ESBWR Seminar – Reactor, Core & Neutronics

September 15, 2006
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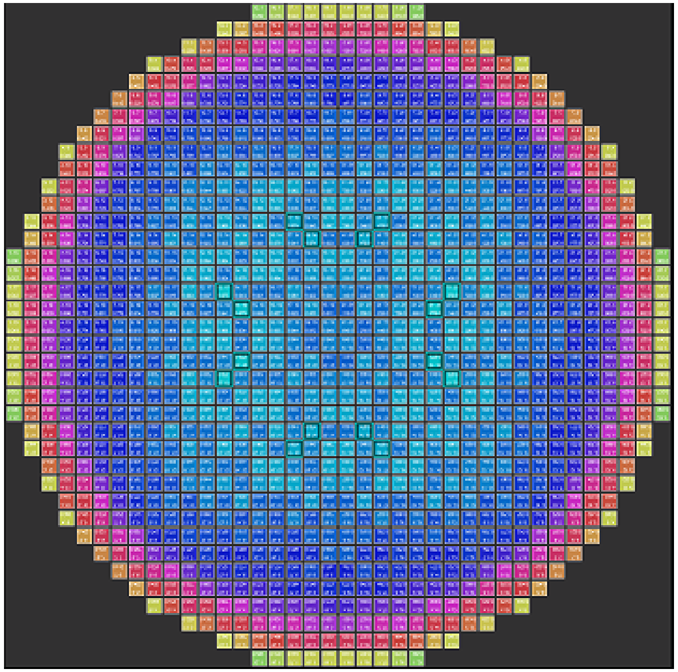
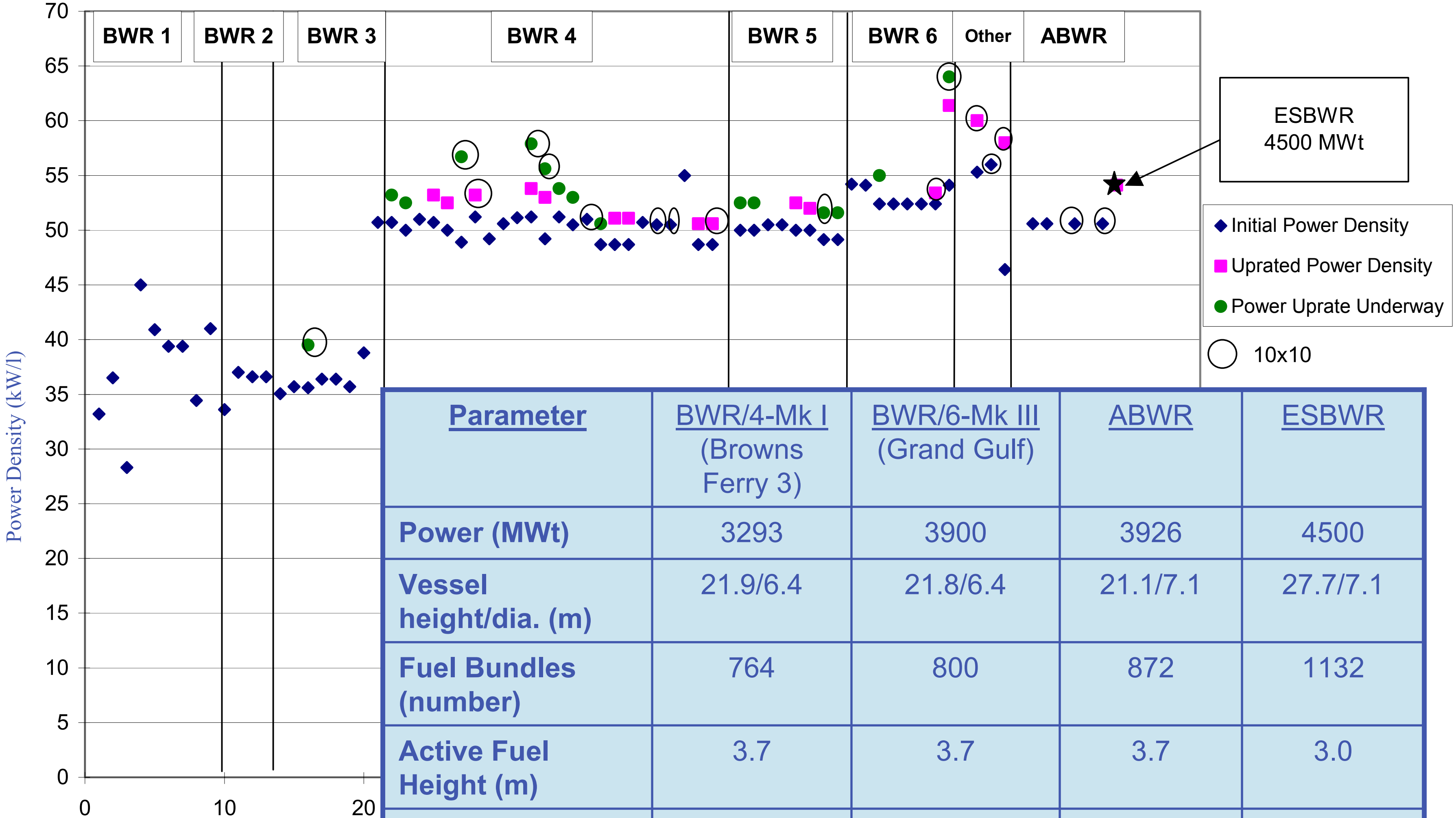
ESBWR Reactor Specification

- 4500 Rated MWth (Reference)
- 1132 Bundles
  > N- Lattice (symmetric water gap)
  > Shortened Active Fuel Length (3.048 m)
  > Moderate Power Density (54.3 kw/liter)
- 269 Control Blades
  > Fine Motion Control Rod Drives (FMCRDs)
    - Fine motion electrical positioning
    - Fast Hydraulic Scram
    - Reduced Fuel Duty



ESBWR Parameter Comparison



Parameter	BWR/4-Mk I (Browns Ferry 3)	BWR/6-Mk III (Grand Gulf)	ABWR	ESBWR
Power (MWt)	3293	3900	3926	4500
Vessel height/dia. (m)	21.9/6.4	21.8/6.4	21.1/7.1	27.7/7.1
Fuel Bundles (number)	764	800	872	1132
Active Fuel Height (m)	3.7	3.7	3.7	3.0
Number of CRDs/type	185/LP	193/LP	205/FM	269/FM

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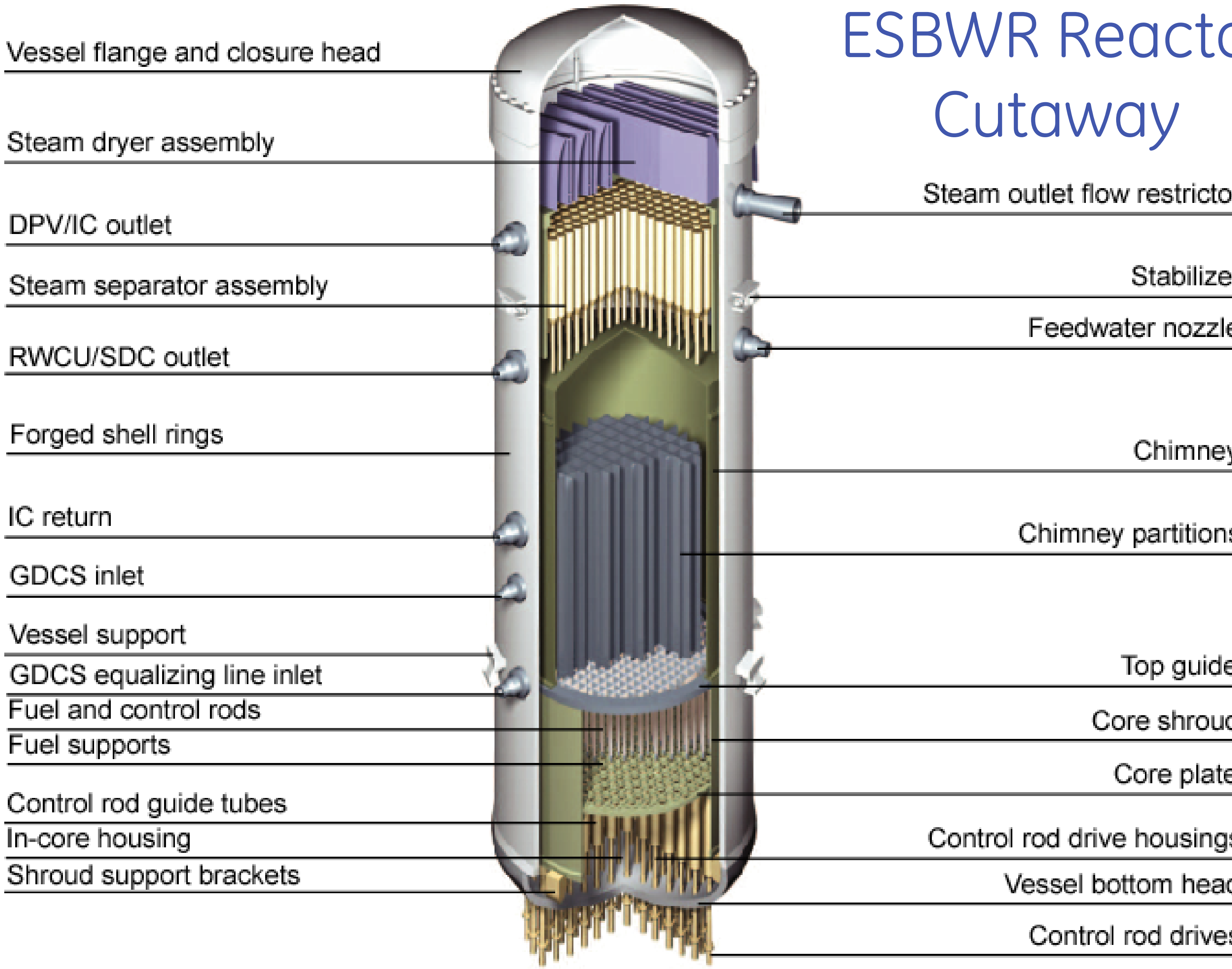
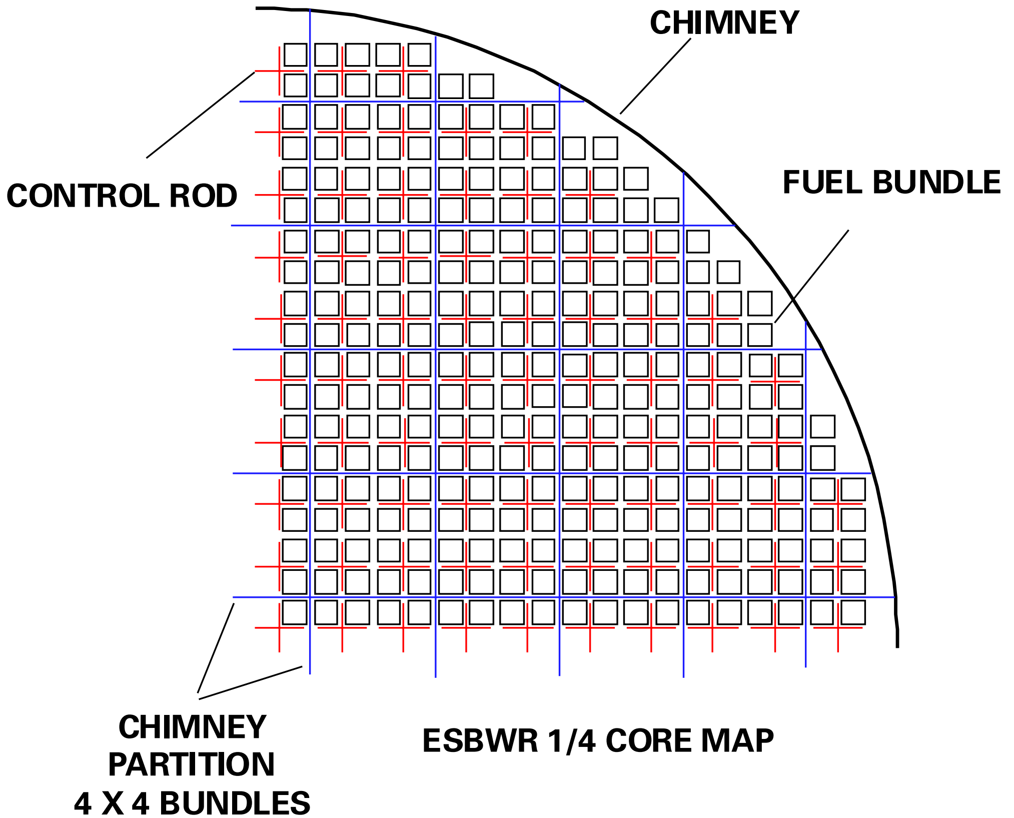
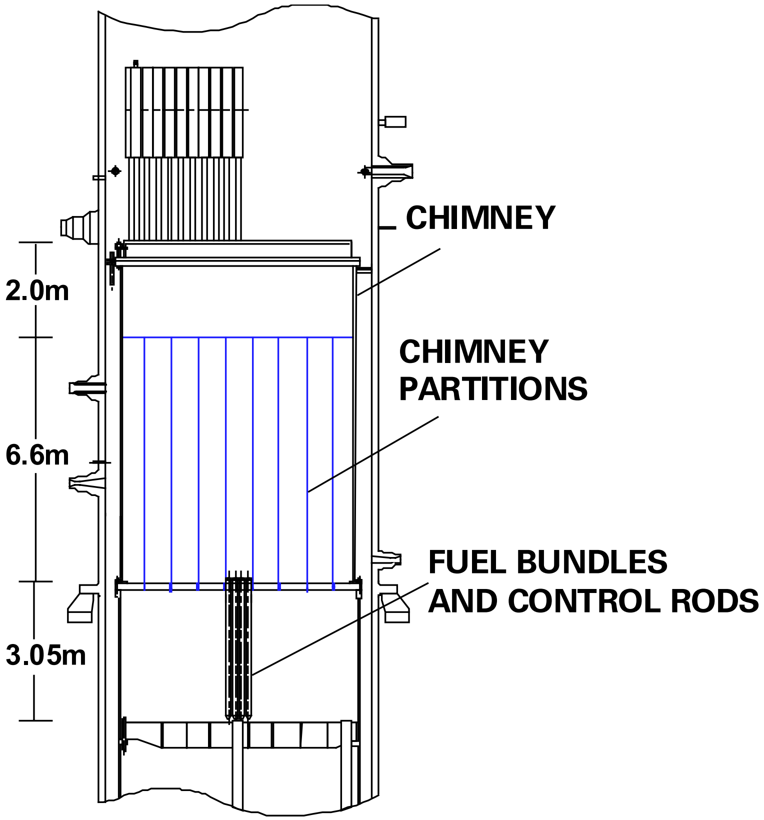
ESBWR Reactor Cutaway



ESBWR Chimney and Partitions



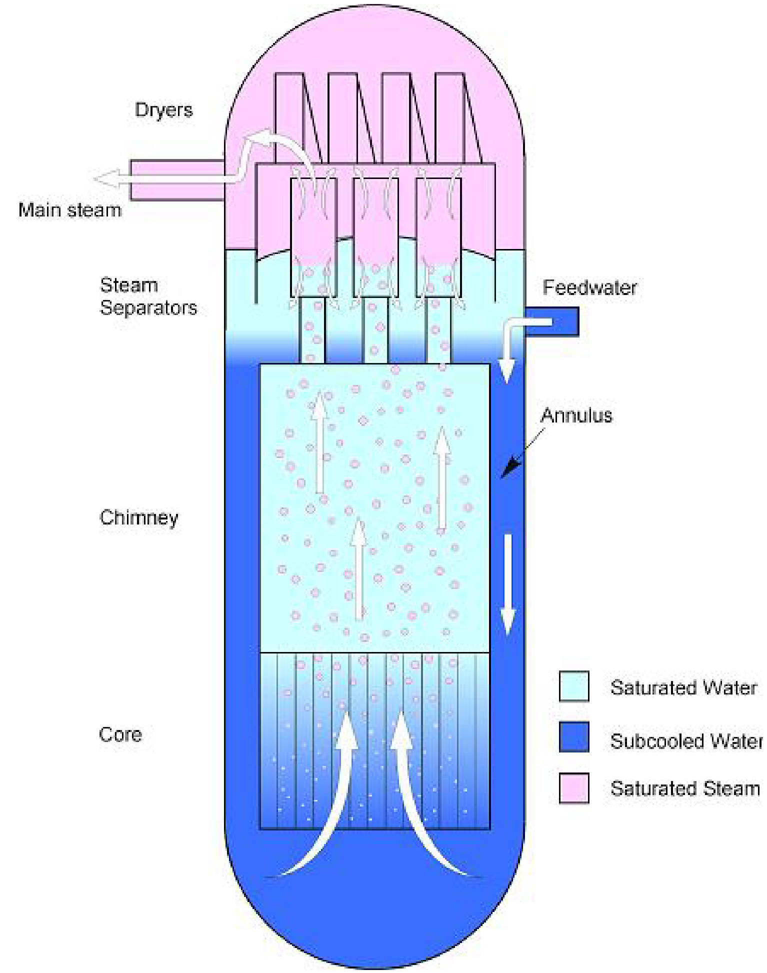


Natural Circulation

It Works in Operating BWR's Today

ESBWR Greatly Improves this Feature

- Differential Water Level Increased by Approximately 27 Feet (~8.2 m)
- Greatly Increases Driving Head to Increase Natural Circulation Flow
- Design Allows for a Band of Acceptable Flow (accounts for uncertainties)
- Simplification Removes Many of the Risks of Forced Circ Plants (i.e. – pump failure)

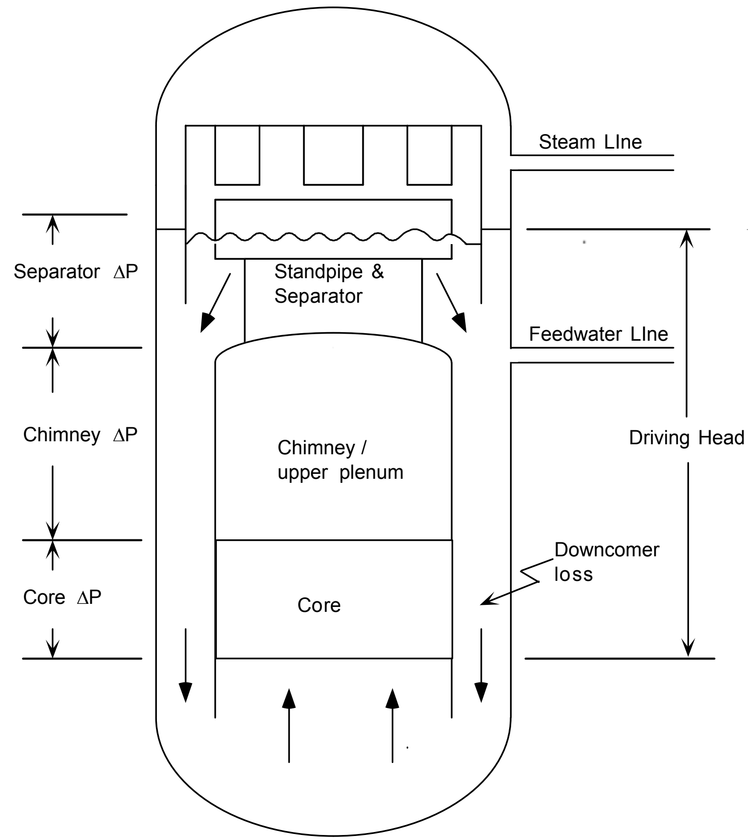


Natural Circulation (cont.)

- Natural circulation proven as an effective technology at Dodewaard reactor (183 MWt)
- Operating BWR data gathered from Stability tests under Natural Circulation and from Recirc Pump trip events benchmarks flow at higher power (> 1000 MWt)
- Ontario Hydro testing - additional large diameter pipe void fraction data to qualify chimney two phase flow predictions
- CRIEPI testing - atmospheric to full pressure – confirms startup characteristics
- TRACG code qualified using above data – predicts natural circulation flow and stability well

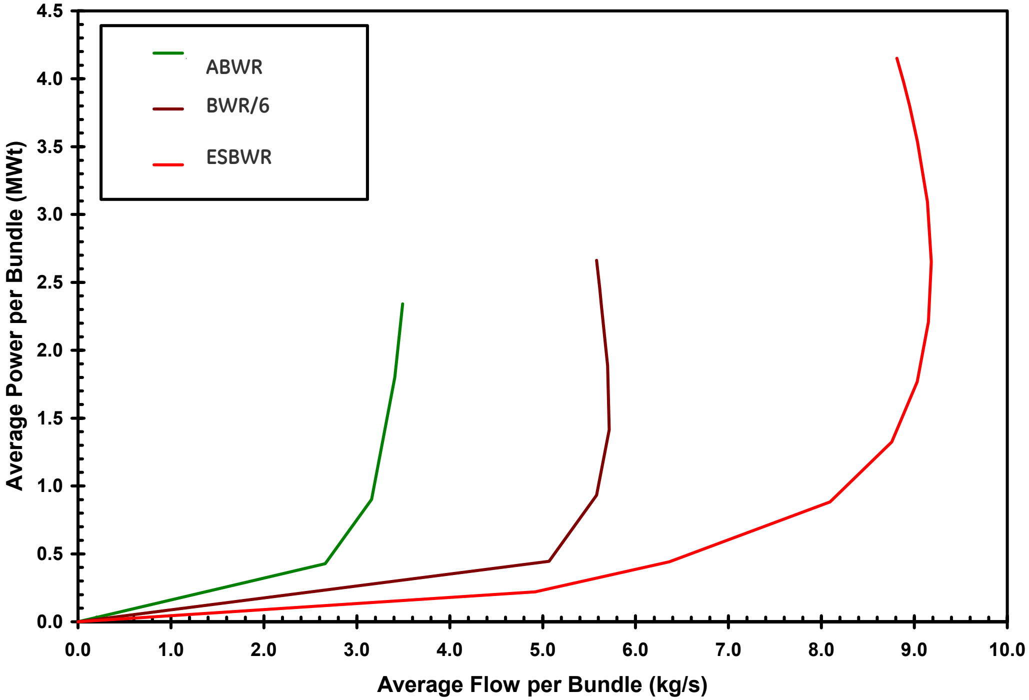
Natural Circulation Flow

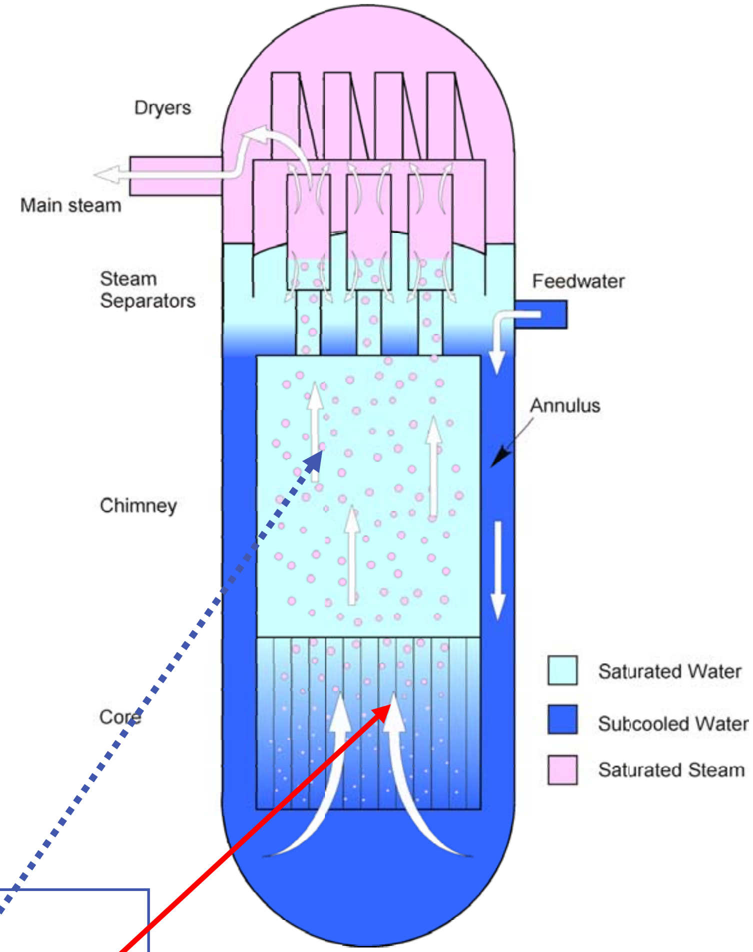
- Core flow depends on
  > driving head
  > losses through the loop
- Driving head
  > proportional to core + chimney height
    – **Void Fraction**
- Loop losses
  > downcomer
    – **Single-phase Δp, handbook loss coefficient**
  > core (fuel bundle)
    – **Two-phase Δp, test data/correlation**
  > chimney ~ small
  > separator
    – **Two-phase Δp, test data/correlation**



Schematic of Flow and Pressure Drops in a Reactor

Enhanced Natural Circulation





- Higher driving head
  - Chimney/taller vessel
- Reduced flow restrictions
  - Shorter core
  - Increase downcomer area

BWR Stability

- Thermal hydraulic
  - Hot channel hydrodynamic
  - Density wave propagation
  - Constant channel pressure drop
  - No power oscillations
- Neutronic coupling
  - > Core-wide
    - Neutronic feedback: void -- reactivity -- power -- heat transfer -- void
    - External loop feedback: flow -- pressure drop -- flow
    - All fuel channels oscillate in phase
    - Oscillations in core flow, core pressure drop, core power
  - > Regional
    - Neutronic feedback: void -- reactivity -- power -- heat transfer -- void
    - Harmonic modes
    - Two or more core regions oscillate out of phase

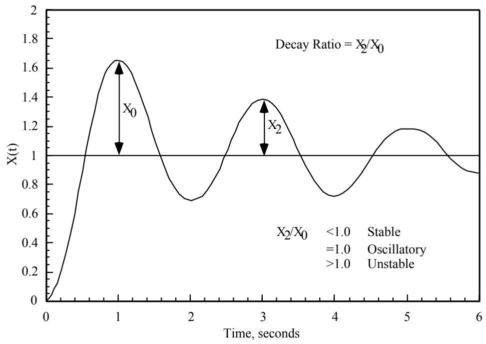
Stability Analysis

Stability analysis performed with TRACG

- Rated operation is limiting for stability
- Channel, “super bundle” and core decay ratios
- Best estimate for BOC, MOC, EOC
- Monte Carlo analysis for 95P/95C at limiting state
- Additional evaluations of stability under transient conditions
  - Loss of Feedwater (LOFW)
  - Loss of Feedwater Heating (LOFWH)
  - Anticipated Transient Without Scram (ATWS)

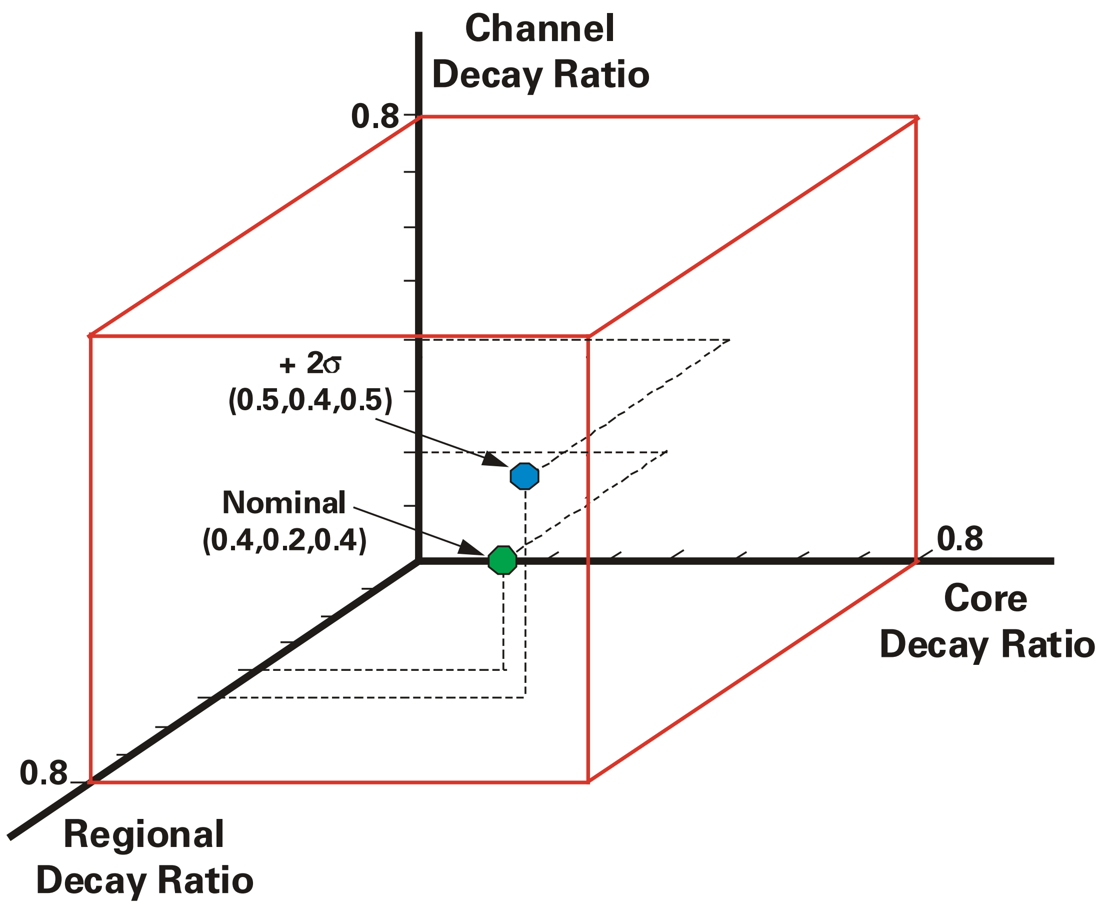
Characterizations of Stability

- Decay ratio
  > Measure of stability when stable; based on linear feedback analogy of 2nd order system (see figure)
    - Channel decay ratio
    - Core decay ratio
      - Core wide instability
      - Regional instability



- Limit cycle
  > Unstable in linear sense; repeated cyclic behavior of physical parameters (e.g., peak-to-peak neutron flux)
  > Oscillation magnitude(s) limited by nonlinear feedback inherent in actual BWR reactor system

TRACG Prediction of ESBWR Stability



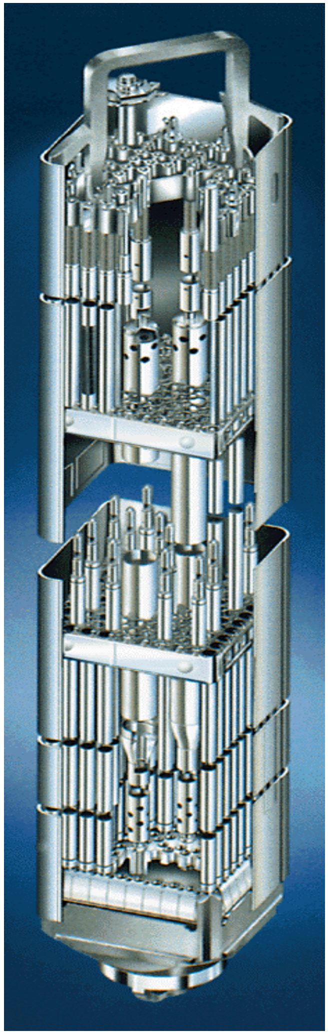
ESBWR expected to have significant stability margin

Natural Circulation / Stability Summary

- ESBWR natural circulation flow is much higher than natural circulation for jet pump/ internal pump plants
- Flow transients from Recirc anomalies not present (i.e. – no runbacks/pump trips challenging stability)
- Allowance for uncertainties is incorporated into design
- Conservative design criteria are satisfied
- Decay ratios have large margin to instability

ESBWR Reference Fuel Bundle Design

- Design Derived from GE14
  - > Proven Components
  - > Supports High Energy Cycles
  - > Supports High Exposure
- 14 Part Length Rods
  - > Improved Pressure Drop
  - > Improved Stability
  - > Improved Shutdown Margin
  - > Improved Fuel Efficiency
- Natural Uranium Blankets
- Power Shaping Zone
  - > Additional Gad at Bottom
  - > Helps Control Power Shape
- Supports 24 month Cycle
  - > Large Cold Shutdown Margin
  - > Large CPR Margin
  - > Large KW/ft Margin



GE 10x10 Fuel

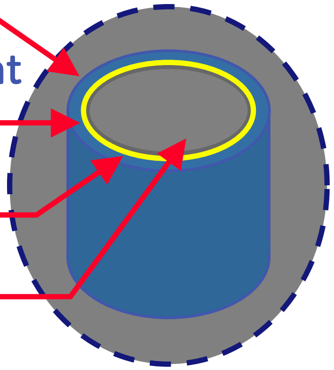
Reliability

Corrosion Resistant Surface

Degradation Resistant Cladding

PCI Resistant Liner

Improved Pellet



Corrosion Resistant Channel

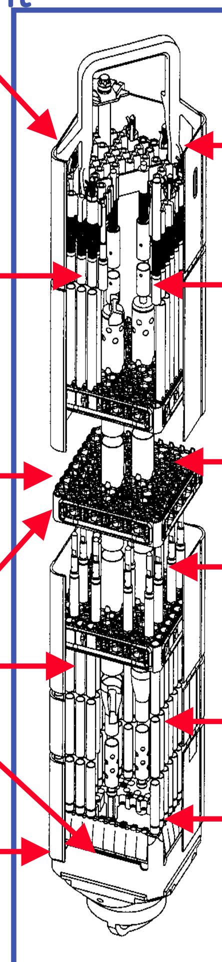
Corrosion Resistant Spacer

Spacer Resistant To Hydrogen Damage

Low LHGR

Debris Resistant Tie Plate

Debris Filter (Optional)



Operational Flexibility

Minimum Pressure Drop Upper Tie Plate

High LHGR Margin

Low Pressure Drop Spacer

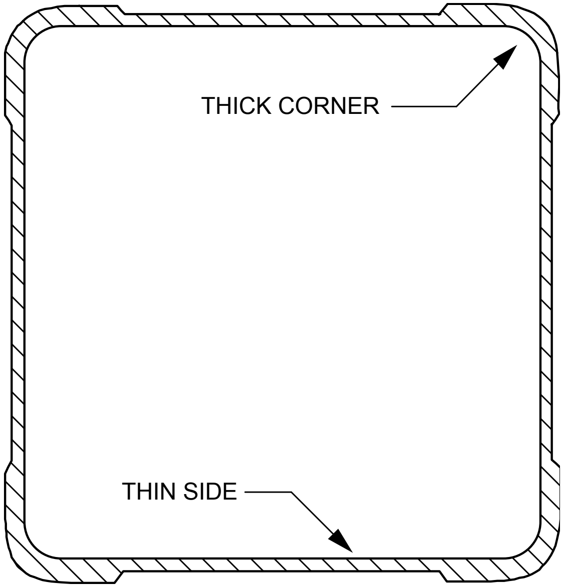
Part-Length Rods Reduce 2-Phase Pressure Drop

Enhanced Critical Power Performance

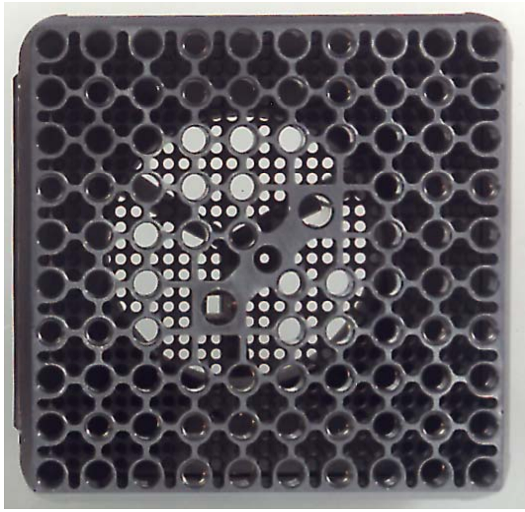
Optimize Single Phase Pressure Drop for Stability

Other Fuel Assembly Features

- Interactive Channel
  - > Protects Fuel Rods & Spacers
  - > Directs Coolant Flow Upward
  - > Thick-Thin Design Minimizes Material
  - > Increases Moderator in Bypass Region
  - > Increases Control Rod Clearance

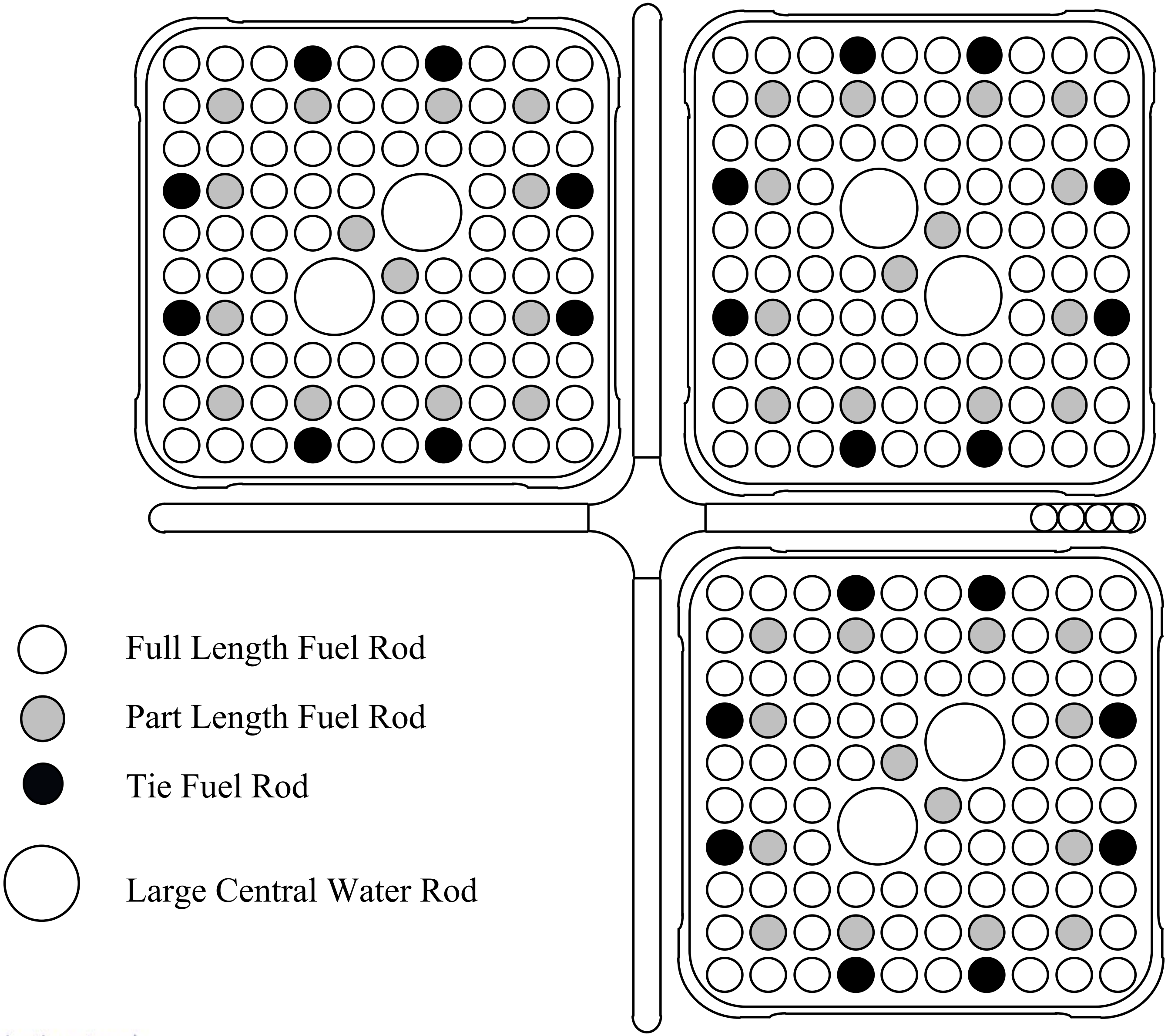


- Debris Filter Lower Tie Plate
  - > Defends Against Debris Entry and Fretting
  - > Improves Stability

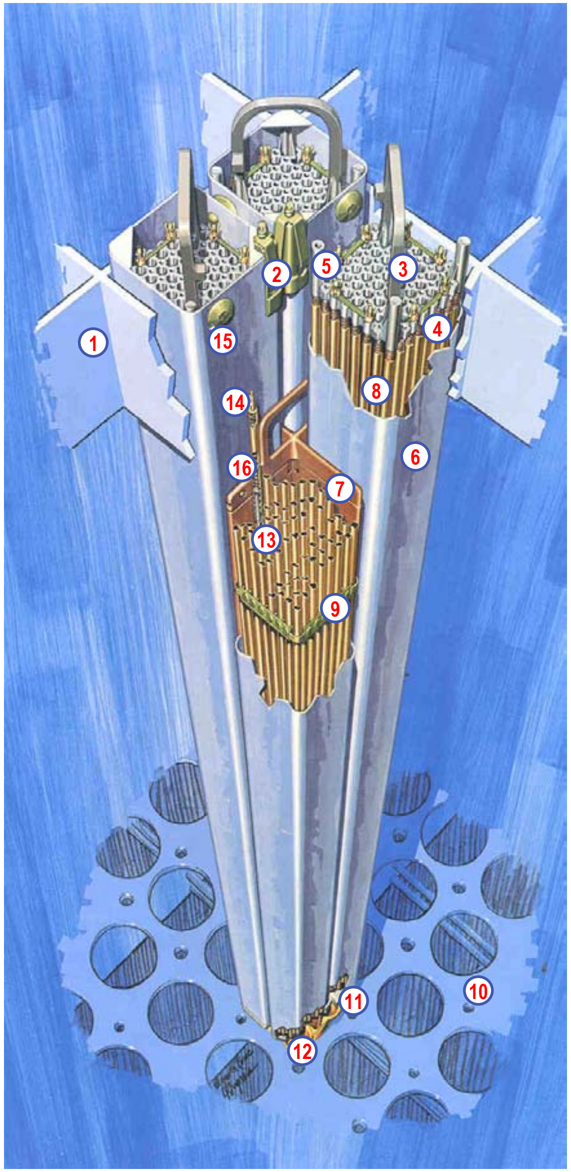


- Low Pressure Drop Upper Tie Plate

Four Bundle Module



BWR Fuel Assemblies and Control Rod



1 Top Fuel Guide
2 Channel Fastener
3 Upper Tie Plate
4 Expansion Spring
5 Locking Tab
6 Channel
7 Control Rod
8 Fuel Rod
9 Spacer
10 Core Plate Assembly
11 Lower Tie Plate
12 Fuel Support Piece
13 Fuel Pellets
14 End Plug
15 Channel Spacer
16 Plenum Spring

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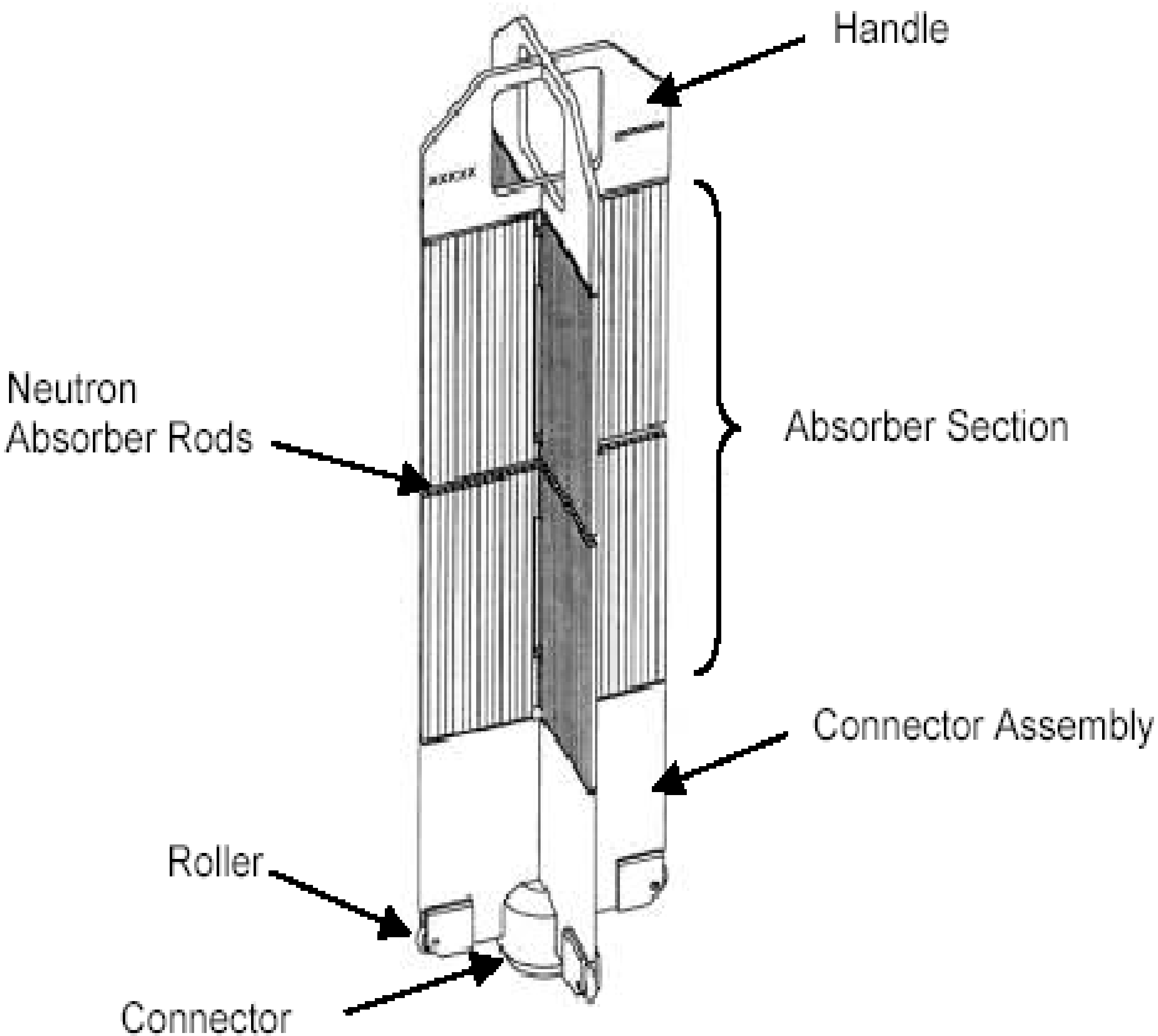
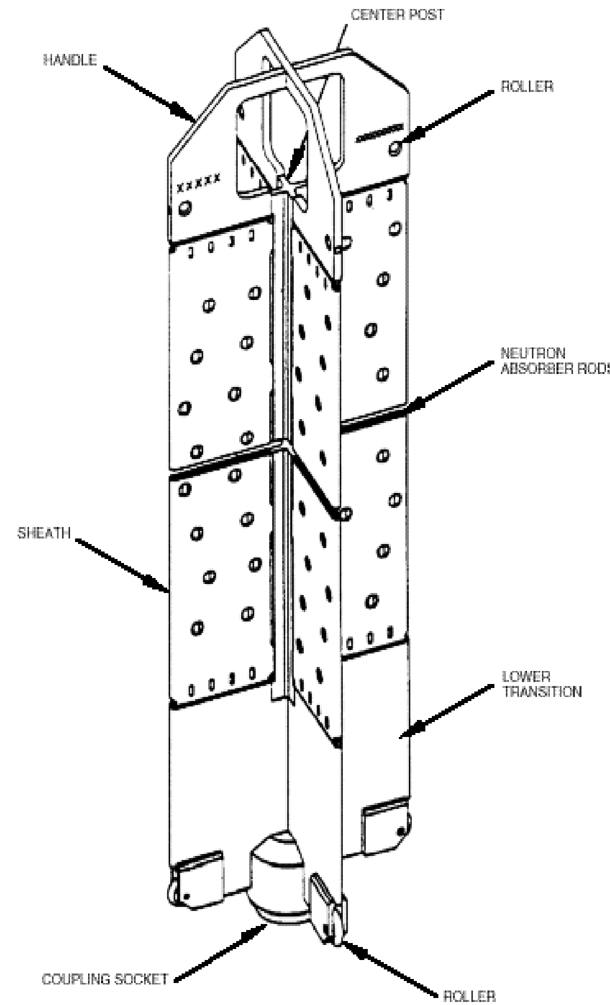
Control Rod

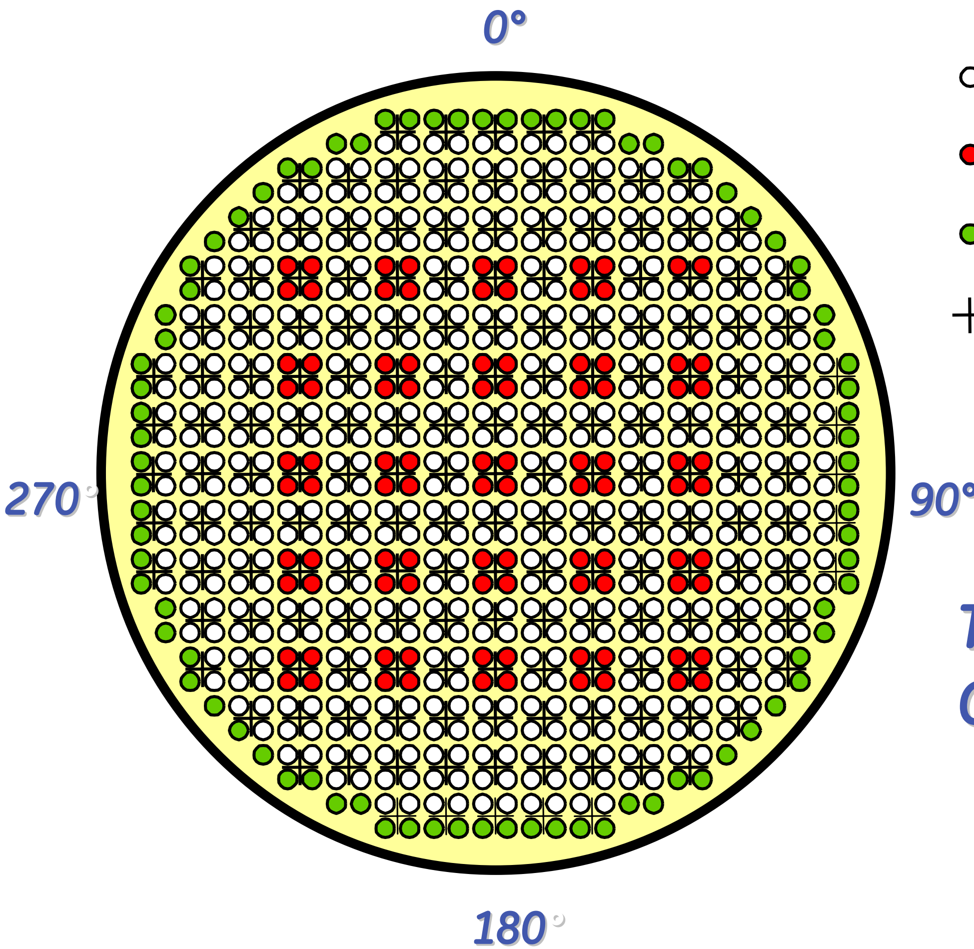


Handle
Neutron Absorber Rods
Absorber Section
Connector Assembly
Roller
Connector



CENTER POST
HANDLE
ROLLER
NEUTRON ABSORBER RODS
SHEATH
LOWER TRANSITION
COUPLING SOCKET
ROLLER

BWR Core Design



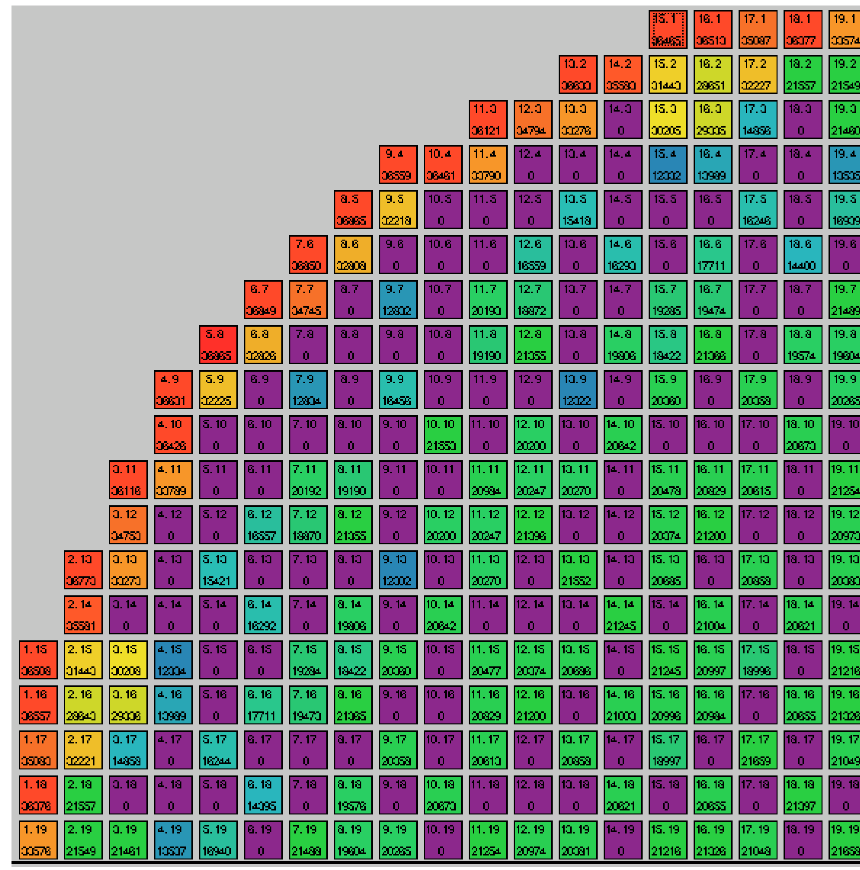
- ○ Fuel Bundle
- ● Control Cell Bundle
- ● Peripheral Bundle
- + Control Blade

Typical Control Cell Core (CCC) Layout

- Low reactivity bundles are placed in the control cells (CC)
- Control rod movement is done with CC rods during operation to compensate for burnup

Loading Example – BOC Exposures

- Loaded for 24 Month Operation
  > 476 Bundles
  > Burn Fuel in Control Cells to Improve Robustness and Reduce Channel Bow (“Control Cell Core”)
  > Most Exposed Fuel Loaded on the Perimeter
  > Center of Core is Fresh and Once Burnt Fuel Only
  > Margin to Exposure Limits



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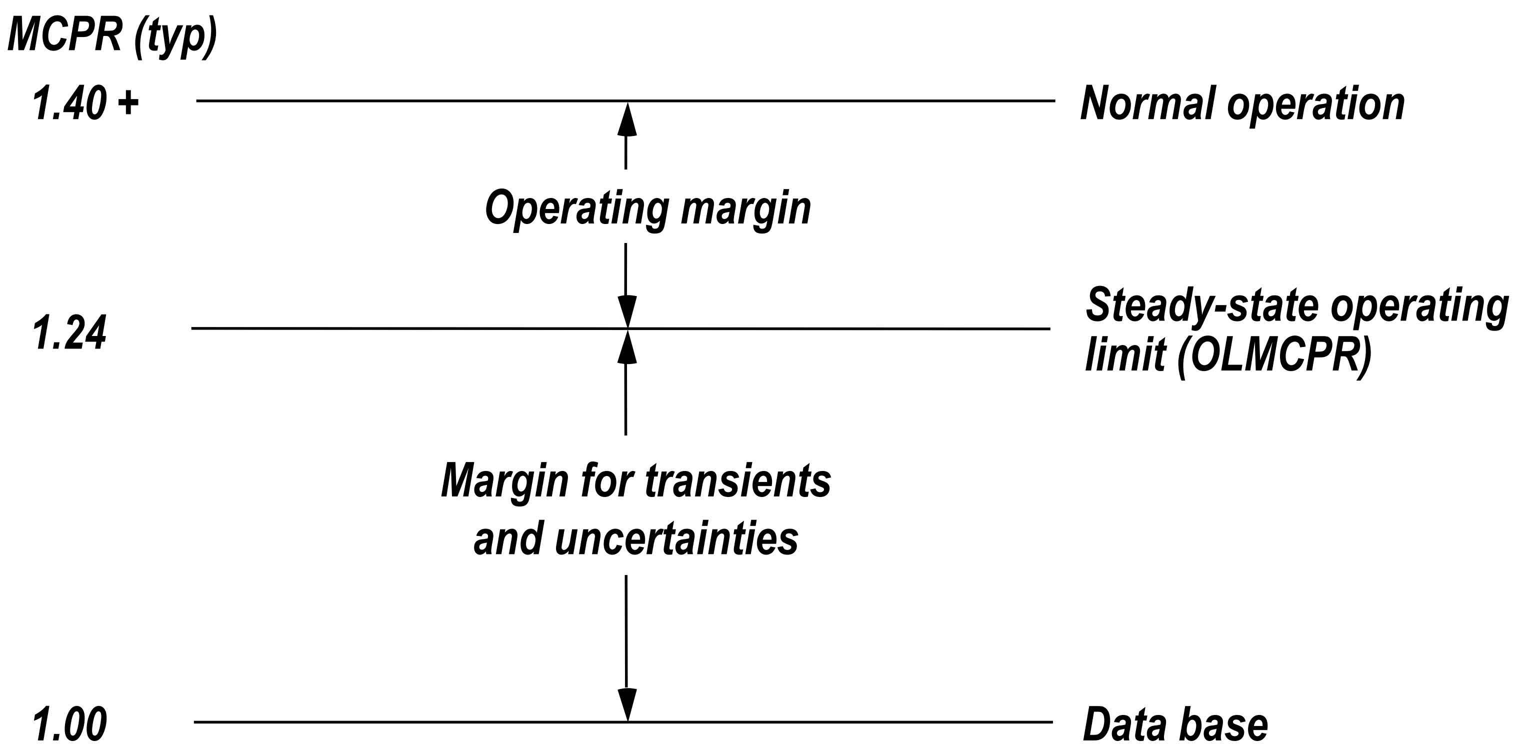
Fuel Thermal Design Objectives

- **Transients**
  - > Avoid clad overheating during normal operation and expected transients
    - – Minimum Critical Power Ratio (MCPR)
  - > Avoid fuel damage due to excessive cladding strain resulting from UO_2 expansion – Maximum Fuel Linear Power (MFLPD)
  - > Maintain less than 1% plastic strain: 25 kW/ft (82 kW/m)
    - – Normal peak pellet < 13.4-14.4 kW/ft (44-47 kW/m)
- **Accidents**
  - > Meet 10CFR50.46 limits
    - – Fuel clad temperature < 2200°F
    - – Local oxidation < 17%
    - – Average oxidation <1%

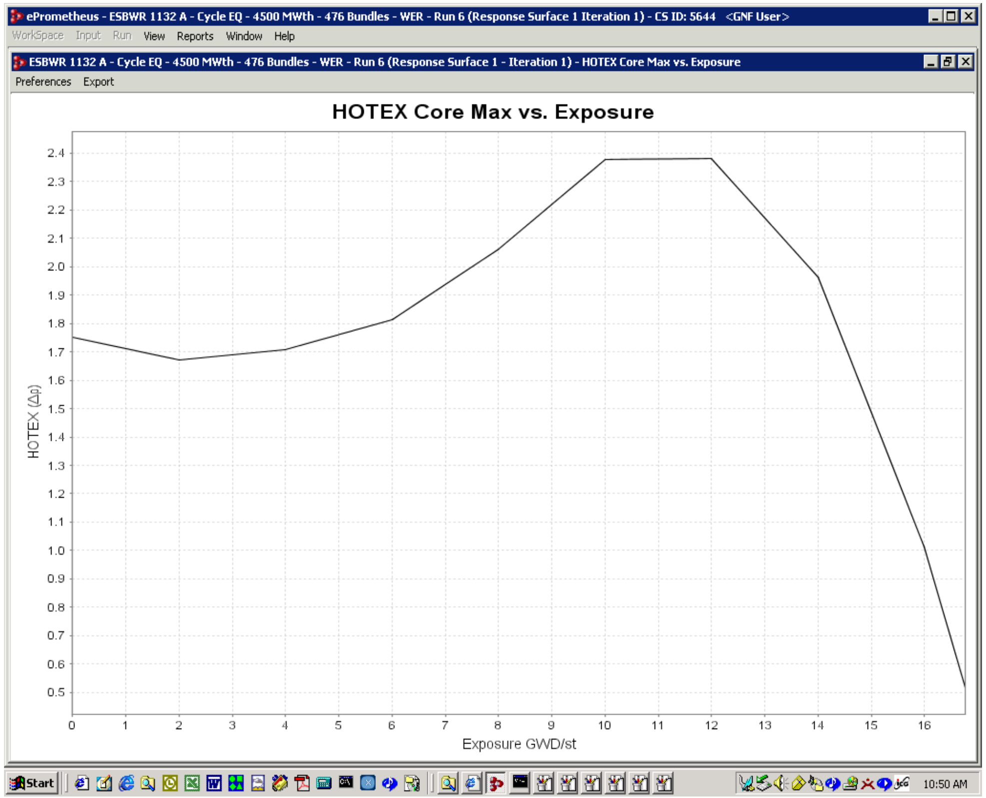
MCPR Design Criterion

Transients caused by single operator error or equipment failure shall be limited such that, considering uncertainties in monitoring the core operating state, more than 99.9% of the fuel rods would be expected to avoid Boiling Transition. (Boiling Transition does not mean fuel failure).



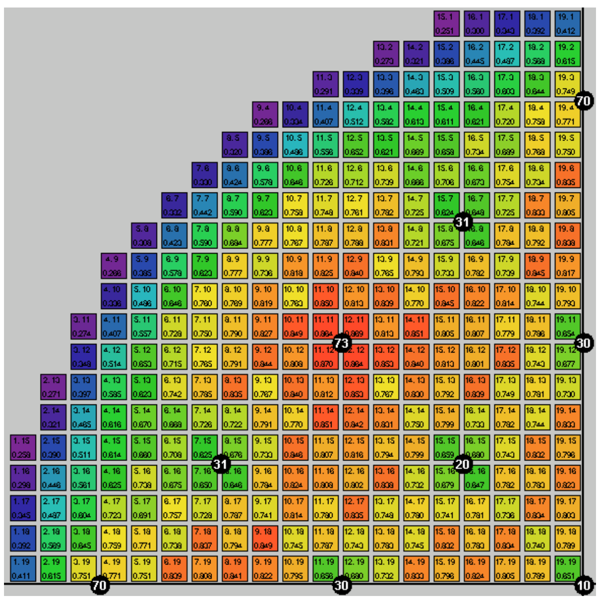
Loading Example – Hot Excess Profile

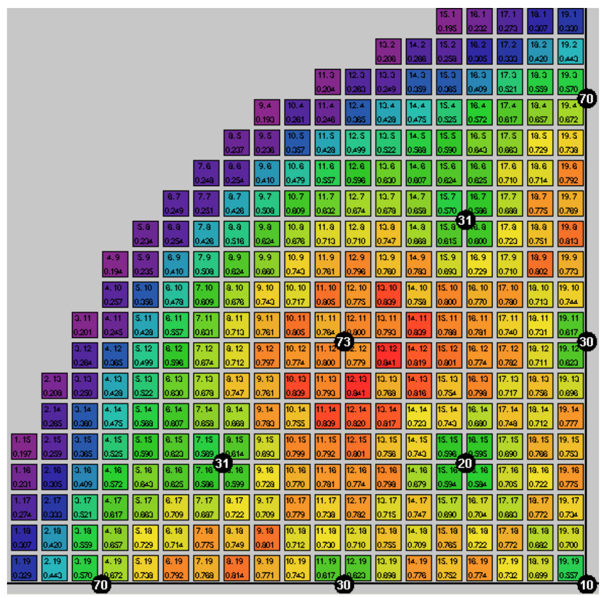
- Smooth Hot Excess Profile
  - > BOC = 1.75%
  - > PHX = 2.50%
- Consistent with Fleet best Practices

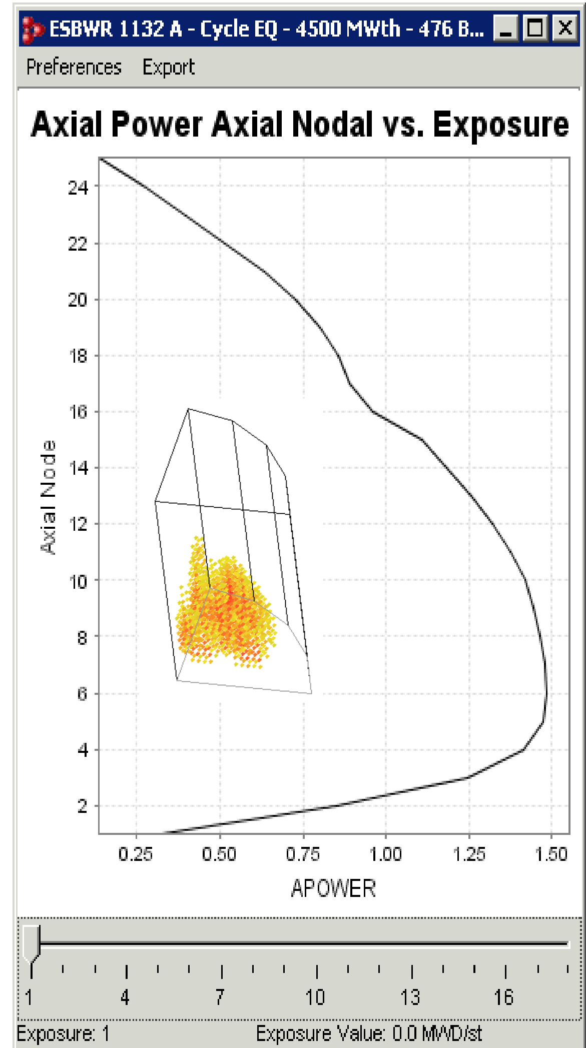


Rod Pattern Example at BOC

- Flexible Rod Patterns
- 15% MCPR and MFLPD Margin
- Axial Shape at Bottom to Maximize Eff.
- Startup in First Set of “A2’s”

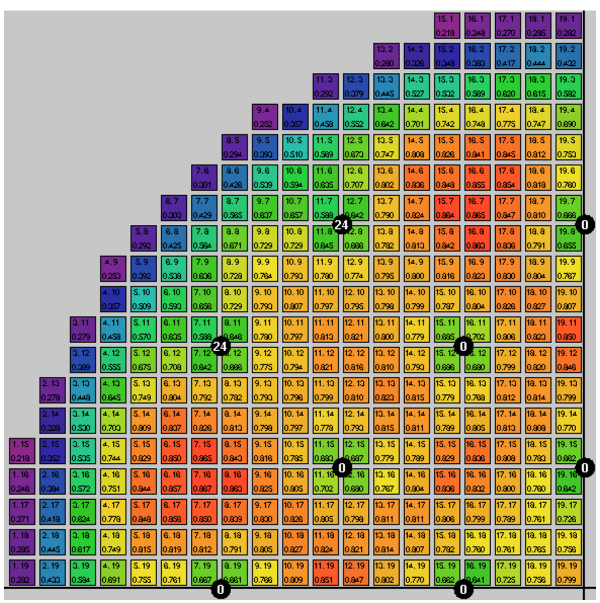


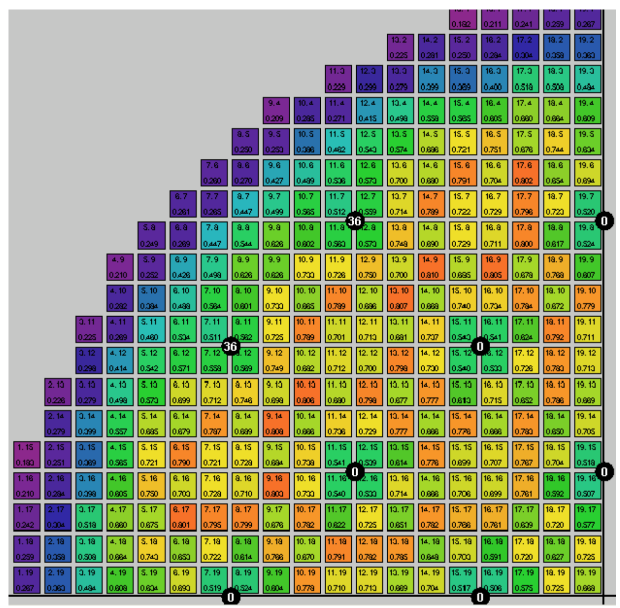


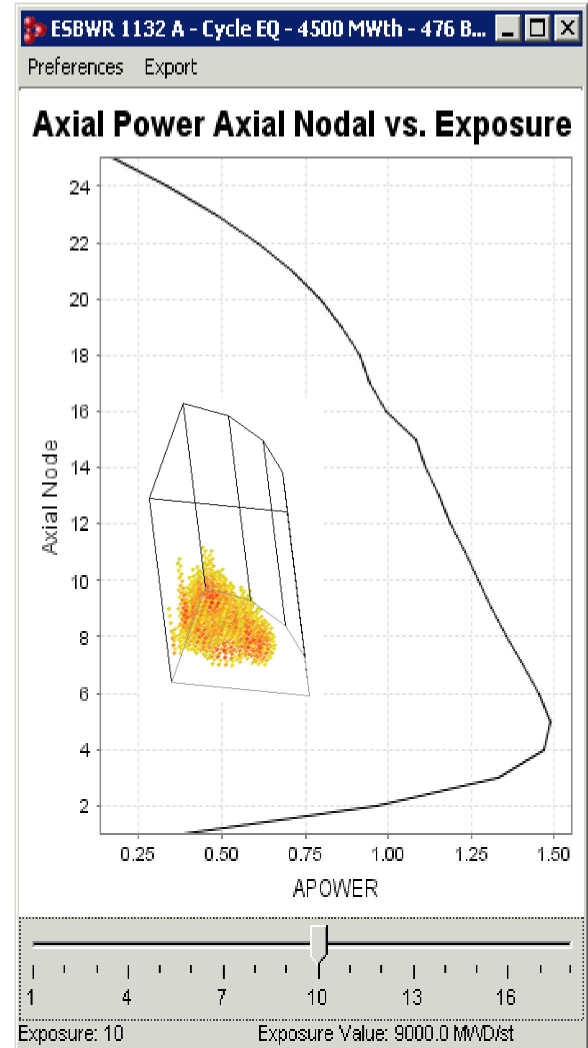


Rod Pattern Example at MOC

- Flexible Rod Patterns
- 15% MCPR and MFLPD Margin
- Axial Shape at Bottom to Maximize Eff.
- Alternate set of “A2’s” for Hot Excess Control

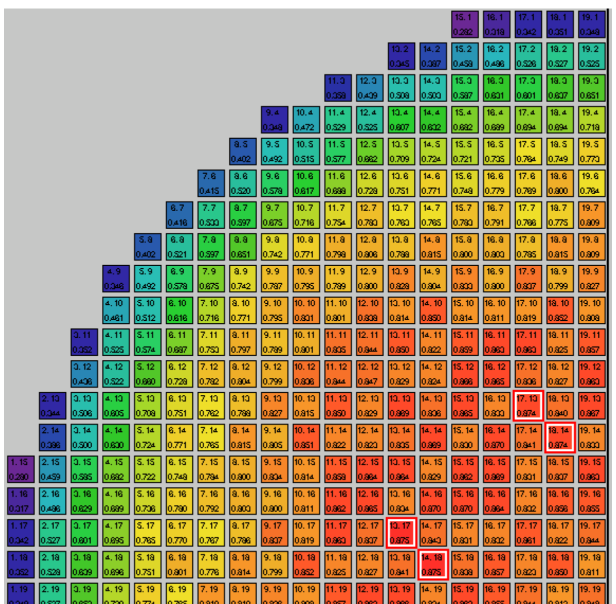


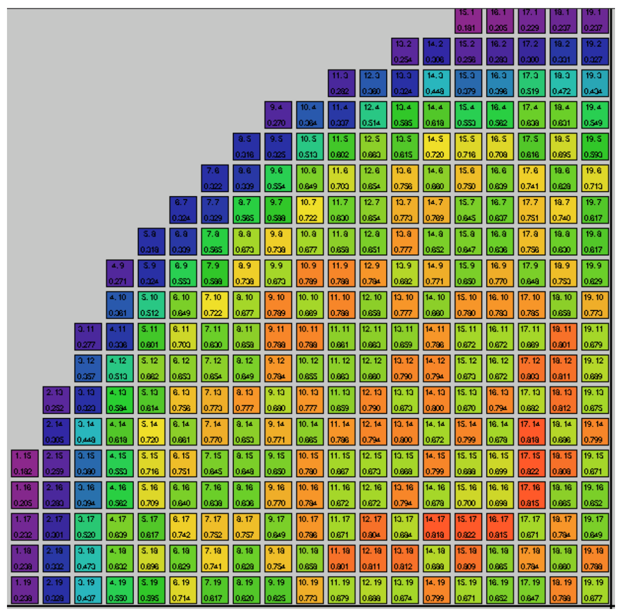


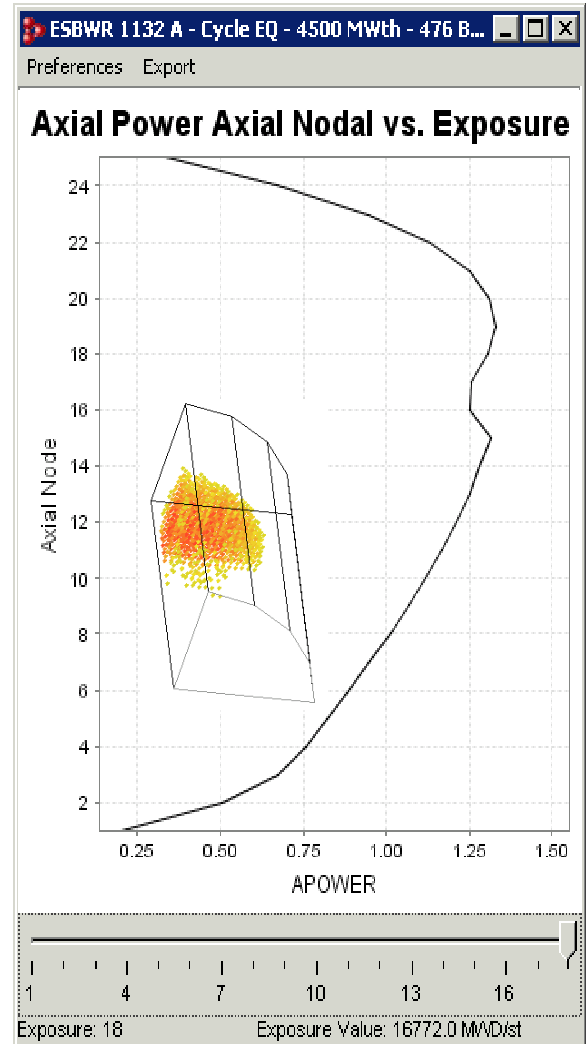


Rod Pattern Example at EOC

- Flexible Rod Patterns
- 15% MCPR and MFLPD Margin
- Axial Shape Moves to Top of Core
- Exit Cycle with First Set of "A2's"

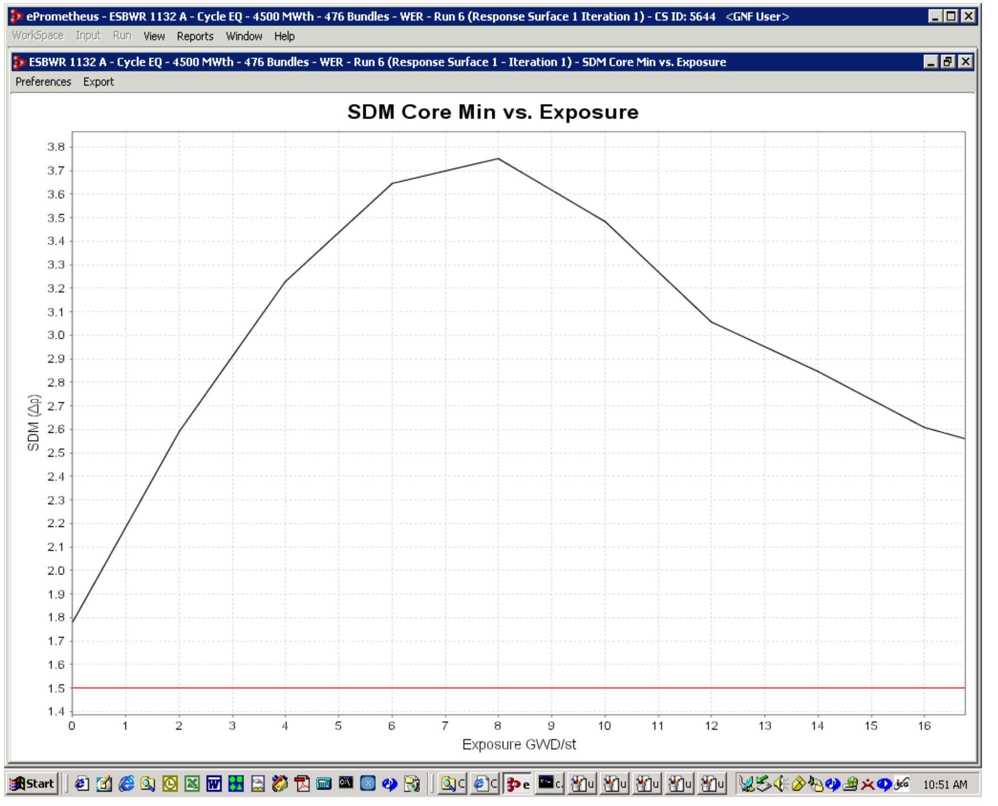






Loading Example – Cold SDM Profile

- Large CSDM
- Minimum at BOC Only
- More Available if Desired
- Allows for Flexible Core Loadings
  - > "Minimum Shuffles", etc



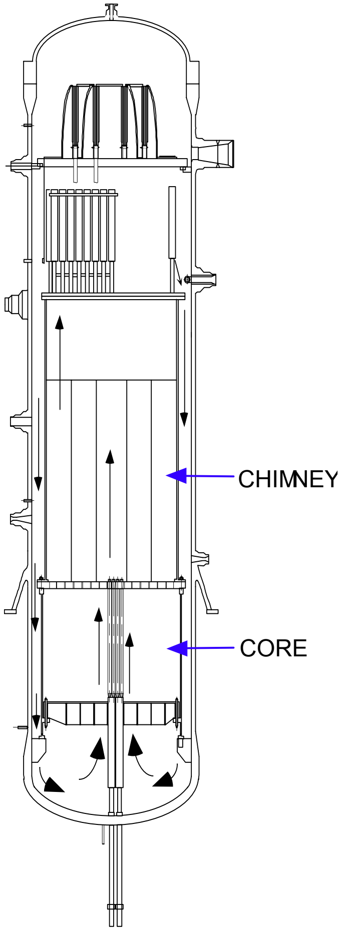
Core & Fuel Design Summary

- ESBWR core employs the same lattice spacing as ABWR and utilizes the evolving fuel product line
  - GNF's 10x10 PCI & corrosion resistant fuel
  - Shorter Active Fuel Length (AFL)
- Fuel cycle lengths from 1 to 2 years can be supported
- Large thermal design margins (> 10%) and reactivity (hot excess & cold shutdown) design margins provide flexibility
  - Core loading
  - Cycle operation
- FMCRD supports slow, incremental changes in control rod positioning to compensate for burnup and to follow load
- Equilibrium core demonstrated in DCD; Representative Initial core to be described in COLA
  - Actual initial fuel loading may be revised to capture benefits of the evolving product line following the normal process for licensing reloads

Startup - Background

ESBWR natural circulation startup

- Generally follow established procedure from Dodewaard plant startup
- Heat up reactor coolant to ~ 85º C with auxiliary boiler heat and decay heat
- Dearate reactor coolant by drawing vacuum on main condenser with steam drain line open
- Withdraw control rods to criticality
- Increase power at controlled heatup rate; overboard excess water via RWCU system
- As pressure increases, open turbine bypass valve to control pressure



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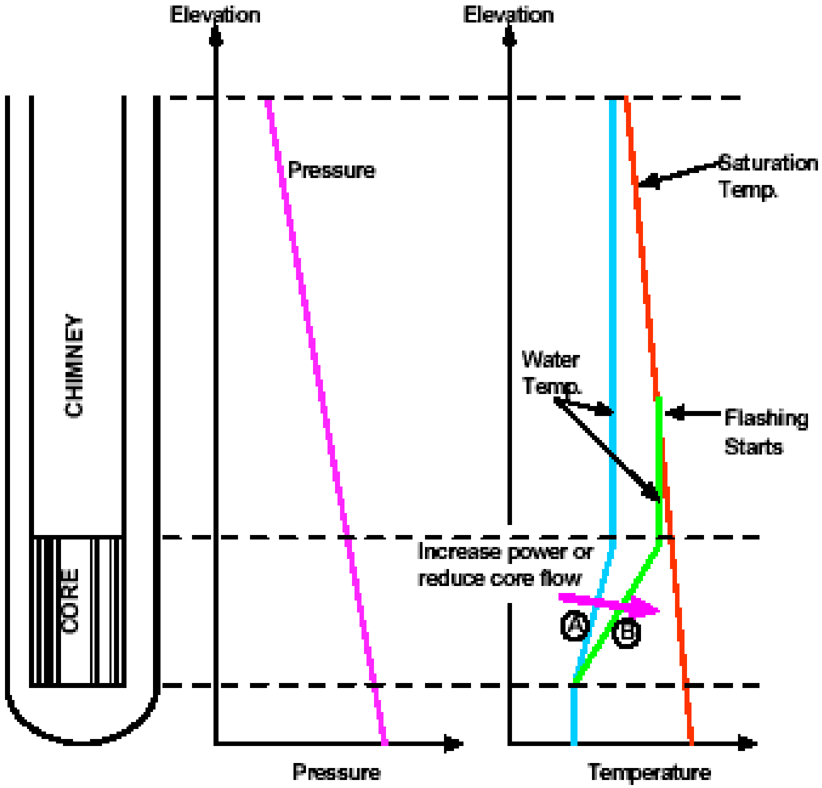
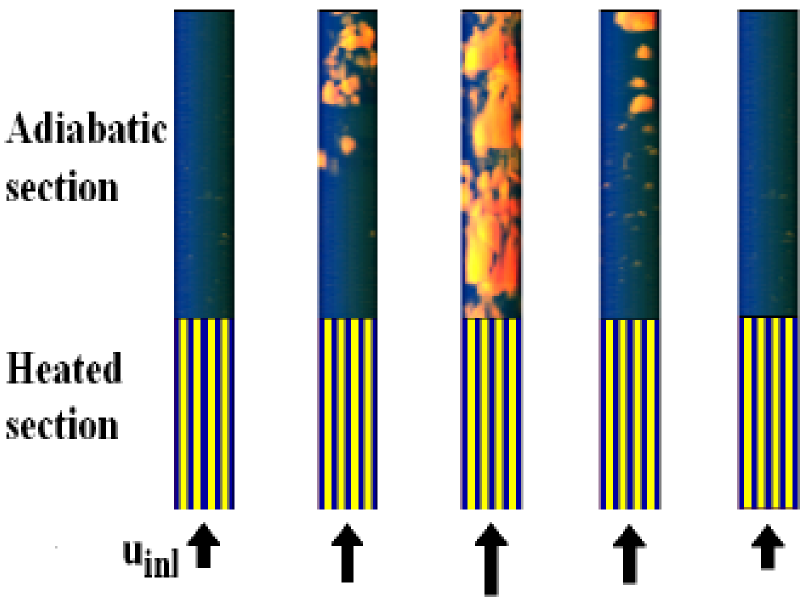
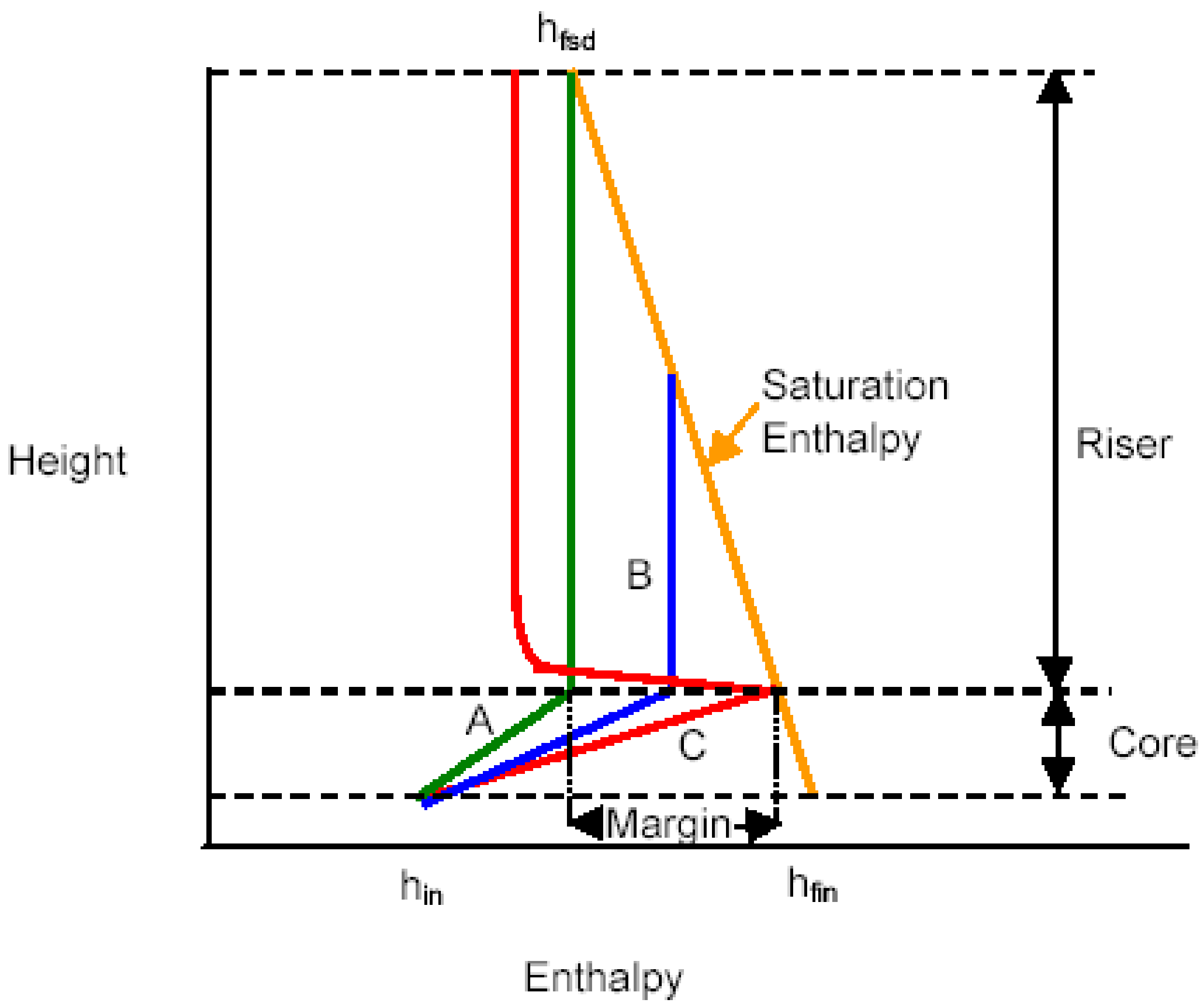
Thermal-Hydraulic Conditions During Startup



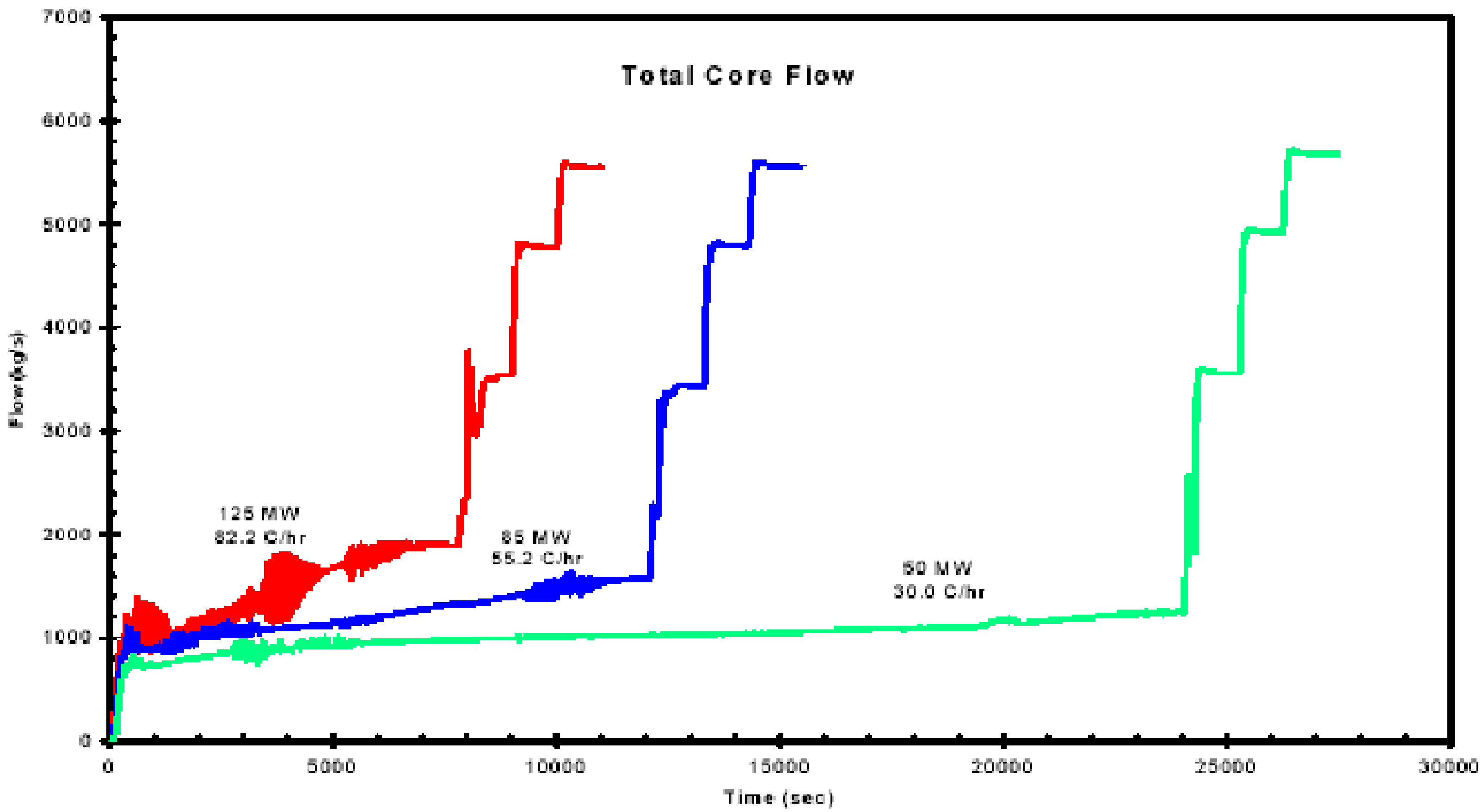
Dynamic conditions



Heatup During Startup



ESBWR Core Flow – Simulation During Startup



No unstable behavior expected at maximum allowable heatup rate (55.2°C/hr)

Startup Summary

- ESBWR will follow a startup procedure similar to that used for Dodewaard
  - > Significant oscillations were not observed at Dodewaard reactor during normal startup
- During startup, core flow is single phase
  - > Voids initiate at top of chimney
  - > No oscillations in neutron flux
  - > No power oscillations
- Startup oscillations do not pose any threat to thermal limits