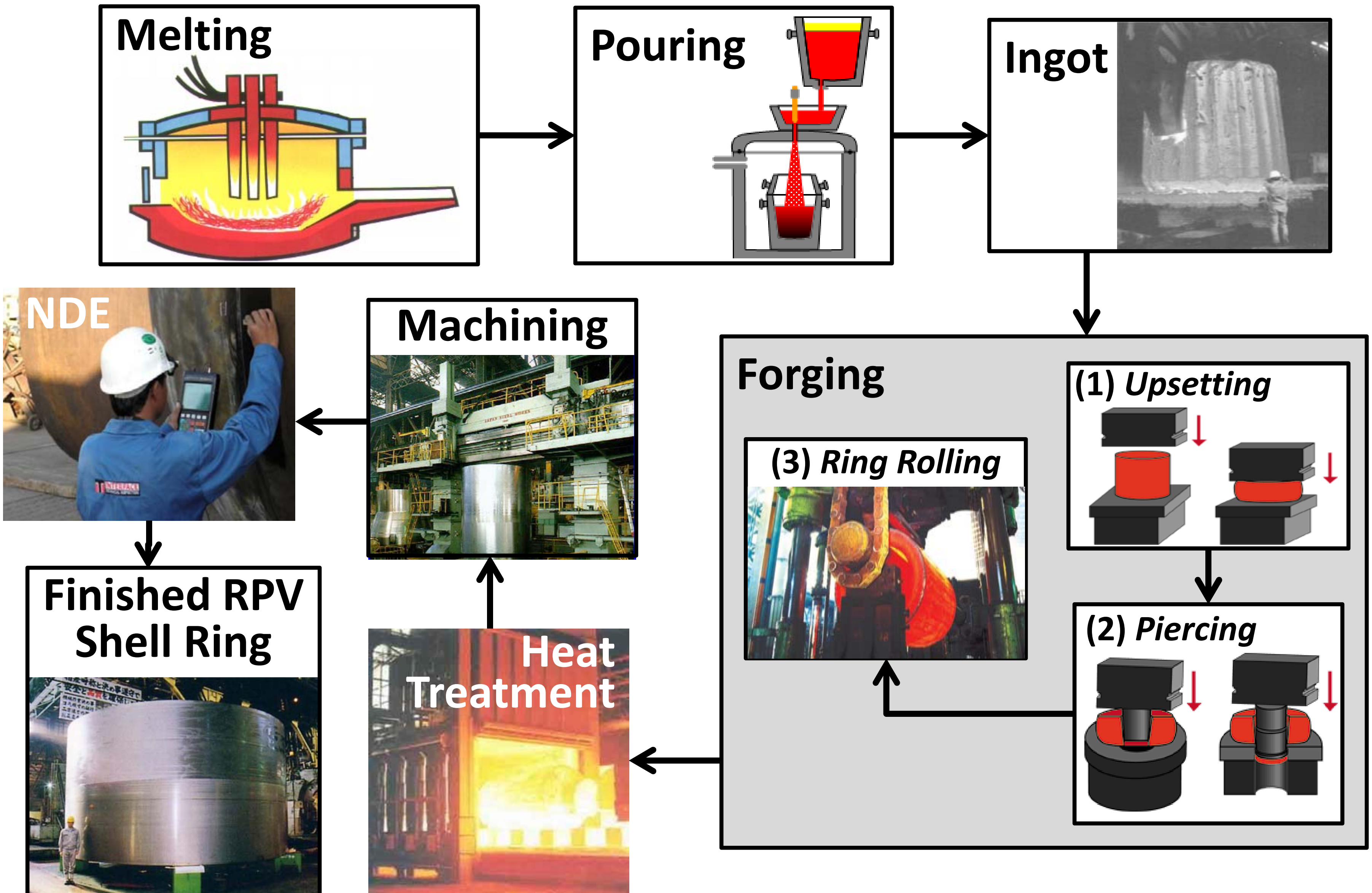
Flakes on a polished and etched cross section of a steel forging



Cross Section of a Single Flake



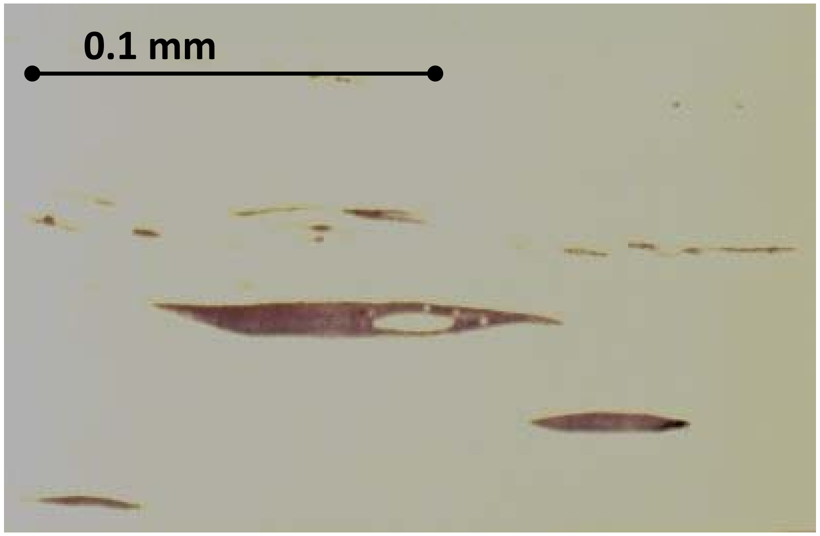
Manufacturing of Forgings for Reactor Vessels



Mechanism of Hydrogen Flaking

- Water vapor reacts with molten steel producing hydrogen (H), which is soluble in steel
- H much more soluble in molten steel than solid steel
- As steel cools, H migrates to inclusions, where it comes out of (solid) solution as H_2 (gas)
- High pressure of H_2 gas plus localized stress causes cracking
- Local variations in chemical composition (segregation) can influence where flakes occur

Inclusions in steel



[Ref: http://www.fgg.uni-lj.si/kmk/esdep/master/wg02/l0100.htm]

History of Hydrogen Flaking

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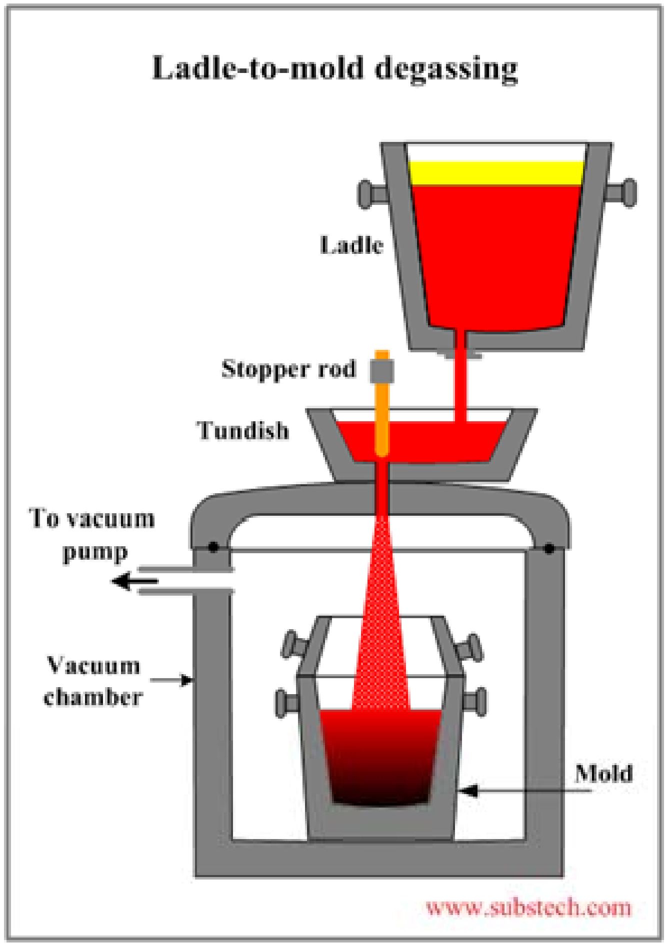
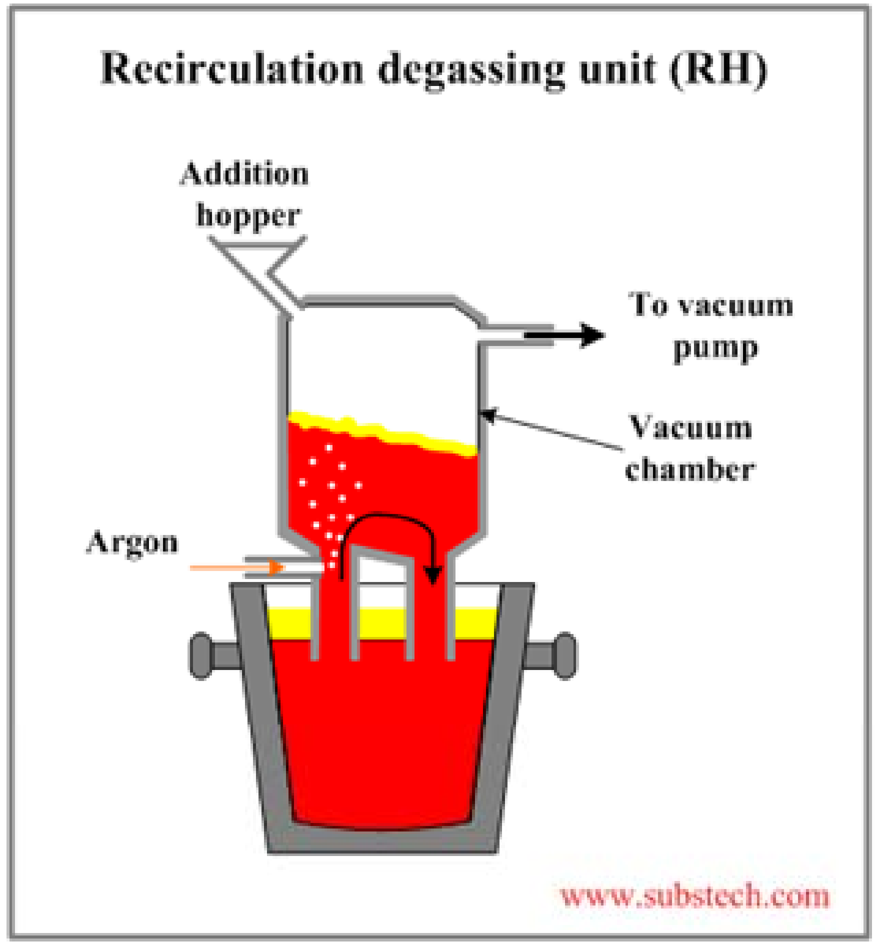
- Known since 1920's
- Caused failures of forgings such as turbine shafts
- Countermeasures for flaking
  - Special heat treatments to reduce hydrogen
  - Controlled cooling practices for forgings
  - Vacuum degassing
- Development of effective vacuum degassing in 1950s essentially replaced other countermeasures

Typical Vacuum Degassing Processes





Factors Contributing to Flaking

- High H content in ingot or forging
  - Inadequate degassing
  - For non-degassed steels, lack of de-hydrogenation heat treatment
  - Tolerable H concentration depends on flaking sensitivity of the steel
- Cooling too fast after forging

Factors Influence Steel's Sensitivity to Flaking

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- **Strength**

  High strength steels – Reactor vessel steels not in this category

- **Thickness**

  Thick parts – Turbine rotor shafts are much thicker than reactor vessel shells

- **Chemical Composition**

  Cleaner steels with lower sulfur, oxygen content create fewer inclusions, causing each inclusion to have a greater H concentration

Forgings in US Reactor Vessels

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- All US reactor vessels have forged nozzles and flanges
- 28 plants have large cylindrical forgings in beltline
- Five forging manufacturers
  - Bethlehem Steel
  - Creusot-Loire
  - Japan Steel Works
  - Ladish
  - Rotterdam Dockyard

- All forgings purchased to ASTM A 508 or ASME SA-508, Class 2 or Class 3
  - Class 3 – higher manganese content, lower molybdenum, and slightly lower maximum carbon
  - Steel must be vacuum degassed
  - De-hydrogenation heat treatment not required, may have been done by steelmakers (proprietary)
- A 508 and construction code (ASME Sec. III) required ultrasonic exam of whole forging

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STRUCTURAL INTEGRITY

Outline

Structural Integrity Assessment

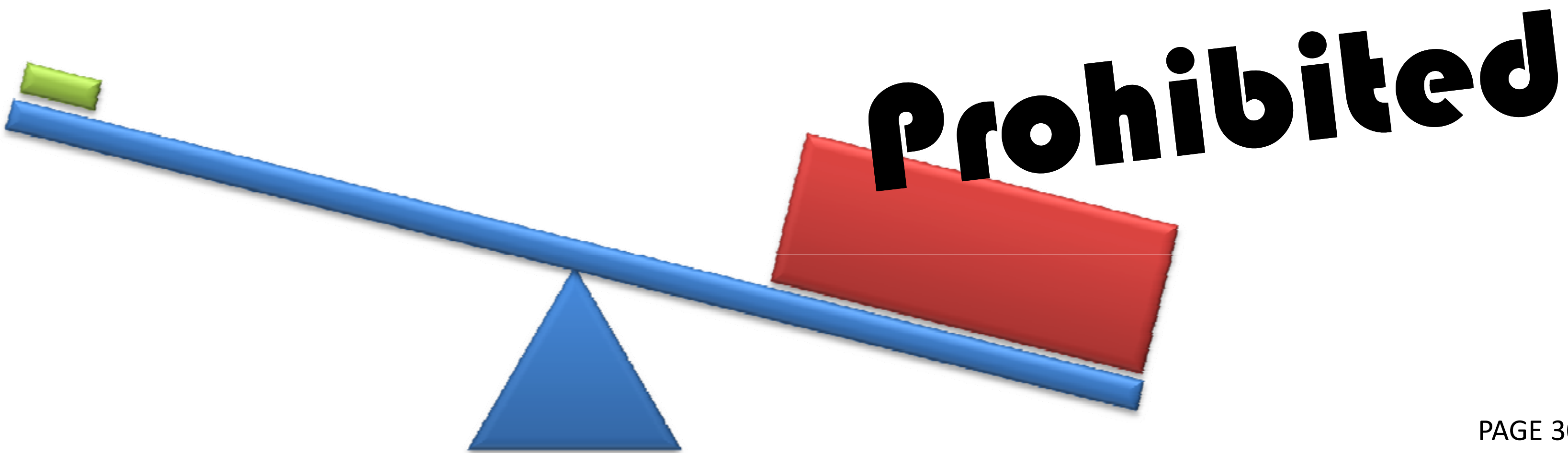
- Structural integrity assessment basics
- Structural integrity assessment of quasi-laminar indications
- Assessment process for QL indications used in Belgium
- Assessment results
- Belgian (FANC) findings & requirements
  - On licensee analysis (January 2013)
  - Regarding on-going efforts

Structural Integrity Assessment

Basics

The structural integrity of nuclear reactor pressure vessels (RPVs) is ensured by requiring that the resistance to fracture (toughness) always exceeds the driving force for fracture that is produced by loading

Fracture Toughness < Fracture Driving Force



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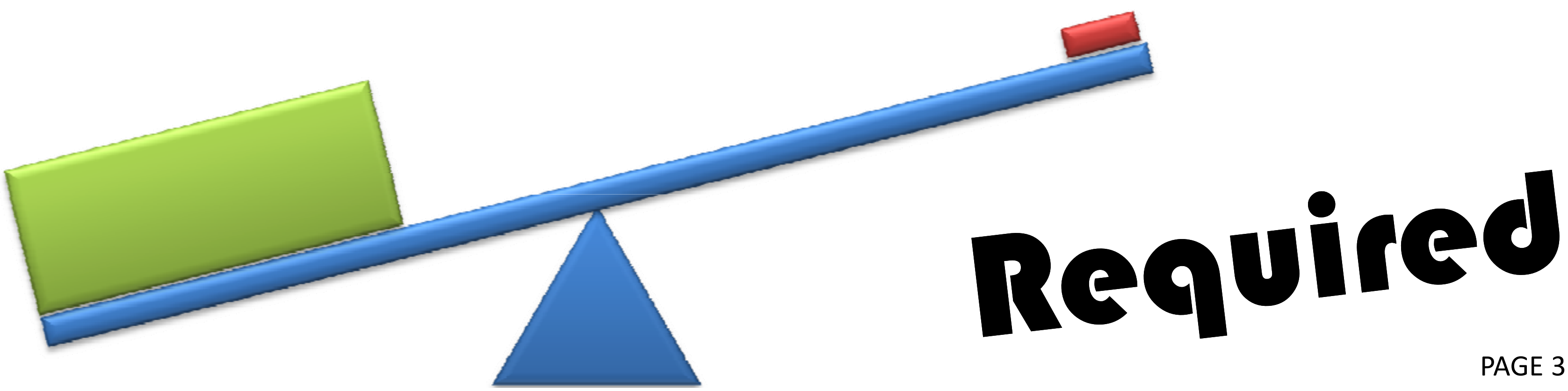

Structural Integrity Assessment

Basics

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Fracture Toughness > Fracture Driving Force

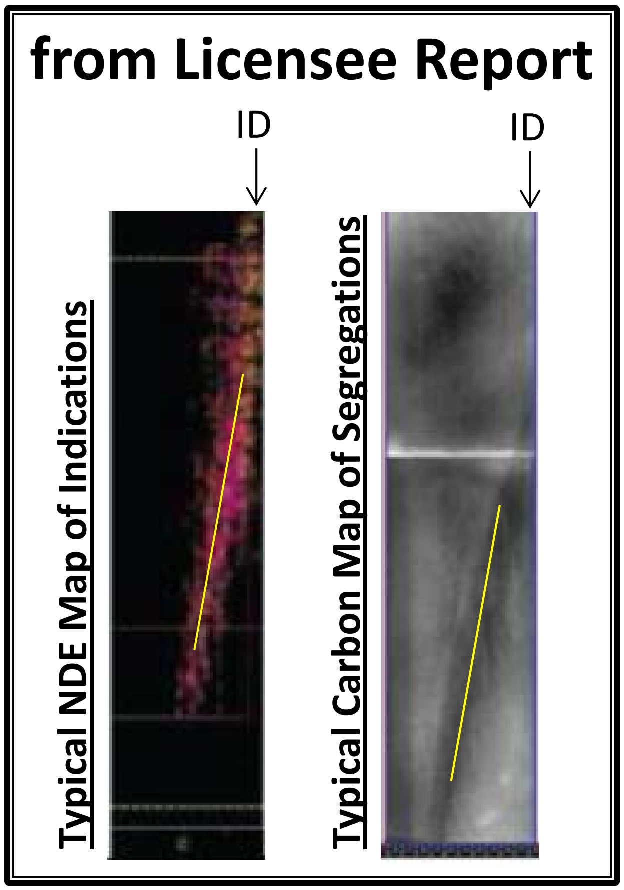
$$K_{Ic}(T, RT_{NDT}) > \sigma \times \sqrt{\pi a} \times F$$

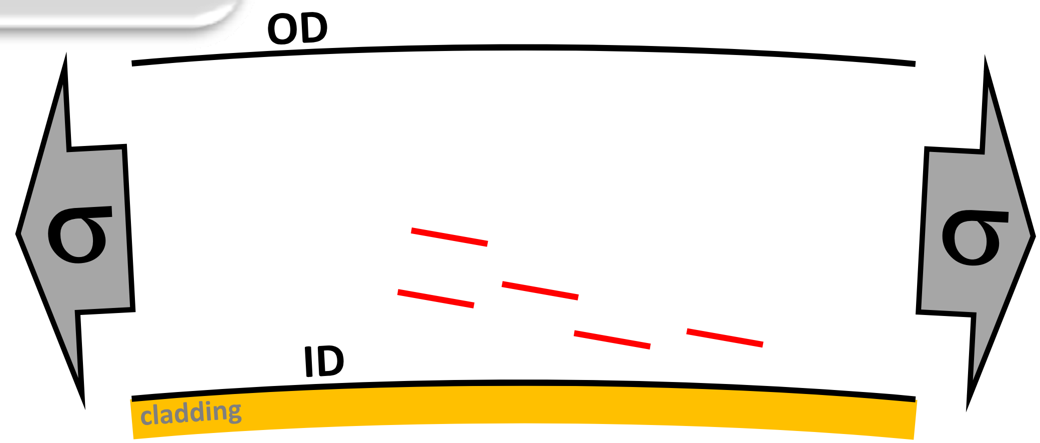
Toughness (K_{Ic}), Embrittlement (RT_{NDT}), Stress (σ), Crack Size (a), Geometry (F)

Structural Integrity Assessment

… of Quasi-Laminar Indications

$$K_{Ic}(T, RT_{NDT}) > \sigma \times \sqrt{\pi a} \times F$$





Inclination of QL indications
- **Nearly parallel to direction of applied stress,**
- **Greatly reduces driving force to fracture**

Item	Description
Quantity	≈ 8000 in one vessel, ≈ 2000 in another vessel
Size	On average: the size of a button (10 mm)
Location	Near clad (≈ 2mm away) to 120 mm from ID
Inclination	Along segregates, inclined ≈ 10° from ID surface

[Ref: http://www.fanc.fgov.be/GED/00000000/3300/3390.pdf]

Assessment Process

for Quasi-Laminar Indications

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$$K_{Ic}(T, RT_{NDT}) > \sigma \times \sqrt{\pi a} \times F$$

Accounted for effects of
- Irradiation (standard formulas)
- Flaw orientation (testing program)
- Segregation (testing program)

Analyzed
- Normal & anticipated
- Emergency & faulted

conditions. Used ASME acceptance criteria.

Analyzed every flaw in the size and location reported by July 2012 inspections.

- Accounted for RPV geometry
- Ignored structural benefit of cladding
- Analyzed measured orientations
- Accounted for flaw proximity

Acceptance Criteria
(ASME SC-XI IWB-3612)

Normal & Anticipated

$$K_{APPLIED} < \frac{K_{Ic}}{\sqrt{10}}$$

Emergency & Faulted

$$K_{APPLIED} < \frac{K_{Ic}}{\sqrt{2}}$$

Assessment Results (1 of 3)

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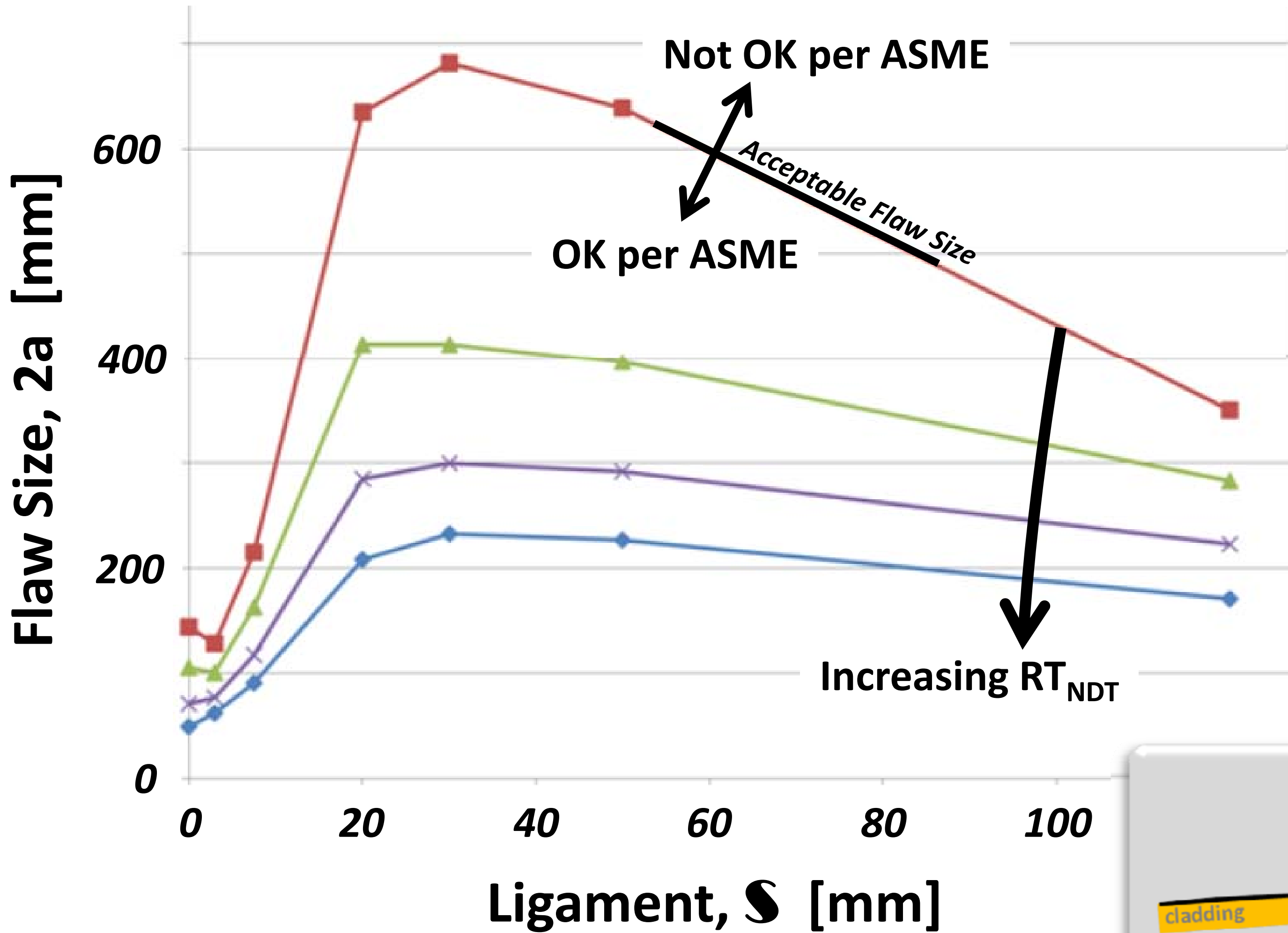
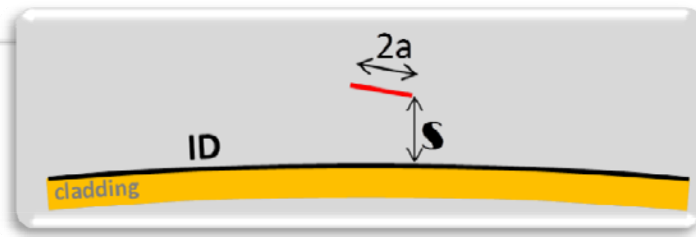


Effect of flaw inclination, proximity to ID, and RT_{NDT} on acceptable flaw size established



[Ref: http://www.fanc.fgov.be/GED/00000000/3300/3390.pdf]

Assessment Results (2 of 3)

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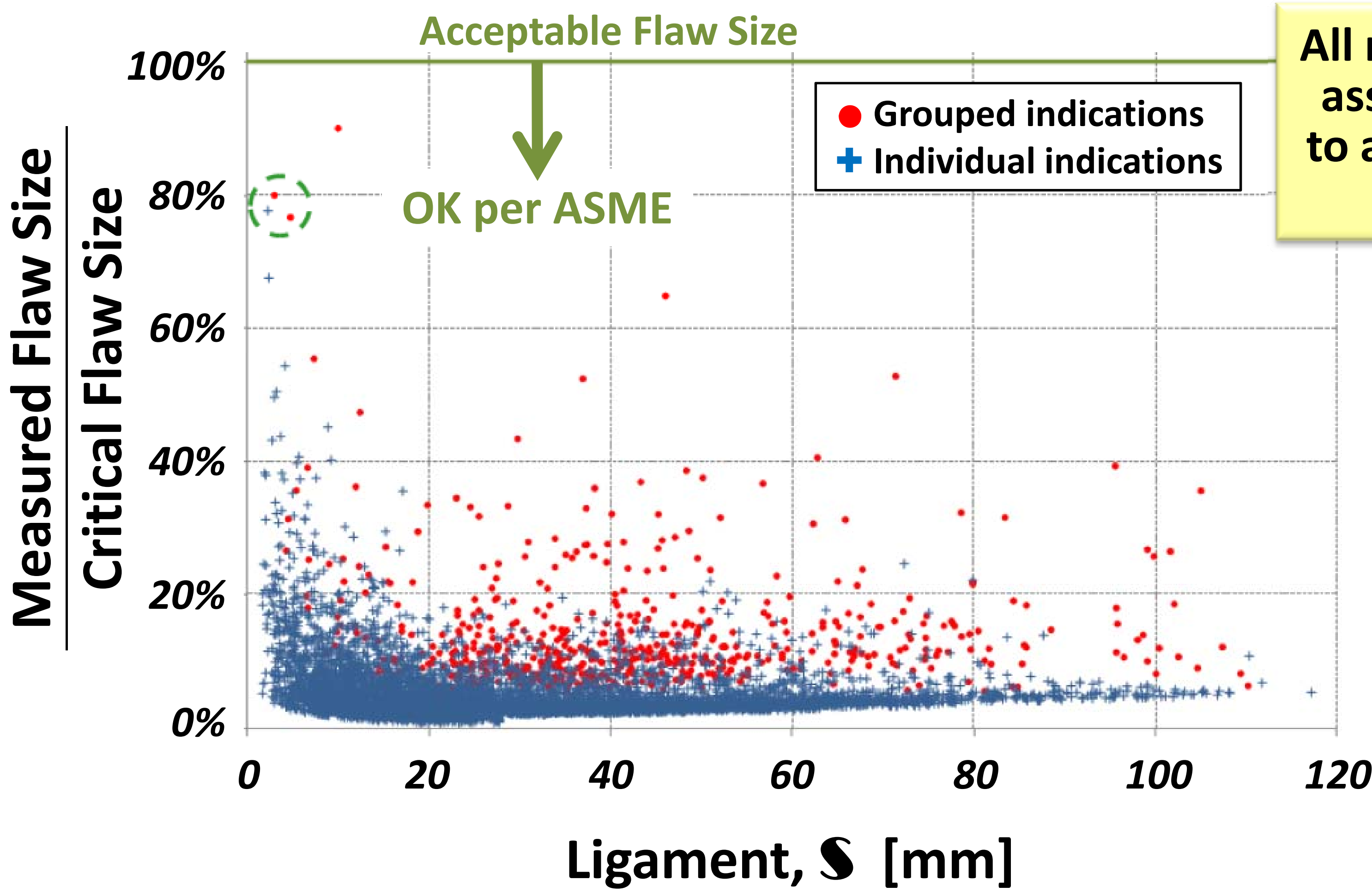

All measured flaws assessed relative to acceptable flaw size curves

[Ref: http://www.fanc.fgov.be/GED/00000000/3300/3390.pdf]

Assessment Results (3 of 3)

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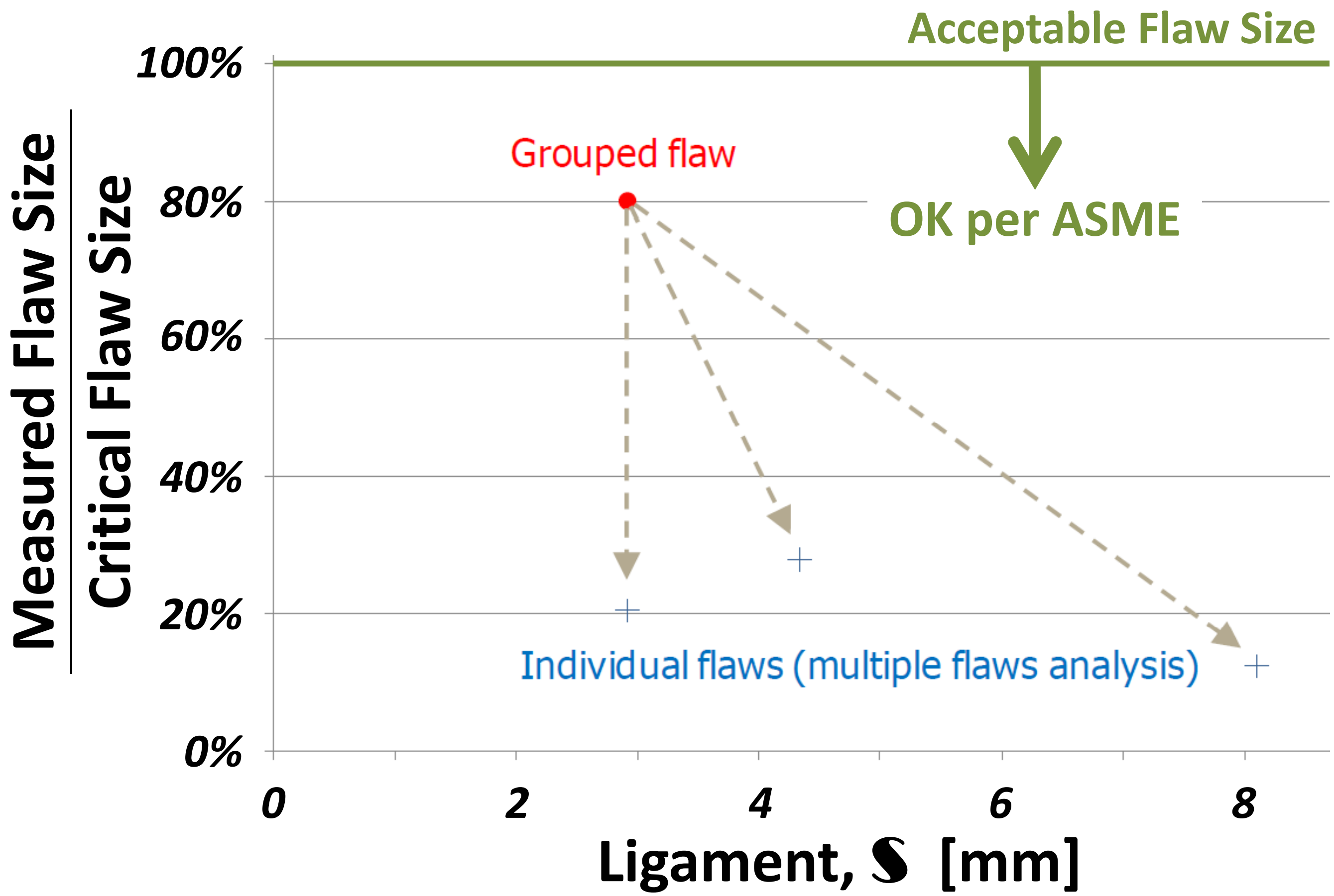
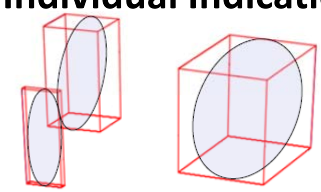
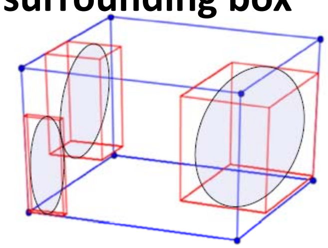


Conservatism of proximity criteria demonstrated

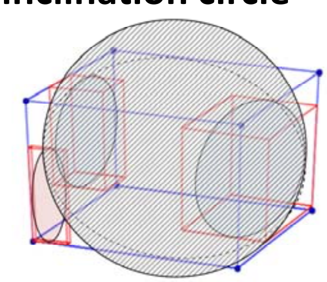
1. **Individual Indications**



2. **Grouped using largest surrounding box**



3. **Represented as highest inclination circle**



Also

- **PFM analysis (using FAVOR) gives probability of crack initiation as ≈10^{-8}**

[Ref: http://www.fanc.fgov.be/GED/00000000/3300/3390.pdf]

Belgian (FANC) Findings

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Ref: http://www.fanc.fgov.be/GED/00000000/3300/3391.pdf

- "In the current state of knowledge and given the available data, ***these open issues do not represent conditions that require a definitive shutdown of the Doel 3 and Tihange 2 reactor units."***
- "However, these open issues lead to some uncertainties that might reduce the conservatism of the licensee's safety demonstration and hence impair the level of confidence in the safe operability of the reactor units in question. As a consequence, ***the Federal Agency for Nuclear Control considers that, in the current state, the Doel 3 and Tihange 2 reactor units may only restart after the requirements listed in the present evaluation report are fulfilled by the licensee."***

On-Going Efforts in S.I.

Required by FANC of Licensee

	Before Re-Start	After Re-Start

Material Properties	• Assess local toughness properties using samples with H_2 flakes
	  • Toughness ahead of the flake
	  • Properties between the flakes
	• Measure residual H_2 content in flakes
		• Effect of irradiation on specimens with H_2 flakes
		• Effect of phosphorus segregation & thermal aging on local toughness

S. I. Analysis	• Demonstrate that the potential for
	  • Flaw under-counting in non-inspected regions
	  • Higher than reported tilt angles
	does not compromise the safety case
	• Perform load test on the RPV with acoustic emission
		• Test large-scale tensile specimens with multiple flakes to
		  • Demonstrate improbability of brittle fracture
		  • Experimentally confirm analytical criteria for grouping multiple flaws

Ref: http://www.fanc.fgov.be/GED/00000000/3300/3391.pdf

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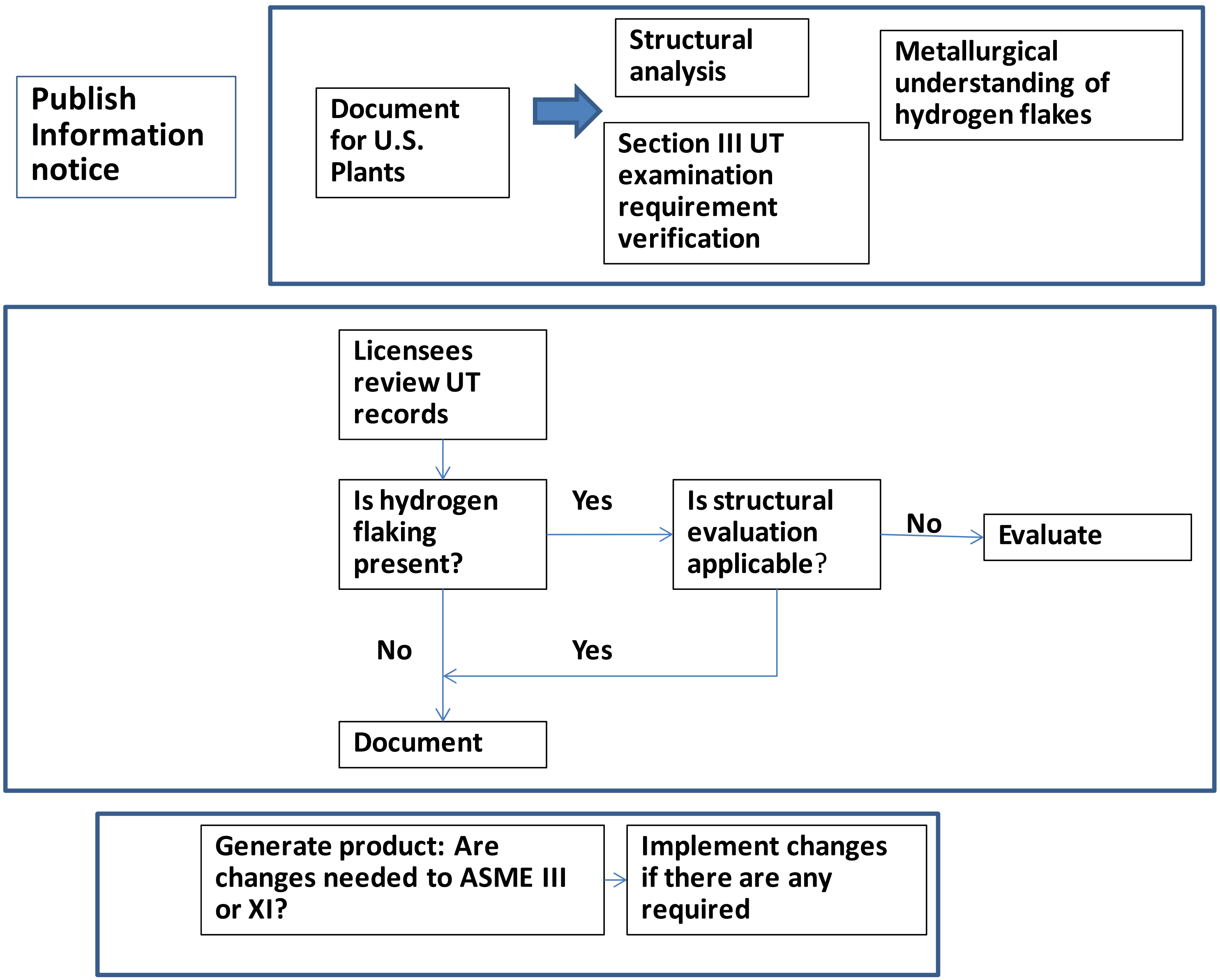
NRC PLANS

NRC Plans


Publish Information notice
Document for U.S. Plants
Structural analysis
Section III UT examination requirement verification
Metallurgical understanding of hydrogen flakes
Licensees review UT records
Is hydrogen flaking present?
Yes
Is structural evaluation applicable?
No
Evaluate
No
Yes
Document
Generate product: Are changes needed to ASME III or XI?
Implement changes if there are any required

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EPRI PRESENTATIONS …