

11A: Evaluation of Pressurized Thermal Shock

Interactions of Thermal-Hydraulics with Fuel Behavior,
Structural Mechanics, and Computational Fluid Dynamics

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Outline

- General overview
 - What is PTS?
- Root Cause
 - reduced fracture toughness (embrittlement)
- Scenarios
- Analysis Approach and Tools
- Recent NRC evaluation of PTS
 - revised PTS rule
- Code Coupling Considerations
- Summary

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 concern related to PTS.
 - RPV wall **embrittlement** due to neutron irradiation
 - some type of **existing flaw** in the RPV wall or weld region
 - 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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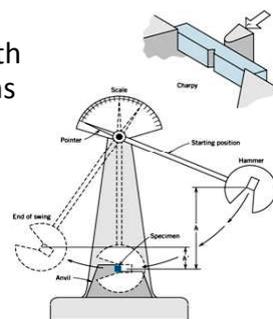
Status in the U.S.

- 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, have been completed to support a revision to the PTS rule.
- The supporting calculations demonstrate that the likelihood of vessel failure due to PTS for all US PWRs is extremely low
 - $\sim 10^{-7}$ /year at 60 years
- References:
 - NUREG-1806 “Technical Basis”
 - NUREG-1874 “Screening Limits”
 - CFR; Federal Register, Vol. 75, No. 1, Monday, January 4, 2010

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Root Cause – Reduced Fracture Toughness

- 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 (i.e. hardening or reduced toughness).
 - hardening starts at the nanometer level
- Reduced toughness 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 toughness.
 - used in all surveillance programs

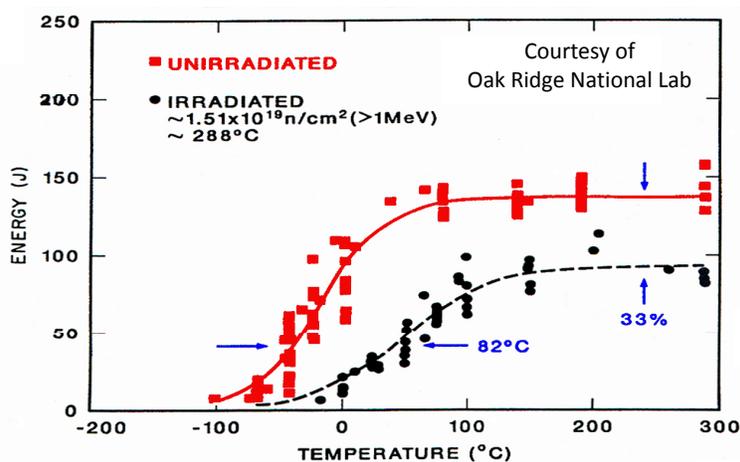


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Charpy V-Notch Impact Energy Curve

(example for one specific steel)



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

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The PTS Concern

- The reduced fracture toughness of a reactor vessel caused by decades of exposure to Neutron radiation could lead to brittle fracture during a rapid cooldown event.
- If a hot RPV wall that has significantly reduced fracture toughness is (1) exposed to a sudden drop in water coolant temperature and (2) contains small flaws in the wall or weld regions, the small flaws could grow into cracks that extend through the RPV wall.
 - flaws are typically associated with manufacturing or weld defects

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Overcooling Is a Possibility

- 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 scenarios have been postulated that can lead to overcooling events in PWRs.

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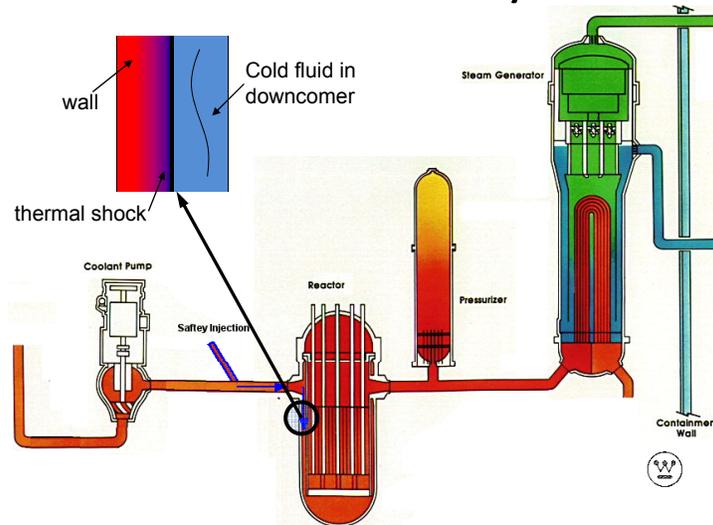
A PTS Scenario (primary side break)

- 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 injection)
 - significant cool down in the downcomer
- Relatively cold water at the RPV wall can challenge the integrity of the vessel under specific conditions.
 - neutron embrittlement
 - flaws (weld flaws, other)
 - thermal shock with sufficient pressure loading
- Isolation of the break and re-pressurization after a significant cooldown is a concern.

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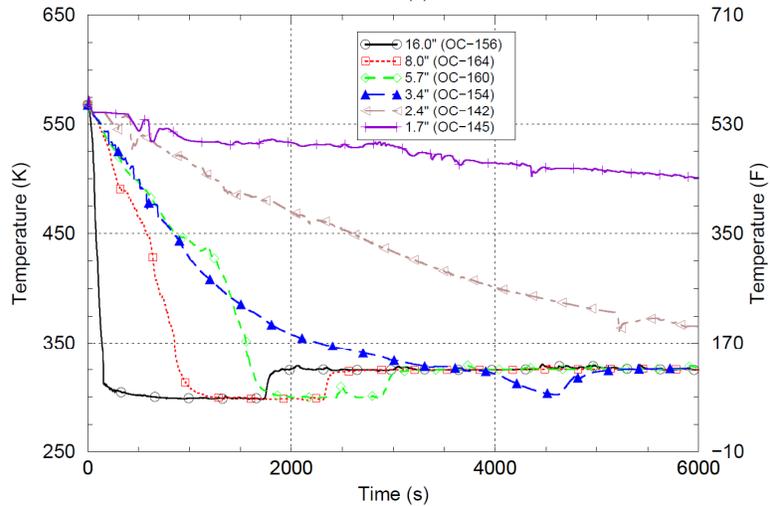
Reactor Coolant System



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Cooldown Rates for Various HL/SL Breaks



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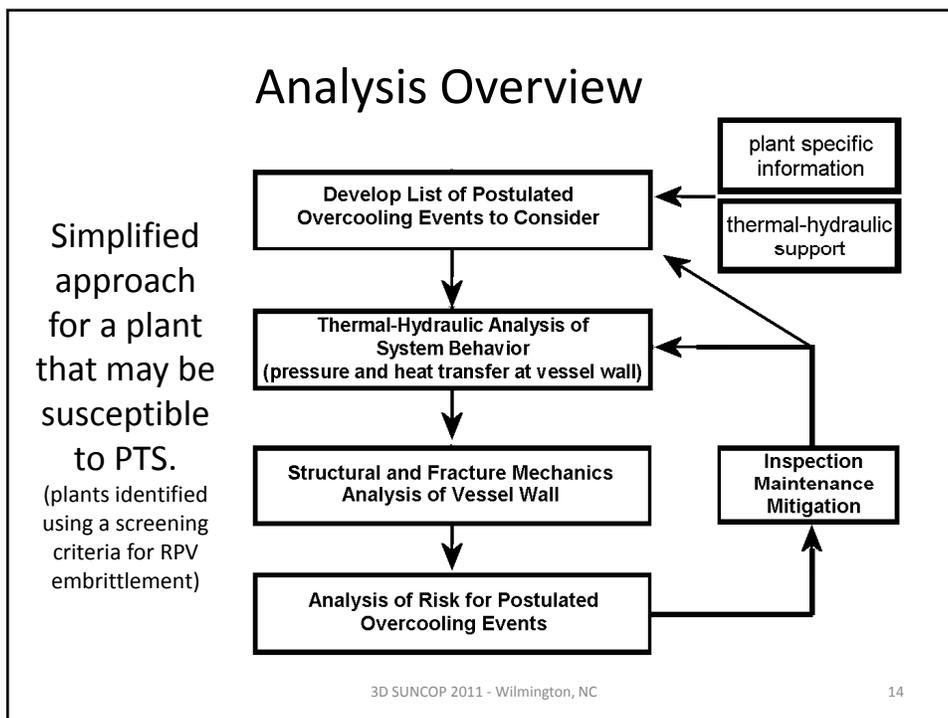
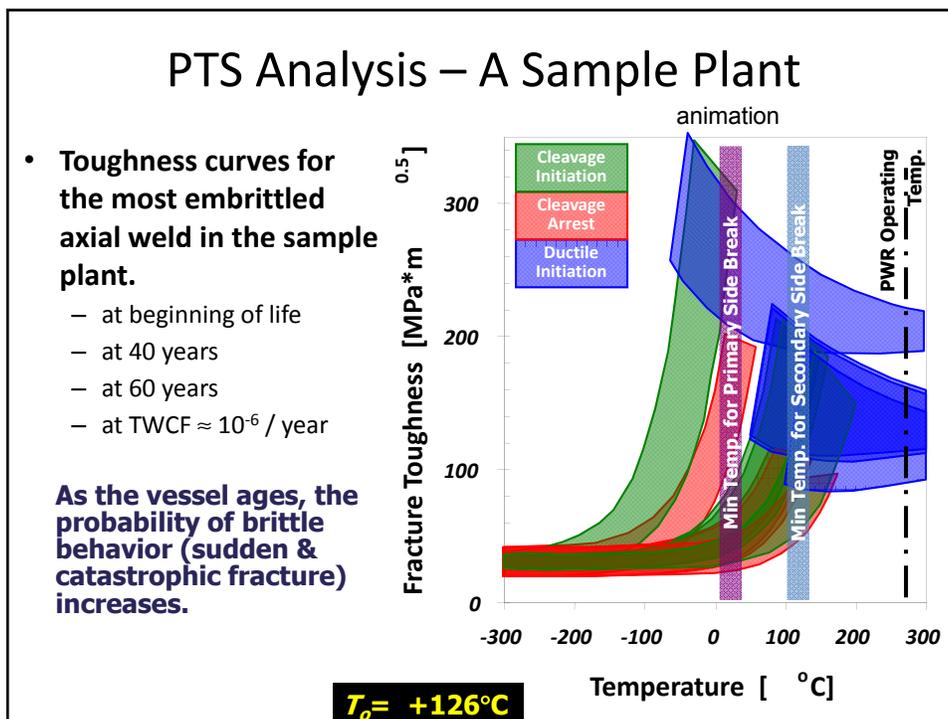
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A PTS Scenario (secondary side break)

- 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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Thermal-Hydraulic Analysis

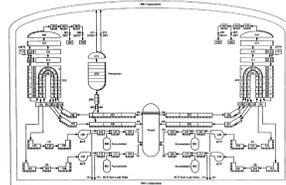
- Given a specific plant with specific material properties (flaws, embrittlement, etc), the goal of the thermal hydraulic analysis is to predict the thermal and mechanical boundary conditions (pressure, temperature, and heat transfer) at the inner surface of the RPV wall that could lead to a pressurized thermal shock.

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Prediction of System Response

- Plant response to postulated overcooling events is computed using systems codes.
 - TRACE, RELAP5, CATHARE, ATHLET, etc.
- Plant specific issues are important.
 - accumulator and safety injection flows
 - location, flow rates, injection 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
- In addition to the “typical” challenges related to system code modeling of transient behavior, there are some additional challenges related to the specific nature of the PTS issue.



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PTS Specific Thermal-Hydraulic Challenges

- System codes provide the overall system response but are not usually well suited for providing local conditions in specific regions.
 - 3D effects
 - cold plumes
 - turbulence
 - mixed convection
 - two-phase flow (saftey injection into hot leg)
 - direct contact condensation

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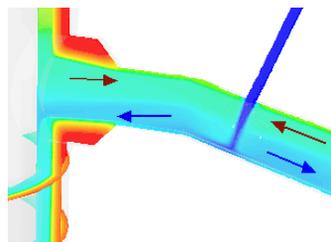
Additional TH Issues

- System code predictions may need to be augmented if the underlying models are not applicable to the physical behavior.
 - 3D behavior may be important
 - multi-phase correlations may be inadequate
- Additional analyses are typically carried out in the cold leg and downcomer region. These analyses typically include models tied to experimental results.
 - regional mixing models and zonal models
 - single-phase CFD for turbulent mixing and plumes
 - multi-phase CFD for condensation and mixing
 - used when cold leg (and downcomer) may be voided
- The updated analyses are typically used to patch (correct) the system code results or may be used to update the system code models directly.
- Direct coupling of CFD tools or regional mixing models with system codes is another option that is considered.
 - coupling provides feedback from the local mixing regions to the overall system response but may be difficult to implement effectively

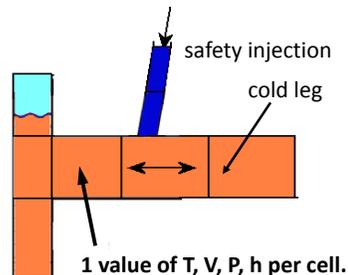
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Consider Safety Injection in Cold Leg



CFD Prediction of cold injection into stagnant cold leg



system code representation of injection into stagnant loop

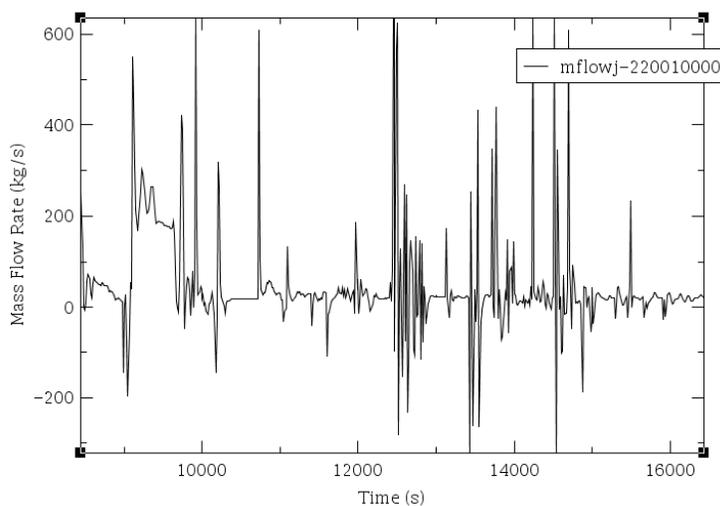
- The 1D pipe components common to system codes cannot predict the stratification and counter current flow expected in the cold leg and downcomer.

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Cold Leg Mass Flow Prediction

(Relap5 1D model – 2" hot leg SBLOCA)

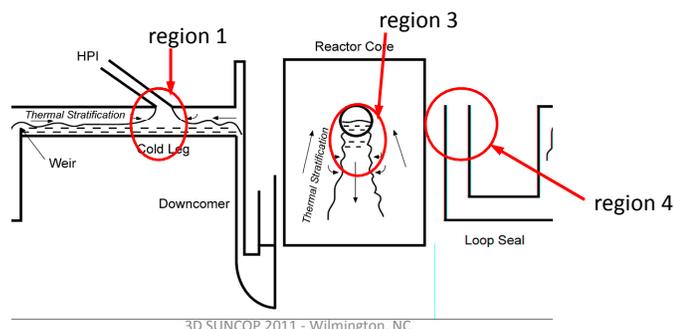


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Regional Mixing Models

- 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 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.



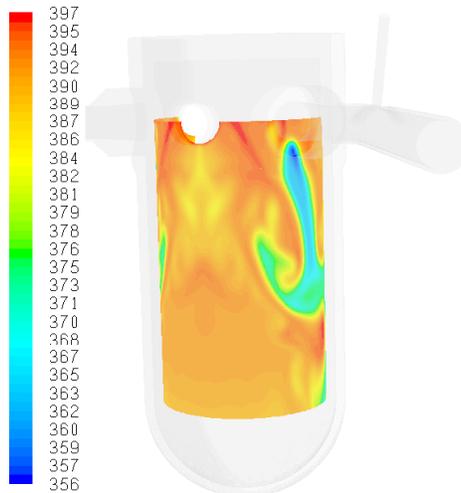
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Computational Fluid Dynamics (CFD) provides insight into the 3D behavior (single phase)

- 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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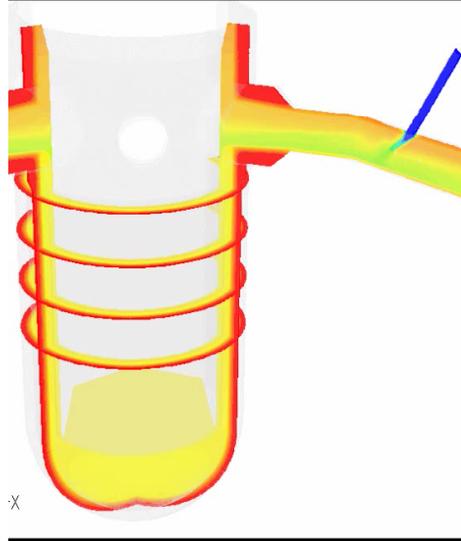
CFD – Single Phase Safety Injection

Temperature contours (blue-cold; red-hot) on the hot leg centerlines and on four horizontal rings in the downcomer region.

Boundary conditions associated with a 2 inch hot leg break.

The cold leg flow is gradually reduced to zero (net) and the stratification in the cold leg increases as the flow rate is reduced.

This particular model includes a thermal shield in the downcomer.



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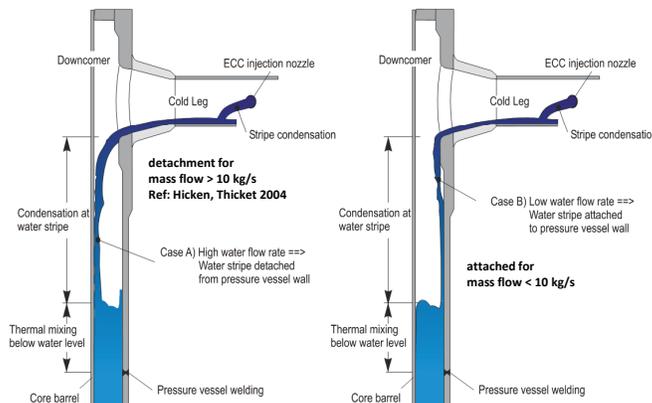
TH – CFD Considerations

- 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 has been accomplished
 - 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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Large Breaks lead to Voided Cold Legs

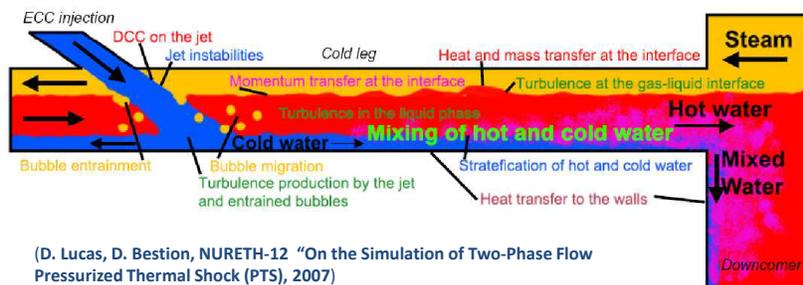


These conditions are far more challenging for codes than the single phase mixing example. Experimental data are limited. Condensation rates, the interfacial area determination, and turbulence issues all play a role. Condensation is the primary mechanism to warm up the injected flow and modeling this 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 methods
- 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
 - Many of these phenomena can be predicted individually
 - integral tests will be needed to test the interactions of the closure models during more realistic scenarios

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TH Overview

- System codes are needed to predict the overall system response to cooldown events.
 - very efficient, many scenarios can be considered
- Additional analyses are needed in many cases to augment the system code predictions.
 - experimental investigations (expensive)
 - regional or zonal models of cold leg and downcomer
 - require extensive validation – efficient operation (minutes)
 - CFD
 - single and two-phase (require validation)
 - long run times (only limited scenarios can be considered)
 - “user-effect” is an issue. PTS specific best practice guidelines are needed.
- Coupled system-CFD codes are being developed to allow the prediction of 3D behavior in a portion of the system domain.
 - coupling brings the expense of CFD to the system codes
 - coupling requires a close look at code to code interactions
 - coupled thermal and stress analysis of the wall is also possible

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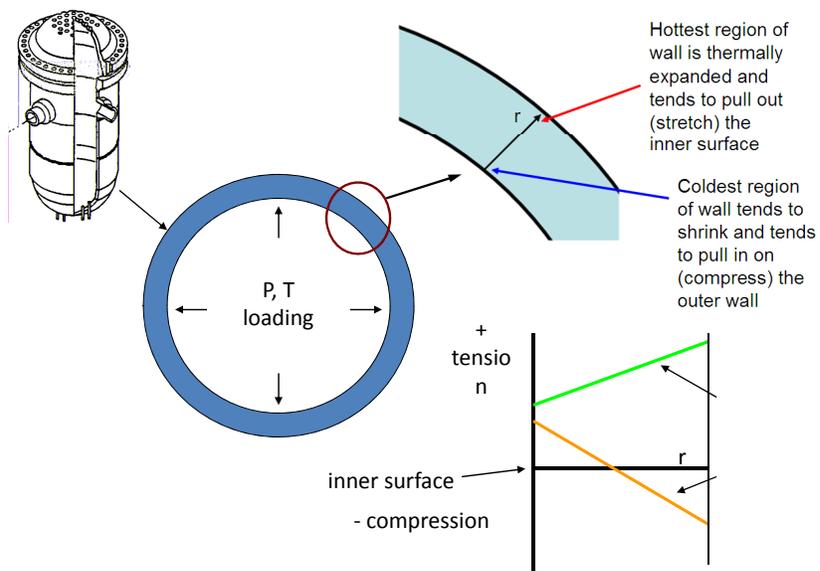
Stress and Fracture Mechanics Analysis

- Given a specific plant with specific material properties (flaws, embrittlement, etc), the goal of the stress and fracture analysis is to predict possible crack growth initiation (and arrest) in the vessel wall due to the thermal and mechanical boundary conditions (pressure, temperature, and heat transfer) at the inner surface of the RPV.

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Structural Mechanics (vessel stress)



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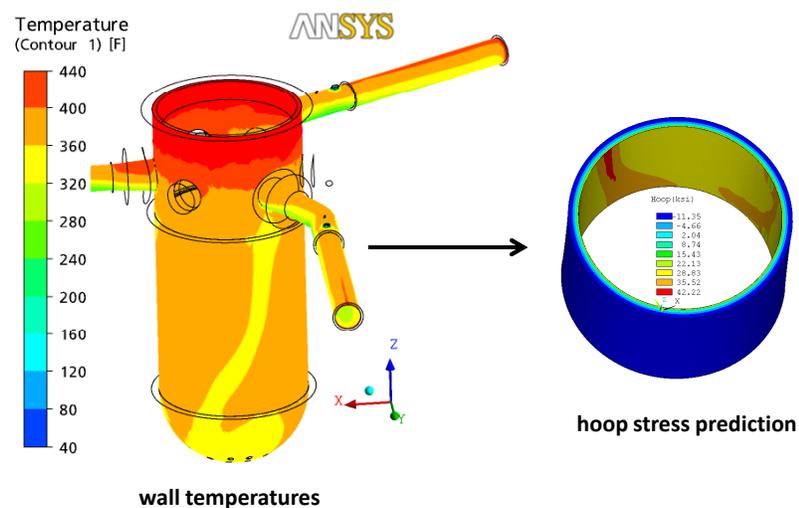
Stress Analysis

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

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Stress Analysis Example (a coupled CFD-FEM model)



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Stress Analysis to Fracture Mechanics

- The stresses in the unflawed vessel are typically below the yield strength of the material.
- The issue is non-ductile failure initiated at crack tips where stress is magnified.
- 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 – KI

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

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Fracture Mechanics – K_{Ic} , K_{Ia}

- Fracture Toughness (K_{Ic}) is obtained from CVN testing or other techniques.
 - based on RTNDT property
 - a function of temperature
 - during PTS evaluations, K_{Ic} varies with time and location (due to temperature and property variations)
 - if $K_I > K_{Ic}$, then the crack initiates
- Crack Arrest (K_{Ia})
 - if $K_I < K_{Ia}$, 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 flaws as they grow

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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
 - 1×10^{-6} events /year screening limit
- References (www.nrc.gov)
 - NUREG-1806 “Technical Basis”
 - NUREG-1874 “Screening Limits”
- Code of Federal Regulations
 - Federal Register, Vol. 75, No. 1, Monday, January 4, 2010

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US Experience (continued)

- 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

US Experience (continued)

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)

US Experience (thermal-hydraulics)

- 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

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US Experience (structural analysis)

- 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.

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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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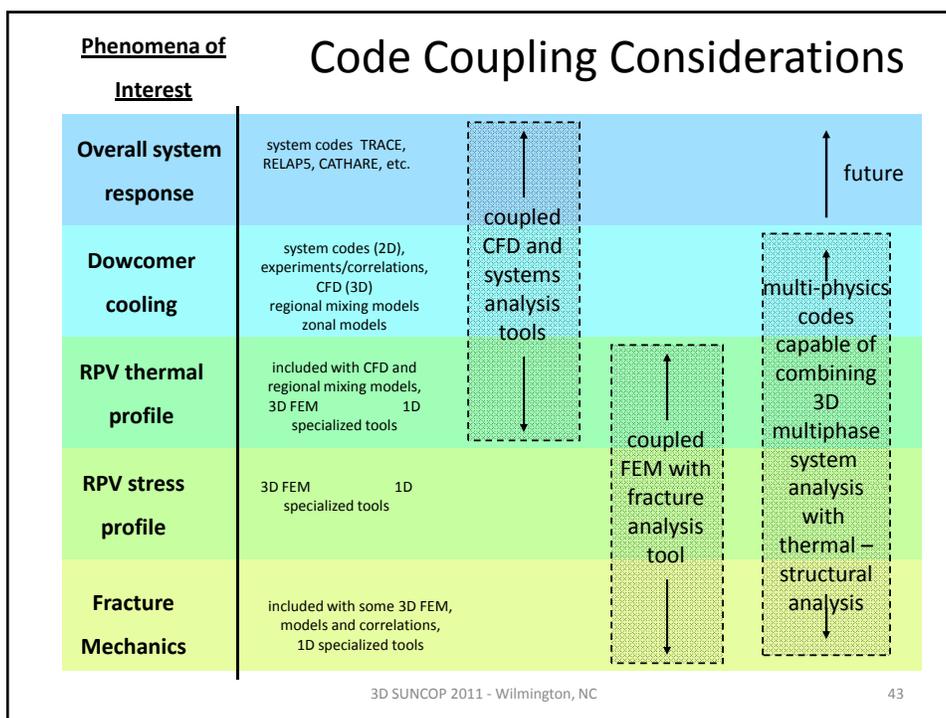
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Mitigation Considerations

- 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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Coupling System Codes – Mixing Model

- 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 most 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.
 - Special care is needed for either coupling approach

TH: Manual One-Way Coupling

- 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: Direct Two-Way Coupling

- 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.

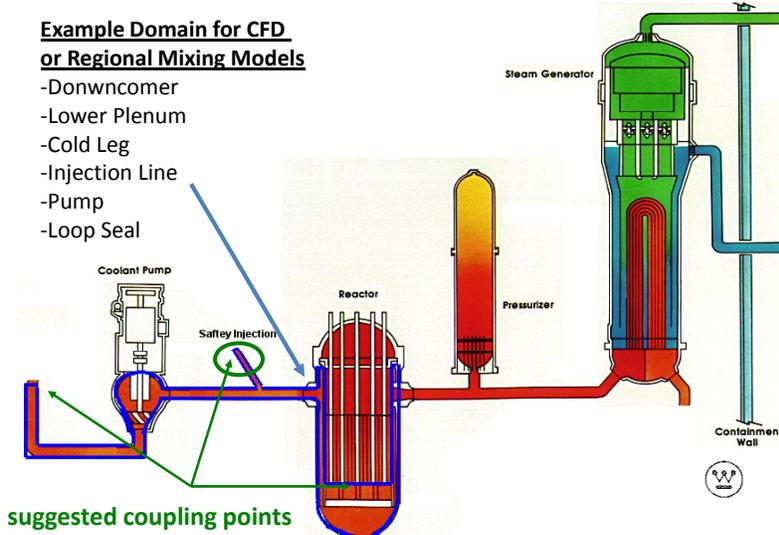
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TH: Code Coupling Boundaries

Example Domain for CFD or Regional Mixing Models

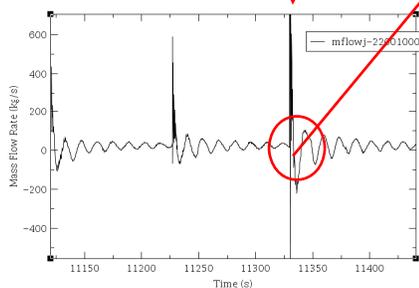
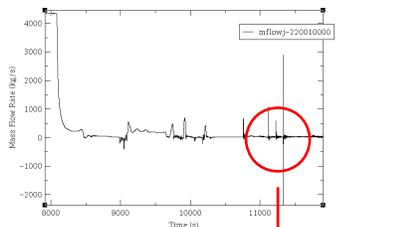
- Downcomer
- Lower Plenum
- Cold Leg
- Injection Line
- Pump
- Loop Seal



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Consider Oscillations



RELAP5 2" HL SBLOCA cold leg mass flow

- Oscillations reaching +/- 3000 kg/s
- Integrates to +/- 500 Kg moving back and forth in pipe
- In many cases, these types of oscillations can be traced to code limitations such as the 1D cold leg component or some other model.
- Engineering judgment is needed for code coupling

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TH: Code Coupling Summary

- System code to regional mixing code (ie: CFD) couplings are available.
- One-way coupling has been most common
- Engineering judgment is needed at the interfaces
 - oscillations and code limitations 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
 - this is not a simple plug-and-play solution

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Fluids - Structural Coupling

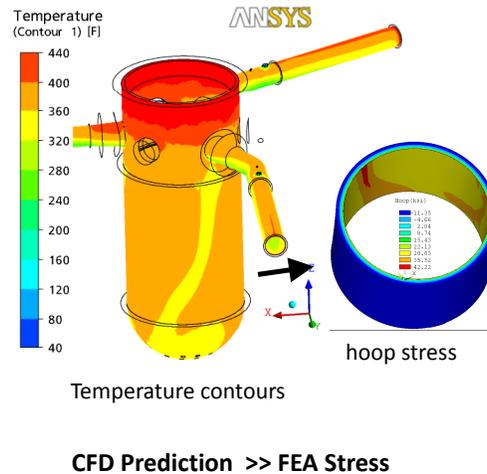
- Tools are available to provide a means of coupling fluid flow predictions with FEM predictions in the solid wall.
 - FSI – Fluid Structure Interactions
- Commercial codes offer this type of coupling.
 - ANSYS
 - CFD/FEA
 - CD Adapco
 - StarCD – ABAQUS (FEM)
 - Starccm+ - Finite Volume Solid Stress

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Fluid Structure Interaction

- 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.



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Summary

- PTS is a plant specific issue brought about by radiation embrittlement
- PTS is a multi-disciplined problem that challenges the vessel.
 - a 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 larger breaks when the cold leg is voided.
 - direct contact condensation
 - two-phase mixing and turbulence issues
 - Coupled TH-stress tools (FSI) are available but are not necessary for accurate PTS simulations.
 - one way coupling is sufficient
- Future analyses of PTS will benefit from PTS specific “best practice guidelines” for system codes, CFD, code coupling, and related issues.

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