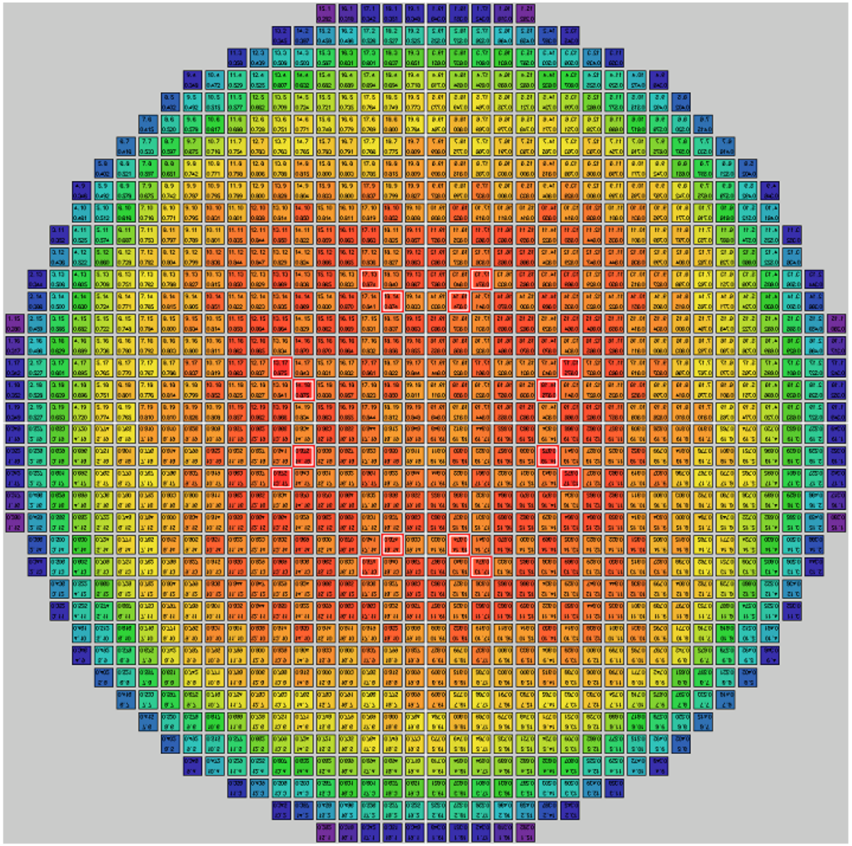
ESBWR Core & Fuel



Core and Fuel Description

Russ Fawcett
Manager - Core, Fuel & Advanced Design
2005-09-29

Topics

Background

Core & Fuel Description

Additional Fuel Licensing Evaluations

Control Rods

Background

- Since early '90s, fuel has been studied in concert with NC reactor development
  - > Lattice number (e.g. 8x8, 9x9, 10x10)
  - > Active fuel length (e.g. 96", 108", 120")
  - > Core size
  - > Lattice type (e.g. ABWR N-lattice & BWR-5 C-lattice)
  - > Core power density (e.g. 40 KW/L to 60 KW/L)
  - > Assembly configuration (e.g. number of spacers & PLRs)
- Reactor core characteristics interact with recirculation loop
  - > Core pressure drop and vessel height affects core flow
  - > Fuel design and power density affect pressure drop (and core flow)
  - > Modern fuel (e.g. GE14) capability influences power plant rating

While Reactor/Fuel Development is Complicated, the Final Design is Simple

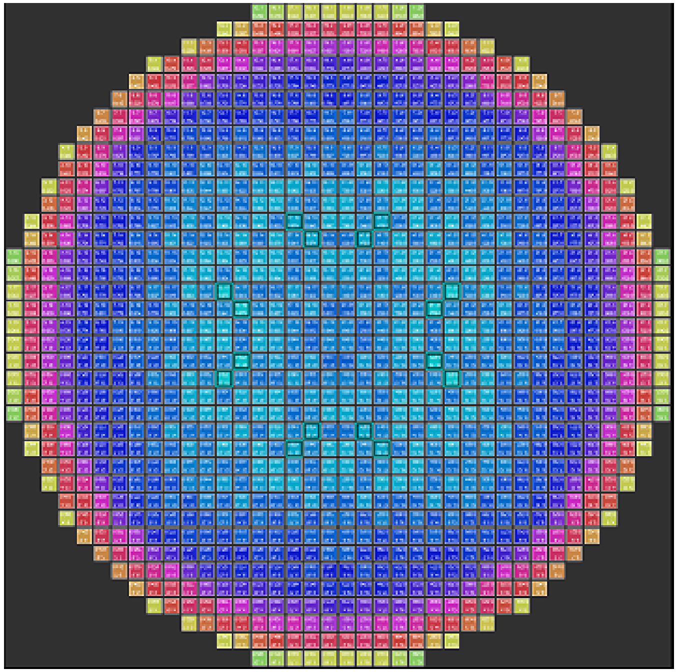
Background

- Technical survey / parametric studies conclude
  - 10x10 BWR fuel provides good balance of key fuel requirements
    - LHGR, MCPR, CSDM, efficiency
  - Supports overall plant power objectives (~1500 MWe)
- Other considerations for fuel
  - Demonstrated in-reactor hardware performance desirable
  - Well understood technical bases
- GE14 with small modifications related to Natural Circulation provides good overall Fuel/Core performance

Core & Fuel Description

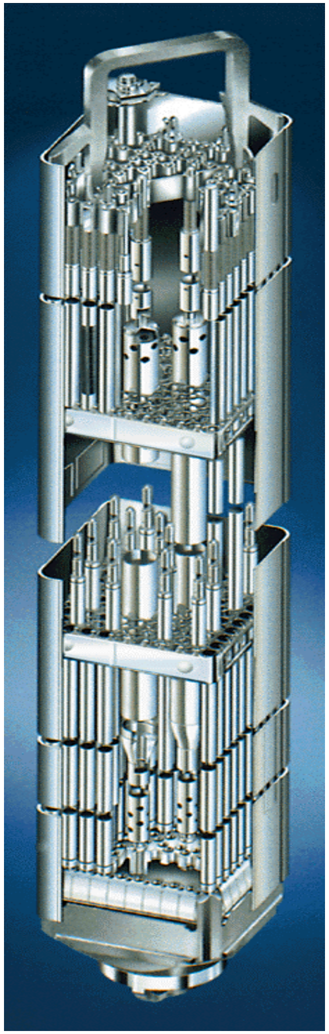
ESBWR Reactor Core Specification

- 4500 MWth Rated Thermal Power
- 1132 Bundles
  - > KKM 240 Bundles
  - > ABWR 872 Bundles
- 269 Control Blades
- FMCRDs (Fine Motion Control Rod Drives)
  - > Fast Scram (good transient response)
  - > Redundant Insertion
  - > Reduced Fuel Duty (small notch size)
- Moderate Power Density (54.3 KW/L)
- N-Lattice (symmetric water gap)
  - > Same as ABWR
  - > Improvement in CSDM



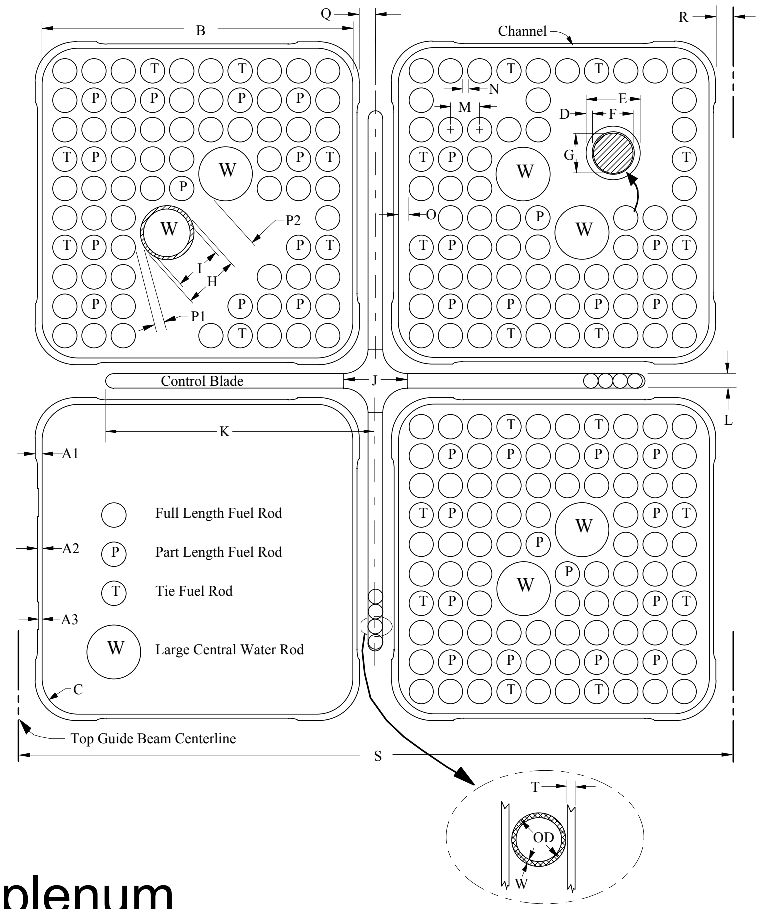
ESBWR Reference Bundle Design

- Design Derived from GE14
  - > Proven Components
    - – Exposures to 68000 MWD/MT
  - > Supports High Energy Cycles
  - > Testing Applies to ESBWR
- Differences
  - > Length reduced for dp
  - > PLR length reduced
  - > Spacer positions slightly altered



GE14 Comparison

GE14 Parameter	BWR 4-6	ESBWR
Lattice Geometry	Reference:	Same
Lower Tie Plate	DFLTP	Same
Spacers	Ferrule	Same
Upper Tie Plate	Standard	Same
Active Fuel Length (Full Length Rods), in.	150	120
Approximate Plenum Length, in.	9	>12
Active Fuel Length (Part Length Rods), in.	84	72
Cladding Material	Zircaloy-2	Same
Spacer Axial Position Above BAF, in		
Spacer 6	17.9	19.7
Spacer 5	36.3	39.4
Spacer 4	54.7	59.1
Spacer 3	73.1	78.7
Spacer 2	91.5	92.5
Spacer 1	106.1	106.3



- GE14 for ESBWR has more fission gas plenum
- Fuel rod SAFDLs conservative for ESBWR

GNF Fuel Experience & Applicability

	GE12	GE14	ESBWR
• Bundles	GE12	GE14	ESBWR
	(# in service)		
> Spacers	>28000	>85000	same
> Upper Tie Plates	>3500	>11000	same
> Lower Tie Plates	"	"	same
> Channels	"	"	shorter
• Rods	GE12	GE14	ESBWR
> Cladding	>32000	>1000000	same
> T/D Ratio	"	"	same
> Length	"	"	shorter
> Pellets	"	"	same

- Thermal Hydraulic Testing
  - Loss Coefficients for Components Apply
  - Friction Affected by Length Change Readily Modeled in Current Methods
- Design and Licensing Methods
  - Lattice Physics Methods Applies (no change to lattice geometry)
  - 3-D Core Simulator Applicable (wide range of core sizes supported)

Reference Equilibrium Cycle Design Basis

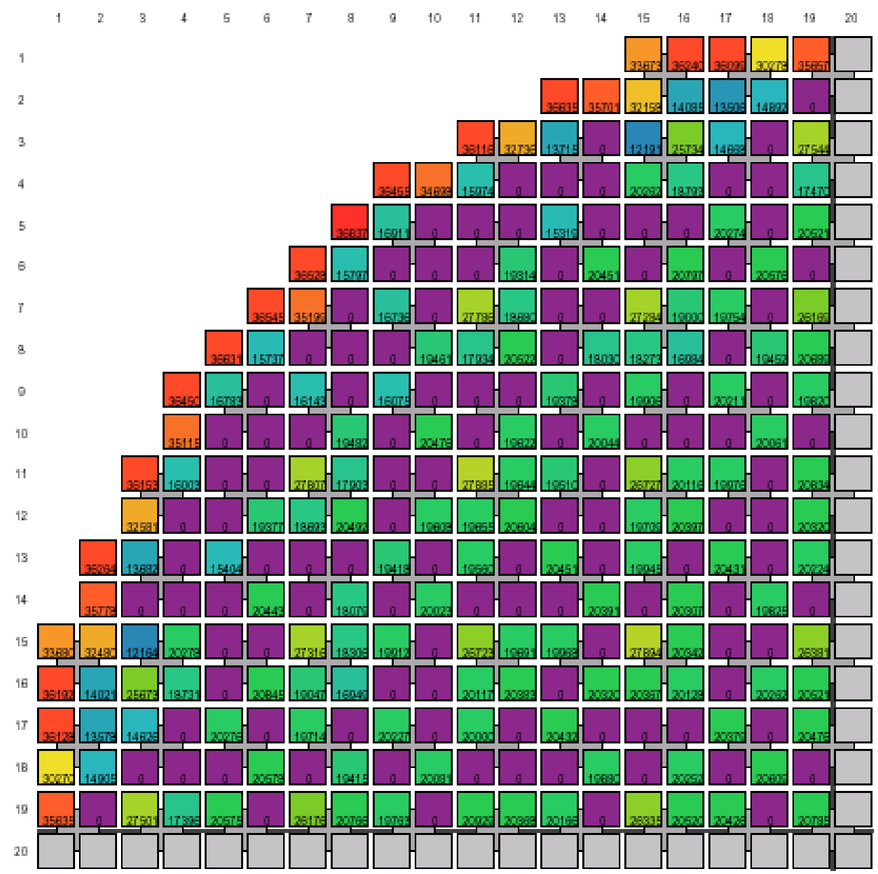
- Reference Operating Parameters
  - > Rated Power = 4500 MWth
  - > Rated Flow = 78.5 Mlb/hr
- Cycle Length = 24 Months
  - > 672 EFPD
- Operating Limit Critical Power Ratio = 1.30
- Standard Reactivity Targets
  - > Minimum Hot Excess @ BOC = 0.8%
  - > Minimum Cold Shutdown Margin = 1.5%
- Thermal Limit Design Margins
  - > >10% CPR
  - > >10% LHGR
- Detailed 3-D Simulations

Reference Nuclear Design for Analysis

- Equilibrium chosen to best represent reactor lifetime
  - > Initial Core is a special case
    - – Analyzed at COL
- Standard design practices applied
- Conforms to operating limits with margin
- 24 month cycle representative of current US preference

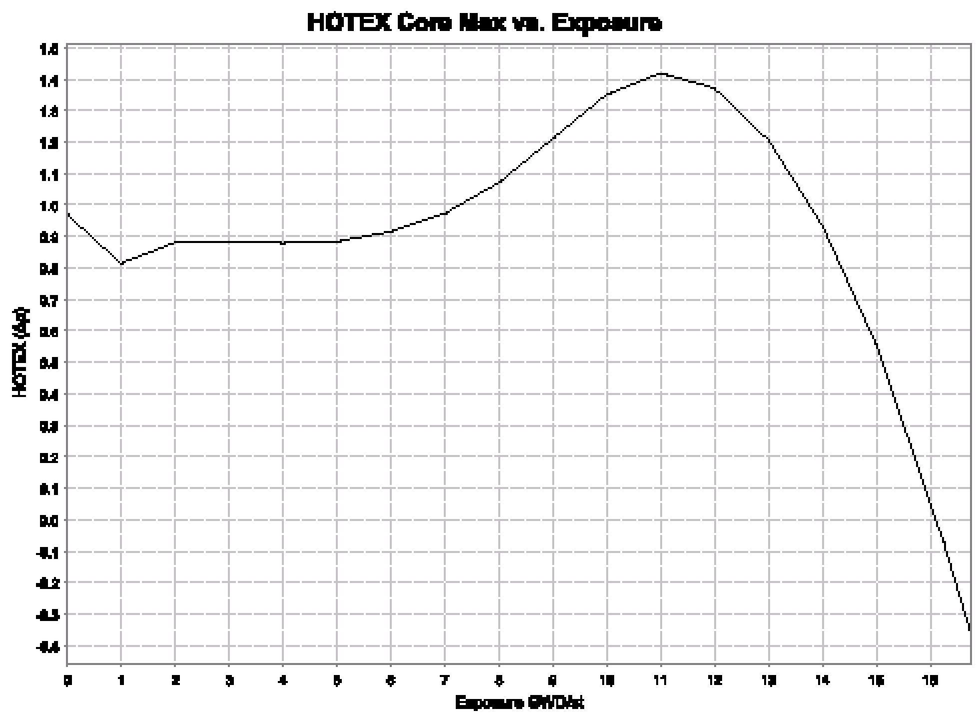
Reference Loading – BOC Exposures

- Designed for 24 Month Operation
  - > Control Cell Core (CCC)
  - > Low Leakage Periphery
  - > Exposure Limit Margin



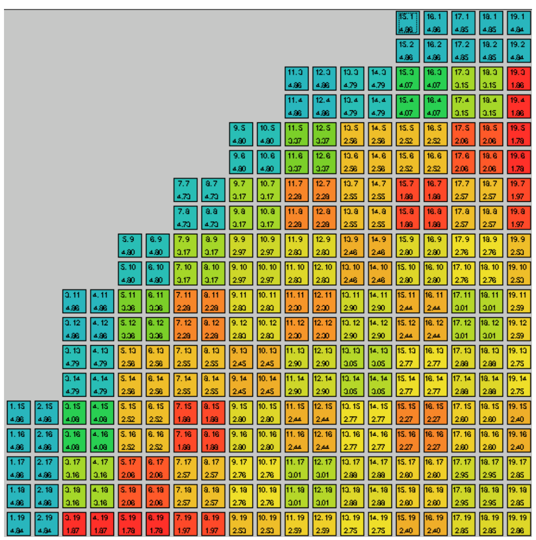
Reference Loading – Hot Excess Profile

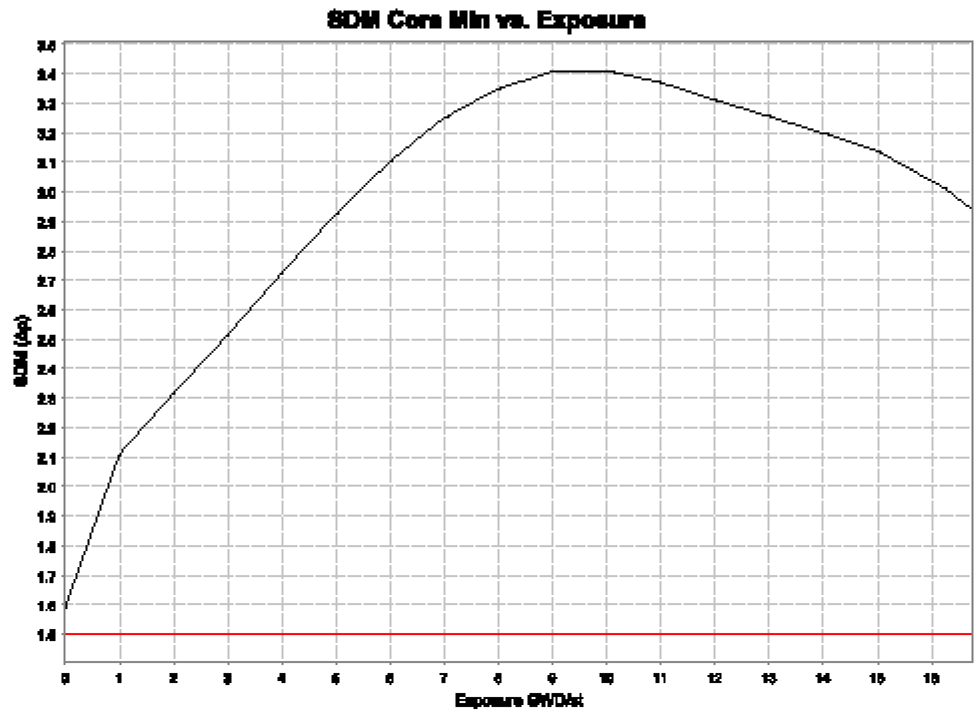
- Normal Hot Excess Profile
  - BOC = 1%
  - PHX = 1.4%
- Consistent with Fleet Practice



Reference Core Cold SDM

- Large CSDM
- More Available if Desired
- Provides Flexible Loadings
  - > "Minimum Shuffles", etc

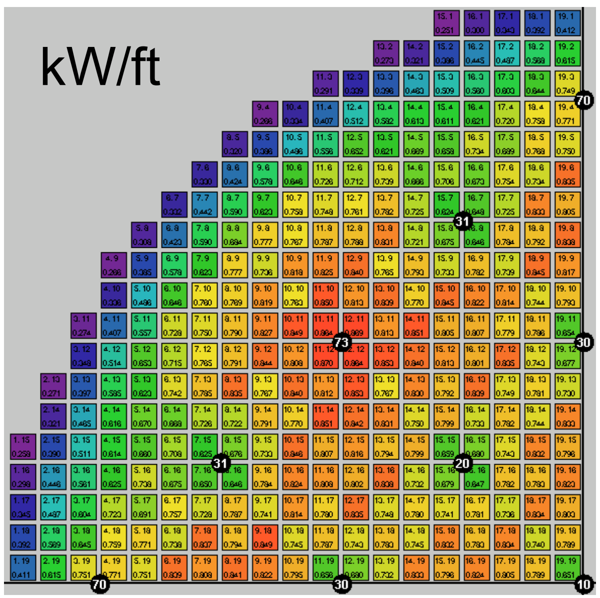


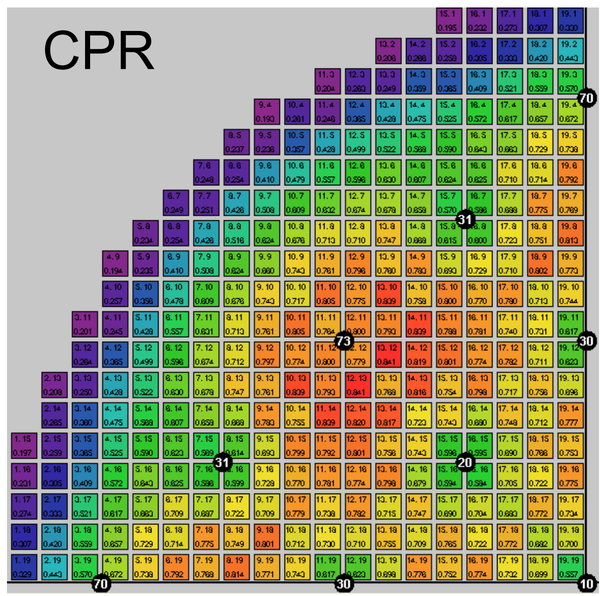


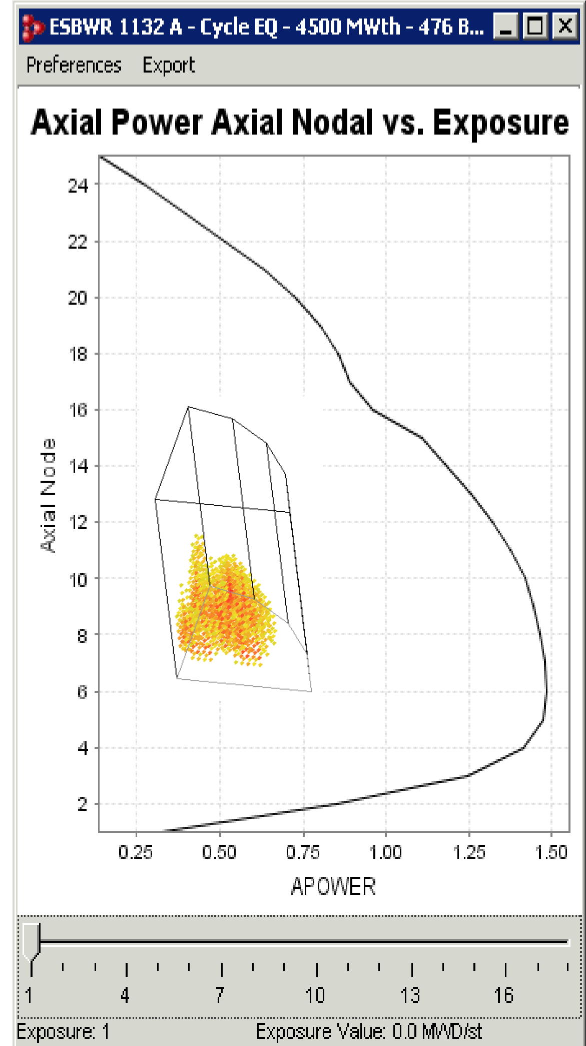
N-Lattice Cores Have Inherent Excess Margin

Rod Pattern at BOC

- Supports Standard (or Increased) Thermal Margin
- Typical Axial Shapes
- Standard Control Rod Patterns

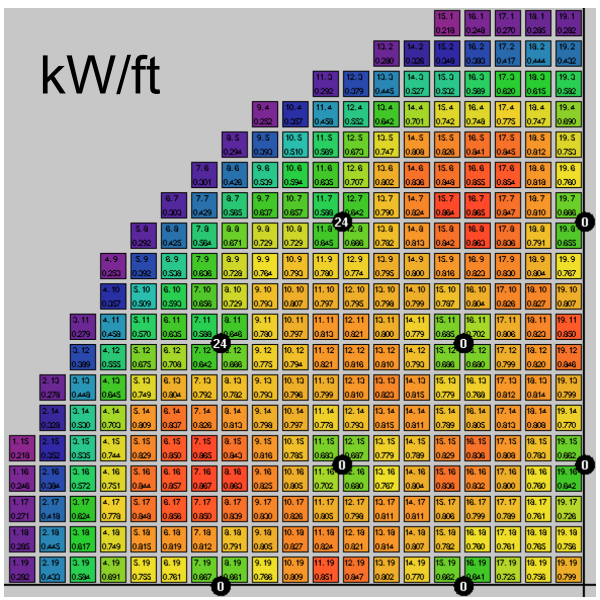


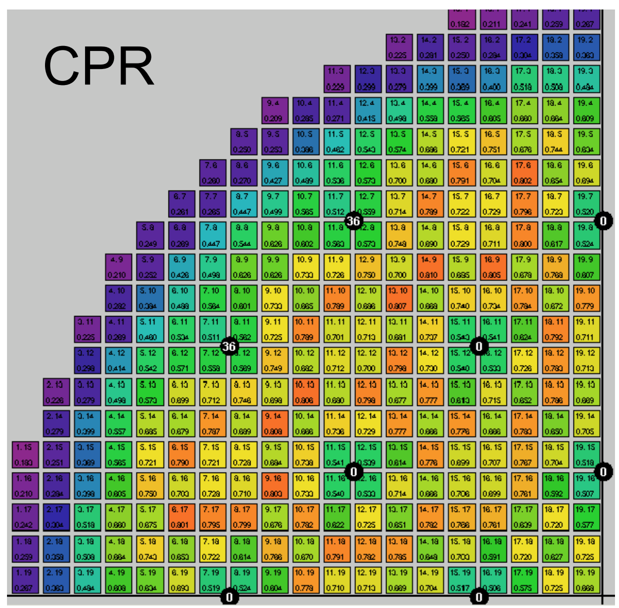


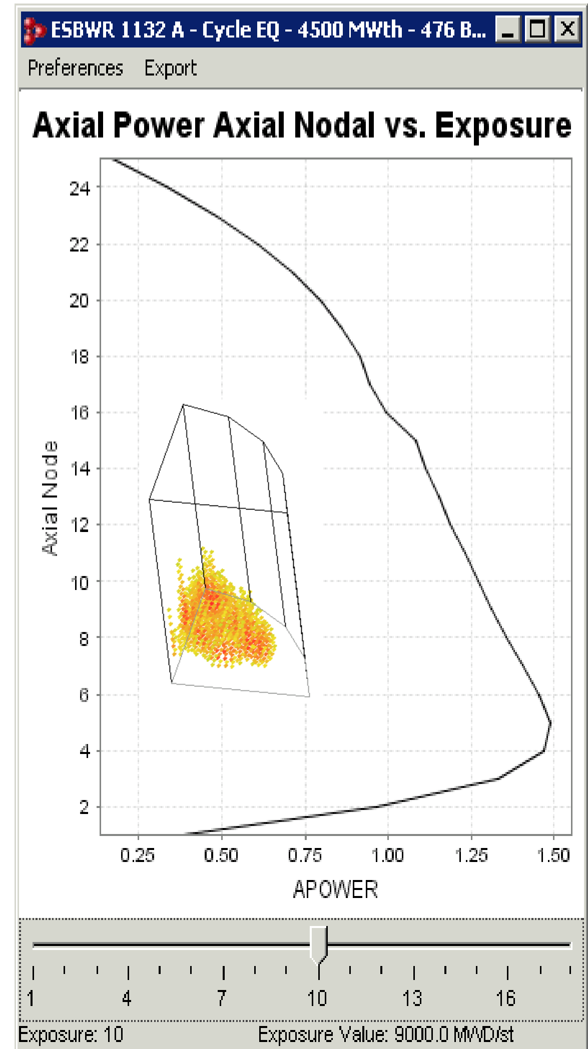


Rod Pattern at MOC

- Flexible Rod Patterns
- Supports Sequence Exchanges (Fuel Duty)

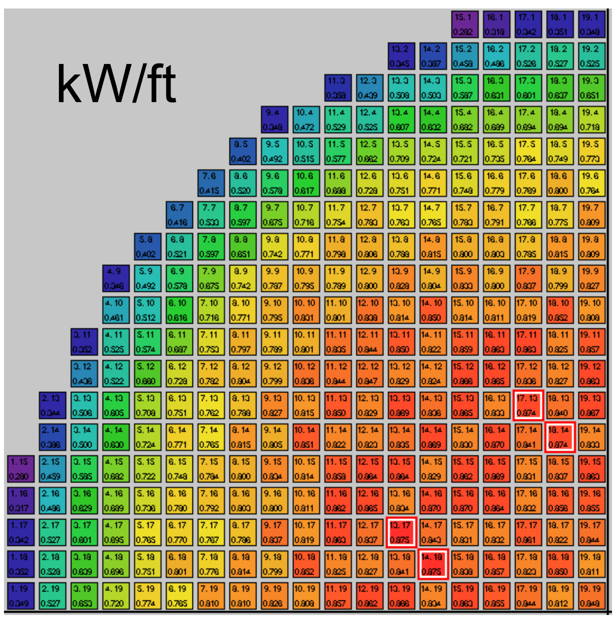


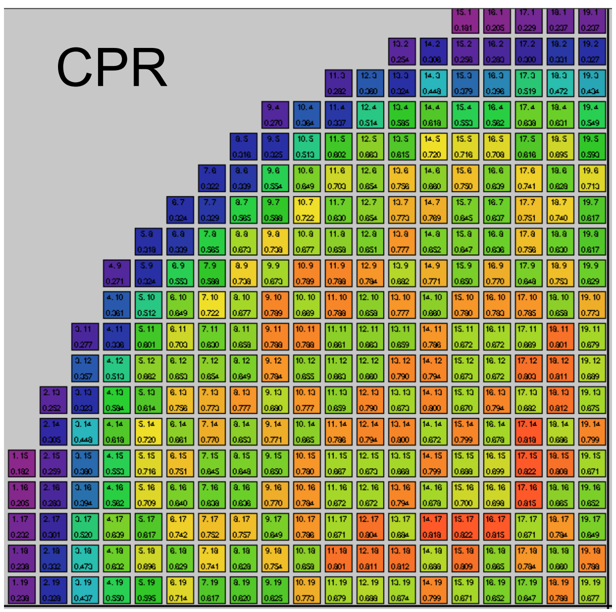


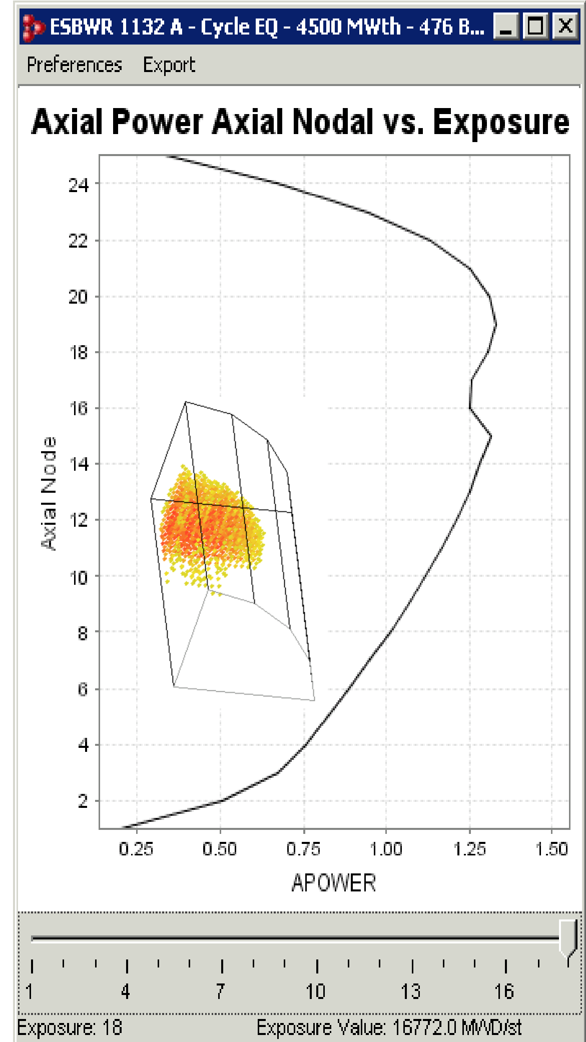


Rod Pattern at EOC

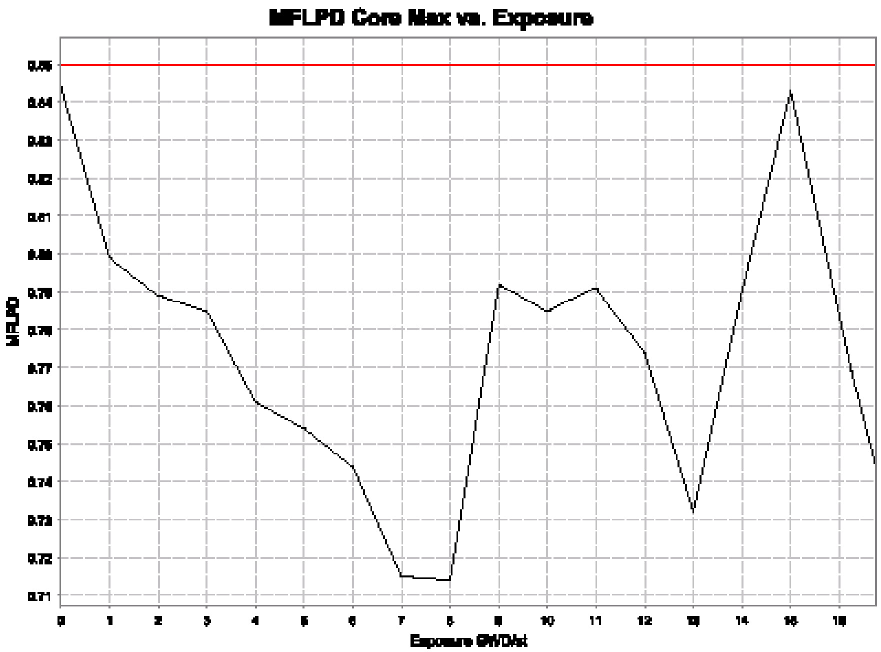
- Axial Shape Moves to Top of Core
- Exit to All-Rods-Out

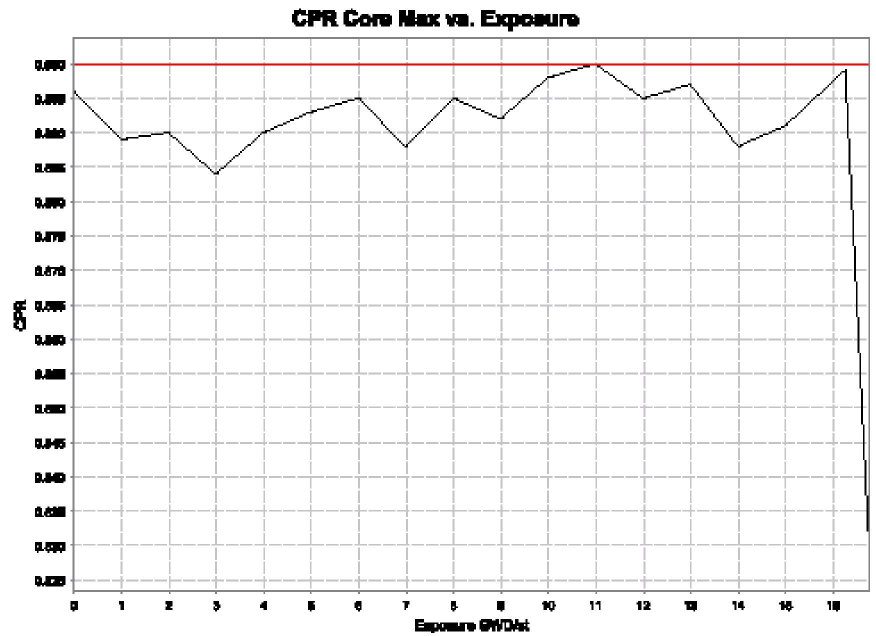






Design Thermal Margin





Additional Licensing Evaluations

Overview

- New Fuel Licensing criteria proposed in DCD Tier 2 Chapter 4.B
  - Scope consistent with GESTAR II
- The following areas are addressed
  - General Criteria
  - Thermal Mechanical
  - Nuclear
  - Thermal Hydraulic
  - OLMCPR
  - Critical Power Correlation
  - Stability
  - Fuel Handling Accident
  - ATWS

GE14 for ESBWR can be shown to meet these criteria

General Criteria

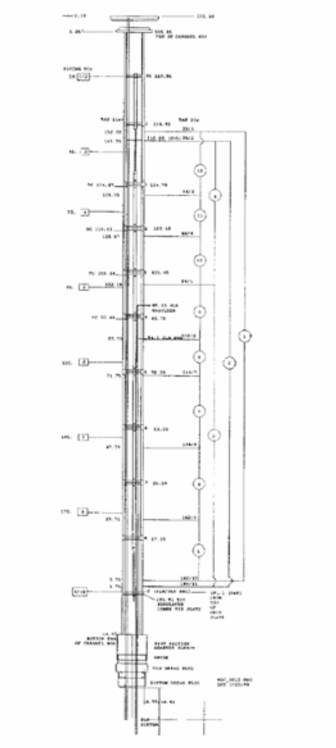
- NRC Approved Methods Shall Be Applied
  - No methods changes required for GE14 ESBWR
    - TGBLA – lattice physics
    - PANAC – core simulator
    - GSTRM – fuel rod thermal-mechanical
- New Features Included in LUAs
  - Component performance confirmed to high exposure
  - No new components in GE14 for ESBWR
- Post-Irradiation Fuel Examination Shall Be Maintained
  - GNF continuously monitors fuel performance

Hydraulic

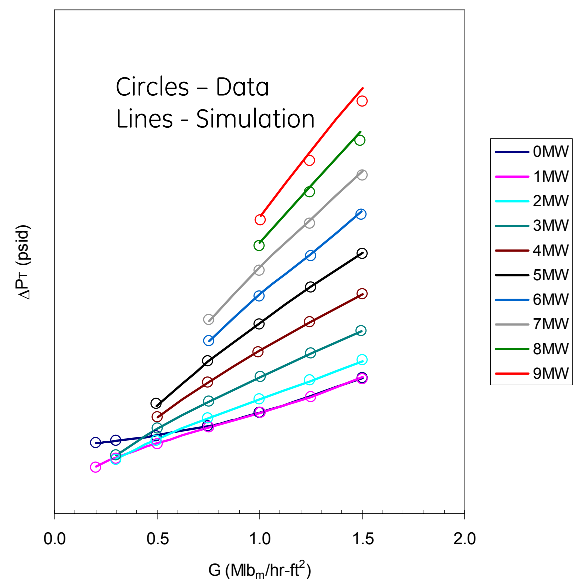
- Flow pressure drop characteristics shall be included in the determination of the OLMCPR
  - GE14 hydraulic model applicable to ESBWR (next charts)
  - Included in detailed analysis

GE14 Bundle Pressure Drop

- Performed full-scale bundle pressure drop tests at the ATLAS Test Facility.
- Form loss coefficients were derived at spacer locations from measured pressure drop data.
- The total bundle pressure drop is defined as the sum of:
  - Wall friction
  - Gravity head
  - Acceleration
  - Spacer Losses
- The spacer loss coefficients are independent of the bundle height, and therefore, applicable to a shorter bundle.

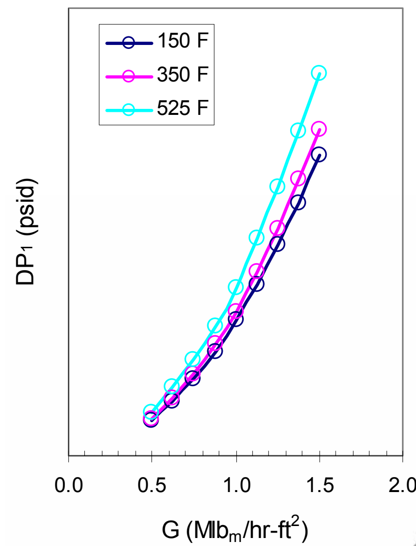


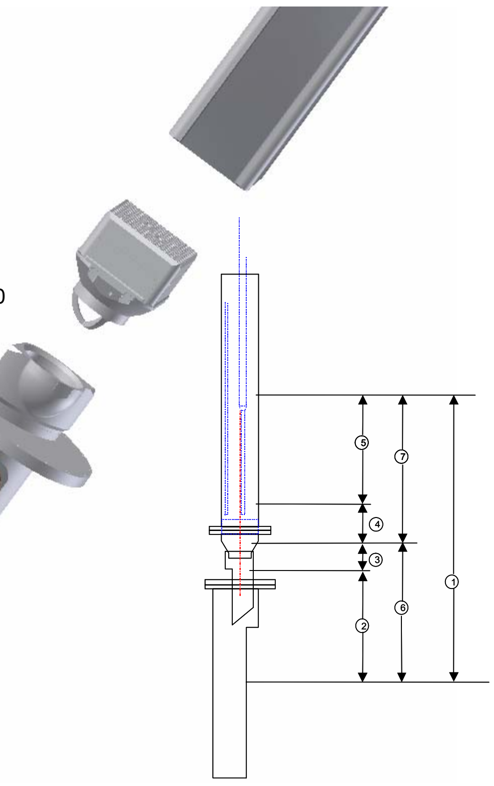
ATLAS GE14 Test Assembly



Single-phase LTP Pressure Drop

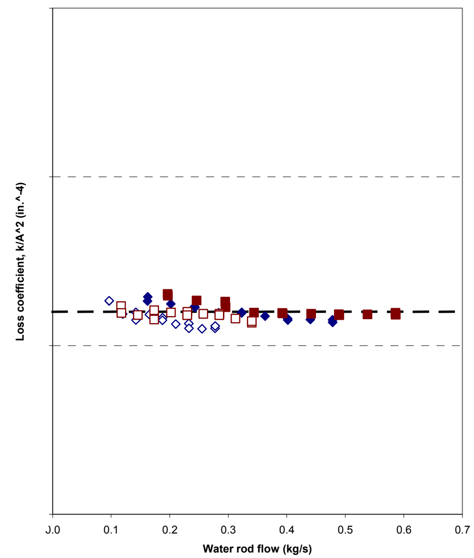
- Performed single-phase pressure drop tests at the ATLAS Single-phase Flow Test Loop.
- Test section consisted of a quarter section of the CRD Housing and fuel support structure, the LTP being tested, and the GE12/14 assembly up to the 1st spacer location.
- Form loss pressure drop coefficients were derived from measured pressured drop for the SEO+LTP losses.
- The tests and the resulting form loss coefficients are independent of the bundle height, and therefore, applicable to a shorter bundle.

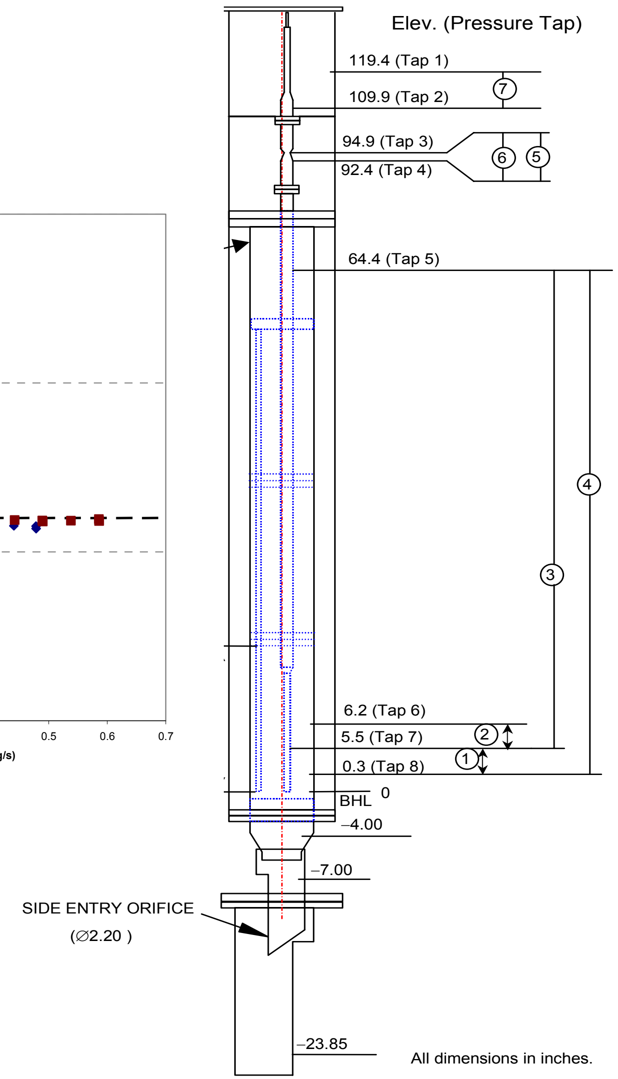




Water Rod Flow Rate and Pressure Drop

- Performed full-scale pressure drop tests at the ATLAS Single-phase Flow Test Loop.
- WR inlet and outlet form loss coefficients were based on full-scale test data (flow rate and pressure drop across inlet and outlet flow holes).
- Loss coefficients are constant over a wide range of flow conditions.
- The WR inlet and outlet flow hole form loss coefficients are independent of the WR height, and therefore, applicable to shorter WRs.





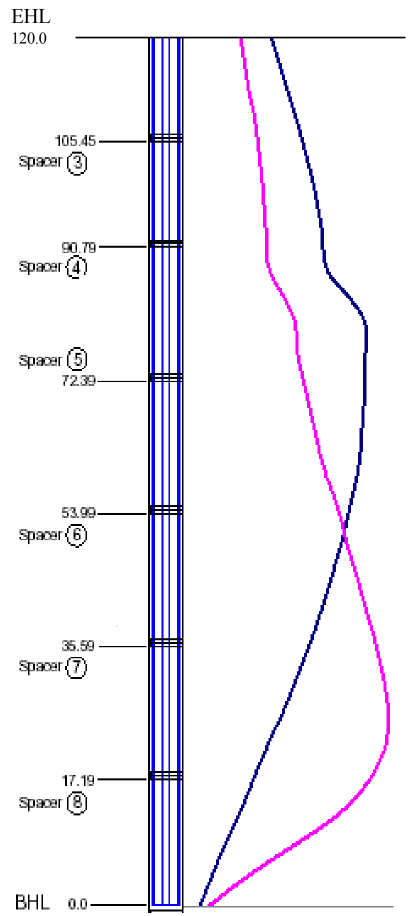
Critical Power Correlation

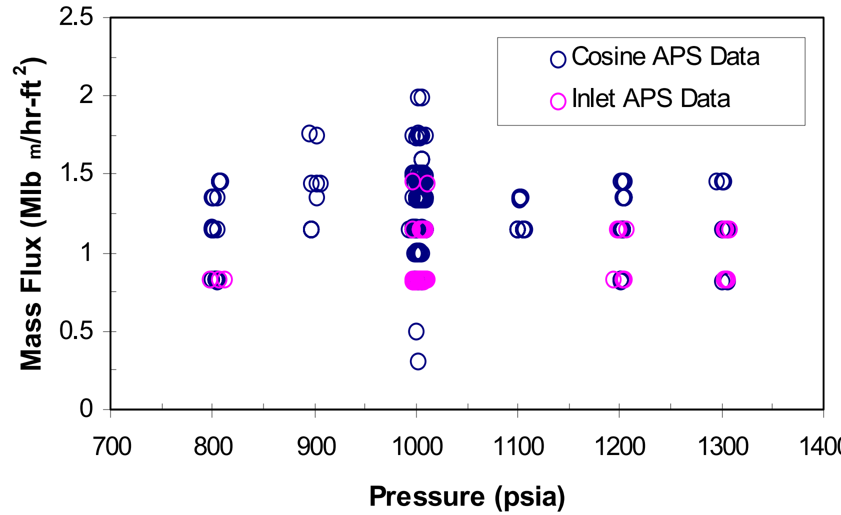
- Correlation Requirements
  - The correlation shall be based on full-scale prototypical test assemblies.
  - Tests shall be performed on assemblies with typical rod-to-rod peaking factors.
  - > The functional form of the currently approved correlations shall be maintained.
  - > Correlation fit to data shall be best fit.
  - > One or more additional assemblies must be tested to verify correlation accuracy
  - > Coefficients in the correlation shall be determined as described in Reference 4B-2 or Reference 4B-3.
  - > The uncertainty of the resulting correlation shall be determined by:

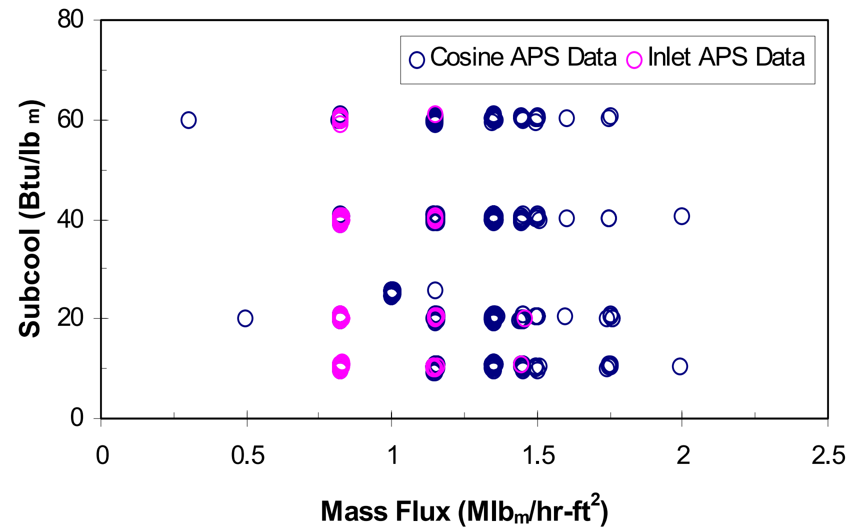
$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(\mu - ECPR_i)^2}$$

CP Correlation (GEXL14 Applicability)

- BT dependent on integrated power to point of dryout
- Dryout at Spacers 3 and 4 not affected by shortened height
- 32% of GEXL14 correlation database derive from Spacers 3 and 4
- ATLAS test data from Spacers 3 and 4 cover a wide range of fluid conditions

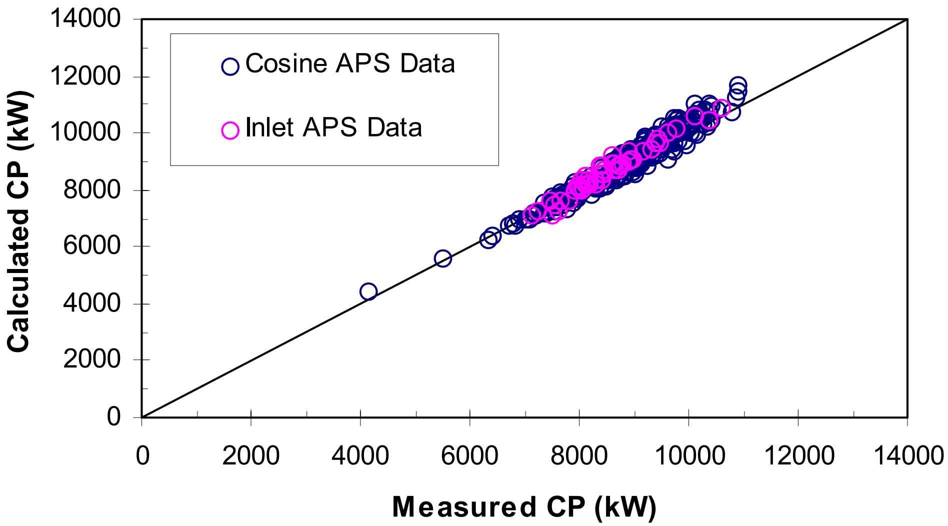




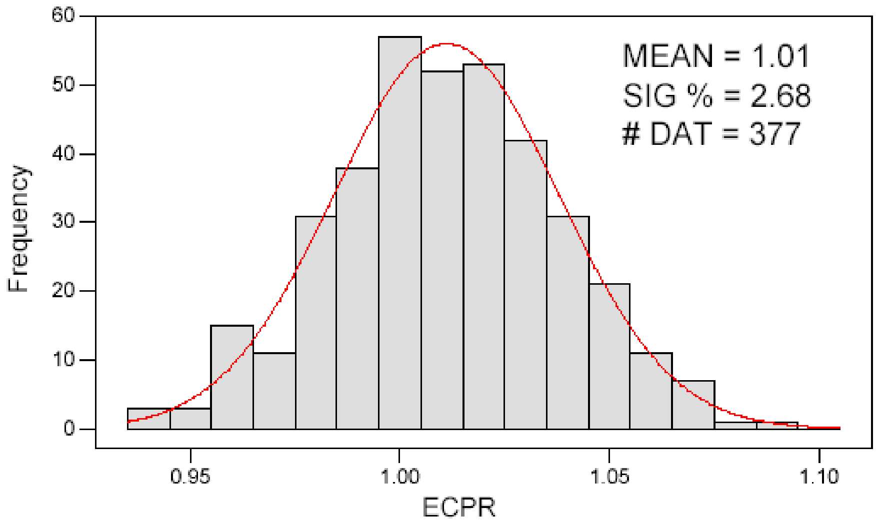


CP Correlation (GEXL14 Statistics)

- Mean ECPR = 1.01
- STDEV = 0.0268
- Data Points = 377



- GEXL14 adequately predicts CP for ESBWR-GE14



Nuclear

- A negative Doppler Coefficient is maintained for all operating conditions
  - Lattice based analysis – GE14 results apply
- A negative Void Reactivity Coefficient is maintained for all operating conditions
  - In-channel voiding
- A negative Moderator Temperature Coefficient is maintained above Hot Standby
- The Prompt Reactivity Feedback shall be negative for all operating conditions
- A negative Power Reactivity Coefficient is maintained above hot standby
  - Dominated by the Void Reactivity Coefficient
- The core shall meet the Cold Shutdown Requirement
  - Demonstrated on a cycle specific basis
  - GE14 ESBWR results provided in Chapter 4
- Fuel storage requirements shall be met

Void Reactivity Coefficient

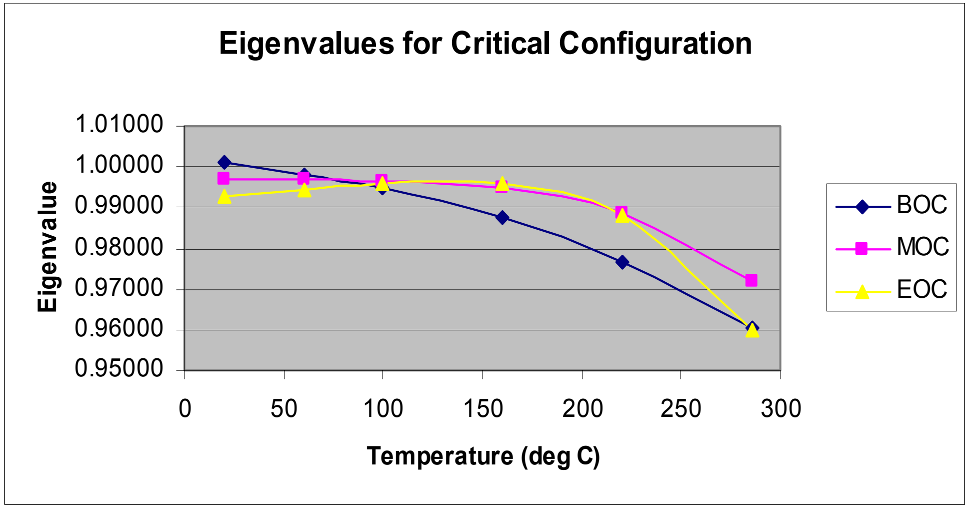
Eigenvalue Results at BOC				
	ARI Configuration		Critical Configuration	
Temperature (deg C)	0% Voids	5% Voids	0% Voids	5% Voids
100	0.94254	0.93713	0.99494	0.99236
160	0.93320	0.92779	0.98732	0.98455
220	0.92170	0.91585	0.97671	0.97364
286	0.90664	0.89774	0.96041	0.95508

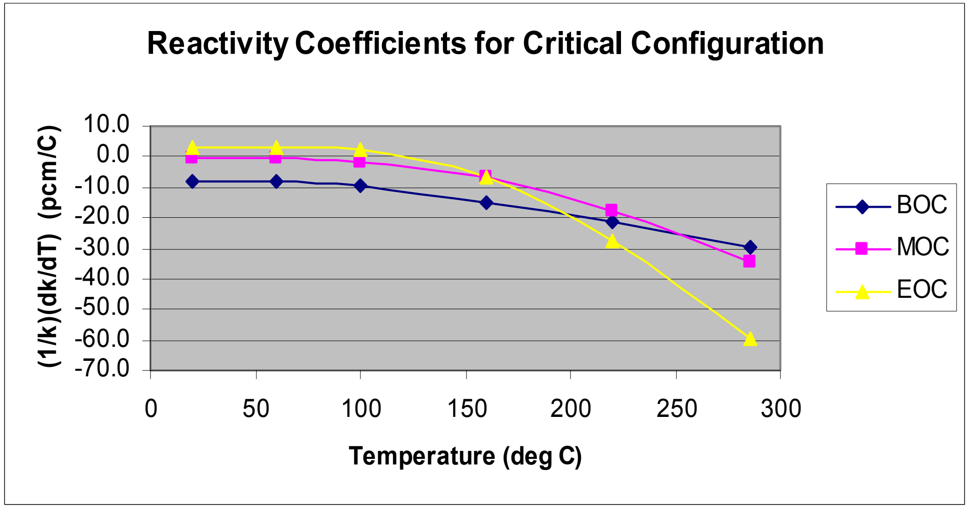
Eigenvalue Results at MOC				
	ARI Configuration		Critical Configuration	
Temperature (deg C)	0% Voids	5% Voids	0% Voids	5% Voids
100	0.92456	0.92023	0.99658	0.99387
160	0.91923	0.91472	0.99487	0.99243
220	0.91066	0.90532	0.98882	0.98679
286	0.89474	0.88473	0.97204	0.96823

Eigenvalue Results at EOC				
	ARI Configuration		Critical Configuration	
Temperature (deg C)	0% Voids	5% Voids	0% Voids	5% Voids
100	0.92461	0.92004	0.99572	0.99122
160	0.92068	0.91585	0.99585	0.99253
220	0.91077	0.90478	0.98783	0.98602
286	0.88689	0.87487	0.96008	0.95649

Requirements Met for Reference ESBWR Design

Moderator Temperature Coefficient





Thermal Mechanical - Fuel Rods

Primary analytical design criteria to prevent fuel rod failure

1. Cladding plastic strain < 1% during AOOs
2. No fuel melting during core-wide AOOs (melting permitted for localized AOOs (RWE)
3. No cladding lift-off (limits rod internal pressure)
4. No cladding creep collapse
5. Stresses and strains do not exceed ultimate stress and strain limits
6. Fatigue and creep rupture usage < 1.0

Thermal Mechanical - Fuel Rods

Other design considerations to prevent fuel rod failure

1. Fuel pellet hydrogen content less than 1 ppm to prevent primary hydriding failure
2. High cladding corrosion resistance to minimize reduction in cladding wall thickness and cladding hydride embrittlement
3. Spacer spring designed to minimize cladding fretting
4. Minimization of duty related failures

Thermal Mechanical - Fuel Rods

Evaluations

1. Performed with GESTR-Mechanical (GSTRM) code and associated methodology
2. Fuel temperature and rod internal pressure calculations performed statistically
3. Cladding strain calculation performed on worst-tolerance basis
4. Approved by the NRC
   - Qualification includes rods with geometry similar to GE14
   - Approval applies to GE14

Thermal Mechanical - Fuel Rods

ESBWR GE14 Applicability

1. Same 2-D 10x10 lattice
2. Same cladding
3. Same fuel pellets
4. Only difference is ratio of plenum volume to fuel volume
   - Impacts only internal pressure calculation
   - Larger ratio reduces calculated internal pressure
   - Ratio for ESBWR GE14 is equal to or greater than for BWR GE14

BWR GE14 T-M analyses conservatively applicable to ESBWR GE14

Thermal Mechanical - Flow Induced Vibration

Design Criteria

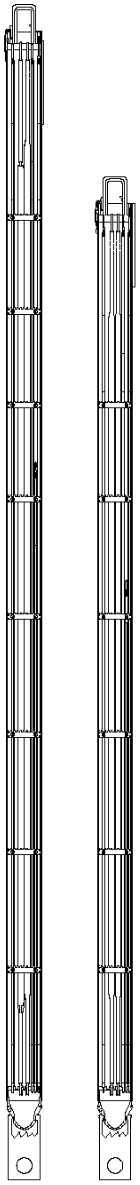
- Loss of fuel rod and assembly component mechanical integrity does not occur due to fretting

Evaluation

- Full Scale Flow Testing

ESBWR GE14 Applicability

- Spacer axial distribution similar
- 2-D Lattice same as GE14
- Flow rates lower in ESBWR
- GE14 in ESBWR bounded by forced circulation fleet



Thermal Mechanical - Channel

Design Criteria

•Channel failure shall not occur due to excessive deformation or fracture.

Evaluations

•Elastic stress and deflection predictions due to channel wall ΔP.

•Thermal stress predictions due to the various temperature gradients.

•Fatigue and stress rupture analyses which consider the combined effect of pressure-temperature cycling and hold time.

•Elastic plastic analysis of channel wall permanent deflection.

•Channel stress due to control rod contact.

•Channel/lower tie plate differential thermal expansion analysis.

Thermal Mechanical - Channel

ESBWR GE14 Applicability

- Channel Duty in terms of pressure and temperature for ESBWR are bounded by the current generation of BWR plants and therefore, the GE14 channel, resized to fit the ESBWR core, will be adequate for that application.

Thermal Mechanical - Fuel Spacer

Design Criteria

- Stresses and Strains do not exceed Component Ultimate Stress and Strain Limits
- Fatigue limits of material is not exceeded
- Fuel rod failure due to spacer-fuel rod fretting does not occur
- Fuel Coolability is maintained at combined seismic and LOCA conditions

Evaluations

- Fuel spacer acceptability is proved by testing in accordance with NRC approved methods. The bounding load condition is seismic loading. Tests are conducted to demonstrate spacer fatigue capability and compliance with load limits and demonstrate coolability is maintained by showing minimal deformation at the combined loaded condition. Fretting wear is addressed by assessing FIV test results

ESBWR GE14 Applicability

- ESBWR fuel spacer is identical to current GE14 BWR/2-6 designs
- Current evaluations are applicable to ESBWR due to same geometry and similar loadings.

Thermal Mechanical - Water Rod

Design Criteria

- Stresses and Strains do not exceed Component Ultimate Stress and Strain Limits

Evaluations

- Calculations are performed to determine component stresses at the bounding load conditions and compared to the criteria. The load conditions take into account: shipping and handling loads, seismic induced bending moments and the pressure differential across the water rod. The design is also evaluated using finite element analysis to determine the critical buckling load.

ESBWR GE14 Applicability

- ESBWR water rods are identical to current GE14 BWR designs except the length is adjusted to fit the shorter bundle length.
- Current evaluations for GE14 BWR designs are applicable to the ESBWR due to the similar geometry and loadings.

Thermal Mechanical - Tie Plates

Design Criteria

- Stresses and Strains do not exceed material stress and strain capabilities
- Fuel Coolability is maintained at combined seismic and LOCA conditions

Evaluations

- Adequacy of tie plate designs is demonstrated by mechanical finite element analysis and/or mechanical testing for bounding fuel handling and seismic load conditions.

ESBWR GE14 Applicability

- ESBWR tie plates are identical to current GE14 BWR/4-6 designs
- Current evaluations are directly applicable to ESBWR due to identical geometry and reduced ESBWR fuel assembly weight.

Summary

- GE14 SAFDLs apply to ESBWR application
- GE14 engineering tests applicable, or bounding, for ESBWR
- GE14 for ESBWR can be shown to comply with fuel licensing requirements as with the current fleet
- Results will be documented and provided to NRC

Control Rods

Overview

- For steady state nuclear and safety analysis, BWR-6 OEM blade geometry used
  - > Establishes reference rod worth for the ESBWR
  - > Consistent with fleet practice
  - > Physical blade design required to have equivalent worth
- Mechanical criteria provided in Chapter 4.C
- Marathon blade expected to be applied

Mechanical Criteria

Control Rod Loads Evaluated:

-Shipping
-Handling
-Normal operation and transients (scram and jogging), including the effects of anticipated operational occurrences (AOOs), infrequent incidents and accidents.
-Pressure differentials
-Thermal gradients
-Flow and system induced vibration
-Testing may be used to evaluate loading conditions such as demonstrating control rod insertion capability for fuel channel deformation and vibrations due to safe shutdown earthquakes.

General Design Approach:

-The analyses consider the effects of manufacturing tolerances, swelling and irradiation growth.
-Loads must not exceed the ultimate stress and strain limit of the material.
-Cumulative fatigue must not exceed a fatigue usage factor of 1.0.

Materials:

-The external control rod materials must be capable of withstanding the reactor coolant environment for the life of the control rod.
-Effects of crudding, crevices, stress corrosion and irradiation upon the material must be included in the control rod and core evaluations.
-Irradiation effects to be considered include material hardening and absorber depletion and swelling.