Idaho National Engineering and Environmental Laboratory

Performance and Safety Studies for Multi-Application, Small, Light Water Reactor

James E. Fisher, S. Michael Modro, Kevan D. Weaver
INEEL

Jose Reyes, John Groome
Oregon State University

Pierre Babka
NEXANT, Inc

2002 RELAP5 Users Seminar
Park City, Utah
September 4-6, 2002

NERI Initiative

- *Create a reactor plant concept*
  - *performance*
  - *safety*
  - *economy*
- *Test in an integral test facility*
- *Small, natural circulation light water reactor*
- *Electric power generation*
- *Process heat application with deployment in a variety of locations*

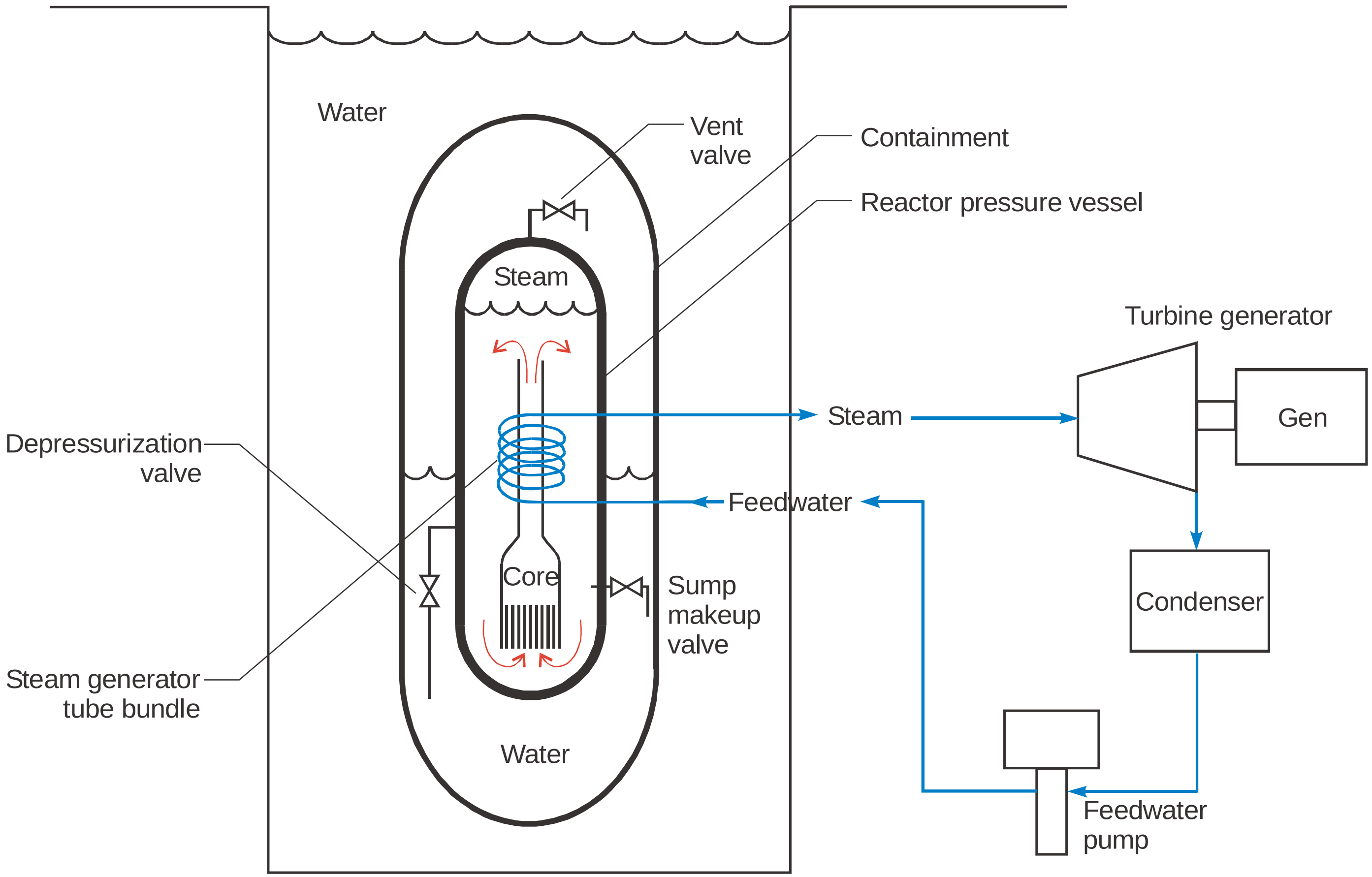
Significant Design Features

- *Reactor and steam generator enclosed in a single vessel*
- *Natural circulation primary system*
- *Containment submerged in a pool of water*
- *Reduced reactor coolant pressure, steam pressure*
- *Simplified NSSS and balance-of-plant systems*
- *Refueling and maintenance simplified (pull and replace)*

Steam Generator

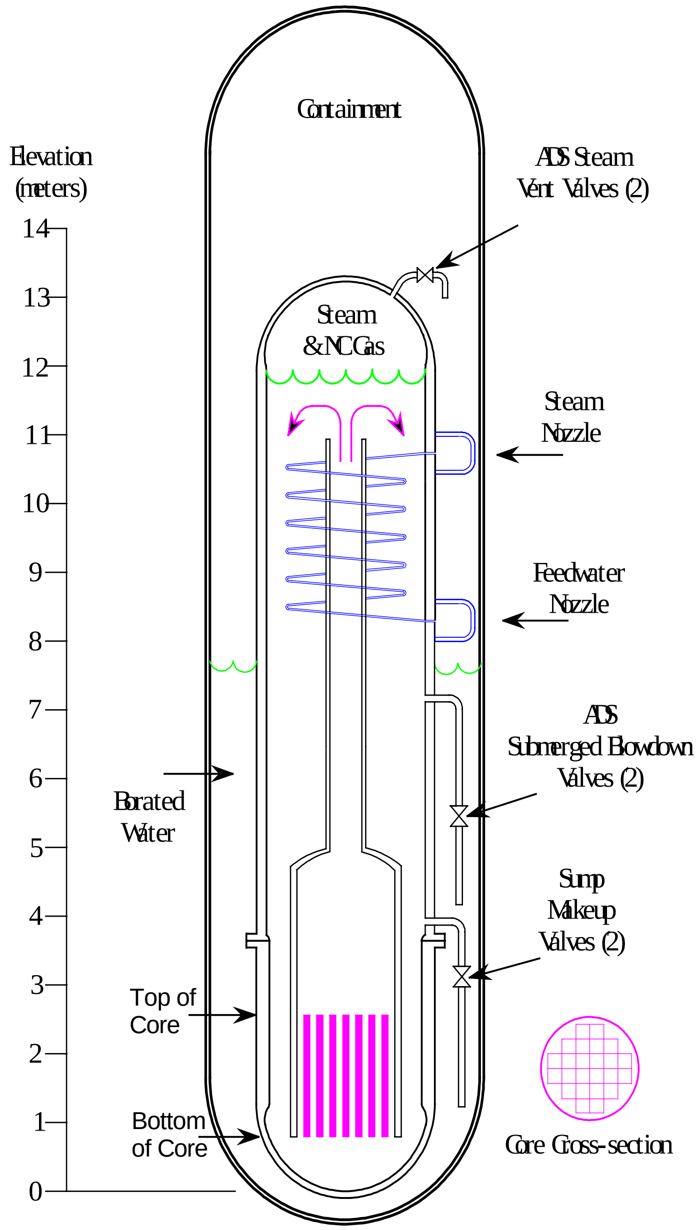
- *Located in the upper annular region of the pressure vessel*
- *Helical-tube design*
- *Once-through heat exchanger*
- *Approximately 1000 tubes, upwardly spiraling pattern*
- *Primary coolant flows downward in annular space (shell-side of heat exchanger)*
- *Cold feedwater enters tubes at bottom*
- *Superheated steam collected at the top*

Simplified Heat Cycle Diagram

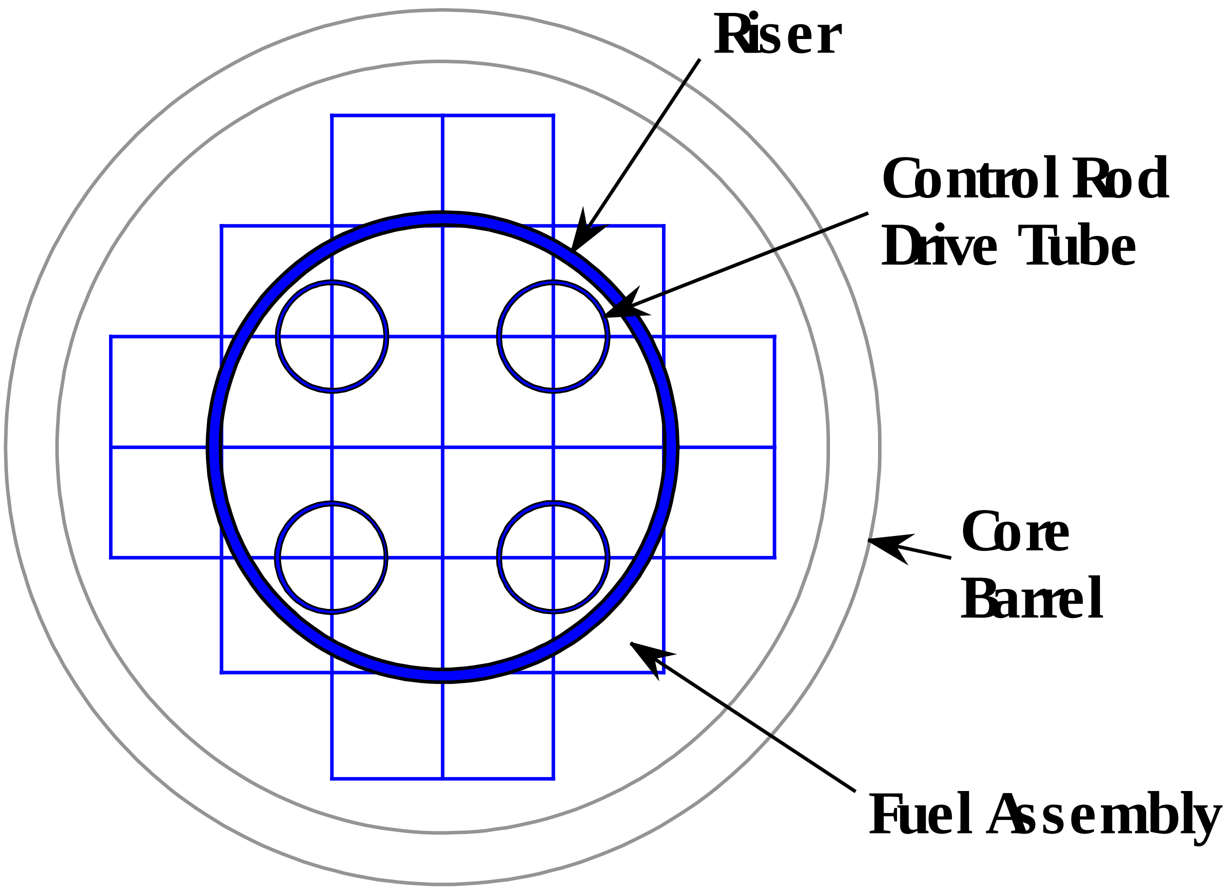


Containment and Internals

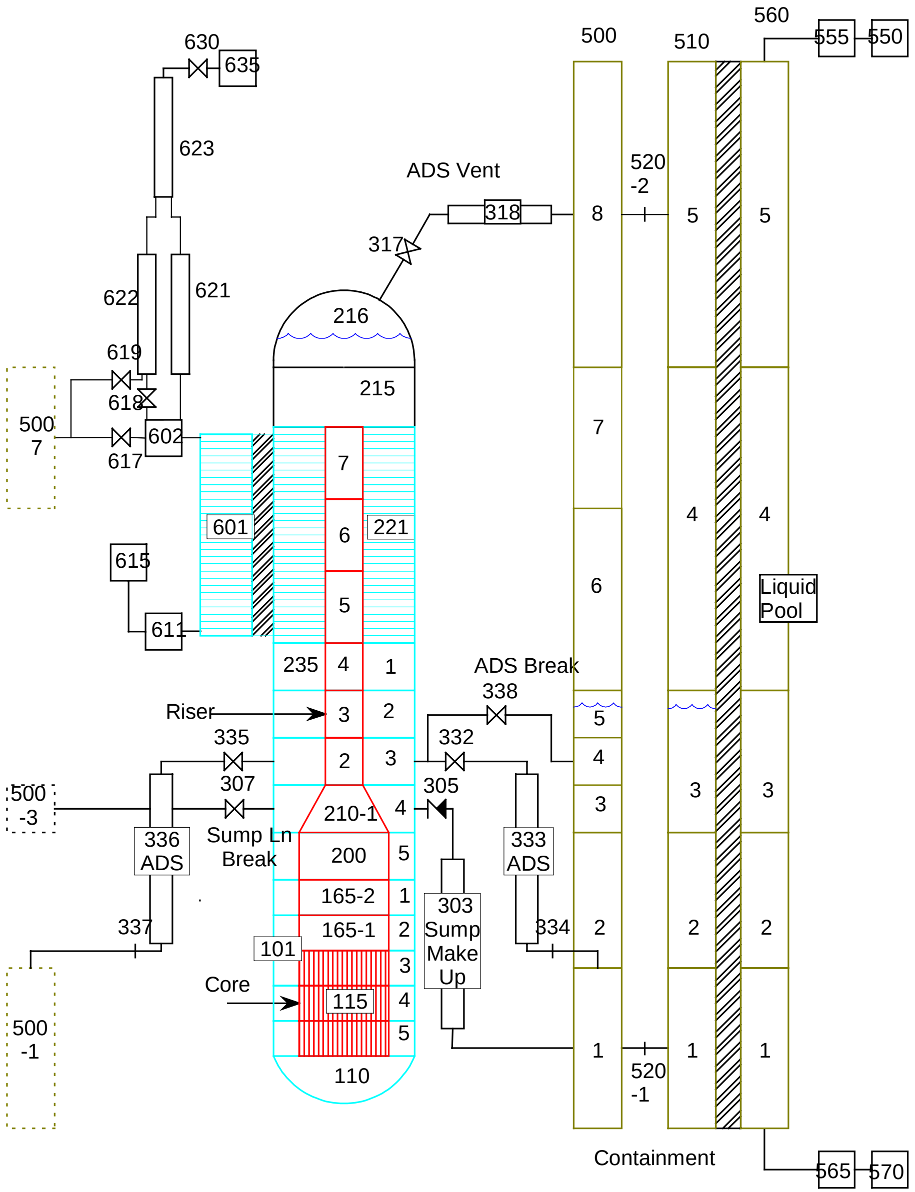
- *Redundant piping systems*
- *4-inch diameter ECCS piping*
  - *ADS steam vent lines (ASME code safety valves present but not shown)*
  - *ADS submerged blowdown lines*
  - *Sump makeup lines, present in previous version of design, now shown to be unnecessary*



Top View of Fuel Bundle



RELAP5 Nodalization Diagram



Power Plant Boundary Conditions

- *35 MWe rated electrical load*
- *Steam supply pressure = 1.52 MPa (220 psia)*
- *Small superheat desired (~10 K)*
- *Thermal efficiency ~23% because of low temperature conditions*
- *NSSS must supply 150 MWt*

Steady-state Operating Conditions

- Reactor core operates in subcooled forced convection
- Hot channel is in subcooled nucleate boiling
- Natural circulation flow in primary system

Primary pressure	7.8 MPa	1130 psia
Mass flow rate	596 kg/s	1311 lbm/s
Core inlet temperature	491.8 K	425.6 F
Core outlet temperature	544.4 K	520.3 F
Saturation temperature	567.4 K	561.7 F

FSAR Chapter 15 Guidelines for Current Generation PWRs

- *Normal operation and operational transients*
- *Faults of moderate frequency*
  - *No fuel failure*
  - *No excessive system or containment pressure*
- *Infrequent faults*
  - *Minor fuel damage may result in outage*
  - *No significant radioactivity release*
- *Limiting faults*
  - *No public exposure beyond 10CFR100 guidelines*
- *Beyond design basis accidents*

Normal Operation and Operational Transients

- *Includes power operation, startup, hot shutdown, hot standby, cold shutdown, refueling*
- *Power Operation: satisfactory performance with listed parameter set*
  - *Hot assembly/hot fuel pin included in model*
  - *Hot assembly has 5% flow reduction, no mixing with average core*
  - *Axial peaking factor = 1.36*
  - *Hot assembly radial factor = 1.1*
  - *Hot fuel pin radial factor = 1.4*
  - *CHF Ratio ~ 7.2*
- *No assessment for non-power operation*
- *Analysis performed for beginning-of-life conditions only*

Faults of Moderate Frequency

- *Rod withdrawal accidents*
  - *Subcritical initial condition (not yet analyzed)*
  - *At power*
- *Inadvertent opening of steam vent valve or ADS blowdown valve at power*
- *Loss of normal feedwater*
- *Loss of AC power*
- *Turbine trip*
- *Feedwater flow increase*
- *Accidental depressurization of main steam system*

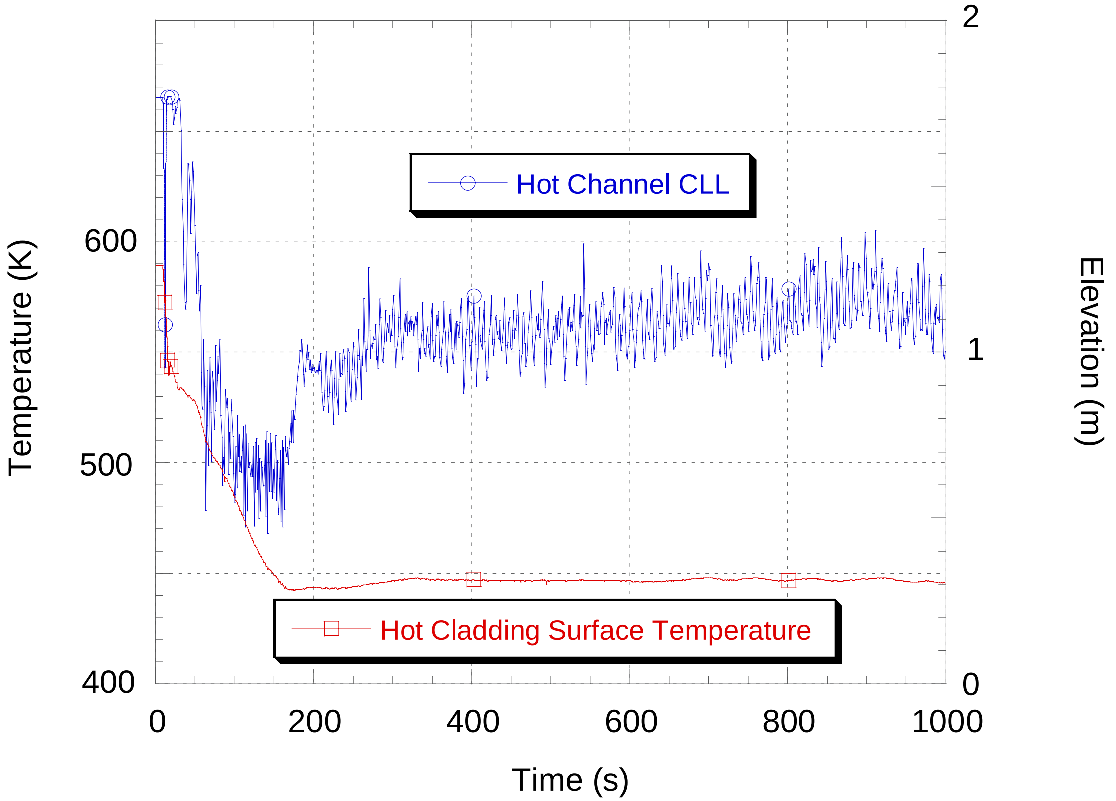
Control Rod Withdrawal Accident at Power

- *Reactivity ramp insertion at 0.115 $/second*
- *High power scram @165 MW + 0.2 s delay*
- *Maximum power = 170 MW*
- *Minimum CHFR = 6.9*
- *No cladding surface temperature excursion*
- *ADS opens at 96 s on high system pressure*
- *Containment pressure < 0.7 MPa*

ADS Blowdown Line Nozzle Break

- ***More severe than inadvertent opening of ADS blowdown line valve***
- ***Second ADS submerged line valve opens normally***
- ***Failure of both sump makeup line valves to open***
- ***Core collapsed liquid level sufficient to provide cooling***
- ***No cladding thermal excursion***

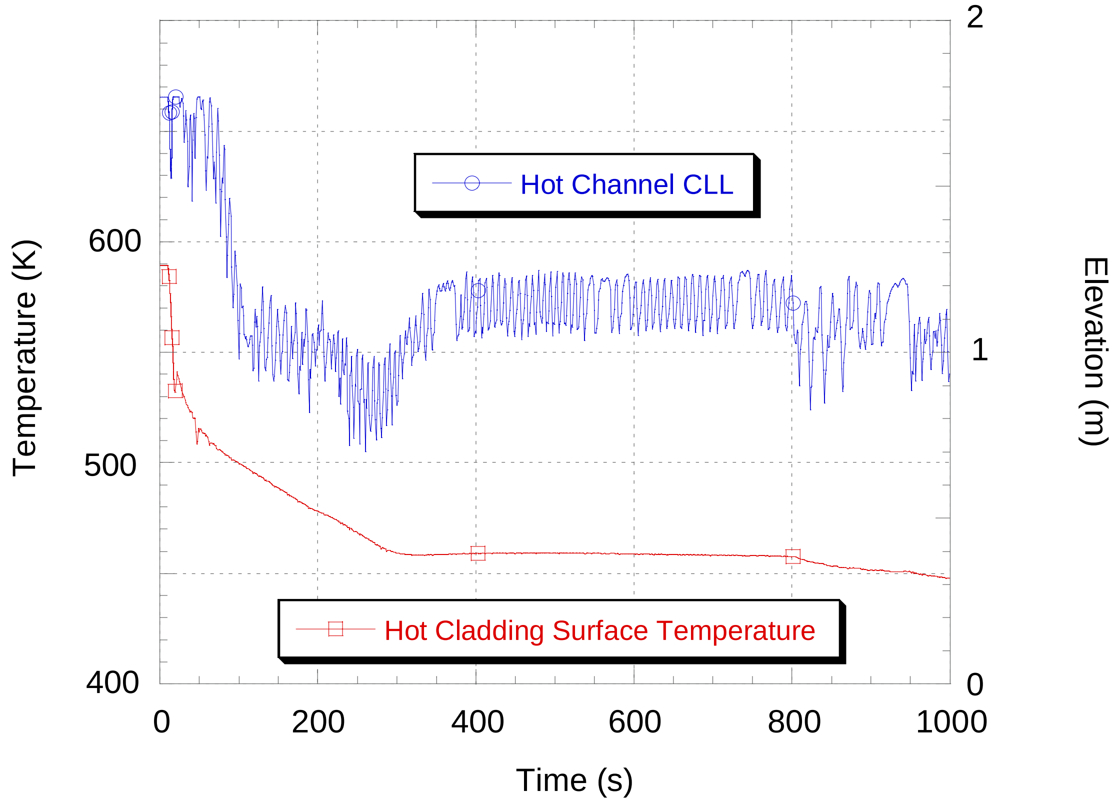
Hot Channel Collapsed Liquid Level and Hot Fuel Pin Cladding Surface Temperature



Steam Vent Line Nozzle Break

- ***More severe than inadvertent opening of vent line valve***
- ***Failure of one ADS submerged line valve to open***
- ***Failure of both sump makeup line valves to open***
- ***Core collapsed liquid level sufficient to provide cooling***
- ***No cladding thermal excursion***

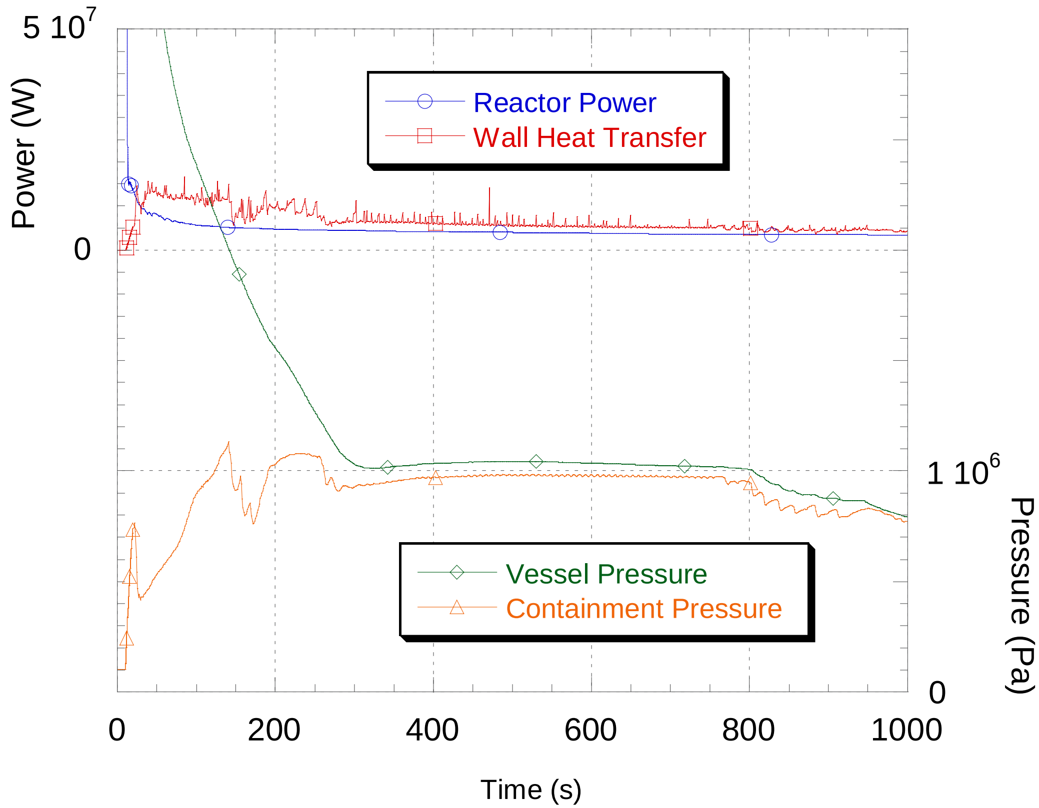
Hot Channel Collapsed Liquid Level and Hot Fuel Pin Cladding Surface Temperature



Steam Vent Line Nozzle Break

- ***Heat rejection through containment wall removes core decay heat***
- ***ADS depressurizes primary system***
  - ***establishes natural circulation flow and decay heat removal***
  - ***limits maximum containment pressure***
- ***Satisfies requirements for Faults of moderate frequency***

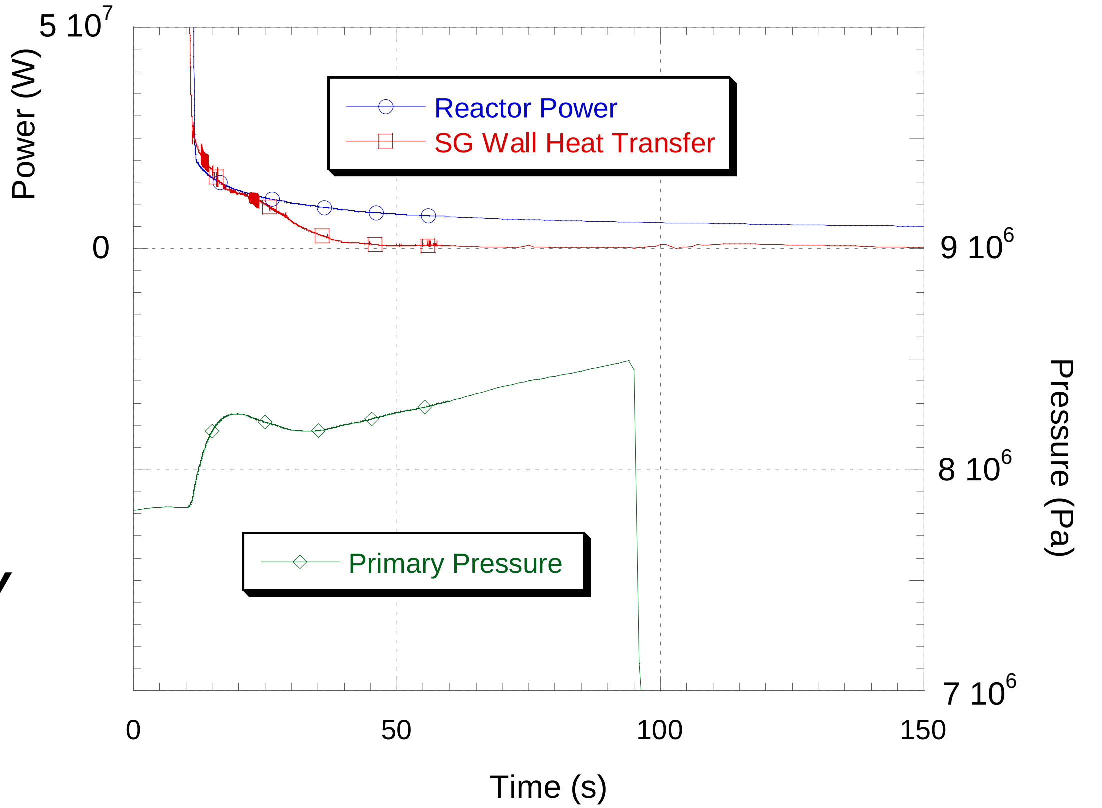
Reactor Power/Heat Rejection and Vessel/Containment Pressure



Loss of Feedwater

- ***Reactor scram 0.1 s after feedwater pump trip***
- ***ADS actuates at 95 s, depressurizing primary system***
- ***If reactor scram on SG low level, ADS actuates at 20 s.***
- ***Resembles inadvertent opening of ADS blowdown valve***
- ***Satisfies requirements for faults of moderate frequency***
- ***More limiting operationally than turbine trip or loss of AC power***

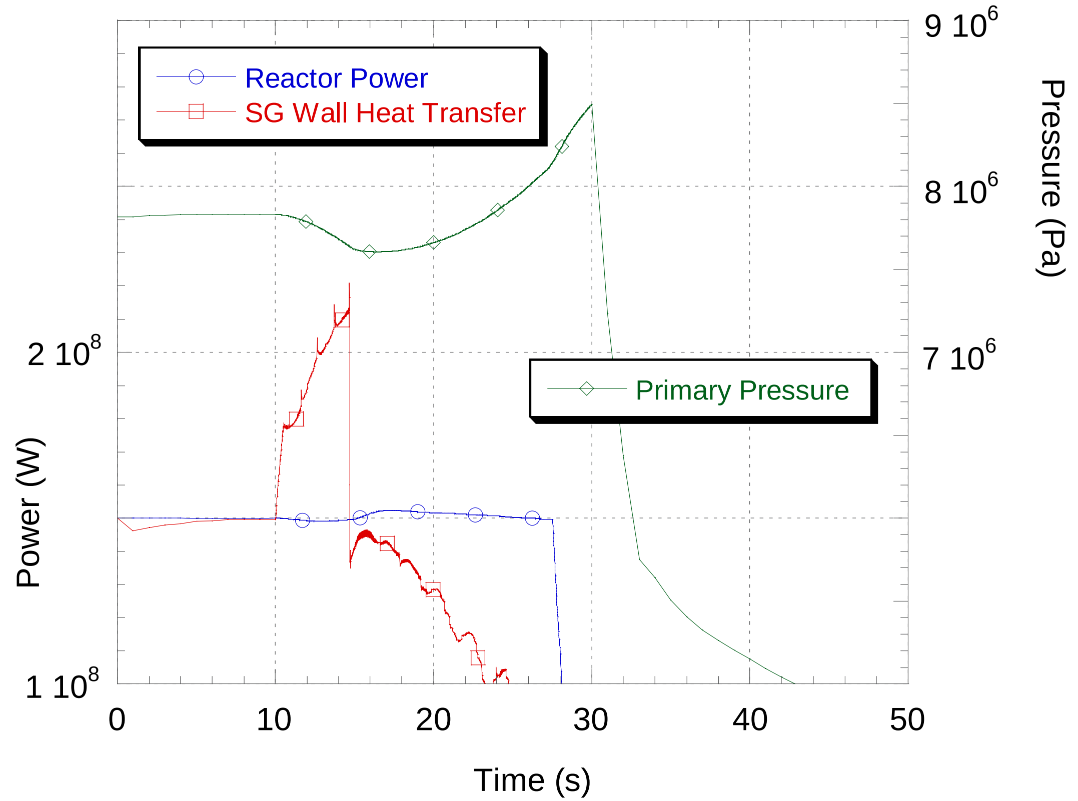
Reactor Power/Heat Rejection and Primary Vessel Pressure



Feedwater Flow Increase

- ***Feedwater flow ramp to 250% in 0.5 s***
- ***Feedwater flow terminated on high SG CLL (1.2 m + 1 s) at 15 s***
- ***Turbine tripped on low SG mass (300 kg + 0.5 s) at 27 s***
- ***Reactor scram 0.1 s after turbine trip***
- ***ADS actuates at 30 s***
- ***Maximum reactor power is 152 MW at 17 s.***
- ***Within limits for faults of moderate frequency***

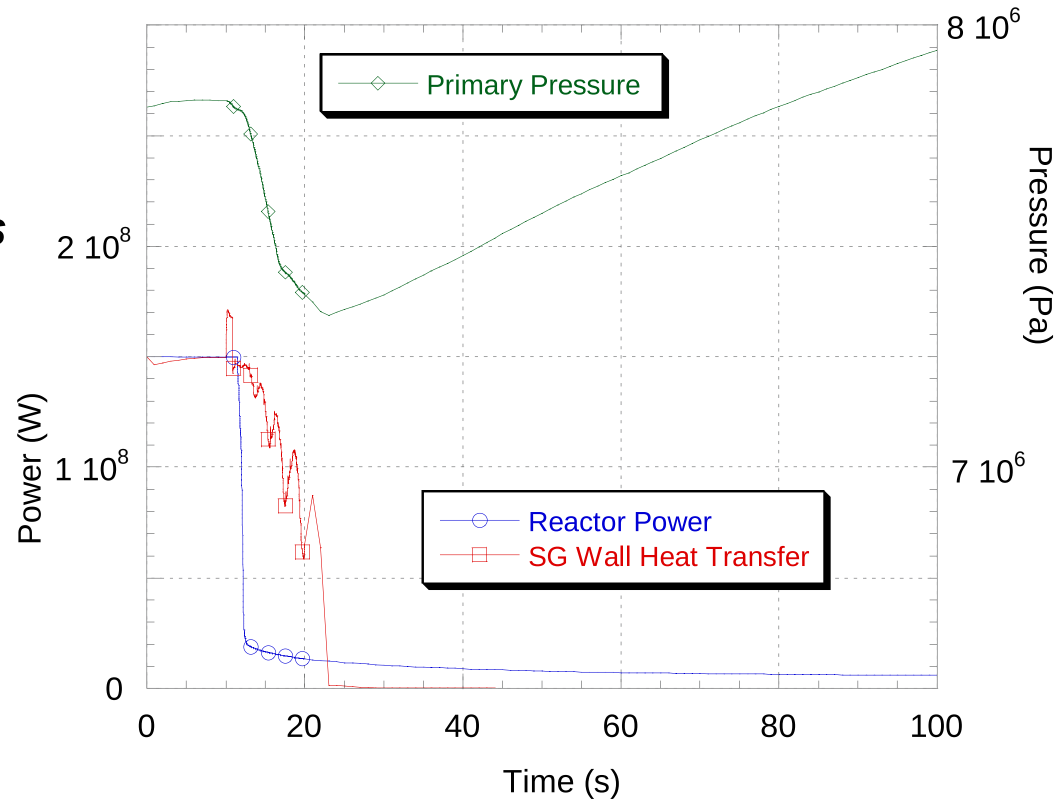
Reactor Power/Heat Rejection and Primary Vessel Pressure



Accidental Depressurization of Main Steam System

- ***Main steam line break to atmosphere***
- ***Feedwater trip and reactor scram occur at 10.9 s***
- ***SG empty at 23 s***
- ***Primary pressure decreases to 7.3 MPa, then increases slowly.***
- ***Automatic depressurization sequence begins when primary pressure exceeds 8.5 MPa***
- ***Within limits for faults of moderate frequency***

Reactor Power/Heat Rejection and Primary Vessel Pressure



Infrequent Faults

- *Small ruptured primary system pipes or cracks in large primary system pipes*
- *Minor secondary system pipe breaks*
- *Improper fuel assembly position (loading accident)*
- *Complete loss of forced reactor coolant flow*

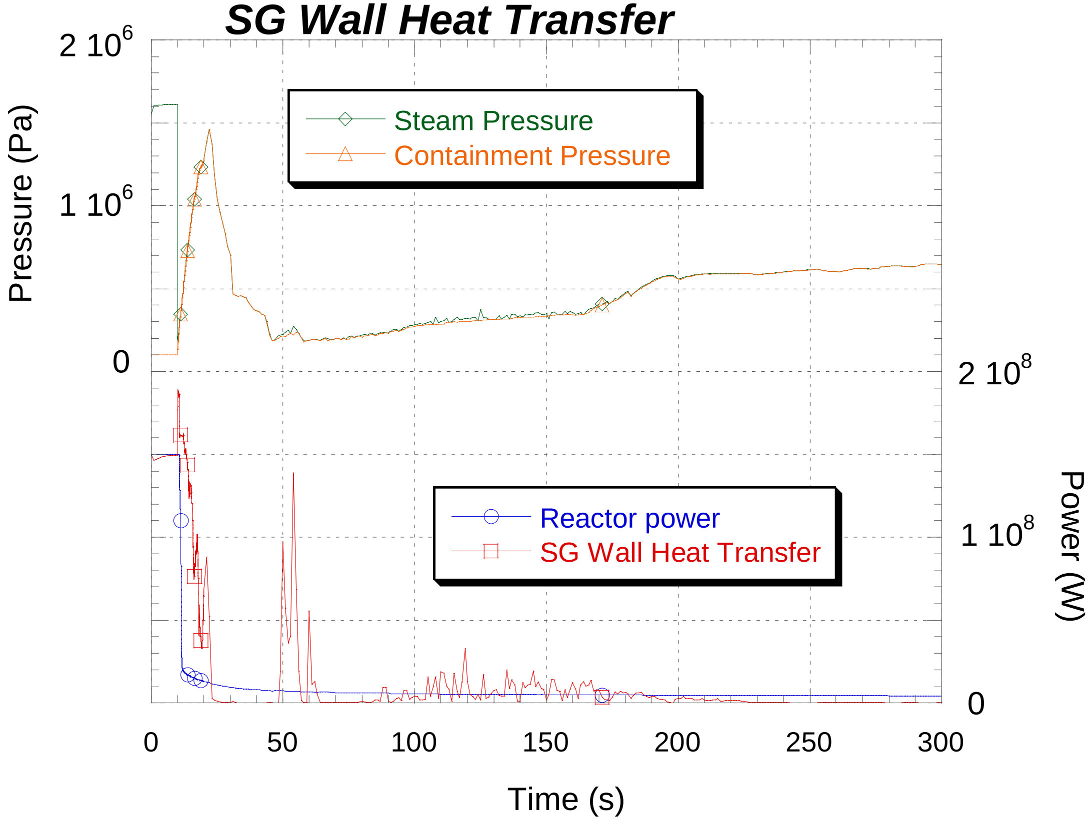
Limiting Faults

- *Major primary system pipe breaks*
  - *Steam vent line nozzle break*
    - *Failure of one ADS submerged line valve to open*
    - *Failure of both sump makeup line valves to open*
  - *ADS blowdown line nozzle break*
    - *Second ADS submerged line valve opens normally*
    - *Failure of both sump makeup line valves to open*
  - *Collapsed liquid level sufficient to provide cooling*
  - *No cladding thermal excursion*
- *Steam generator tube rupture (not analyzed)*
- *Fuel handling accident (not analyzed)*
- *Major secondary system pipe breaks*
  - *Main steam line break*
- *Rod ejection accident*

Main Steam Line Break Inside Containment

- ***Break main steam line at nozzle***
- ***Containment pressure maximum 1.5 MPa (218 psia)***
- ***ADS initiation at 20 s (primary pressure < 7.4 MPa with containment pressure > 150 kPa)***
- ***ADS submerged blowdown line effective in controlling containment pressure***
- ***Within limits for limiting faults***

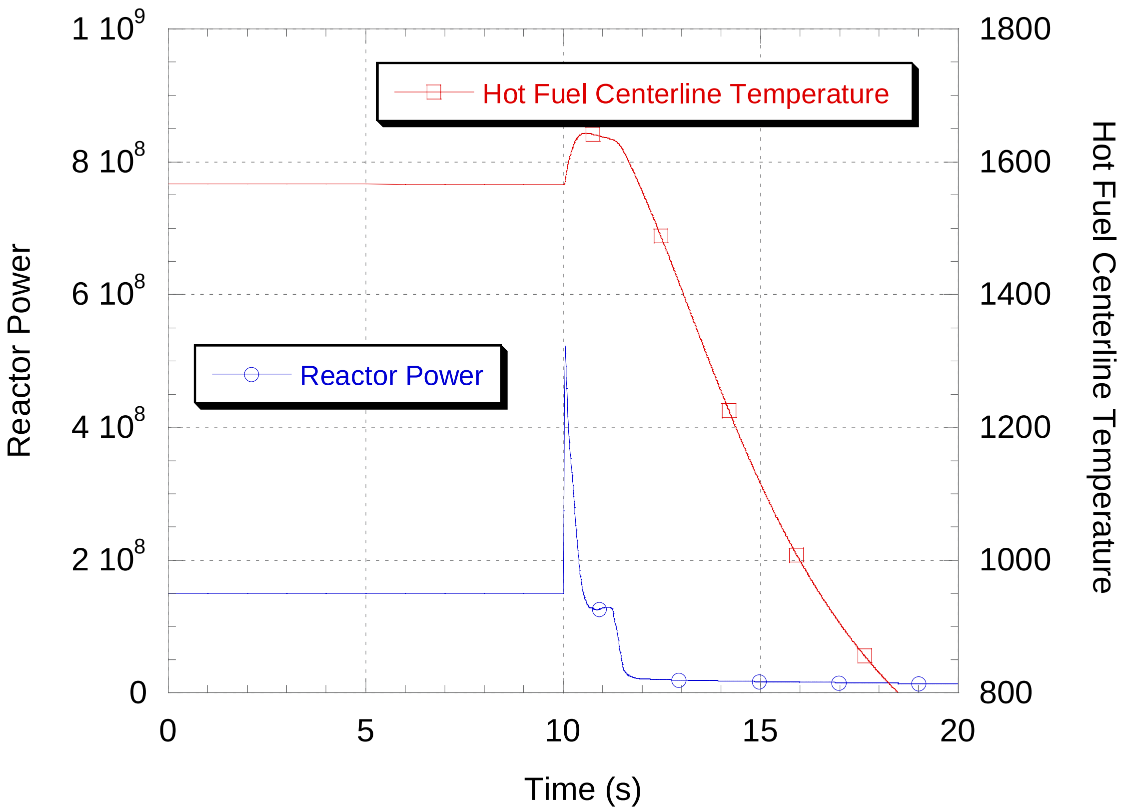
Steam and Containment Pressure / Reactor Power and SG Wall Heat Transfer



Rod Ejection Accident

- ***0.75 $ inserted in 1 10^{-5} s***
- ***Power spike to 520 MW***
- ***Fuel centerline temperature increase 75 K in hot fuel rod***
- ***Coolant temperature increase ~5 K***
- ***Doppler (-0.005 $/K) and Moderator (-0.08 $/K) about equally effective for power turning***
- ***Maximum fuel enthalpy increase 13 cal/gm***

Reactor Power and Hot Fuel Centerline Temperature



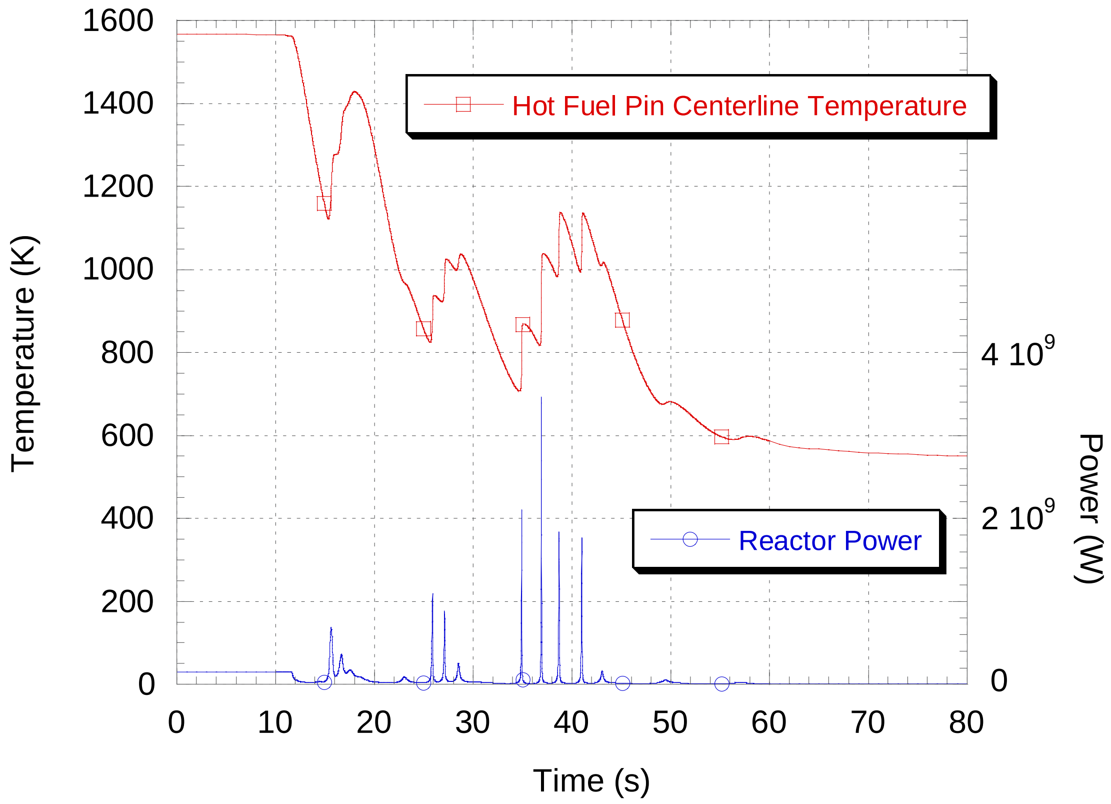
Beyond Design Basis Accidents

- *Anticipated transients with failure to scram*
  - *Loss-of-feedwater*
  - *Inadvertent ADS steam vent valve opening*
  - *Inadvertent ADS blowdown valve opening*

Inadvertent Opening of Steam Vent Valve with Failure of Reactor to Scram

- ***Power spikes to maximum of 3500 MW***
- ***Maximum fuel enthalpy increase 72 cal/gm***
- ***No significant fuel heatup***
- ***No fuel damage***
- ***Boron effective only at t > 500 s***
- ***Within limits for credible accidents***

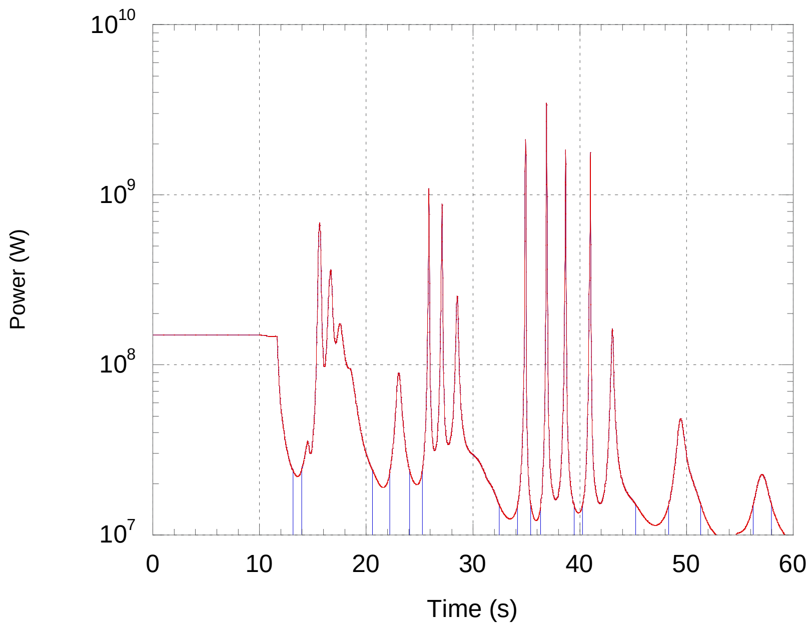
Hot Fuel Centerline Temperature and Reactor Power



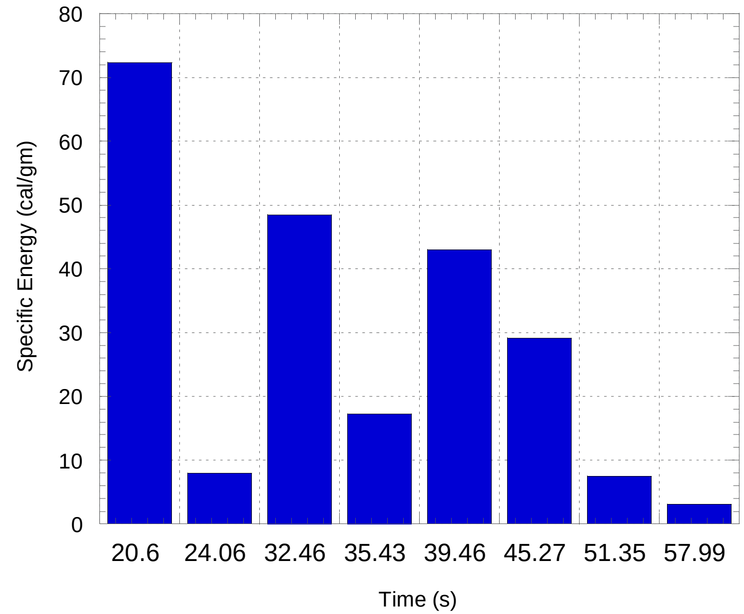
Calculation of Maximum Fuel Pin Energy Density

$$Specific\ Energy\left(\frac{cal}{gm}\right) = \frac{Energy\,(J)}{V_{fuel}\,(m^3)} \times \frac{1.36\,(F_{ax}) \times 1.4\,(F_{rad})}{6336\ fuel\ rods} \times \frac{1\,m^3}{10980 \times 1000\ gm} \times \frac{1\,cal}{4.1868\,J}$$

Reactor Power Intervals



Energy Deposition in Hot Fuel Pin



Conclusions

- *Calculations performed for beginning-of-life conditions*
- *No significant transient cladding temperature excursions*
- *Containment pressure within acceptable limits*
- *All transients demonstrate stable system end state*
  - *Adequate coolant recirculation between containment and vessel*
  - *Stable vessel collapsed liquid level*
  - *Adequate cooling of reactor core*
  - *Adequate heat is rejected to ultimate heat sink*