BW-JAH-2011-248
Attachment 3

mPower Reactor Design Overview Workshop Slides (Non-Proprietary)

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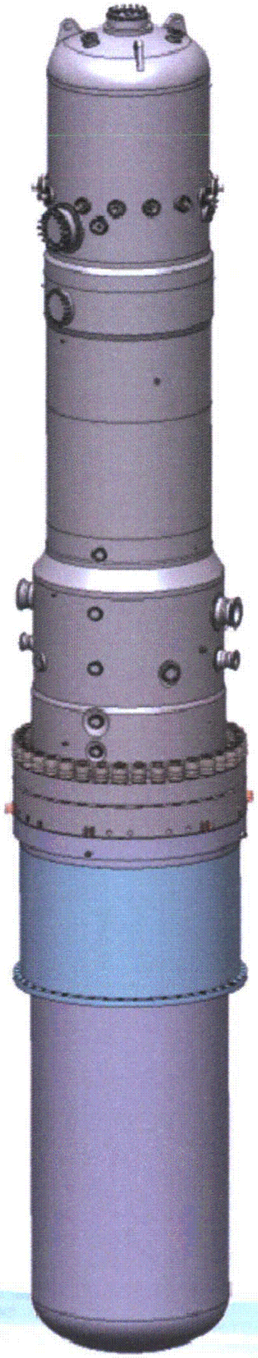

B&W mPower Reactor Design Overview Workshop

April 21, 2011

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Workshop Agenda

Topic	Lead Speaker
Introduction	Jeff Halfinger
Plant Overview	Mike Childerson
Reactor	Mike Edwards
Fuel and Core Design	Vince Bilovsky
Primary Systems	John Malloy
I&C Systems	Brian Arnholt
Site Layout	Al Scott
Safety Analysis	Eric Williams
Test Programs	Doug Lee
Summary	Jeff Halfinger

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Plant Overview

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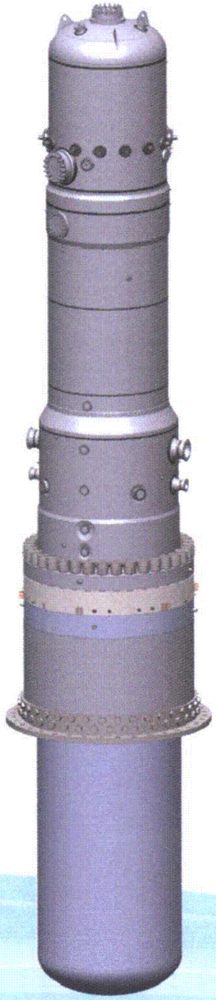
Goal and Value Proposition



Develop and deploy, by 2020, an SMR design that is:

- Proven: GEN III^{+}, established NRC regulation
- Safe: Robust margins, passive safety
- Practical: Standard fuel, construction and O&M
- Benign: Air-cooled, underground, small footprint

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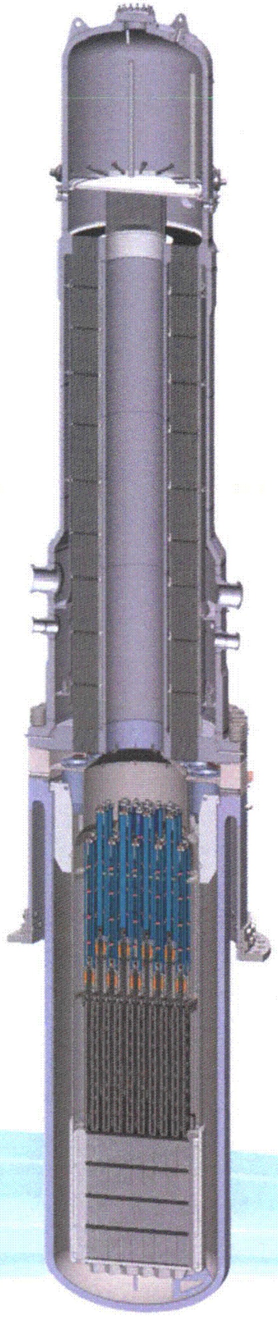
High-Level Requirements



- 125 MWe Nominal Output per Module and 60-Year Plant Life
- NSSS Forging Diameter Allows Domestic Forgings and Unrestricted Rail Shipment
- Passive Safety Requirements – Emergency (Diesel) Power Not Required
  - Minimize Primary Coolant Penetrations, Maximize Elevation of Penetrations
  - Large Reactor Coolant Inventory
  - Low Core Power Density
- Standard Fuel (less than 5% U^{235})
- Long Fuel Cycle, 4+ Year Core Life
- Spent Fuel Storage on Site for Life of Plant
- No Soluble Boron in Primary System for Normal Reactivity Control
- Conventional/Off-the-Shelf Balance of Plant Systems and Components
- Accommodate Air-Cooled Condensers as well as Water-Cooled Condensers
- Flexible Grid Interface (50 Hz or 60 Hz)
- Digital Instrumentation and Controls Compliant with NRC Regulations

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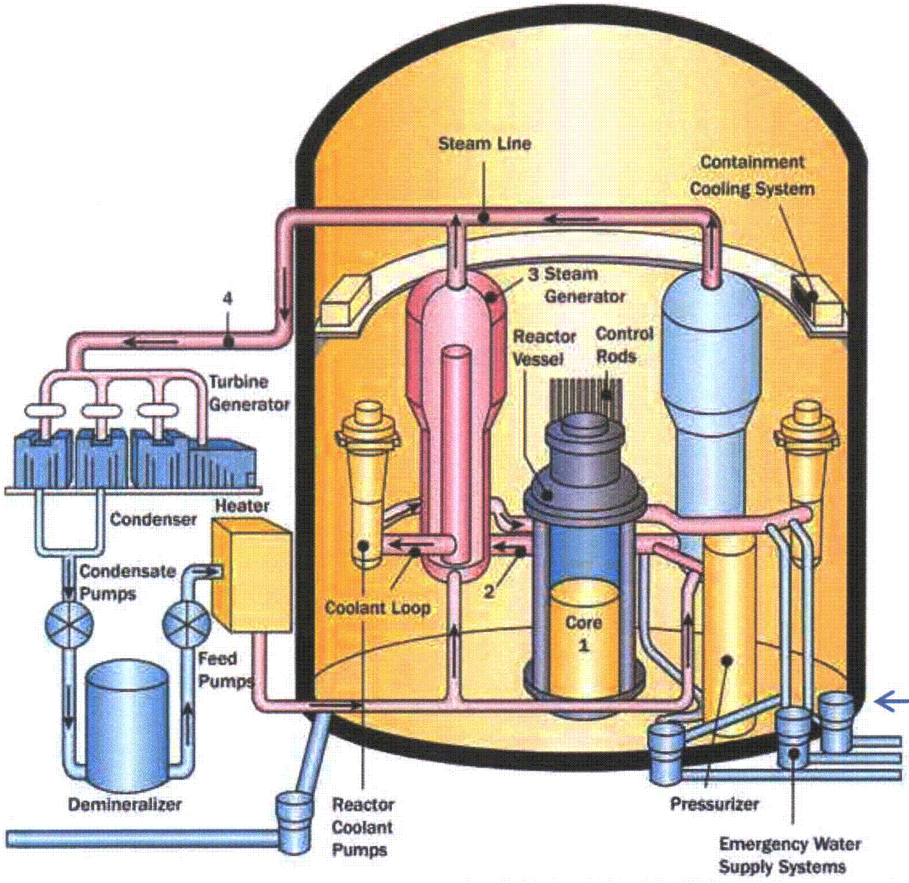
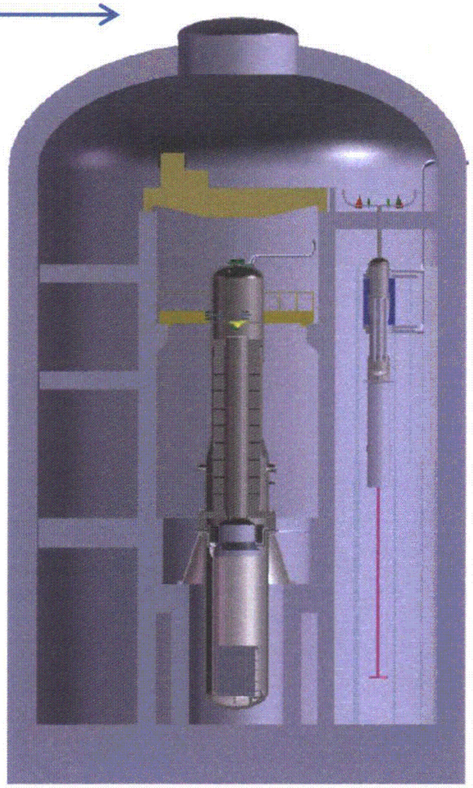
Traditional PWR versus B&W mPower Reactor

Typical Pressurized-Water Reactor



Grade
Level

B&W mPower Reactor



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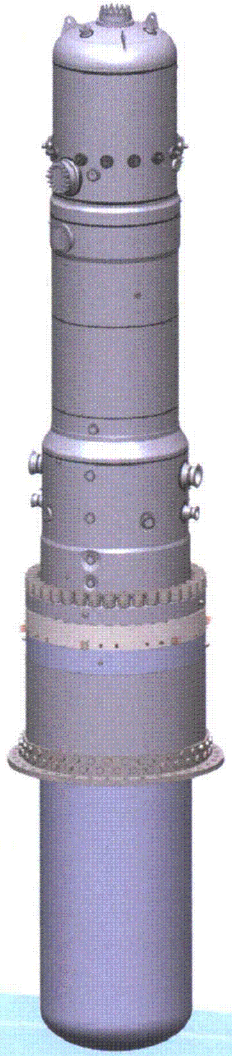
Inherent Safety Features



- Low Core Linear Heat Rate
  - Low Power Density Reduces Fuel and Clad Temperatures During Accidents
  - Low Power Density Allows Lower Flow Velocities that Minimize Flow Induced Vibration Effects
- Large Reactor Coolant System Volume
  - Large RCS Volume Allows More Time for Safety System Response in the Event of an Accident
  - More Coolant Is Available During a Small Break LOCA Providing Continuous Cooling to Protect the Core
- Small Penetrations at High Elevation
  - High Penetration Locations Increase the Amount of Coolant Left in the Vessel after a Small Break LOCA
  - Small Penetrations Reduce Rate of Energy Release to Containment Resulting in Lower Containment Pressures

Key Features of the Integral RCS

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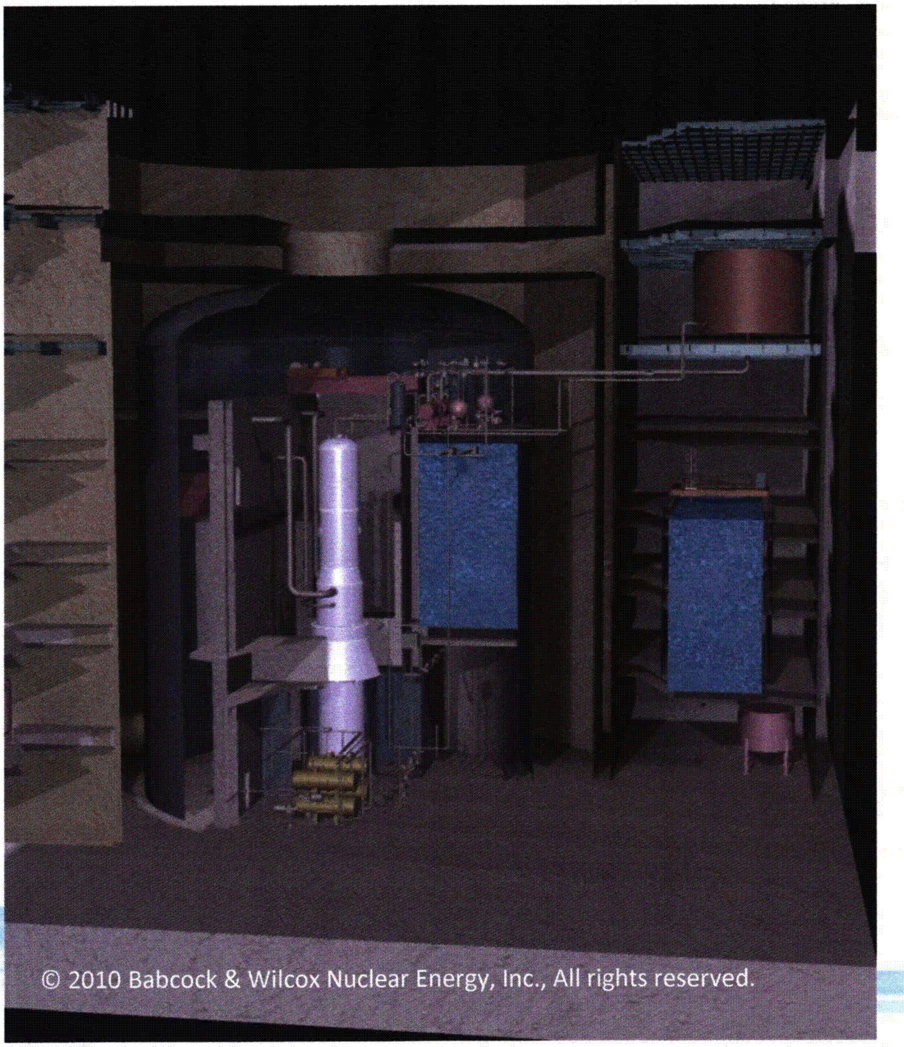
Containment Requirements

- Underground containment and fuel storage buildings
  - Favorable seismic response
  - Missile protection
- Environment suitable for human occupancy during normal operation
- Simultaneous refueling and NSSS equipment inspections
- Leakage free
- Volume sufficient to limit internal pressure for all design basis accidents



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Instrumentation and Controls

- State of the Art Digital System
- Provides Monitoring, Control and Protection Functions [
- Separate Safety and Non-Safety Systems
- Implement Lessons Learned from Current Licensing Activities
- Northrop Grumman under Contract to Develop Digital Control System Architecture]

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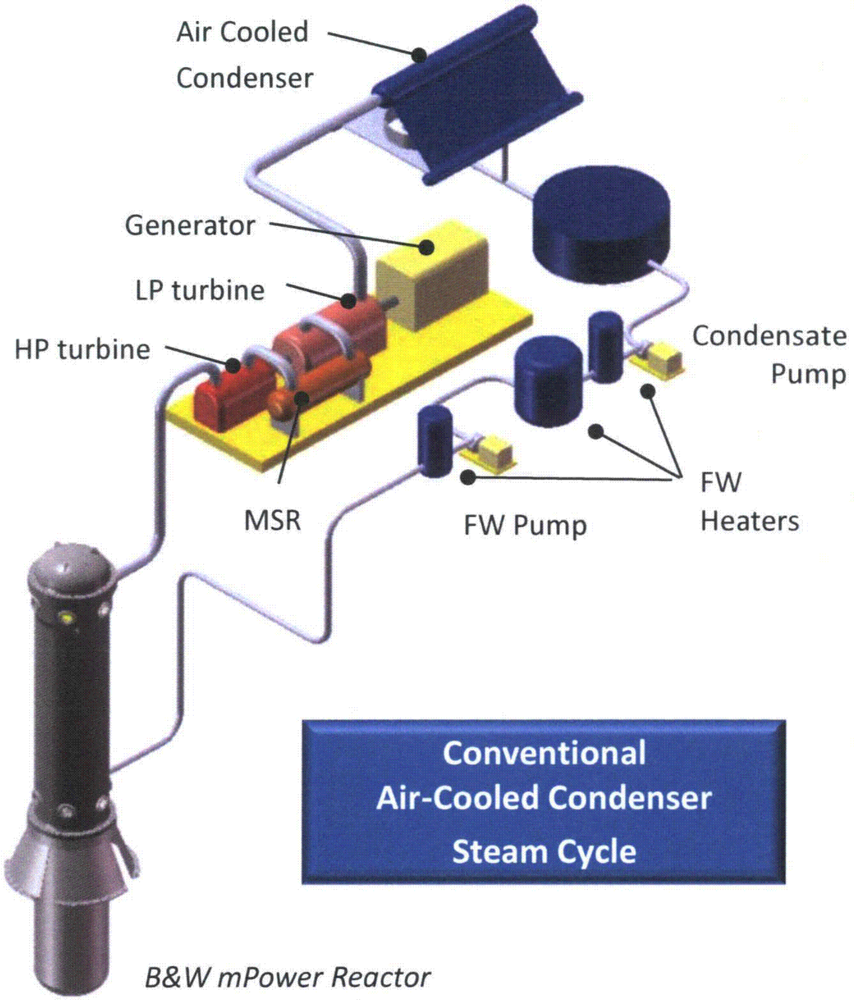
Balance of Plant Design

- Plant designed to produce a nominal 125 MWe
  - Air-cooled condenser (Baseline)
  - Water-cooled condenser
- Conventional steam cycle equipment (small, easy to maintain and replace)
- BOP operation not credited for design basis accidents
  - All fuel can be cooled for a minimum of 72 hours without any BOP system



Conventional Air-Cooled Condenser Steam Cycle

B&W mPower Reactor 125 MWe Module

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Major Structures, Systems, and Components

REACTOR

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B&W *mPower* Reactor

Design Characteristics	
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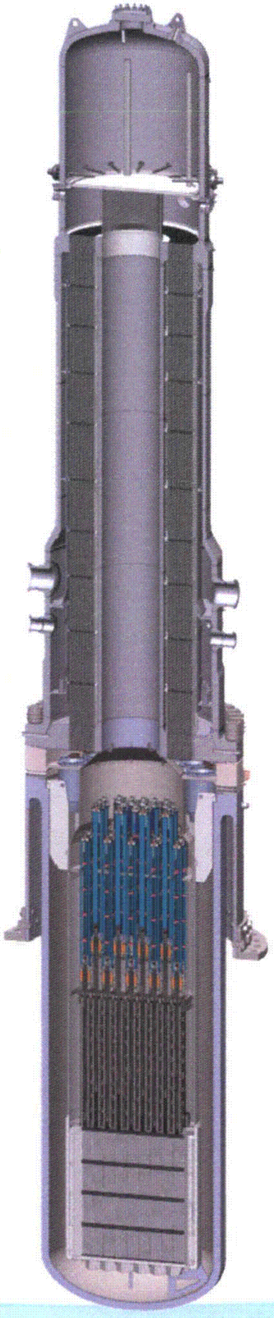

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Operating Conditions

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B&W *mPower* Reactor

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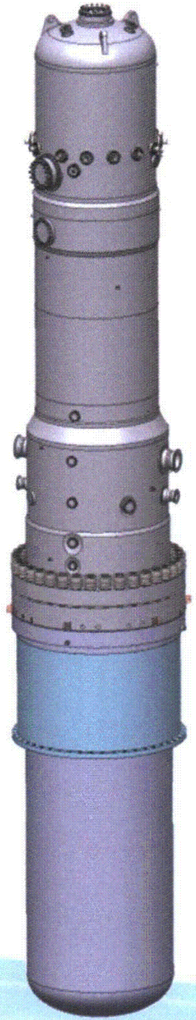

B&W mPower **Reactor**

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Upper Vessel

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- Characteristics
- Integral Pressurizer & Steam Generator
- [ ]
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Pressurizer

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- Arrangement
  - [ ]
- Materials
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Steam Generator

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- Arrangement
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- Materials
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Upper Internals Assembly

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Reactor Coolant Pump

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Upper Internals Assembly

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Control Rod Drive Mechanism

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Lower Vessel & Core Support

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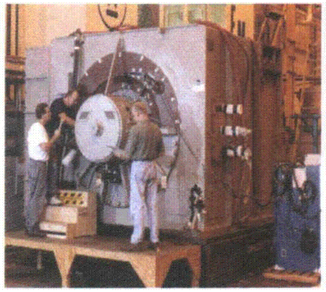

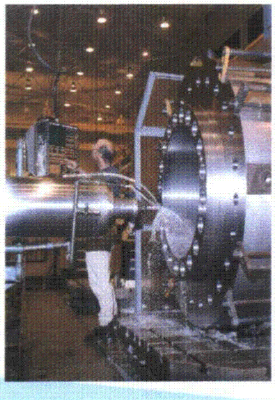

Reactor Coolant Pump (RCP) Overview

Reactor Coolant Pumps

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Curtiss Wright Design Experience Summary

- Design agent and traditional supplier of Reactor Coolant Pumps (RCPs) for the primary coolant loop in Westinghouse Pressurized Water Reactors
- Extensive experience with canned motor design/manufacture for centrifugal and axial configurations
- Canned motors are based on designs qualified for submerged severe shock and vibration survivability, well suited for long service life and seismic forces applications
- CW electrical machines, including the mPower RCP, are designed to provide maintenance free operation, operate under high ambient pressure and temperature, and resist corrosion in a submerged environment

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RCP Key Requirements

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RCP Design

Parameter	Value	Value (SI)
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RCP Development & Test Plan

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Control Rod Drive Mechanism (CRDM)

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Key CRDM Design Criteria

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Key CRDM Design Parameters

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Material Selection

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Test Plan

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Fuel and Core Design

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Design Objectives – Core and Fuel Assembly

- Ensure that assemblies are mechanically designed to remain leak tight and maintain structural integrity under all possible conditions
- Load enough fuel inventory to accommodate a 4 year operating cycle at a capacity factor of > 95%
- Optimize fuel assembly design to maximize fuel utilization
- Maintain conservative peaking factors and linear heat rate throughout the operating cycle
- Ensure a shutdown margin of > 1% $\Delta k_{eff}/k_{eff}$ under the most reactive conditions and highest worth CRA cluster stuck out
- Initially meet a MDNBR > 1.3 for limiting thermal-hydraulic conditions and ultimately confirm that it is bounding
- Identify (large) safety margins

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Mechanical Design Features

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Babcock & Wilcox Proprietary Information

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Mechanical Design Features

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Core Design Features

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Babcock & Wilcox Proprietary Information

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Control Rod Configuration

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Shut-Down Margin Analysis

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Core Axial Power Distribution

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Axial, Radial, and Nodal Peaking

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Thermal-Hydraulic Analysis Approach

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Thermal-Hydraulic Analysis Results

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Thermal-Hydraulic Analysis Results

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Thermal-Hydraulic Analysis Results – Subchannel

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Fuel/Core Design Summary

- **Mechanical Design**
  - ✓ Simple Fuel Assembly Design
  - ✓ Mechanical Tests To Qualify The Design are in Process
  - ✓ Fuel Performance Analysis and Topical Planned for 2012
- **Nuclear Design**
  - ✓ Sufficient Excess Reactivity For Extended Cycle (4-Year) Core Operation
  - ✓ Conservative Nuclear Design With Comfortable Margins
  - ✓ Nuclear Design Methodology Topical to be completed in February 2012
- **Thermal-Hydraulic Design**
  - ✓ Large Thermal Margins Resulting From Low Linear Heat Rate
  - ✓ Good Margins With Conservative DNBR
  - ✓ Critical Heat Flux Test Program In Progress
  - ✓ Thermal-Hydraulic Design Methodology Topical To Be Prepared in 2012

Reference Static Core Design is Established. Transient Analyses are Underway.

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NSSS Systems

Topics

- *Systems Design Approach*
- *Reactor Coolant System*
  - *Functions*
  - *Key Features*
  - *Unique characteristics*
- *Reactor Coolant Inventory and Purification System*
  - *Functions*
  - *Modes of Operation*
- *Emergency Core Cooling System*
  - *Functions*
  - *Modes of Operation*
- *Summary*

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Systems Design Approach

- *Improve Safety*
  - Large reactor coolant inventory for design power level
  - Small vessel penetrations placed as high as possible above the core
  - No soluble boron used in normal operation
  - Passive safety system
- *Integrate Functionality to Reduce System/Component Count*
  - Majority of reactor coolant system (RCS) integrated into one vessel
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- *Maximize System Reliability through PRA Risk Insights*

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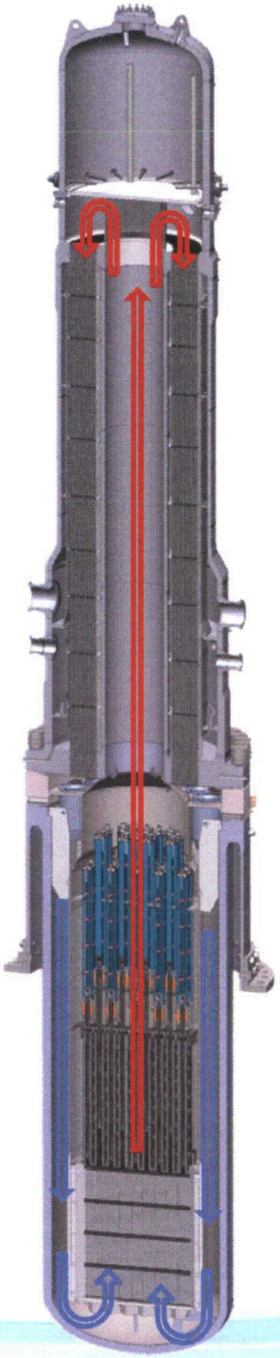
RCS Functions

- Maintain reactor coolant boundary integrity
- Transfer energy produced in the reactor core to the steam generator by forced circulation
- Maintain RCS pressure during normal and upset operating conditions using electrical heaters and pressurizer spray
- Provide protection of the RCS from over-pressurization by pressure relief devices for all design basis events
- Provide for venting of non-condensable gasses from the high points following severe accidents



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Key Features of the Integral RCS

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Unique RCS Characteristics

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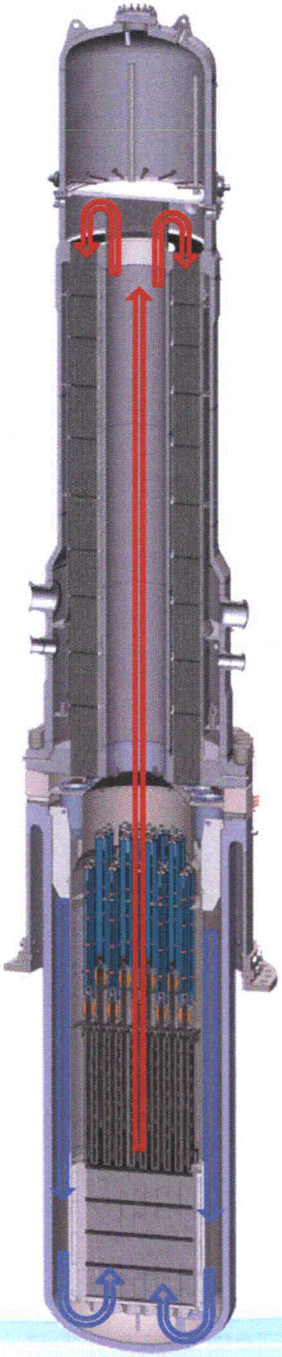

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RCIPS Functions

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RCIPS Normal Purification

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RCIPS Normal Decay Heat Removal

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RCIPS High Pressure Decay Heat Removal

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ECCS Functions

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ECCS During Normal Operation

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Passive Decay Heat Removal

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ECCS Automatic Depressurization

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Low Pressure Injection & Long-Term Decay Heat Removal

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Diverse, Redundant Shutdown

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Summary

- *RCIPS and ECCS designed to maximize the benefits of the integral RCS*
- *Number of systems/components minimized by:*
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- *System reliability and plant safety improved by:*
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  - Use of PRA risk insights throughout the design process

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I&C Design and Simulation Overview and Main Control Room Concept Layout

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I&C Philosophy

- Highly-Reliable, Integrated and Scalable Digital I&C System
- I&C System Must Have Highest Degree of Licensing Certainty
  - Complies with Regulatory, URD Requirements
  - Minimizes Regulatory Challenges with Digital I&C...Cyber-Security, Diversity, Independence
- Integrated, Modernized Human-Factored Design
- High-level of Plant Automation
  - Control of Startup, Shutdown, Load Following...Support Staffing Plan
- Deliver Comprehensive O&M Strategy
  - Use of Commercially-Available Components
  - Managed Obsolescence

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High-Level I&C Design Requirements/Goals

- DCS configuration must support:
  - Passive ECCS/ESF
  - 72 hour battery operation
  - No active safety-related HVAC Requirements
  - Must support single failure for Safety/Non-Safety DCS
  - Must support Main Control Room and HFE
  - Must support Cyber Security Requirements
  - Must accommodate and interconnect diverse hardware/software platforms
  - Must address NRC concerns about previous Digital I&C applications

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I&C System Key Design Attributes

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I&C System Top Level Architecture Overview

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Plant-Level DCS and HSI Functions

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Two-Pack Conceptual Total Plant I&C Architecture

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Initial Two-Pack MCR Concept

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Initial MCR Concept - Plan View

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Initial MCR Concept – Top View

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Initial MCR Concept – Offset Elevation

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I&C System Framework

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I&C Functions – Plant Protection Layer

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I&C Functions[

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I&C Functions – [

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I&C Design Progress

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Top-down approach to define requirements

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Recent Licensing Issues

Digital I&C Licensing Issues

- Communication Independence
- Design Complexity
- Common Cause Failures and Diversity
- Non-safety Control of Safety Systems
- Quality Assurance for Digital I&C Platform

mPower Approach to Risk

- Establish Rigorous Requirements Management Program (traceability)
- Pre-application engagement with NRC staff on Software Quality Assurance Program Development
- Function Design Requirements Specifies Explicit System Independence

mPower™ I&C System Specification Tree

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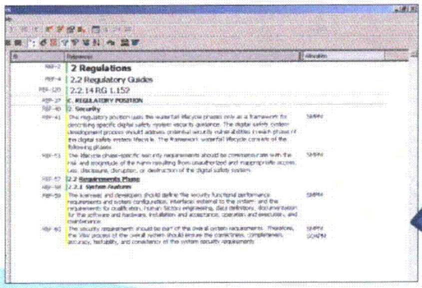
Requirements Traceability



2 Regulations

2.2 Regulatory Guides

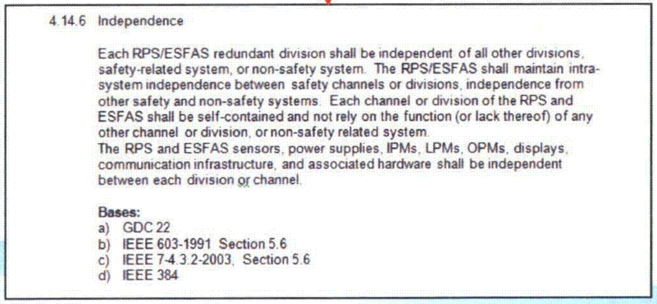
2.2.14 RG 1.152

C. REGULATORY POSITION

2. Security

2.2 Requirements Phase

2.2.1 System Features



4.14.6 Independence

Each RPS/ESFAS redundant division shall be independent of all other divisions, safety-related system, or non-safety system. The RPS/ESFAS shall maintain intra-system independence between safety channels or divisions, independence from other safety and non-safety systems. Each channel or division of the RPS and ESFAS shall be self-contained and not rely on the function (or lack thereof) of any other channel or division, or non-safety related system.
The RPS and ESFAS sensors, power supplies, IPMs, LPMs, OPMs, displays, communication infrastructure, and associated hardware shall be independent between each division or channel.

Bases:
a) GDC 22
b) IEEE 603-1991 Section 5.6
c) IEEE 7-4.3.2-2003, Section 5.6
d) IEEE 384

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Diversity and Defense-in-Depth with I&C Systems

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Technology & complexity for DAS shows strong reliance on functional requirements

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DCS Vendor Selection

- Northrop Grumman Selected as DCS Design Vendor
  - Self-Contained Business, with Capabilities in:
    - Engineering Design, Manufacturing, QA, Project Management, Testing and Equipment Qualification
  - 30 years experience Delivering Digital I&C systems to Nuclear Navy
  - Acquired Westinghouse Nuclear Instrument & Control Division in 1996
  - Depth of Technical Capabilities (Eng, Mfg, Euip. Qualification, R&D)
  - Systems Integration Ability (experience with integration of wide variety of Commercial-Off-The-Shelf platforms)
  - Software QA and Design Lifecycle (Established Capability Maturity Model Integration Level 5 Certification)
  - Experience in Nuclear Instrumentation
  - Cyber-Security Capabilities
  - Cohesive Programmatic Approach ("Partnership/Risk-Sharing")

Engineering Simulator Initiative Scope

- Current
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- Future Potential
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Initial Simulation and Modeling Roadmap

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Site Layout Overview

Two Module Site Arrangement Plan View

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Two Module Site Arrangement Cross Section – Looking West

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Reactor Containment Building Plan View [ ]

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Reactor Containment Building Plan View El. [ ]

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Reactor Containment Building Plan View El. [ ]

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Reactor Containment Building Plan View [ ]

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Reactor Containment Building Cross Section – Looking East

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Reactor Containment Building Cross Section – Looking South

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Reactor Service Building
Cross Section of 3D Model

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Reactor Service Building
Plan View [ ]

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Reactor Service Building Plan View – [ ]

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Reactor Service Building Plan View –[ ]

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Reactor Service Building Plan View –[ ]

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Reactor Service Building Plan View –[ ]

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Reactor Service Building

Roof Plan

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Reactor Service Building Cross Section Looking West

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Safety Analysis and Methods

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Introduction

- Purpose
  - Introduce the B&W mPower safety analysis codes and methods
- Process
  - Computer Codes
  - Methodology
  - SRP events not applicable to mPower
  - mPower specific events
- Outcome
  - Enhanced pre-application technical exchange

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Computer Codes

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Industry standard accident analysis codes

Code Validation

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Methodology

- Appendix K based approach
  - All heat sources accounted for conservatively (initial power level, decay heat, passive heat sinks)
  - Worst time in life (peaking factors, reactivity feedback)
  - Highest worth rod stuck out of core
  - Conservative discharge model applied for breaks
  - Spectrum of break sizes and locations
  - Single active failure criterion
  - Delays in protection system functions

- Pre-Application Submittals to NRC
  - Accident Analysis Methods Technical Report (2011)
  - LOCA Methodology Topical Report (2012)
  - Non-LOCA Methodology Topical Report (2013)

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Methodology and Code Usage

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Categories of Events

Accident Category	Examples of Initiating Events
Increase/Decrease in heat removal by secondary system	[
Decrease in RCS flow	
Reactivity and power distribution anomalies	
Increase/Decrease in reactor coolant inventory	
Radioactive releases	
Anticipated Transients Without Scram	
Containment pressure and temperature rise	]

SRP Events Not Applicable to B&W mPower Reactor

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B&W mPower Reactor Specific Events

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Conclusion

- Codes and Methods
  - Use of industry standard accident analysis codes
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- SRP Assessment
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Development Testing Programs

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Development Testing Programs

- Component Tests
  - Reactor Coolant Pump
  - CRDM
  - Fuel Mechanical Testing
  - CRDM/Fuel Integrated Test
  - Fuel Critical Heat Flux
  - Emergency High Pressure Condenser
- Integrated Systems Test (IST)
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Center for Advanced Engineering Research (CAER)
Bedford, VA

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Verification & Validation Plan

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IST Objectives

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Integral Reactor Phenomena

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Integration of PIRT with IST

- Purpose
  - Phenomenological Understanding of NSSS Design
  - Support Licensing and Regulatory Efforts
  - Promote More Cost Effective Resource Allocations
- Process
  - Utilized Established Methodology
  - [ ]
  - Report Complete
- Benefits
  - Outcomes of IST Will Strongly Support the Design
  - Integration of IST with Other B&W mPower Development Efforts

B&W *mPower* Reactor and IST Loop

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Systems Simulated in IST

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IST Test Scope

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IST Status

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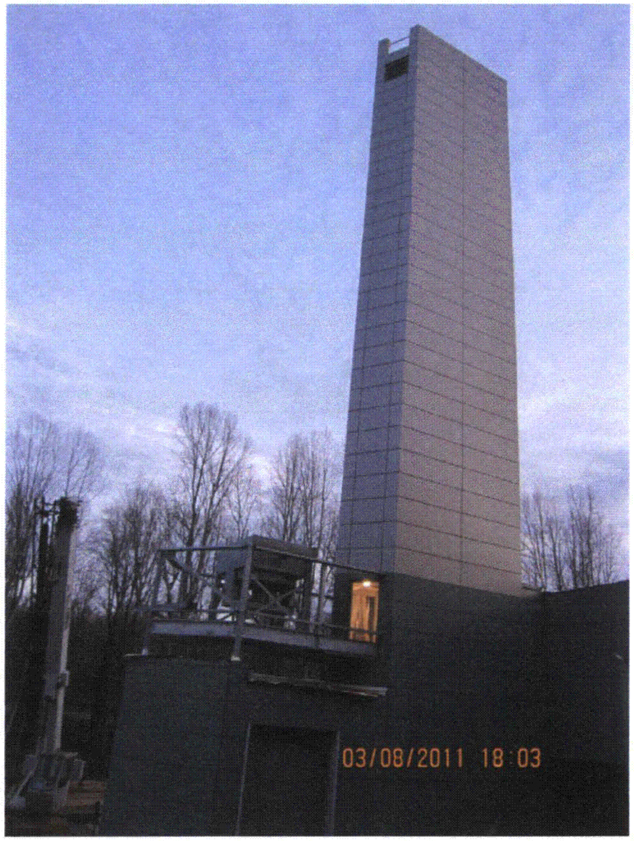
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Summary

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Unique Design Features

- *Integral NSSS with No Large Primary System Penetrations*
  - *Internal steam generator and pressurizer, with conventional core design*
  - *Innovative internal control rod drive mechanisms and reactor coolant pumps*
- *Simplified Reactor Operations*
  - *4+ year fuel cycle with complete core replacement*
  - *No soluble boron system for reactivity control*
- *Improved Reliability and Plant Safety*
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  - Use of PRA risk insights throughout the design process
- Dedicated Integrated Systems Test Facility

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Design Considerations for "Fukushima-Type" Events

Events and Threats	B&W mPower Reactor Design Features
Earthquakes And Floods	• **Seismic attenuation**: Deeply embedded reactor building dissipates energy, limits motion • **"Water-tight"** : Separated, waterproof reactor compartments address unexpected events
Loss of Offsite Power	• **Passively safe**: AC power, offsite or onsite, not required for design basis safety functions • **Defense-in-depth**: 2 back-up 2.75MWe diesel generators for grid-independent AC power
Station Blackout	• **3-day batteries**: Safety-related DC power supports all accident mitigation for 72 hours • **APU back-up**: Auxiliary Power Units inside reactor building recharge battery system • **Long-duration "station keeping"**: 7+ day battery supply for plant monitoring/control
Emergency Core Cooling	• **Gravity, not pumps**: Natural circulation decay heat removal; water source in containment • **Robust margins**: Core power density (11.5kW/m) and small core (425MWth) limit energy • **Slow accidents**: Maximum break small compared to reactor inventory (4.7x10-5m^2/m^3)
Containment Integrity and Ultimate Heat Sink	• **Passive hydrogen recombiners**: Prevention of explosions without need for power supply • **Internal cooling source**: Ultimate heat sink inside underground shielded reactor building • **Extended performance window**: Up to 14 days without need for external intervention
Spent Fuel Pool Integrity and Cooling	• **Protected structure**: Underground, inside auxiliary containment, located on basemat • **Large heat sink**: 30+ days before boiling and uncovering of fuel with 40 years of spent fuel

Multi-layer defense ... mitigates extreme beyond-design basis challenges