BREDA – a path to support LTO for the current units

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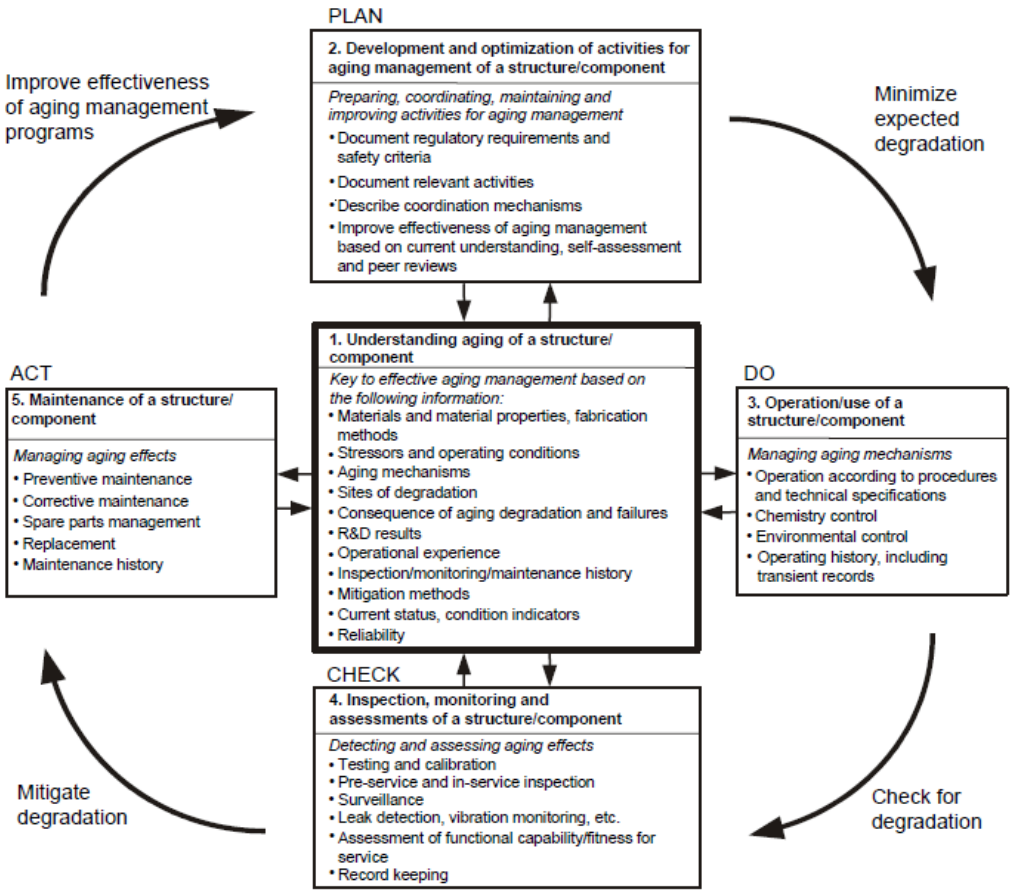
In addition to NKS, the support from the Finnish nuclear safety program, the SAFIR2022-program, the Swedish Radiation Safety Authority, SSM, the Finnish radiation and nuclear safety authority, STUK and the Swedish Centre for Nuclear Technology, SKC as well as the Swedish and Finnish Nuclear Power Plants permit holders and owners (Ringhals AB, Forsmarks Kraftgrupp AB, OKG AB, Vattenfall AB and Uniper), (TVO and Fortum) for the work is gratefully acknowledged by the project team.



- PLAN
  - Minimize expected degradation
- DO
  - Check for degradation
- CHECK
  - Correct unacceptable degradation
- ACT
  - Improve AMP effectiveness

- Even though the IAEA way of AM is Plan-Do-Check-Act, it all starts with proper treatment of ageing mechanisms!

The idea: Barsebäck as a Research and Development Arena

Using the retired Reactor Pressure Vessel of Barsebäck 2 to study the actual outcome of the irradiation induced ageing of the RPV with respect to the surveillance program prediction;

And by taking samples in a “non-affected” zone, distinguish the effect of thermal ageing on the outcome;

Providing a platform for experience exchange and networking for the next generation of researchers in the area and by that, ensure knowledge retention in a crucial area for LTO;

The support from NKS enables the connection between the Swedish effort on materials extraction, testing and modelling of brittle failure and the Finnish effort on mechanical testing as well as the exchange part of the scope!

The team:

The testing team:
Chalmers University – Dept of Physics
KTH – Dept of Engineering Mechanics
VTT

The stakeholders, beneficiaries, recipients, supporters, (and reference group):
Energiforsk
Forsmark Kraftgrupp AB
OKG AB
Ringhals AB
SSM
STUK

And of course: *Bengt's RPV*

Project team as of 2020

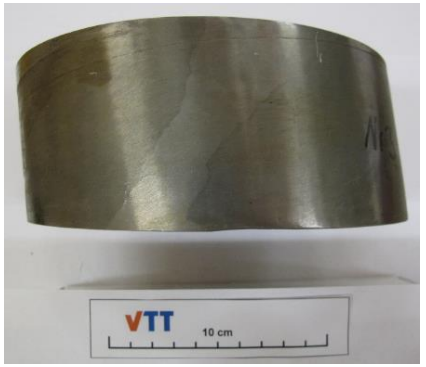
Reactor pressure vessel installed in B2, photo: Barsebäck Kraft

Extraction of the trepans:

Samples were extracted by drilling

Work performed by Ringhals AB under the auspices of Energiforsk

The technique has since been utilized to extract materials from the pressurizer of Ringhals 2



Test scope:

RPVH studied from two trepans

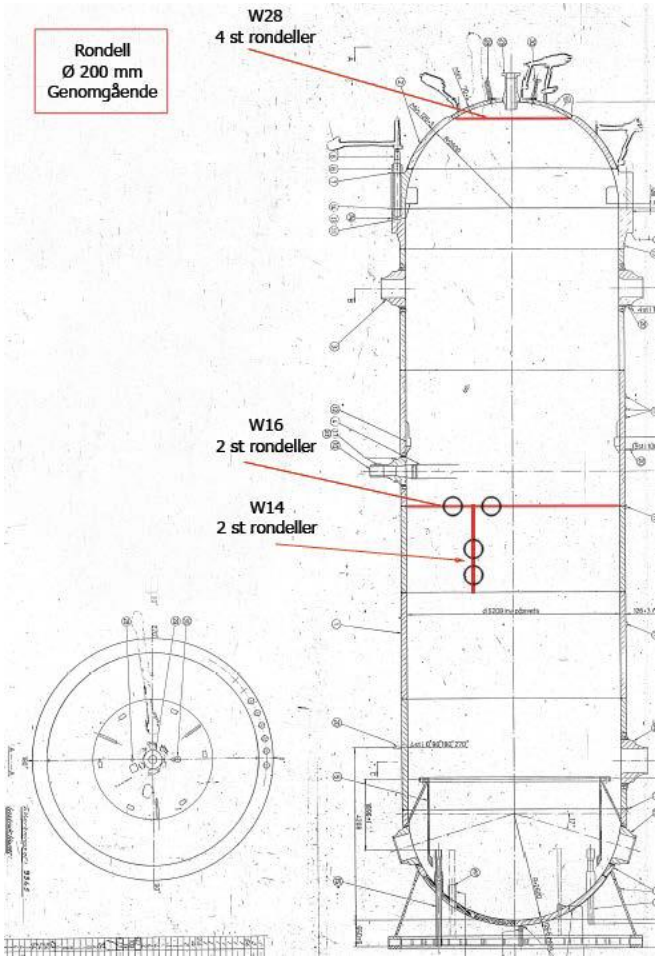
- Investigations *finished*

Beltline weld seams in two directions

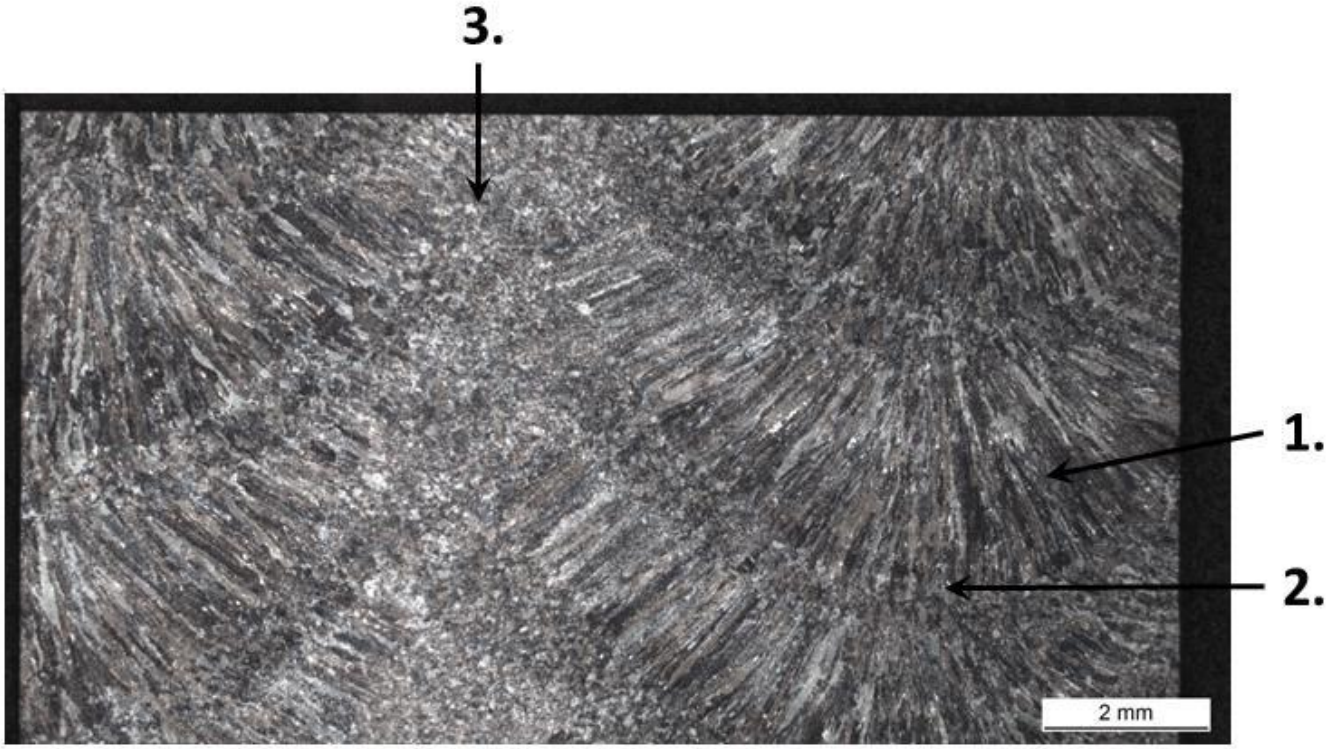
- Axial weld seam W14 (*finished)*
- Circumferential weld seam W16 (**underway)**

Trepans investigated at ¼ T depth

- Corresponding with surveillance program



Microstructure characteristics in multi-layer weld:



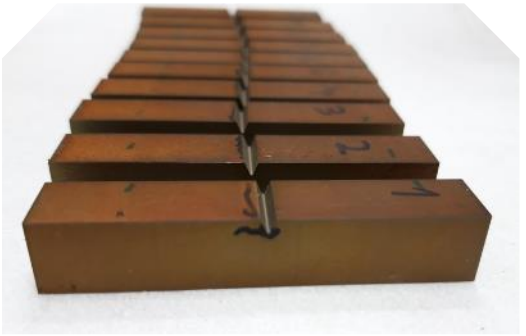
1. Dendritic region, 2. Reheated region, 3. Twice reheated region

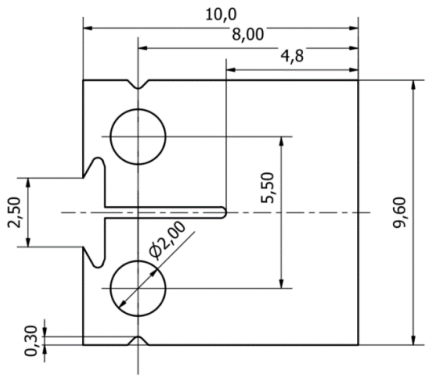
Photo: U. Ehrnsten

Mechanical testing:

Test program includes:

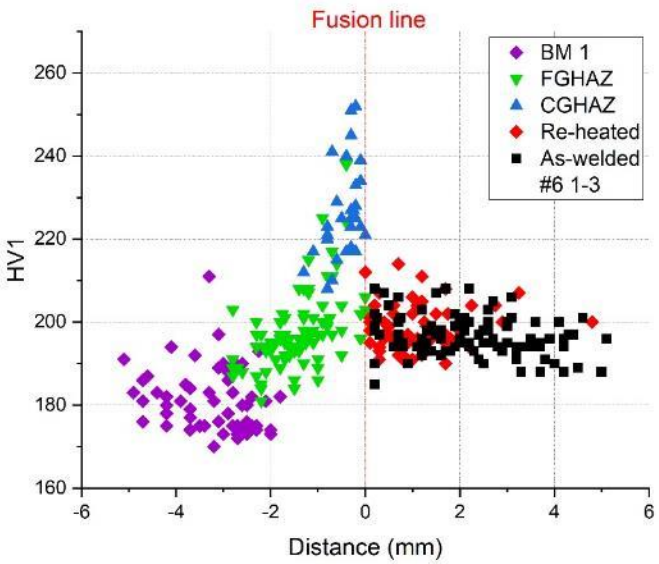
- Hardness testing
- Tensile testing
- Impact testing (”Charpy-testing”)
- Fracture mechanics testing



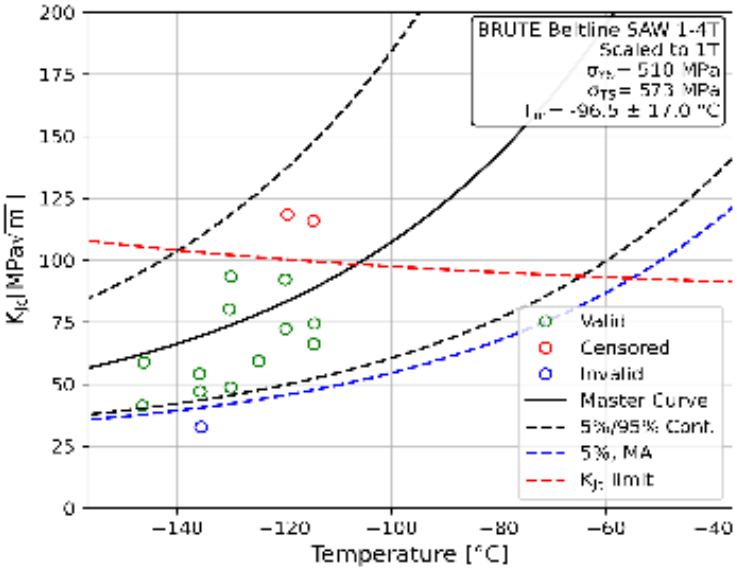


Example results:

Hardness profile over fusion boundary - Beltline



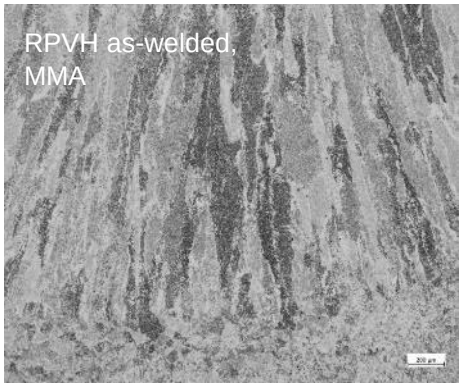
Fracture mechanics testing ”Master curve” - Beltline

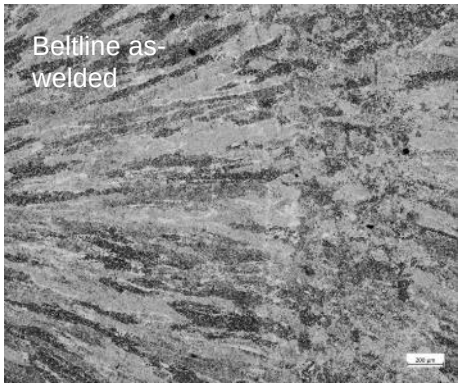


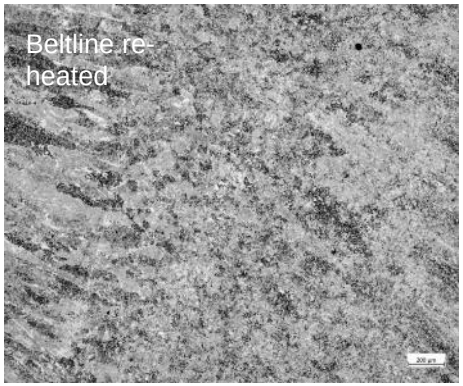
Microscopy

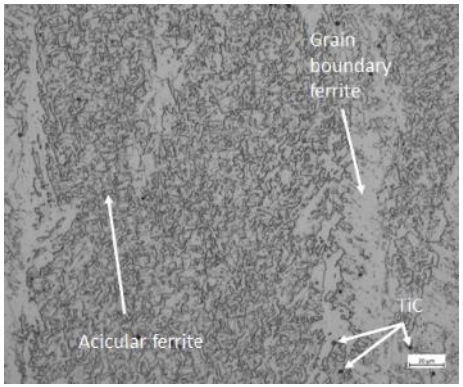
Microstructure of the welds is typical of high quality welds

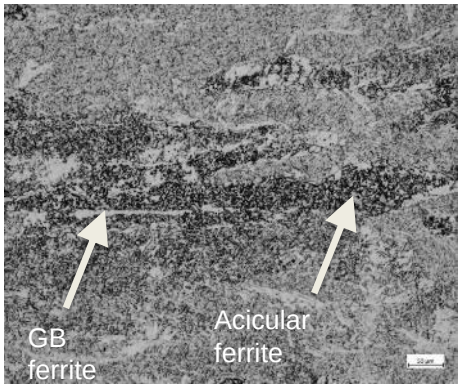
Possibly minor differences between the RPVH and beltline weld microstructures

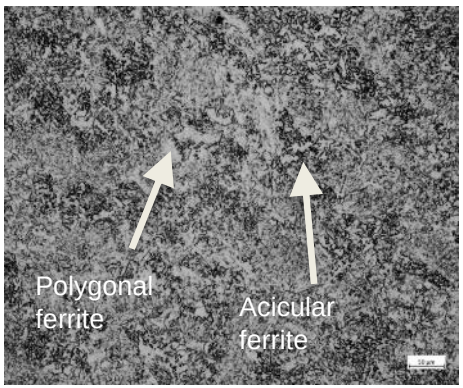








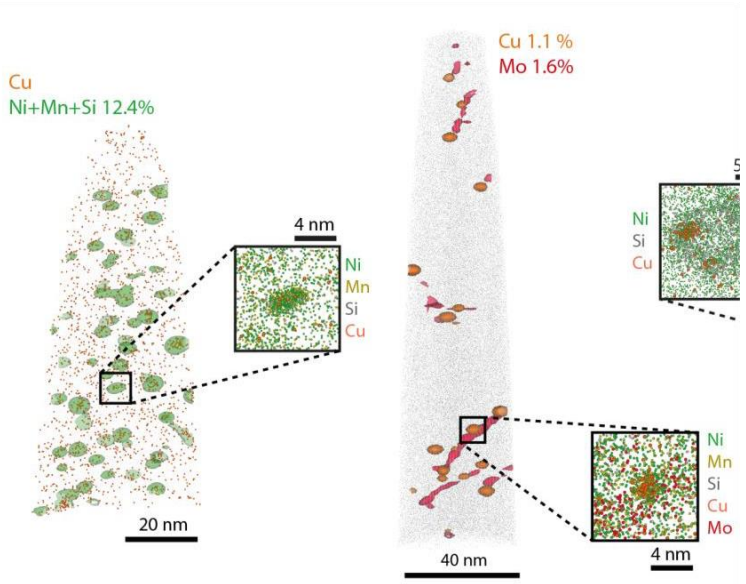




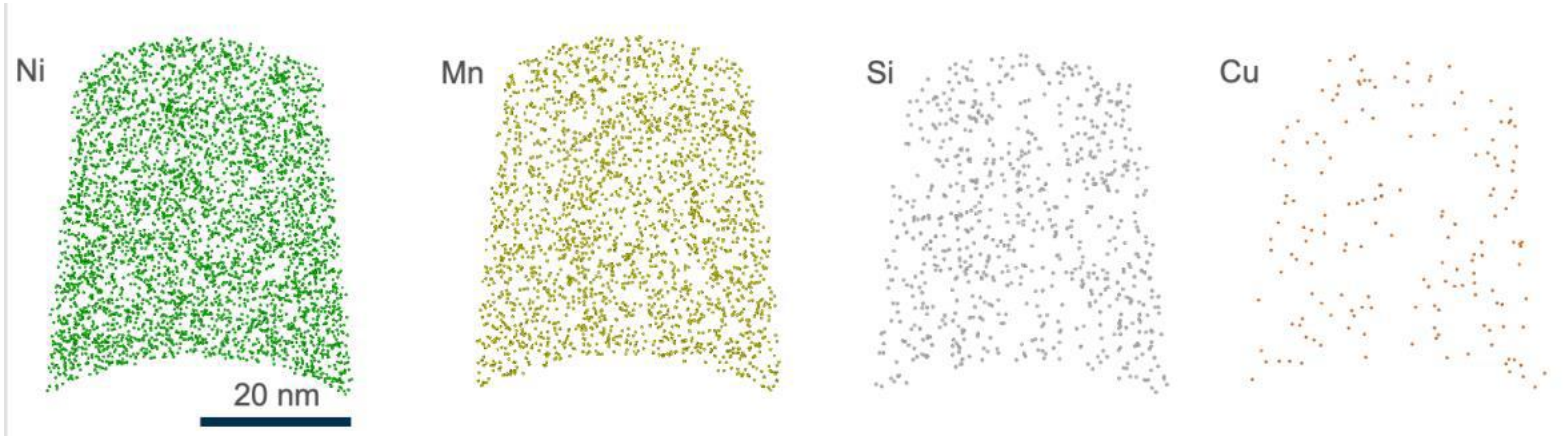
Photos: N. Hytönen / N. Hytönen et al, Int J Minerals, Metallurgy and Materials, vol 28, #5, 2021

High resolution microscopy

In the PWR-irradiated and thermally aged material, there is plenty of Ni-Mn-Cu-Si-agglomerates!



K. Lindgren



From: NKS-431

5 nm thick slices from the APT reconstruction of the analysis of the irradiated Material from B2. No clusters are observed.

Modelling efforts:

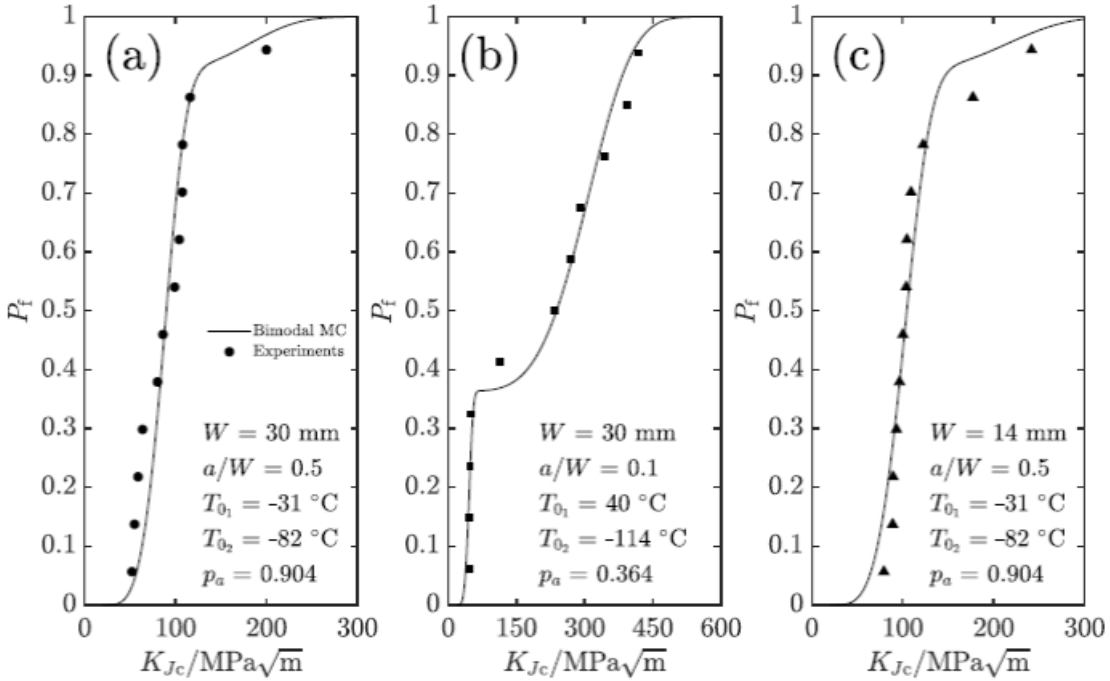
Traditionally, brittle failure of aged Low Alloy Steel have been attributed to cleavage of carbides followed by the onset of brittle fracture

The results from the testing of thermally aged material indicates a co-existing failure mode, in this case grain boundary failure

Current modelling effort is concerned with developing a general model that predicts this co-existence and to correctly structure the risk-ranking of failure for this behavior!

Modelling efforts:

Comparison of predicted failure probabilities from the bimodal master curve with rank probabilities for experimental fracture tests



M. Boåsen et al, EFM vol 262, 2022, paper id 108248

The outcome so far:

2 (and a half) defended Ph.D. theses

1 successful Masters Thesis with the student taking on a Ph.D: position

1 post-doc completed

Multiple research visit executed, the latest (but not last) as recent as in April (Daniela Klein visiting VTT to study fracture surfaces and interact with Jari Lydman and Noora Hytönen)

Successful network has been established enabling knowledge retention and exchange on a daily basis and connection between Sweden and Finland as nuclear operating countries!

6 paper publications in relevant and high impact journals

Conclusions:

No discernable effect of thermal aging detected during mechanical and microstructural investigation of the RPVH

Preliminary data shows a relatively large conservatism with respect to outcome in plant vs surveillance program

Note: testing not completed yet

The use of miniature CT-specimens gives useable results with respect to the needs for fitness to service and regulatory acceptance needs

The actual RPV is microstructurally similar to the archive samples welded to emulate the vessel and used for surveillance purposes

Questions