Study of the margin against fracture for reactor pressure vessels subjected to pressurized thermal shock transients

WPS-MAF

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Outline of the presentation

- Theoretical background
  - Brittle fracture
  - Warm pre-stressing (WPS)
- Background
- WPS-MAF
  - Research description
  - Status
  - Recent results
  - Ongoing and planned research
- Expected results and future needs

Acknowledgments
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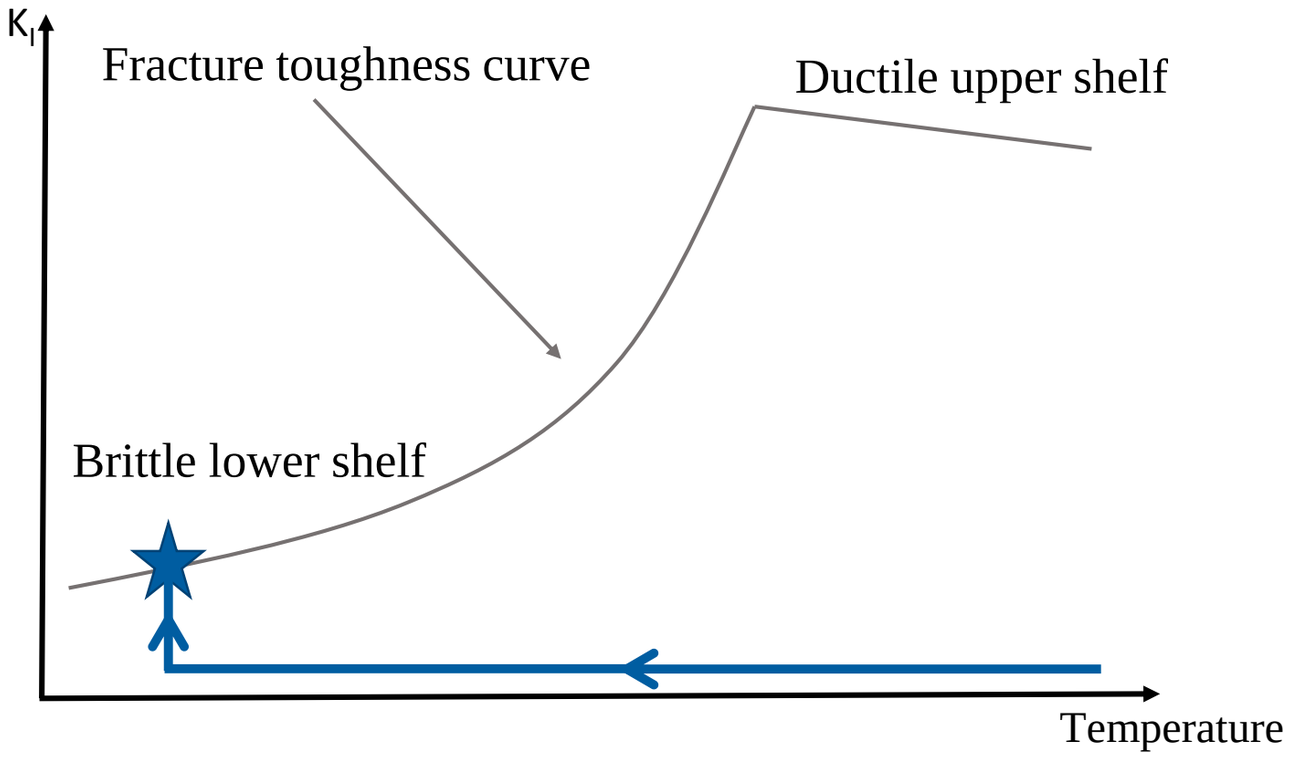
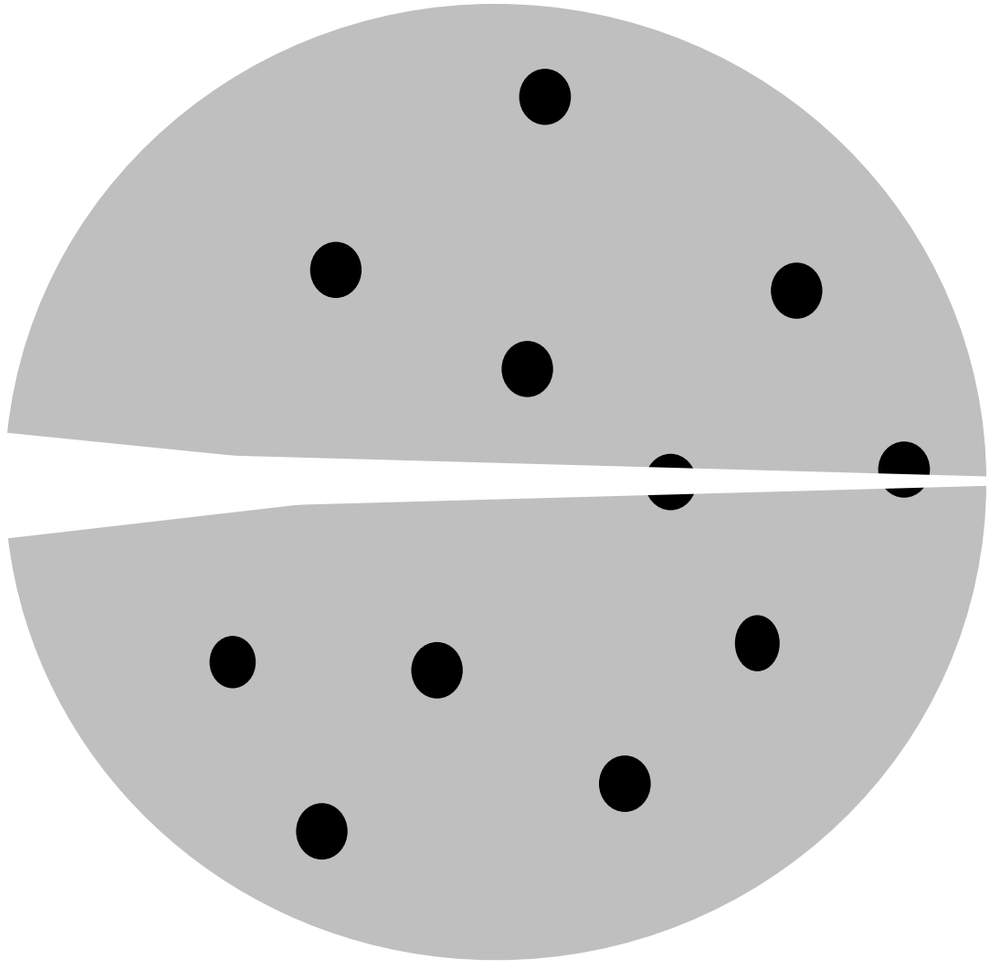
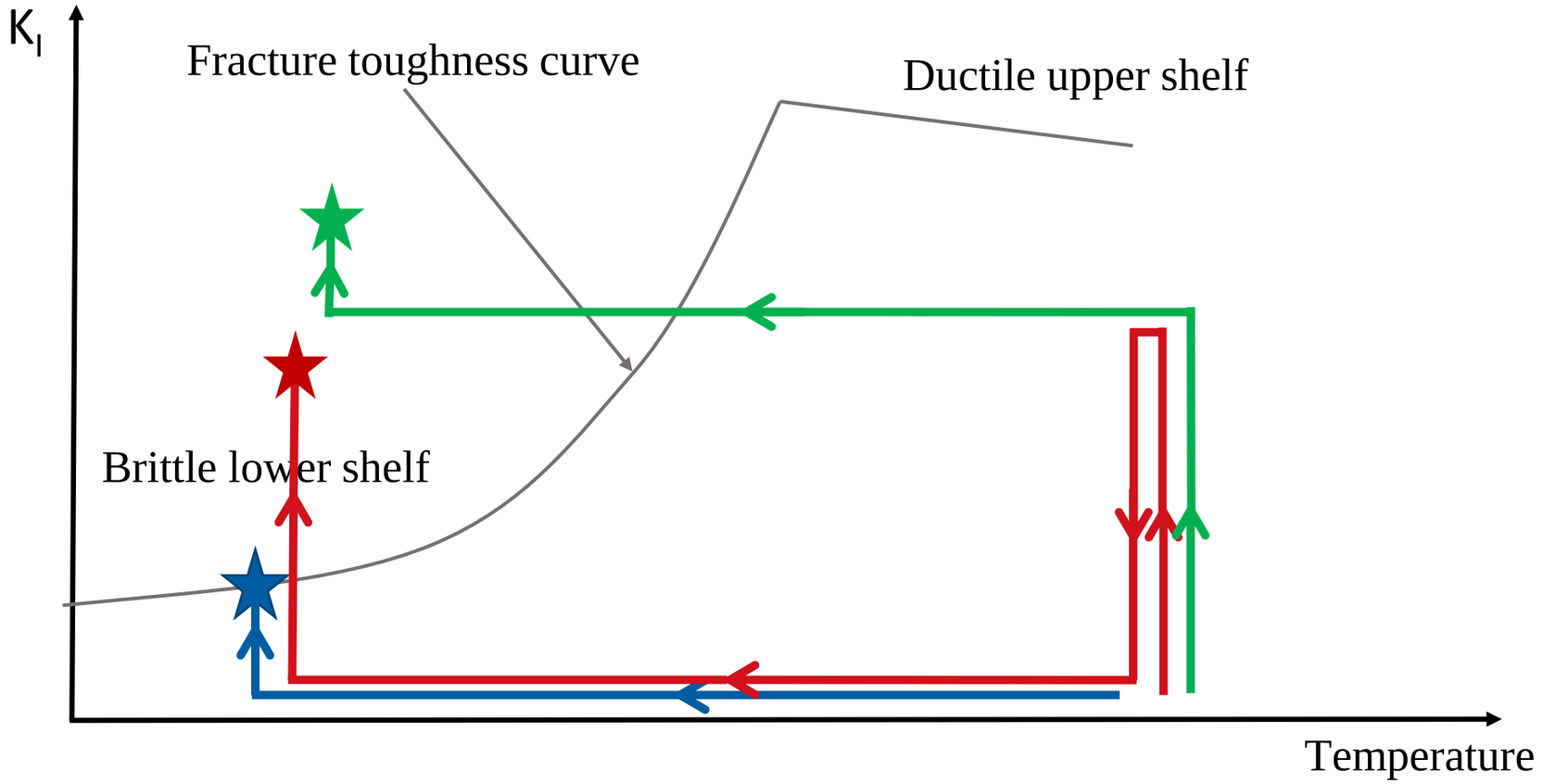
Theoretical background – Brittle fracture





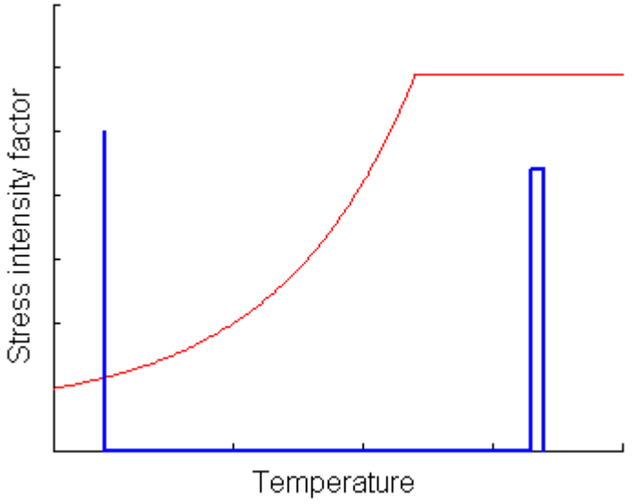
Theoretical background – Warm pre-stressing

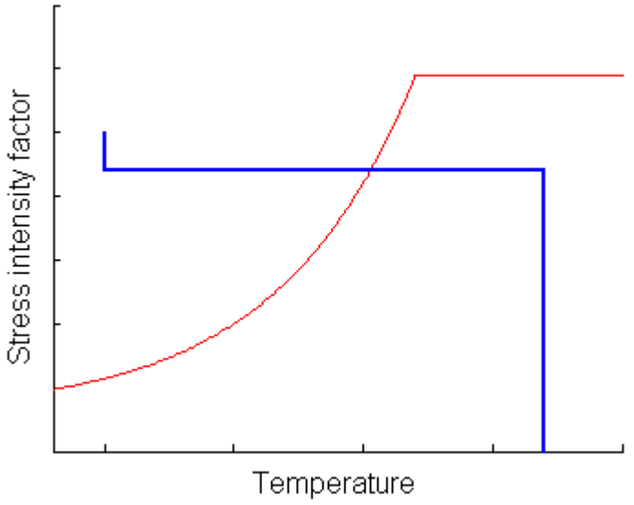


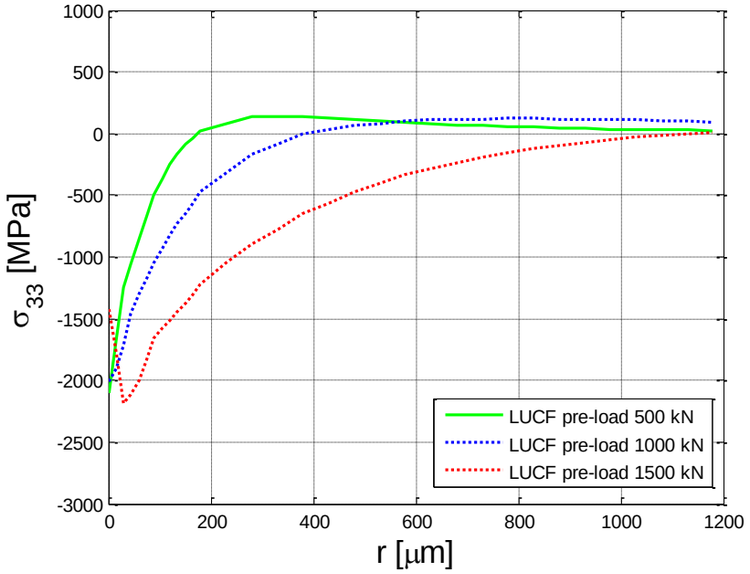
Theoretical background – Main mechanisms

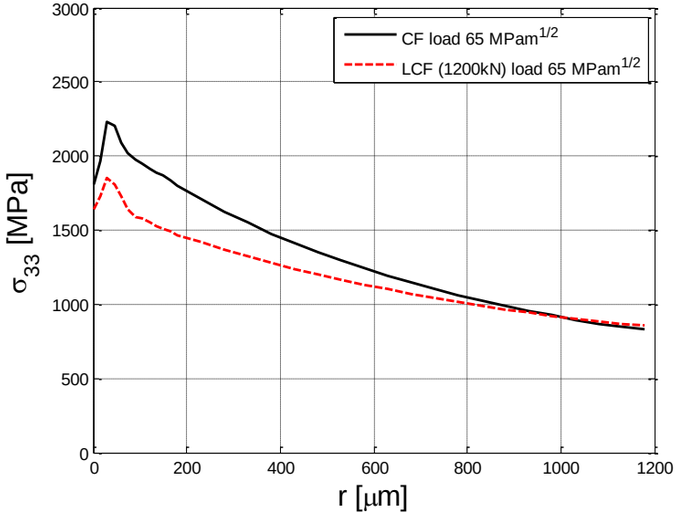
The WPS effect can be attributed to the following main mechanisms:

- Introduction of a beneficial compressive residual stress field in front of the crack tip, due to local plastic deformation from the preloading and unloading
- Blunting of the crack tip
- Change of yield properties due to lowering of temperature
- Deactivation of cleavage initiation sites by pre-straining

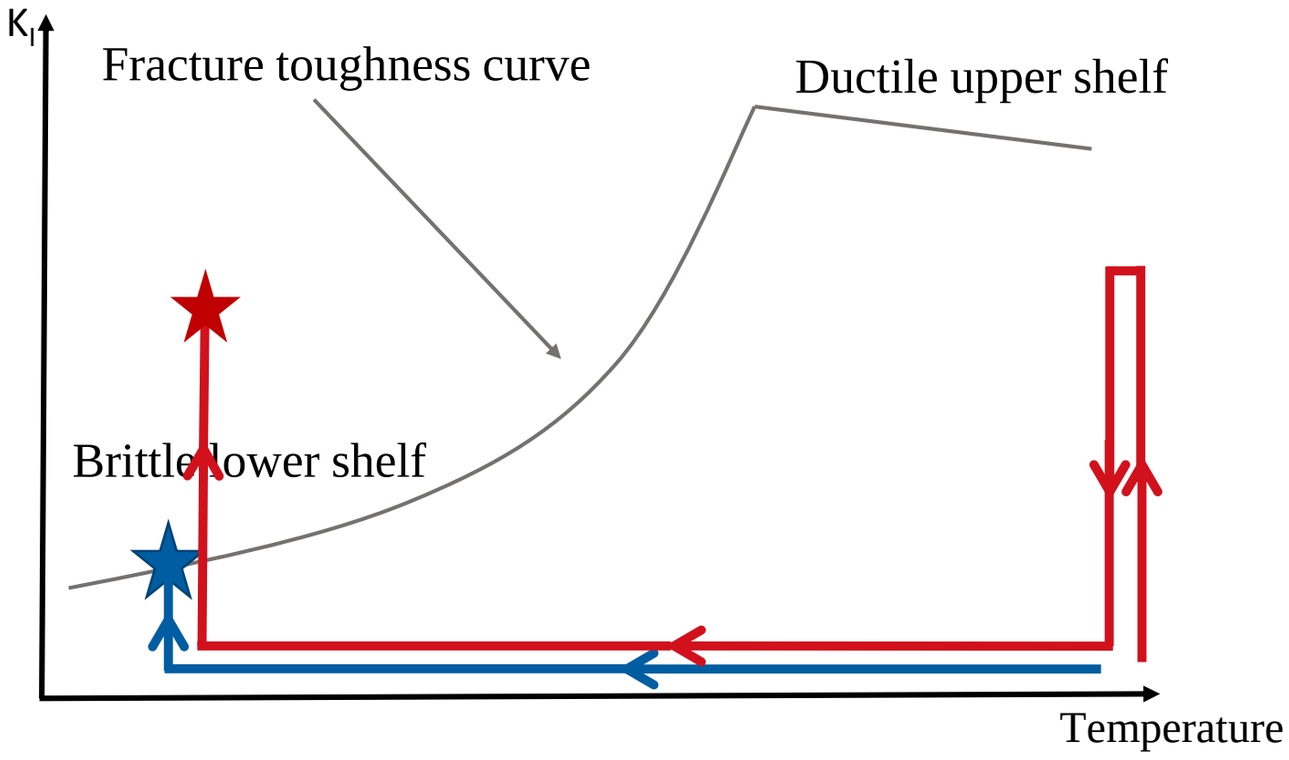


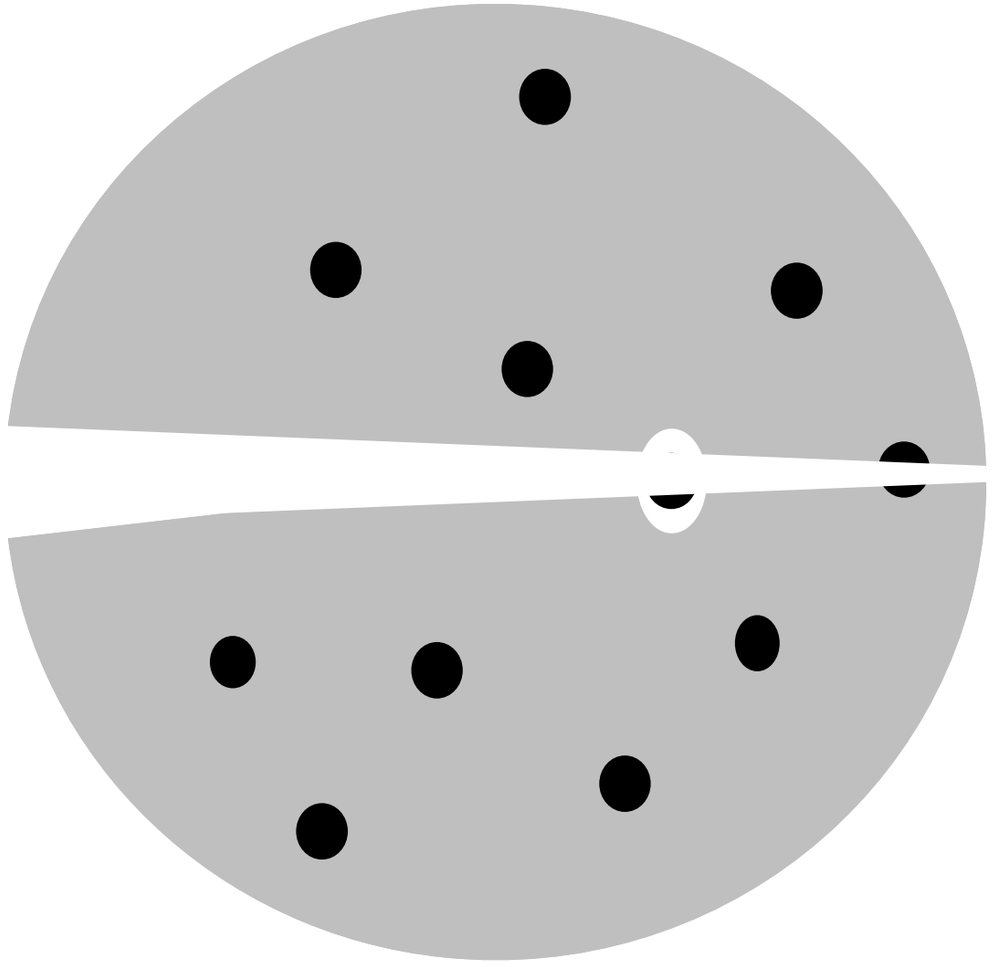




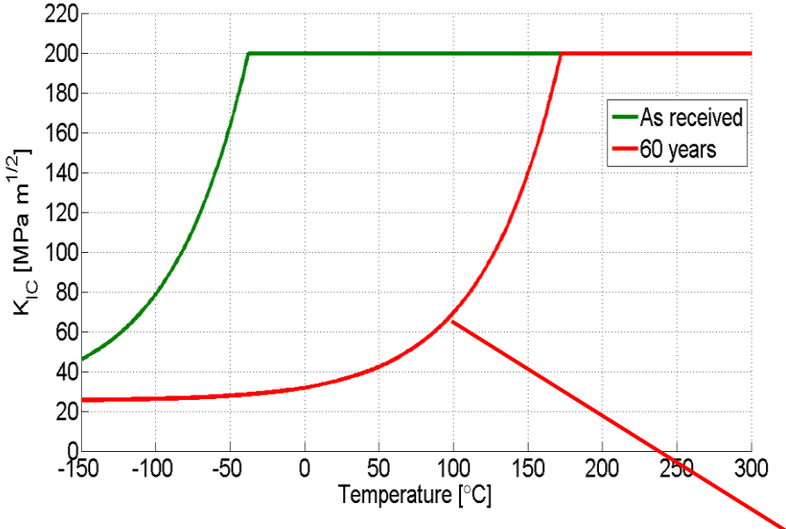


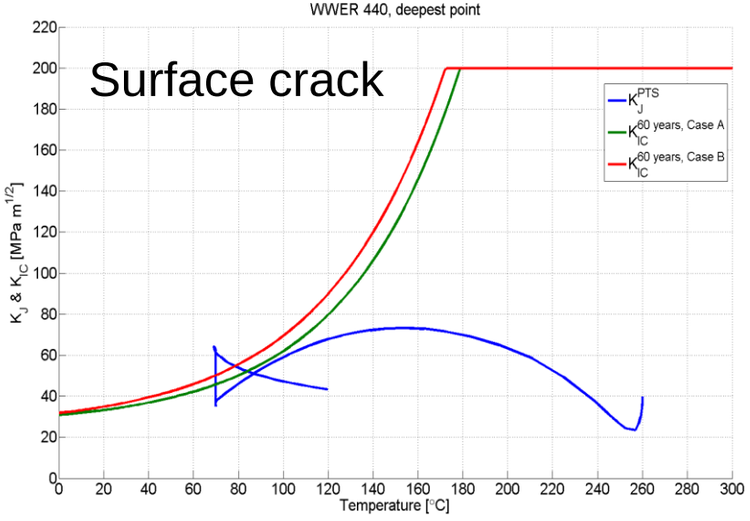
Theoretical background – Main mechanisms

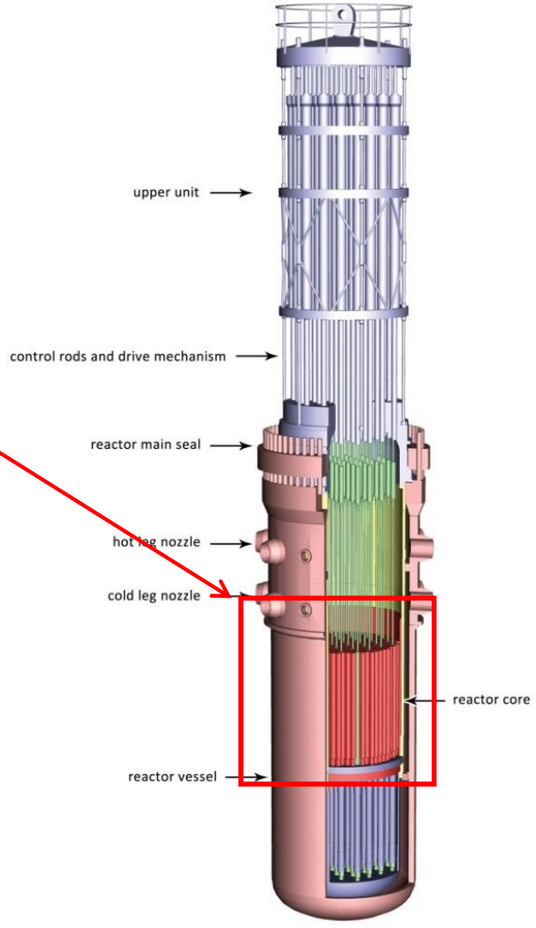


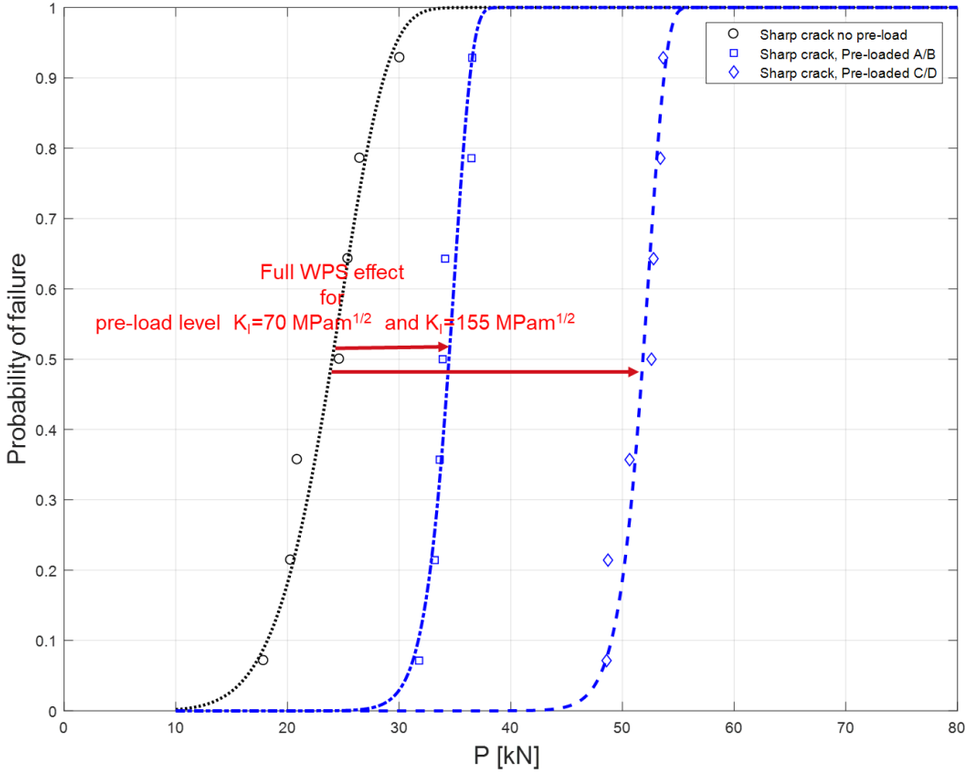


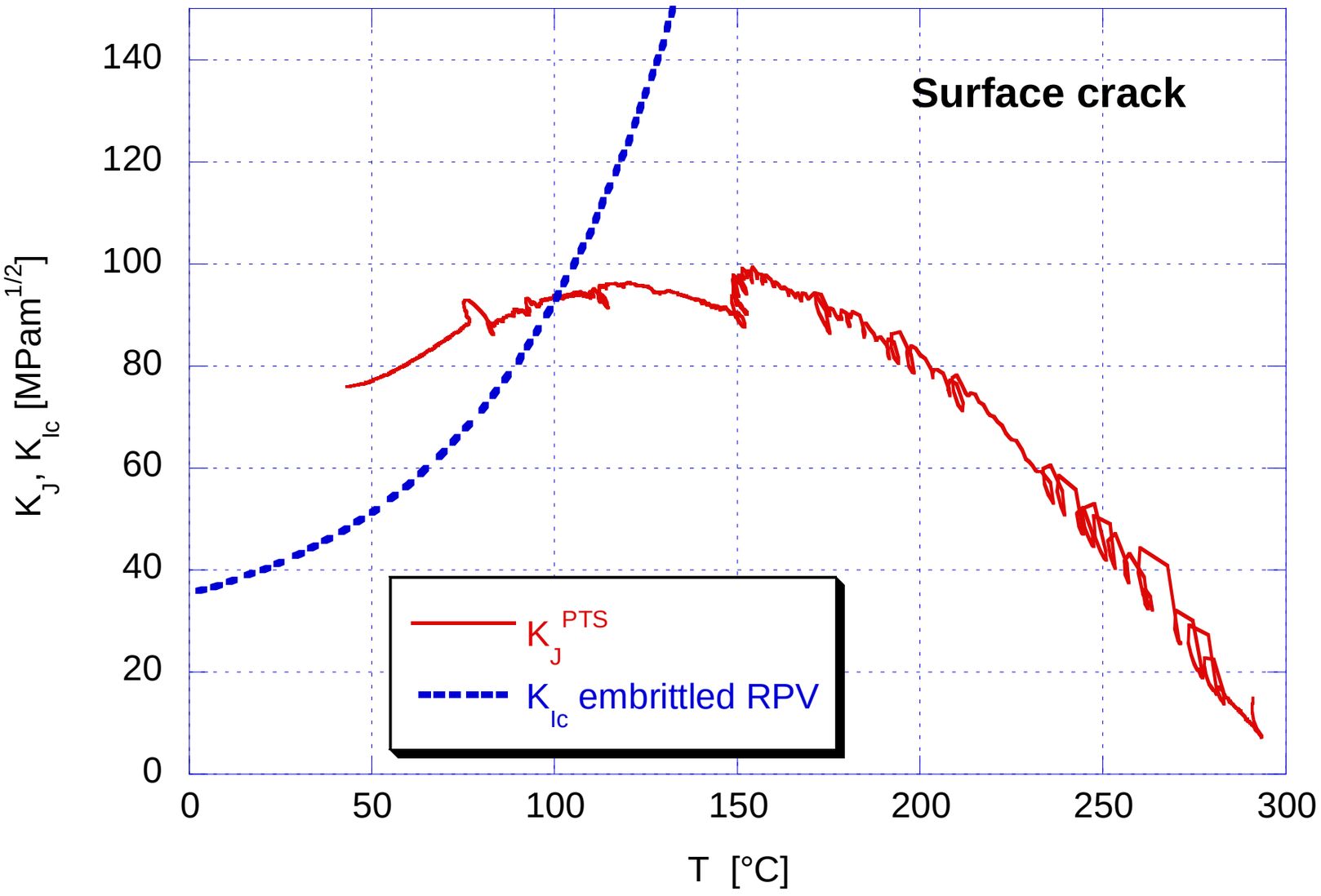
Background


As received
60 years
K_{IC} [MPa m$^{1/2}$]
Temperature [°C]


WWER 440, deepest point
Surface crack
K_J^{PTS}
$K_{IC}^{60\ years,\ Case\ A}$
$K_{IC}^{60\ years,\ Case\ B}$
K_J & K_{IC} [MPa m$^{1/2}$]
Temperature [°C]


upper unit
control rods and drive mechanism
reactor main seal
hot leg nozzle
cold leg nozzle
reactor core
reactor vessel


Sharp crack no pre-load
Sharp crack, Pre-loaded A/B
Sharp crack, Pre-loaded C/D
Full WPS effect
for
pre-load level K_I=70 MPam$^{1/2}$ and K_I=155 MPam$^{1/2}$
Probability of failure
P [kN]


Surface crack
K_J, K_{Ic} [MPam$^{1/2}$]
T [°C]
0
20
40
60
80
100
120
140
0
50
100
150
200
250
300
K_J^{PTS}
K_{Ic} embrittled RPV

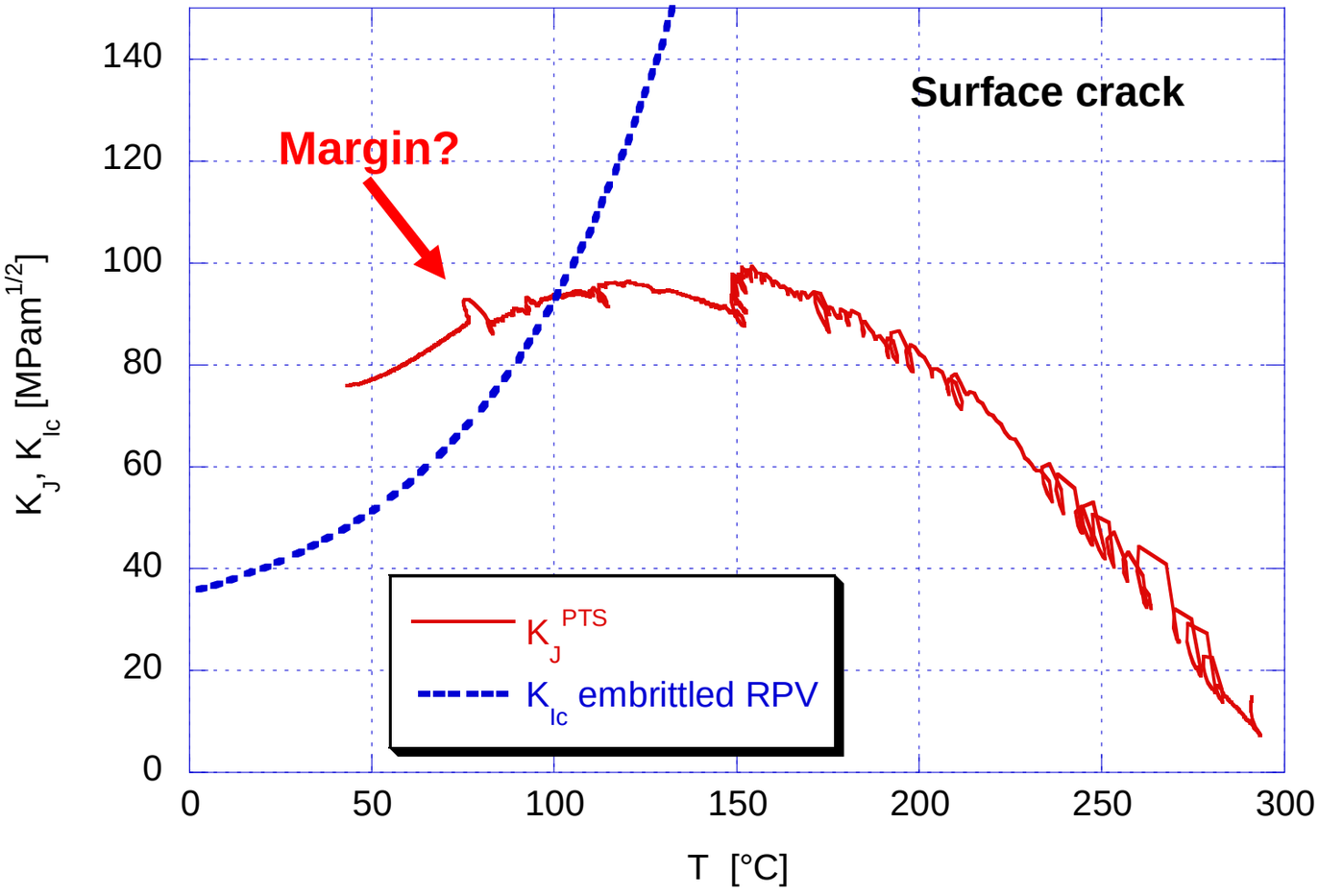
WPS-MAF

WPS-MAF is a joint Swedish and Finish research project. The group is made up by KIWA and KTH from Sweden and VTT from Finland.

This research project aims to answer what the margin and probability of fracture is during the cooling part of a typical PTS transient in a RPV.

For this to be possible a non-local probabilistic model for cleavage fracture that accounts for effects of load history and changes in temperature will be developed.

To be able to develop such a model a large experimental program will be conducted where the material is characterized at several temperatures from the transition region to the lower shelf region. Also validating tests will be performed.

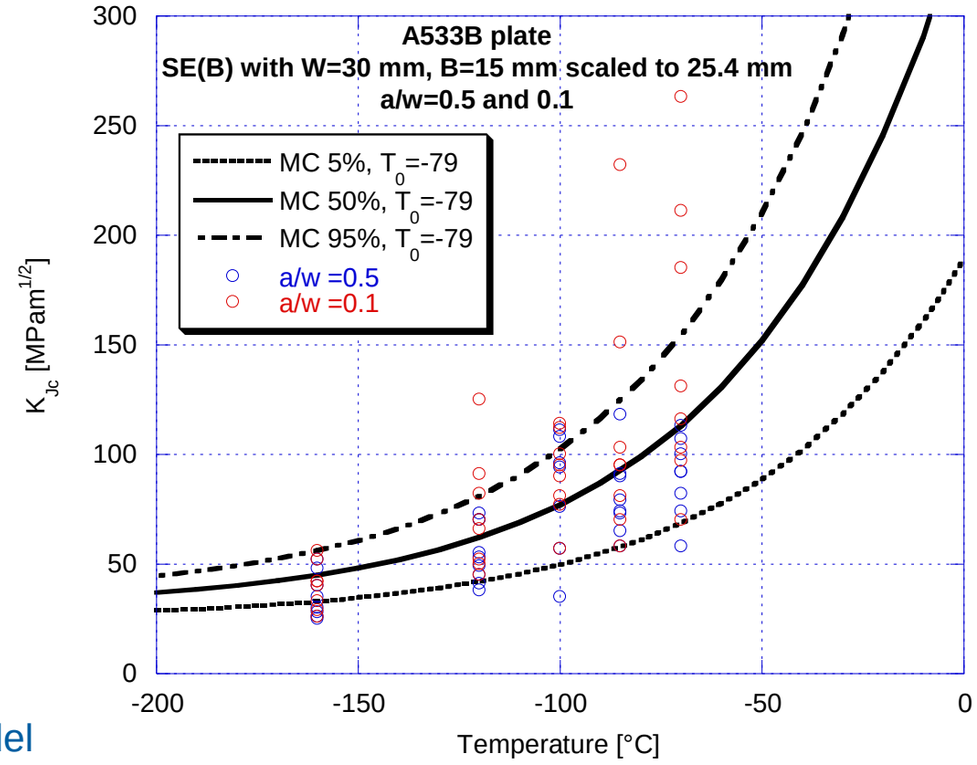


WPS-MAF Progress

WP1

The outline of the test program has been finalized. The material used in the test program is supplied by VTT and is the ferritic reactor pressure vessel steel A533B-1. The test program consists of 140 individual fracture tests and 18 tensile tests. Below the different tests are listed:

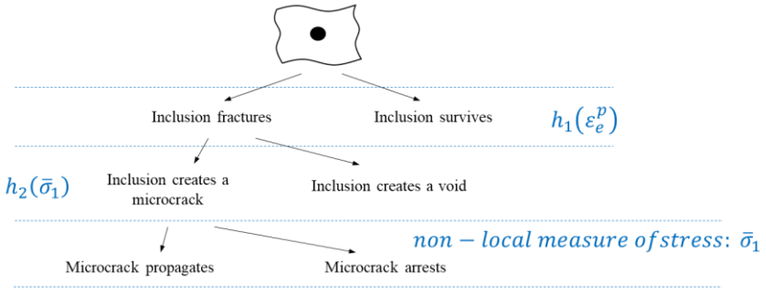
- 18 uniaxial tensile tests
  Tested at 5 different temperatures
  Finished
- 12 SE(B), *W*=10 mm, *a/W*=0.5
  Used to determine the master curve
  Finished
- 80 SE(B), *W*=30 mm, *a/W*=0.5 and *a/W*=0.1
  High and low constraint specimens tested at 5 different temperatures
  Finished
- 32 SE(B), *W*=30 mm, *a/W*=0.5 and *a/W*=0.1
  Specimens subjected to WPS transient used for validation of developed model
  Finished
- 16 3PB, elliptical surface cracked specimen
  Delayed (probably summer 2022)



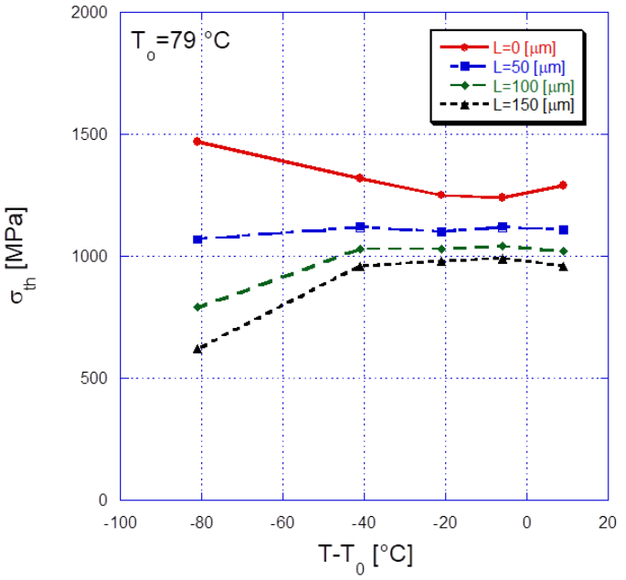
WPS-MAF Progress

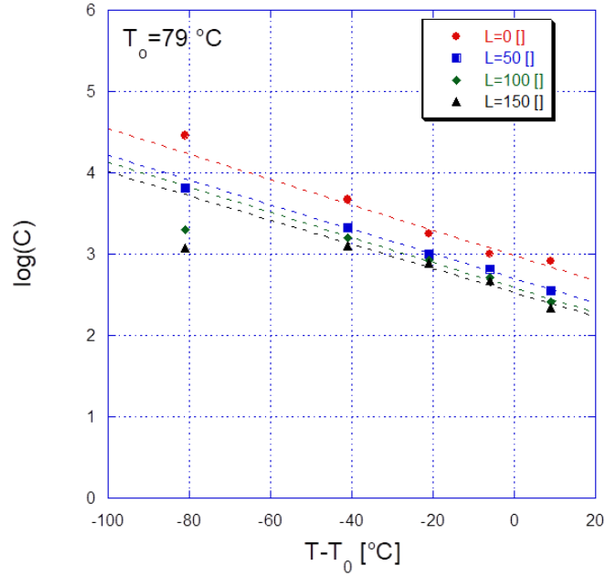
WP2

- The work in evaluating the influence from temperature on the model parameters have been started and completed.
- A modification has been implemented to account for load history effects (deactivation of initiation sites).
- Validation of the modified model using the WPS tests is ongoing.



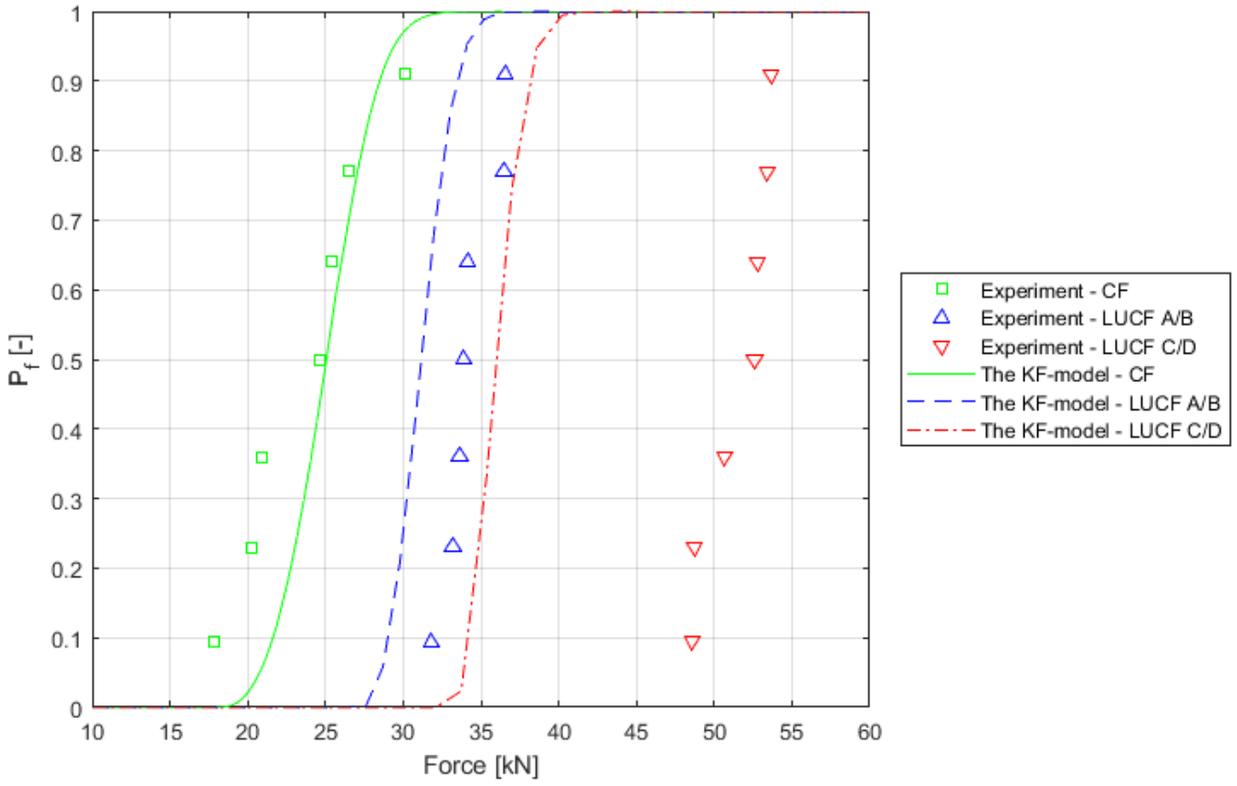
$$P_f = 1 - \exp\left[-\int_V h_1(\varepsilon_e^p) \cdot h_2(\bar{\sigma}_1) \frac{dV}{V_0}\right]$$



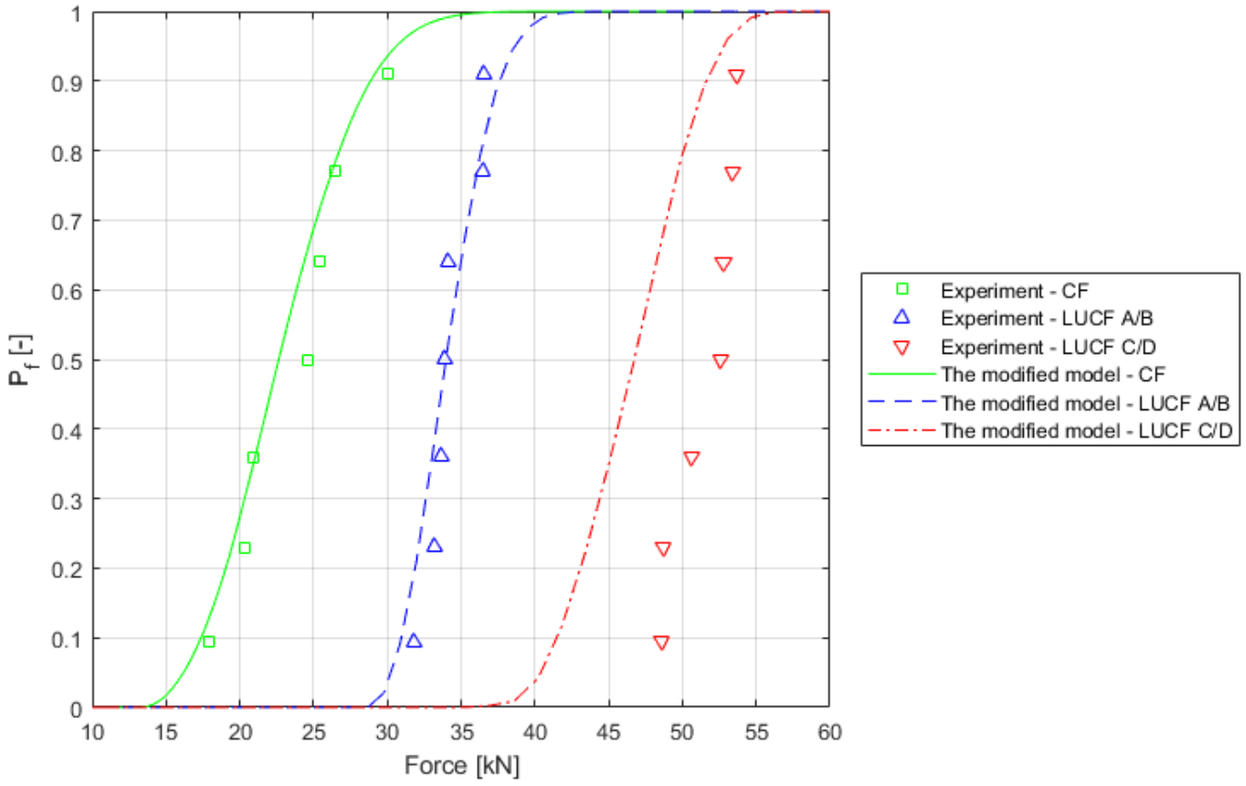


WPS-MAF Recent results

The original KF-model

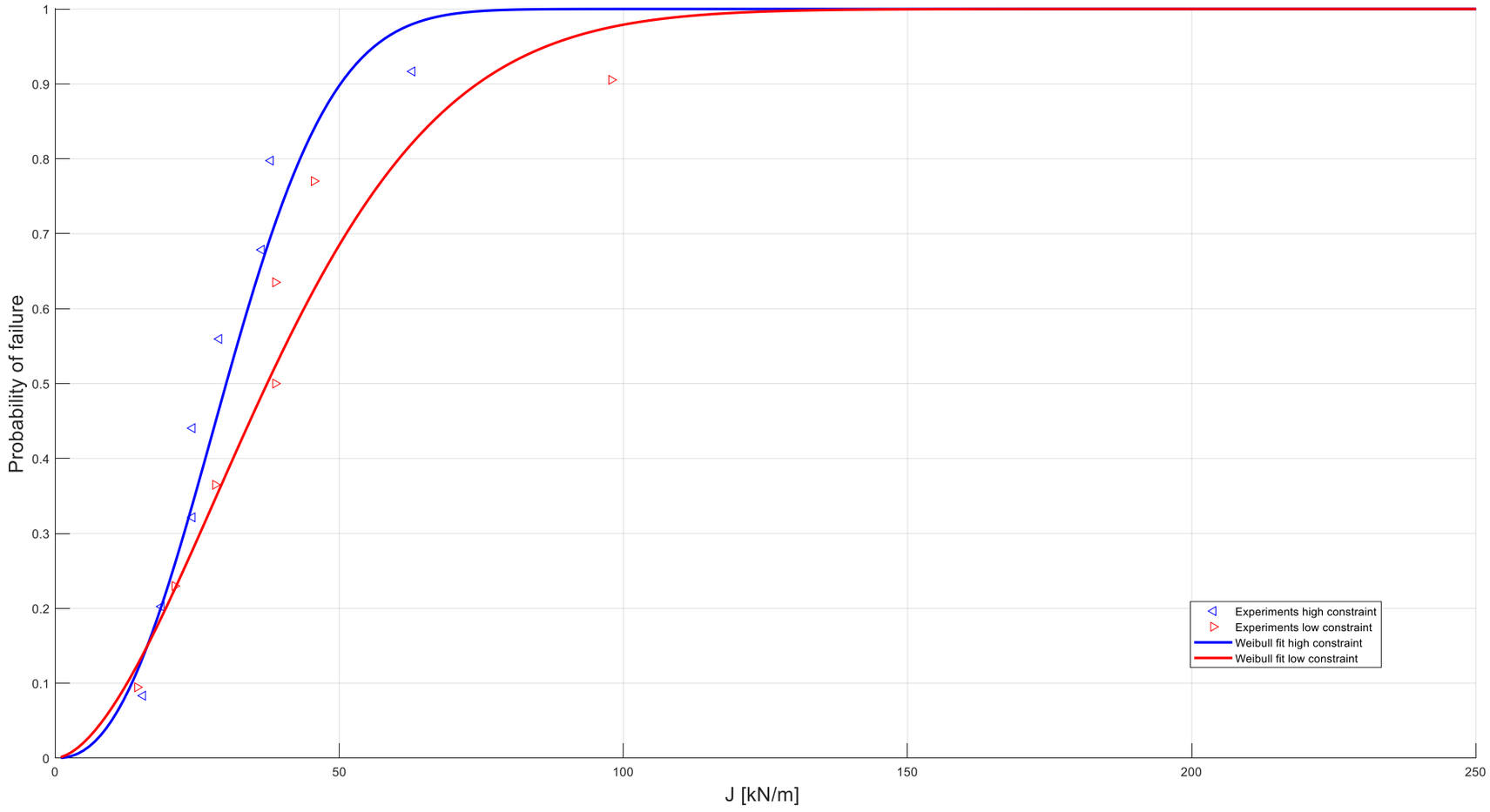


The modified KF-model



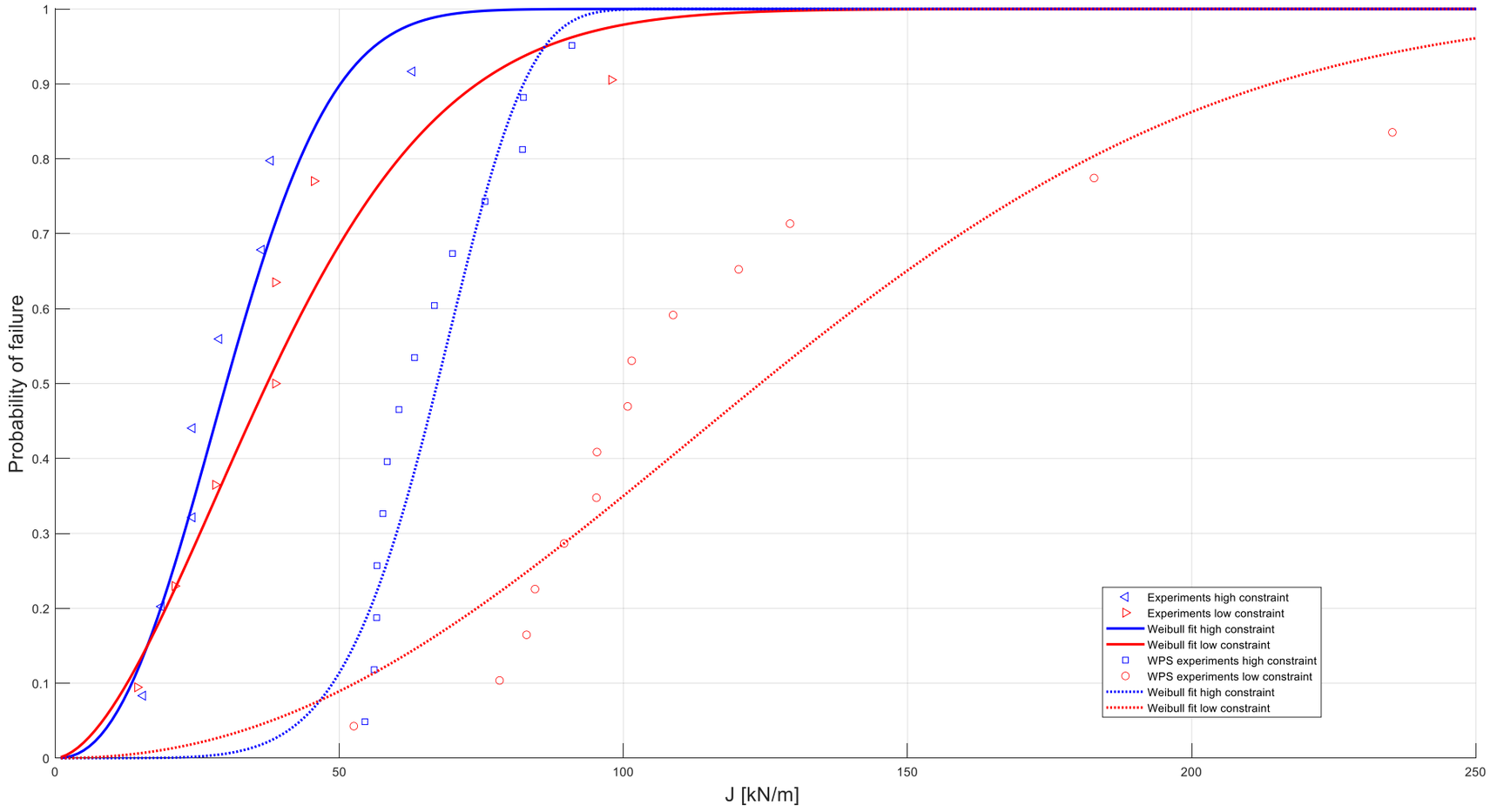
WPS-MAF Recent results

- 3PB specimens with deep and shallow cracks
- Loading: Cool-Fracture (CF)
- Fracture loading at -85 °C



WPS-MAF Recent results

- 3PB specimens with deep and shallow cracks
- Loading: Cool-Fracture (CF) and Load-Cool-Fracture (LCF)
- Fracture loading at -85 °C



WPS-MAF Planned research 2022

In 2022 the focus will be model development and application of model (WP2 and WP3).

WP2: In 2022 further work towards finalizing the model will be performed. This involves validation of the modifications to the part of the model that is related to particle cracking and the incorporated temperature evolution laws for the model parameters in the model. The WPS tests performed in WP1 will be used for the validation.

WP3: In 2022 it is planned that the model will be applied to a RPV subjected to a PTS transient, and the evaluation of the probability of failure. To be able to evaluate the margins to fracture during the cooling sequence of the transient, the transient will be disturbed with increased loads at several temperatures. Each of these disturbances will lead to a separate analysis where the probability of fracture will be calculated, determining the margin to fracture. Thus, reaching the goal and answering what the margin to fracture is during cooling part of a PTS transient.

WPS-MAF Expected results and future needs

Expected results from WPS-MAF:

- In theory, a component would not fracture when the load is held constant during the cooling. But as have been shown the loading path is not always smooth. Hence, the importance to quantify the margins to fracture during a PTS transient. This is the aim and expected result of WPS-MAF. This will give guidance on the application of excising engineering methods.
- Within WPS-MAF a non-local probabilistic model is being developed that consider both temperature and loading history effects. This will make it possible to numerically predict the fracture probability for components subjected to complex loading paths within the nuclear industry.
- The experimental results will also increase the understanding of the interaction between constraint effects and the WPS effect.

Future needs:

- Even though work on the WPS effect have been done since the 70:s there are still gaps in the knowledge about the WPS effect and it's use for real components during realistic loading transients. One of these gaps is related to the effect from residual stress fields on the WPS effect. An experimental program to look at the effect on the interaction between a prior residual stress field and the WPS effect would be valuable. This could also be strengthened by a numerical study to advance the understanding even further of the interaction between a prior residual stress field and the WPS effect.