Review of Studies Regarding Risk-Informing Regulations for Normal Operating Transients

Terry Dickson
Computational Sciences and Engineering Division
Oak Ridge National Laboratory

Mark EricksonKirk
Office of Nuclear Regulatory Research
United States Nuclear Regulatory Commission

19th International Conference on Structural Mechanics in Reactor Technology (SMiRT)
August 2007 - Toronto, Canada

Overview of Presentation

- Statement of Objectives
- Current Regulations for Normal Operating Transients
- Cool-down transients associated with reactor shutdown

  (a) Currently bounding cool-down transients

  (b) Potential regulatory relaxations that ensure safety

  (c) Parameterized transients – more realistic conditions
- Heat-up transients associated with reactor start-up
- Conclusions

Overview of Presentation

- Statement of Objectives
- Current Regulations for Normal Operating Transients
- Cool-down transients associated with reactor shutdown

  (a) Currently bounding cool-down transients

  (b) Potential regulatory relaxations that ensure safety

  (c) Parameterized transients – more realistic conditions
- Heat-up transients associated with reactor start-up
- Conclusions

Objective: Derive a technical basis for a risk-informed revision of regulations for Normal Operating Transients

• Consistent with revision to the Pressurized Thermal Shock (Hypothetical Accident Transients) Regulations

• PTS - proposed new acceptance criteria of 1.0×10^{-6} failed RPV per reactor operating year

• Method – Perform PFM* analyses for normal transients

*Probabilistic Fracture Mechanics

Overview of Presentation

- Statement of Objectives
- Current Regulations for Normal Operating Transients
- Cool-down transients associated with reactor shutdown

  (a) Currently bounding cool-down transients

  (b) Potential regulatory relaxations that ensure safety

  (c) Parameterized transients – more realistic conditions
- Heat-up transients associated with reactor start-up
- Conclusions

The P-T curve is currently derived using ASME Section XI – Appendix G

(1) assumes a surface breaking flaw of depth equal to ¼ of the RPV wall

(2) includes a factor of 2 to account for sources of stress not included in the formulation

(3) maximum heat-up / cool-down rate of 100 °F /hr (56 °C /hr)

For a given cool-down transient

the allowable pressure is determined by:

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

where:

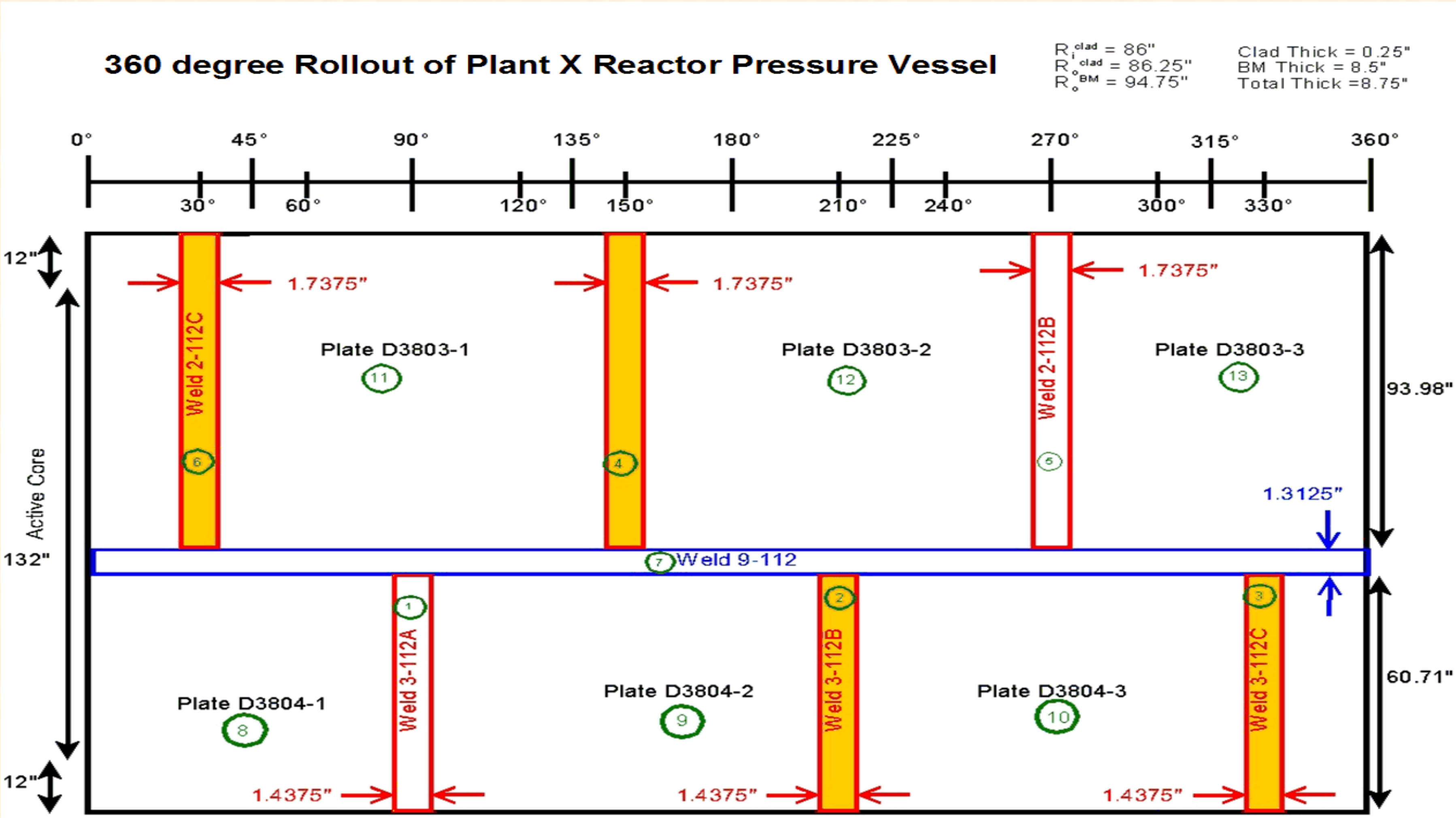
$K_{Ic}(t)$ is the ASME lower-bound crack initiation curve

$K_{IT}(t)$ is the thermally-induced stress intensity factor (t / 4 flaw)

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

Probabilistic Fracture Mechanics (PFM) analyses performed on Plant X

Note that all postulated flaws are embedded flaws



Overview of Presentation

- Statement of Objectives
- Current Regulations for Normal Operating Transients
- Cool-down transients associated with reactor shutdown

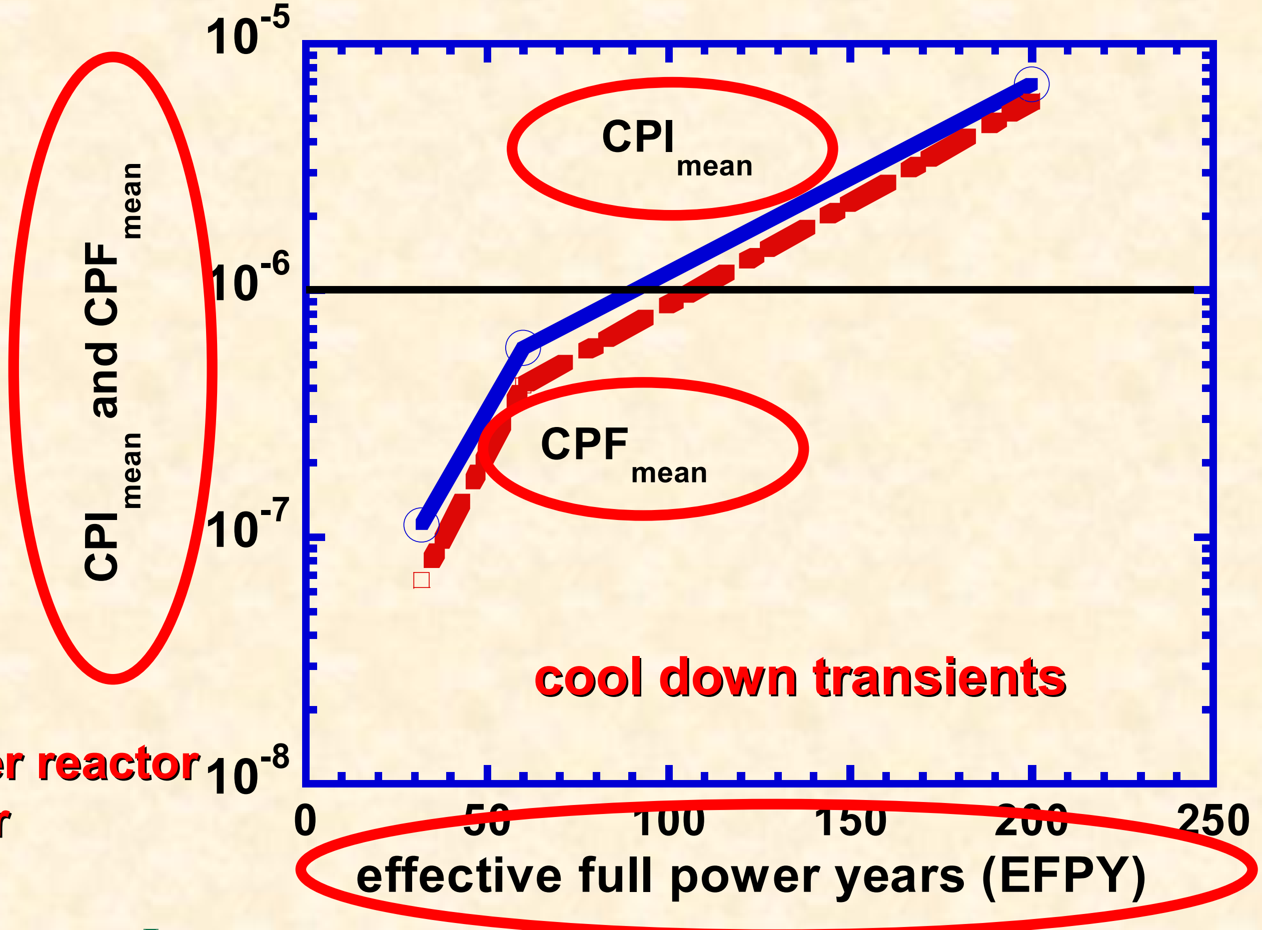
  (a) Currently bounding cool-down transients

  (b) Potential regulatory relaxations that ensure safety

  (c) Parameterized transients – more realistic conditions
- Heat-up transients associated with reactor start-up
- Conclusions

PFM results for bounding transients use the PTS acceptance criteria of $1.0x10^{-6}$*

(performed with 05.1 version of FAVOR)



*failed RPV per reactor operating year

Overview of Presentation

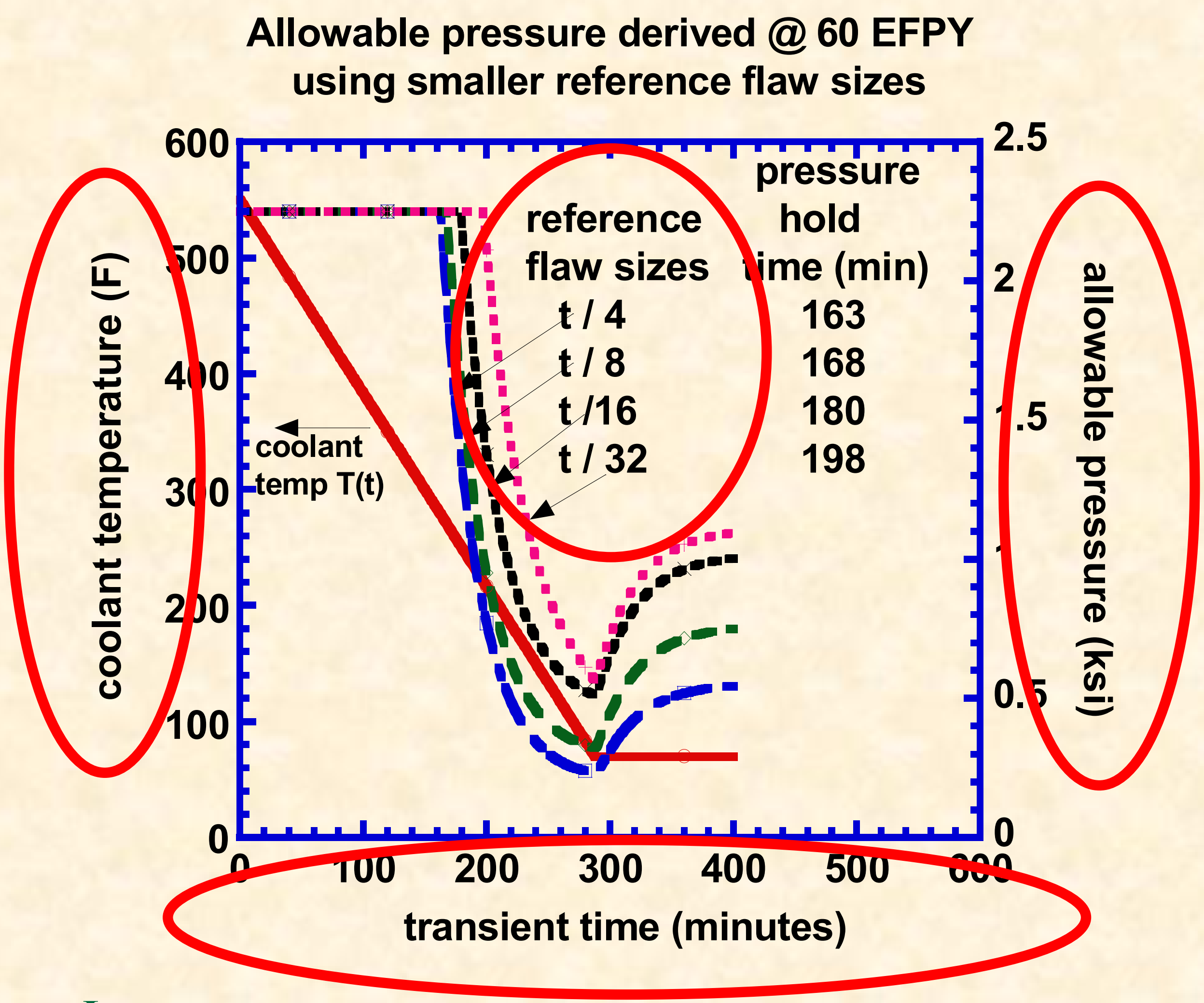
- Statement of Objectives
- Current Regulations for Normal Operating Transients
- Cool-down transients associated with reactor shutdown

  (a) Currently bounding cool-down transients

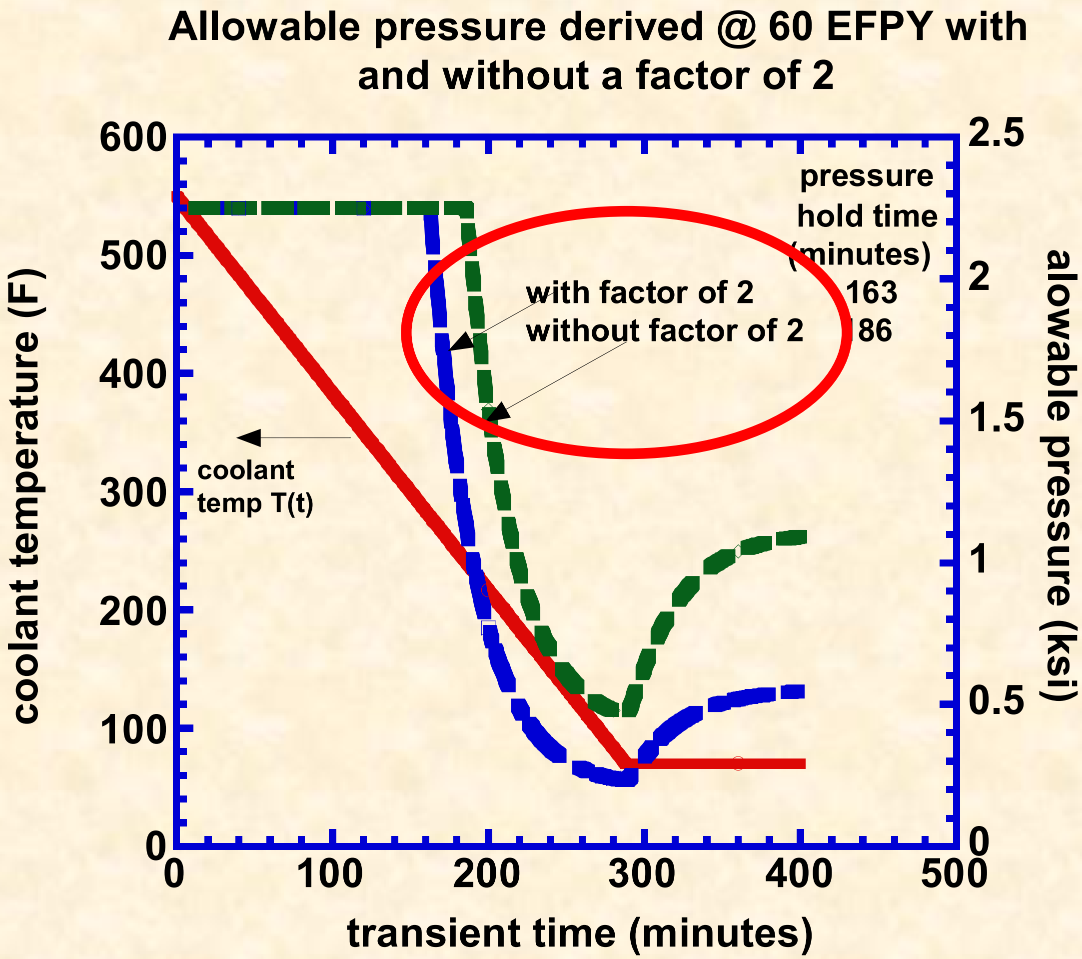
  (b) Potential regulatory relaxations that ensure safety

  (c) Parameterized transients – more realistic conditions
- Heat-up transients associated with reactor start-up
- Conclusions

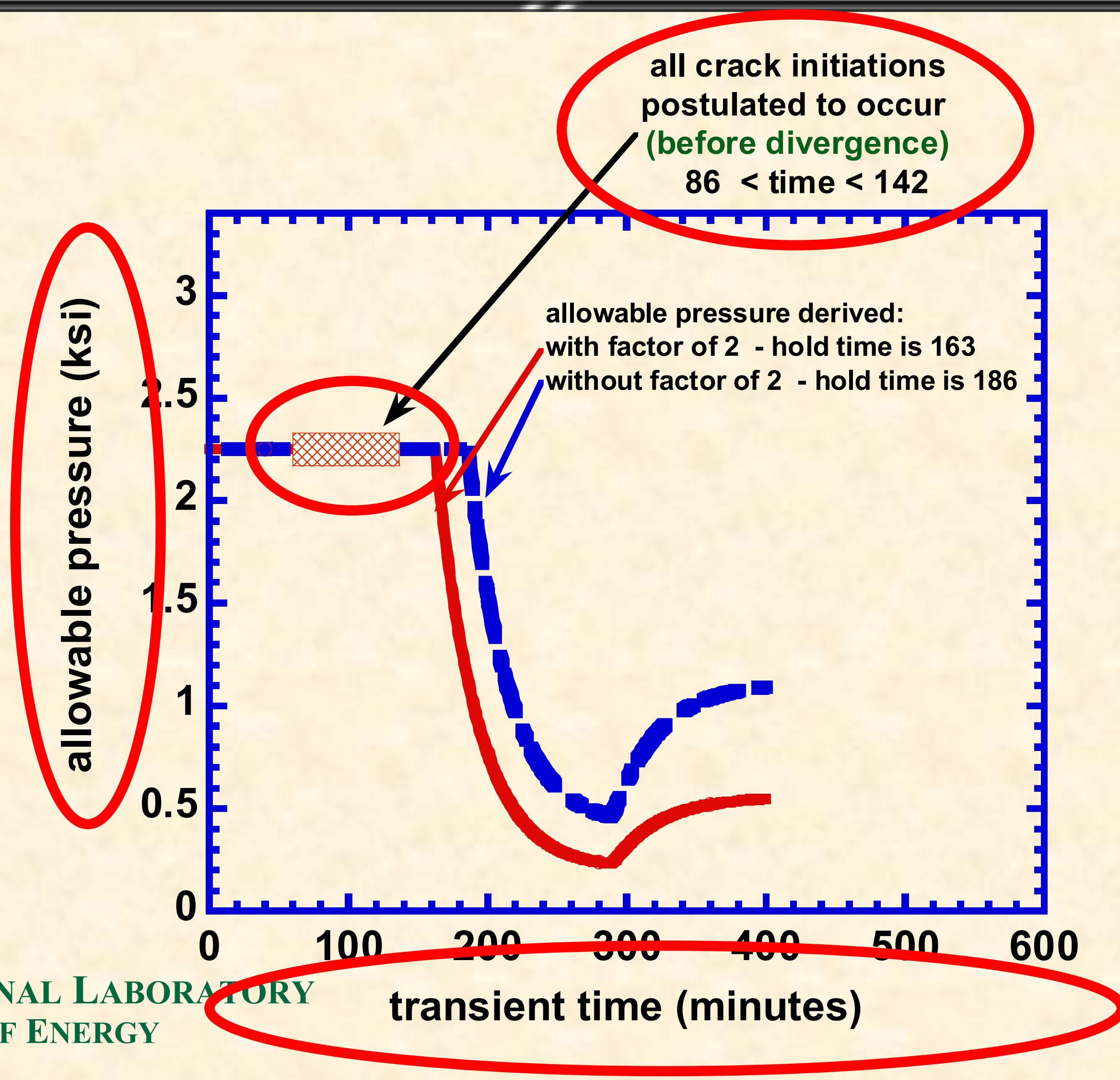
PFM analyses were performed to determine impact of smaller reference flaw sizes in the derivation of allowable pressure



PFM analyses were performed to determine impact of removing factor of 2 in the derivation of allowable pressure



These Simplified Relaxations do not Impact PFM Solutions; therefore, Do Not Increase the Calculated CPI or CPF.



Overview of Presentation

- Statement of Objectives
- Current Regulations for Normal Operating Transients
- Cool-down transients associated with reactor shutdown

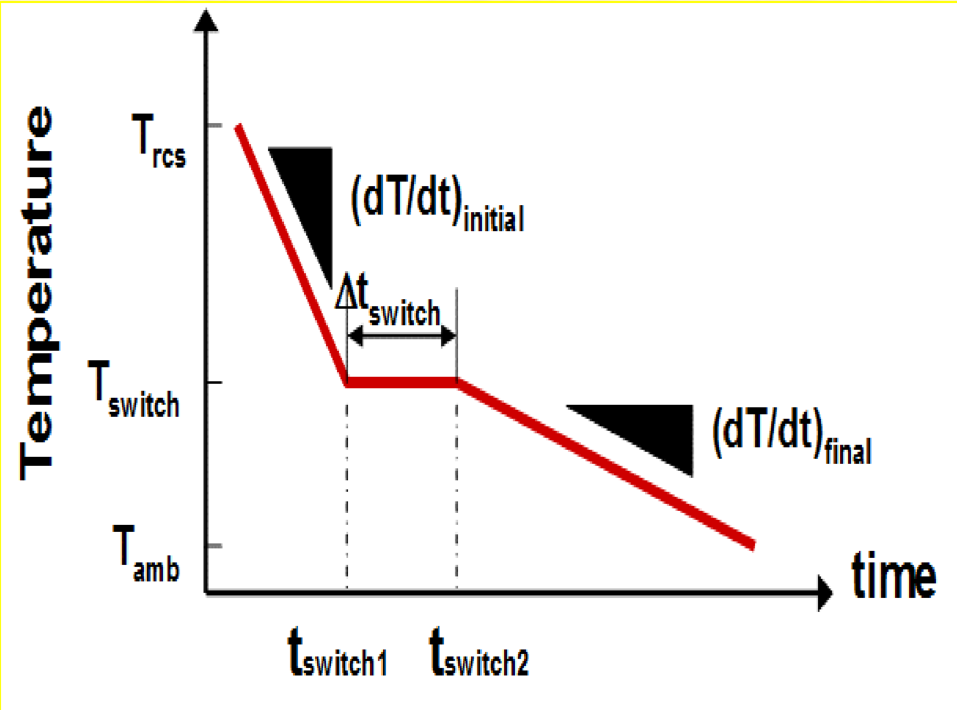
  (a) Currently bounding cool-down transients

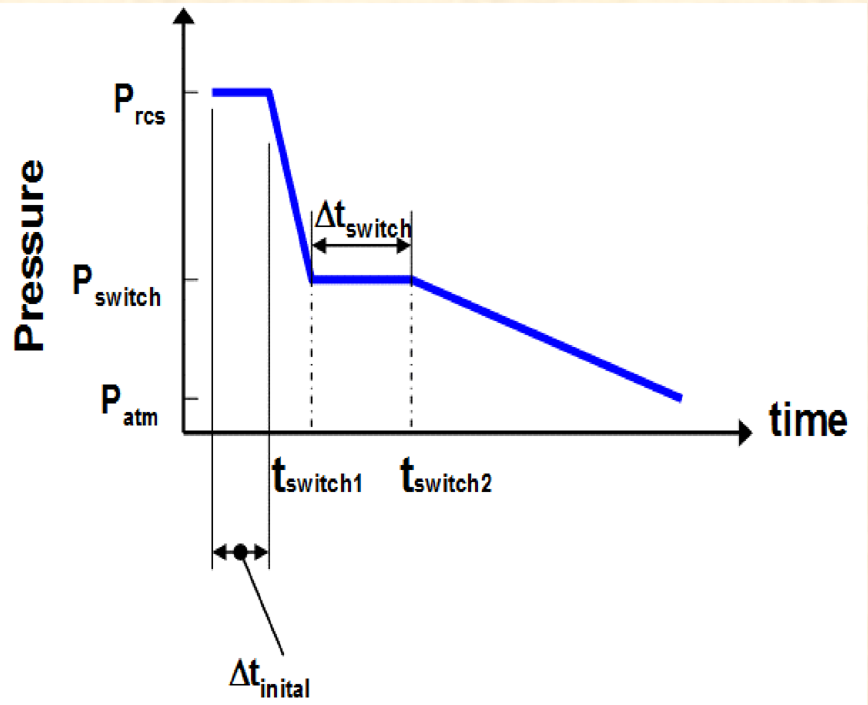
  (b) Potential regulatory relaxations that ensure safety

  (c) Parameterized transients – more realistic conditions
- Heat-up transients associated with reactor start-up
- Conclusions

Cool-down transients associated with reactor shutdown were parameterized in terms of several variables

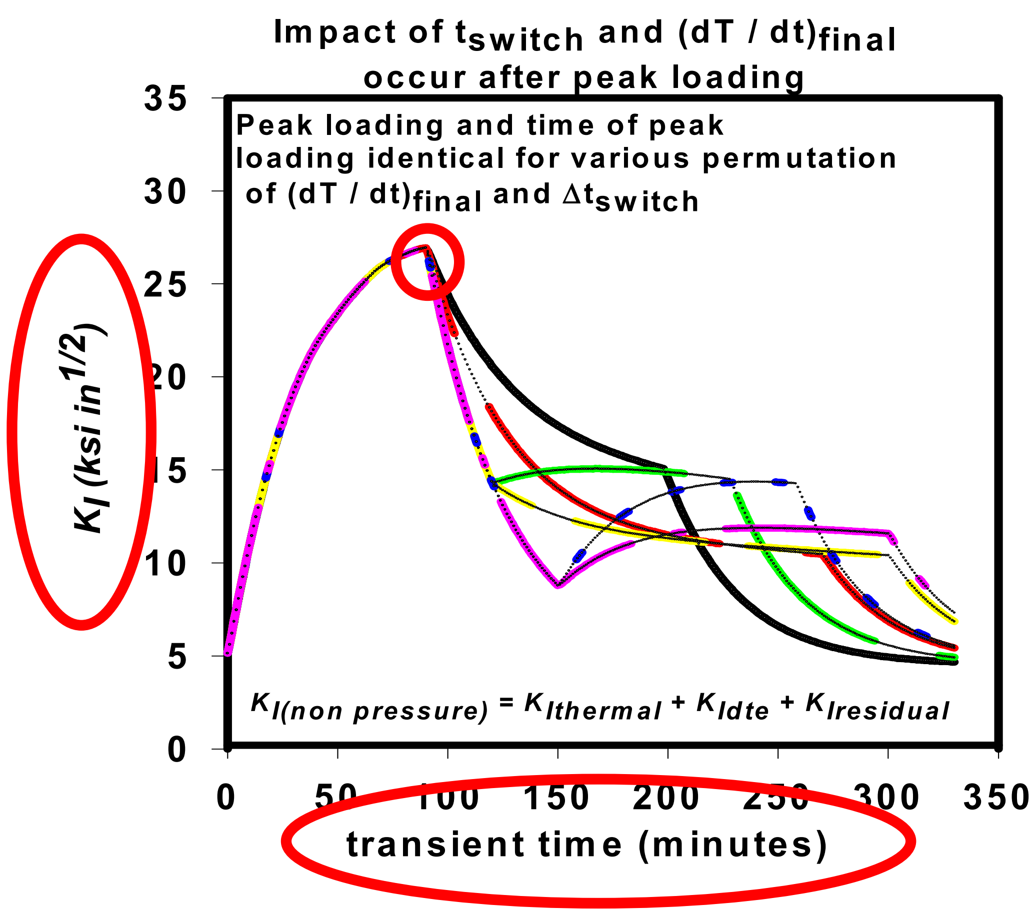
- cool-down rates: $\{(dT/dt)_{initial}$, $(dT/dt)_{final}\}$,
- plateau temperature and pressure $\{(T_{switch})$, $P_{switch})\}$,
- time duration pressure and temperature remain at plateau (Δt_{switch}),
- pressure hold time $\Delta t_{initial}$





PFM solutions are invariant with respect to Δt_{switch} and $(dT / dt)_{final}$ when warm prestress is included in the model

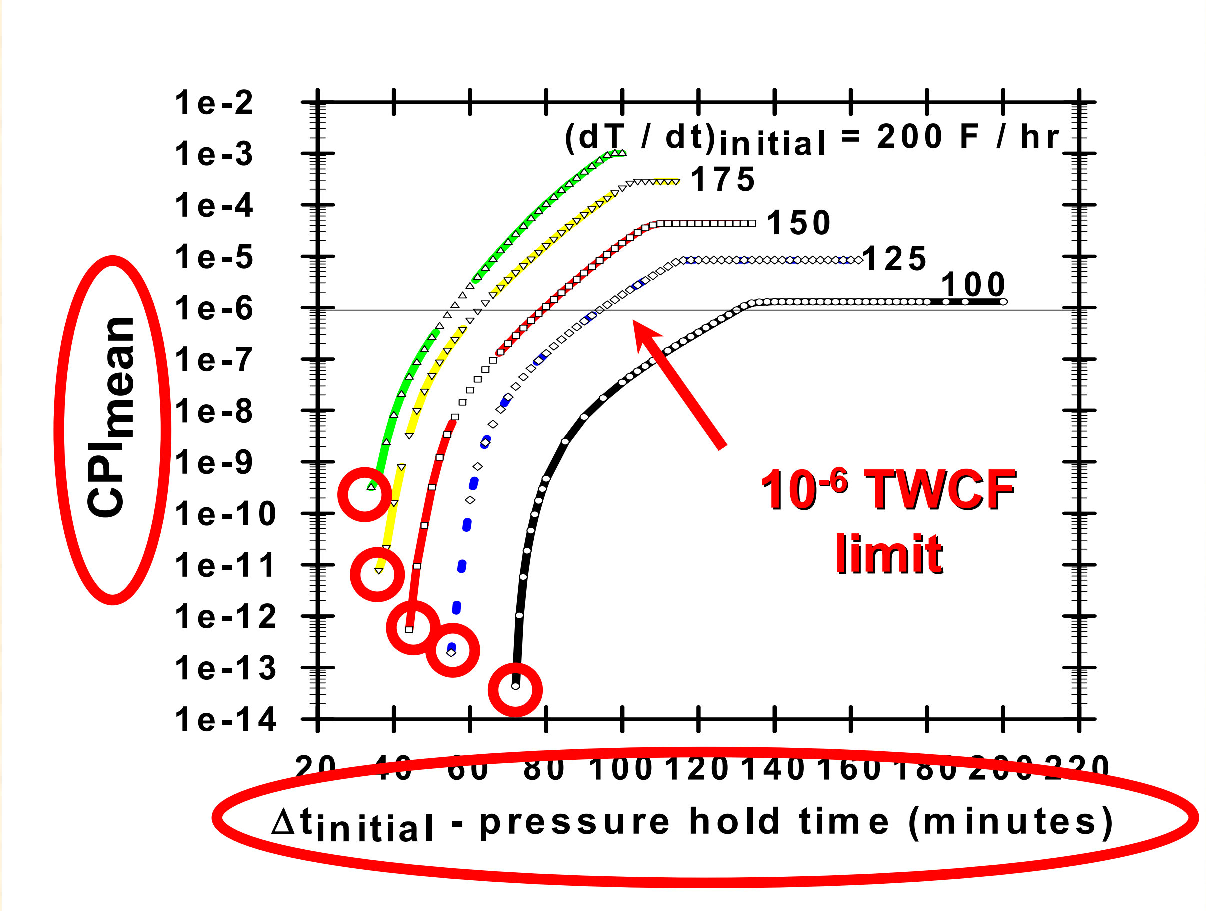
effects of Δt_{switch} and $(dT/dt)_{final}$ occur after the time of peak loading



PFM analyses were performed with FAVOR 06.1 for Plant X @ 60 EFPY for a range of cool-down scenarios

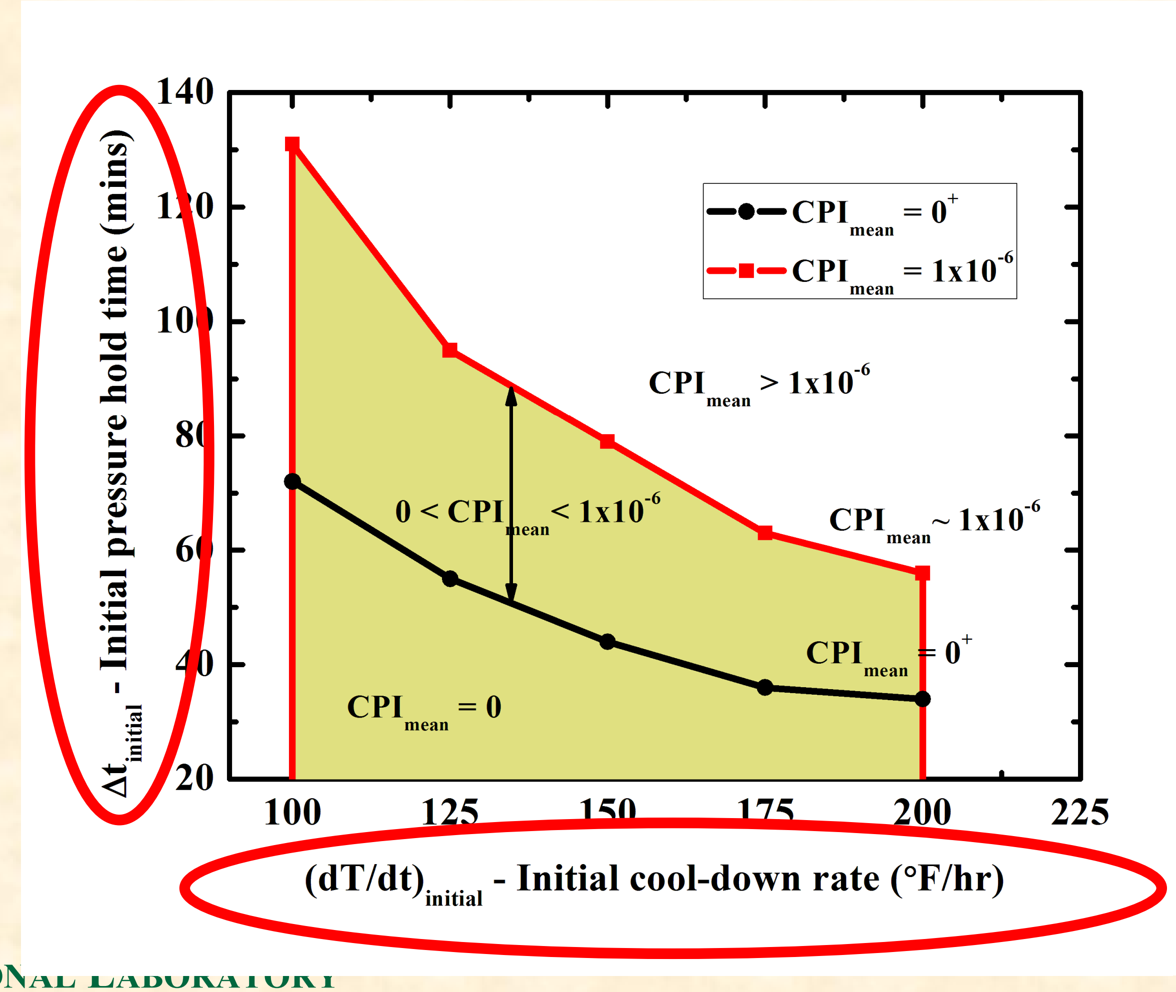
$(dT/dt)_{initial}$ = 100 to 200 °F (56 to 111 °C) / hr ; P_{switch} = 0.40 ksi (2.8 MPa)

over a range of pressure hold time $\Delta t_{initial}$



PFM results can be applied to determine a range of parameters that satisfy TWCF limit (10^{-6})

Initial cooling rates exceeding current limit of 100 °F / hr can be allowed if restrictions are placed on pressure hold time



Overview of Presentation

- Statement of Objectives
- Current Regulations for Normal Operating Transients
- Cool-down transients associated with reactor shutdown

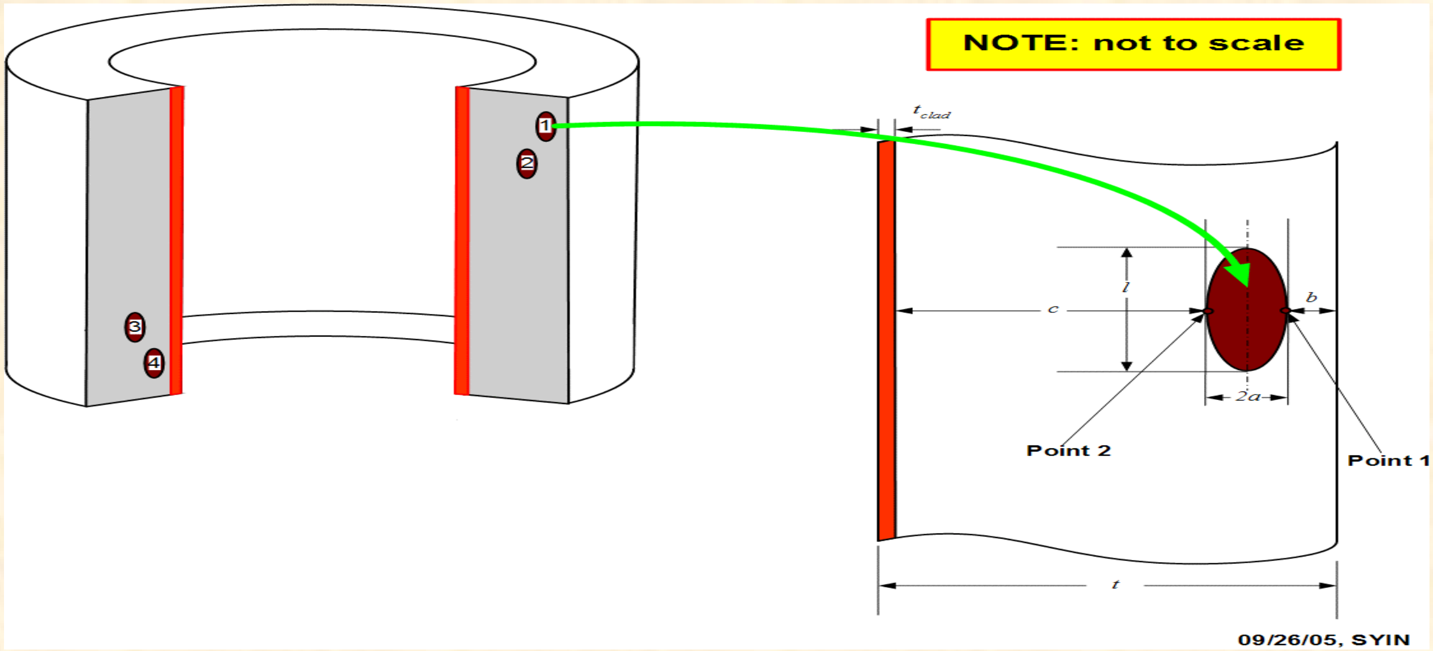
  (a) Currently bounding cool-down transients

  (b) Potential regulatory relaxations that ensure safety

  (c) Parameterized transients – more realistic conditions
- Heat-up transients associated with reactor start-up
- Conclusions

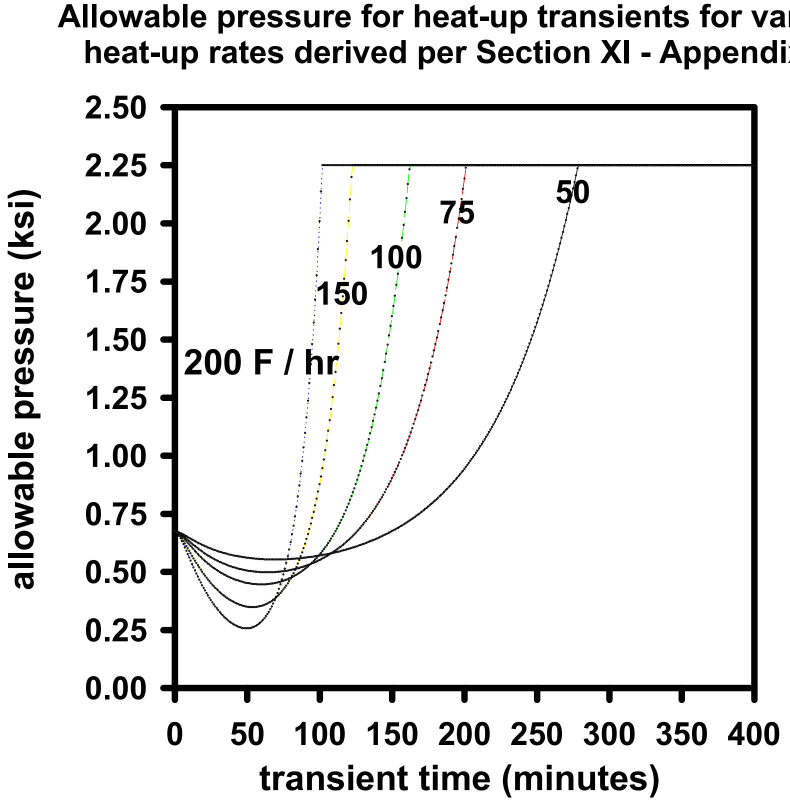
FAVOR^{HT} was Developed to Perform Fracture Analyses of Heat-Up Transients (such as those associated with reactor start-up)

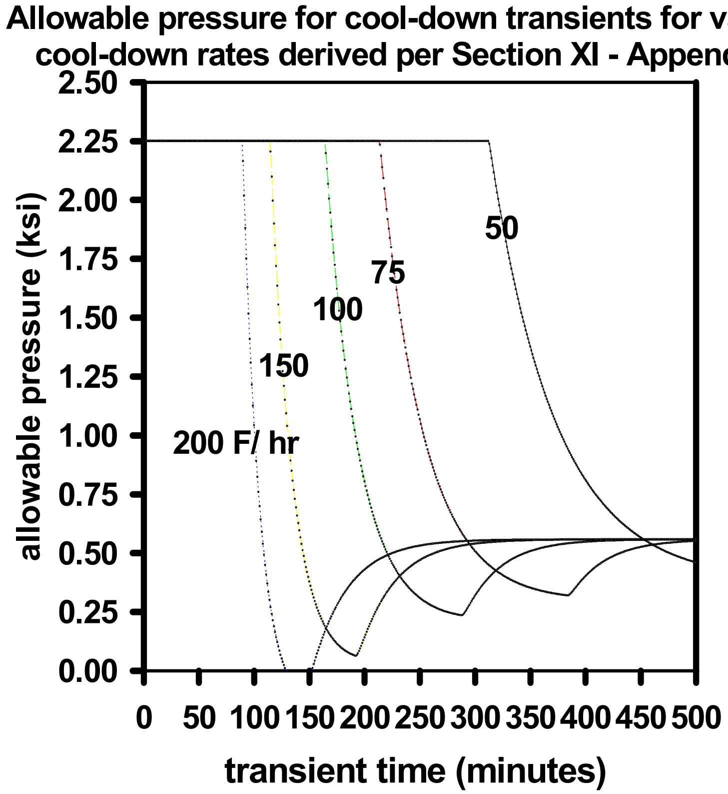
- Previous versions of **FAVOR designed for** analysis of cool-down transients (fracture analyses of **flaws on or near RPV inner surface**)
- **FAVOR^{HT} designed for** analysis of heat-up transients (fracture analyses of embedded **flaws near RPV outer surface**)



PFM analyses were performed for Plant X @ 60 EFPY for a range of heat-up and cool-down rates

- •FAVOR 06.1 used for cool-down transients
- •FAVOR^{HT} 06.1 used for heat-up transients



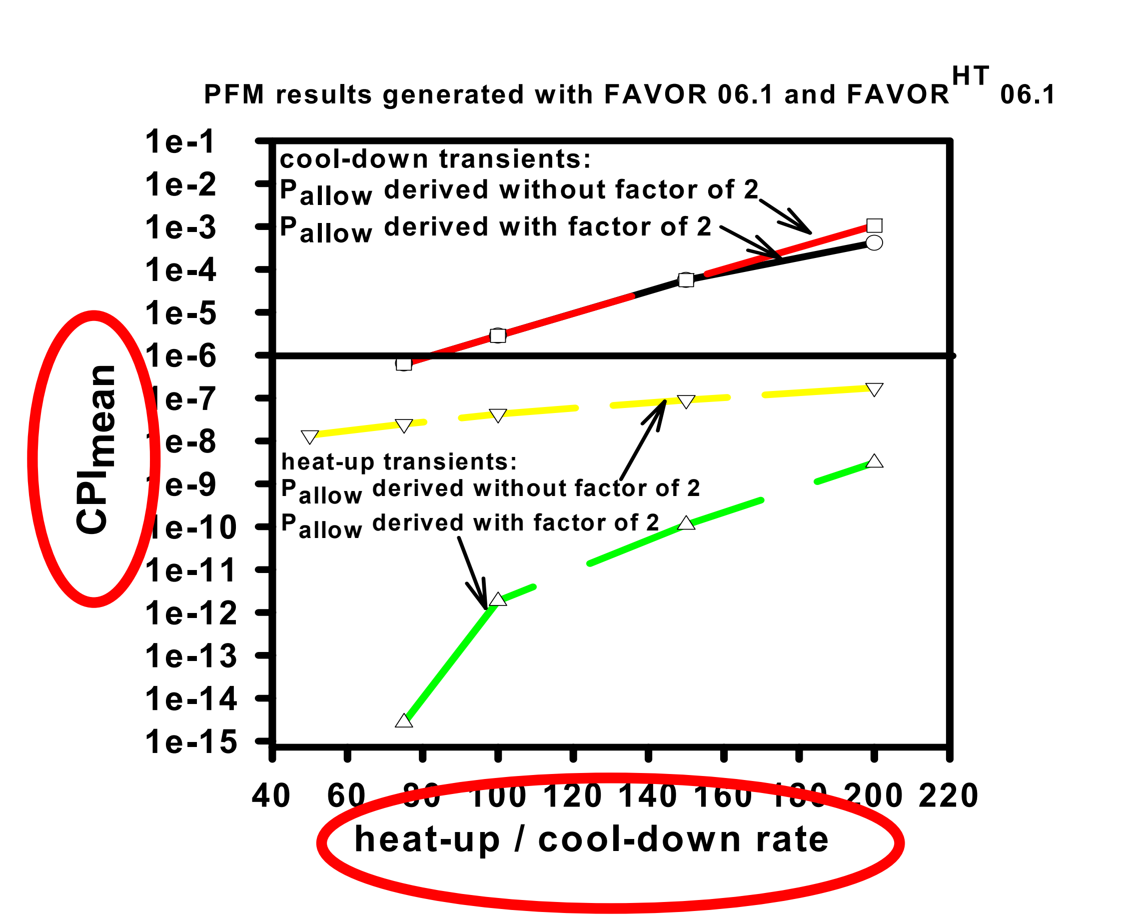


PFM results for heat-up transients are orders of magnitude lower compared to comparable cool-down transients

For heat-up transients:

(1) the removal of the factor of 2 significantly increases CPI_{mean}

(2) PFM solutions are not sensitive to inclusion of WPS



Conclusions
(Based on our Analyses of Plant X @ 60 EFPY)

(1) PFM analyses for "currently bounding" cool-down transients satisfy the TWCF limit used for PTS of 10^{-6}

(2) For cool-down transients, our calculations indicate that neither of the following changes increase risk
   (1) Removing the factor of two on pressure
   (2) Using a smaller reference flaw size

(3) Initial cooling rates exceeding the current maximum of 100 °F / hr can remain below the 10^{-6} limit if the initial pressure hold time is restricted

(4) There is potential to develop parametric relationships that satisfy risk-informed criteria for normal cool-down transients.

(5) Risk associated with reactor heat-up transients are orders of magnitude lower than that for comparable cool-down transients