FAVPRO

Fracture Analysis of Vessels - Probabilistic

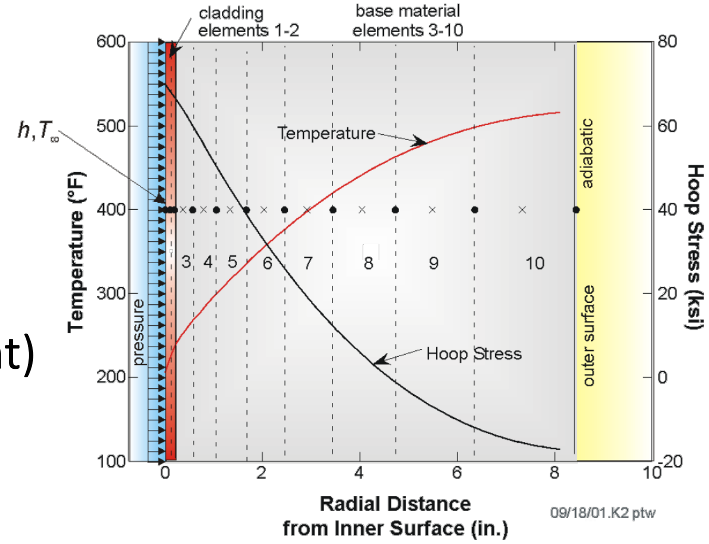
NRC's New Probabilistic RPV Integrity Assessment Code

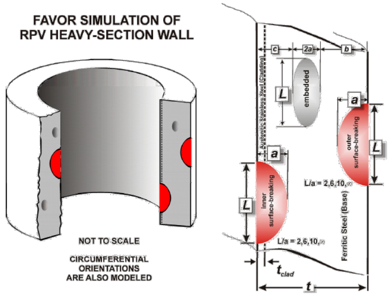
U.S. NRC
Presented by David Rudland, for
Christopher Nellis, Christopher Ulmer, Ellie Cohn, and Patrick Raynaud

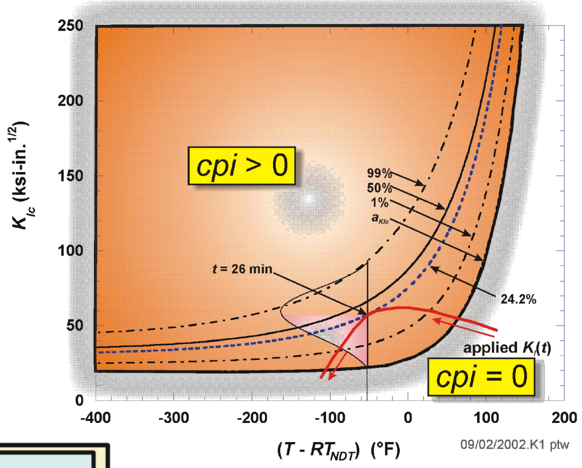
U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

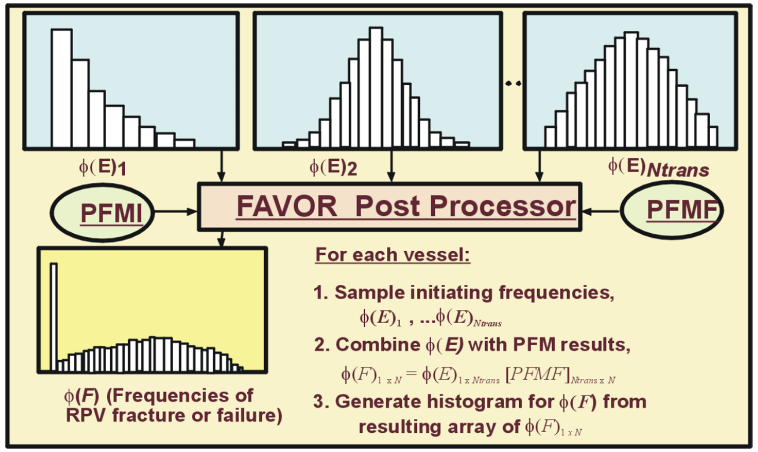
What is FAVPRO?

- Probabilistic Fracture Mechanics tool for RPV integrity assessment
- Focus on cylindrical vessel beltline
- 1D finite element axisymmetric solver
  - Stresses and temperatures (from any TH transient)
  - Stress intensity factors (ID, OD, embedded flaws)
- Run modes
  - Through-wall profiles (T, σ, SIFs…)
  - Time histories
  - Critical reference temperature (embrittlement) for crack growth
  - Conditional probabilities of crack growth initiation (CPI) and vessel fracture (CPF)
- Combination of conditional probabilities and transient frequencies to generate frequencies of crack growth initiation (FCI) and through-wall crack failure (TWCF)





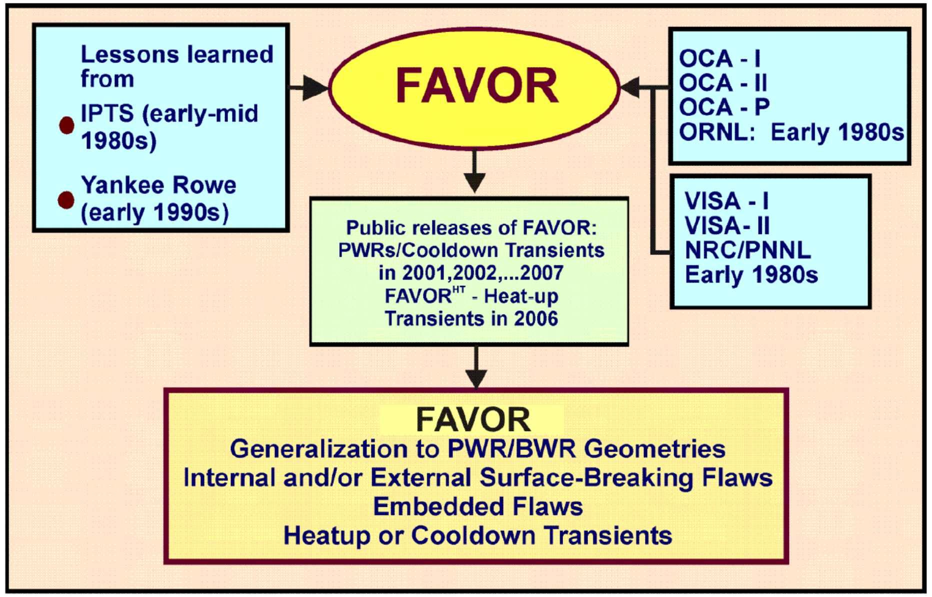




FAVPRO Validated Capabilities

- Heatup and cooldown transients
  - 1D finite element solution for temperatures and stresses
  - User specified material properties
  - Weld residual stress option
  - Crack-face pressure option
  - Stress-free temperature model for cladding residual stress
- Flaw populations
  - Semi-elliptical internal or external surface flaws
  - Elliptical embedded flaws within base metal
    - Cannot model semi-elliptical sub-cladding flaws
  - As-found flaw population or sampled population from specified distributions
- Stress intensity factor influence coefficients approach for K calculations
  - ASME solutions for base metal
  - Custom solutions for cladding (ID surface flaws)
- Warm prestress options
- Several embrittlement trend curves
- Ductile tearing and crack arrest options
- Vessel chemistry and fluence sampling
- Resampling option for crack growth

FAVPRO's Ancestor: FAVOR

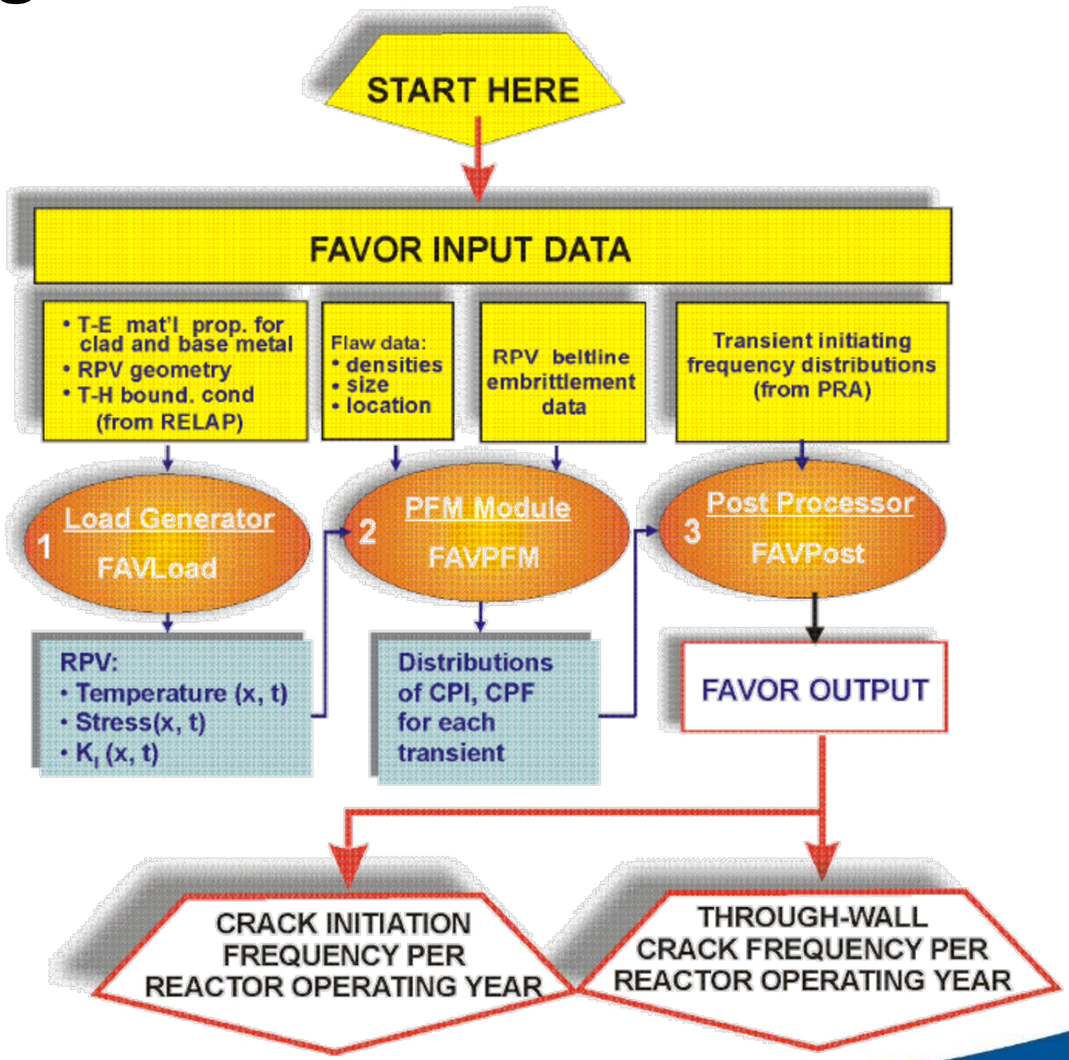


- Created in the 90s under the Heavy Section Steel Technology (HSST) program
  - Combined attributes of OCA-P (ORNL) and VISA-II (PNNL) codes
- Initially targeting Pressurized Thermal Shock (PTS) transients for PWRs
- Later expanded to all heat-up and cooldown transients, for both PWR and BWR
- Used for the PTS re-evaluation project which resulted in updating 10 CFR 50.61
- Used to develop the basis for alternate PTS rule 10 CFR 50.61a

- Recent uses include:
  - Shallow flaw issue disposition
  - Doel and Tihange laminar flaw evaluations
  - RG 1.99 Rev 2 re-evaluation
  - NuScale confirmatory calculations (FAVPRO)

FAVPRO's Beginning: FAVOR-v16.1

- Developed and issued by ORNL late 2016
- Was the final version of FAVOR issued by the Heavy Section Steel Technology (HSST) Program at Oak Ridge National Laboratory (ORNL)
- FAVOR = FAVLOAD + FAVPFM + FAVPOST
  - 3 sequential executable programs
  - Information passed via formatted text files
- Serial and sequential code
- Software Quality Assurance (SQA) gaps
  - ML20017A171
  - ML20017A170



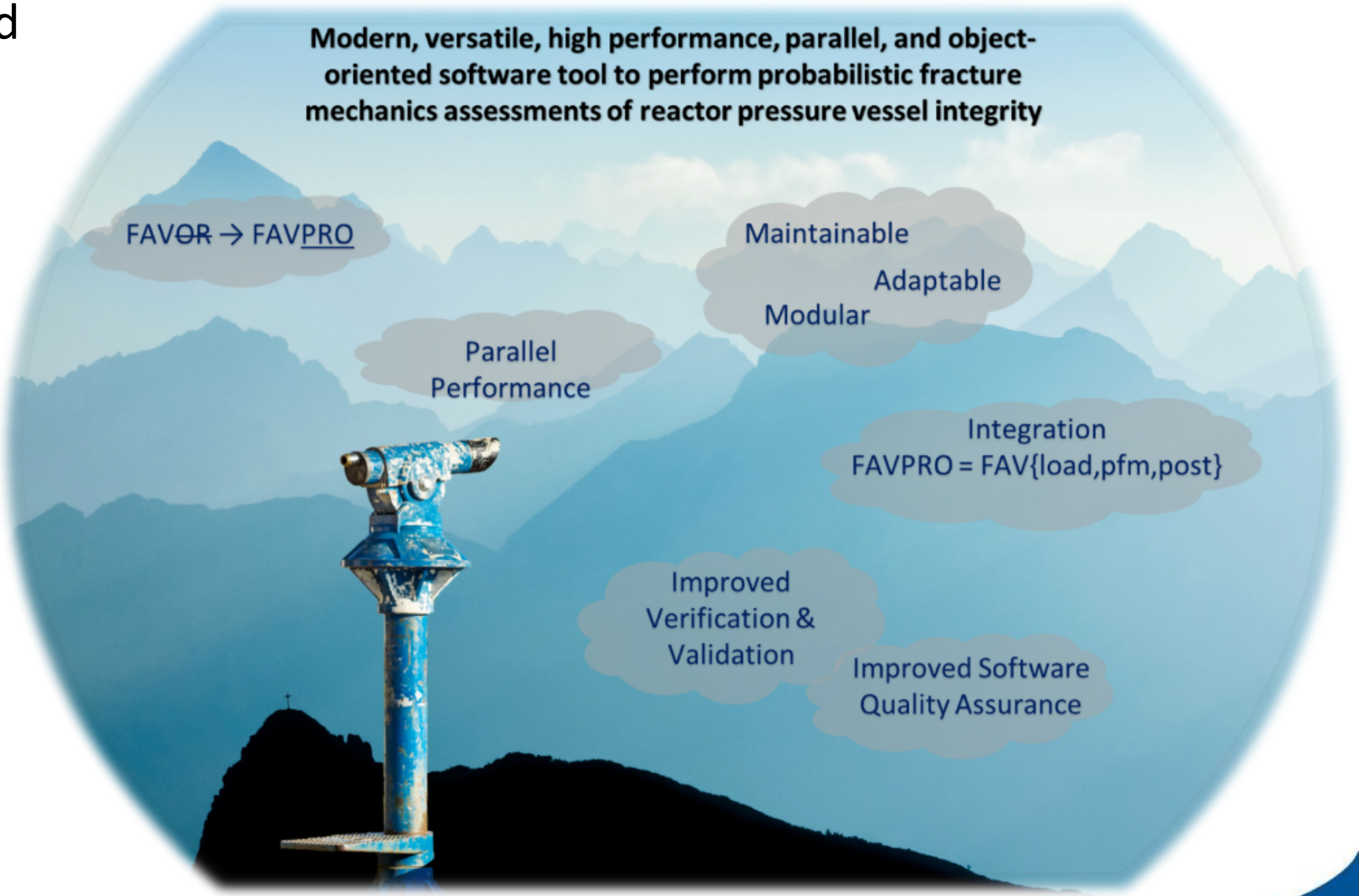
Final FAVOR Version: FAVOR-v20.1.12
Released on June 4, 2021

- New build system
- Source code improvements:
  - Convert to free form '.f90' files
  - Modularization
  - Begin removal of obsolete Fortran
- Testing improvements:
  - New integration tests
  - A few unit tests
  - Automatically run testing on GitHub for all code changes

- Documentation
  - Automatically generated developer documentation
    - FORD: Fortran Documenter
    - Detailed code descriptions from source parsing
  - Created new SQA documents:
    - SQAP: ML21180A161
    - CMMP: ML21180A167
    - SRD: ML21246A230
    - SDD: ML22132A068
  - Created new Manuals:
    - User Manual: ML21175A301
    - Theory Manual: ML21175A300

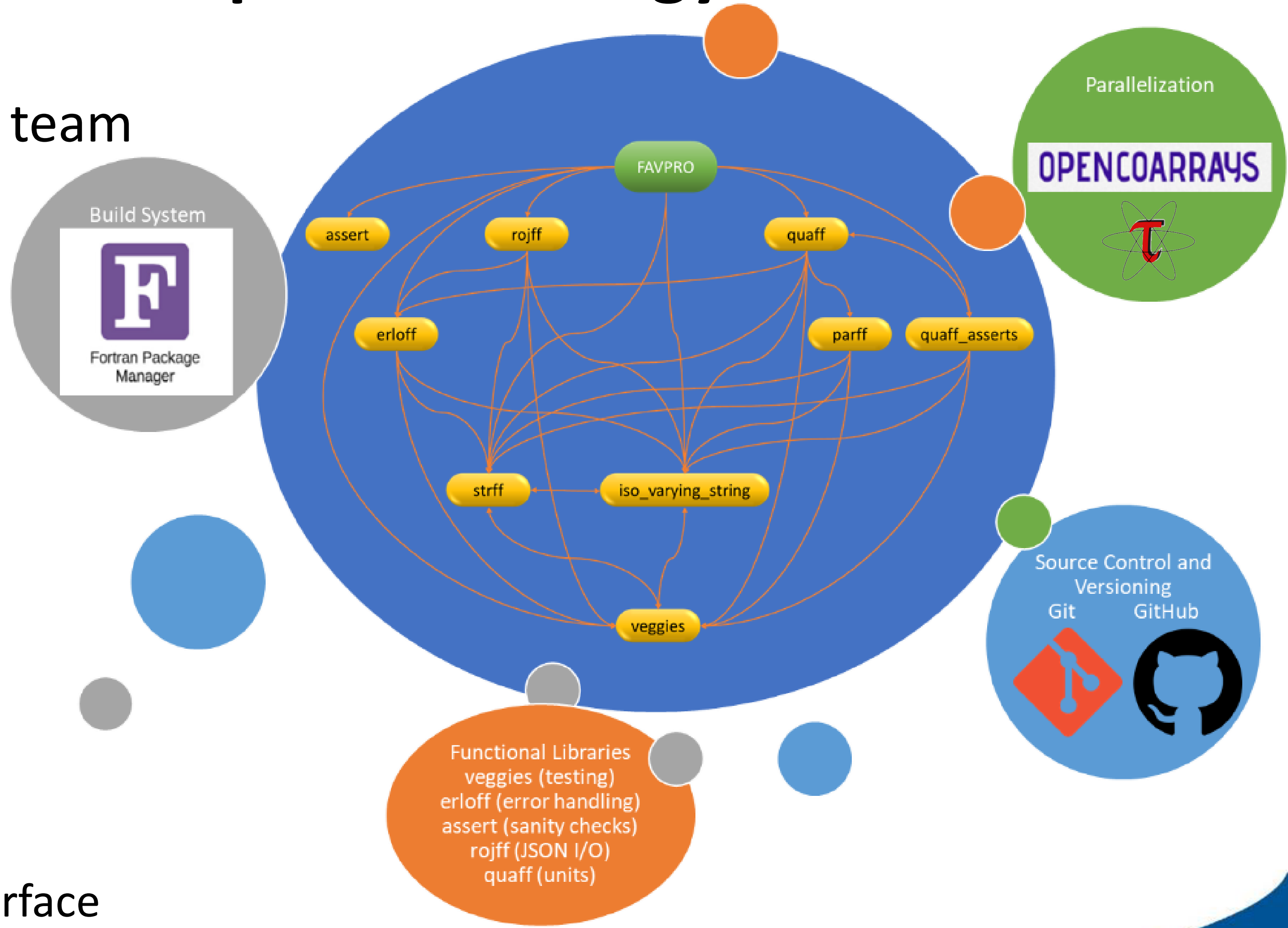
Vision and Goals for FAVPRO

- Completely refactor FAVOR to create an improved tool with equivalent capabilities, written in modern Fortran
- GOALS
  - Maintainability
  - SQA and V&V improvements
    - Testing
    - Documentation
  - Modularity, adaptability, easier feature development
  - Modern programming
    - Object-oriented code
    - Parallel code
  - Maximize automation for testing and documentation
  - Program integration: 3 FAVOR into 1 FAVPRO
  - Use State-of-Practice tools and libraries
    - GitHub: source control
    - State-of-practice build system
    - State-of-practice unit testing framework
    - Standardized I/O via Java Script Object Notation (JSON)



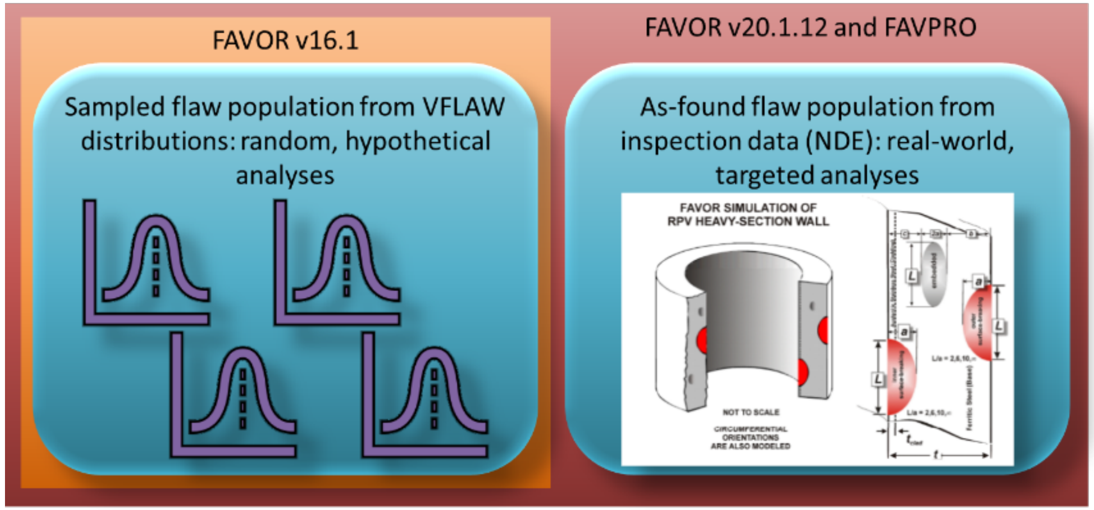
FAPVRO 'Agile' Development Strategy

- Close collaboration within development team
- 'Sprints' and 'scrums'
- Rapid internal release cycle (~60 days)
- 3-year project with team of ~12 people
- Used modern Fortran
  - High performance, object oriented, parallel
  - Growing community of developers
- Use of many open-source libraries
  - fpm: building and testing
  - OpenCoarrays parallelization
  - quaff: quantities for Fortran -> unit tracking
  - rojff: return of JSON for Fortran -> JSON interface
  - Etc…



FAVPRO Features: Flaw Treatment and Fracture Mechanics Update

- Flaw modeling options
  - VFLAW sampled flaw distributions
    - Relies on output from legacy VFLAW code
    - Can be produced ‘manually’ to force some flaw distributions
    - Cannot be used to specify actual flaws
  - As-found flaw specification
    - JSON input file format
    - Allows specification and placement of actual flaws
- Stress intensity factor (SIF) calculations
  - Use of ASME solutions wherever possible
  - Still use Abaqus-generated custom solutions for cladding contribution to SIF



Flaw type	FAVOR	FAVPRO
Inner Surface Flaw (cladding contribution)	ABAQUS	ABAQUS
Inner Surface Flaw (base metal contribution)	ABAQUS	ASME
Outer Surface Flaw	ABAQUS	ASME
Embedded Flaw	ASME	ASME

FAVPRO Features: Embrittlement Trend Curves (ETC)

- Currently available ETC
  - RG-1.99 Rev. 2
  - EONY 2000 and 2006
  - Kirk 2007, Radamo 2007, and Kirk+Radamo 2007
    - Early versions of ASTM model
    - Replaced by ASTM E-900
- Future: add non-US 'mainstream' embrittlement trend curves to the FAVPRO options?
  - Japanese model (update to JEAC4201, presented at FONTEVRAUD-10 in 2022)
  - French model (2011: FONTEVRAUD-7, or more recent if available)

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	

FAVPRO Features: Fracture Toughness Models

- In FAVOR and FAVPRO v1.0: ORNL toughness model
  - Based on RT_{NDT}

$\widehat{\Delta T}_{RELATIVE} = T(\tau) - \widehat{RT}_{NDT}(r, \cdots)$ in °F

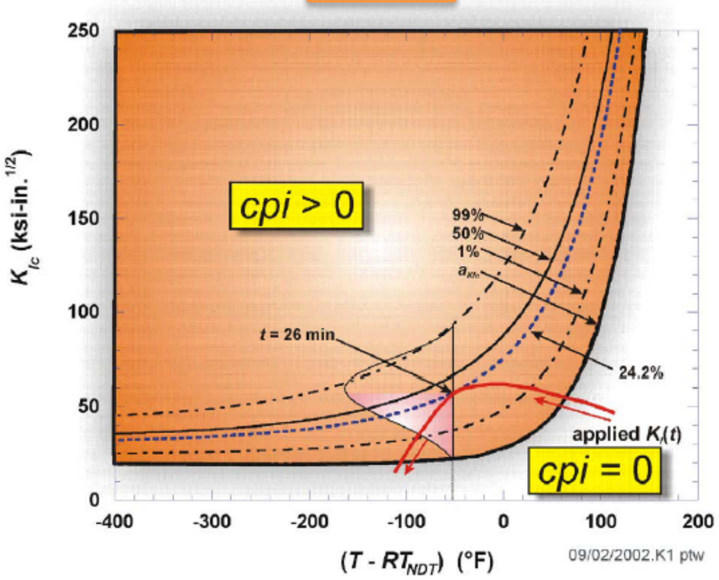
$$K_{Ic}(\widehat{\Delta T}) = \widehat{a}_{K_{Ic}}(\widehat{\Delta T}) + \widehat{b}_{K_{Ic}}(\widehat{\Delta T})\left[-ln(1-\Phi_{K_{Ic}})\right]^{1/c_{K_{Ic}}} \text{ for } 0 < \Phi_{K_{Ic}} < 1$$

for $a \le K_{Ic} \le K_{Ic(max)}$

$$a_{K_{Ic}}(\widehat{\Delta T}_{RELATIVE}) = 19.35 + 8.335\,exp\left[0.02254(\widehat{\Delta T}_{RELATIVE})\right] \quad [\text{ksi}\sqrt{\text{in.}}]$$

$$b_{K_{Ic}}(\widehat{\Delta T}_{RELATIVE}) = 15.61 + 50.132\,exp\left[0.008(\widehat{\Delta T}_{RELATIVE})\right] \quad [\text{ksi}\sqrt{\text{in.}}]$$

$$c_{K_{Ic}} = 4$$



- Upcoming in FAVPRO v1.1: Master Curve model
  - Based on T_0 (based on ASTM E1921)

$$K_{Jc}^{p} = 20 + (K_o - 20)\{-ln(1-p)\}^{1/4}$$

$$K_o = 31 + 77 \cdot exp[0.019(T - T_{o(adj)})]$$

Values of K are expressed in MPa√m

temperature are expressed in °C

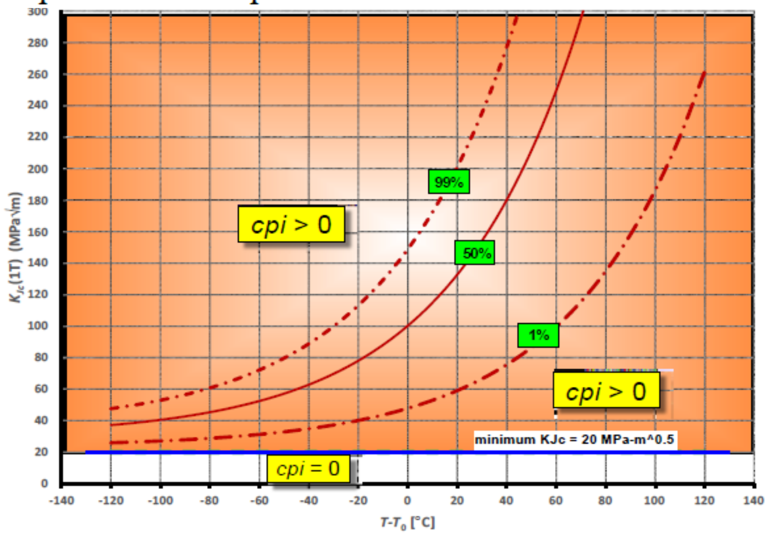
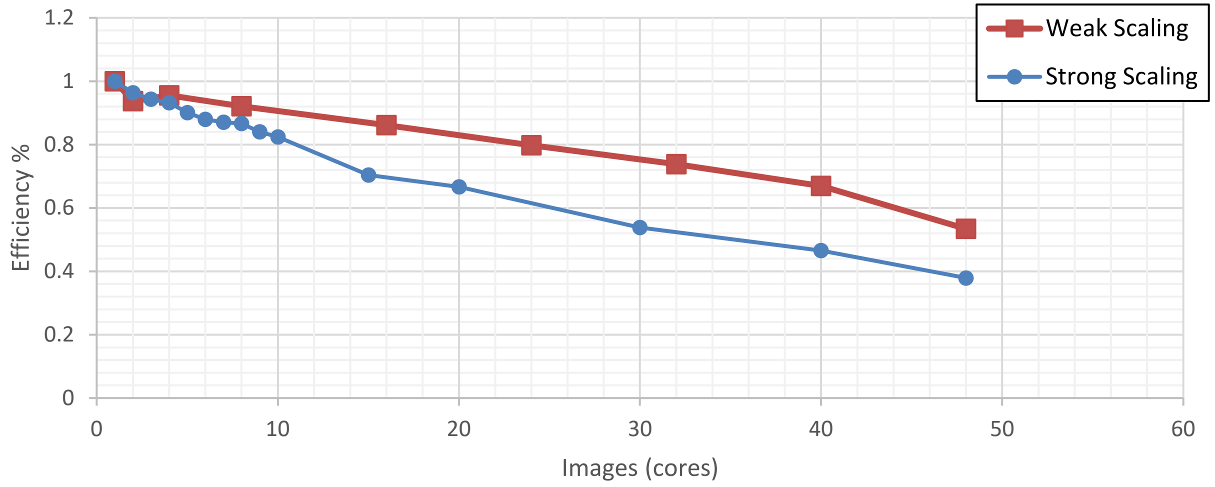
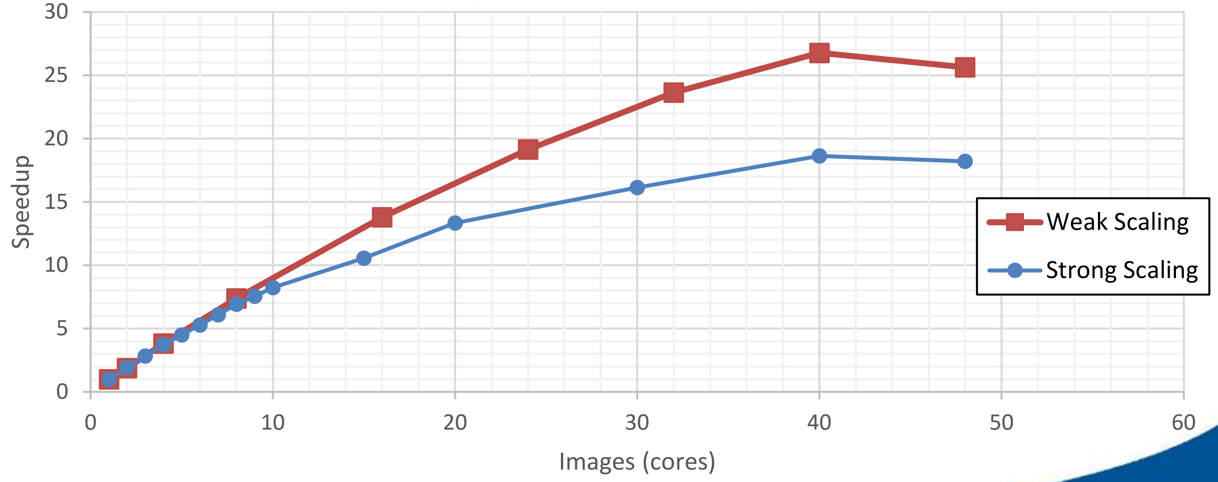


Image from PVP2024-121814

FAVPRO Feature: Parallel Execution of Probabilistic Calculations

- Two FAVPRO executables are distributed
  - Serial executable: faster for deterministic calculations and small probabilistic problems
  - Parallel executable: faster for large probabilistic calculations using 'mpiexec'
- Example for 48 core server
  - 100k simulations (strong scaling)
  - 12.5k simulations per processor (weak scaling)
  - Good scalability
  - Efficiency diminishes as machine resources are used up (as expected)





FAVPRO SQA and V&V

- Git/GitHub version control and independent tracking of changes
  - Transparency, critical reviews, automated unit and integrated testing
  - Code merging requirements must be met
- Updated SQA documentation (next slide)
- Increased V&V testing
  - Over 300 unit-tests
  - Around 80 integration-tests
  - Run automatically at every code change on Windows, Linux, and MacOS
  - Run for serial and parallel run modes

Summary of FAVPRO SQA Configuration Documents

SQA Document	Status
Software Quality Assurance Plan (SQAP)	Published ML24095A318
Configuration Management and Maintenance Plan (CMMP)	Published ML24095A319
Software Requirements Document (SRD)	Under development
Software Verification & Validation Plan and Results Report (SVVPR)	Published for FAVPRO v0.1.15 ML24102A185
Software Design Document (SDD)	Theory Manual and FORD Documentation
Software Test Plan(s) (STPs)	GitHub README file
Software Test Results Report(s) (STRRs)	GitHub Actions Log

Code Distribution Item	Status
Implementation Documentation	Ongoing
1. FAVPRO executables	Frequent internal releases on GitHub (current 1.0.0)
2. User's Manual	Published ML24113A237
3. FAVOR Theory Manual	Published ML24113A239
4. Acceptance Test Problems	GitHub CI

FAVPRO Automatic Input Generator (AIG)

Click if you wish to import existing input from FAVLOAD, FAVPFM, FAVPOST, or As-Found Flaw input

Select File and Import Inputs

File last imported:
D:\Network\RPV\FAVOR\Bugs and Inquiries\FAVOR Performance Test Case\POST.in

Update Sheets to be Populated

Do you wish to create new...

Load Input?	No
PFM Input?	No
Post Input?	No
VFLAW Input?	No
	Several
	Several
	Several
As-Found Flaw Input?	No

IMPORTANT: Fill in the sheets in the order they are presented

Key

Follow these instructions

Input descriptions

Fill these cells in: these are required inputs

Do not change these cells: values calculated based on other inputs

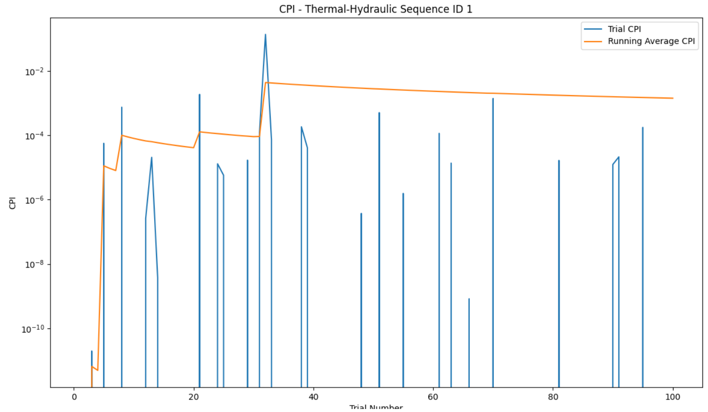
Optional Inputs: to be filled in as appropriate

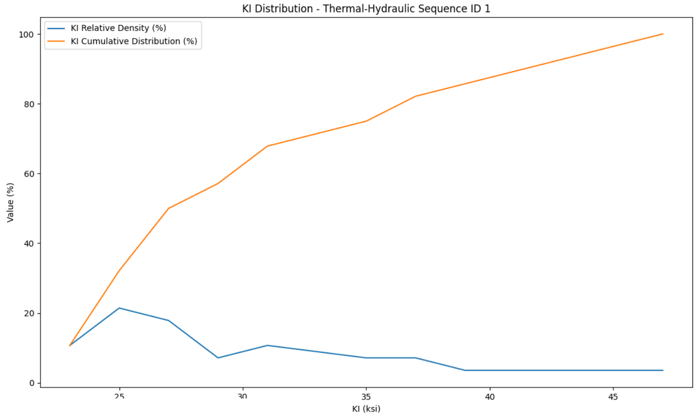
- Read in and convert old input files
- Produce new inputs
  - LOAD
  - PFM
  - POST
- Produce flaw inputs
  - VFLAW
  - As-Found Flaws

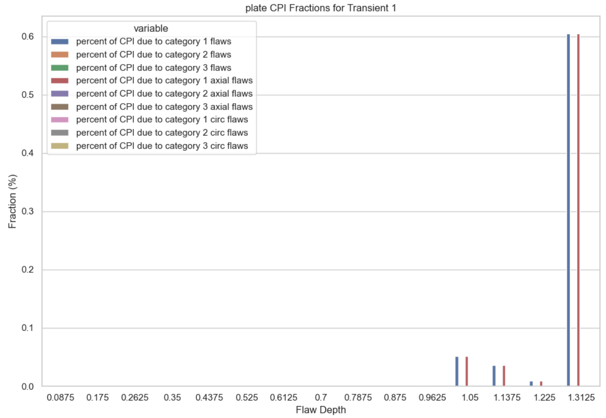
FAVPRO Output Visualization

- Python scripts
- Goal: Read in any FAVPRO output file and easily extract and visualize FAVPRO output data

```
PS V:\Documents\Repos\FAVPRO> python .\tests\integration\inputs\VT\FAVPRO_VT.py
Importing matplotlib (already installed)
Importing numpy (already installed)
Importing pandas (already installed)
Importing seaborn (already installed)
Importing xlsxwriter (already installed)

These are the JSON files available for visualization:

1. ver_5_ref.json

Which file would you like to visualize?
1

'ver_5_ref' directory and sub-directories created if they did not exist.

These are the keys available for visualization:
1. CPI output
2. CPF output
3. analysis output
4. All

Which key would you like to visualize?
4

Would you like to see the plots one by one? (y/n)
y
What would you like to do next?

1. I am done
2. I want to continue visualizing
1
PS V:\Documents\Repos\FAVPRO>
```







FAVPRO User Group

- To obtain FAVPRO (or FAVOR):
  - Fill out the NRC Codes NDA
  - Once approved, the code executables (FAVPRO), input generator (FAVPRO-AIG), and visualization tool (FAVPRO-VT) are downloaded via NRC's BOX service
- All approved users automatically become members of the User Group
  - Annual meetings (hopefully more often in the future)
  - Newsletters (quarterly)
  - 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.
- What about source code?
  - Can be obtained on special case-by-case basis
    - Need to show tangible benefit to NRC

Summary and Perspectives

- FAVPRO is a new modern tool to replace FAVOR
- Enhanced SQA pedigree and V&V testing
- Modern, modular, parallel code for enhanced performance, enhanced user experience, and enhanced adaptability
- New features:
  - As-found flaw modeling
  - Standard conforming K solutions where possible (ASME)
  - New embrittlement trend curves to reflect the latest standards and research
- **FAVPRO is a robust and resilient foundation that can be built upon to add new models, new probabilistic functionality, new materials, and new physical models to adapt to the rapidly evolving nuclear technology landscape**