CFD FOR
NUCLEAR REACTOR SAFETY APPLICATIONS
(CFD4NRS-3) WORKSHOP

Challenges for the Extension of Limited Experimental Data to Full-Scale Severe Accident Conditions using CFD

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CFD4NRS-3
September 14-16 2010

Introduction

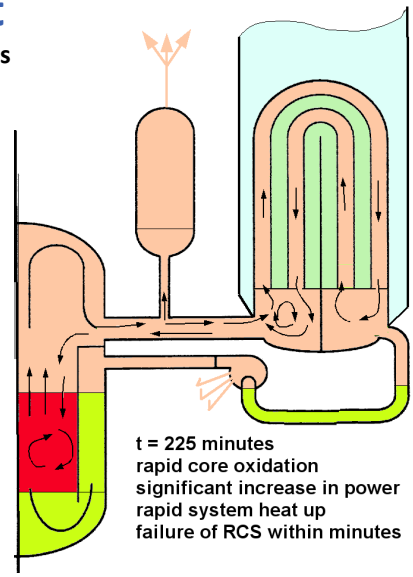
- The NRC has been studying thermal-hydraulic phenomena related to low-probability **severe accident induced failure** scenarios in pressurized water reactors (PWRs).
- These scenarios are important because of the potential for containment bypass caused by an induced steam generator (SG) tube failure.
- Severe accident analysis tools such as MELCOR or SCDAP/RELAP5 (and others) are used to predict the system behavior during these types of events.

A Scenario of Interest

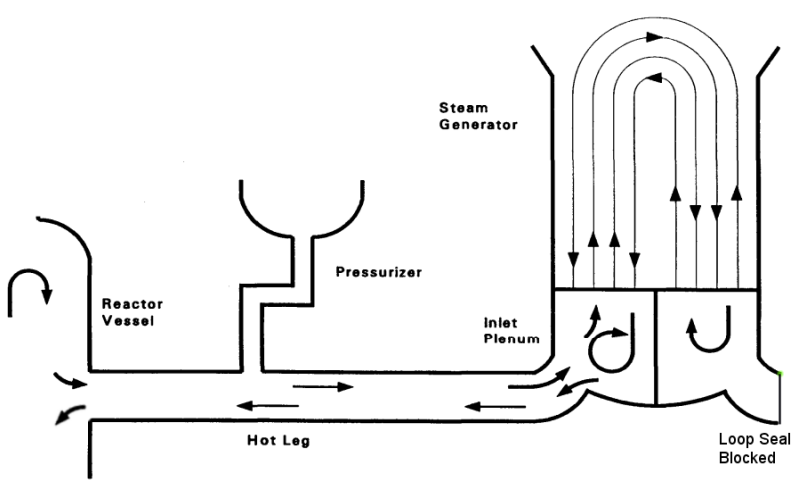
station blackout with additional failures

- loss of offsite power, failure of diesel generators to start, and failure of all auxiliary feedwater systems
- primary inventory lost through reactor coolant pump seal LOCA and secondary inventory is boiled off
- secondary system dries out and safety relief valves start cycling, primary inventory lost through valve cycling and pump seal LOCA
- loop natural circulation stops as primary inventory falls, inventory falls below hot leg
- natural circulation of superheated steam begins, core and system heat up.
- core uncovers, core oxidizes and produces significant power, system heat up accelerates and induced failure is predicted for RCS components.

More likely scenarios involve some auxiliary feedwater or operator actions that significantly delay and/or eliminate the failures.

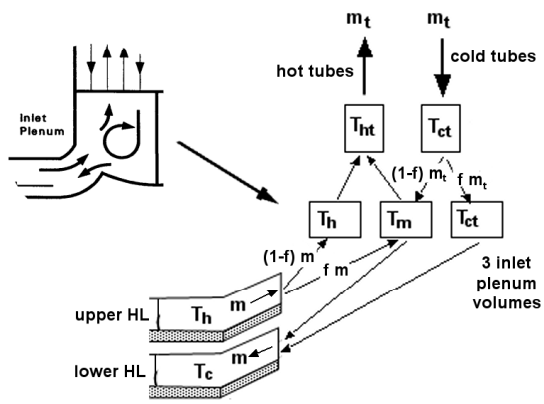


Flow Pattern of Interest

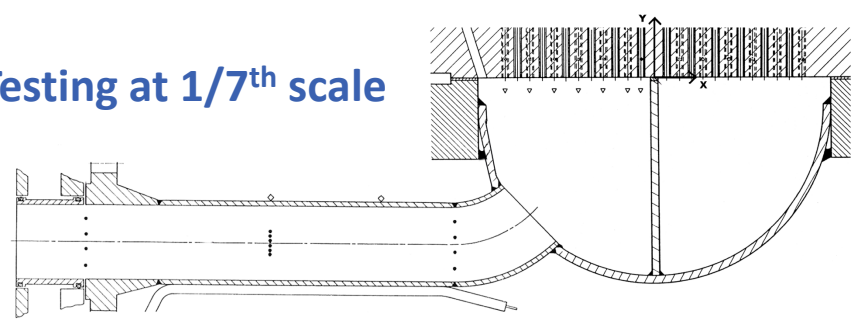


System Code Modeling for Inlet Plenum

Loop flows are modeled with a split hot leg and a split tube bundle connected by mixing volumes in the inlet plenum. Flow splits (i.e. mixing fractions) are determined from experimental results and/or 3D code simulations.



Testing at 1/7th scale



- 1/7 scale based upon Westinghouse model 44/51 SG
- SF6 for working fluid
- includes ½ of the vessel and 216 SG tubes
- steady and transient tests
- temperature measurements
- used as basis for mixing and entrainment as well as a benchmark for CFD and systems codes

Encouraging Results at 1/7th Scale

Parameter	Westinghouse 1/7th Test Data*	FLUENT Prediction	Difference
Heat Loss at Tubes (kW)	3.56	3.69	3.7 %
# Hot Tubes	75	82	7 tubes (3.2%)
# Cold Tubes	141	134	-7 tubes
T_h Hot Leg (average Hot T (°C))	159.3	155	-4.3 °C
T_c Hot Leg (average Cold T (°C))	86.8	80.1	-6.7 °C
m Hot Leg (mass flux (kg/s))	.06	.0586	-2.3 %
T_{hl} Tubes (average Hot T (°C))	100.8	100	-0.8 °C
T_{cl} Tubes (average Cold T (°C))	64.7	64.7	0
m_t Tubes (mass flux (kg/s))	0.12	0.1206	0.5 %
m_t/m (recirculation ratio)	2.01	2.06	2.5 %
f (mixing fraction[2])	0.85	0.81	-4.7 %

Reference: NUREG-1781

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Limitations of Test Data

Scaling issues
- inlet plenum geometry
- SG tube heat transfer rates
- Re, Gr, etc.

Instrumentation
- mass flows inferred from energy balances
- limited thermocouple readings
- lack of measurements in mixing region
- lack of repeatability / uncertainty estimate

A "lack of experiments under reactor conditions" leads to the need for CFD predictions
- assessment of CFD for NRS Problems (NEA/CSNI/R(2007)13, pg. 32)

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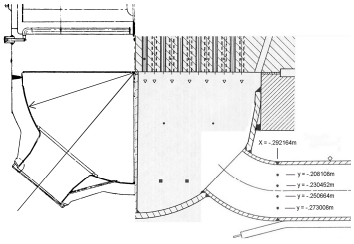
Benefits of CFD

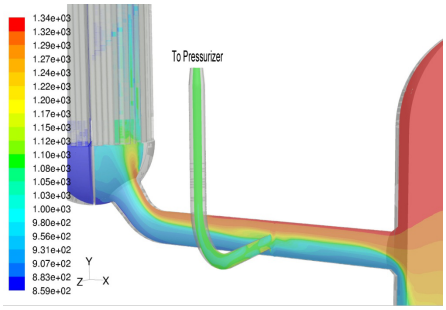
- improved understanding of complex flow field
- detailed variations across tubes and hot leg
- sensitivity studies are completed that are not included or possible in test program
- mixing model improvements and testing
- variations in geometry are easily considered
- full-scale modeling under severe accident conditions
  - high temperatures, steam-hydrogen mixture

Initial Full-Scale Studies



Lessons Learned

- geometry is important
- hot leg entrainment is significant
- flows can be unsteady
- SG heat transfer is important



Updated Model Development

Lessons Learned
- 1/7th scale benchmark exercise
- initial full-scale modeling exercise

State of the art – recommendations (NEA/CSNI/R(2007)13
- main difficulties
  - include hot leg, pressurizer surge line, and primary side of SG
  - include heat exchange with structures
  - at high temperatures, include radiation
  - fluid properties, consider hydrogen
- applications require
  - validated models for mixing and stratification
  - validated radiative exchange model
  - simplified but accurate representation of the tube bundle
  - validated models of depresurization induced by opening safety valves.

Geometry Considered

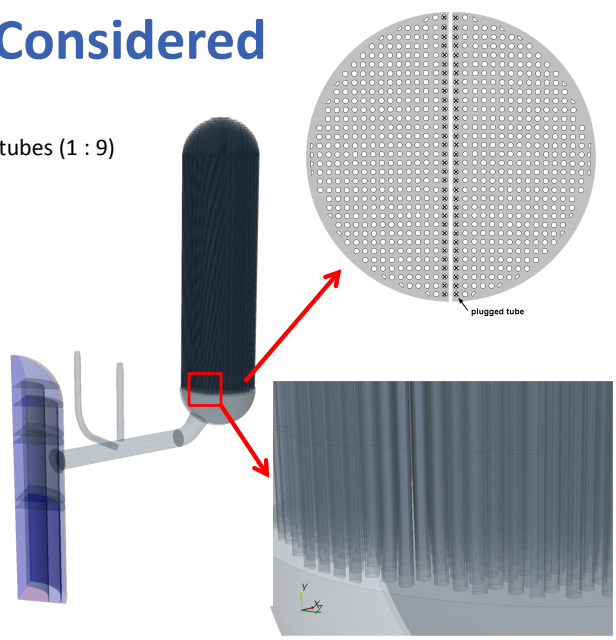
Primary side of SG
- reduced number of tubes (1 : 9)

Hot leg

Surge line
- top, side, or none

Vessel upper plenum
- portion of vessel added
- loop flow is buoyancy driven

Finite volume mesh
- GAMBIT
- hex-dominant
- 7.8 million cells

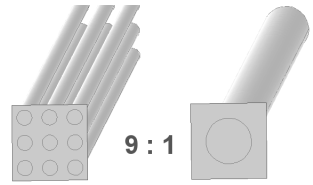


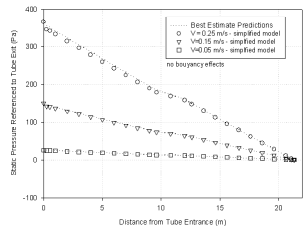
Tube Bundle Model

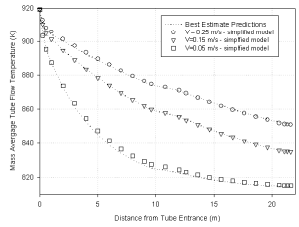
Design Goals
- match flow area, height, pressure drop, and heat transfer rates
- mesh size limited to allow multiple predictions within reasonable timeframe.

Approach
- reduced number of tubes
- porous media models applied in tube region
  - augments pressure drop
  - augments heat transfer rate
- development of porous media constants based on comparison of prototypical tube model with simplified tube model over range of interest

Results
- match flow area, height, pressure drop, and heat transfer rates (i.e. temperature drop along tubes)







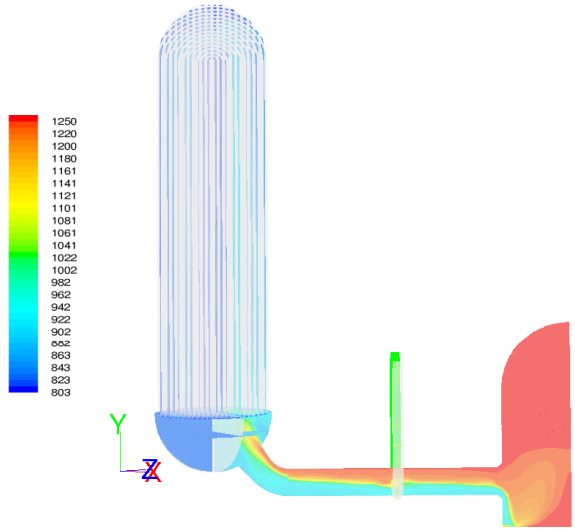
Model Selection

Model selection based on experience and guidelines
- 1/7th scale benchmark exercise
- initial full-scale modeling exercise
- Best Practice Guidelines.. CFD in NRS applications (NEA/CSNI/R(2007)5

FLUENT 6.4 model selections
- transient RANS, 0.05s time step, steady BC's
- ¼ symmetry for vessel region
- Reynolds stress turbulence model, with buoyancy effects
- temperature dependent properties, steam and hydrogen
- segregated solver, 2nd order differencing
- gravity, porous option for tubes

Overview of Predictions

Temperature contours on vertical plane through hot leg axis.



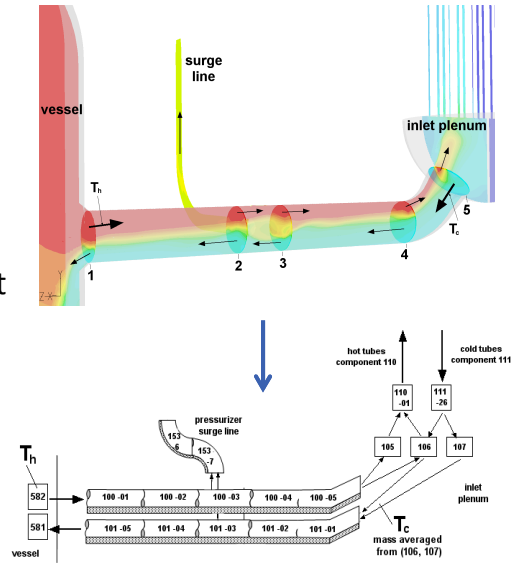
Analysis of Results

Simulations are run to ensure steady average behavior and time step convergence

- multiple (40 or more) snapshots at 1 or 2 second intervals are used to determine average system behavior
- mass flow and temperature for each tube is monitored at 0.1 second intervals
- mixing and entrainment as well as temperature variations are determined from the averaged behavior

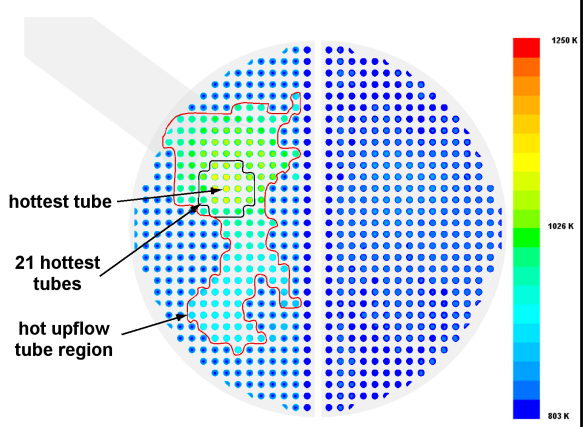
Results for System Codes

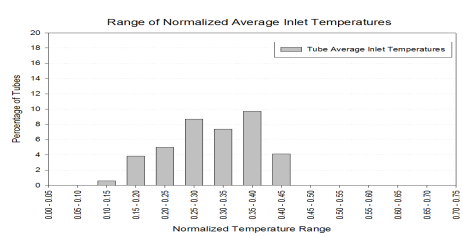
- hot leg flow rate correlation
- surge line flow/temperature
- mixing and entrainment in the hot leg and inlet plenum
- SG tube bundle flows and flow area
- hot-tube distributions



Hot Tube Variations

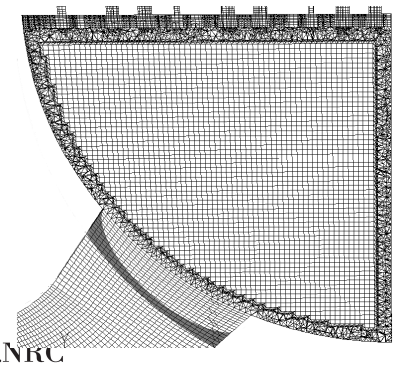
- The predictions provide a distribution of temperatures across the tube bundle. The number and location of tubes within specific temperature ranges is predicted to support the determination of tube failure probability.
- Temperatures are normalized and binned into ranges for easy adaptation to transient system code predictions.

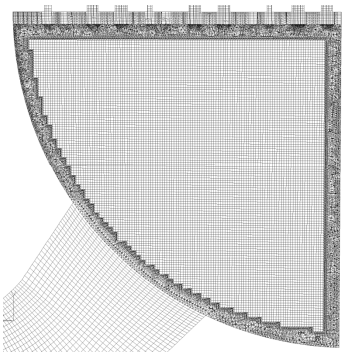




Grid Independence

Inlet plenum mesh design is based upon lessons learned from the initial benchmark studies at 1/7th scale along with the initial full-scale simulations. The inlet plenum mesh consists of cubic cells in the central region with all cubes aligned with the hot leg axis. A 3-5 layer tetrahedron transition layer is used out towards the walls and tube sheet. The 1 million inlet plenum cells are refined to 8 million cells for a confirmation of grid independence. No significant grid dependence is predicted.





Summary of Predictions

- Mixing, entrainment, flow rates, temperatures, and hot-tube distributions are predicted for a variety of severe accident conditions.
- Results support the NRC's analysis of severe accident induced tube failures.
- Sensitivity studies have improved the NRC's understanding of the phenomena that can impact the relative heat transfer rates in the primary system under these complex flow conditions.
- Variations in SG inlet plenum geometry and plant specific features are considered

Challenges / Future Work

- Secondary side flows are not considered and can impact the heat transfer rate to the SG tubes.
  - tube bundle heat transfer variations could be significant
- Full transient analysis with depressurization events caused by relief valves is not considered here.
  - the quasi-steady assumption should be verified
- Transient analysis of heat exchange to additional structures in addition to the SG tubes.
- Mixed convection in the hot leg along with radiative exchange with the optically thick gas.
  - a practical model is needed.
- Validation of models for specific flow phenomena under severe accident conditions is needed.
  - counter current flow in hot leg
  - mixed convection and radiative heat transfer
  - rising thermal plume in a confined space

Questions?