

3D S.UN.COP 2008: 9th Seminar
13 - 31 October, 2008

Session III
Interaction of Thermal-Hydraulics with Fuel
behavior, Structural Mechanics and
Computational Fluid Dynamics

Pressurized Thermal Shock Analysis Techniques

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Outline

- General Description and Overview of PTS
- Analysis Tools and Techniques for PTS
- Recent NRC Evaluations of PTS to support a revised PTS rule in the US
- Code Coupling Options and Issues
- Summary

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Status in the US

(reference: NUREG 1806 www.nrc.gov)

- Recent analysis, based on an ability to better model plant operations and loads on the vessel wall, has demonstrated that the old US PTS rule (10 CFR 50.61) was based on some overly conservative analyses.
- New analyses, using realistic input values and explicit treatment of uncertainties, has been completed and is being used to support a revision to the PTS rule.
- The proposed rule has been made available for public comment and a final rule making is anticipated by the summer of 2009.
- The supporting calculations demonstrated that the likelihood of vessel failure due to PTS for all US PWRs was extremely low ($\sim 10^{-8}$ /year).

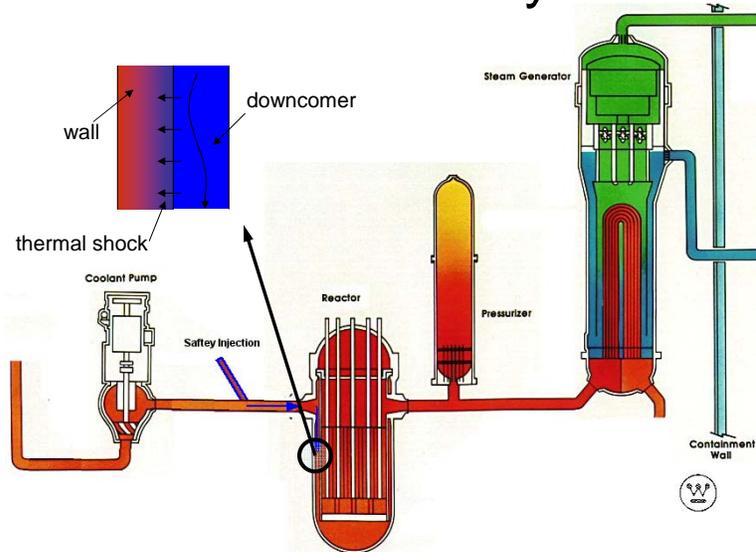
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What is PTS?

- Pressurized Thermal Shock (PTS) refers to a condition that challenges the integrity of the reactor pressure vessel (RPV).
- 3 Conditions lead to this safety issue.
 - RPV wall **embrittlement** due to neutron irradiation
 - some type of **existing flaw** in the RPV wall
 - a rapid **drop in temperature** (Thermal Shock) while the pressure (Pressurized) remains high enough to result in crack initiation and growth
 - primary and secondary side events are possible

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Reactor Coolant System



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Overcooling Can Happen

- Rancho Seco, 1978
 - 305 °C to 140 °C in 1 hour with P at 2000 psi
 - Control System error reduced feedwater flow
 - Aux. Feed turned on and reduced P and T
 - HPI started and all Aux. Feed ran for 1 hour
- Three Mile Island (1979) was also an overcooling event.
- In addition, many plausible sequences have been postulated that can lead to overcooling events in PWRs.

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A PTS Scenario (primary side LOCA)

- Loop Flow stagnates due to a LOCA
 - breaks larger than about 3.5 cm can result in voided regions in the loops and a loss of loop circulation
- Primary side injection of cold water (~10-30 °C)
 - cold leg injection (or in some plants, hot leg, or vessel)
 - significant cool down in the downcomer
- Pressure and heat transfer (cooling) at RPV wall can challenge integrity of vessel.
 - neutron embrittlement adjacent to core
 - flaws in vessel (weld flaws, other)
 - thermal shock due to cooldown
- Isolation of the break and a re-pressurization of the cooled down system is also a major concern.

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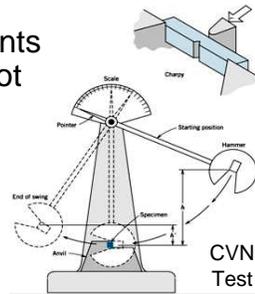
A PTS Scenario (Secondary side Break)

- MSLB or other large secondary side break
 - secondary side boils at low pressure
- Primary side temperatures cool off rapidly
 - efficient heat transfer across SG tubes
 - primary side temperatures approach 100 °C in the steam generator
 - natural circulation draws cooler water into the downcomer
- Pressure and heat transfer (cooling) at RPV wall can challenge integrity of vessel
 - neutron embrittlement adjacent to core
 - flaws in vessel (weld flaws, other)

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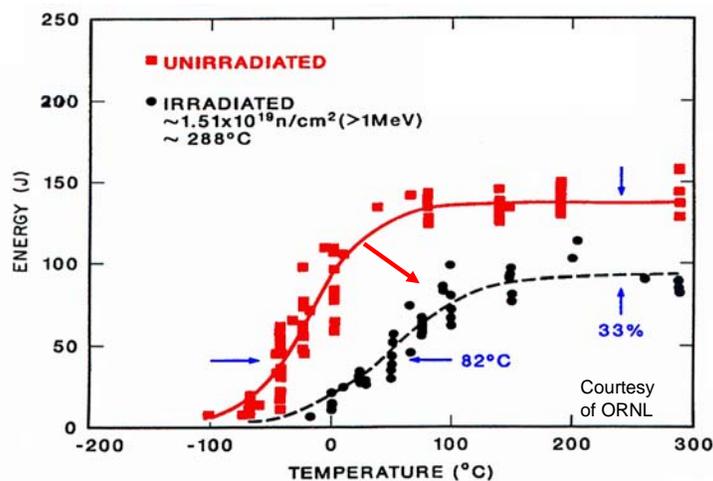
Neutron Fluence (the root cause)

- Exposure to high energy neutrons in the vessel beltline region reduces the fracture toughness of the vessel wall.
 - neutron fluence is the time integral of neutron flux
- Trace impurities like copper and phosphorous lead to the embrittlement (or hardening).
 - hardening starts at the nanometer level
- This is mainly an issue with older plants where the weld compositions were not adequately controlled.
- Charpy-V-notch (CVN) impact specimens are one method to measure the embrittlement.
 - used in some surveillance programs.



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Charpy-V-Notch Impact Energy Curve



Effect of radiation damage on the CVN transition characterization of ferritic steels

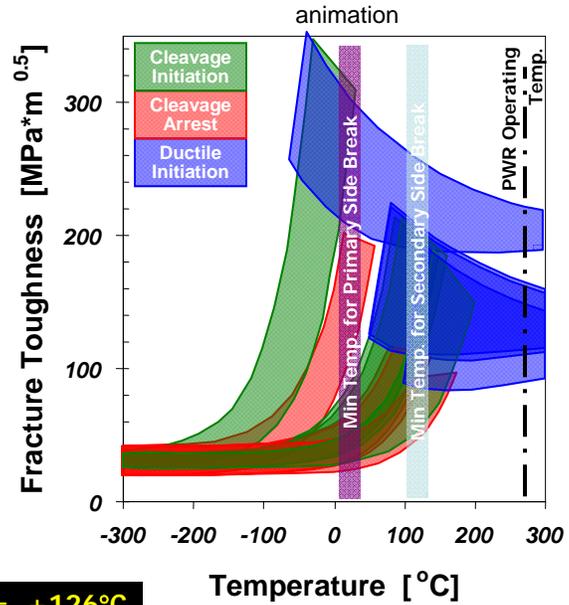
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Neutron Embrittlement for A Plant

- **Toughness curves for the most embrittled axial weld in the sample plant.**

- at beginning of life
- at 40 years
- at 60 years
- at TWCF $\approx 10^{-6}$ / year

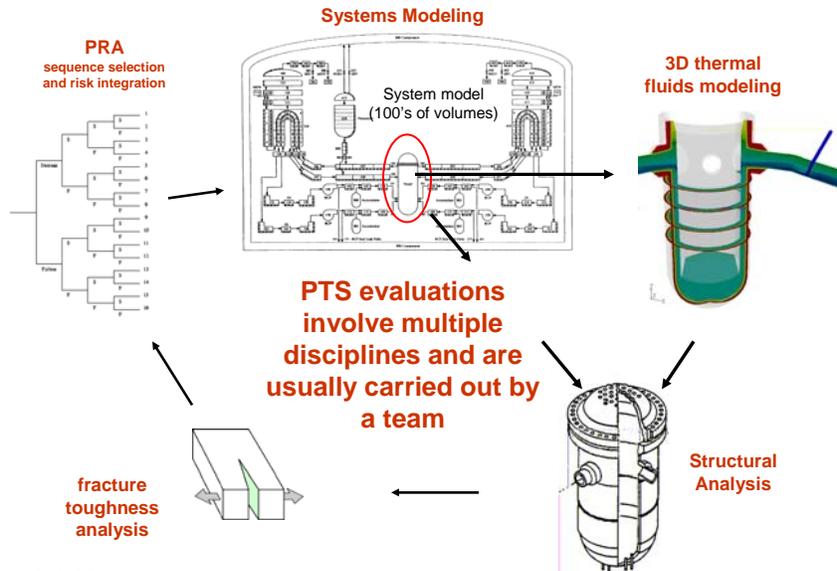
As the vessel ages, the probability of brittle behavior (sudden & catastrophic fracture) increases.



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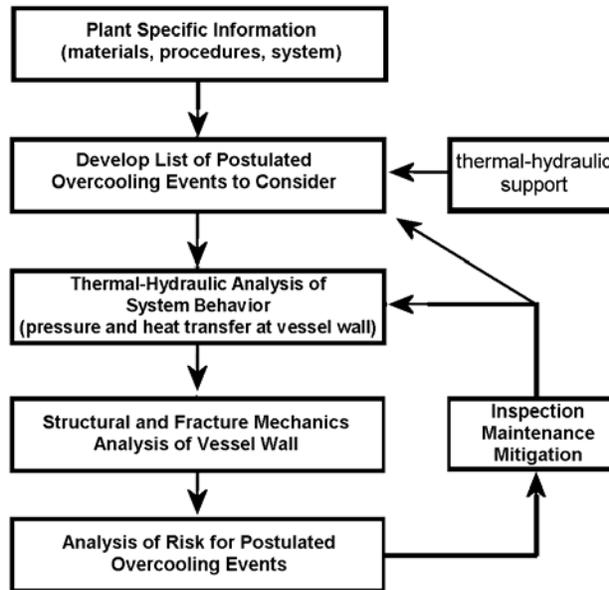
$T_o = +126^\circ\text{C}$

What needs to be Considered?



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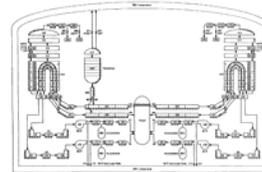
Simplified
View of
PTS
Analysis
Approach



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Prediction of System Response

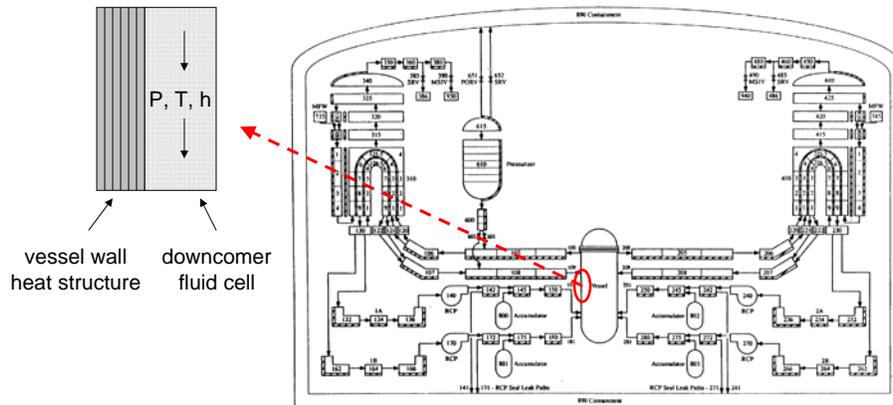
- Plant response to overcooling events is computed using systems codes.
 - CATHARE, RELAP5, TRACE, ATHLET, etc.
- Plant specific issues are important.
 - accumulator and safety injection flows
 - location, flow rates, temperatures
 - break flow size and location
 - upper plenum bypass flows (vent valves also considered)
 - condensation during ECC and re-pressurization
 - prediction of the interruption and resumption of natural circulation flows (full loop natural circulation)
 - valve opening and re-closure
- Goal of TH analysis is the determination of P, T, and heat transfer coefficient (h) histories in the downcomer region.
 - these conditions apply the thermal and mechanical boundary conditions that leads to PTS of the vessel wall



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System Code Model

The goal of system model is to predict the local fluid conditions in the downcomer



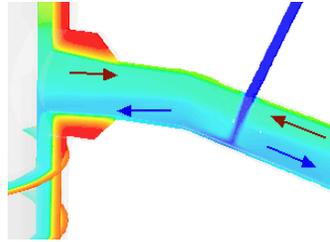
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Additional TH models

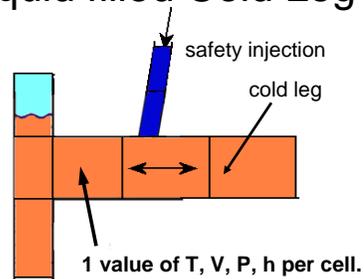
- System code predictions may need to be augmented if the underlying code assumptions are not applicable to the expected physical behavior.
 - 3D behavior may be important (system codes are 1D)
 - multi-phase correlations may be inadequate
- Additional analyses focus on the downcomer region and use the system code predictions as boundary conditions.
 - regional mixing models and zonal models
 - rely on correlations tuned to experiments
 - single-phase CFD for turbulent mixing and plumes
 - validated using experimental results
 - two-phase CFD for condensation as well as mixing
 - validated using experimental results
 - Used when cold leg (and downcomer) may be voided
- Coupling of CFD tools or regional mixing models with system codes is another option.
 - coupling provides feedback from the local mixing regions to the overall system response

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Consider Injection into a liquid filled Cold Leg



CFD Prediction of injection into stagnant loop



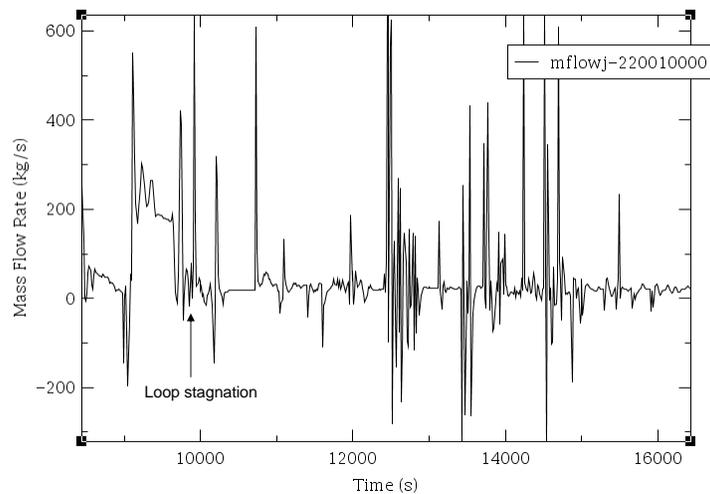
system code representation of injection into stagnant loop

- This is one region where system codes are deficient. 1D models cannot account for the counter-current flow in the cold leg or the presence of a cold stripe in the downcomer. This phenomena can be estimated from experimental results, associated correlations, and CFD techniques. The significance of these issues must be considered in light of the overall uncertainty and the expectations for the TH results.

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Cold Leg Mass Flows

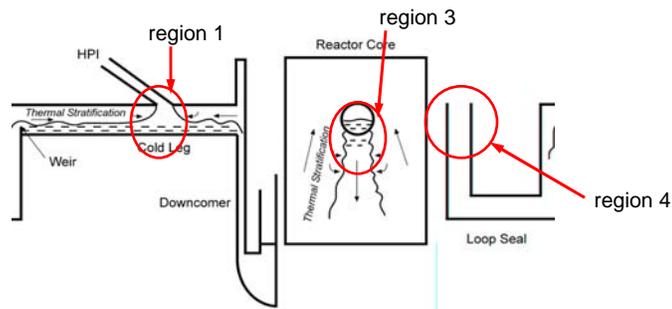
(RELAP5 1D model – 2" hot leg SBLOCA)



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Regional Mixing Models

- Models such as REMIX are focused on the cold leg, downcomer, and other mixing volumes.
 - NUREG/CR-3701 “REMIX ...” K. Iyer, et. al. 1986
 - These models typically rely on a set of assumptions that may not always be valid.
 - General modeling approach extended to two-phase conditions during PTS-ICAS (1999).
 - Models are very efficient to run. Many scenarios can be considered.

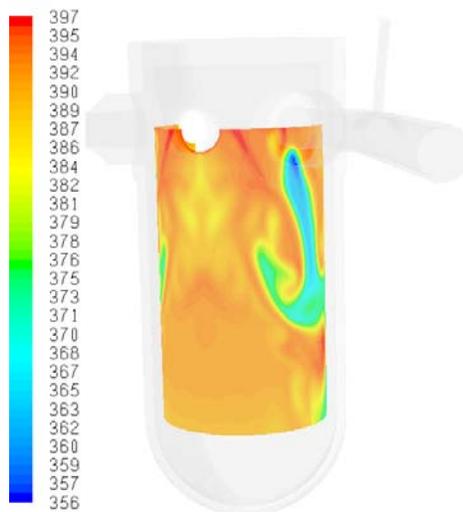


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Computational Fluid Dynamics (CFD) provides insight into the 3D behavior (single phase)

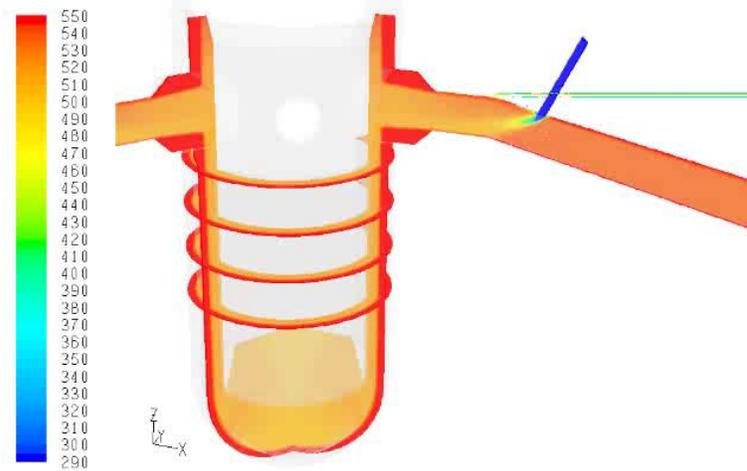
- stratification in the cold leg is significant when loop flow stagnates
- downcomer flows can be significant, adjacent plumes can interact
 - may need to model entire downcomer (360°)
- wall treatment is important, mixed convection can be significant
- modeling of all mixing regions is needed to predict the cooldown rate

downcomer temperatures during safety injection into cold leg temperature contours (blue – cold)



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CFD – Single Phase Safety Injection



Contours of Static Temperature (K) (Time=8.5900e+02) Jul 22, 2008
FLUENT 6.3 (3d, pbns, rke, unsteady)

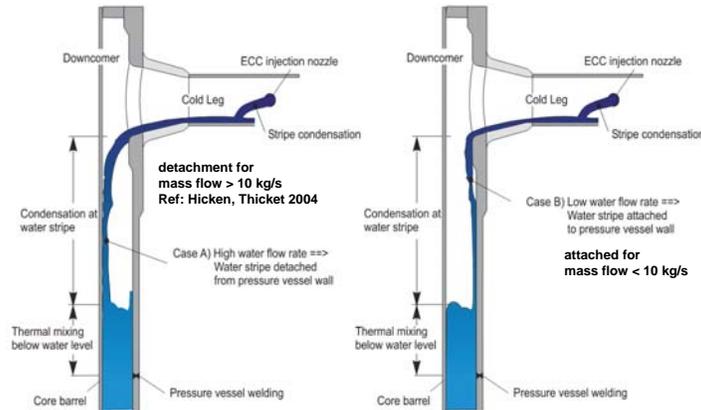
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TH – CFD Outlook

- Single phase CFD is a mature technology but careful consideration is still required.
 - best practice guidelines are available and should be updated when appropriate
 - “Best Practice Guidelines for the use of CFD in Nuclear Reactor Safety Applications” NEA/CSNI/R(2007)5
 - “Further work is needed” in the area of single phase CFD simulations (ref. Best Practice Guidelines..)
- Multi-Phase CFD is an emerging technology.
 - many challenges still exist
 - adequate data, suitable for detailed model validation, are rare
 - significant work is underway
 - NURESIM:SP2 (reference deliverable D2.1.1, D. Lucas)
 - focusing on PTS
- CFD is time intensive work.
 - only a limited number of predictions are practical

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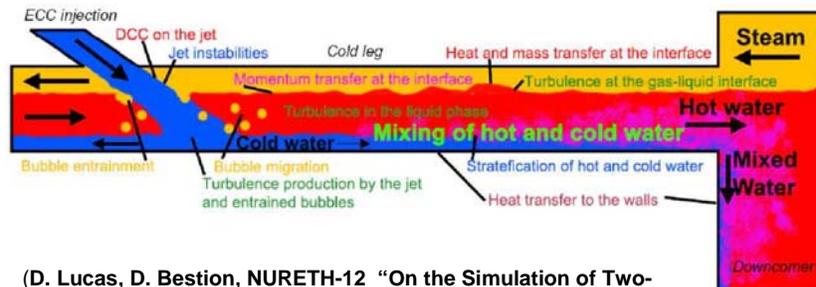
Consider Voided Cold Legs Condensation in Steam (reference. E.F. Hicken, Thicket 2004)



These conditions are far more challenging for codes than the single phase mixing example. Experimental data are limited. Condensation rates, the interfacial area determination, and turbulence issues all play a role. Condensation is the primary mechanism to warm up the injected flow and modeling this process is challenging.

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Partially Voided Cold Legs



(D. Lucas, D. Bestion, NURETH-12 "On the Simulation of Two-Phase Flow Pressurized Thermal Shock (PTS), 2007)

Similar to the fully voided cold leg, these conditions are very challenging for codes. Experiments at full-scale would be cost prohibitive. There are multiple layers of interacting phenomena associated with this problem. Efforts are underway, as outlined in the reference above, to address these issues one by one with the goal of one day providing reliable CFD simulations which integrate all of the complexities of this problem. A review of relevant test data is provided in "Deliverable D2.1.2: Review of the Existing Data Basis for the Validation of Models for PTS" by D. Lucas, 2005.

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TH Experiments

- Experiments play a vital role in the evaluation of PTS events.
 - experiments are typically very expensive
 - useful for validating mixing models or CFD
- A significant number of single phase experiments have been completed.
 - Creare, SAI, Purdue (USA), Belgium, Finland, Japan, COSI (France)
 - HDR and UPTF (Germany) provided full scale data
- Two phase experiments are also underway in many areas.
 - deliverable D2.1.2: Review of the Existing Data Basis for the Validation of Models for PTS” by D. Lucas, 2005
 - separate effects experiments can be used to develop individual closure models for specific physical phenomena of interest
 - Not all phenomena are fully understood at this time
 - integral tests will be needed to test the interactions of the closure models during more realistic scenarios

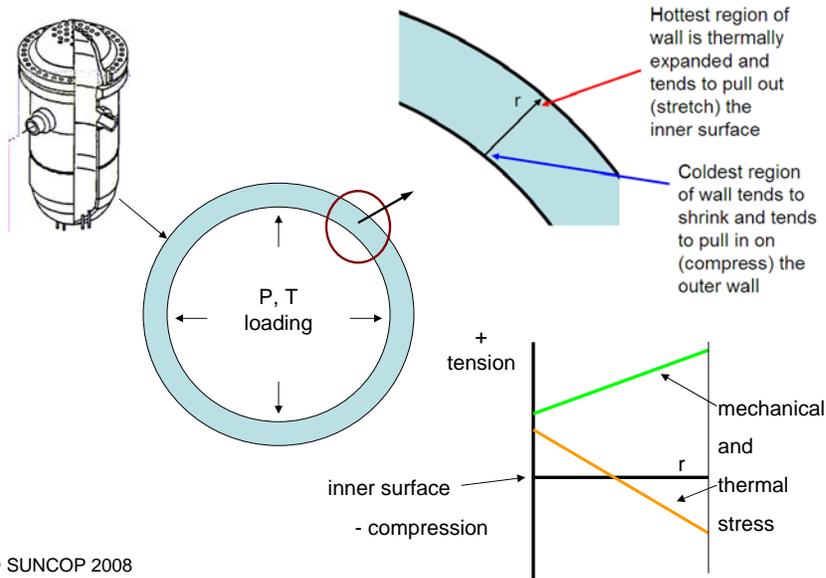
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TH State-of-The-Art

- System codes are needed to predict the overall system response to cooldown events.
 - very efficient, many scenarios can be considered
- Additional analyses are sometimes needed to augment the system code predictions.
 - experimental investigations (very expensive)
 - regional or zonal models of cold leg and downcomer
 - require extensive validation
 - CFD
 - single and two-phase (require validation)
 - relatively expensive (only limited scenarios can be considered)
- Coupled system-CFD codes are being developed to compute the details during the system analyses.
 - coupled stress analysis is also possible
 - coupling brings the expense of CFD to the system codes
 - coupling requires a close look at code to code interactions
- The “user effect” is still an issue. Problem specific best practice guidelines would benefit the analysis of PTS.

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Structural Mechanics- Thermal Hoop Stress

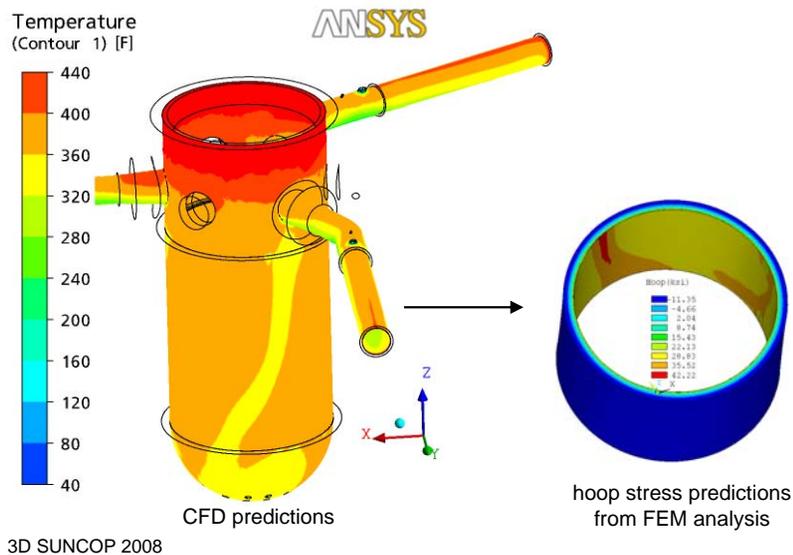


Structural Mechanics

- The pressurized thermal shock to the vessel wall is typically computed using classical 1D or 3D finite element methods.
- The predictions typically use the TH conditions at the inner surface of the vessel wall as boundary conditions.
 - pressure applies the mechanic stresses
 - temperature profiles cause the thermal stresses
- The total stress field is computed as a function of time and location in the vessel wall.

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Coupled Analysis Example (CFD-FEM)



Structural Mechanics (continued)

- The stresses in the unflawed vessel are typically below the yield strength of the material.
- The issue is non-ductile failure initiated at flaw locations where stress is amplified.
- Fracture Mechanics methods are used to compare the fracture toughness (K_{Ic}) of the material to a stress intensity factor (K_I).
 - If $K_I > K_{Ic}$, then crack propagation can initiate

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Fracture Mechanics – K1

- Once the stress field is computed, the stress intensity factor (K1) can be obtained.
 - $K1 = f$ (flaw orientation, flaw geometry, stress field)
 - superposition is used to compute K1 after the stresses are determined for the unflawed geometry
 - K1 can be computed directly if flaw geometry is modeled
 - inner surface breaking flaws are most challenging
 - for uniform vessel conditions (hoop stress > axial)
 - $K1_{\text{axial flaws}} > K1_{\text{circumferential flaws}}$ - due to geometry of vessel
 - During a PTS scenario, K1 varies with time (stress field) for a given flaw location

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Fracture Mechanics – K1c, K1a

- Fracture Toughness (K1c) is obtained from CVN testing or other techniques.
 - based on RTNDT
 - determined as a function of temperature
 - during PTS evaluations, K1c varies with time (temperature) and location.
- Crack Arrest (K1a)
 - if $K1 > K1c$, then the crack initiates
 - if $K1 < K1a$, then the crack arrests
 - many flaws initiate and then arrest deeper into the vessel
 - circumferential flaws are more likely to arrest
 - stress increases on axial flaw as it grows

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Recent US Experience

- The NRC has recently put forth a technical basis to revise the PTS screening criteria based on an updated “risk-informed” PTS analysis of US PWRs.
- General Approach
 - probabilistic risk assessment (PRA)
 - event sequences identified with expected frequency
 - TH evaluation of events
 - similar events represented by single event
 - Probabilistic fracture mechanics (PFM)
 - estimates probability of crack penetrating RPV wall
 - Estimation of through wall crack frequency (TWCF)
 - integration of event frequencies with crack penetration frequencies.
 - TWCF determined as a function of the age of the plant
 - 5×10^{-6} events /year screening limit

(Ref: NUREG 1806 “Technical Basis for Revision of PTS Screening Limit in the PTS Rule: Summary Report”, 2006
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US Experience (part 2)

- Primary breaks dominate the TWCF.
- Secondary side breaks play a smaller role.
- Severity of the transient is controlled by 3 factors.
 - initial cooling rate
 - minimum temperature
 - pressure retained in the primary system
- Significance of a transient depends on these 3 factors and the event frequency.
 - risk informed
- Risk-dominant sequences
 - medium and large primary breaks
 - stuck open primary valve that later recloses

(Ref: NUREG 1806 “Technical Basis for Revision of PTS Screening Limit in the PTS Rule: Summary Report”, 2006
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US Experience (part 3)

Factors contributing to the severity and risk-dominance of various transient classes

Transient Class		Transient Severity			Transient Likelihood	TWCF Contribution
		Cooling Rate	Minimum Temperature	Pressure		
Primary Side Pipe Breaks	Large-Diameter	Fast	Low	Low	Low	Large
	Medium-Diameter	Moderate	Low	Low	Moderate	Large
	Small-Diameter	Slow	High	Moderate	High	~0
Stuck-Open Valves, Primary Side	Valve Recloses	Slow	Moderate	High	High	Large
	Valve Remains Open	Slow	Moderate	Low	High	~0
Main Steam Line Break		Fast	Moderate	High	High	Small
Stuck-Open Valve(s), Secondary Side		Moderate	High	High	High	~0
Feed-and- Bleed		Slow	Low	Low	Low	~0
Steam Generator Tube Rupture		Slow	High	Moderate	Low	~0
Mixed Primary & Secondary Initiators		Slow	Mixed		Very Low	~0
Color Key		Enhances TWCF Contribution		Intermediate	Diminishes TWCF Contribution	

(Ref: NUREG 1806 "Technical Basis for Revision of PTS Screening Limit in the PTS Rule: Summary Report", 2006)

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US Experience (part 4)

- RELAP5 was used to predict the downcomer temperatures and pressures.
 - values passed to probabilistic fracture code (FAVOR)
- Plume (or thermal stripe) strength at the region of the downcomer adjacent to the core was estimated to be less than 10°C from the mean RELAP5 temperature.
 - CFD, experiments, and REMIX approaches were used to support the thermal-hydraulic evaluation
 - downcomer variations were within the uncertainty of the RELAP5 predictions
 - uncertainty was governed by the boundary conditions
- No additional TH analyses (CFD, regional mixing models, etc) were used in the final analyses.
 - RELAP5 predictions deemed to be sufficient

(Ref: NUREG 1806 "Technical Basis for Revision of PTS Screening Limit in the PTS Rule: Summary Report", 2006)
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Structural and Fracture Mechanics **US Experience (continued)**

- For larger breaks the thermal stress is higher than the pressure induced stress.
- For re-pressurization transients (stuck valve closure), the pressure induced stress dominates.
- Destructive Evaluations have looked at flaw geometry, location, and density.
 - flaw density is highest in welds
 - fusion line flaws are most common
 - this means flaws are generally aligned with weld
 - axial weld – axial flaws ; circumferential weld – circ. Flaws
- Axial Flaws dominate the TWCF.

(Ref: NUREG 1806 "Technical Basis for Revision of PTS Screening Limit in the PTS Rule: Summary Report", 2006
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Maintenance and Inspection

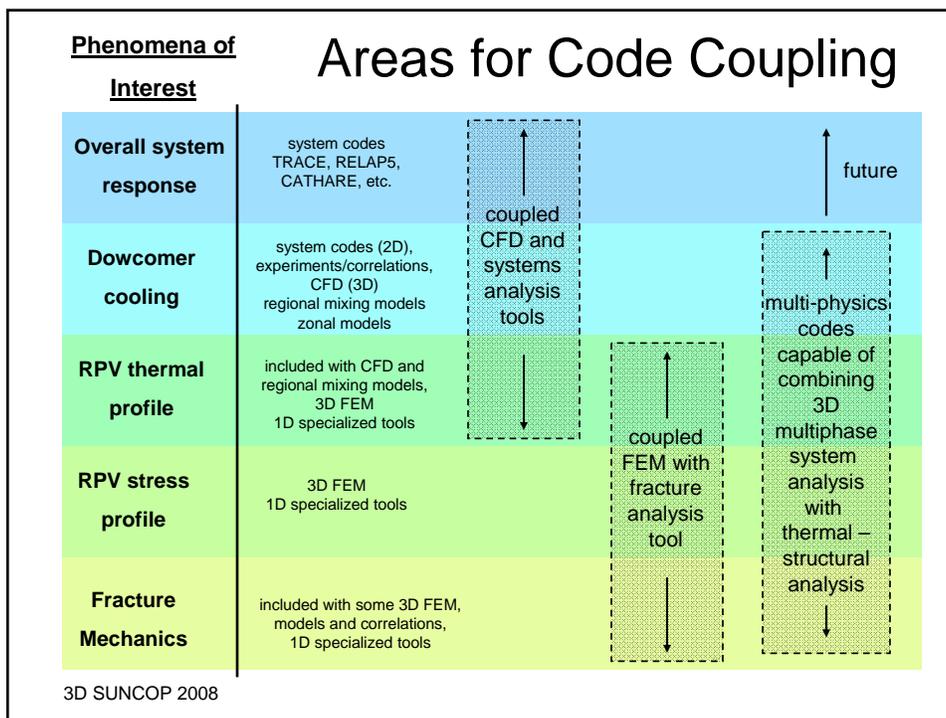
- Typical inspection activities
 - surveillance capsules
 - specimens pulled from capsule and sent for testing
 - fluence monitoring
 - vessel in-service-inspection (ISI)
 - ultrasonic inspection of beltline welds
 - visual inspection at specific intervals
- Maintenance
 - may include additional shielding
 - annealing the vessel is an option

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Safety and Mitigation

- Mitigation strategies for PTS have been considered.
 - neutron shielding to delay embrittlement
 - spot fluence reduction at key welds
 - annealing the vessel
 - heating the safety injection water or limiting the flow rates
 - low leakage cores (limiting neutron flux)
- Other mitigation items
 - reactor vessel vent valves
 - tripping feedwater pumps on high SG levels
 - isolation of steam generators during MSLB
 - reduced HPI flow during small LOCAs
 - operator actions are less important for medium to large breaks
- The desire to flood a reactor system with cold water to avoid a core damage scenario must be tempered with the knowledge of PTS and its implications.

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System Code – 3D Mixing Models Coupling Options

- It is common for 3D mixing models or CFD to be used to augment the system code predictions during PTS.
 - Manual 1-way coupling is common.
 - boundary conditions are passed from system codes to CFD or regional mixing models (no feedback)
 - Direct code coupling tools are available and may provide an improved tool for predicting the TH conditions during PTS scenarios.
 - The FLUENT-RELAP5 code coupling is one example of this type of direct coupling.

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TH : One-Way Code Coupling (Some Considerations)

- Engineering judgment is required to “prepare” boundary conditions taken from one code and applied to another.
 - Are oscillations real?
 - What additional values are needed? (turbulence, profile shapes, etc..)
- One-way coupling does not provide feedback to the overall system behavior based upon the impact of the 3D mixing.

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TH : Two-Way Code Coupling (Some Considerations)

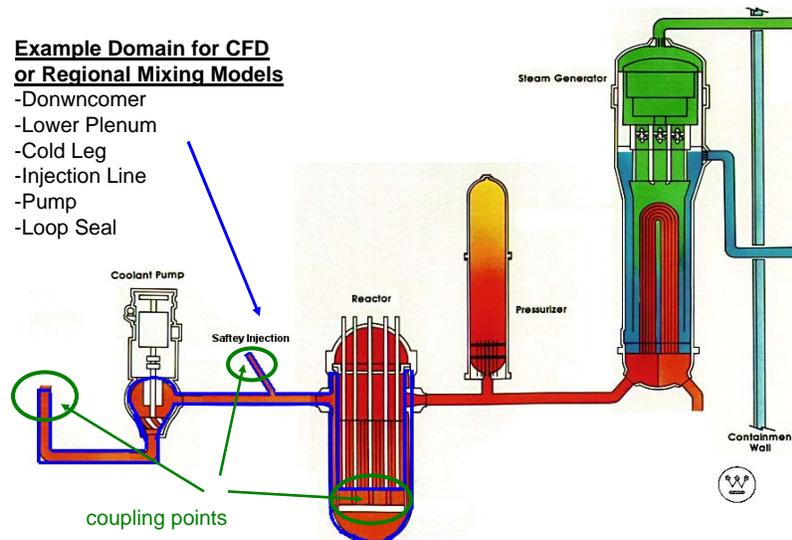
- Two-way coupling provides feedback to the system response related to the 3D behavior of the system in a local region.
- Coupling points need to be selected carefully?
 - conditions should be well defined and the codes should be consistent in that region.
 - flow in 1 direction
- Engineering judgment is still needed to “prepare” the boundary conditions even for two-way couplings.
 - Are system code oscillations physical, numerical, or an effect of some 1D modeling assumption?
 - How do you go from 1D to 3D?
 - profiles, additional terms, etc.

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TH: Code Coupling Boundaries

Example Domain for CFD or Regional Mixing Models

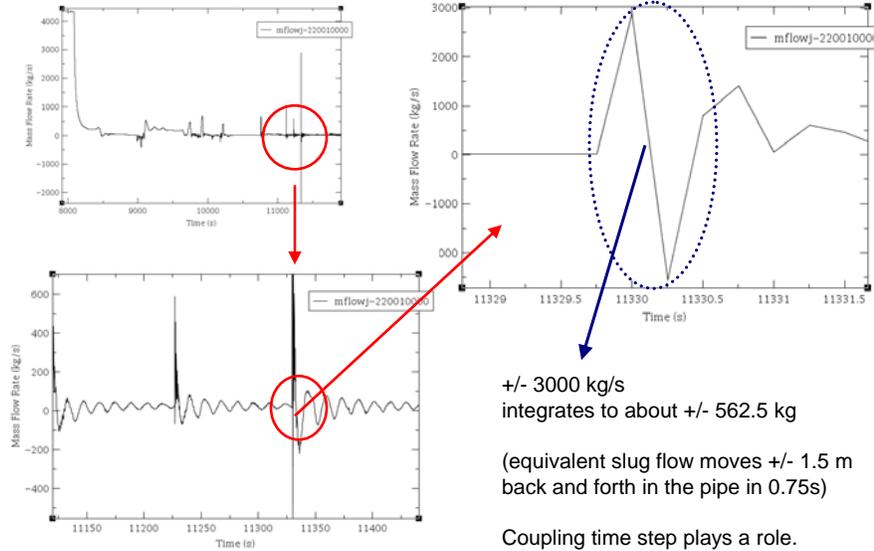
- Downcomer
- Lower Plenum
- Cold Leg
- Injection Line
- Pump
- Loop Seal



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Consider System Code Oscillations

Cold Leg Mass Flow (RELAP5 – 2" HL SBLOCA)



+/- 3000 kg/s
integrates to about +/- 562.5 kg
(equivalent slug flow moves +/- 1.5 m
back and forth in the pipe in 0.75s)
Coupling time step plays a role.

TH: Code Coupling Summary

- System code to regional mixing code (ie: CFD) couplings are available.
- One-way coupling is common
- Engineering judgment is needed at the interface.
 - this is not a simple plug-in solution
 - Oscillations and code differences need to be considered
- Two-way coupling can provide feedback to the system response based on more detailed analysis of the 3D flows and mixing in the cold leg and down comer region.
 - although automated, this approach still requires a great deal of user attention at the interfaces between the codes

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Coupling of Multi-Physics tools Fluid Mechanics and Stress (FSI)

- Tools are available to provide a means of coupling fluid flow predictions with FEM predictions in the solid wall.
 - FSI – Fluid Structure Interactions
- Commercial codes offer this type of coupling.
 - ANSYS
 - CFD/FEA
 - CD Adapco
 - StarCD – ABAQUS (FEM)
 - Starccm+ - Finite Volume Solid Stress

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Example: ANSYS FSI

- ANSYS offers 1 and 2 way coupling between a Finite Element Solver and either CFX or FLUENT.
- Mesh does not have to be conformal.
- CFX-FEA link built into the ANSYS workbench.
- FLUENT-FEA link is currently more explicit but will be upgraded in V12.
- Codes communicate within each time step to avoid explicit instabilities.
- Control provides options to couple in many different ways.

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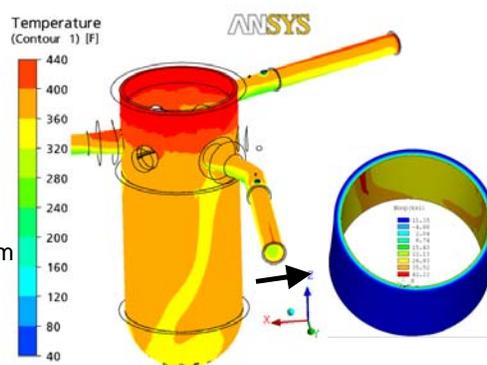
Example: CD-Adapco FSI

- STAR-CD is coupled internally to a finite volume stress code.
- Additional stress options available via STAR-CD – ABAQUS coupling.
- Corrections applied during the iterations for a given time step to provide implicit coupling behavior.
- Starccm+ code also coupled to finite volume stress tool for FSI.

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FSI Coupling for PTS

- 1 – way coupling is sufficient.
 - stress does not impact the flow field.
 - can be done in serial
- In this example, solid wall temperature profile was computed using CFD tool.
 - Stress computed directly from CFD prediction of $T(x)$ and the applied pressure.
 - Could have applied thermal conditions to boundary of FEA model and let FEA model determine the thermal profile and stress.



CFD Prediction >> FEA Stress

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Summary

- PTS is a plant specific issue
- PTS is a multi-disciplined problem that challenges the vessel.
 - a most critical component in the RCS boundary
- Tools available for PTS evaluations are continuing to improve.
 - Coupled system-CFD tools may provide advantages for PTS evaluations when system code assumptions are violated in the area of interest.
 - 3D mixing and entrainment issues
 - counter-current flows in the cold leg and downcomer region
 - TH tools, especially in the area of two phase flows, are under significant development and will provide improved predictions of downcomer cooling in the future
 - direct contact condensation
 - Two-phase mixing and turbulence issues
 - Coupled TH-stress tools (FSI) are available but are not necessary for accurate PTS simulations.
 - stresses don't interact with FLUID boundary conditions
- The nuclear safety community will benefit from specific “best practice guidelines” for code coupling and CFD related issues.

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