FAVPRO

Fracture Analysis of Vessels – Probabilistic

User Group Public Meeting

July 29, 2025

Meeting Agenda

Time (EDT)	Topic	Presenters/Participants
9:00am – 9:15am	Opening Remarks	NRC
9:15am – 9:25am	Regulatory Perspective on FAVPRO	NRC
9:25am – 9:40am	FAVPRO v1.1 Overview	NRC
9:40am – 10:00am	FAVPRO Demonstration	NRC
10:00am – 11:00am	Open Discussion and Q&A • Use cases by GRS, Fortum, and Kinectrics	All

FAVPRO 1.1 Overview

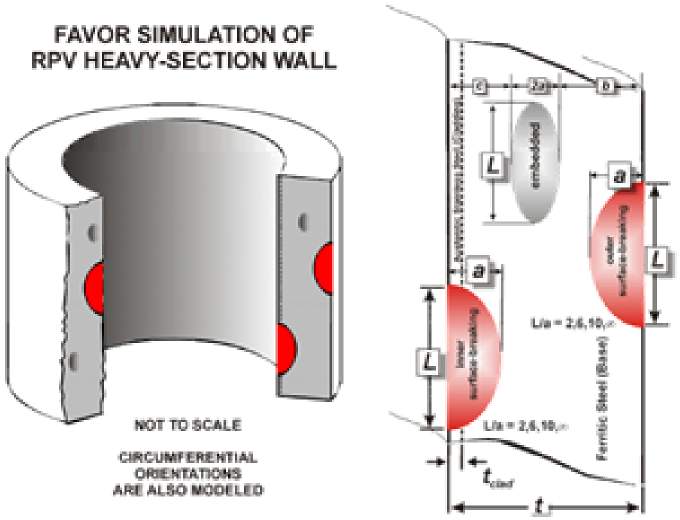
FAVPRO User Group Meeting

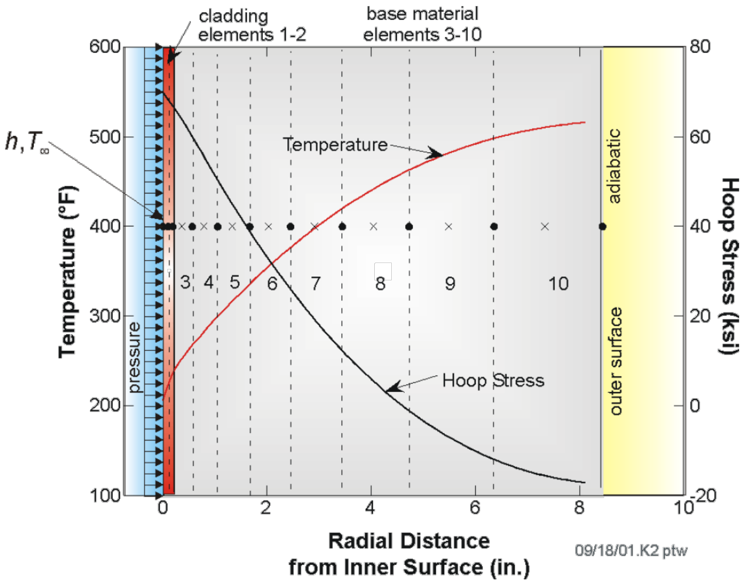
July 29, 2025

Christopher Ulmer

FAVPRO Overview

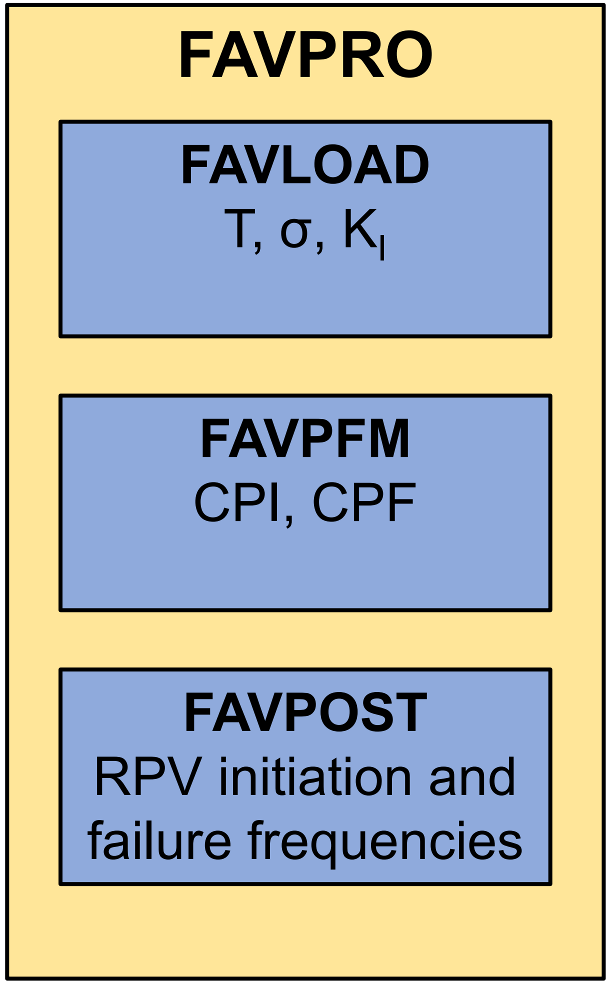
- Probabilistic fracture mechanics (PFM) tool for reactor pressure vessel (RPV) integrity assessment
- Cylindrical beltline 1D finite element axisymmetric solver
- User-defined thermal hydraulic transients and flaw populations
- Deterministic run modes
  - Through-wall profiles (T, σ, SIFs…)
  - Time histories
  - Critical RT_{NDT} for crack growth
- Probabilistic run mode
  - Conditional probabilities of crack growth initiation (CPI) and through-wall crack failure (CPF)
- Combination of conditional probabilities and transient frequencies to generate frequencies of crack growth initiation (FCI) and through-wall crack failure (TWCF)





FAVPRO's Origins

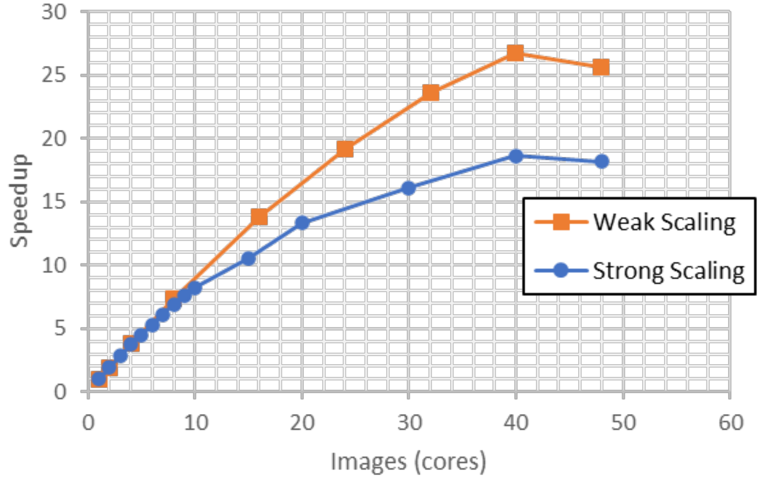
- Developed from FAVOR-v16.1 which was issued by ORNL in 2016
- Integrated FAVLOAD, FAVPFM, and FAVPOST into a single tool
- Addressed Software Quality Assurance (SQA) gaps
- Refactored FAVOR into modern Fortran for improved maintainability and modularity
- Enhanced SQA, V&V, testing, and documentation
- Used state-of-practice tools and libraries (e.g., GitHub, JSON)



FAVPRO Enhancements

- Fortran 2018: modern, object-oriented, parallel programming language
- Use of open-source libraries for building, testing, and parallelization
- JSON standard input and output files
- Stress intensity factor calculations using ASME and custom solutions
- Embrittlement trend curves
- Serial and parallel executables for different calculation needs
- Git/GitHub version control and independent tracking of changes
- Automated unit and integration testing
- Over 300 unit-tests and 78 integration-tests

Fortran Package Manager



FAVPRO v1.1 Key Changes

- Removal of superseded embrittlement trend curves
  - EONY 2006 model now matches 10 CFR 50.61a
- New fracture toughness model options and updates to ductile tearing and arrest models
  - Added Master Curve toughness model
  - Described in ASME Code Case N-830-1 and MRP-418 Rev. 1
  - Fracture toughness model selection in input
  - RT_{NDT} or T_0 references temperatures

Embrittlement Trend Curves	
FAVOR	**FAVPRO**
RG-1.99 Rev. 2	RG-1.99 Rev. 2
EONY 2000	EONY 2000
EONY 2006	EONY 2006
~~Kirk 2007~~	ASTM E900
~~Radamo 2007~~	
~~Kirk + Radamo 2007~~	

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Cleavage Crack Initiation Fracture Toughness

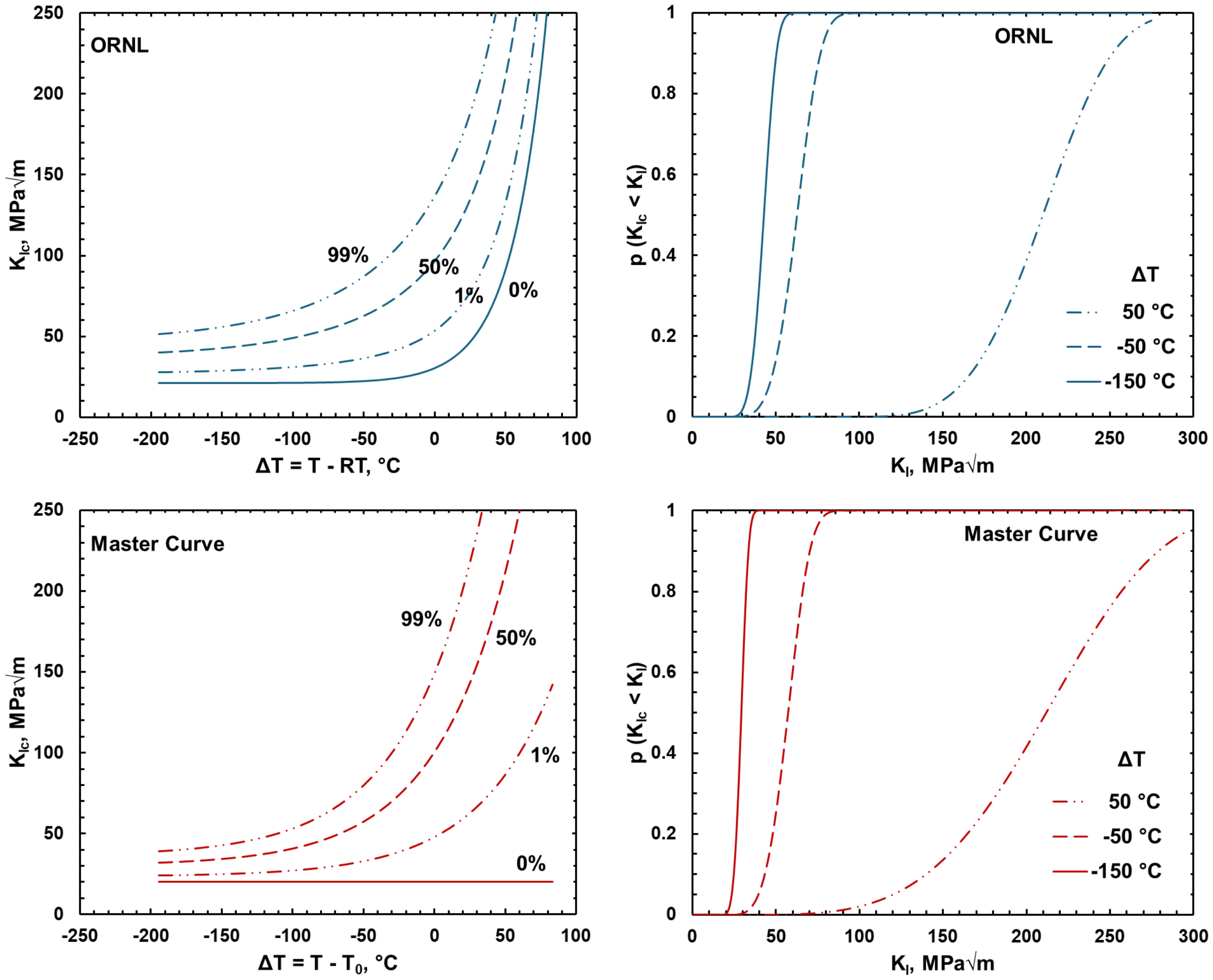
$$\mathbf{K_{Ic} = a + b[-\ln(1-p)]^{1/4}}$$

ORNL (FAVOR) Model

$\Delta T = T(t) - RT$	°C
$a(\Delta T) = 21.287 + 9.169\exp[0.04057(\Delta T)]$	$MPa\sqrt{m}$
$b(\Delta T) = 17.173 + 55.151\exp[0.0144(\Delta T)]$	$MPa\sqrt{m}$

Master Curve (N-830-1) Model

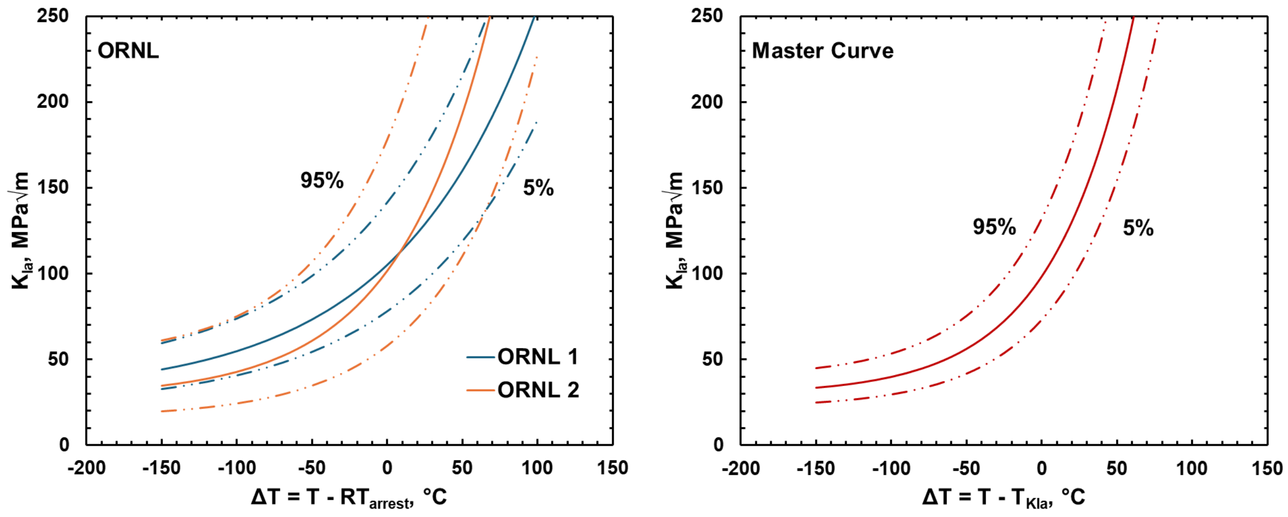
$\Delta T = T(t) - T_0$	°C
$a(\Delta T) = 20.0$	$MPa\sqrt{m}$
$b(\Delta T) = 31.0 + 77.0\exp[0.019(\Delta T)] - 20.0$	$MPa\sqrt{m}$



Cleavage Crack Arrest Fracture Toughness

$$\mathbf{K_{Ia} = exp\left(\mu + \sigma\Phi^{-1}(p)\right)}$$

$$\mu = \ln(K_{Ia}^{mean}) - \frac{\sigma^2}{2}$$



ORNL Model 1

$$\Delta T = T(t) - RT_{arrest} \quad °C$$

$$K_{Ia}^{mean} = 30.035 + 76.966\exp(0.0109\Delta T) \quad MPa\sqrt{m}$$

$$\sigma = 0.18$$

ORNL Model 2

$$\Delta T = T(t) - RT_{arrest} \quad °C$$

$$K_{Ia}^{mean} = 30.035 + 77.778\exp(0.01618\Delta T) \quad MPa\sqrt{m}$$

$$\sigma = 0.3405$$

Master Curve Model

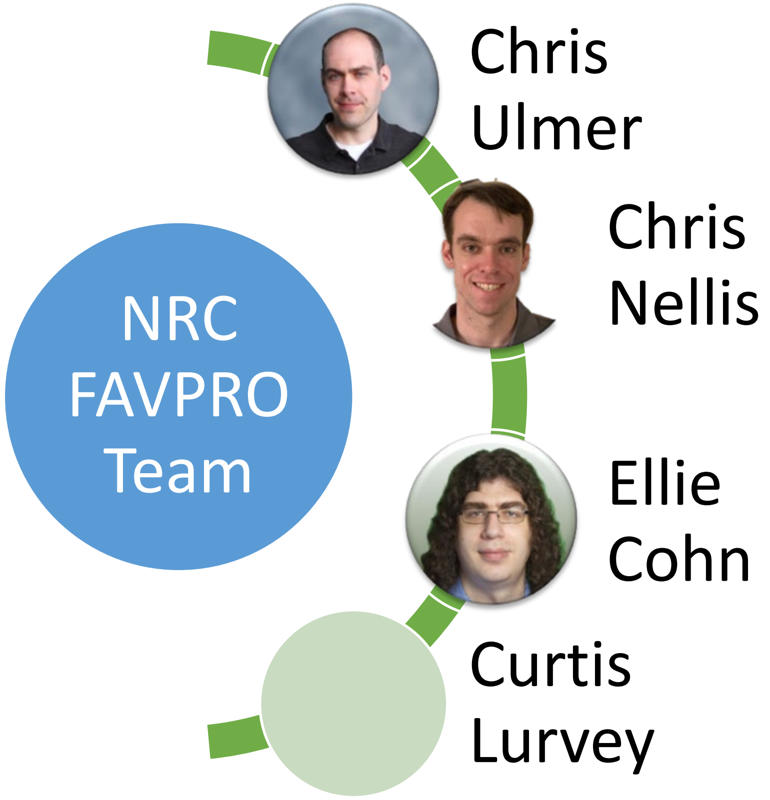
$$\Delta T = T(t) - T_{KIa} \quad °C$$

$$K_{Ia}^{mean} = 30 + 70\exp(0.019\Delta T) \quad MPa\sqrt{m}$$

$$\sigma = 0.18$$

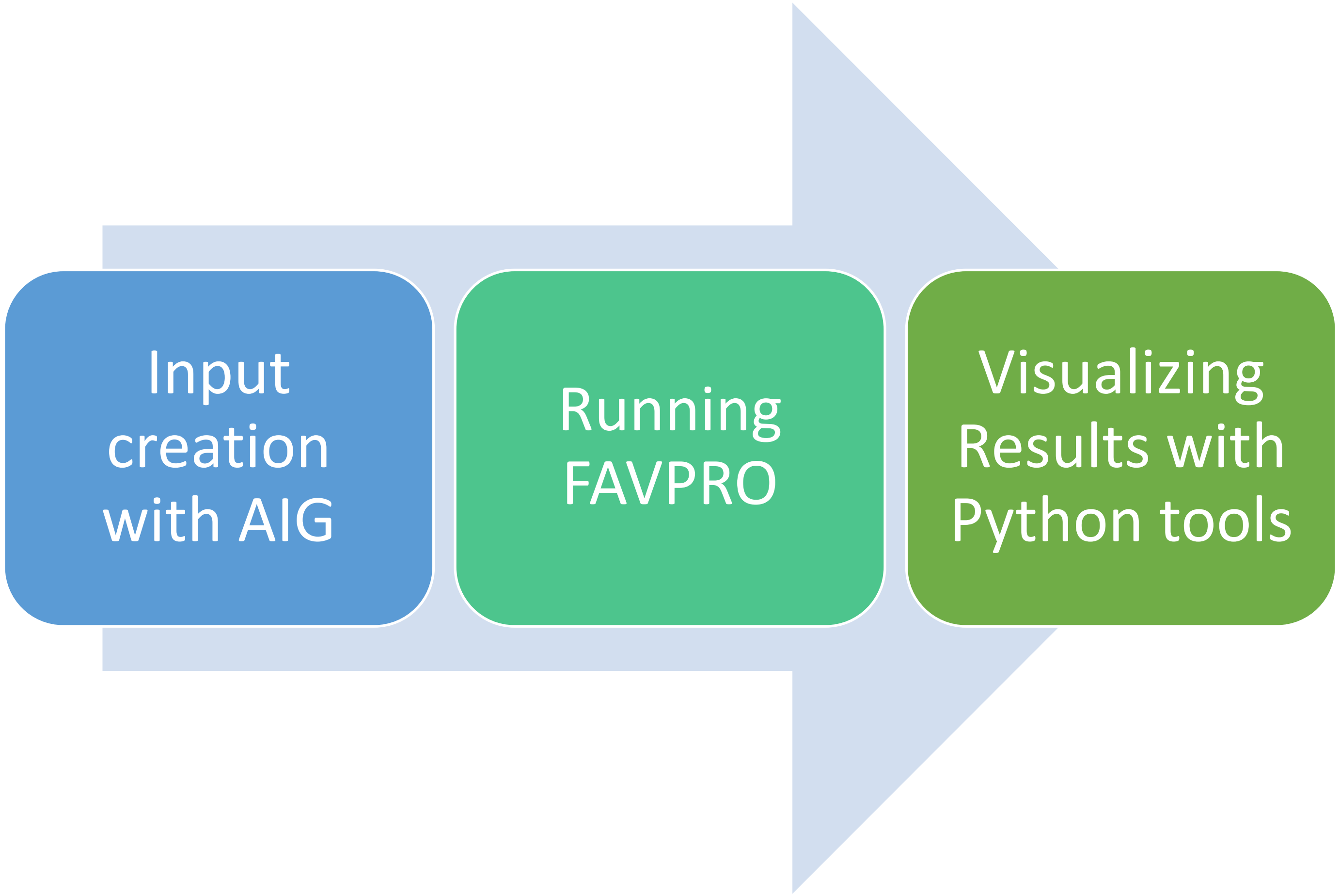
FAVPRO User Group

- To obtain FAVPRO:
  - Fill out the NRC Codes NDA
  - Once approved, the code executables (FAVPRO), input generator (FAVPRO-AIG), and visualization tool (FAVPRO-VT) are shared
- All approved users automatically become members of the User Group
  - Annual meetings
  - New code versions (as soon as they are available)
  - User input to the development team is strongly encouraged
    - Please tell us about bugs, desired new features, etc.
- Cost: free!
  - Could change at some point, but not in immediate future



FAVPRO Demonstration

- Review FAVPRO tools and process
- Highlight toughness model selection



Open Discussion and Q&A

- FAVPRO Use Cases
  - GRS, “Case Study on German RPV with FAVPRO”
  - Fortum, “Implementation of FAVPRO in Loviisa NPP safety analysis”
  - Kinectrics, “Introducing Constraint Effects on Fracture Toughness…”
  - Others?
- User Suggestions
- User Issues
- Questions

Regulatory Perspective on FAVPRO

FAVPRO User Group Meeting
July 29, 2025

David Dijamco

Currently, there are no regulations that are based on FAVPRO.

However, there are regulations (or alternative) that are based on the precursors to FAVPRO.

- 10 CFR 50.61a (FAVOR)
- 10 CFR 50.61 (VISA, precursor to FAVOR)
- Alternative to 10 CFR 50.55a, i.e., to ASME Code Section XI inservice inspections of BWR circumferential welds (FAVOR)
- These are all based on nil-ductility reference temperature, RT_{NDT}, as required by regulations.

Reference temperature model based on T_0

A reference temperature model based on T_0 is now in FAVPRO (most recent addition).

The associated fracture toughness model, based on ASME Code Case N-830-1, is now also in FAVPRO.

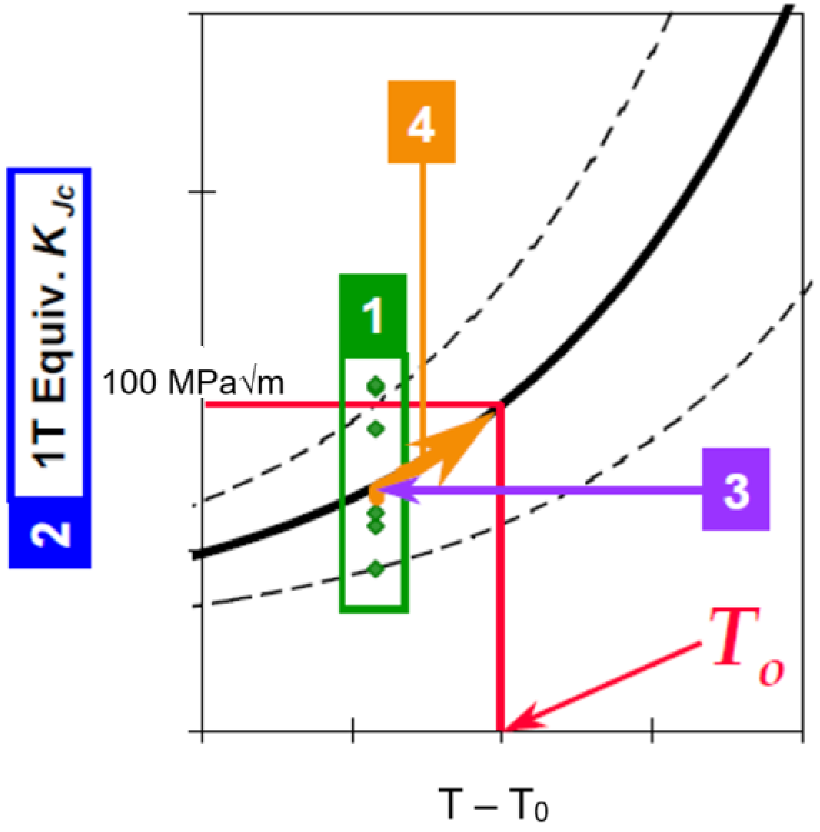
T_0 Overview

Definition from ASTM E1921

T_0 is the test temperature at which the median of the K_{JC} distribution from 1T size compact tension specimens will equal 100 MPa√m

Observations

- Based on direct measurements of fracture toughness
- Studies have shown that T_0 is lower than RT_{NDT} for 95% of reactor pressure vessel (RPV) ferritic materials; this demonstrates conservatism in the current approaches to RPV integrity that are based on RT_{NDT}



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T_0 in the ASME Code

ASME Code, Section III, NB-2331 ASME Code, Section XI, Appendix A and Appendix G ASME Section XI Code Case N-830	Accepted uses of T_0
ASME Section XI Code Case N-830-1 ASME Section XI Code Case N-914	Proposed uses T_0

How could FAVPRO be leveraged?

Proposal to the Commission to revise embrittlement regulations for RPVs in 10 CFR Part 50 (SECY-22-0019, ML21314A215)

- Perform T_0-based runs to develop technical basis
- Can be performed with ASTM E900 embrittlement trend curve (modeled in FAVPRO)

Compare/contrast probabilistic analyses of RT_{NDT}-based methodologies with a T_0-based methodology

Case Study on German RPV with FAVPRO

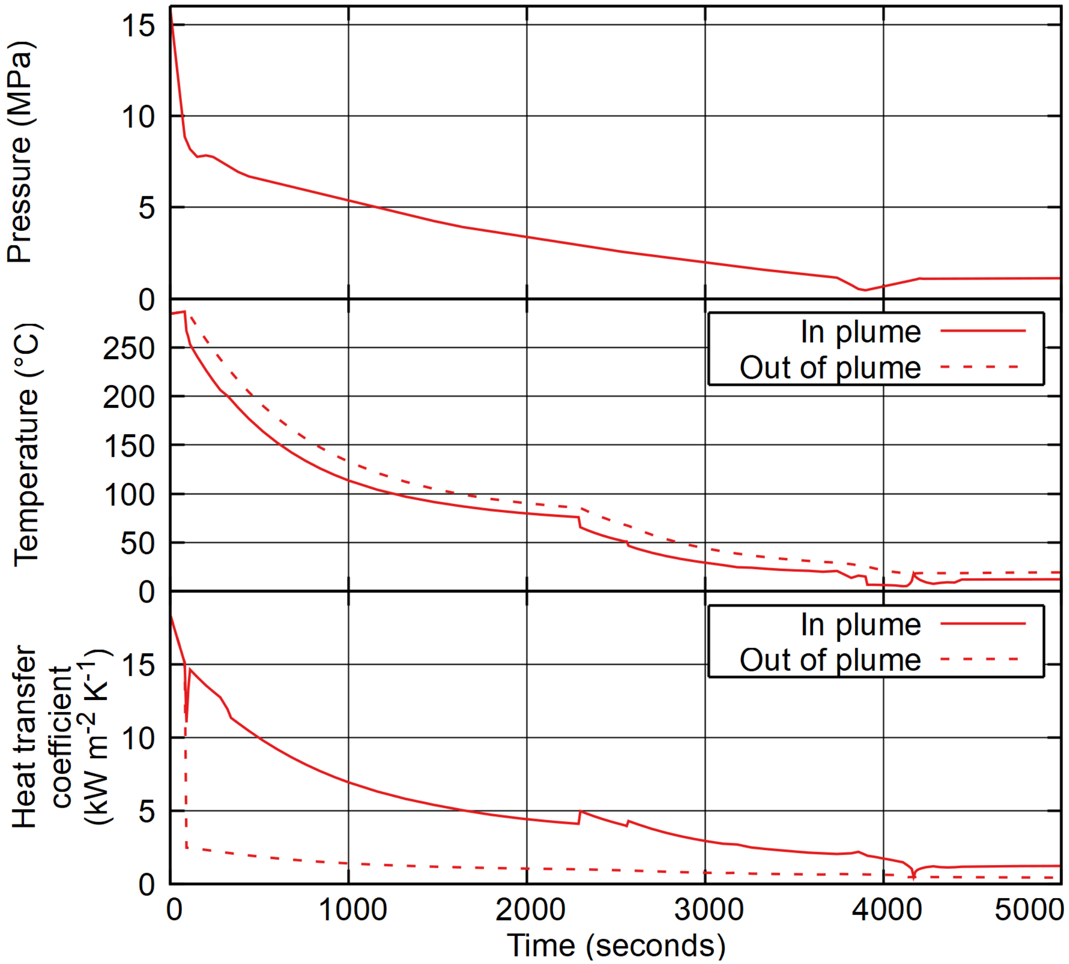
Jens Arndt*, Klaus Heckmann, Jürgen Sievers
GRS gGmbH, Cologne, Germany
*Email to: jens.arndt@grs.de

Supported by:
Federal Ministry
for the Environment, Climate Action,
Nature Conservation and Nuclear Safety
based on a decision of
the German Bundestag

Deterministic RPV integrity assessment

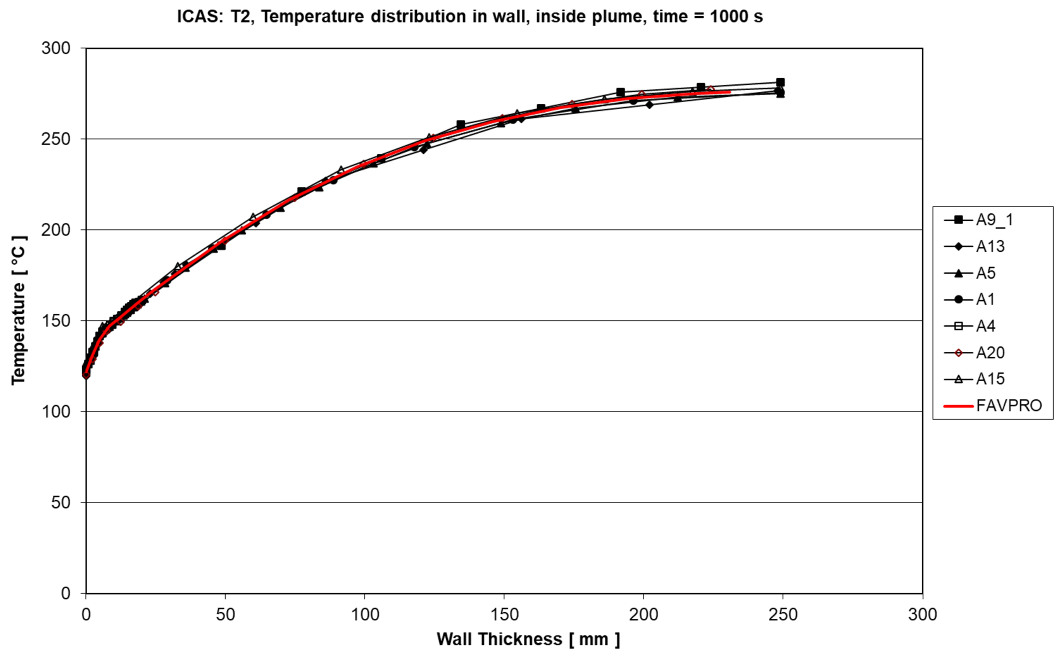
- RPV
  - German 4 loop PWR 1300 MW design
  - 243 mm (B) + 6 mm (C) wall thickness
  - Ferritic reactor steel 22 NiMoCr 37
- Transient and cracks - case T2C2 from International Comparative Assessment Study (ICAS, 1999)
  - Asymmetric 50 cm² leak transient
  - Different fluid temperatures inside and outside the cooling strip
  - Cooling plume width changes to only a minor extent during the course of the transient
  - Circumferential semi-elliptical surface crack of depth 16 mm including the clad thickness and length 96 mm

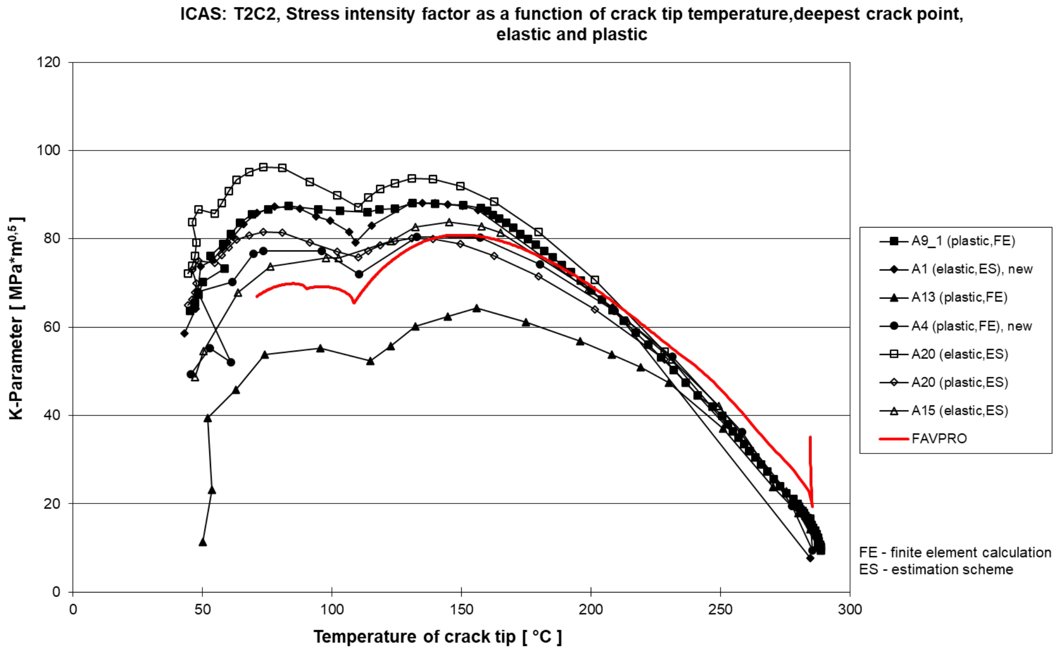
T2-LOCA-Transient

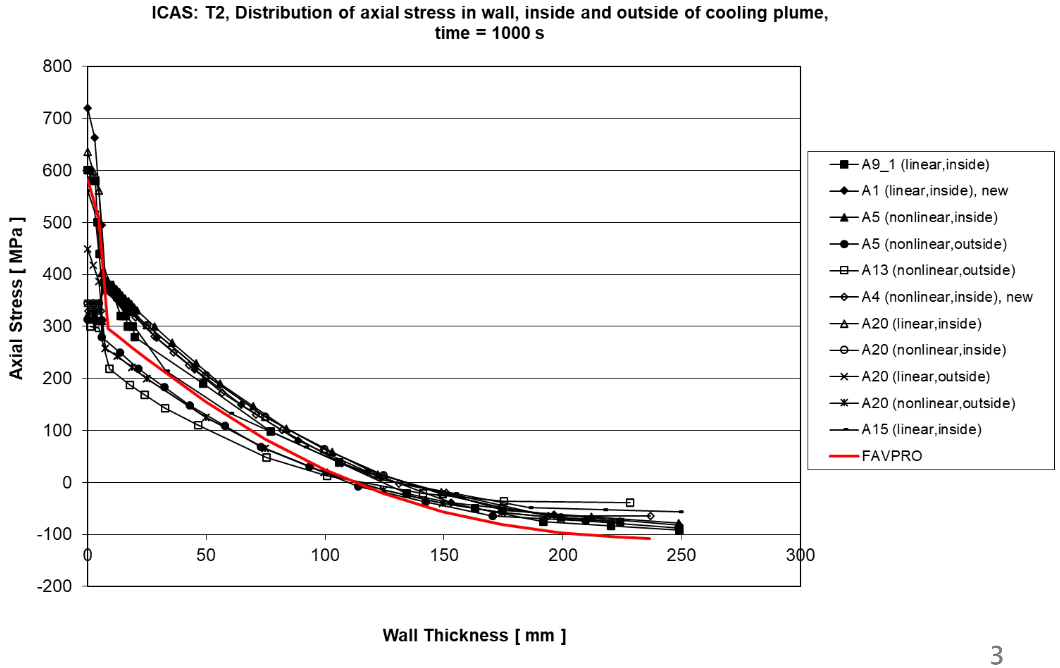


FAVPRO - Case study on German RPV

- Results of wall temperatures and axial stresses show a very good agreement with other participant’s results of ICAS benchmark
- Results of stress intensity factors (K) show a good agreement with other participant’s results of ICAS benchmark. The scatter of the results is mainly due to the use of different methods (elastic / elasto-plastic)
- Next step is the probabilistic assessment based on the calculation of CPI and CPF in the base metal







IMPLEMENTATION OF FAVPRO IN LOVIISA NPP SAFETY ANALYSIS

FAVPRO User Meeting July 29, 2025
Marko Kosonen, Strength Analysis Trainee
Fortum Engineering & Projects | AMS Analysis, Modelling and Simulation

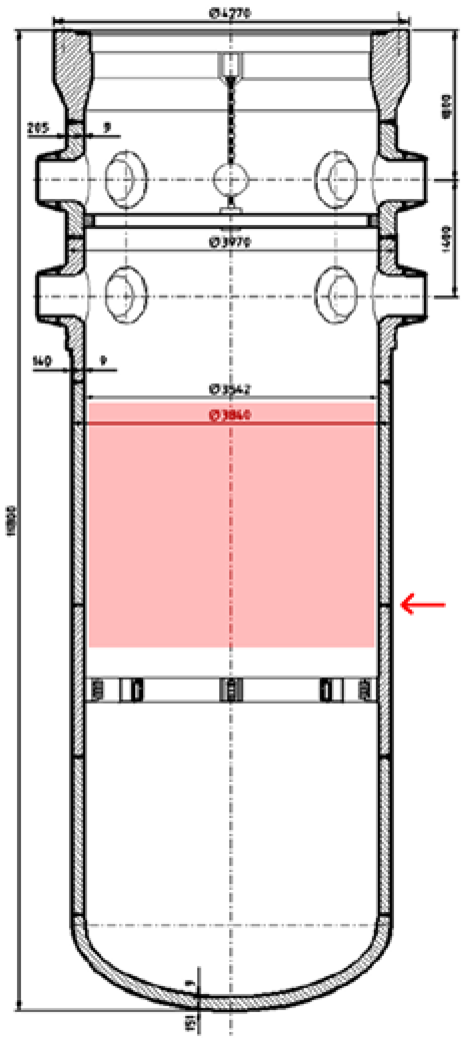
Background

General information and motivation for using FAVPRO

- Two VVER-440 PWR's commissioned in 1977 and 1980. In 2022 both plant units were granted lifetime extensions until 2050. $R_i/t \approx 12$.
- Licencing in Finland is primarily based on deterministic analysis. Brittle fracture probability must be calculated if the risk cannot be determined to be negligible (by the deterministic analyses).
- Resulting conditional probabilities are added to plant level PRA model for further risk assessment.
- Current analyses have been performed with modified OCA-P code. Now studying modern codes to find a suitable replacement.

RPV and current analysis specific information

- 2 annular ring-forgings and 1 circumferential weld in the beltline region considered in the analyses.
- ~10 mm clad accounted for in thermal and stress distribution solutions.
- T-H data for almost 200 PTS transients including variants with external cooling (EPTS).
- Separate analyses for axial flaws in base material and circumferential flaws in weld.
- Plant and material specific fracture toughness and T_0 irradiation shift data is input from explicit equations (master curve).
- Fluence data with axial and annular variation, attenuation in RPV wall is based on max fluence.



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FAVPRO implementation

- Interest in fully utilizing the probabilistic operating mode of the PFM module. Other modes may also be found useful.
- Warm prestressing effect (WPS) or weld residual stress not included, at least initially.
- First analyses with surface breaking flaws (Category 1) only to compare results with old analyses. Should be expanded to category 2 later.
- Flaw depth distribution is still based on old analyses (Marshall report) with depth being the only variable. There is a need for us to find modern alternatives for distribution, including ones with different aspect ratios.
- Application of master curve fracture toughness model and Regulatory Guide 1.99 Rev. 2 embrittlement model.
- We need to curve fit our plant and material specific embrittlement curves (irradiation shift model) with weld and chemistry-factor override. Select CF for best match with our curves, e.g., with the least squares method.
- Sub region discretization for one circumferential weld and two ring-forgings. Thin weld fusion lines above and below the weld as recommended by the FAVPRO Theory Manual.
- Subregions with different fluence levels are used to simulate our calculated fluence distribution. Subregion area proportional to the fraction of volume experiencing a certain fluence level.

Issues and questions

Issues

- AIG macros that produce JSON input files generate commas in place of dots, but only in some locations. Might relate to excel regional settings or result from other excel issue. Fixed by changing Windows display language.
- Transients with different time length in the same load input produce errors. Do they need to be analysed separately?
- Have not managed to run analyses in parallel. Have not ruled out issues with Microsoft MPI or system settings.
- Probabilistic PFM module requests surface, plate and weld VFLAW files. So, cannot run an analysis with surface VFLAW file only.

Questions

- Any feasible way to simulate external cooling transients? Option to input separately calculated thermal or stress solution?
- Axial surface breaking flaws in base material?
- Embrittlement model input explicitly as a function?
- Embrittlement model echo in output or a visualization option?
- SI output in Visualization Tool?

Thank You.

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Introducing Constraint Effects on Fracture Toughness in Ductile-Brittle Transition Region into FAVPRO: Master Curve Based Toughness Adjustment via Index Temperature (T_0) Shifting

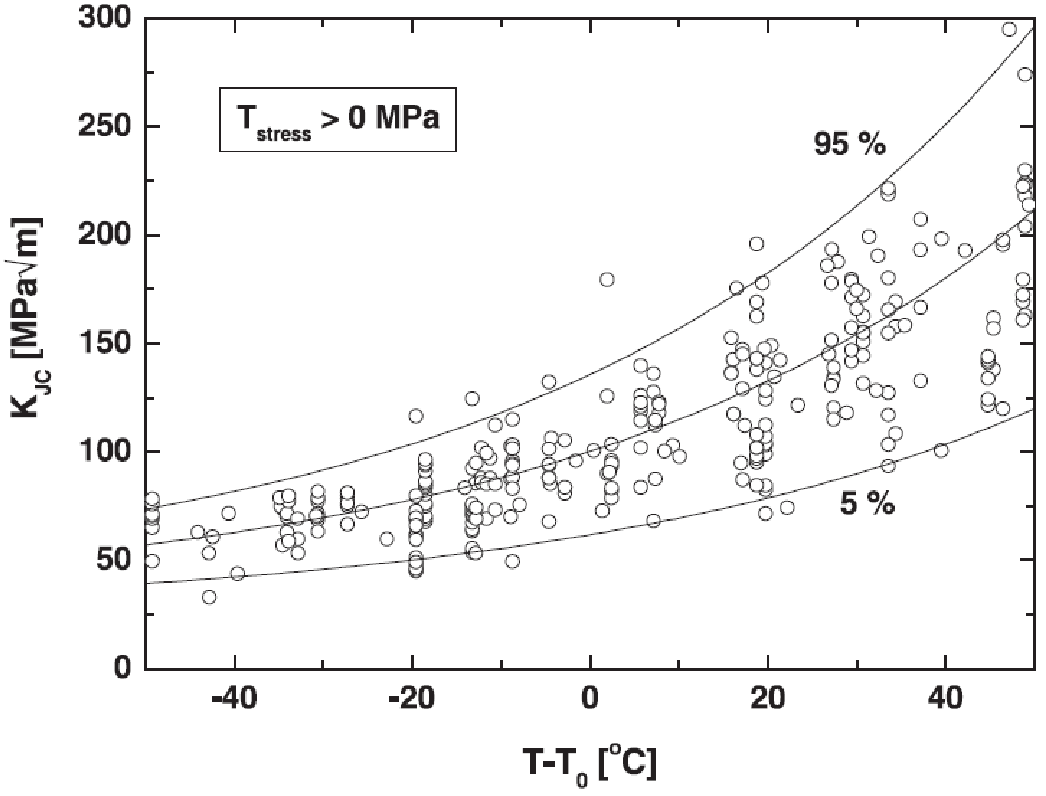
Steven Xu, Kinectrics

NRC Public Meeting – FAVPRO User Meeting

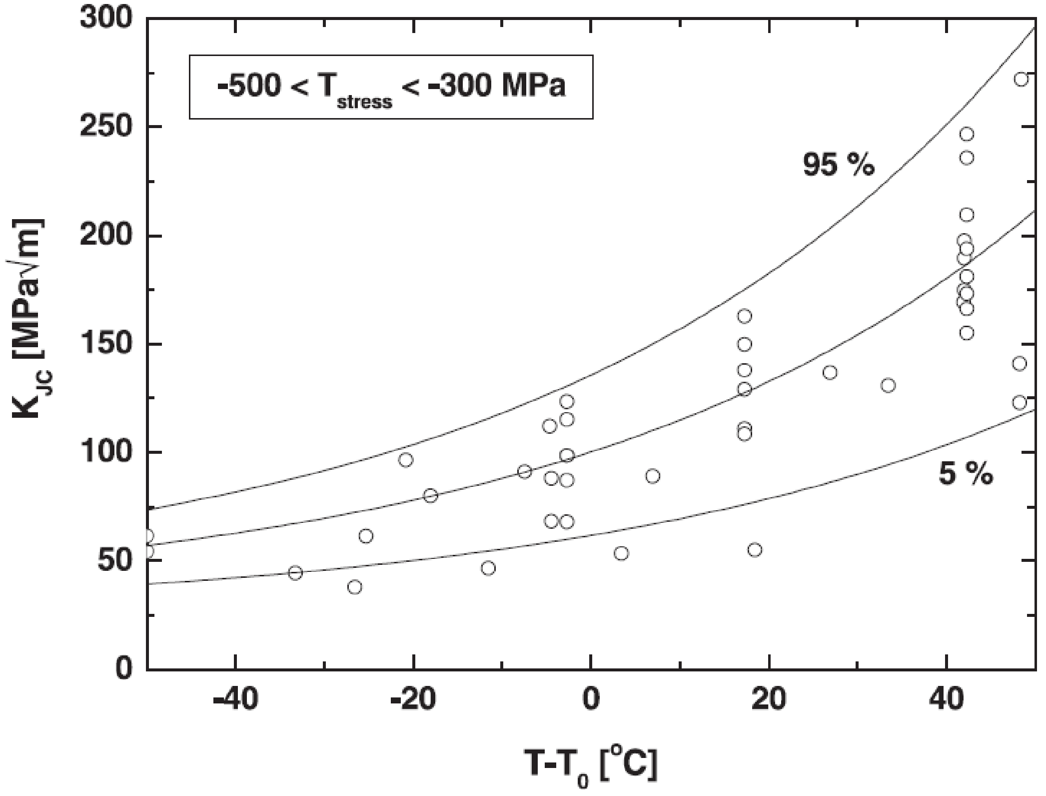
July 29, 2025

Kim Wallin developed an empirical relation between *T*-Stress and Master Curve index temperature T_0 to adjust constraint conditions

(Engineering Fracture Mechanics, 2001)



Master curve for SE(B) specimens with deep crack. $\Delta T_0 = 0$



Master curve for SE(B) specimens with shallow crack. $\Delta T_0 = T_{stress}/(10\ \text{Mpa}/°\text{C})$

Introducing Constraint Effects on Fracture Toughness in Ductile-Brittle Transition Region into FAVPRO

- The Master Curve (MC) based toughness adjustment method by shifting index temperature (T_0) has been implemented into API 579-1/ASME FFS-1 since the 2021 Edition
  - To support the implementation, the simple method was benchmarked by the Weibull stress calculation

- Ongoing activities to validate the simple method of shifting MC T_0
  - ASME PVP2025 Panel Sessions on Constraint Effects for Nuclear Structural Components: Plan to validate the simple method using the low and high constraint fracture toughness data from Framatome-EDF and Mitsubishi Heavy Industries (MHI)

- Plan to introduce constraint effects on toughness into FAVPRO
  - Collaboration between NRC and the FAVPRO user community
  - Implementation is relatively straightforward
  - Support initiative of introducing the constraint effects on fracture toughness into ASME Code Section XI
  - Update (e.g. verification, benchmark results) will be reported at future user meetings