

Safety Aspects of SMRs: A PRA Perspective

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Topics Covered / Disclaimer

- ▶ Quick Overview of SMR Technologies
- ▶ Safety Advantages
- ▶ PRA Challenges
 - ▶ Modeling
 - ▶ Data
- ▶ Policy / Regulatory Challenges
- ▶ Conclusions

Disclaimer:

SMR designs, PRA and Regulatory issues presented are my personal views, not particular to any one SMR, and incomplete.

A Brief Overview of SMR Technologies

- ▶ Small power reactors (lower than 300 MWe) are not new and have been used in submarines and district heating for many years
- ▶ SMRs may be built as modules in central manufacturing plants and transported to the site and plugged in with capacity added incrementally
- ▶ Three classes of SMRs being designed: LWRs, fast reactors and graphite-moderated high temperature reactors
- ▶ Examples:
 - ▶ **PWRs**: NuScale (45 MWe), mPower (180 MWe), Holtec (145 MWe), Westinghouse SMR (225 MWe), **Argentina - CAREM (27 MWe), South Korea – SMART (100 MWe)**
 - ▶ **Liquid Metal-Cooled Fast Reactors**: GE Hitachi PRISM (300 Mwe), Toshiba 4S (10 Mwe), Hyperion (25 Mwe), and Advanced Reactor Concepts ARC-100 (100 Mwe)
 - ▶ **High Temperature Gas-Cooled Reactors**: NGNP Alliance (prismatic 300 MWe).

SMR-Related Developments in the U.S.

- ▶ In March 2012 DOE signed agreements with Hyperion, Holtec, and NuScale for constructing demonstration SMRs at its Savannah River site in SC.
- ▶ DOE is discussing similar arrangements with four other SMR developers
- ▶ DOE is expected to very soon announce a major funding for two SMR designs
- ▶ SMRs are already in operation in Siberia: four co-gen 62 MWt graphite-moderated boiling water units with water/steam channels through the moderator operate since 1976 for district heating and generation of 11 Mwe per unit (much cheaper rate than fossil fuel alternatives in this Arctic region)

A Few Key Safety and Operational Features / Challenges of SMRs



- ▶ Small scale natural cooling and heat transfer during normal power production emergencies
- ▶ Integrated steam generators leading to different heat transfer regimes and design, material integrity, radiation damage, design basis accidents and beyond design basis accidents behaviors
- ▶ In pool and/or underground operation (affecting different radiation release, noble gases and volatile source term and retention, corrosion concerns, new seismic, external flood, high wind and other external event loads)
- ▶ Multi-module sites with new module-to-module connections and interactions
- ▶ Highly digital and multi-module control room design and operation of multiple modules by the same operator
- ▶ New manufacturing, transportation, and construction methods and processes (for example centrally manufactured, assembled and transported to the site rather than constructed in an in-situ manner)
- ▶ Completely new refueling approach, and in some SMRs new fuel assembly and core configuration design

Examples of SMRs: NGNP Alliance & mPower Reactors

AREVA Prismatic Reactor

Power: 625 MWt

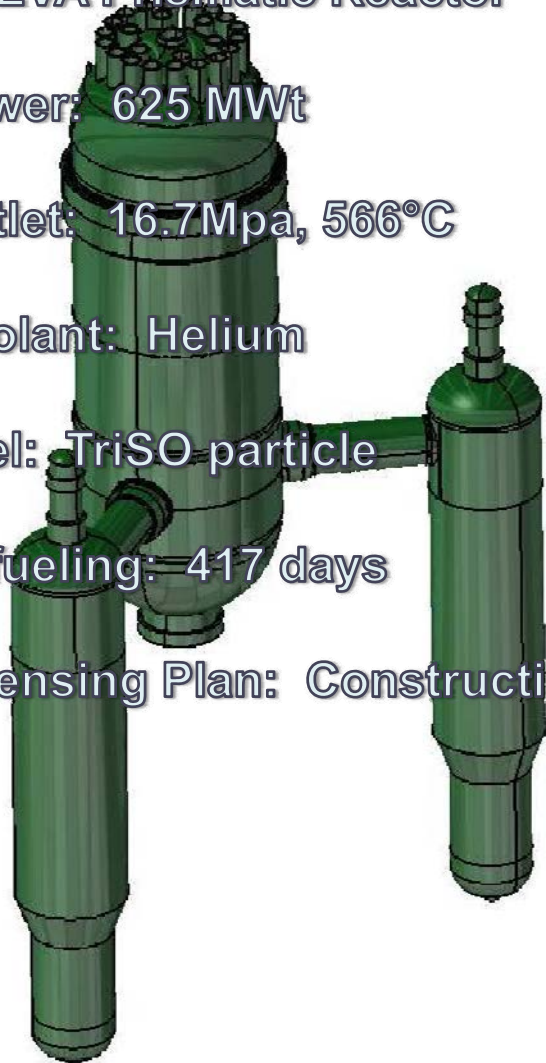
Outlet: 16.7 Mpa, 566°C

Coolant: Helium

Fuel: TriSO particle

Refueling: 417 days

Licensing Plan: Construction Permit



mPOWER

Power: 530 MWt, 180 Mwe

Outlet: 609°F

Coolant: Light water

Fuel Design: Standard PWR fuel

Refueling: 4 years

Licensing Plan: Design Certification



An Example of SMR: Basic NuScale Parameters



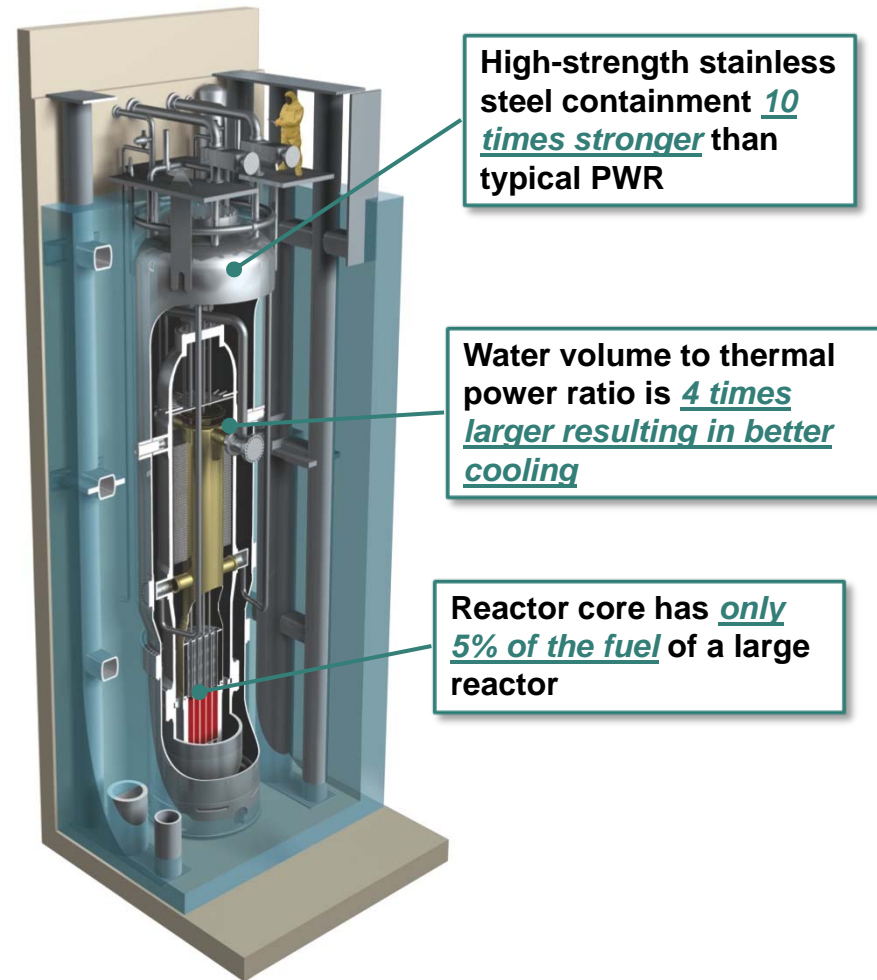
Overall Plant	
• Net Electrical Output	540 MW(e)
• Plant Thermal Efficiency	30%
• Number of Power Generation Units	12
• Nominal Plant Capacity Factor	> 90%
Power Generation Unit	
• Number of Reactors	One
• Net Electrical Output	45 MW(e)
• Steam Generator Number	Two independent tube bundles
• Steam Generator Type	Vertical helical tube
• Steam Cycle	Superheated
• Turbine Throttle Conditions	3.1 MPa (450 psia)
• Steam Flow	71.3 kg/s (565,723 lb/hr)
• Feedwater Temperature	149° C (300° F)
Reactor Core	
• Thermal Power Rating	160 MWt
• Operating Pressure	8.72 MPa (1850 psia)
▪ Fuel	UO ₂ (< 4.95% enrichment)
▪ Refueling Intervals	24 months



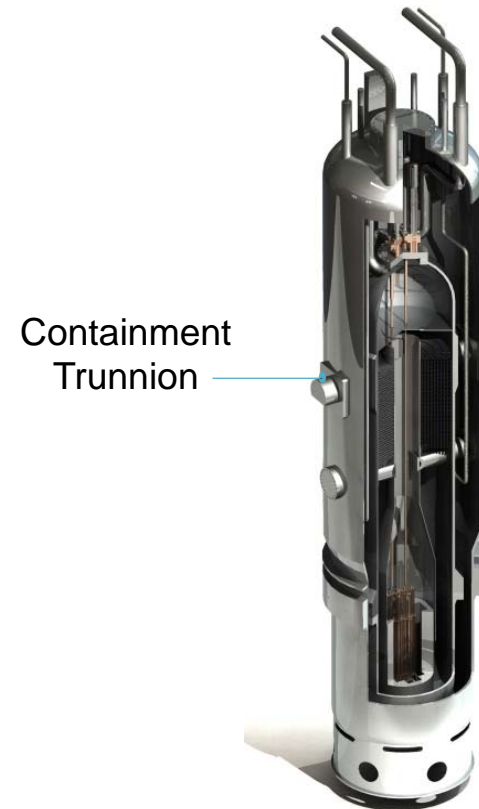
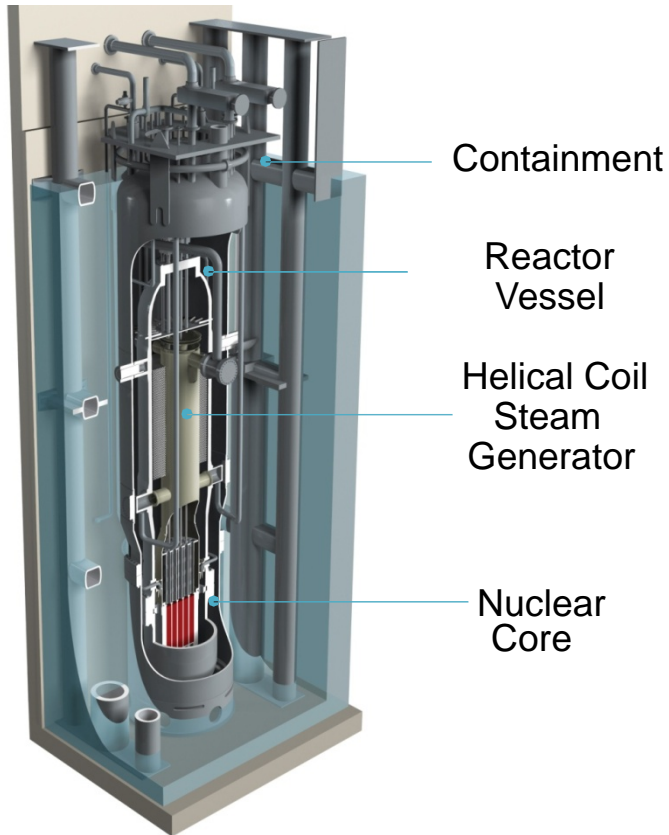
Safety Features on NuScale

45 MWe Reactor Module

- ▶ **Natural Convection for Cooling**
 - ▶ Inherently safe natural circulation of water over the fuel driven by gravity
 - ▶ No pumps, no need for emergency generators
- ▶ **Seismically Robust**
 - ▶ System is submerged in a pool of water below ground in an earthquake resistant building
 - ▶ Reactor pool attenuates ground motion and dissipates energy
- ▶ **Simple and Small**
 - ▶ Reactor is 1/20th the size of large reactors
 - ▶ Integrated reactor design, no large-break loss-of-coolant accidents
- ▶ **Defense-in-Depth**
 - ▶ Multiple additional barriers to protect against the release of radiation to the environment

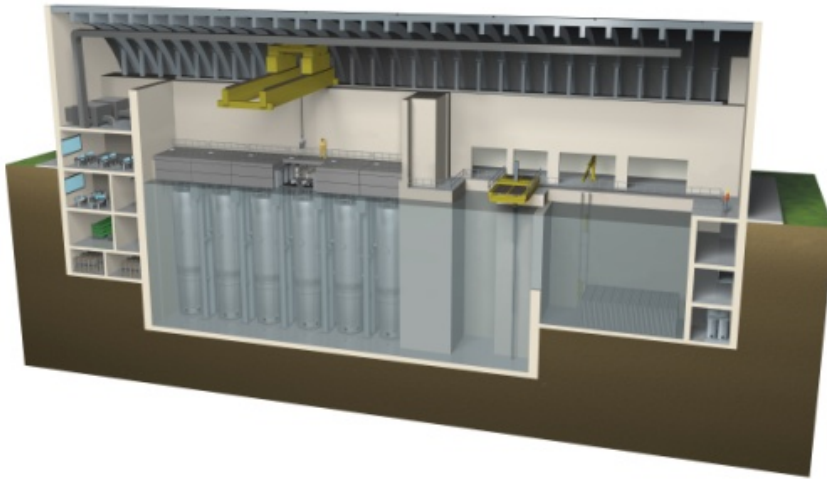


NSSS and Containment of NuScale

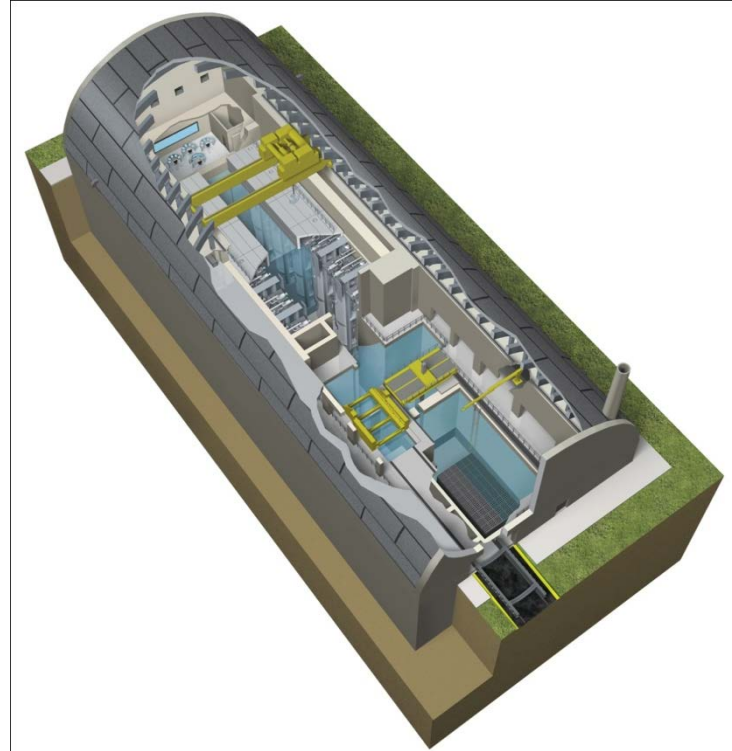


Reactor Building of NuScale

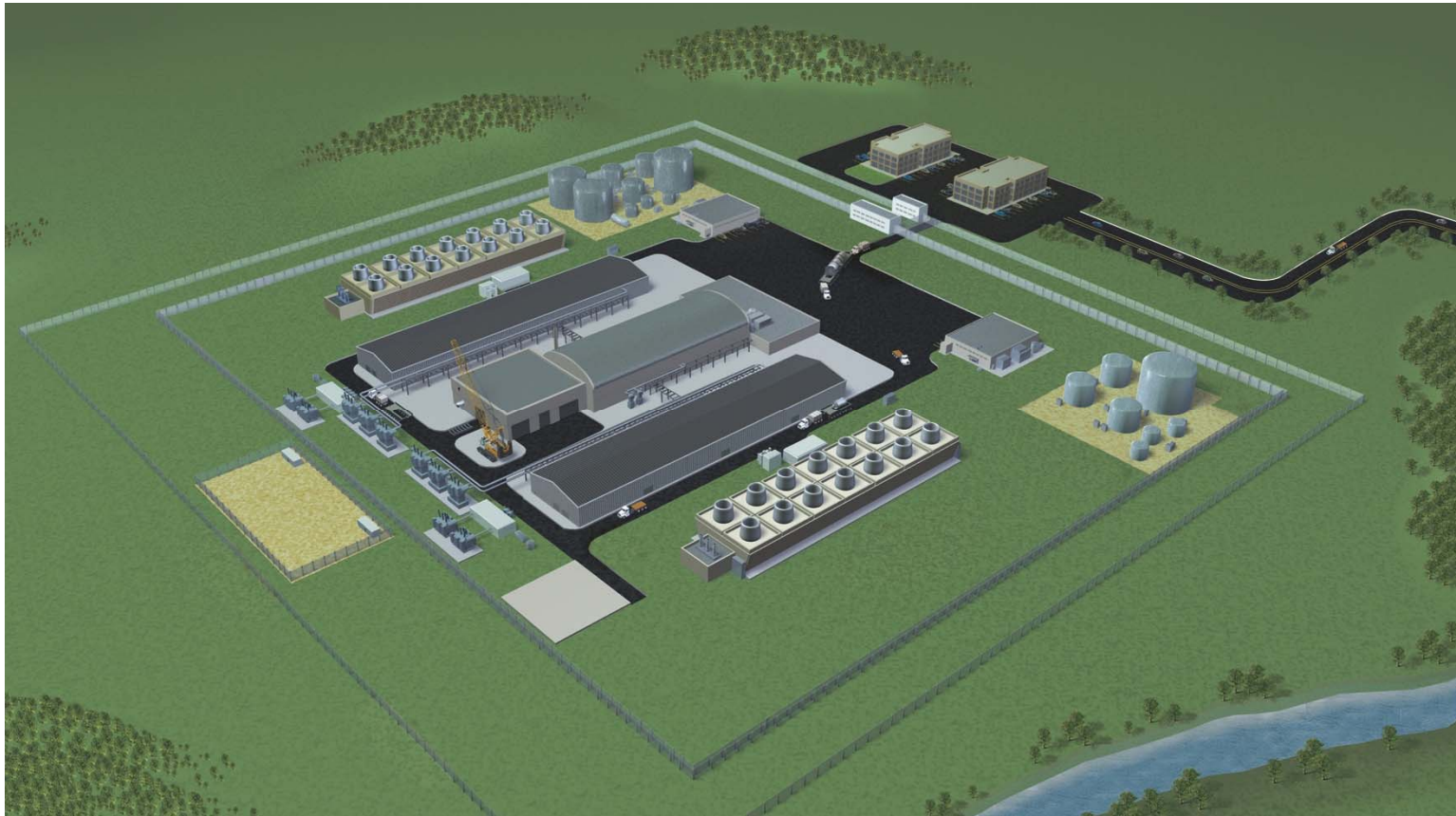
12 modules, 45 MWe each produces 540 MWe



Cross-sectional View of Reactor Building

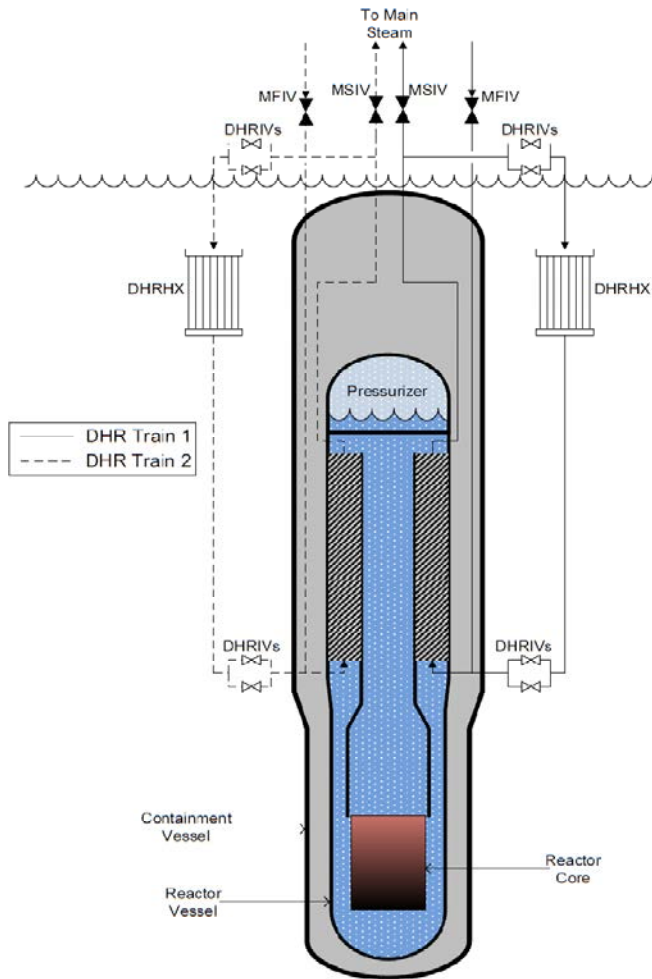


A NuScale Site Schematic





NuScale Decay Heat Removal Using Steam Generators

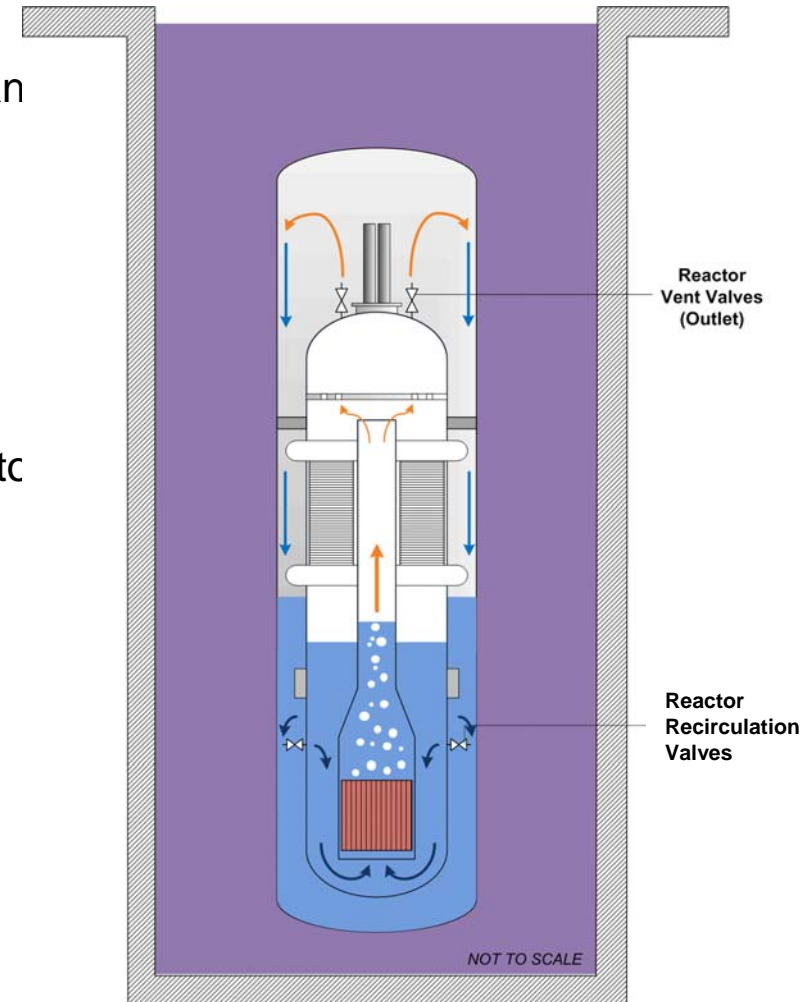


- ▶ Two independent single-failure-proof trains
- ▶ Closed loop system
- ▶ Two-phase natural circulation operation
- ▶ DHRX heat exchangers nominally full of water
- ▶ Supplies the coolant inventory
- ▶ Primary coolant natural circulation is maintained
- ▶ Pool provides a 3 day cooling supply for decay heat removal



NuScale Decay Heat Removal Using the Containment

- ▶ Provides a means of removing core decay heat and limits containment pressure by:
 - ▶ Steam Condensation
 - ▶ Convective Heat Transfer
 - ▶ Heat Conduction
 - ▶ Sump Recirculation
- ▶ Reactor Vessel steam is vented through the reactor vent valves (flow limiter)
- ▶ Steam condenses on containment
- ▶ Condensate collects in lower containment region
- ▶ Reactor Recirculation Valves open to provide recirculation path through the core
- ▶ Provides +30 day cooling followed by indefinite period of air cooling.



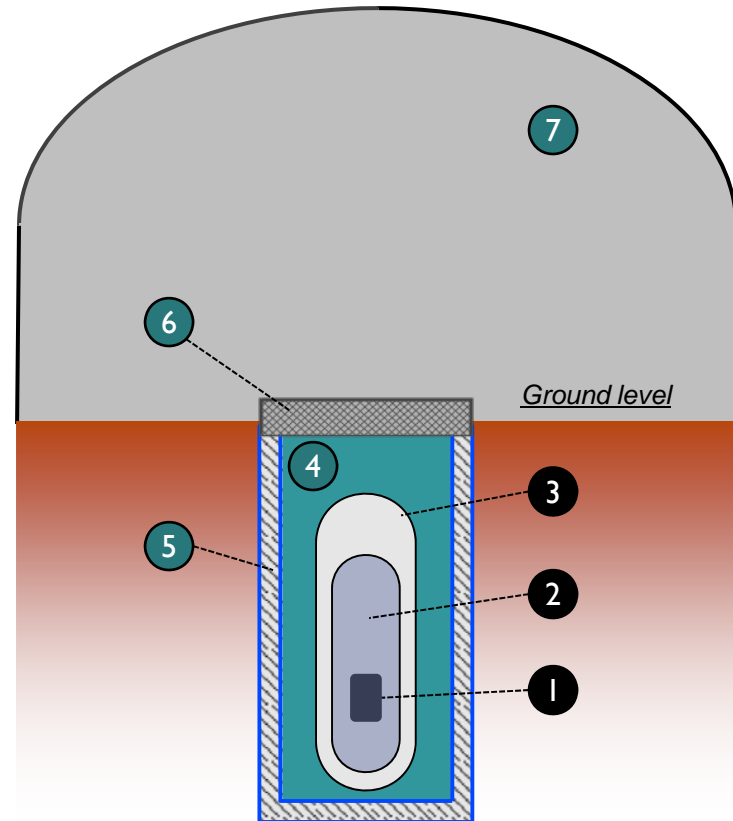
Added Barriers Between Fuel and Environment

Conventional Designs

1. Fuel Pellet and Cladding
2. Reactor Vessel
3. Containment

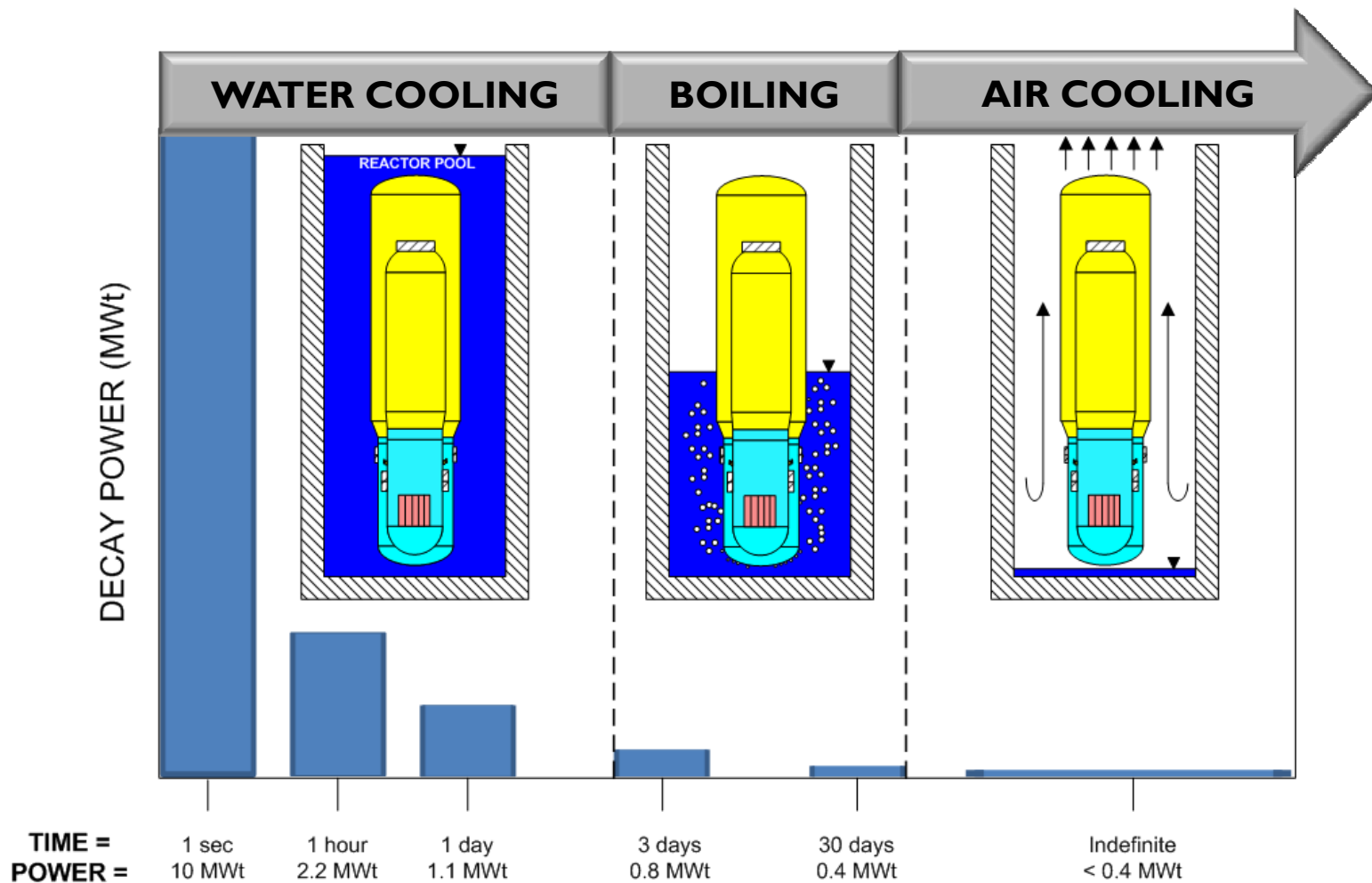
NuScale's Additional Barriers

4. Water in Reactor Pool (4 million gallons)
5. Stainless Steel Lined Concrete Reactor Pool
6. Biological Shield Covers Each Reactor
7. Reactor Building



Stable Long Term Cooling

Reactor and nuclear fuel cooled indefinitely without pumps or power



Comparison of NuScale to Fukushima-Type Plant



Fukushima		NuScale Plant	
Reactor and Containment			
Emergency Diesel Generators Required		None Required	
External Supply of Water Required		Containment immersed in 30 day supply of water	
Coolant Supply Pumps Required		None Required	
Forced flow of water required for long term cooling		Long term (Beyond 30 days) cooling by natural convection to air	
Spent Fuel Pool			
High Density Fuel Rack		Low Density Fuel Racks	
Water Cooling		Water or Air Cooling Capability	
Elevated Spent Fuel Pool		Deeply Embedded Spent Fuel Pool	
Standard Coolant Inventory		Large Coolant Inventory 4 times the water of conventional spent fuel pools per MW power	

SMR PRA Modeling Considerations/Complexities

- Integrated Design
 - Integrated Steam Generator / Health Management
 - Integrated Control Rod Drive Mechanism
 - Integrated RCP
 - New Containment-RCS Interactions
 - Integrated Pressurizer
- Passive systems
 - Operability / conditions of operation
 - Failure modes
 - Thermal/mechanical failure mechanisms (e.g., PTS)
 - Long-term component/structure degradation

SMR PRA Modeling Considerations/Complexities (Cont.)

- Multi-Module Risk

- Direct Dependencies

- ✧ Common initiating events / shared SSCs
 - ✧ Shared instrumentation, control, fiber optics, other cables, electric divisions
 - ✧ Shared systems (e.g., FPS)
 - ✧ Capacity of shared equipment (e.g., batteries)

SMR PRA Modeling Considerations/Complexities (Cont.)

- Multi-Module Risk (Cont.)
- **Indirect Dependencies**
 - » Human/organizational Pre-imitating event dependencies
 - » Post accident human actions (operators, fire brigade, etc.
 - » Common environments (caused by)
 - ▶ Natural events
 - ▶ Internal events (e.g., SBO)
 - ▶ Internal events external of the system (e.g., Fire)
 - ▶ Accident-induced dependencies (for example hydrogen explosion at Unit 3 of Fukushima disabled fire pumps used for seawater injection at Unit 2. Also, fire/explosion at Unit 4 was caused by leakage of hydrogen released from Unit 3 through shared duct-work with Unit 4)

Schroer's Multi-Unit Classification

► Seven Commonality Classes

1. Initiating Events
2. Shared Connection
3. Identical Component
4. Proximity
5. Human
6. Organizational
7. Independent

Schroer reviewed Licensee Event Reports (LERs) from 2000 to 2011 that of 4207 total LERs reported in 2000-2011, 392 LERs affected multiple units (9% of total)

Other SMR PRA Modeling Considerations/Complexities

- Severe accident phenomena
 - Relevance of severe accident phenomena
 - ✧ H generation / explosions
 - ✧ Containment failure modes
 - ✧ Melt-through phenomena
 - ✧ Integrity of integrated structures such as steam generators
 - ✧ Integrity of instrumentations
- Long-term cooling
 - Capacity of heat sinks (24 hr, 72 hr, or longer accidents)
 - Conditions necessary to maintain long-term cooling

Other SMR PRA Modeling Considerations/Complexities (Cont.)



- HRA
 - Control room crew dynamics
 - Errors of commission
 - Recovery actions / accessibility
- External events
 - Seismic hazard
 - Fragilities of integrated structures
 - Combined external initiators
- Spent fuel pool considerations
 - Interplay with the operating modules
- ✓ Low Power & Shutdown Events

Need for Failure Data

- ▶ Lack of data on equipment failure
 - ▶ Smaller units, less stress
 - ▶ Submerged units
- ▶ Initiating event frequencies (are legacy data applicable? What about new initiators?)
 - ▶ Internal
 - ▶ Integrated components
 - ▶ External

Policy / Regulatory Issues

- ▶ CDF of a single module or site? Definition of multi-module CDF?
- ▶ No LERF?
- ▶ What is considered as LRF? What is meant by large?
- ▶ Method for SSC classification
 - ▶ RAW/FV measures (with respect to a module or multi-module?)
 - ▶ What are the significant levels of RAW/FV?
 - ▶ F-C curves?

Conclusions

- SMR PRAs are very different from conventional plant PRAs
- Traditional solutions, methods and data are inadequate
- More research needed to develop new or improve PRA methods
- Reliability tests may be necessary to develop data
- New standards, regulatory guidance, early interactions between the applicants and NRC may be needed

