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

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NRC / Nuclear Industry Representative meeting
August 21, 2008 - Rockville, Maryland

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

  (d) Inclusion of Inner Surface Breaking Flaws
- Heat-up transients associated with reactor start-up
- Conclusions and what's next

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

  Note: Risk acceptance criteria has not yet been agreed to by staff for routine heat up and cool-down transients. Factors to consider include (a) definition of "failure," and (b) tolerable frequency

- Method – Perform PFM* analyses for normal transients

*Probabilistic Fracture Mechanics Application of latest version of FAVOR

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**

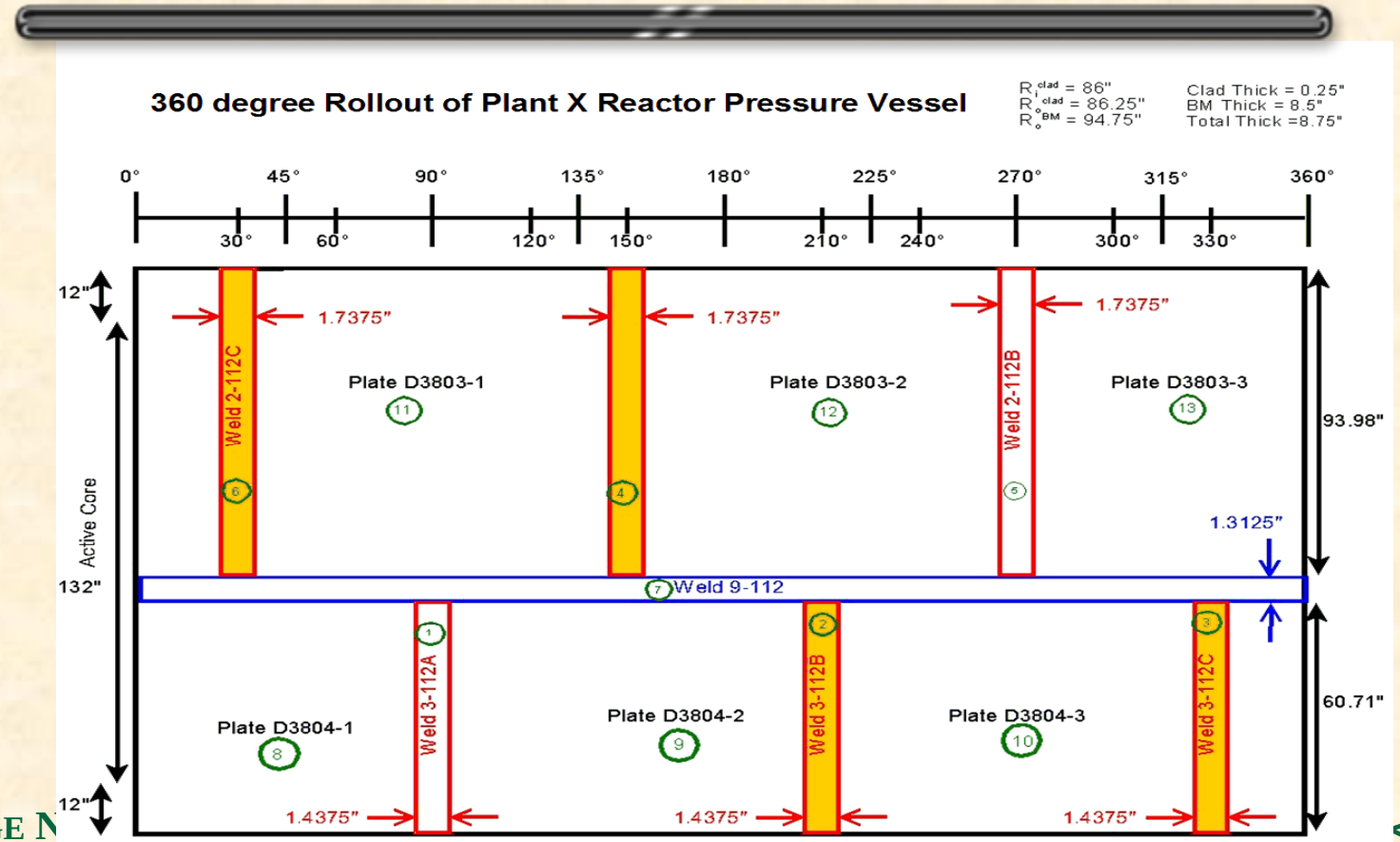
$K_{IT}(t)$ **is the thermally-induced stress intensity factor (t / 4 flaw)**

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

All PFM analyses for normal cool-down transients thus far (previous and current publications) were performed on Plant X using neutron fluence maps that correspond to 60 EFPY

RPV discretized into over 60 K subregions to accommodate azimuthal and axial variations in neutron fluence

Each RPV in Monte Carlo PFM analysis postulated to have approximately 5700 embedded flaws uniformly distributed though the first 3/8 of the base metal



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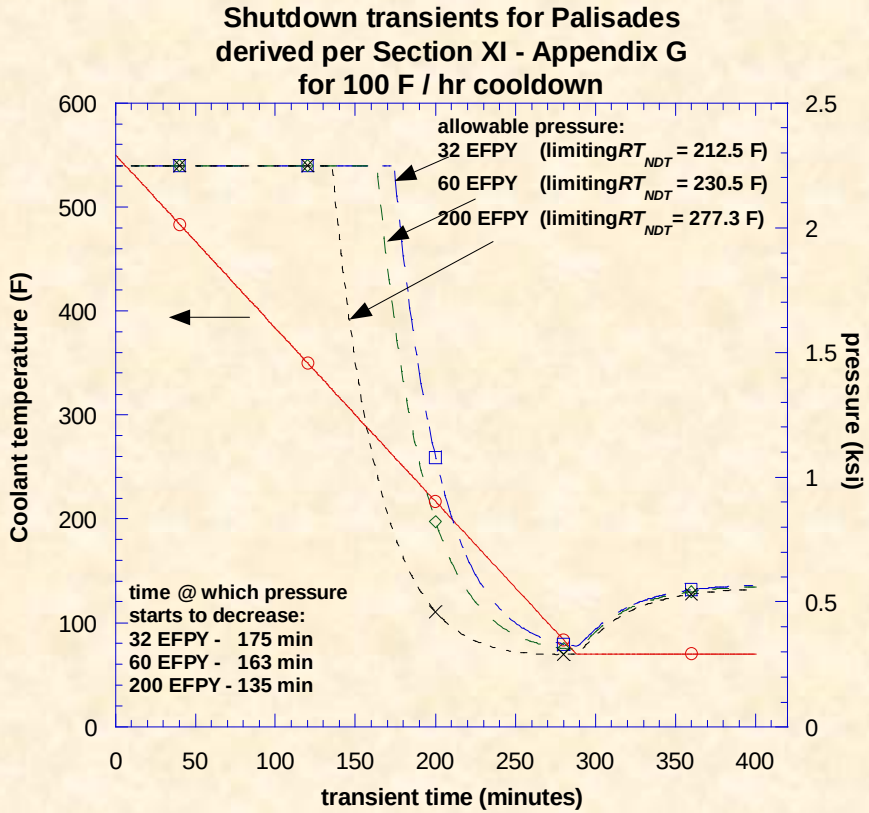
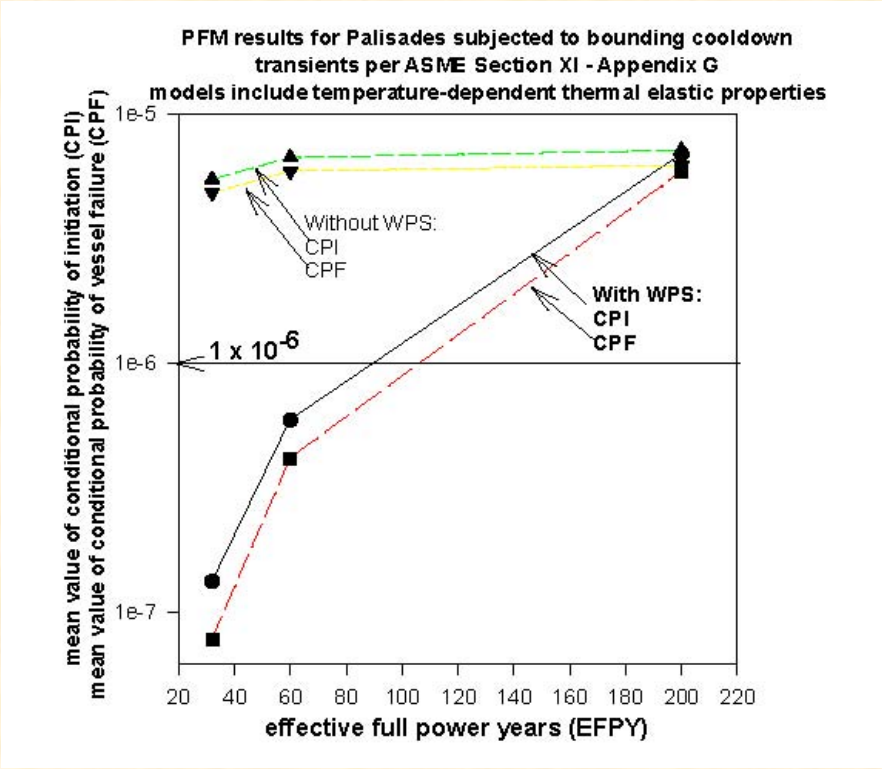
Scoping PFM analysis results for bounding cool-down transients are in compliance with proposed new acceptance criteria (for PTS) of 1.0e-6 failed RPVs per reactor operating year for over 60 EFPY

(when model includes WPS)

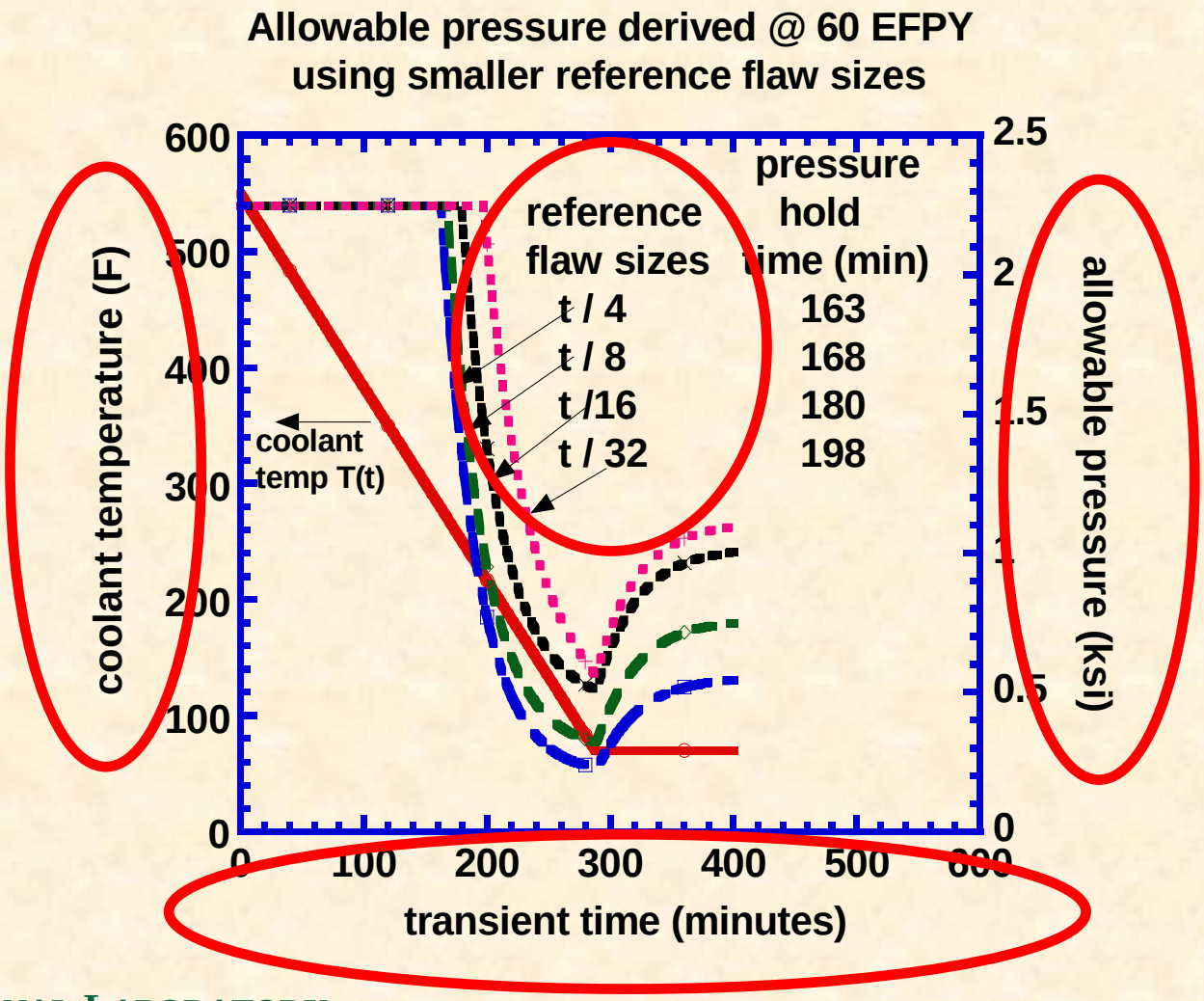
Bounding cool-down transients for Palisades per Section – XI Appendix G



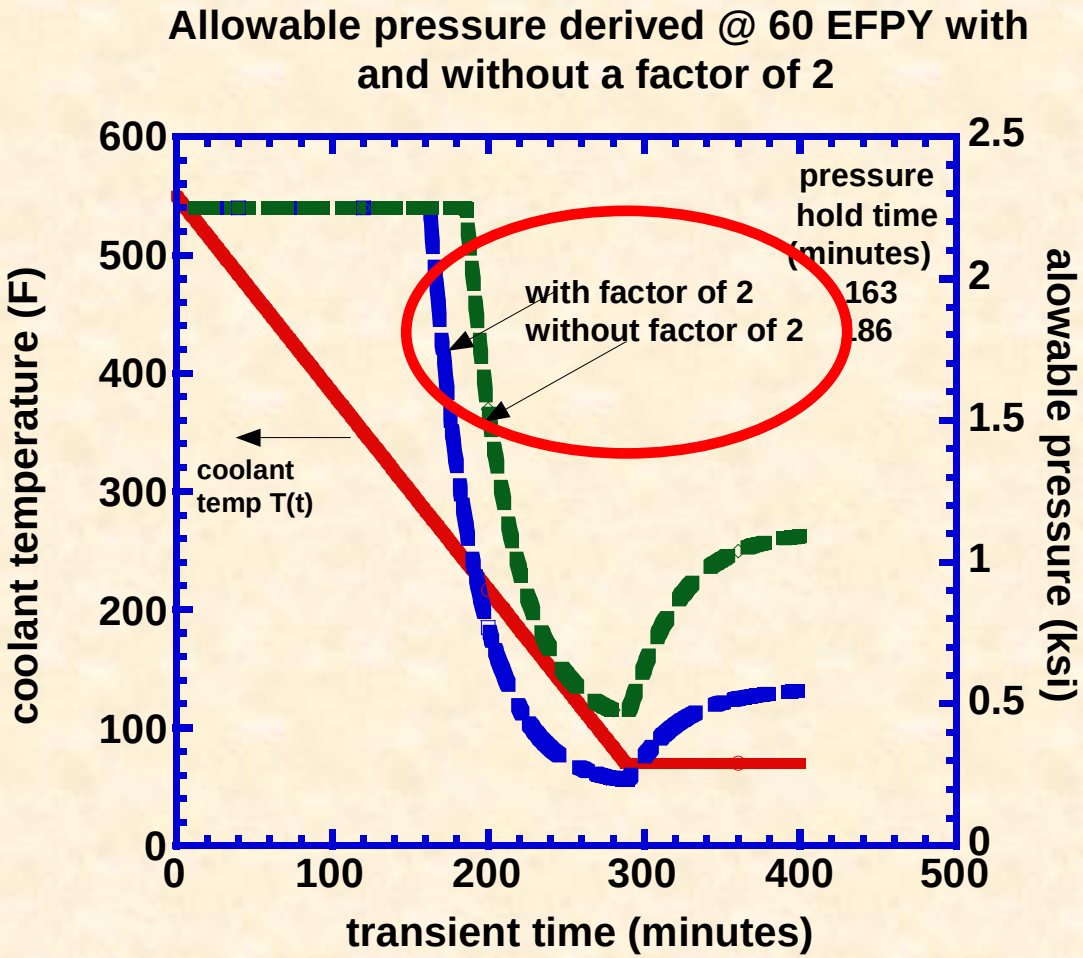
CPI and CPF computed with and without WPS:



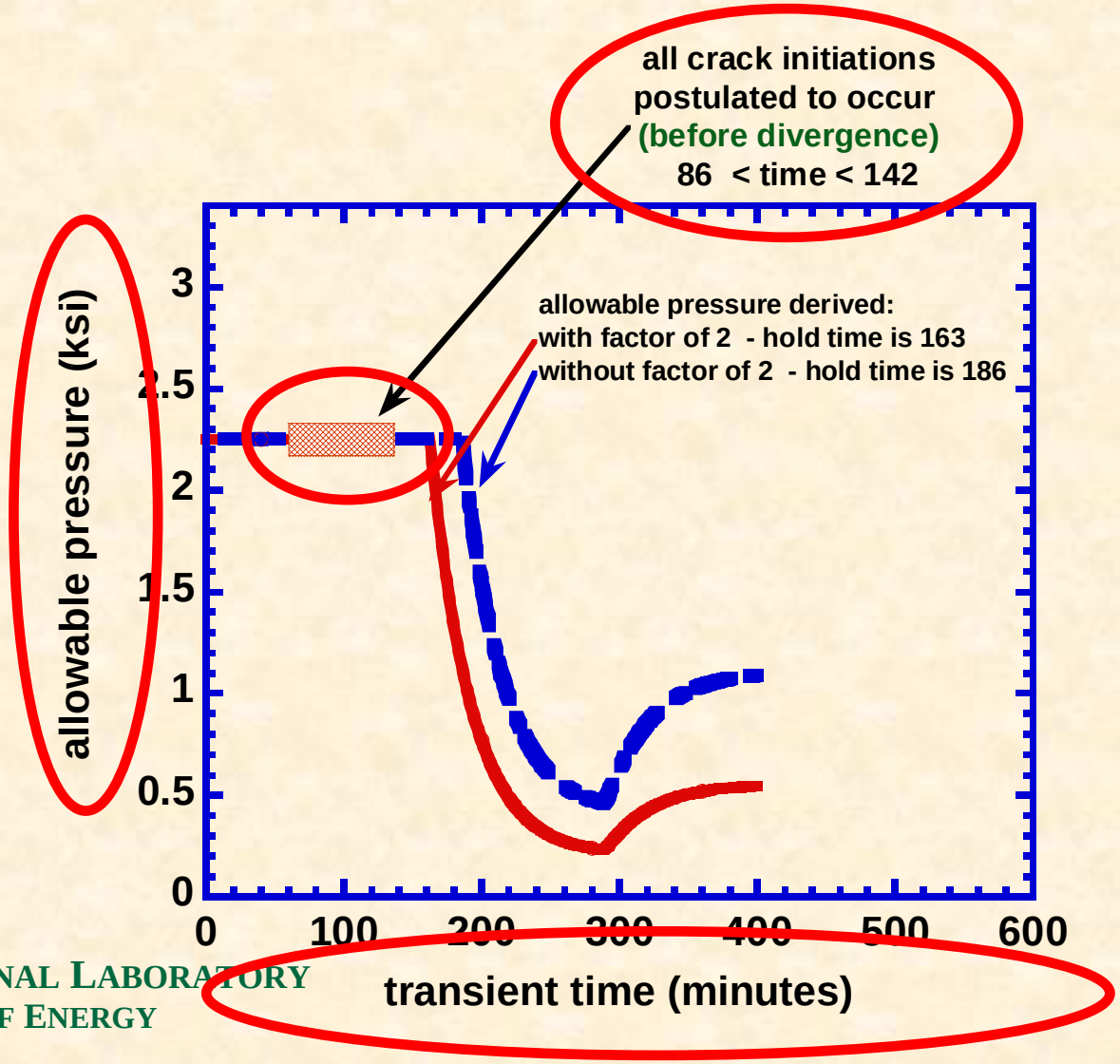
PFM analyses were performed to determine impact of smaller reference flaw sizes in the derivation of allowable pressure



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; all predicted crack initiations and failures occur before transients diverge



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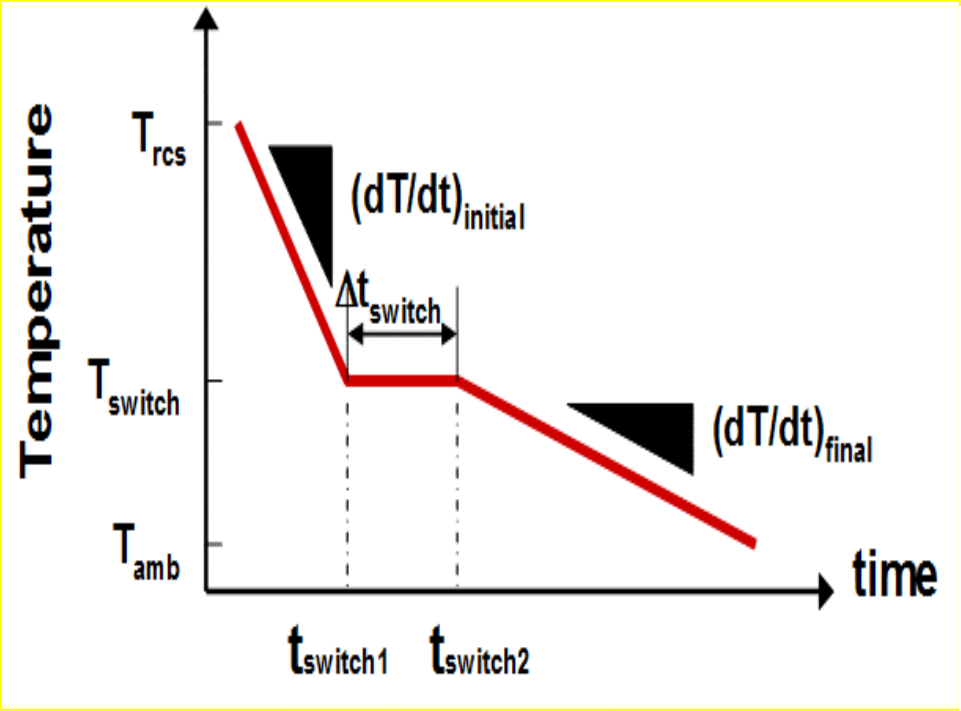
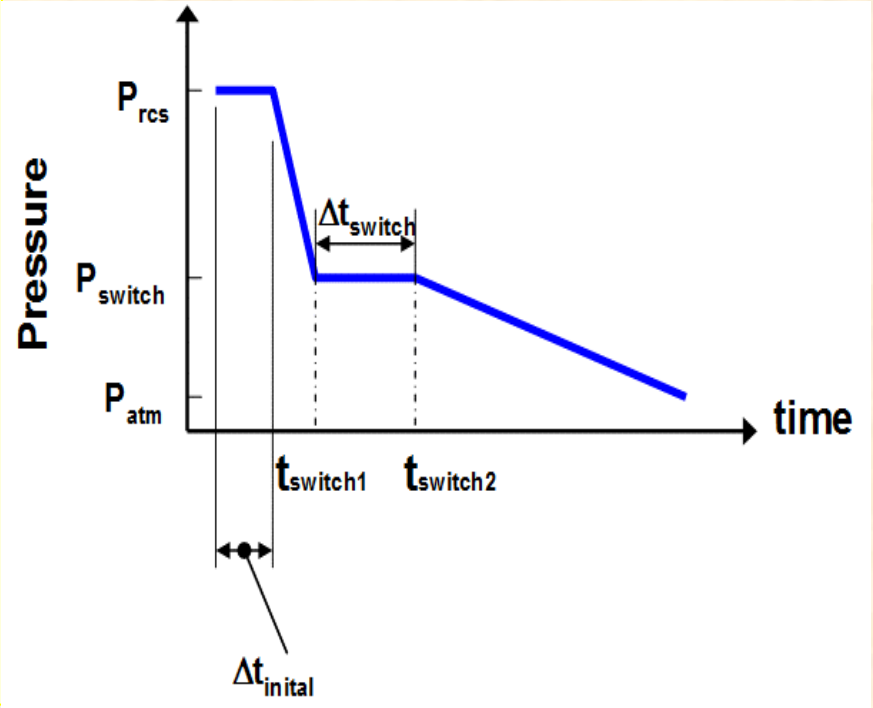
Cool-down transients associated with reactor shutdown were parameterized in terms of several variables

- 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 $\Delta t_{initial}$





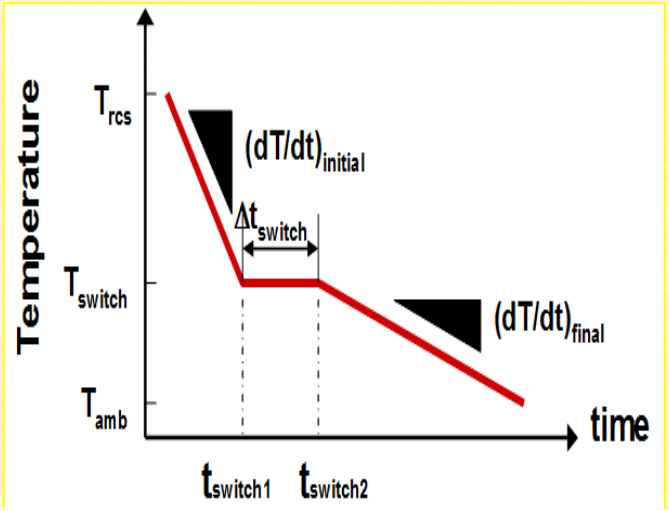
Review of results and subsequent conclusions from previous PFM analyses / publications* of parameterized cool-down transients associated with reactor shutdown

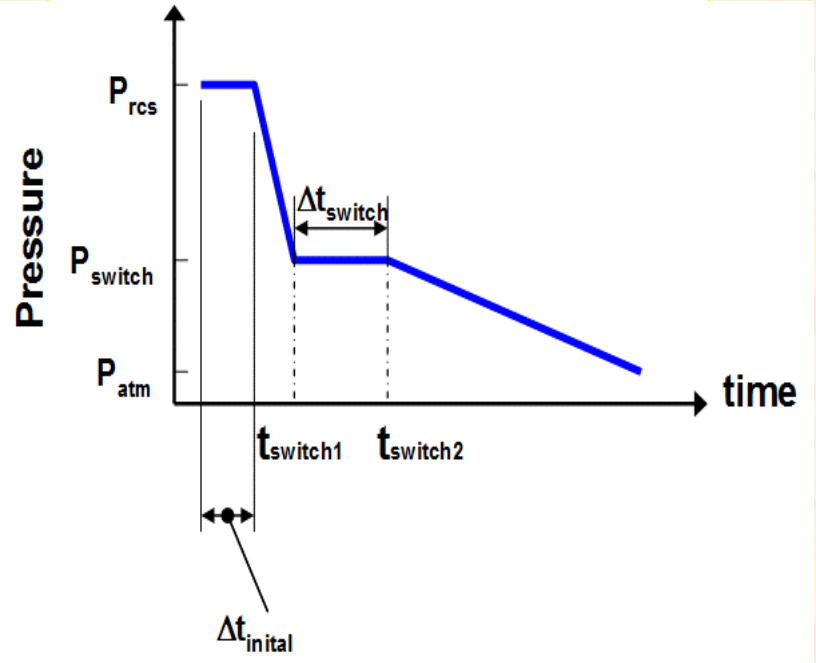
* Dickson, T.L. and EricksonKirk, M.T., **Scoping Analyses of Parameterized Cool- Down Transients Associated with Reactor Shutdown**, Paper number PVP2007-26865, Proceedings of 2007 ASME Pressure Vessels and Piping Division Conference July 22-26, 2007, San Antonio, Texas.

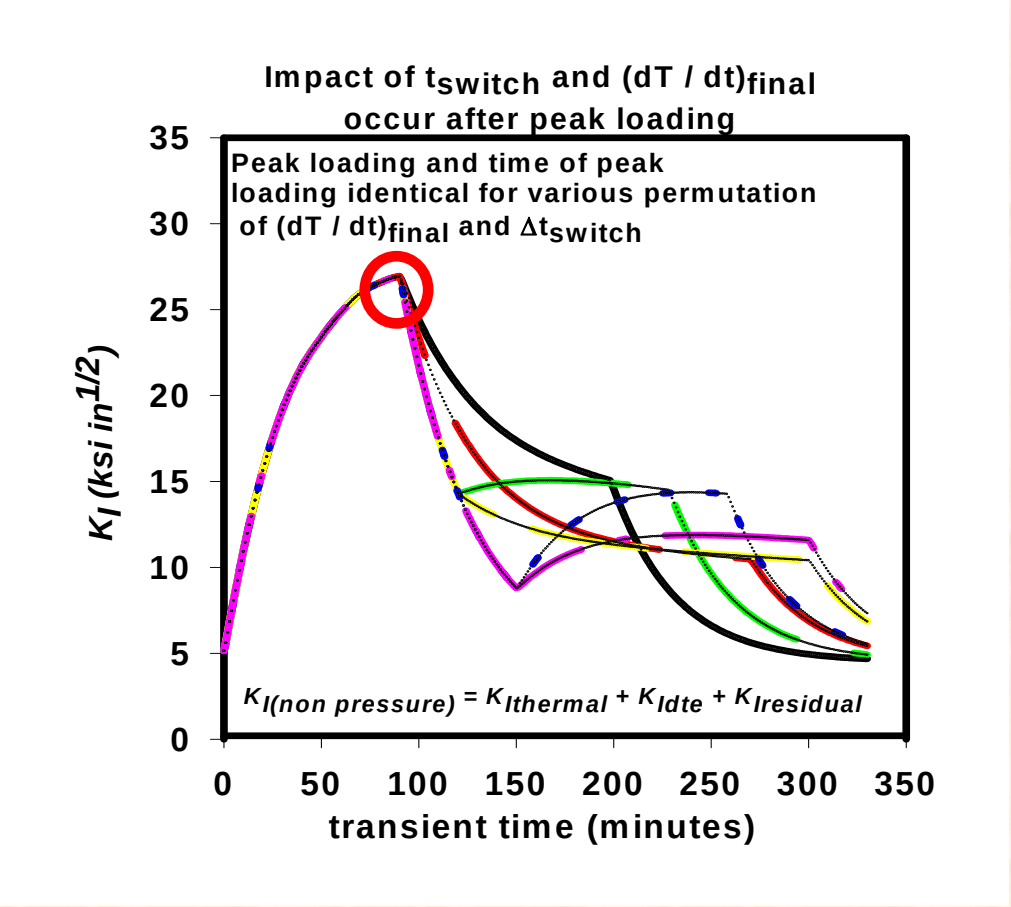
- Dickson, T.L. and EricksonKirk, M.T., **Review of Studies Regarding Risk-Informing Regulations for Normal Operating Transients**, Paper number G02/1, Proceedings of the 19th Structural Mechanics in Reactor Technology (SMiRT) Conference, August 2007, Toronto, Canada.
- Dickson, T.L. and EricksonKirk, M.T., ***The Inclusion of Inner Surface Breaking Flaws in Probabilistic Fracture Mechanics Analyses of Reactor Vessels Subjected to Planned Normal Cool-Down Transients****, Paper number PVP2008-61392,* Proceedings of 2008 ASME Pressure Vessels and Piping Division Conference July, 2008, Chicago, Texas.

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







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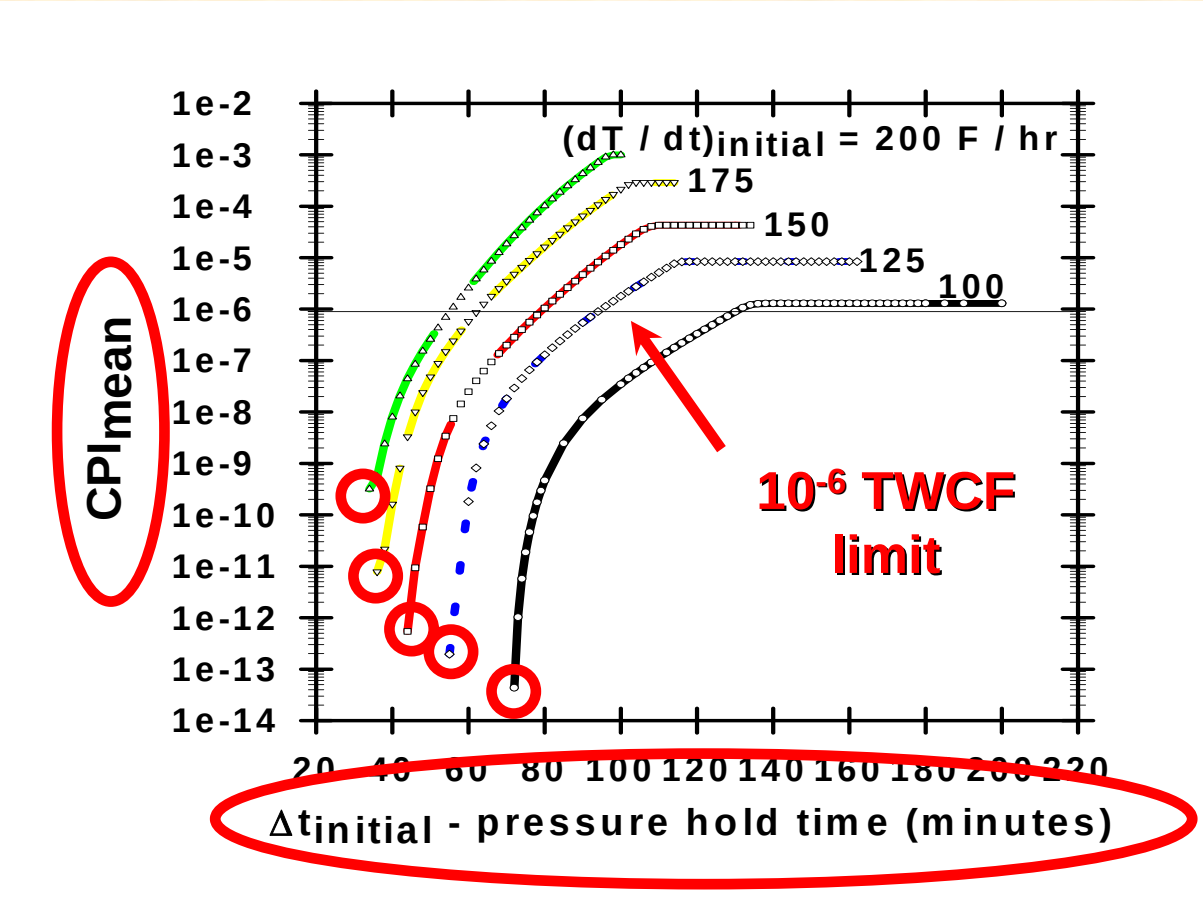
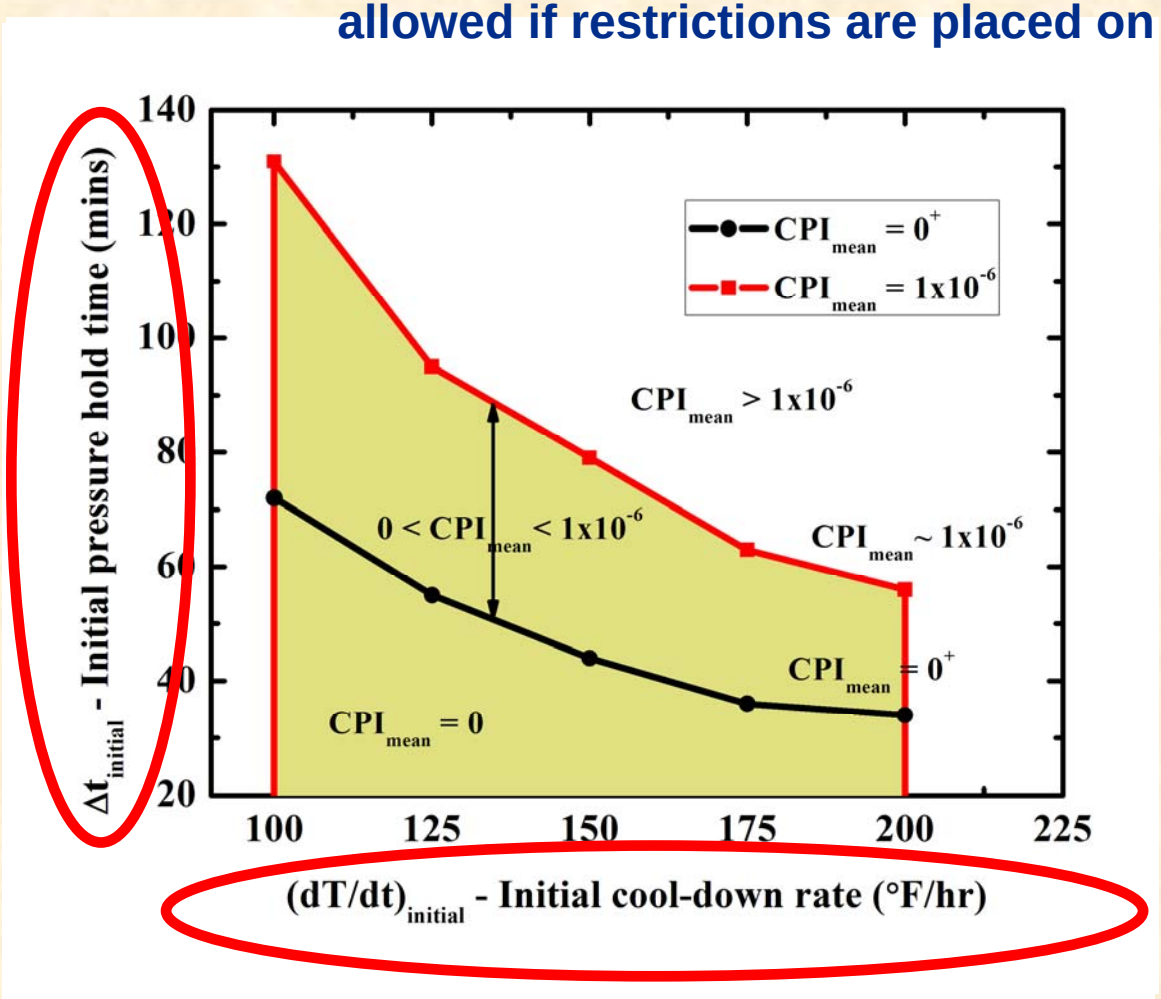
PFM analyses were performed with FAVOR 06.1 for Plant X @ 60 EFPY for a range of cool-down scenarios

$(dT/dt)_{initial}$ = 100 to 200 °F (56 to 111 °C) / hr ; P_{switch} = 0.40 ksi (2.8 MPa) over a range of pressure hold time $\Delta t_{initial}$



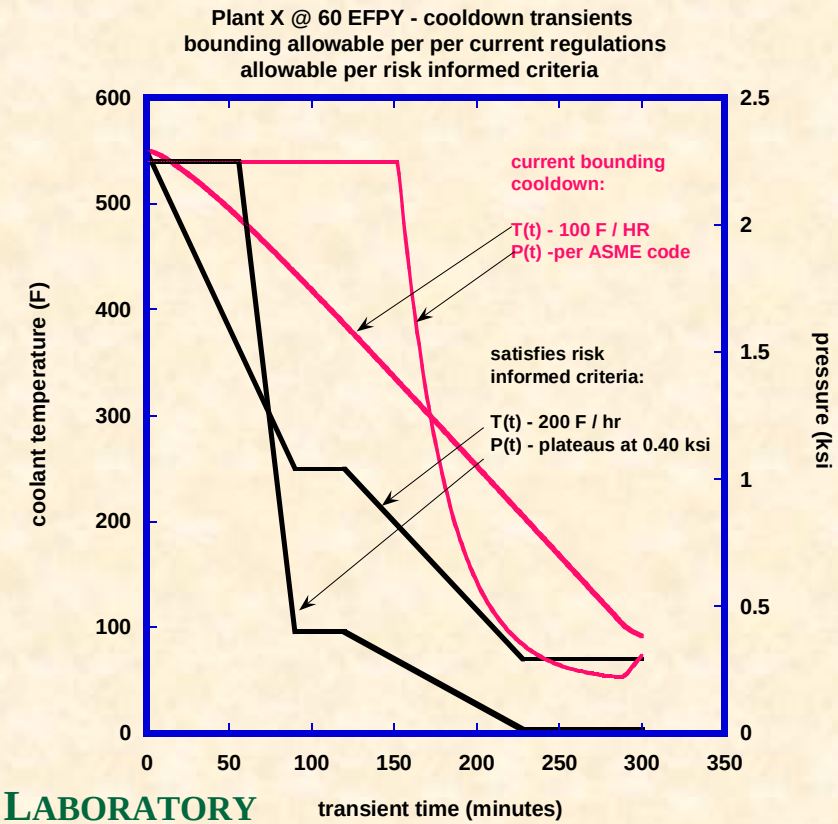
PFM results can be applied to determine a range of parameters (a window of operations) that a risk informed limit, such as (10^{-6})

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



<u>NOTE</u>: CPI_{mean} of 0 and 10^{-6} used for purpose of illustration only.

Risk informed approach results in considerable relaxation of maximum cool-down rate relative to bounding transient derived from ASME Section XI – Appendix G



How Does the Introduction of Inner-Surface Breaking into the PFM Model

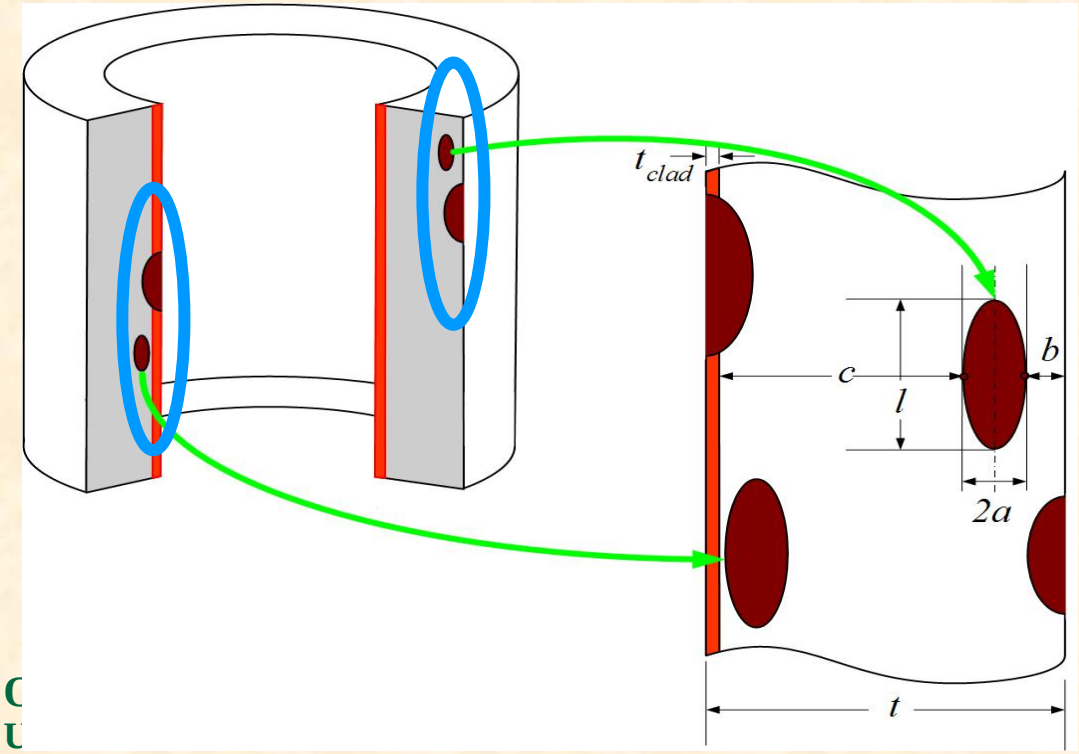
Impact the results and subsequent conclusions of the previous PFM analyses of parameterized cool-down transients associated with reactor shutdown

Attempt to generalize previous results / conclusions

Each RPV in the Monte Carlo analysis was postulated to have 2 circumferentially-oriented inner surface breaking flaws of specified depth

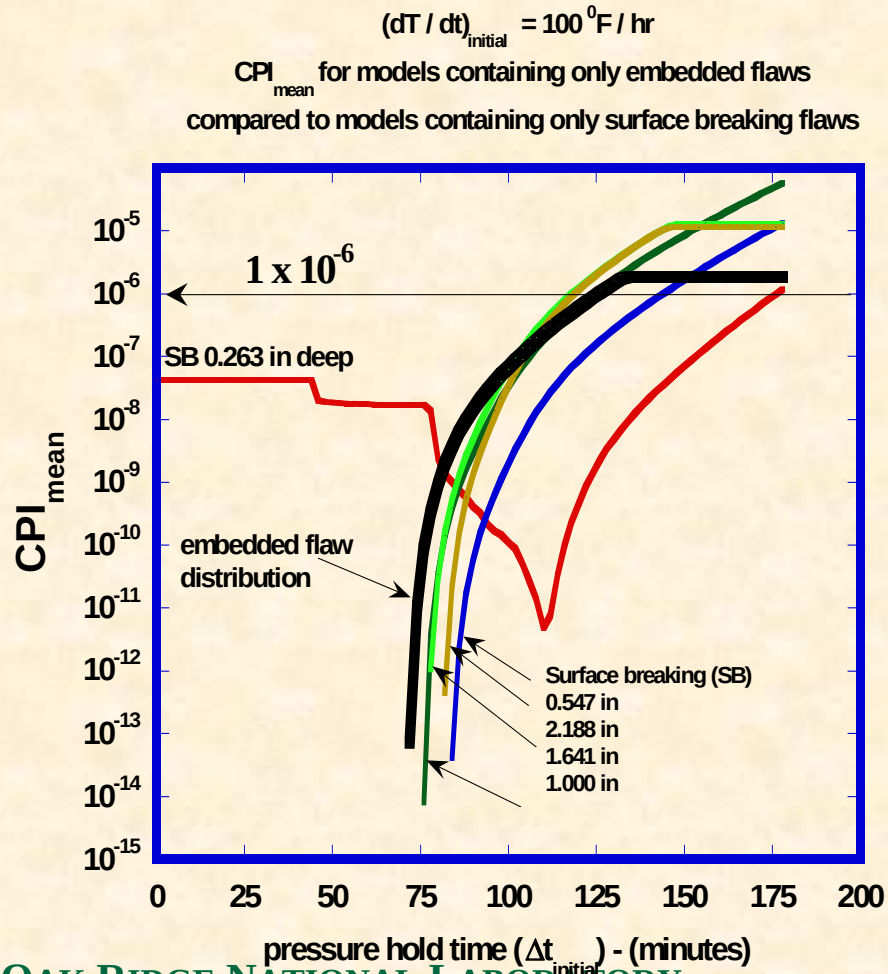
aspect ratio distribution: 67.45%, 20.76%, 3.96%, 7.83% have aspect ratios of 2, 6, 10, and continuous 360 degree flaws, respectively

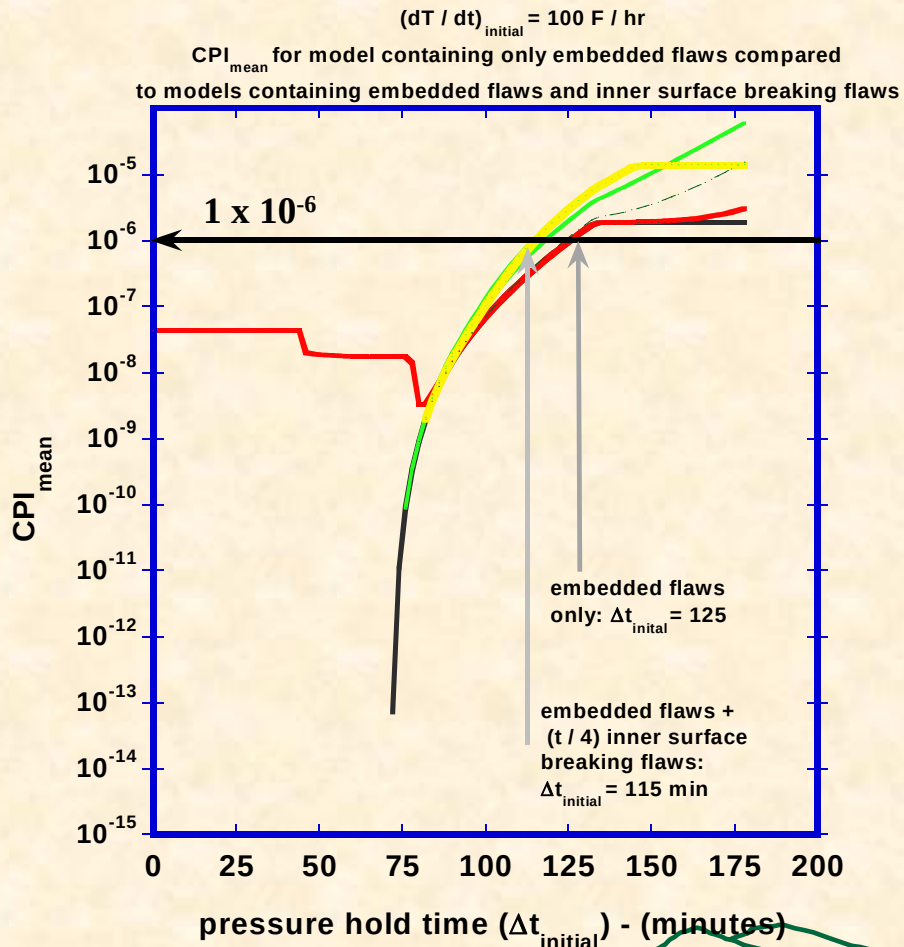
Consistent with PNNL flaw distribution for RPVs with single layer cladding



- **External surface-breaking flaws and embedded flaws near outer surface are relevant to heat-up transient**
- **Internal surface-breaking flaws and embedded flaws near inner surface are relevant to cool-down transient**

For $(dT / dt)_{initial}$ = 100 F / hr; the inclusion of inner surface breaking flaws in the model (in addition to embedded flaws) reduces the allowable pressure hold time ($\Delta t_{initial}$) from 125 minutes to 115 minutes



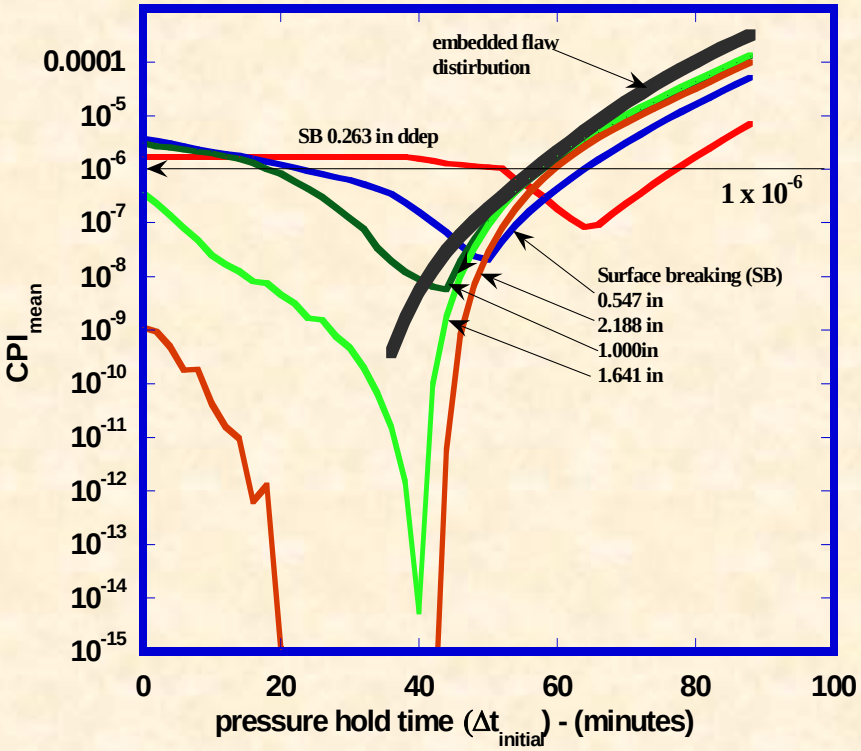


For $(dT / dt)_{initial}$ = 200 F / hr; the inclusion of inner surface breaking flaws in the model (in addition to embedded flaws); there is NO value of $\Delta t_{initial}$ that satisfies $1x10^{-6}$ limit;

therefore; the operating window is closed for $(dT /dt)_{initial}$ = 200 F / hr

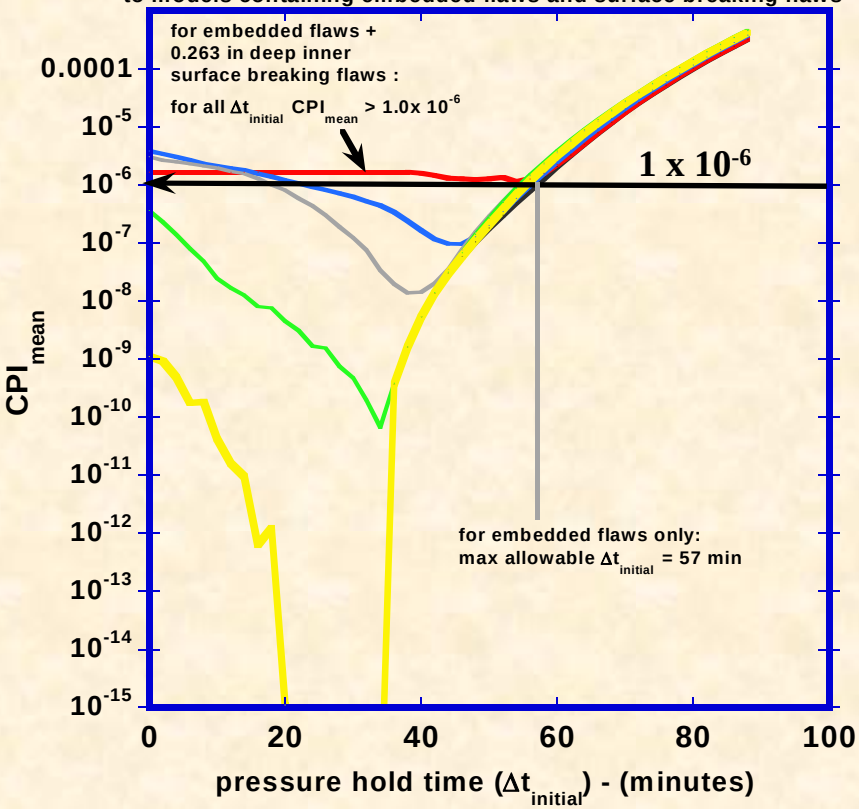
$(dT / dt)_{initial} = 200\ ^0F / hr$

CPI_{mean} for models containing only embedded flaws compared to models containing only inner surface breaking flaws



$(dT / dt)_{initial}$ = 200 F/ hr

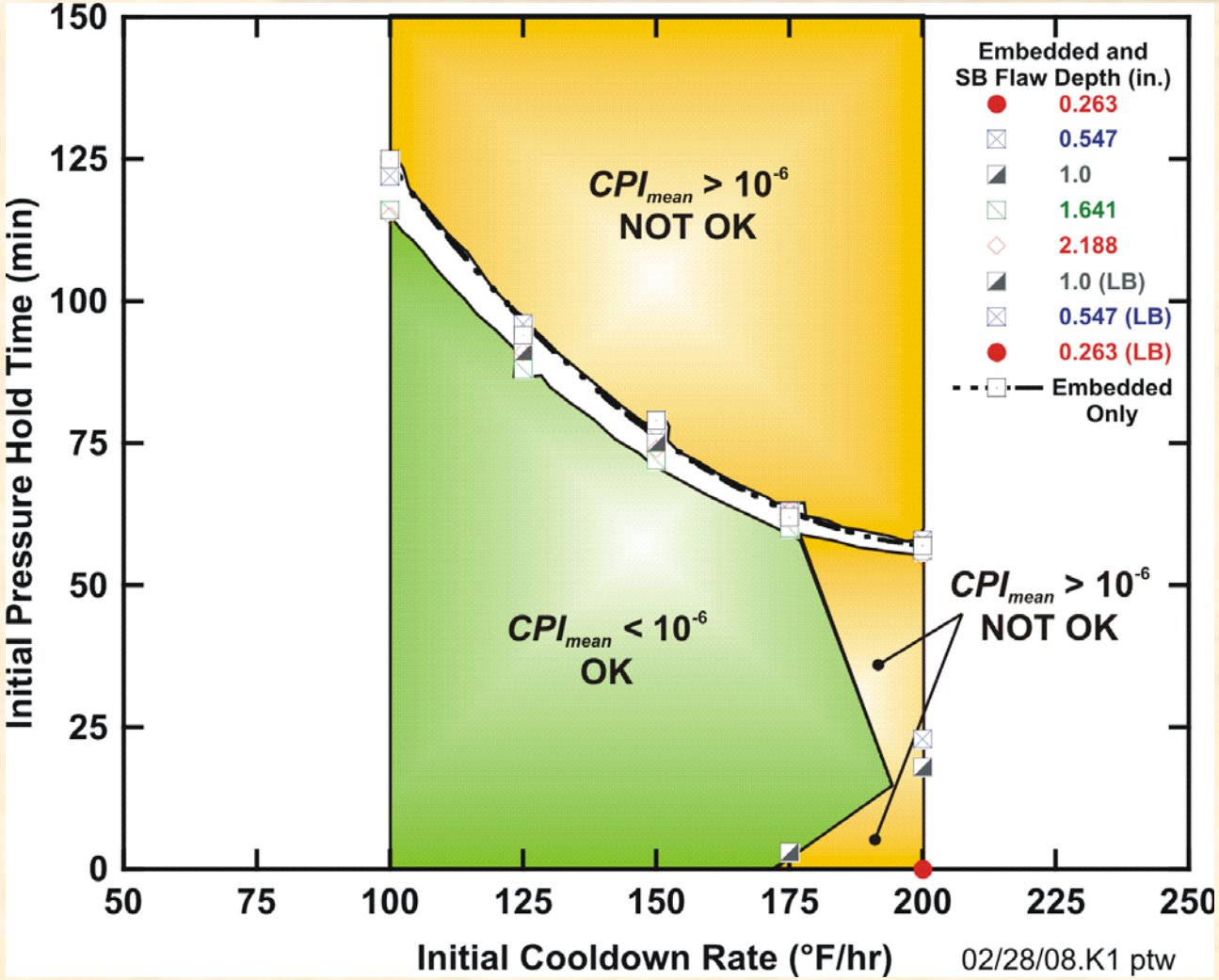
CPI_{mean} for model containing only embedded flaws compared to models containing embedded flaws and surface breaking flaws



The previously defined window within which planned reactor cool-down operations can be conducted while remaining below the 10^{-6} limit is slightly reduced by the introduction of inner-surface breaking flaws

(1) Maximum cooling rate reduced from 200 F / hr to 175 / hr

(2) maximum allowable $\Delta t_{initial}$ slightly reduced



<u>NOTE</u>: CPI_{mean} of 0 and 10^{-6} used for purpose of illustration only.

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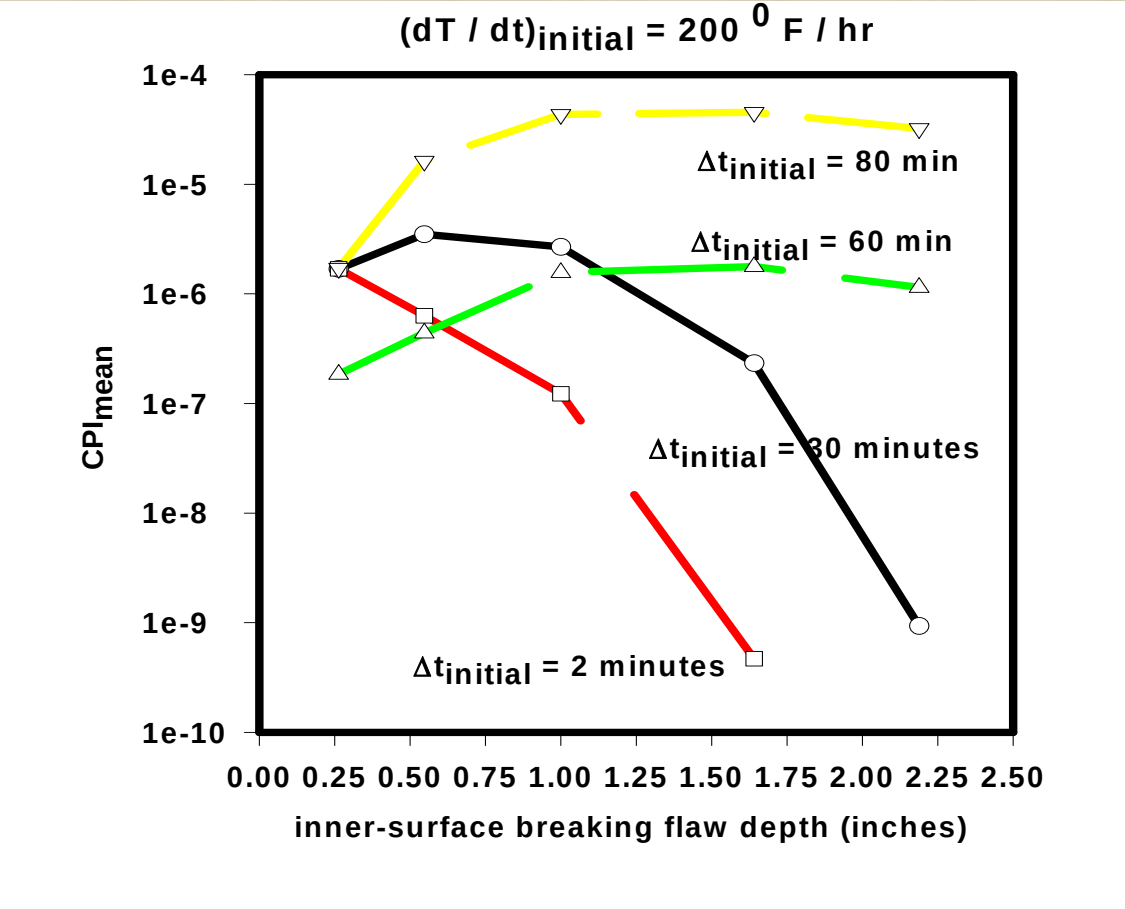
A counter-intuitive result from this analysis is that the risk of cleavage fracture does not always increase with increasing inner-surface breaking flaw depth

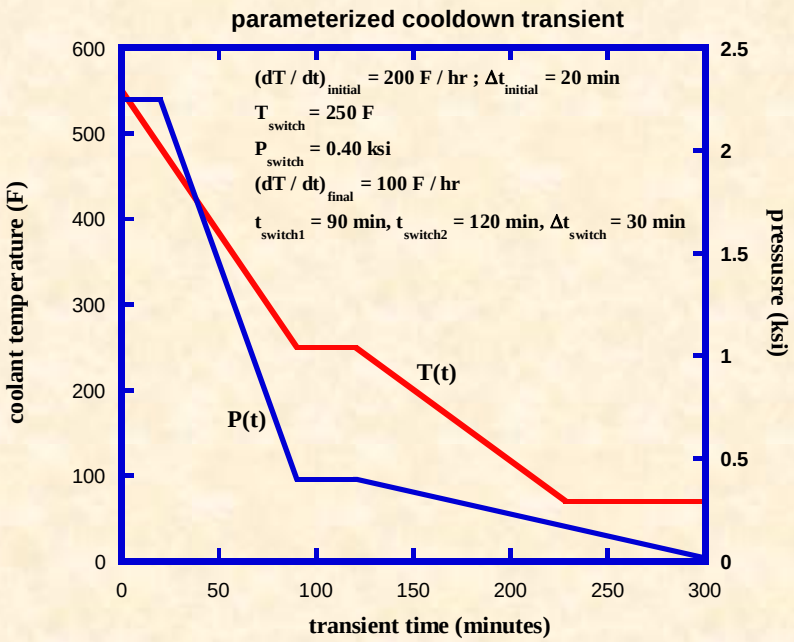
For some combinations of $\{(dT/dt)_{initial}, \Delta t_{initial}\}$ the applied K_I for deeper inner-surface breaking flaws reach their peak loading at earlier transient times when the temperature and subsequently the fracture toughness are higher

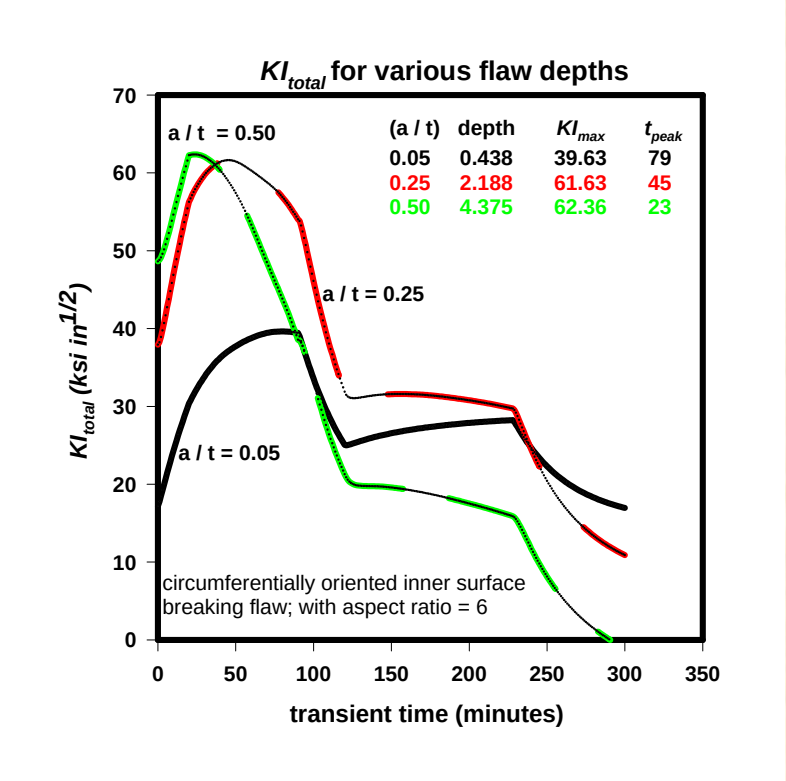
Subject of future publication(s) – mechanistic insights



The time at which the time rate of change of KI_{total}, designated as $d(KI_{total}) / dt$, equals zero corresponds to t_{peak}, the time at which KI_{total} reaches it maximum value, which due to WPS, is the last transient time at which a crack can be predicted to initiate in cleavage fracture, also, the last transient time at which a non-zero CPI may be predicted

Subject of future publication(s)

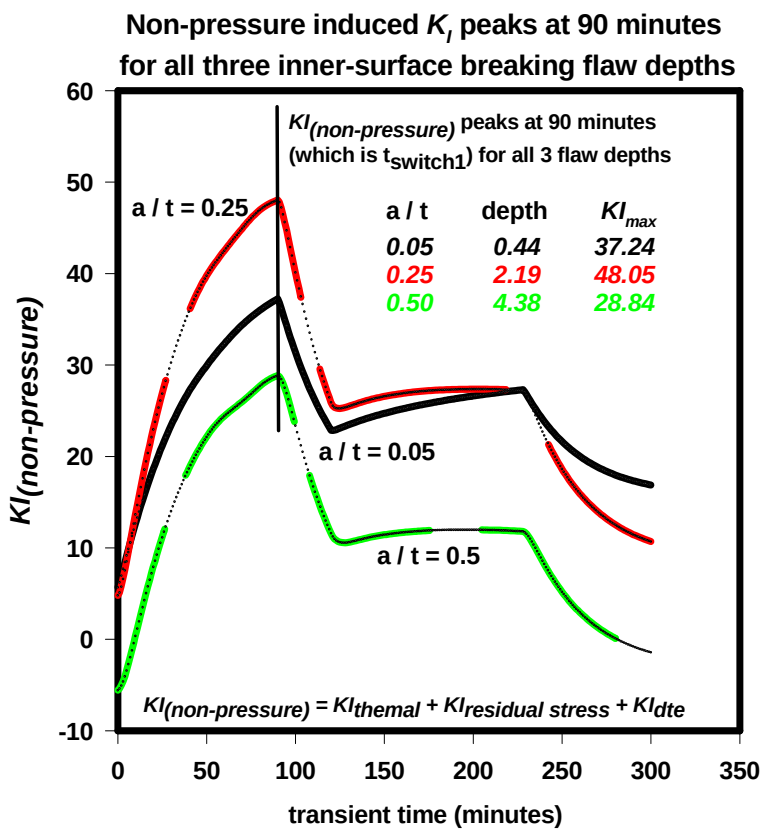


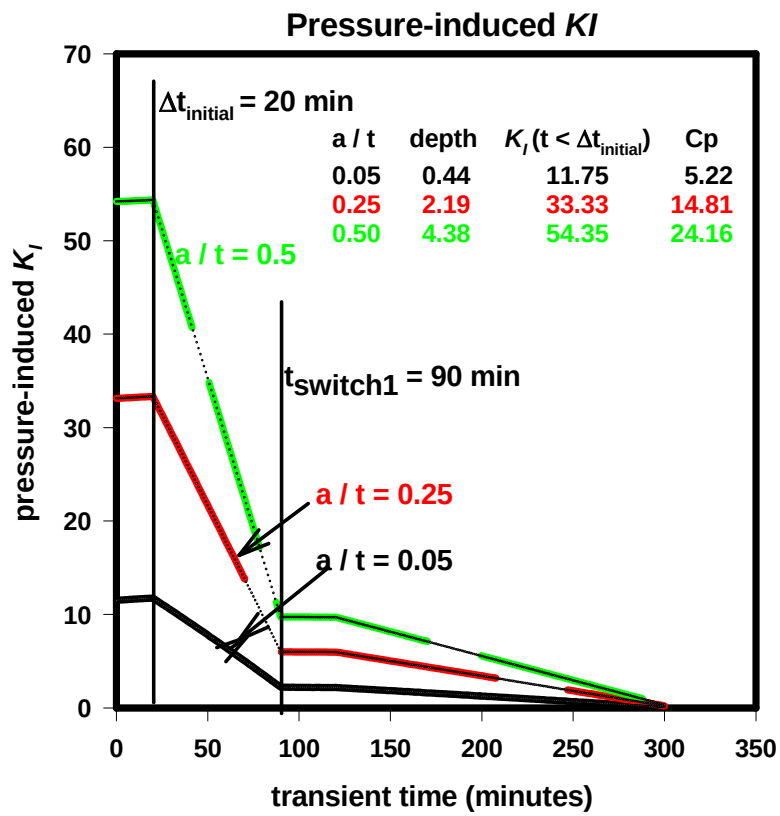


$$KI_{total} = KI_{(non\text{-}pressure)} + KI_{(pressure)}$$

$$t_{peak} \text{ occurs when } dKI_{total} / dt = (dK / dt)_{pressure} + (dK / dt)_{non\text{-}pressure} = 0$$

$(dK / dt)_{pressure}$ decreases with flaw depth more rapidly than $(dK / dt)_{non\text{-}pressure}$ increases





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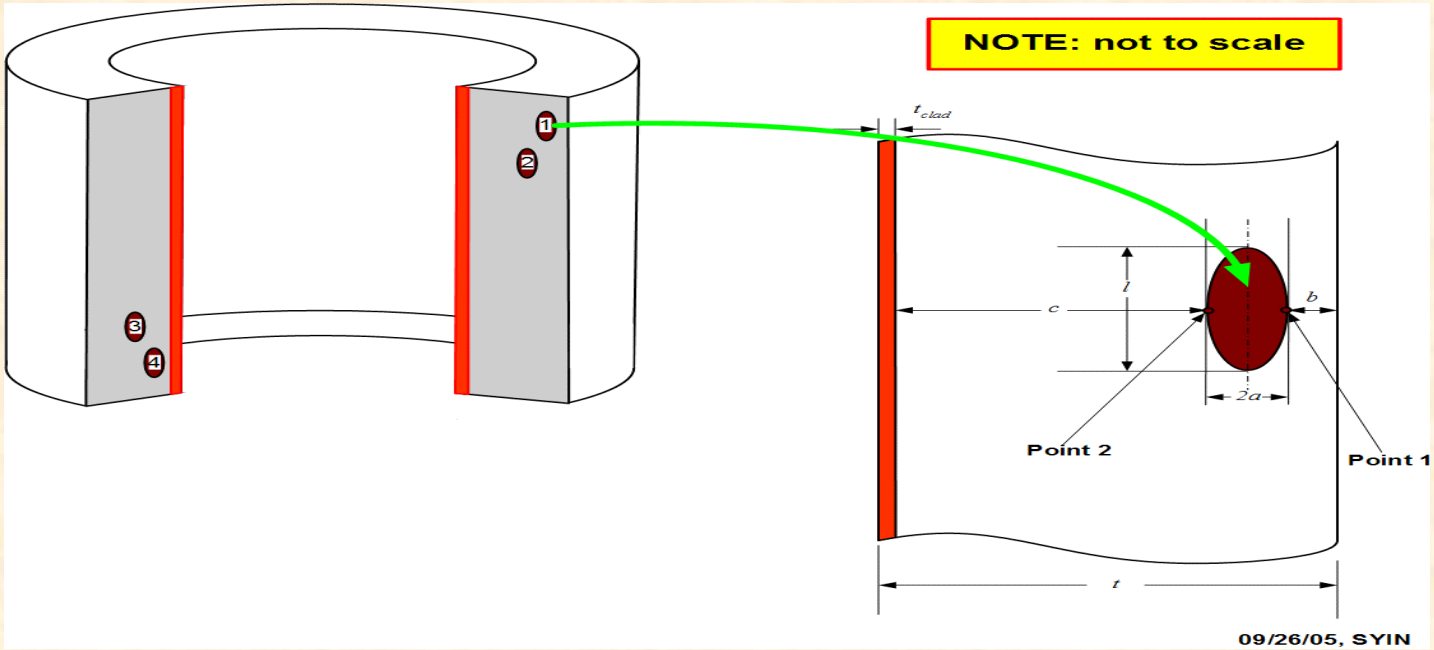
- **Heat-up transients associated with reactor start-up**
- **Conclusions and what's next**

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

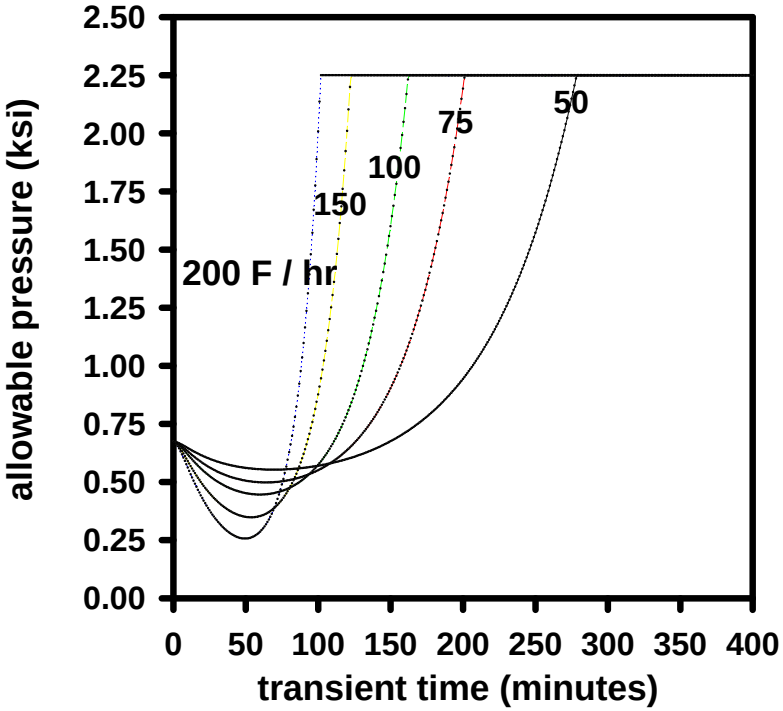
- Previous versions of **FAVOR designed for** analysis of cool-down transients (fracture analyses of **flaws on or near RPV inner surface**)
- **FAVOR^{HT} designed for** analysis of heat-up transients (fracture analyses of embedded **flaws near RPV outer surface**)



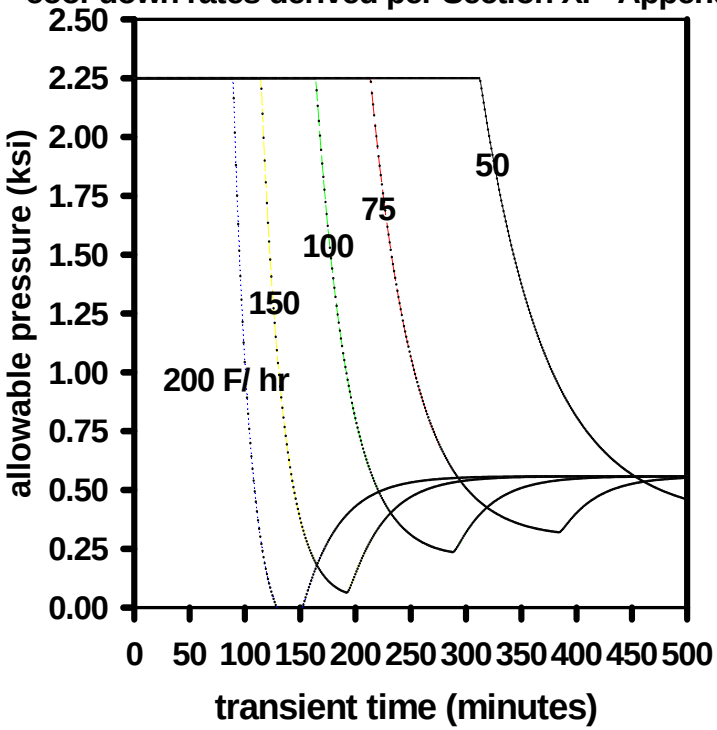
PFM analyses were performed for Plant X @ 60 EFPY for a range of heat-up and cool-down rates

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

Allowable pressure for heat-up transients for various heat-up rates derived per Section XI - Appendix G



Allowable pressure for cool-down transients for various cool-down rates derived per Section XI - Appendix G

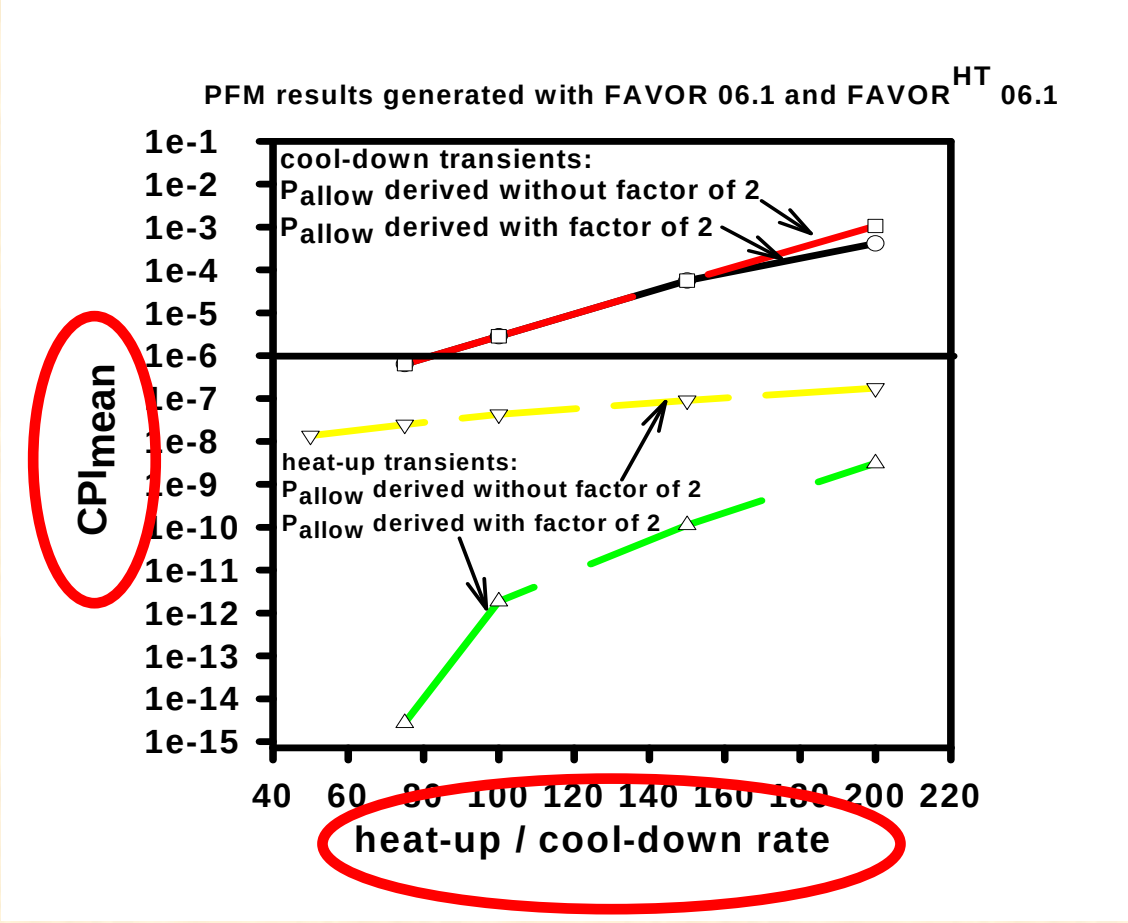


PFM results for heat-up transients are orders of magnitude lower compared to comparable cool-down transients

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 limits on CPI_{mean} of both 0 and 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

Conclusions – continued

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

(6) The introduction of inner-surface breaking flaws into the model does not significantly impact the CPI_{mean}-based operating window previously derived using only embedded flaws, i.e., it:

(a) Reduces the maximum cool-down rate to ~ 175 F / hr

(b) slightly reduces the maximum allowable values of $\Delta t_{initial}$

(7) Regardless of flaw type, there is a complex interaction between $(dT/dt)_{initial}$ and $\Delta t_{initial}$ which determines the time and magnitude of peak loading, which when WPS is included in the model, has a very significant impact on the PFM solution

(8) PFM results vary by orders of magnitude as a function of pressure hold time $\Delta t_{initial}$

(9) Counter-intuitive result: for some cool-down transients, the risk of brittle fracture does not always vary proportionally with flaw depth; applied *KI* for deeper flaws reach their peak loading value at earlier transient times when the temperature and fracture toughness are higher.

What's next

- August 21 meeting between NRC / industry
- Need more precise transient characterization
- PFM analyses of other plants at other EFPY

  Characteristic of Plant X is that the most embrittled regions are axial welds

  Similar analyses for RPVs in which the plate regions are the most highly embrittled could produce different results / conclusions ?
- Generalization of FAVOR to include:

  (a) ability to also perform analyses of heat-up transients

  External surface-breaking flaws

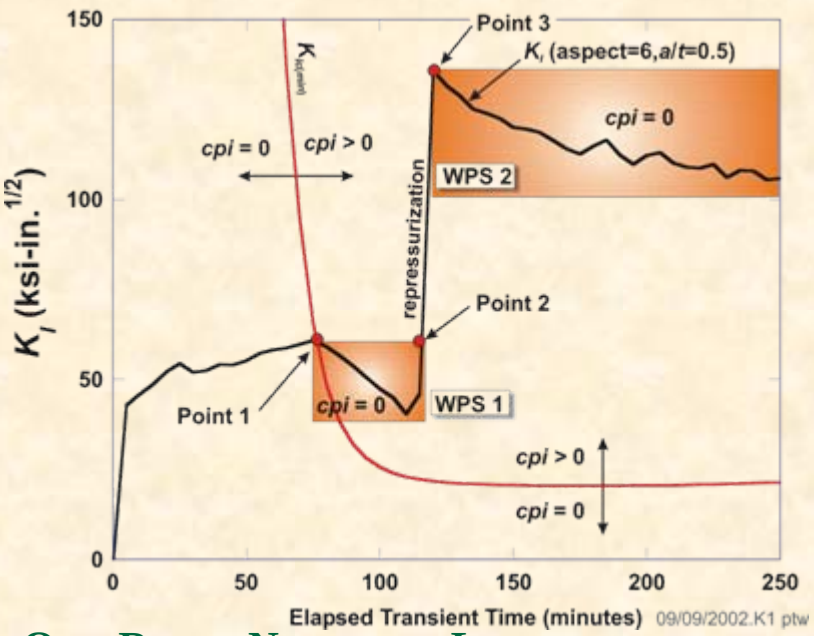
  Embedded flaws in outer 3/8 of RPV wall

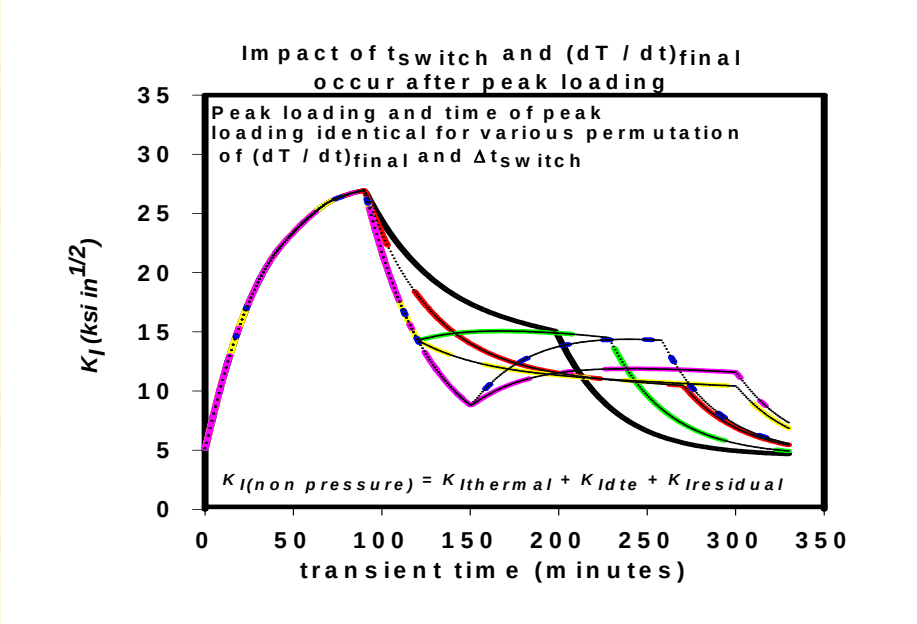
  (b) influence coefficients for internal / external surface breaking flaws

  for BWR geometries
- Long-term cyclic plasticity effects for normal transients (ORNL paper by Sean Yin, et al; paper 61387)
- Re-visitation of the WPS model – sensitivity analyses with "conservative principle" WPS model
- Incorporation of models that reflect NDE probability and sizing uncertainty
- Definition of vessel "failure," and tolerable frequency of vessel "failure"

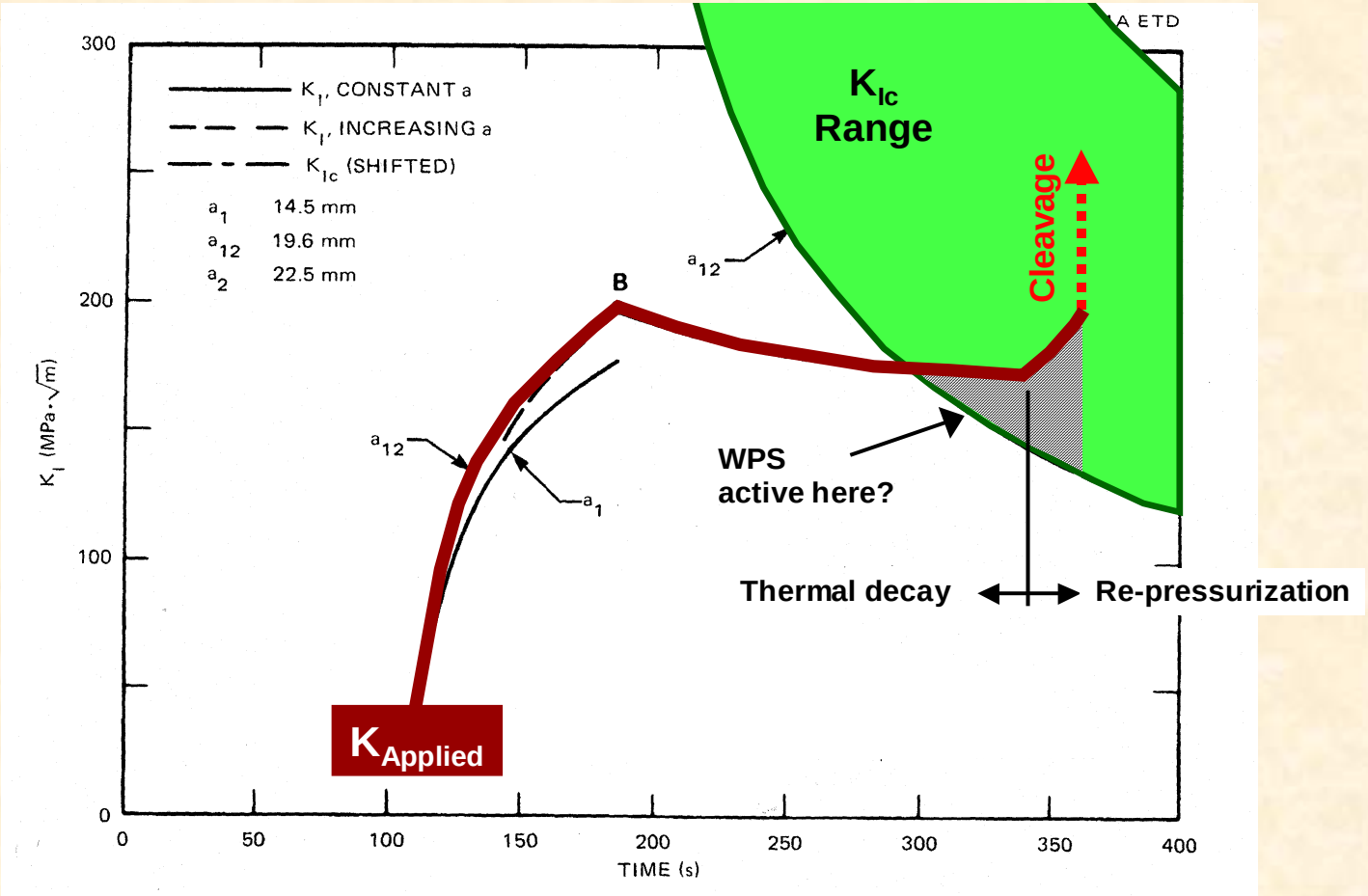
Currently adding an additional option for "conservative principle" interpretation of warm pre-stress in FAVOR

- Current WPS model in FAVOR: conditions required for cpi > 0
  - $K_I > K_{min}$ *(Weibull "a" parameter)*
  - $K_I(t)$ > previous maximum value $K_{I(max)}$
  - cpi = 0 in reloading phase(s) until $K_I(t) > K_{I(max)}$
- "Conservative principle" interpretation of WPS: conditions required for cpi > 0
  - $K_I > K_{min}$ *(Weibull "a" parameter)*
  - $K_I(t) > K_I(t\text{-}1)$, *i.e., positive slope*
  - *cpi > 0 in reloading phase(s) if* $K_I(t) > K_{min}$

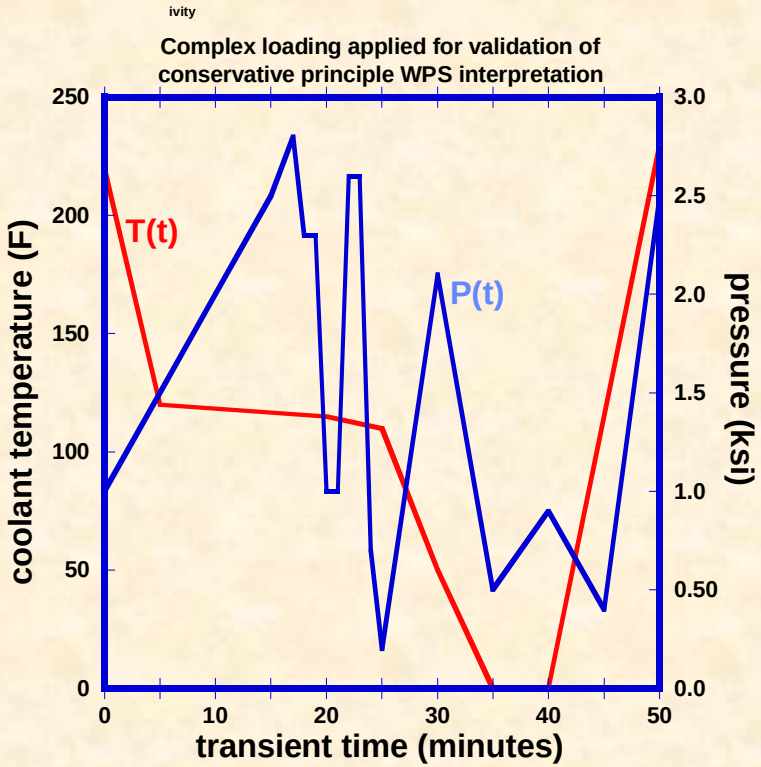


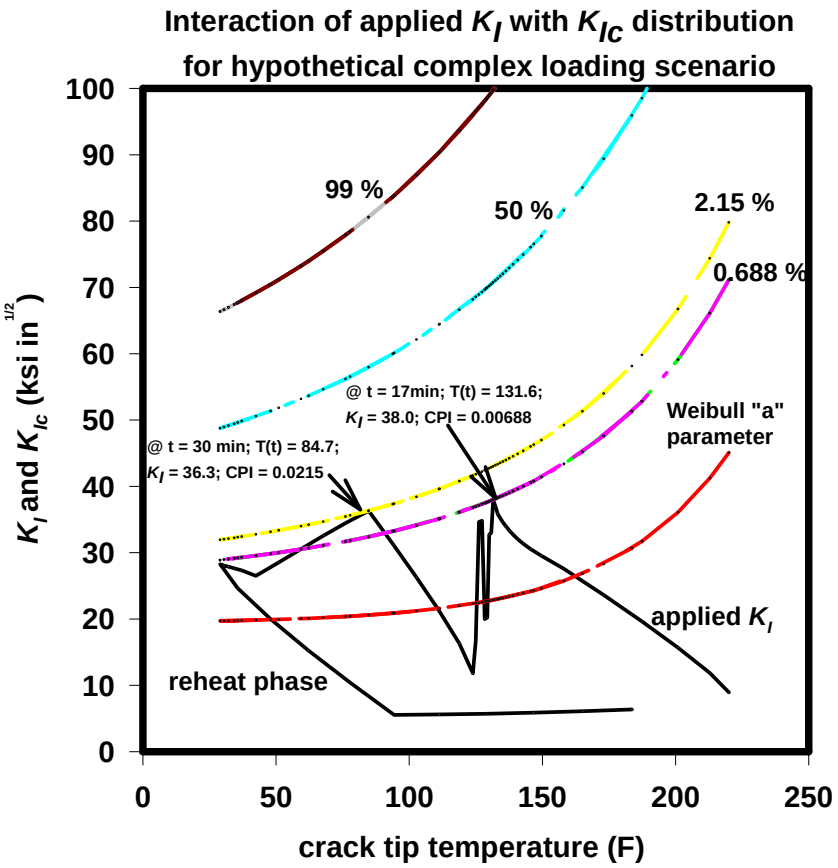


Variation of *Kapplied* and *KIc* with time in PTSE-2 showing evidence of a potential WPS effect beginning at around 300 seconds.



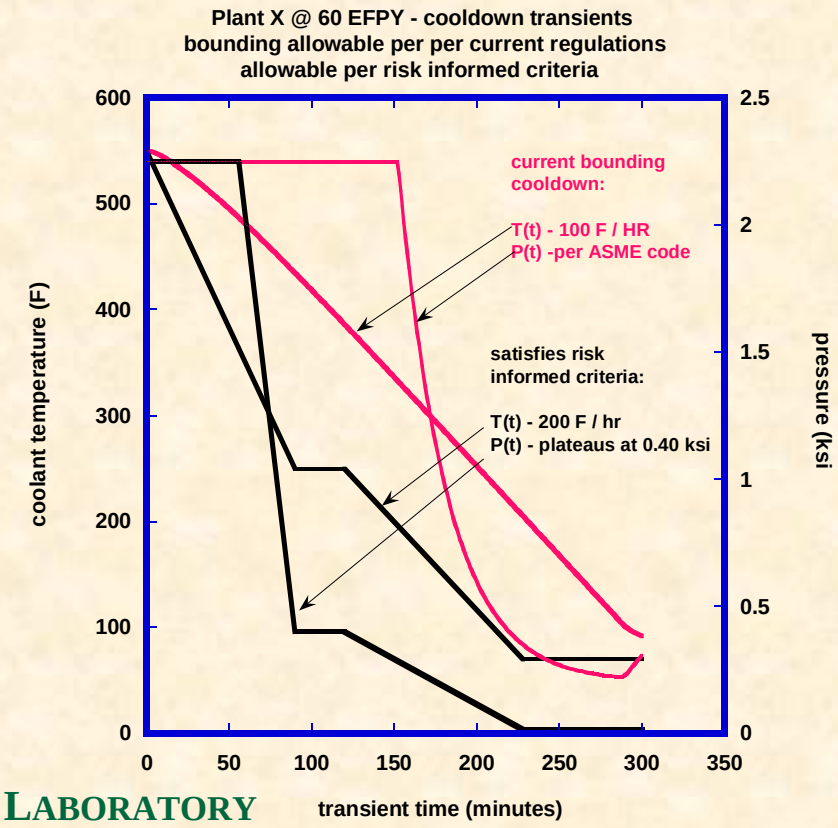
A hypothetical complex loading scenario is being used to validate the implementation of the "conservative principle" interpretation of WPS into FAVOR





Backup Slides

Risk informed approach results in considerable relaxation of maximum cool-down rate relative to bounding transient derived from ASME Section XI – Appendix G

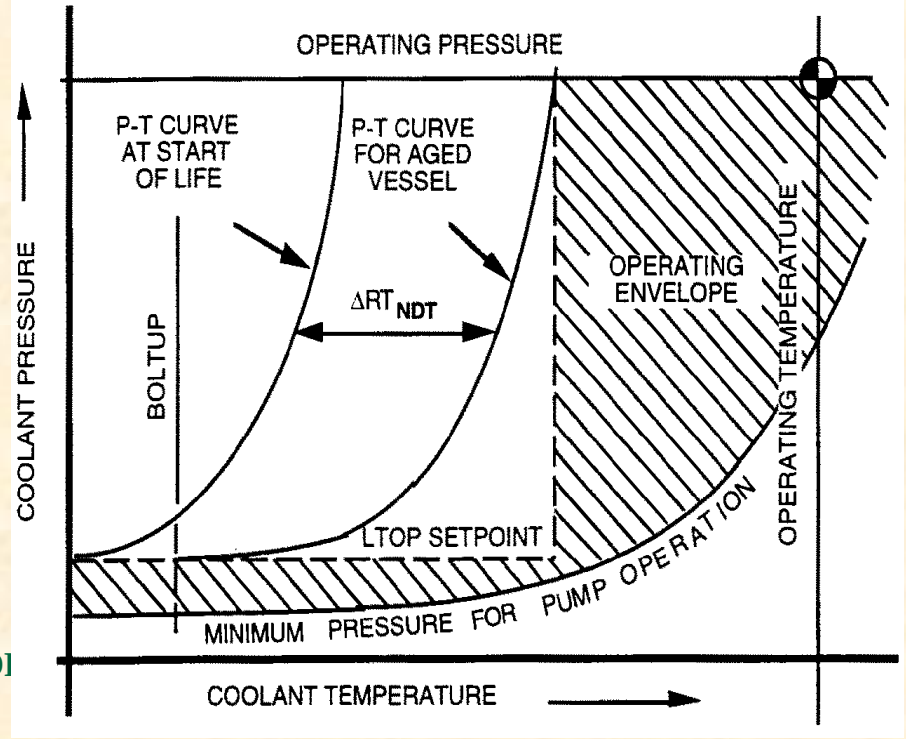


The P-T operating envelope is progressively restricted to accommodate the effects of irradiation embrittlement of the RPV material

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

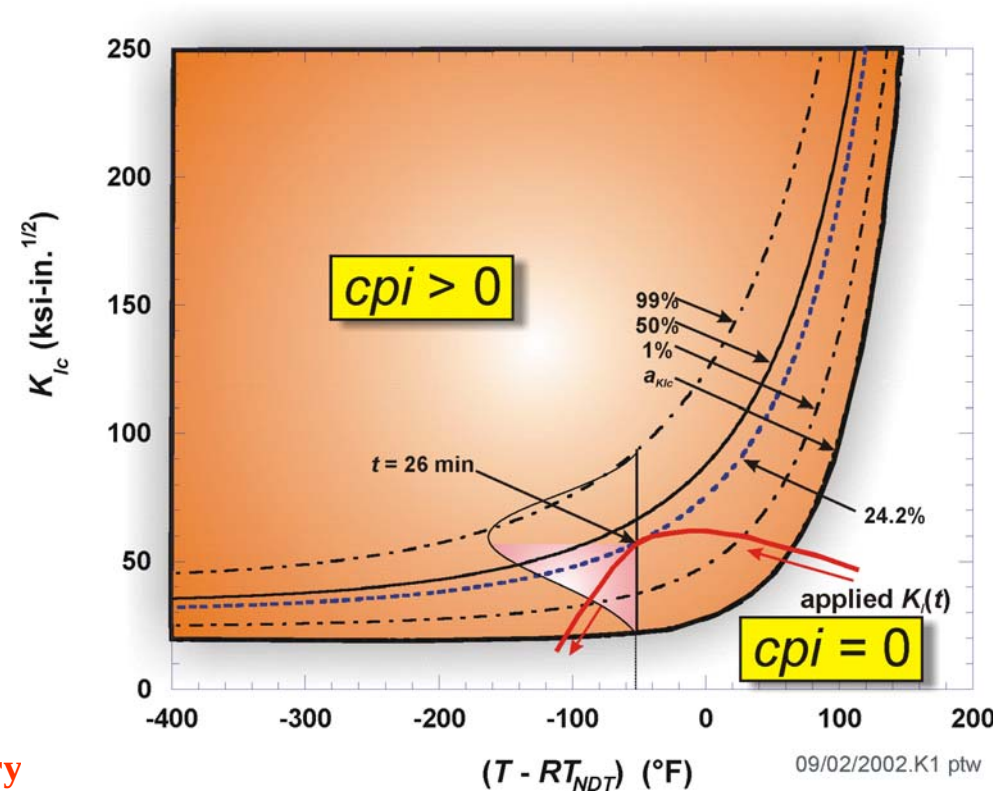
An objective of ORNL study is to determine if a technical basis can be established to support a relaxation to the methodology in ASME Section XI – Appendix G



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



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