Thermal-Hydraulic Analysis Results of a Seismically-Induced Loss of Coolant Accident Involving Experiment Out-of-Pile Loop Piping at the Idaho National Laboratory Advanced Test Reactor

Doug Gerstner
Cliff Davis

Battelle Energy Alliance

Idaho National Laboratory

International RELAP5 Users Group 2013

September 2013

Idaho Falls, ID

www.inl.gov

Idaho National Laboratory

Presentation Overview

- ATR Overview
- ATR Primary Coolant System Design
- ATR Experiment Loop Design
- PCS LOCA Summary
- Experiment Loop LOCA Challenges
- Experiment Loop LOCA Solutions
- Final Safety Analysis Results

Reactor Description

Reactor Type

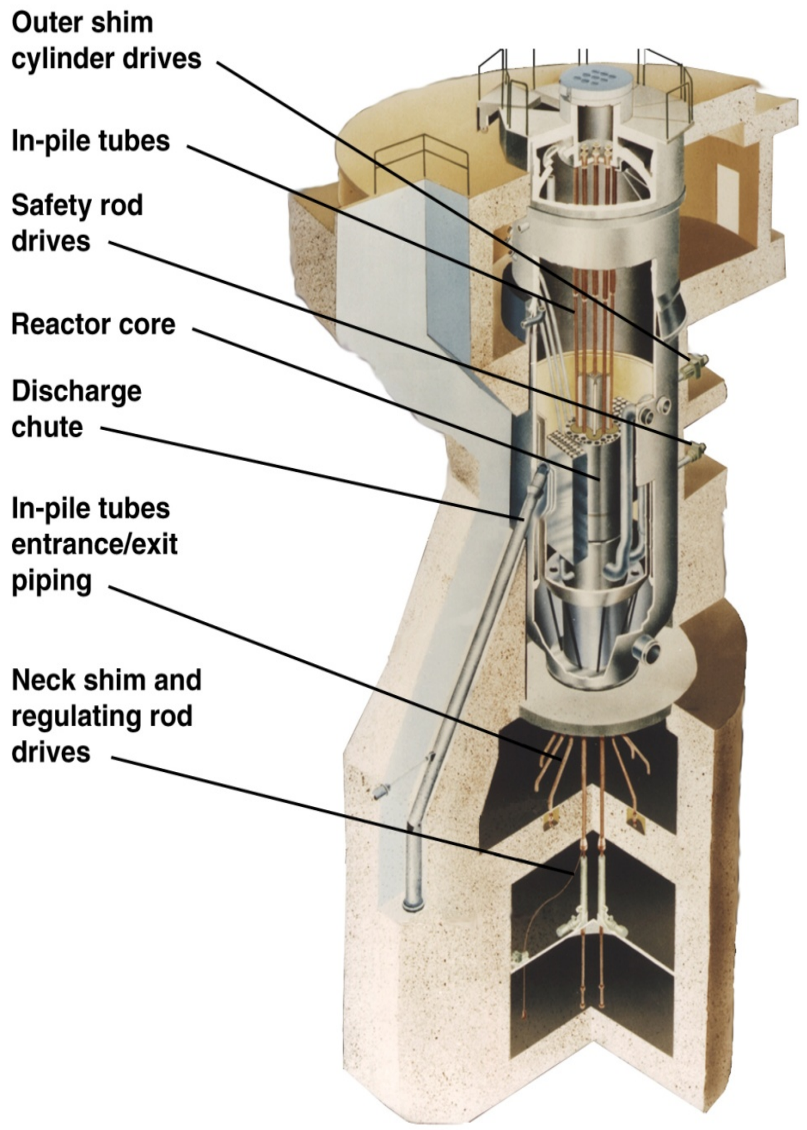
- Pressurized, light-water moderated and cooled; beryllium reflector
- 250 MW_t (Full Power)

Reactor Vessel

- 12 ft (3.65 m) diameter cylinder
- 36 ft (10.67 m) high stainless steel

Reactor Core

- 4 ft (1.22 m) diameter and height
- 40 fuel elements, curved-plate, aluminum-clad metallic U-235
- Highly enriched uranium matrix (UAlx) in an aluminum sandwich plate cladding

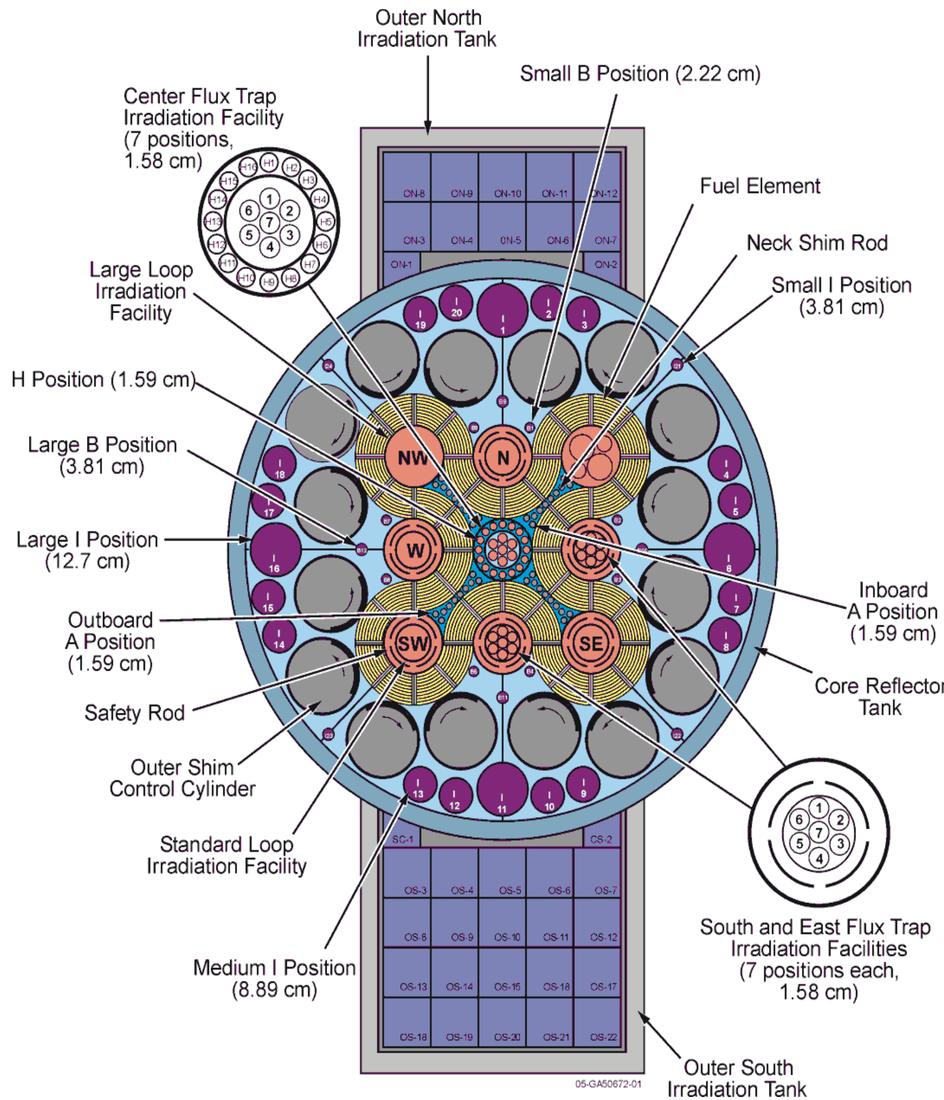


ATR Operating Condition Comparison to PWR

Operating Conditions	ATR	PWR (typ.)
Power (MW_{th})	250	2,000 – 4,000
Power density (kW/ft^3)	28,000	1,550
PCS pressure (psig)	355	2,250
Inlet/Outlet temp. (°F)	125/170	550/600
PCS flow rate (gpm)	48,000	300,000
Coolant mass (lbm)	600,000	450,000
Coolant mass/power ratio (lbm/MW)	2,400	170
Decay heat (MW @ 10s, 1 day)	13, 1.3	135, 19
Fuel enrichment (% ^{235}U)	93	2 – 4
Fuel mass (lbm)	90	180,000
Fuel temp. (°F)	460	2,000 – 3,000
Fission-product inventory	--	10 x ATR

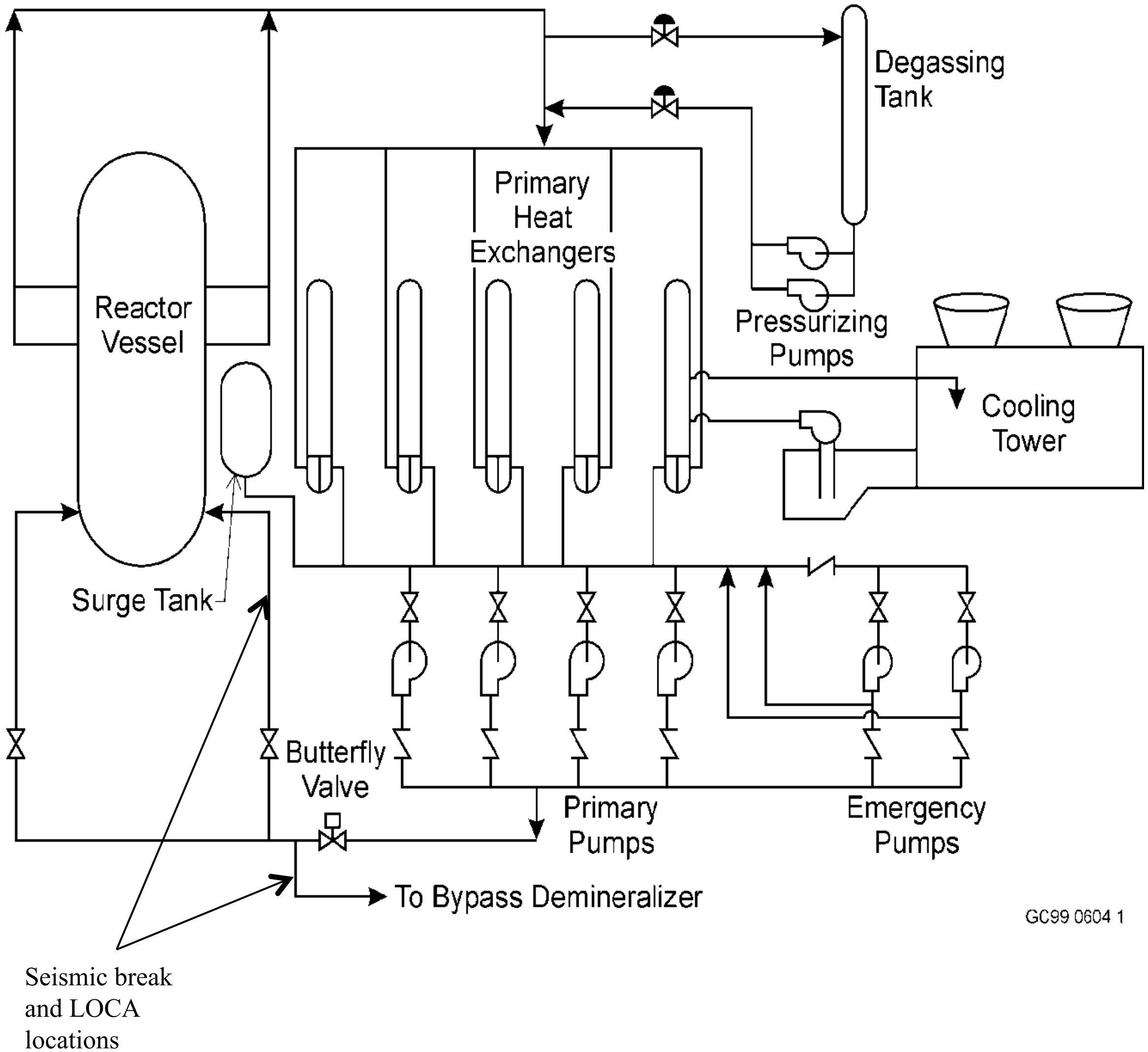
ATR Core Cross Section, Test Positions

- Test size - up to 5.0" Dia.
- 77 irradiation positions:
  - 4 flux traps
  - 6 in-pile tubes
  - 68 positions in reflector
- Approximate Peak Flux:
  - 1 x 10^{15} n/cm^2-sec thermal
  - 5 x 10^{14} n/cm^2-sec fast
- Hafnium Control Drums
  - Flux/power adjustable across core
  - Maintains axial flux shape

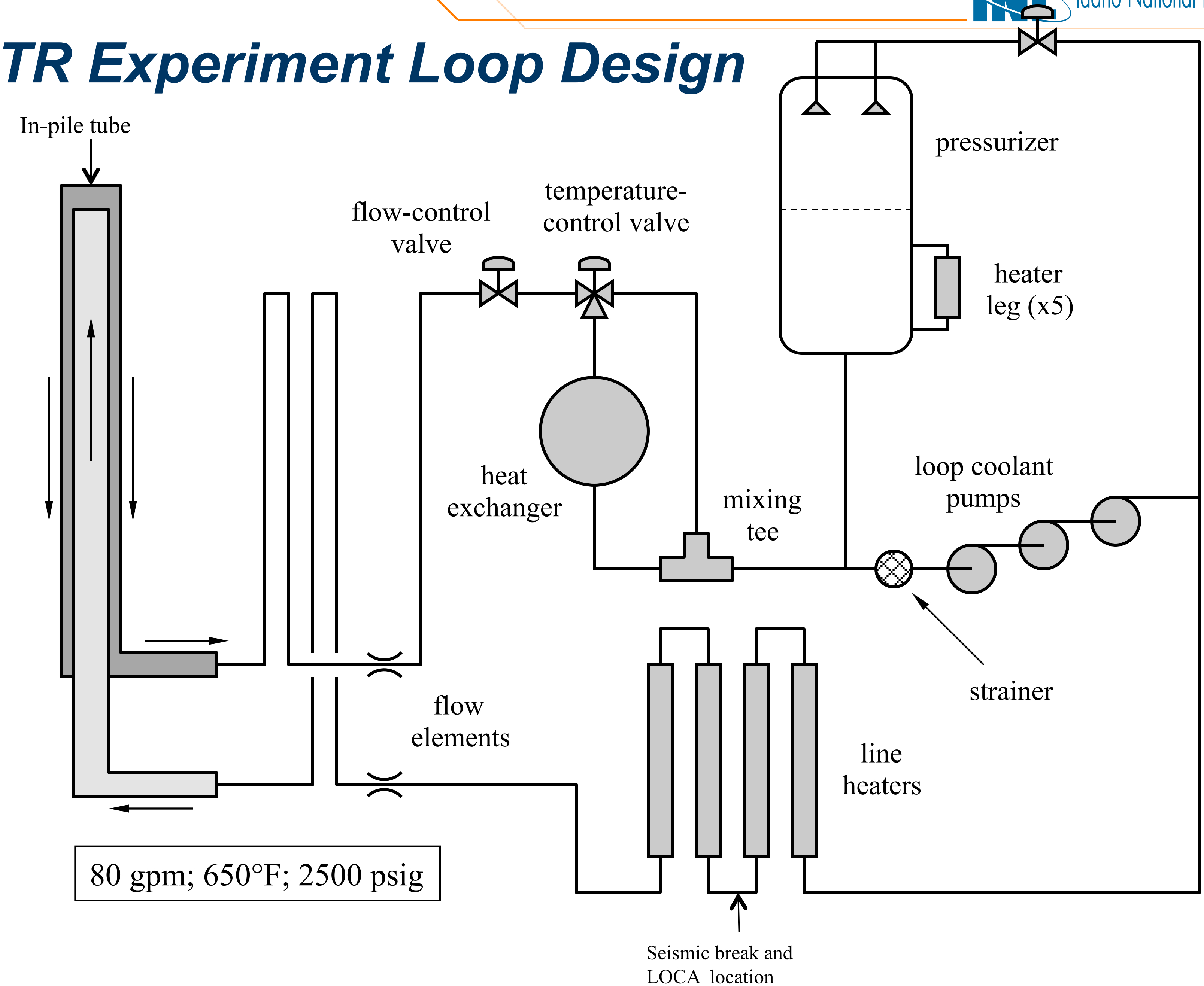


ATR Primary Coolant System Design

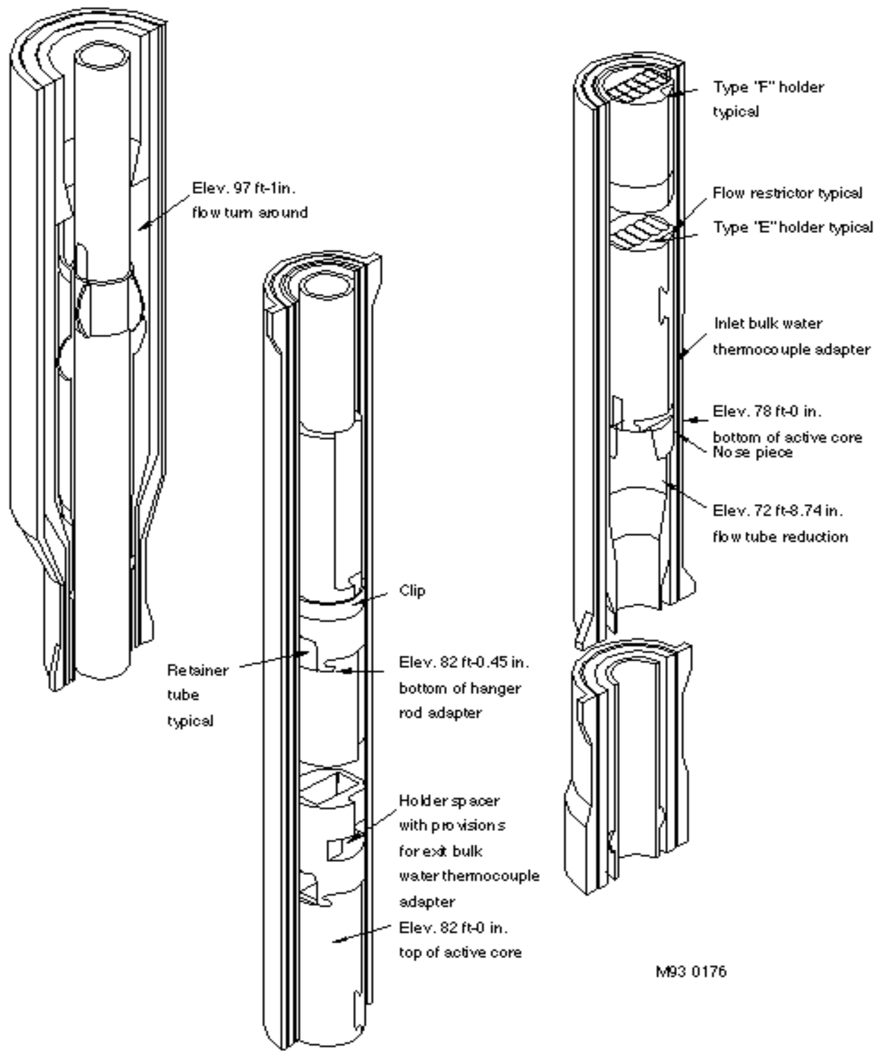
- Forced-flow, moderate-pressure, low-temperature, demineralized light water in a closed loop.
- Pressure drop 100-psi (77-psi) across the core during 3-PCP (2-PCP) operation.
- Nominal core inlet/outlet pressures are 360/260 psig (3 PCP) or 360/283 psig (2 PCP) respectively.
- Nominal core inlet/outlet temperatures are 125/170°F (i.e., below saturation temperature at atmospheric pressure).
- The ATR is designed to operate in the single-phase flow regime and is therefore not normally susceptible to flow instabilities. The core inlet subcooling is nominally greater than 300°F (170 *K).*

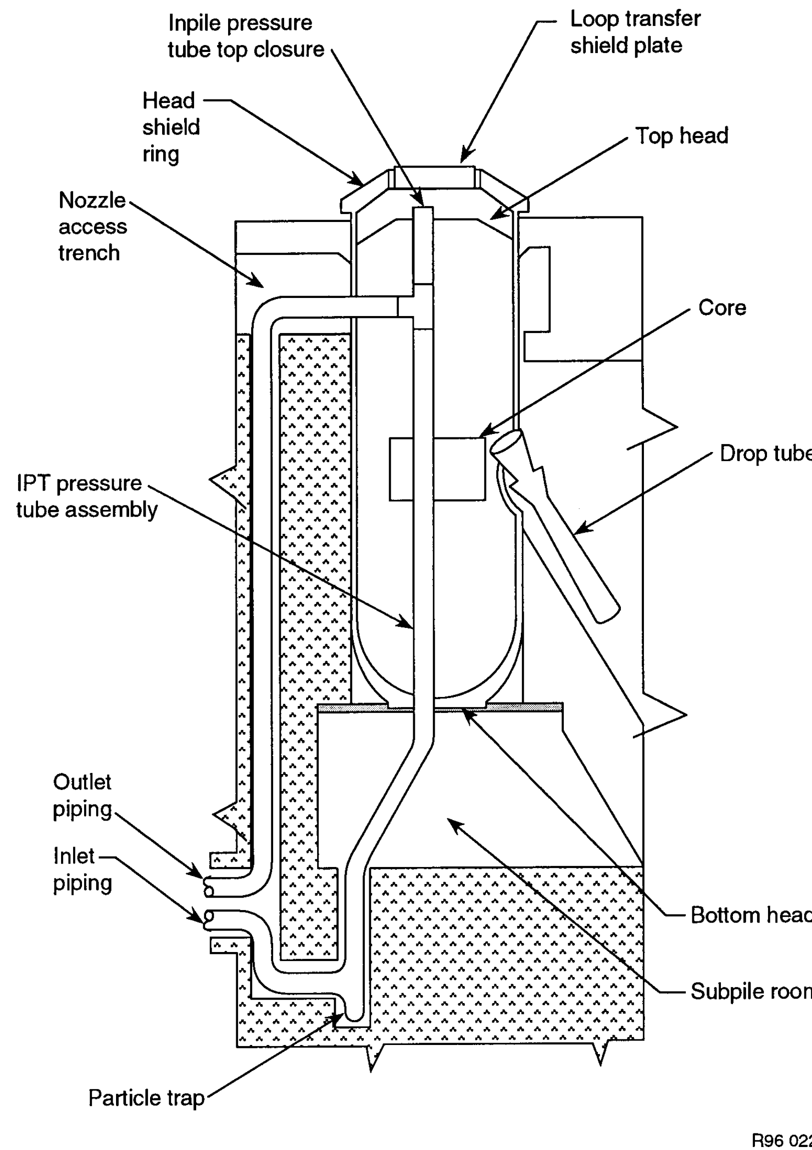


ATR Experiment Loop Design



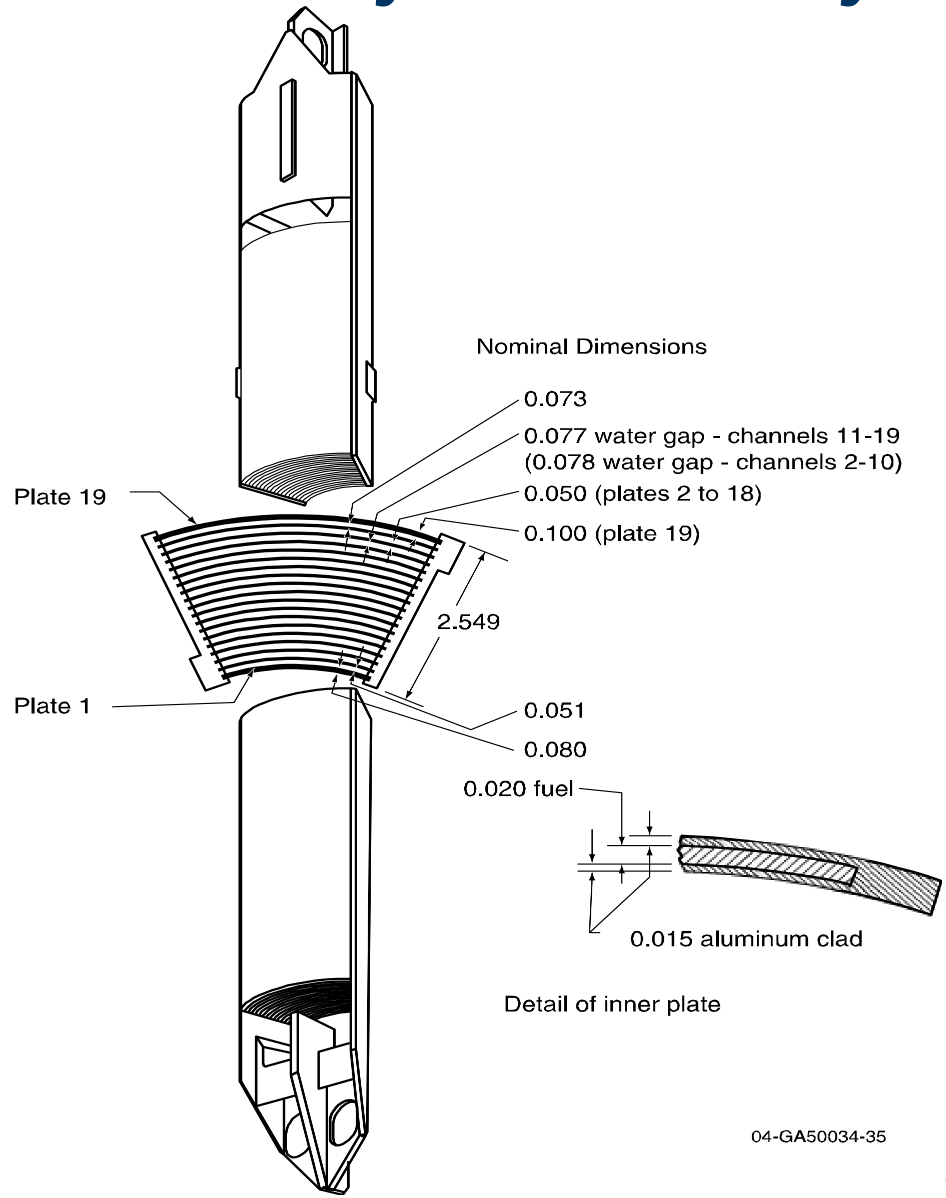
ATR Standard In-Pile Tube (SIPT) Design





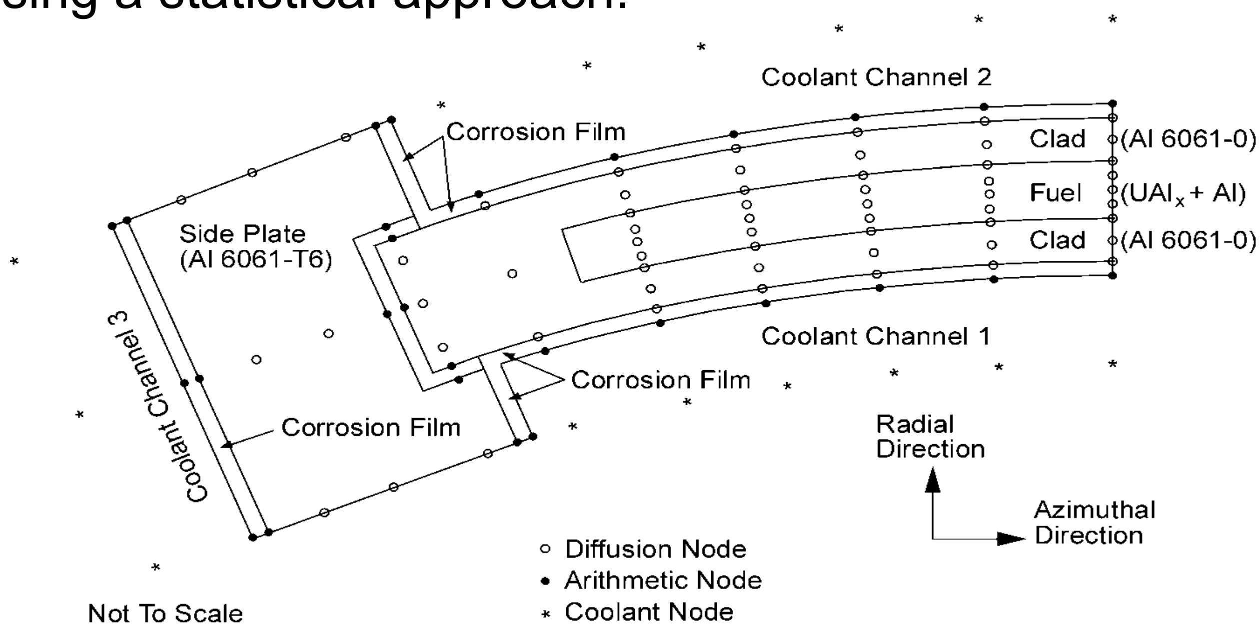
PCS LOCA Thermal-Hydraulic Analysis Summary

- Condition 4 fault, an earthquake was assumed to cause a 1-in. reactor inlet break, a 2.5-in. rupture of the bypass demineralizer inlet line.
- Overall response of the reactor was calculated with the RELAP5 code, and core safety margins were calculated with the ATR-SINDA and SINDA -SAMPLE fuel plate models.
- Core power, top-of-core pressure, core pressure drop, and hot channel inlet and outlet enthalpy as functions of time were obtained from RELAP5 for input into SINDA and SINDA-SAMPLE.
- RELAP5 determines the “hot fuel element” of the 40 fuel elements.



PCS LOCA Thermal-Hydraulic Analysis Summary

- The ATR-SINDA fuel plate model computes the temperature distributions in any of the 19 fuel plates of the "hot" ATR fuel element as determined from RELAP5.
- ATR-SINDA determines the limiting fuel plate (of the 19 fuel plates) in the hot fuel element.
- ATR-SINDA simulates one-half of the fuel plate (azimuthally) and a portion of the adjoining side plate.
- The SINDA-SAMPLE model computes the various safety margins using a statistical approach.

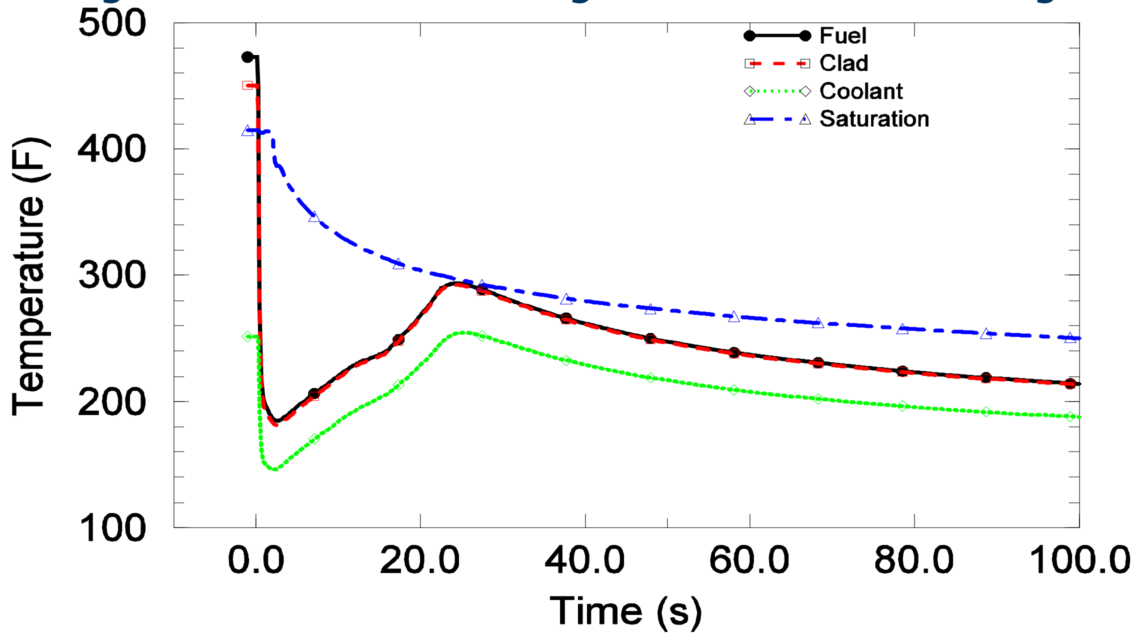


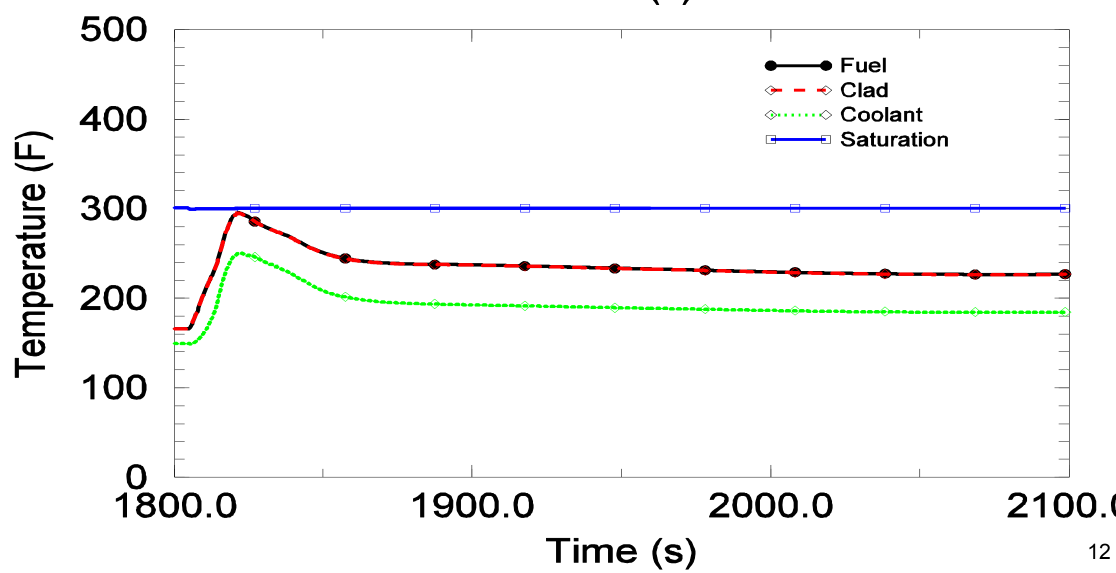
PCS LOCA Thermal-Hydraulic Analysis Summary

Seismic event transient sequence of events	
Event	**Time (sec)**
High Seismic Activity	0.0
Reactor Scram	0.2
Pipe Breaks, Loss of AC Power, PCP and ECP M-10 Trip	2.0
Secondary Pump Coastdown	2.0/12.0
ECP-11 Start (on M-10 low recirculation flow)	4.5
PCP Discharge Valve Close	22.0
EFIS Actuation (low upper plenum pressure (28psia)	229.3
ECP M-11 Coastdown (batteries depleted)	1805.0
Calculation Terminated	6000

PCS LOCA Thermal-Hydraulic Analysis Summary

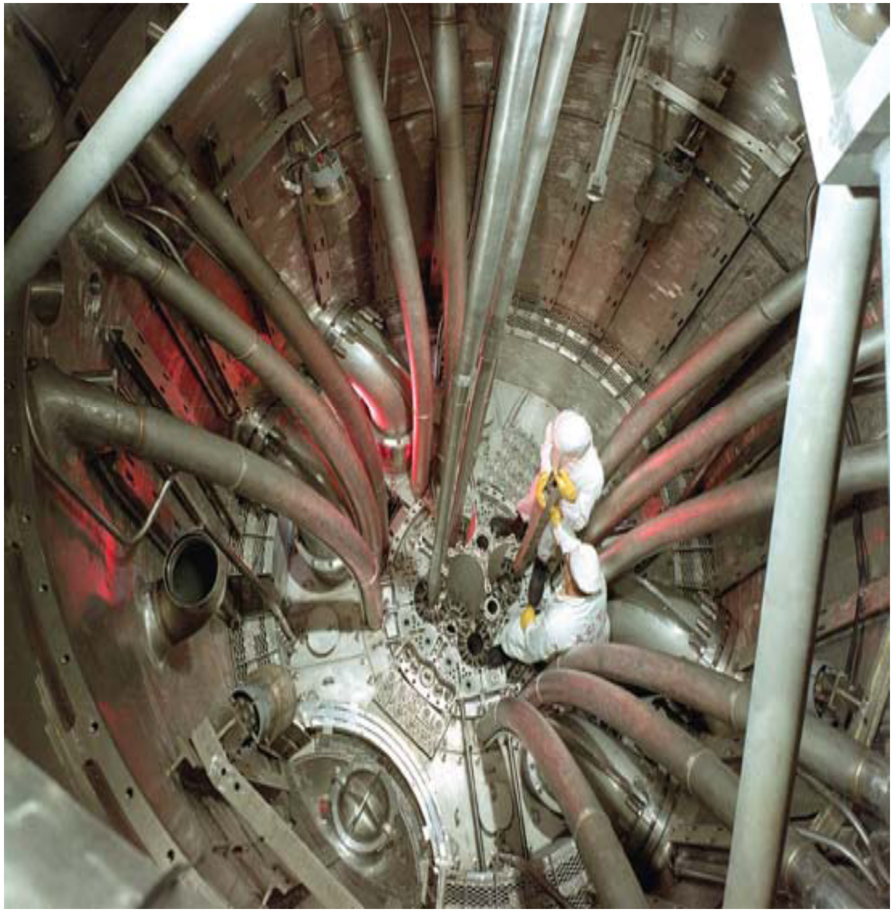
- Maximum hot channel coolant outlet temperatures from ATR-SINDA during the early and late core heatup well below saturation. No boiling.
- Maximum fuel temperatures during the early and late core heatup much less than the temperatures to buckling (710°F) and AWIT (2140°F).
- ATR Plant Protection Criteria (PPC) met (>1.2σ to CHF/FI).





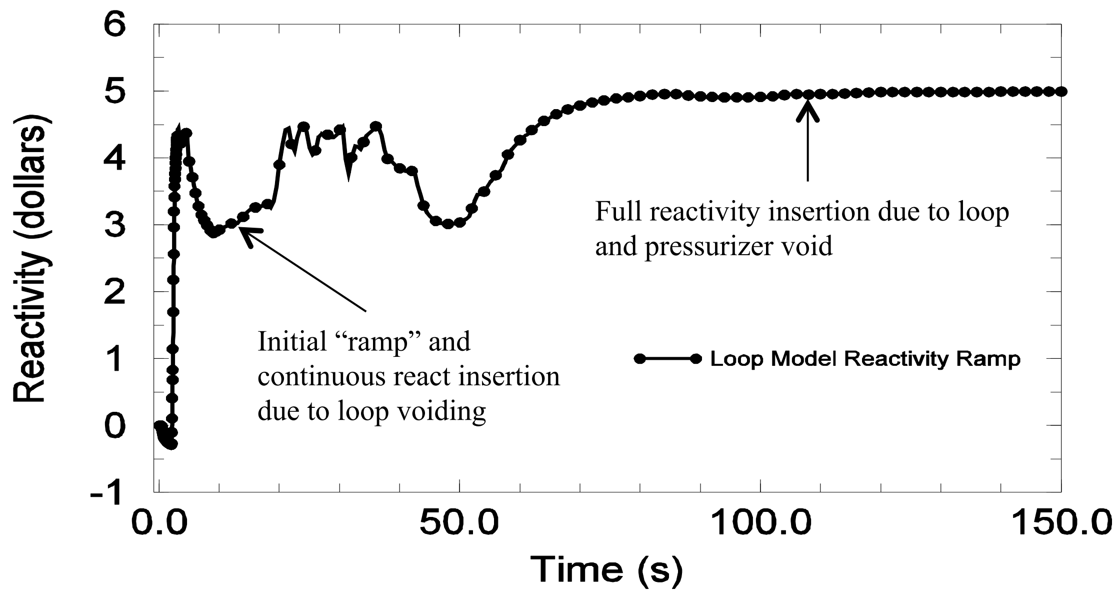
Loop LOCA Thermal-Hydraulic Analysis Challenges

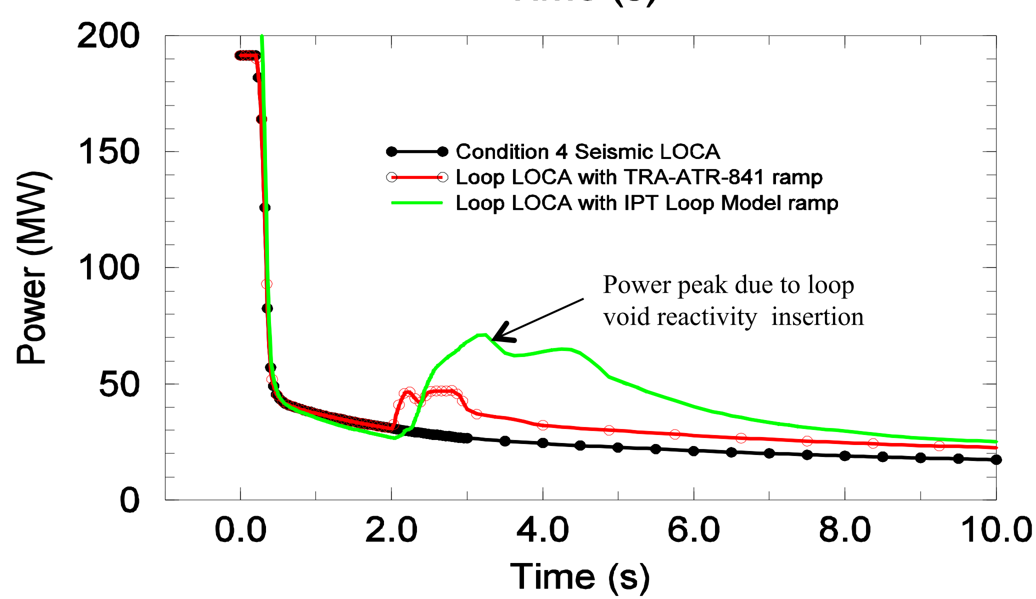
- Seismic break and leakage in all six existing experiment standard in-pile tubes (IPTs).
- IPT experiment void worth for the 6 loops is assumed to be 5.0$ to conservatively bound the reactivity insertion.
- Limiting break is a double ended offset shear of a 1/2-in. pipe in the drain manifold attached to the loop piping at the heater legs.
- This event results in the IPT voiding and a positive reactivity insertion.
- The ATR has strong negative reactivity coefficients for coolant-temperature and coolant-void increases in the fuel element. The coolant-temperature and voiding-increase reactivity coefficients in the flux traps, however, are positive.



Loop LOCA Preliminary T-H Analysis Summary

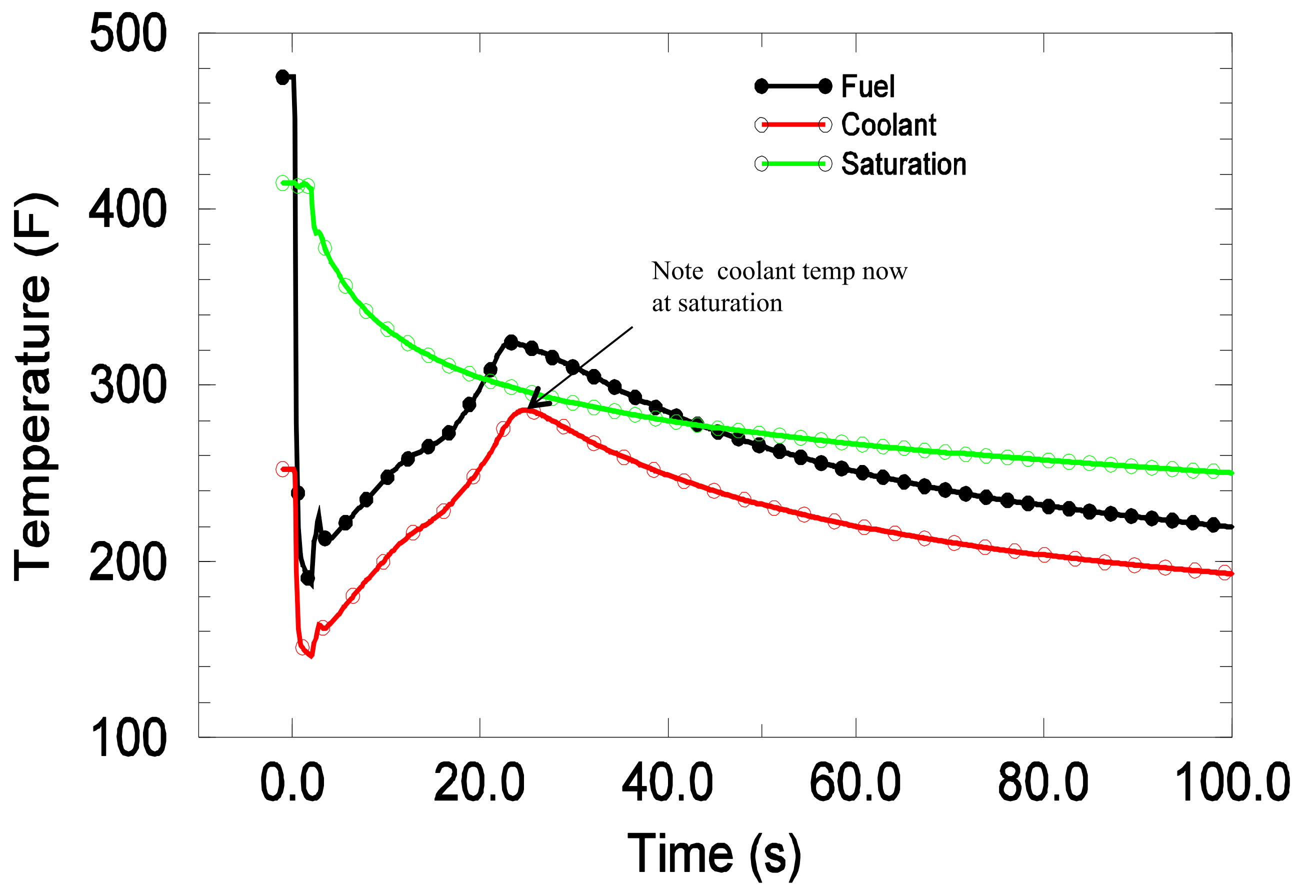
- Preliminary analysis assumed a conservative safety rod worth of 5.8$.
- The ramp and reactivity insertion is extended as loop voids reaching a 5$ total void worth reactivity insertion.
- Core power increases sharply at 2.0 sec as a result of the 6 experiment loop 5$ reactivity insertion ramp.
- The power increases approximately 40 MW as a result of the reactivity insertion.





Loop LOCA Preliminary T-H Analysis Summary

- Added power from the reactivity insertion, in conjunction with the PCS and loop seismic breaks, Loss of Offsite Power, and pump coast downs results in reduced thermal safety margins (<1.2σ to CHF/FI).
- As a result it could not be shown that a 5 loop seismic event will meet the PPC.

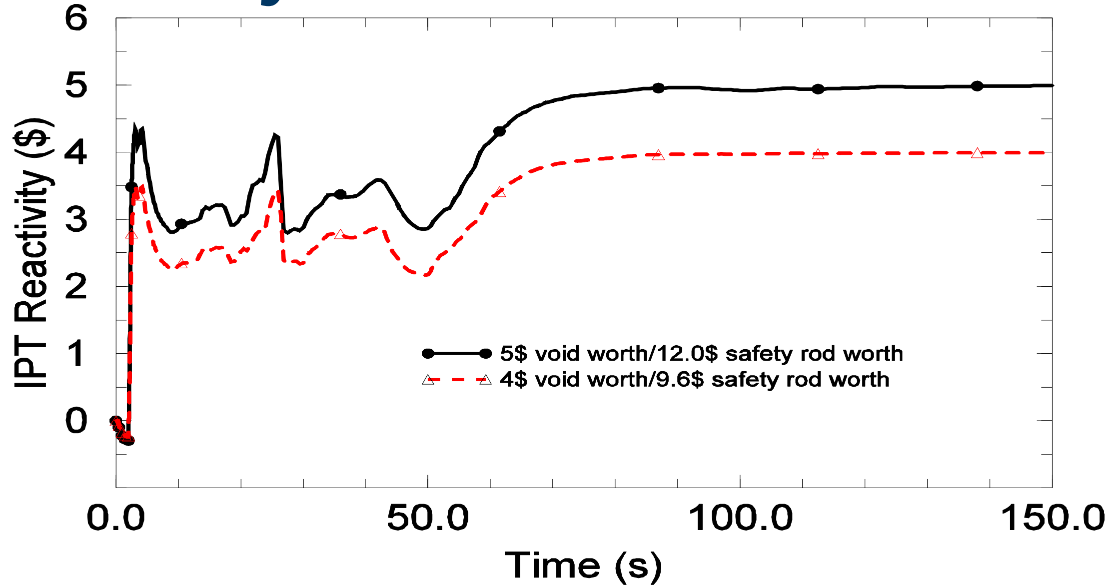


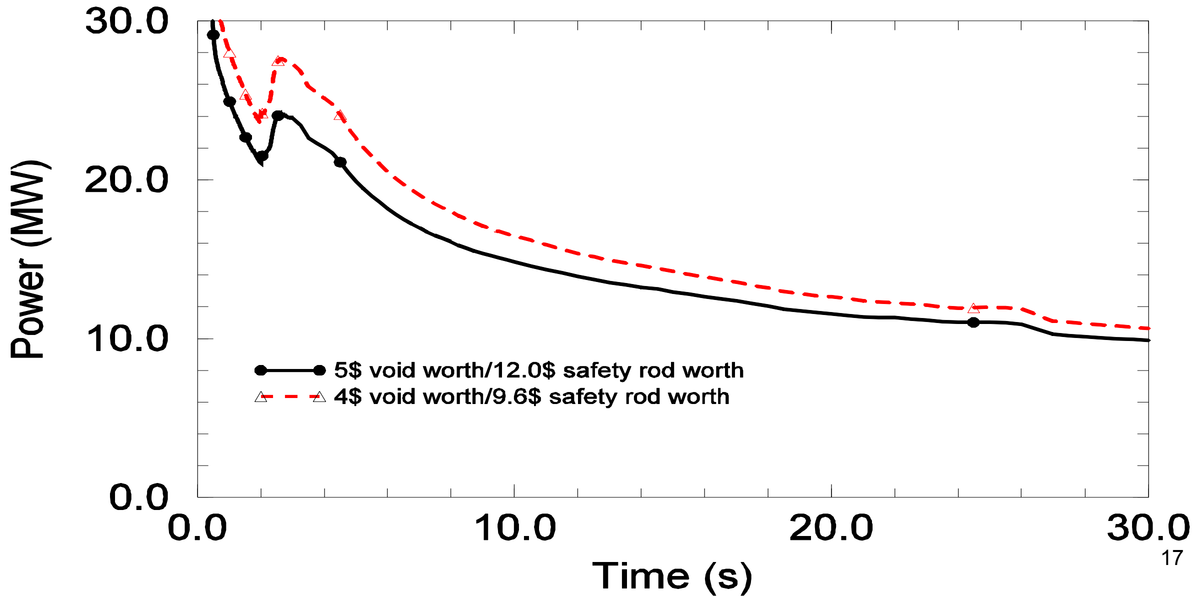
Loop LOCA T-H Analysis Solutions

- Various sensitivity studies were performed to provide a possible path forward.
- Studies varied lobe power, test fission power, IPT void worth, plate power (SINDA), break sizes, and safety rod worth to result in SINDA-SAMPLE safety margins that would meet the Condition 4 PPC.
- A combination of loop void worth and safety rod worth for the analysis chosen based on consideration of the seismic shutdown reactivity basis following the safe shutdown earthquake (SSE).
- Calculations were performed to investigate core safety margins during two seismically induced experiment loop LOCAs. For the first LOCA, a 5.0$ void worth and 12.0$ safety rod worth were assumed. For the second, a 4.0$ void worth and 9.6$ safety rod worth were assumed.
- Safety rod worths obtained from ATR SAR and are based on actual measurements and conservatively reduced to account for uncertainty.

Loop LOCA Final T-H Analysis Results

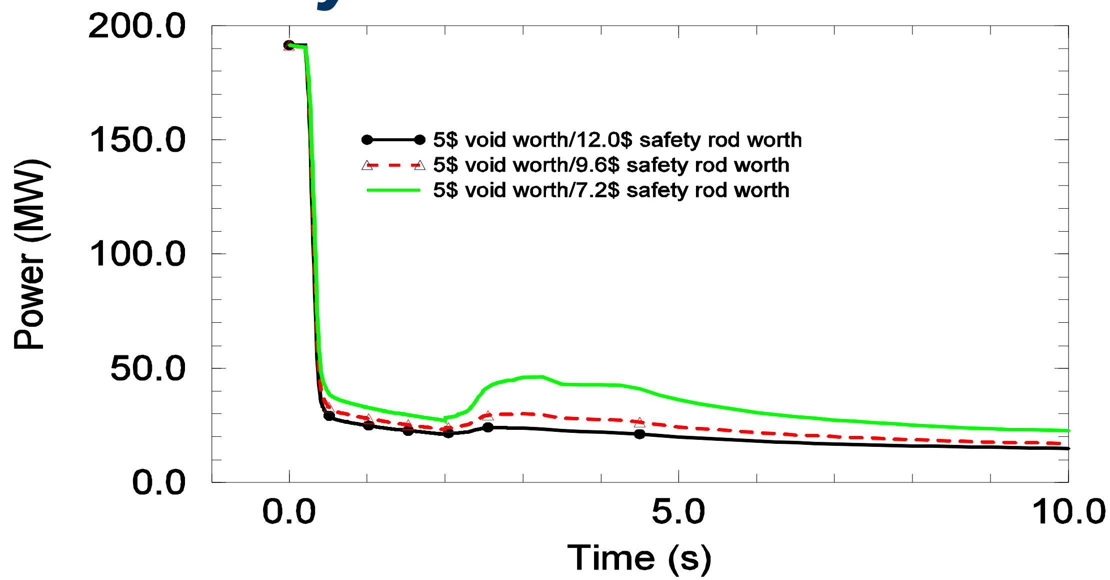
- With 5.0$ void worth and 12.0$ safety rod worth , thermal safety margins are 3.52σ to CHF and 3.75σ to FI.
- With 4.0$ void worth and 9.6$ safety rod worth , thermal safety margins are 3.34σ to CHF and 2.72σ to FI.
- Thermal safety margin limits (>1.2σ to FI and CHF) are met.

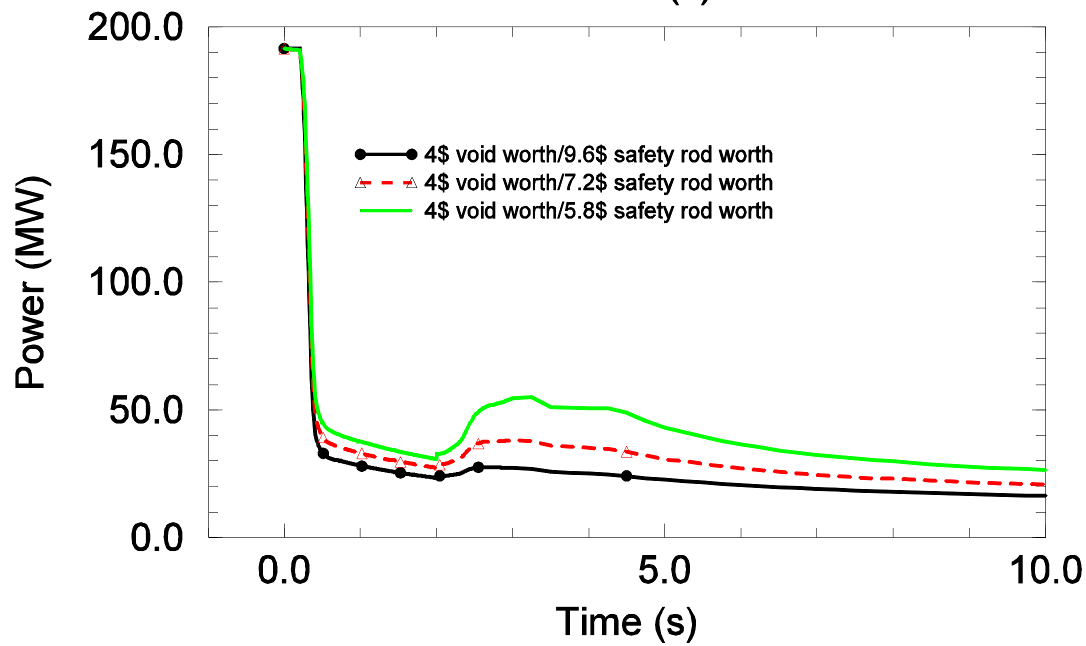




Loop LOCA Final T-H Analysis Results

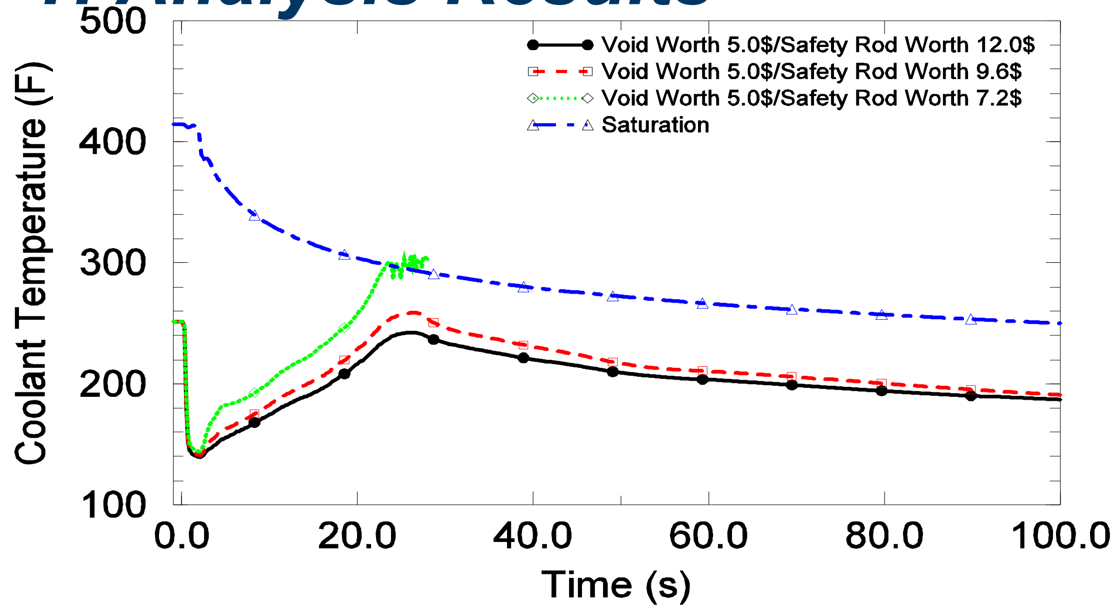
- The most important thermal-hydraulic parameters affecting the approach to thermal safety limits are total void worth and safety rod worth.

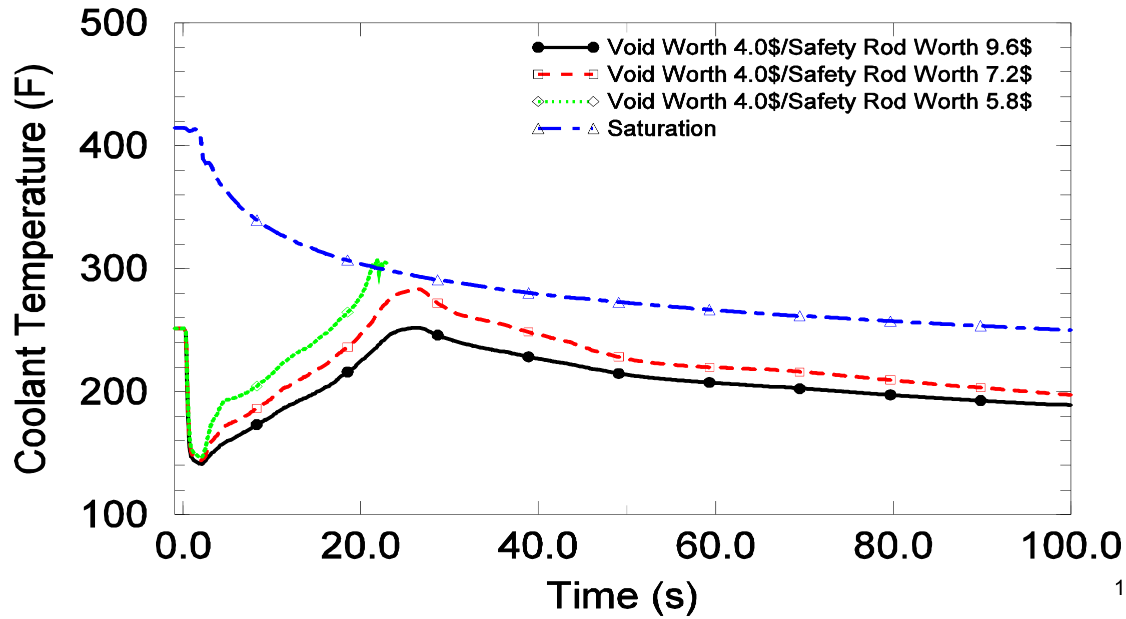




Loop LOCA Final T-H Analysis Results

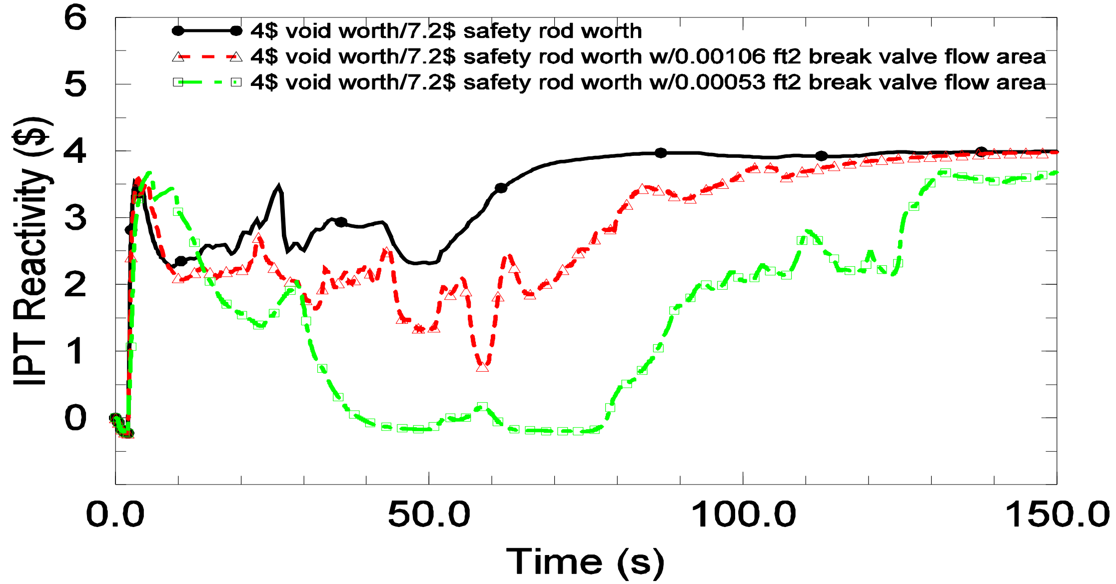
- The limiting approach to thermal margins occurs shortly after the PCP check valves close near 22.0 sec.
- The reduced coolant flow due to PCP coastdown and startup of the emergency pump M-11 is lowest at the time the PCP check valves close, consistent with other seismic LOCA analyses.
- However, the added power from the loop blowdowns at that time results in coolant temperatures that now exceed saturation, resulting in FI.

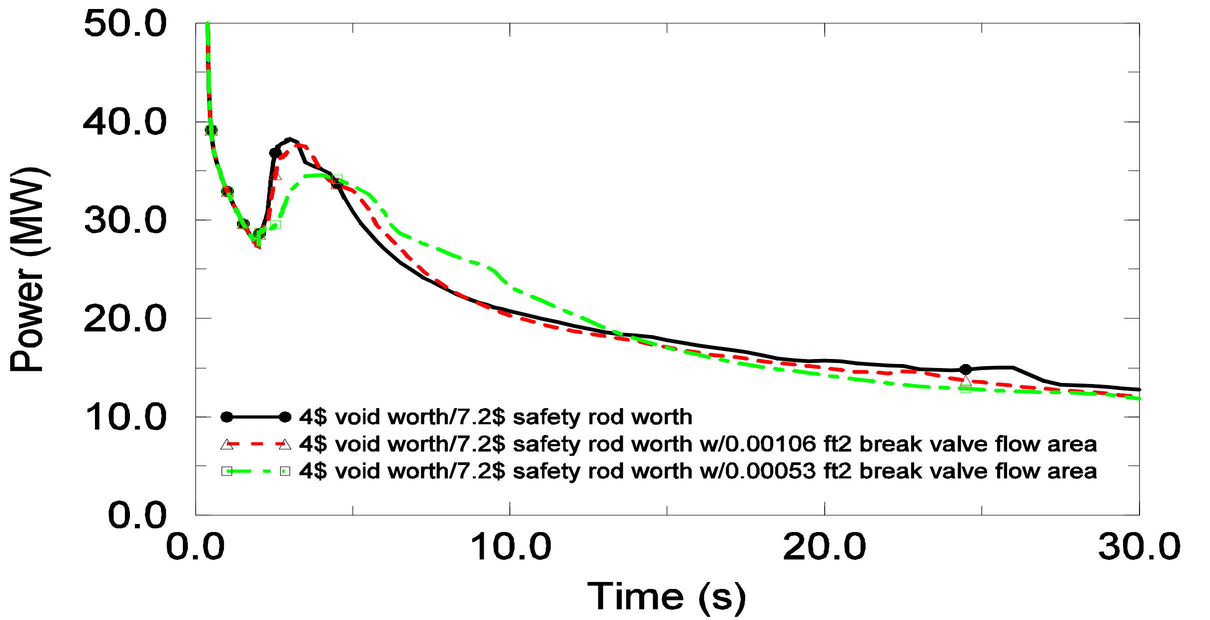




Loop LOCA Safety Analysis Summary

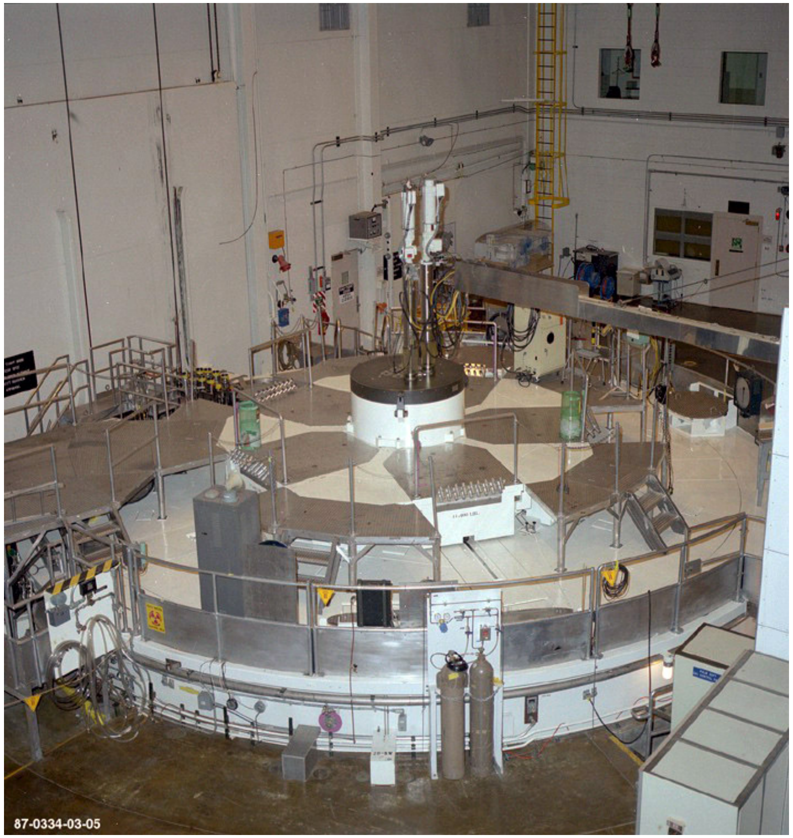
- Thermal safety margins are significantly affected by the assumed break size in the experiment loops.
- Reduced leak rates may allow reduction or elimination of the void worth/safety rod worth restrictions developed to ensure safe shutdown following a SSE and ensure that thermal safety margins are met.





Loop LOCA Safety Analysis Summary

- Loop LOCA scenario requires changes to TSRs to meet both the thermal safety margins and safe shutdown following a seismic event:
  - 6 operable safety rods (5 inserting 12.0$ safety rod worth) with a maximum total loop void worth of > 4.0$ but ≤ 5.0$.
  - 5 operable safety rods (4 inserting 9.6$ safety rod worth) with a maximum total loop void worth restricted to < 4$.
- Seismic analyses underway to better estimate leak rates, and hopefully, reduce or eliminate TSR requirements on loop void worth and safety rod operability



Questions?