Risk-Informed Fracture Evaluation Of Reactor Vessels Subjected To Cool-down Transients Associated With Normal Shutdown

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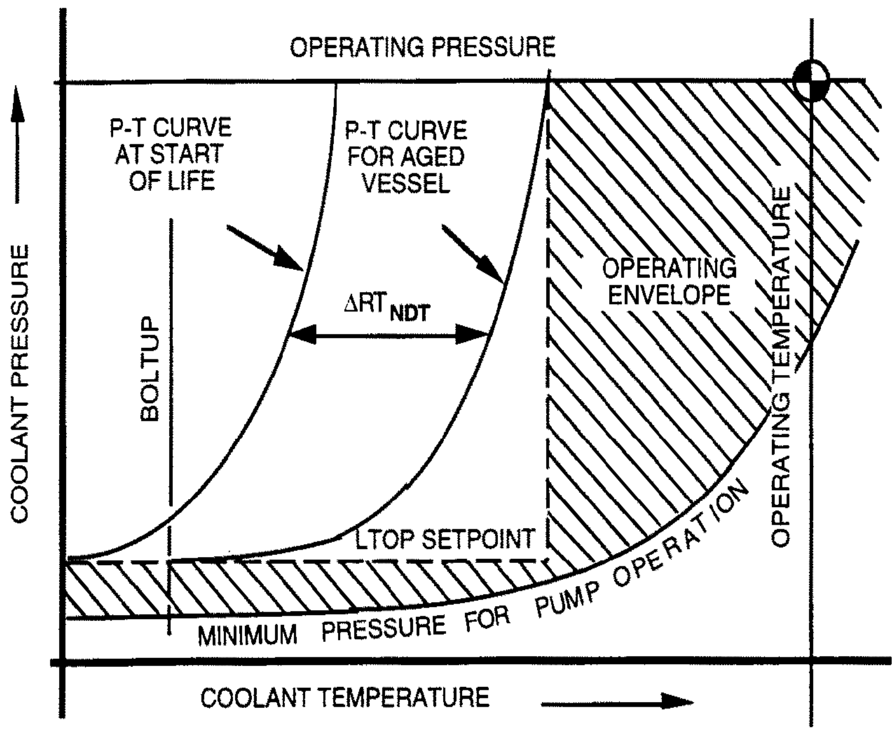
The P-T operating envelope is progressively restricted to accommodate the effects of irradiation embrittlement of the RPV material

The P-T curve controls the upper-bound to the permissible operating envelope for a RPV during normal start-up and cool-down transients

The P-T curve is currently derived using a prescriptive deterministic fracture methodology in ASME Section XI – Appendix G

An objective of ORNL study is to determine if a technical basis can be established to support a relaxation to the methodology in ASME Section XI – Appendix G



The current regulations for deriving transients associated with reactor start-up and shutdown are established by converting the ASME K_{Ic} curve to coordinates of pressure and temperature:

(1) by assuming a surface breaking flaw of depth equal to ¼ of the RPV wall
(2) Including a factor of 2 to account for sources of stress not included in the formulation such as residual stresses, crack face pressure induced stresses, and dte stresses

Per ASME Section XI, Appendix G, the maximum allowable pressure for a given cooldown is determined as follows:

$$P(t) = K_{Ic}(t) - K_{IT}(t) / 2\ Cp$$

where:

$K_{Ic}(t)$ is the ASME lower-bound crack initiation curve

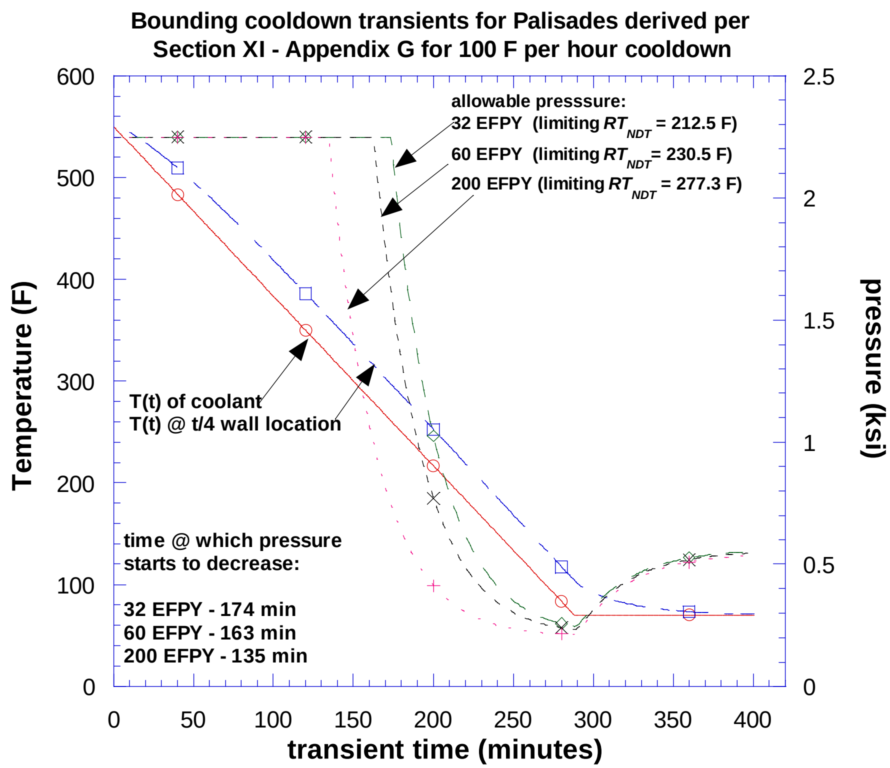
$K_{IT}(t)$ is the thermally-induced stress intensity factor produced by the radial thermal gradient through-the-wall for (t/4) reference flaw

Cp = pressure-induced stress intensity factor produced by 1 ksi pressure loading

PFM analyses were performed with FAVOR to determine probabilities of crack initiation and RPV failure associated with bounding cooldown transients (100 F / hr) derived per Section XI – Appendix G

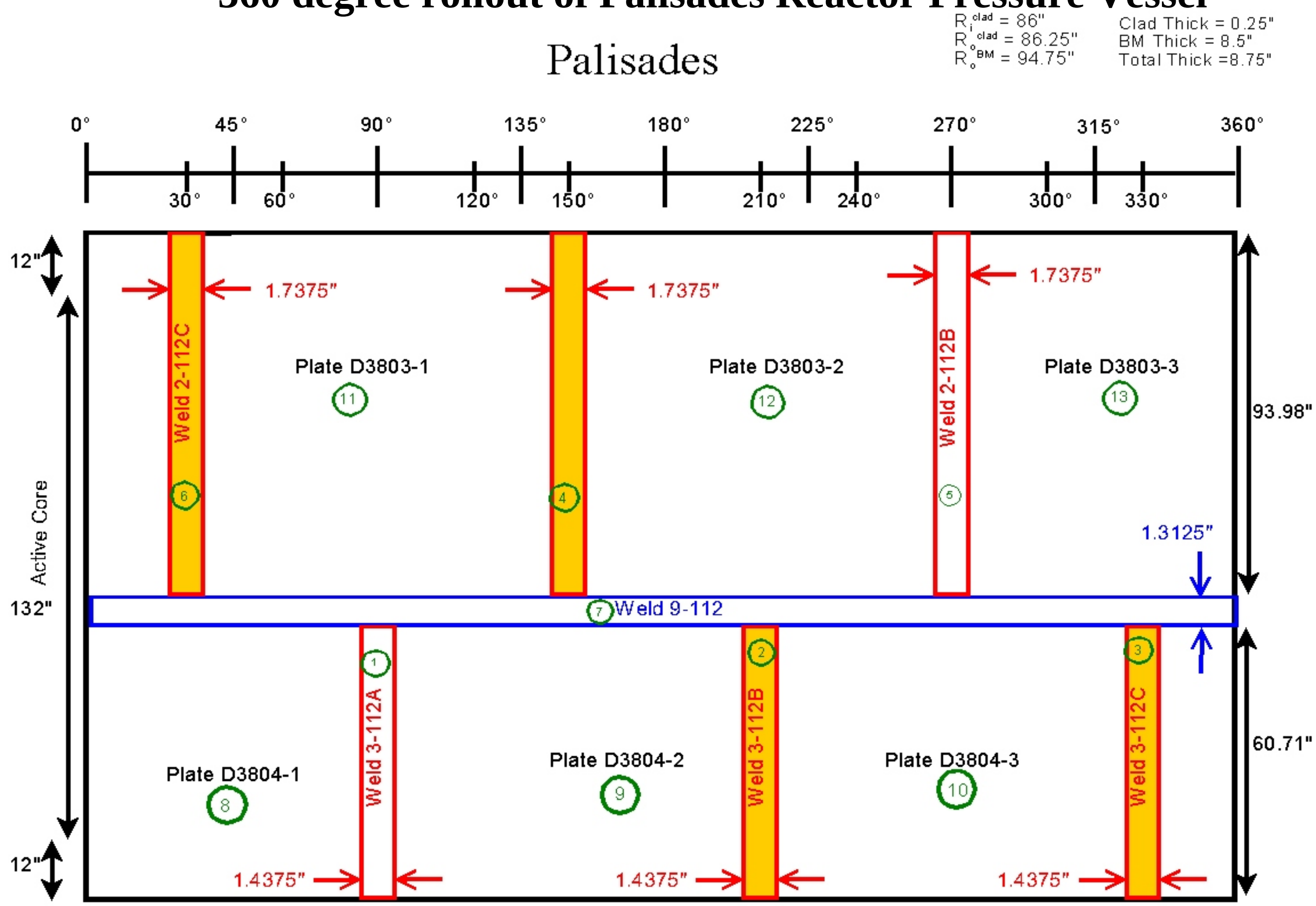
Analyses were performed for Palisades since, from the PTS re-evaluation, it was the most limiting plant

Utilized embrittlement and flaw characterization models from PTS re-evaluation



Scoping PFM analyses for normal operation transients associated with reactor startup and shutdown have been performed for Palisades since it was the most limiting RPV in the PTS re-evaluation (axial welds are the most highly embrittled RPV regions)

360 degree rollout of Palisades Reactor Pressure Vessel



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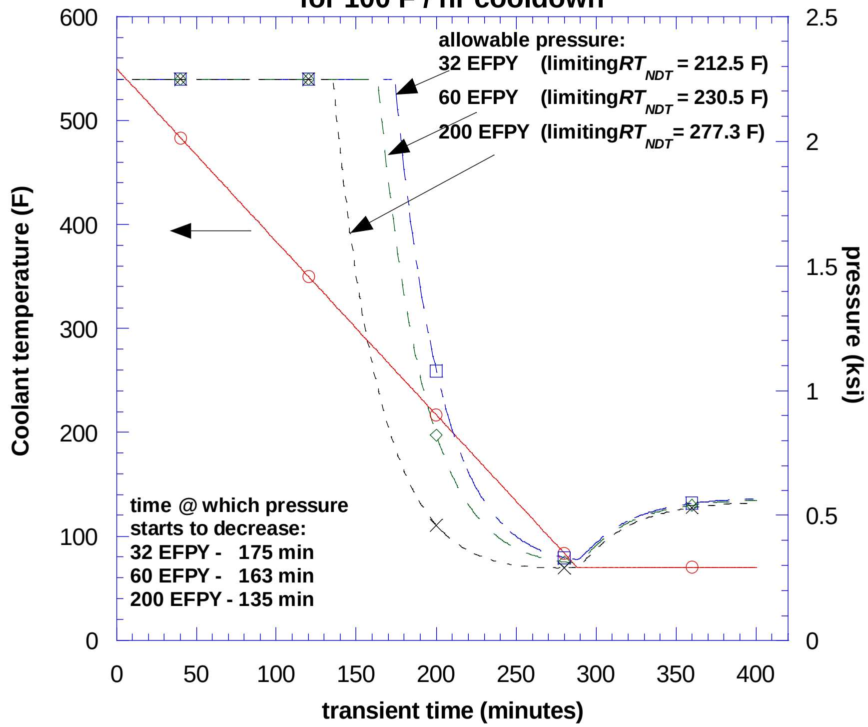
Scoping PFM analysis results for bounding cool-down transients are in compliance with proposed new acceptance criteria (for PTS) of 1.0e-6 failed RPVs per reactor operating year for over 60 EFPY (Consistent with SRM-SECY-06-0124 on PTS Rulemaking Plan) (when model includes WPS and temp-dependent thermal-elastic properties)

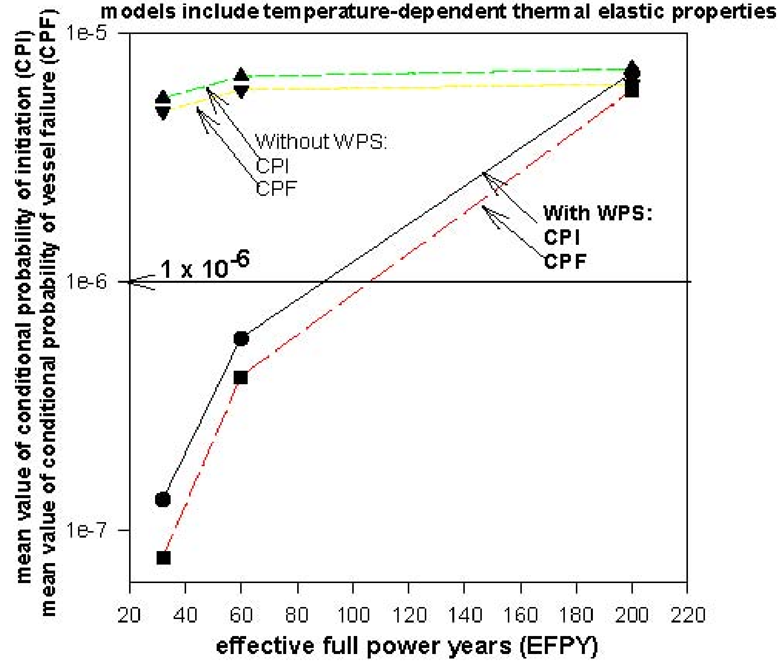
Bounding cool-down transients for Palisades per Section – XI Appendix G

Shutdown transients for Palisades derived per Section XI - Appendix G for 100 F / hr cooldown



CPI and CPF computed with and without WPS: temp-dependent thermal elastic properties

PFM results for Palisades subjected to bounding cooldown transients per ASME Section XI - Appendix G models include temperature-dependent thermal elastic properties



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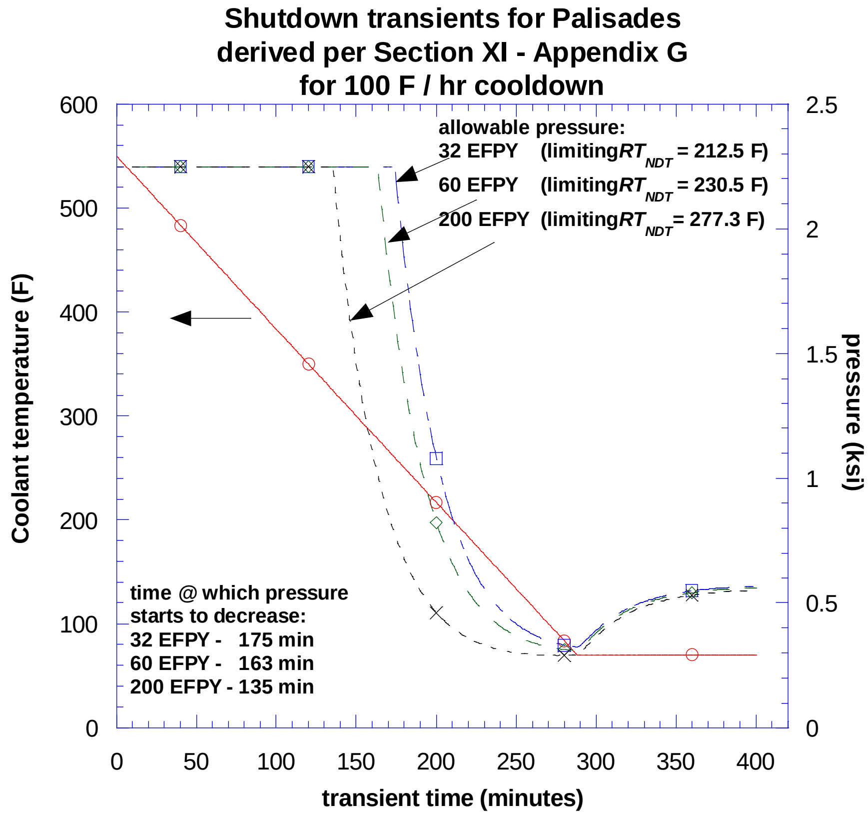
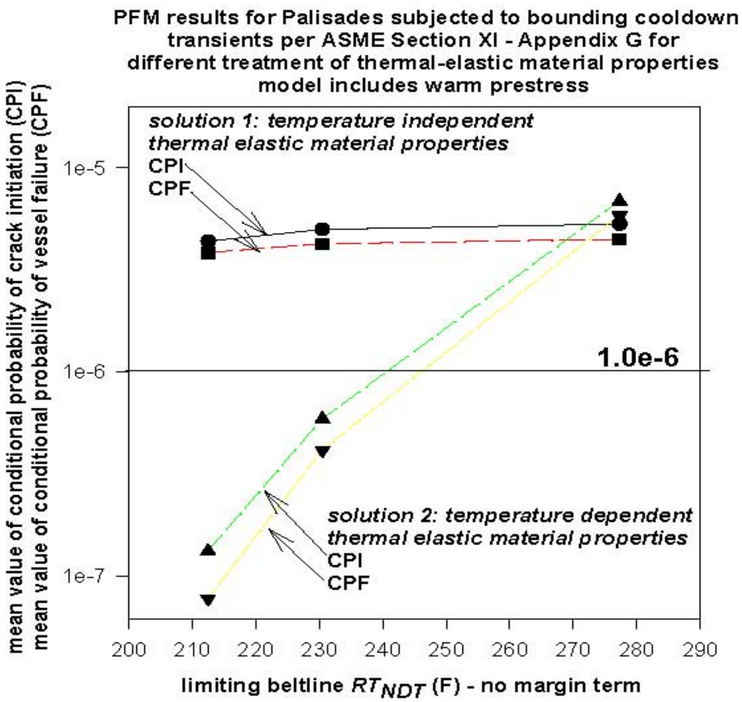
Scoping PFM analysis results for bounding cool-down transients are in compliance with proposed new acceptance criteria (for PTS) of 1.0e-6 failed RPVs per reactor operating year for over 60 EFPY
(Consistent with SRM-SECY-06-0124 on PTS Rulemaking Plan)
(when model includes WPS and temp-dependent thermal-elastic properties)

Bounding cool-down transients for Palisades per Section – XI Appendix G



CPI and CPF computed with WPS: different treatments of thermal-elastic material properties



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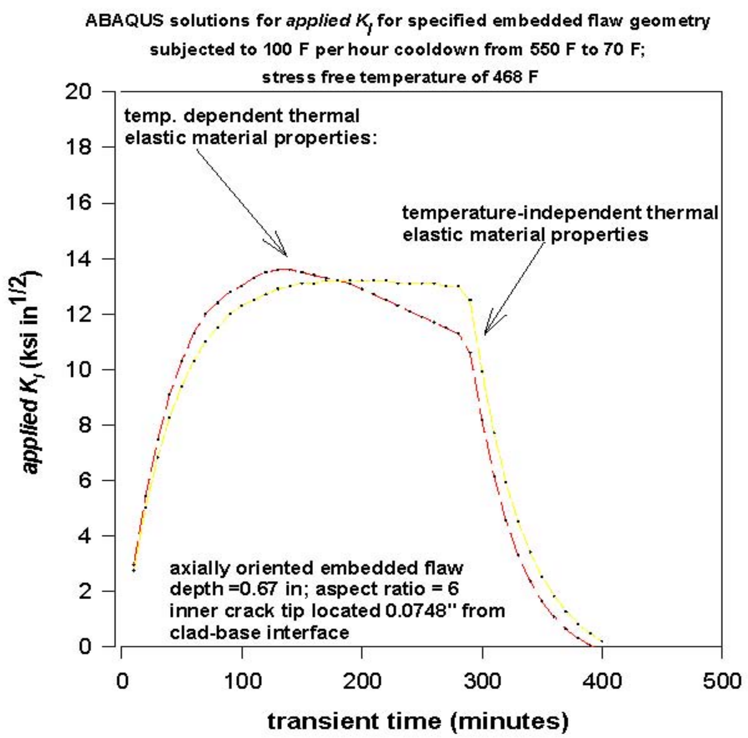
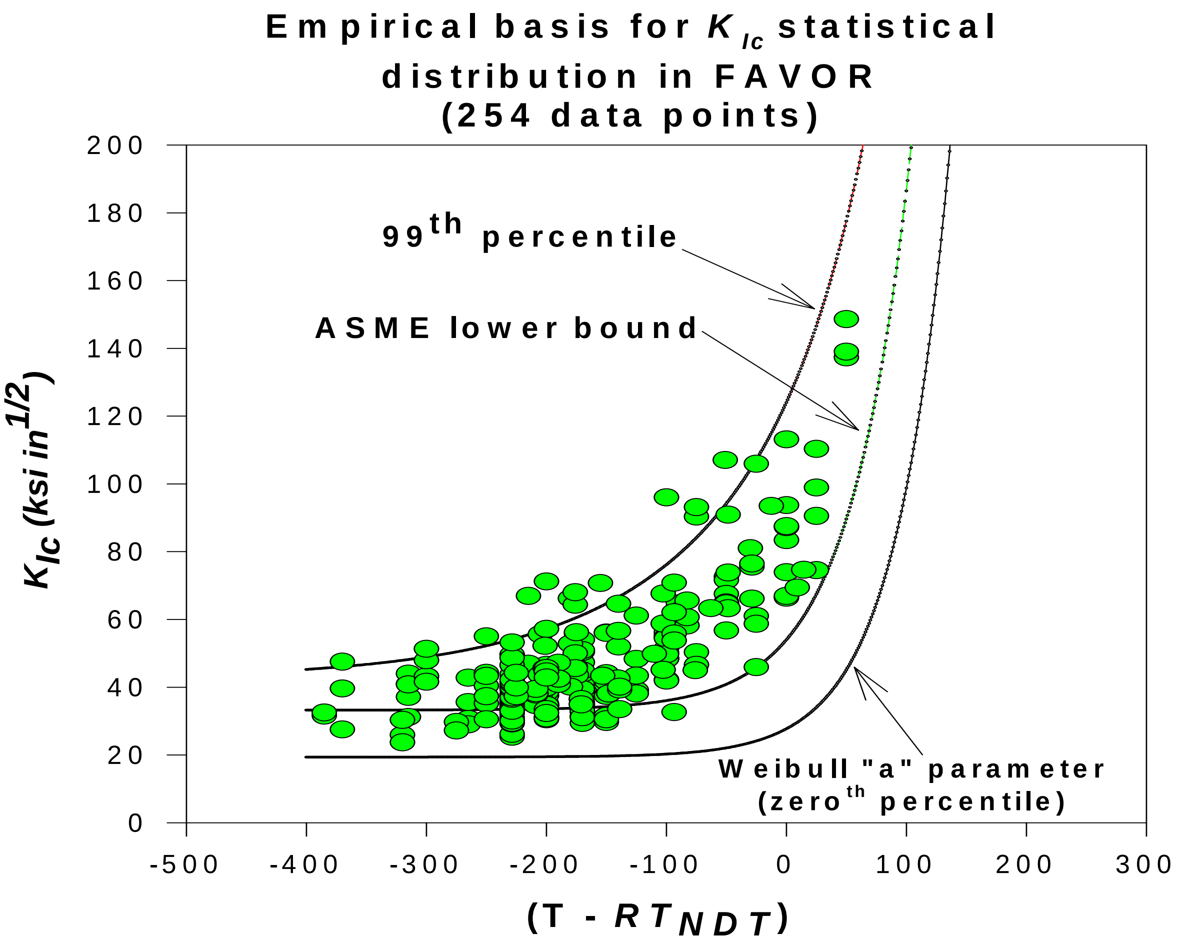
Temperature-dependent thermal-elastic material properties has little impact on magnitude of peak loading; however, causes peak to occur at an earlier time (when fracture toughness is higher), which in conjunction with WPS, can have significant impact on fracture analysis of flaw



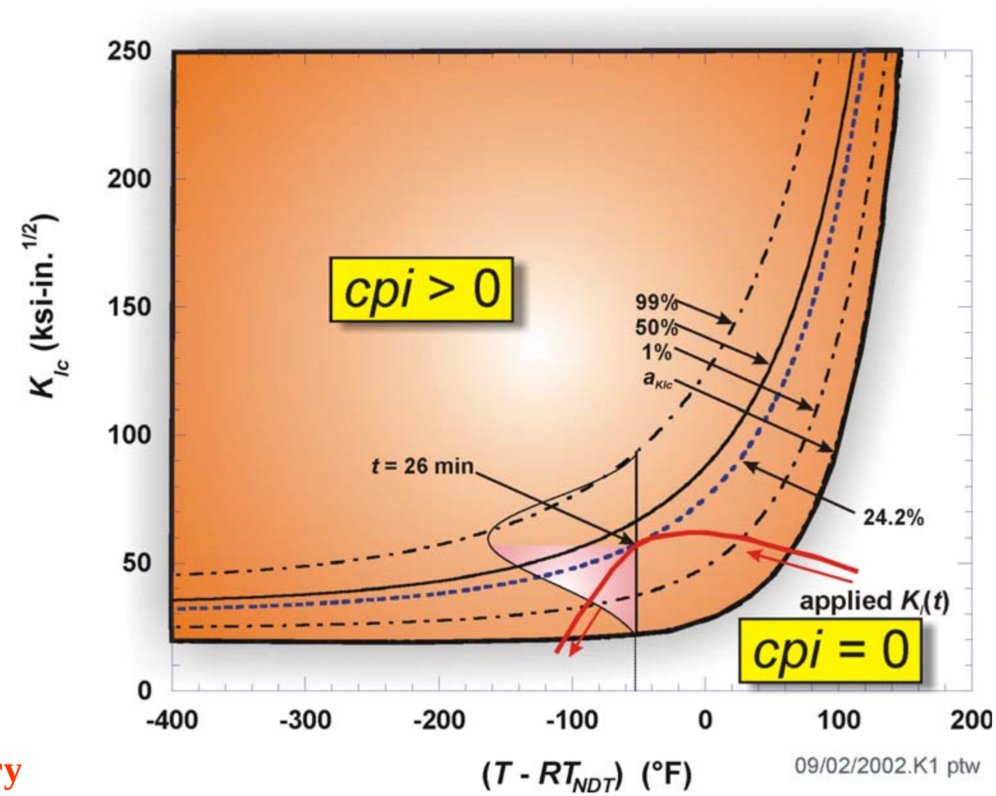
The statistical distribution in FAVOR is based on an extended K_{Ic} database relative to that from which the ASME lower bound-curve was derived



FAVOR Review: cpi is determined from interaction of *applied* K_I and K_{Ic}

Without WPS: for cpi > 0, *applied* K_I must be greater than Weibull "a" parameter which is the lower bound at any transient time

With WPS: for cpi > 0, *max* K_I must be greater than Weibull "a" parameter at transient time before maximum load is reached



Possible approaches to risk informing Section XI – Appendix G

(I) Provide technical basis for providing a relaxation to the current prescriptive deterministic method, such as:

(a) Remove factor of 2 in derivation of acceptable pressure
(b) Modification of reference flaw size

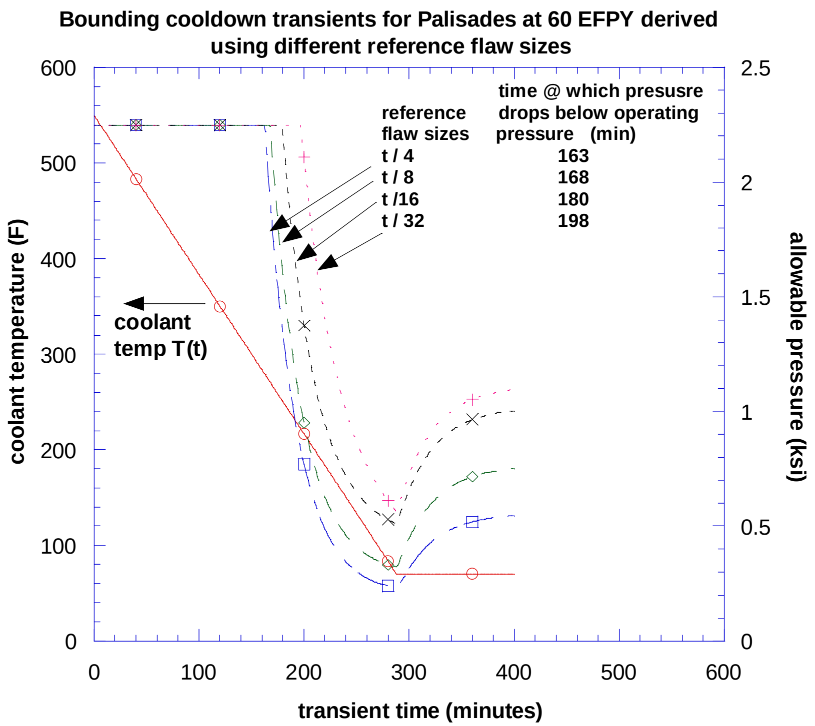
(II) Entirely new rules for deriving limiting P-T curves

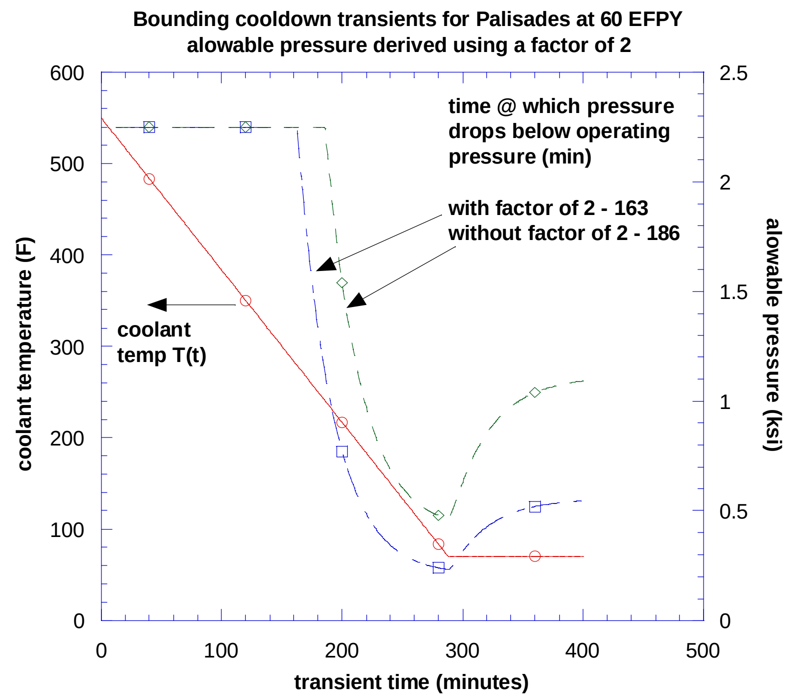
Scoping PFM analysis indicated that relaxations in Section XI – Appendix G deterministic fracture methodology that allow higher pressures

(1) smaller reference flaw size than current t / 4 size
(2) removing the factor of 2 on pressure in derivation

did not increase risk – when WPS included in model

All initiations and failures occur at full pressure: Before transients diverge





Summary and Conclusions

Scoping PFM analyses performed with FAVOR (LEFM) for bounding cool-down transients associated with plant shutdown for Palisades over plant life

Applied identical PFM models used in PTS re-evaluation

PFM solutions are sensitive to inclusion of WPS in model and treatment of thermal elastic material properties

PFM results are consistent with proposed new acceptance criteria (1.0e-6 failed RPVs per reactor operating year) for over 60 years (consistent with SRM-SECY-06-0124 on PTS Rulemaking Plan)

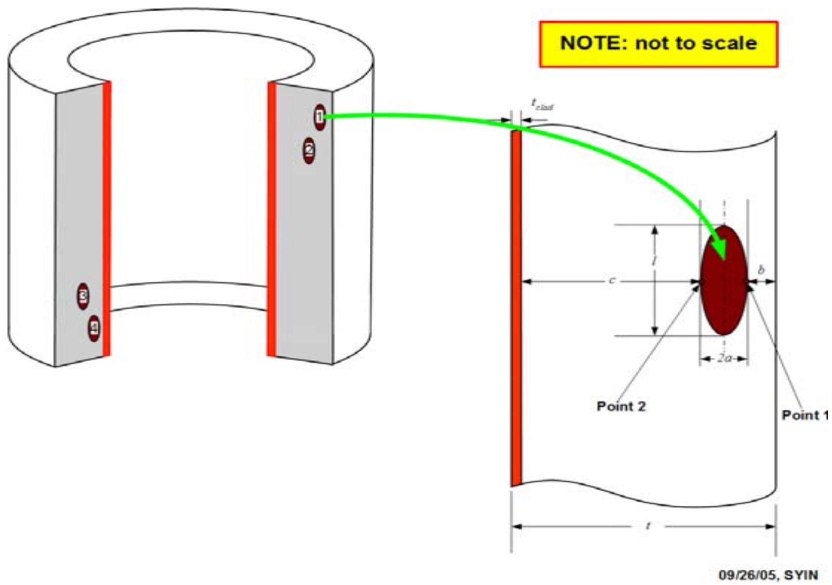
Additional PFM scoping analyses demonstrated current regulations can be relaxed without increasing risk

ORNL recently developed the FAVOR^{HT} to Calculate Crack Initiation Probabilities for Heat-Up Transients

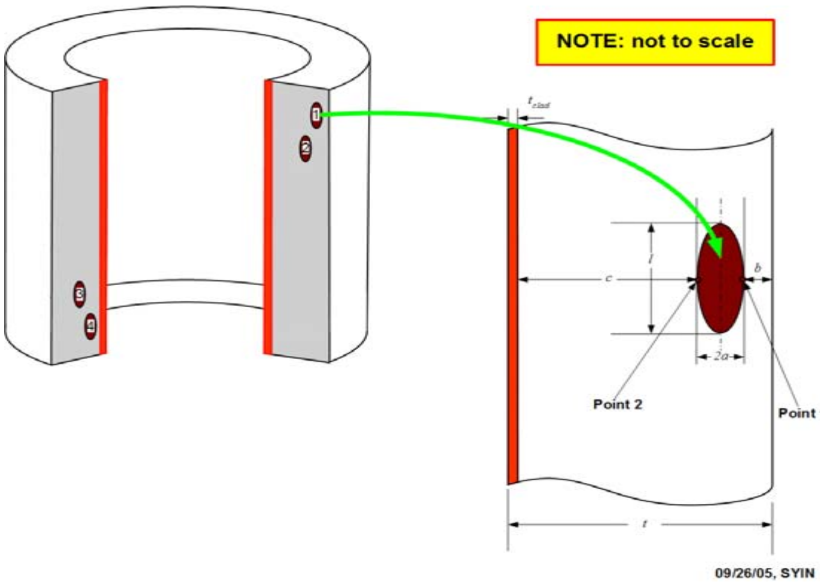
- During cool-down transients associated with reactor shutdown and PTS, tensile stresses tend to open existing cracks on or near the RPV inner surface
- During heat-up transients associated with reactor startup, tensile stresses tend to open existing cracks on or near the RPV outer surface
- Previous versions of FAVOR designed for analysis of cool-down transients (fracture mechanics of flaws on or near RPV inner surface)
- Therefore, a major requirement for the development of FAVOR^{HT} is to have a validated computational methodology for calculating applied K_I for embedded flaws near the RPV outer surface

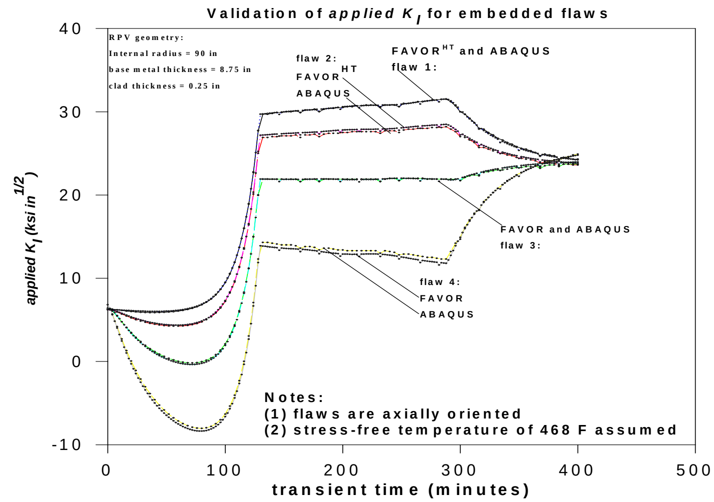
The methodology utilized by FAVOR for calculating the applied K_I for embedded flaws near the RPV inner surface has been adapted for calculating the applied K_I for embedded flaws in the outer half of the RPV wall

This is accomplished by resolving the nonlinear through-wall stress profile at each time step in a coordinate system that has its origin at the RPV outer surface, as opposed to the RPV inner surface, as is done when calculating the applied K_I solutions for embedded flaws in the inner half of the RPV (with respect to the wetted inner surface)



The adaptation of the methodology used by FAVOR (for calculating applied K_I for embedded flaws near the RPV inner surface) has been validated for calculating the applied K_I for embedded flaws close to the RPV outer surface by successfully comparing results with ABAQUS models

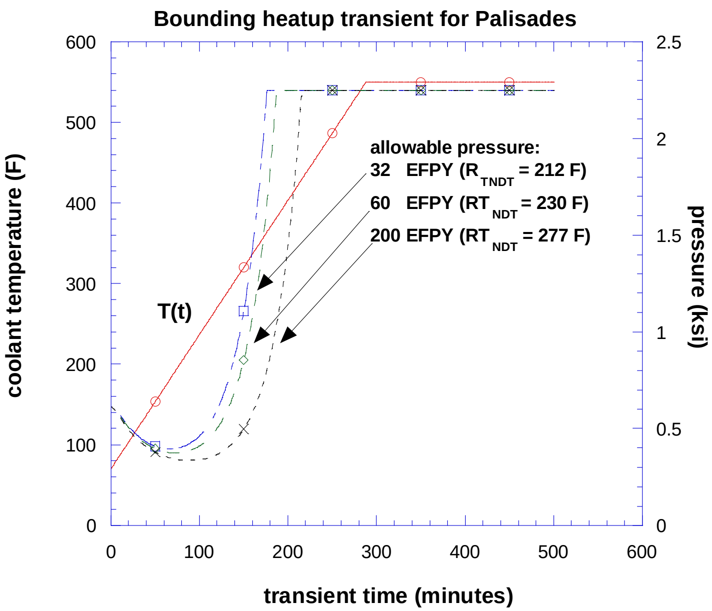




flaw model number	c (mm)	b (mm)	depth (2a) (mm)	length (mm)	largest difference in ABAQUS and FAVOR (ksi $in^{1/2}$)
1	189.55	12.7	20	80	0.18
2	126.05	76.2	20	80	0.35
3	69.85	132.4	20	80	0.27
4	6.35	195.9	20	80	0.53

PFM scoping studies for heatup transients performed with preliminary versions of FAVOR^{HT} indicate very small probability of cleavage fracture

Also, no ductile tearing, as initiating mechanism predicted



EFPY	*FAVHT CPI due to flaws in outer 3/8 t*	*FAVOR CPI due to flaws in inner 3/8 t*	**Total CPI**
32	0.0e+0	0.0e+0	0.0e+0
60	1.00e-10	0.0e+0	1.00e-10
200	7.94e-10	0.0e+0	7.94e-10

Flaws postulated to reside in inner 3/8 t analyzed with FAVOR code; flaws postulated to reside in outer 3/8 t analyzed with FAVOR^{HT} code.

All flaws postulated to have CPI > 0 resided in outer 3/8 t.