Power & Energy Society™
PES Chapter
IEEE Croatia Section

Uloga malih i modularnih reaktora u razvoju nuklearne energetike
The role of current SMRs in the development of nuclear power

Prof.dr.sc. Davor Grgic, ZVNE, FER
Predavanje i tribina u organizaciji HND i IEEE PES
Zagreb 17.02.2011.

Content/Organization

- First part based on presentation done by Dan Ingersoll (ORNL) at University of California at Berkeley in 2009
- More technical data added for selected SMR designs
- Some Q&As added to clarify current position of SMRs and their pros and cons

Suppose you need to buy a new car…

H1 Hummer

EPR
(1600 MWe)

Cadilac
Escalade

AP-1000
(1150 MWe)

Smart Car

?

Some Basic Terminology

IAEA definitions:

Small:	< 300 MWe	*Small and Medium-sized Reactors (SMR)*
Medium:	300-700 MWe	
Large:	> 700 MWe	

Related but less precise terms:

Grid-Appropriate Reactors (GAR)

Small Modular Reactors (SMR)

Right-Sized Reactors (RSR)

Deliberately Small Reactors (DSR)

Small Nuclear Power Plants Were First Developed for Defense Applications

- The United States began developing small nuclear reactors for naval propulsion beginning in the early 1950s
- The U.S. Air Force explored nuclear powered aircraft, but discontinued the program in 1961
- The U.S. Army built 7 small stationary power plants and 1 floating power plant for remote operations:

Reactor	Power (MWe)	Type	Location	Startup	Shutdown
SM-1	2	PWR	Fort Belvoir, Virginia	1957	1973
SM-1A	2	PWR	Fort Greely, Alaska	1962	1972
PM-1	1	PWR	Sundance, Wyoming	1962	1968
PM-2A	1	PWR	Camp Century, Greenland	1960	1962
PM-3A	1.5	PWR	McMurdo Station, Antartica	1962	1972
SL-1	1	BWR	Arco, Idaho	1958	1960
MH-1	10	PWR	Panama Canal (Sturgis)	1967	1976
ML-1	0.5	GCR	Arco, Idaho	1961	1966

1955; The USS Nautilus, becomes the world’s first nuclear powered submarine

USS *NAUTILUS* (SSN-571)
Launched: January 21, 1954

The USS Nautilus; circa 1964

1962; The NS Savannah (United States) enters service. The second civilian nuclear vessel, but the first civil nuclear cargo vessel

Nimitz – class carriers

USS *John C. Stennis* (CVN 74)

USS *John C. Stennis* (CVN 74)	
Funding authorized	Fiscal Year 1988
Keel laid	March 13, 1991
Launched	November 11, 1993
Commissioned	December 9, 1995
Nickname	*Johnny Reb*

USS *Nimitz* (CVN 68)

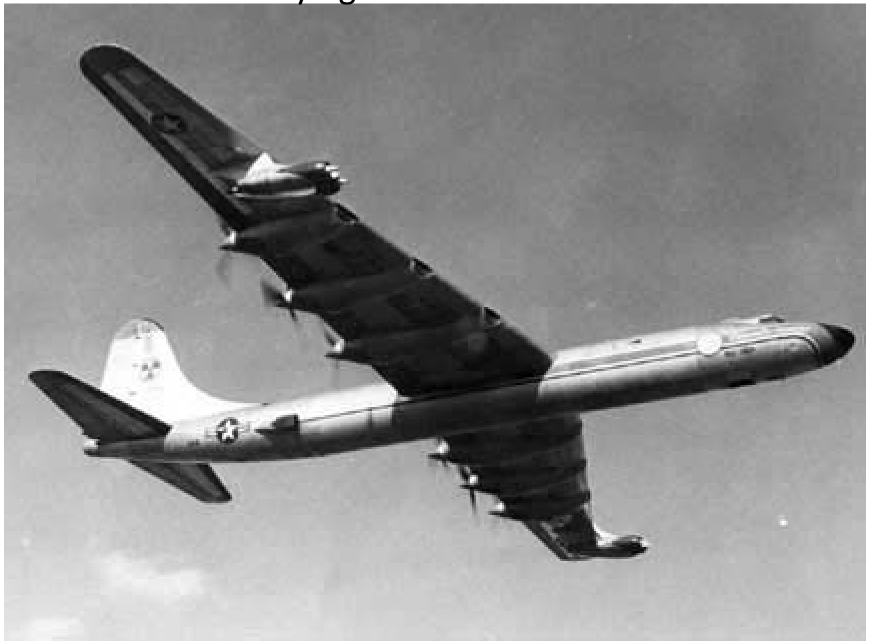
USS *Nimitz* (CVN 68)	
Funding authorized	Fiscal Year 1966
Keel laid	June 22, 1968
Launched	May 13, 1972
Commissioned	May 3, 1975
Nickname	*Old Salt*

Nimitz-class carriers

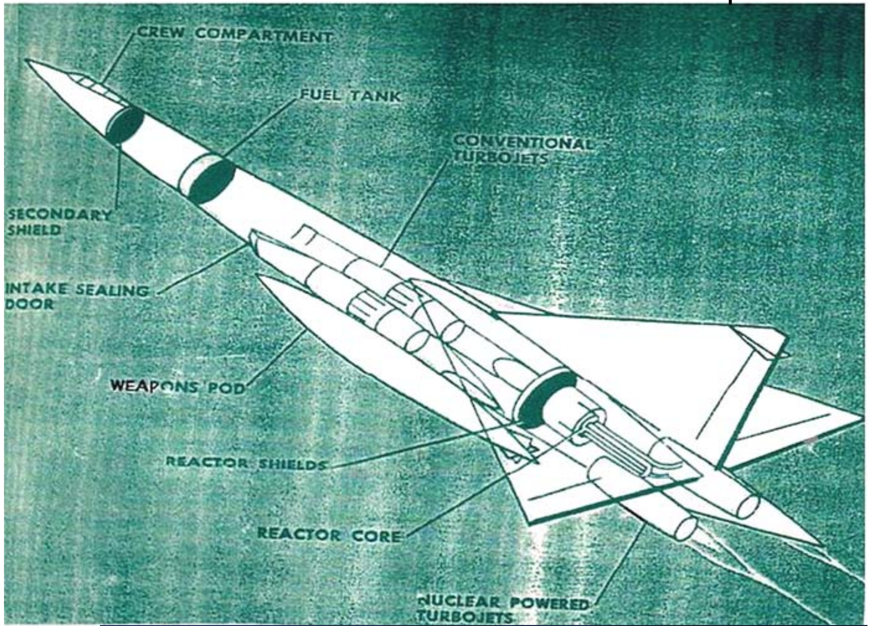
- The powerplant for the *Nimitz-class carriers is located on the Fourth Deck* and is under heavy security.
- Although the details of their powerplants are largely classified, the *Nimitz-class carriers are powered by two Westinghouse* A4W reactors, each providing enough steam to generate between 104 and 194 Mwe (140,000 and 260,000 shp).
- The reactor cores for *Nimitz and Dwight D. Eisenhower are estimated to have an operational life of 13 years, with* those for *Vinson and the remaining class carriers estimated at 15 years.*
- The A4W reactors heat pressurized water, which in turn heats a separate water loop and turns it into high-temperature, high-pressure steam. The steam drives the ship’s four main-propulsion turbines, generators, and auxiliary machinery, and also provides steam for the four catapults.
- The Nimitz-class carriers displace between 95,000 and 104,000 tons (86,182 and 94,347 tonnes), fully loaded, depending on which carrier one views.
- *Nimitz-class* carriers are officially listed as having a top speed of 30 knots (56km/h), but its true speed remains classified.
- A typical Nimitz-class carrier has a ship’s company of approximately 3,200 personnel and another 2,480 in the air wing.

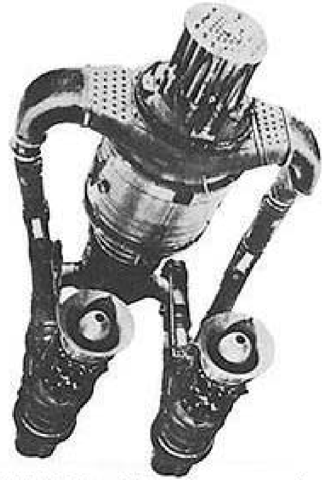
July 1955; First flight of the Convair X-6 with a 3 MW thermal air cooled reactor. The reactor is not propulsive, but only for airborne shielding tests.

Convair X-6 Flying reactor test bed



WS-125 Nuclear Powered bomber concept





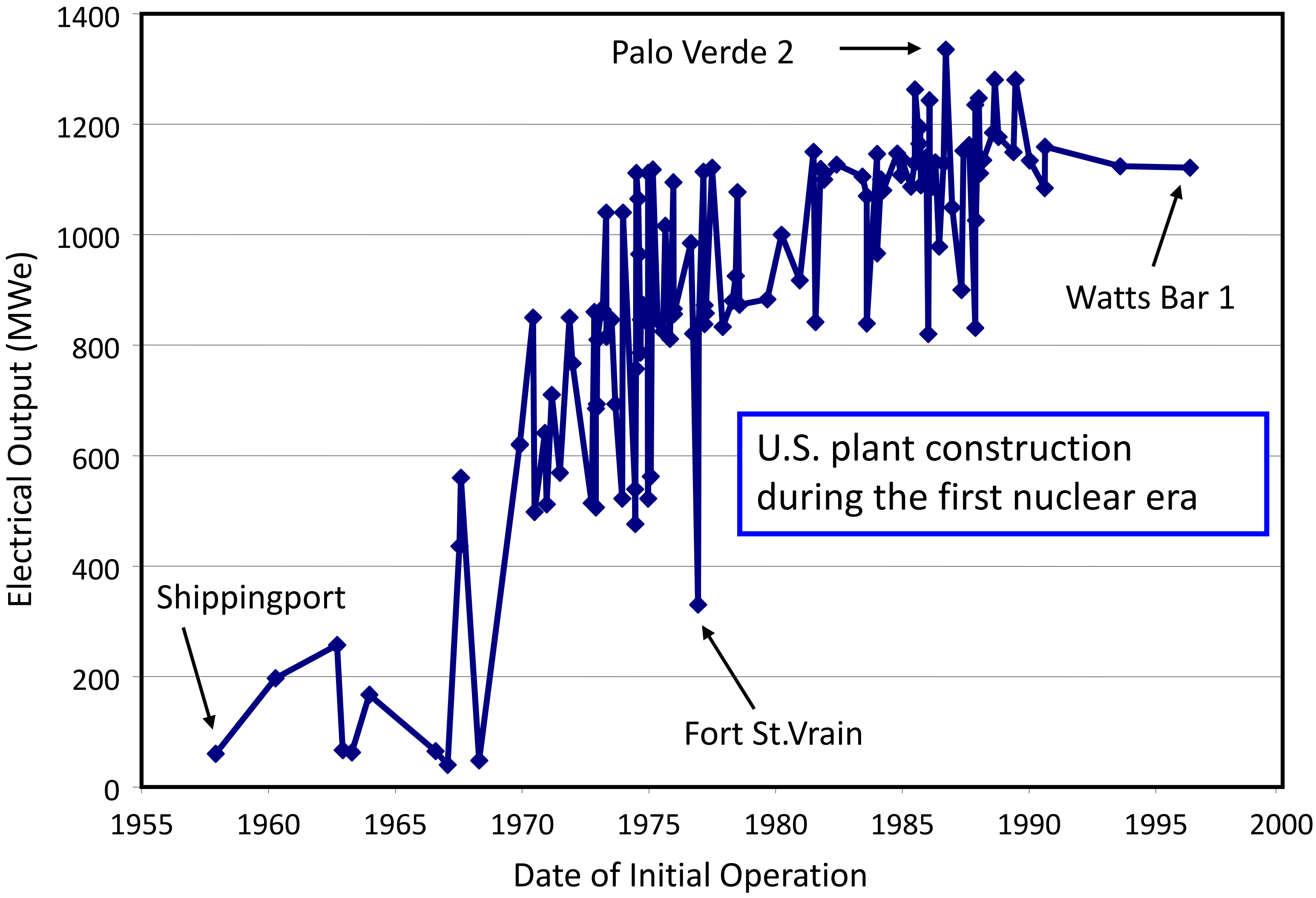
The HTRE-3 without supporting structure.

Left: The HTRE-3 reactor showing the relation of the turbines to the reactor.

Right: The HTRE-3 reactor – turbine test stand. *(Yes it worked!)*

HTRE-3

The U.S. Initially Built Smaller Sized Commercial Nuclear Power Plants



Weinberg Study (1985) Introduced the Notion of Smaller, Simpler, Safer Reactors

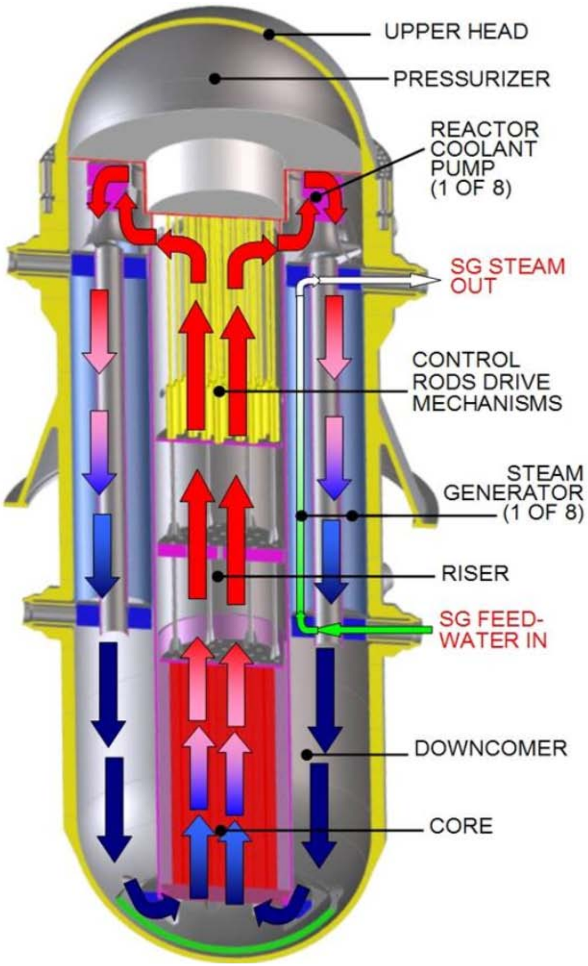
- Motivated by lessons learned from the *first nuclear era*
- Explored emerging reactor designs that were inherently more forgiving than large LWRs
- Main findings:
  - Incrementally-improved, post-TMI LWRs pose very low risks to the public but investor risks and high, uncertain capital cost may limit market viability
  - Large LWRs are too complex and sensitive to transients
  - Inherently safe concepts are possible and should be pursued, such as:
    - The Process Inherent Ultimately Safe (PIUS) reactor
    - The Modular High-Temperature Gas-Cooled Reactor (MHTGR)

*A. M. Weinberg, et al, *The Second Nuclear Era*, Praeger Publishers, 1985

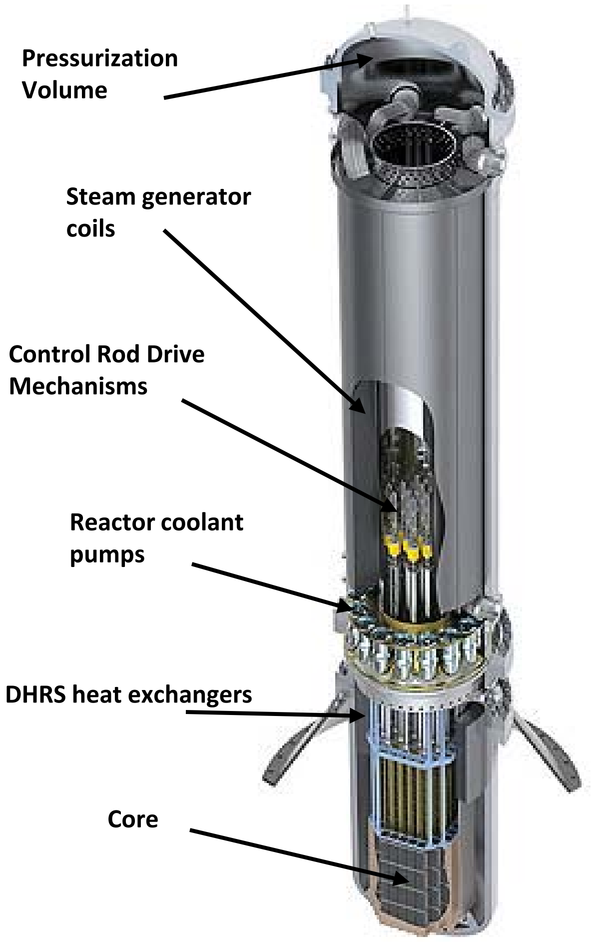
Sampling of SMR Concepts Under Development World-Wide

- Integral PWR: CAREM (Ar), IMR (Jp), IRIS (US), NuScale (US), mPower (US), SCOR (Fr), SMART (RoK)
- Marine derivative PWR: ABV (RF), KLT-40S (RF), NP-300 (Fr), VBER-300 (RF)
- BWR/PHWR: AHWR (In), CCR (Jp), MARS (It)
- Gas-cooled: GT-HTR-300 (Jp), GT-MHR (US), HTR-PM (Ch), PBMR (SA)
- Sodium-cooled: 4S (Jp), BN-GT-300 (RF), KALIMER (RoK), PRISM (US), RAPID (Jp)
- Lead/Pb-Bi-cooled: BREST (RF), ENHS (US), LSPR (Jp), STAR/SSTAR (US), SVBR-75/100 (RF)
- Non-conventional: AHTR (US), CHTR (In), Hyperion (US), MARS (RF), MSR-FUJI (Jp), TWR (US)

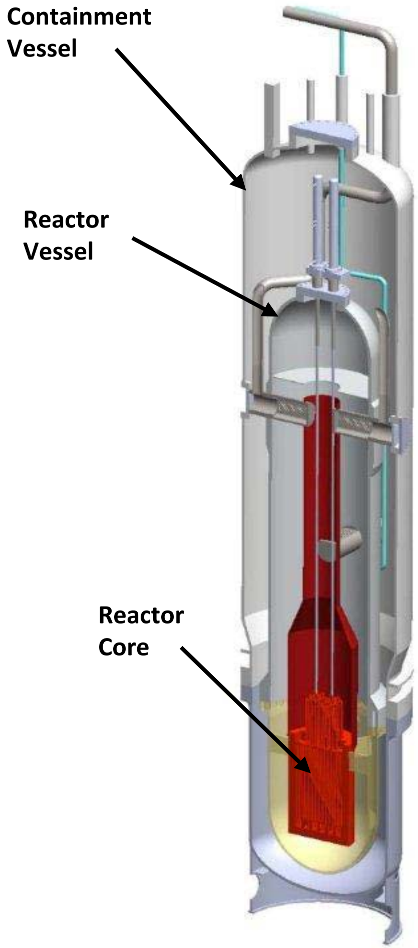
LWR-Based SMR Designs Under Development in U.S.



IRIS (Westinghouse)



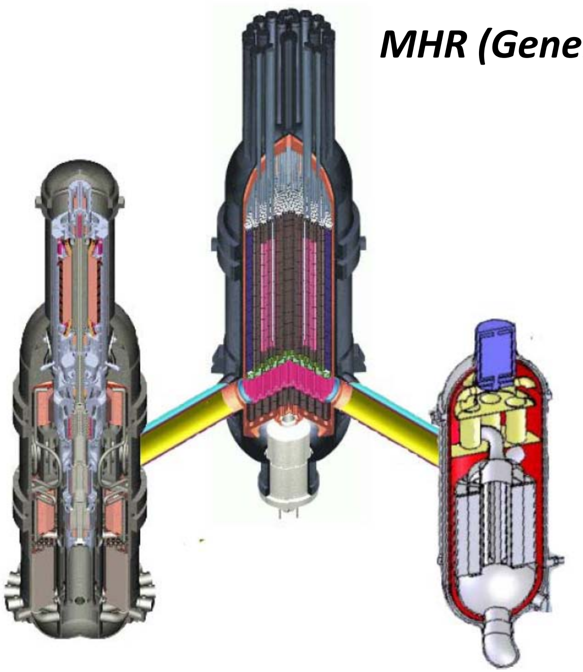
mPower (Babcock & Wilcox)



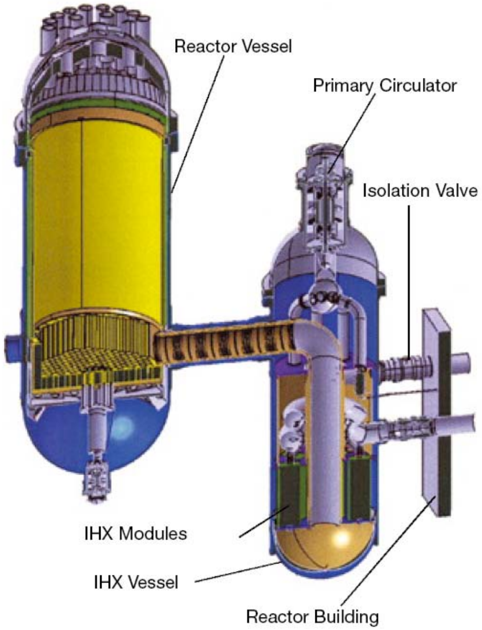
NuScale (NuScale)

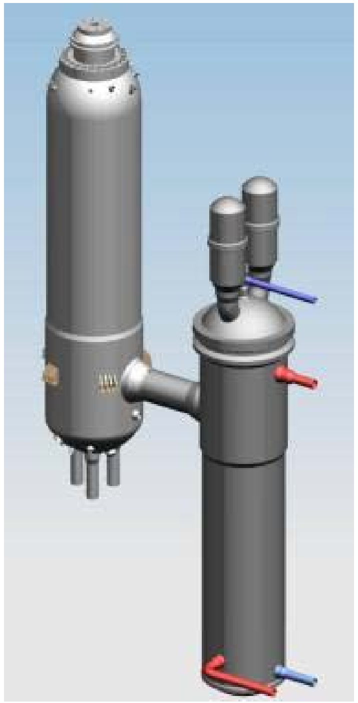
Gas-Cooled SMRs (NGNP options)

MHR (General Atomics)



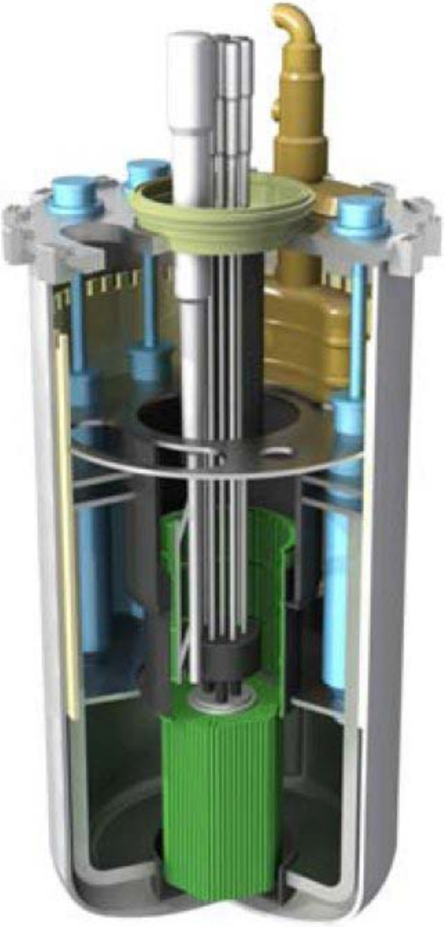
ANTARES (Areva)



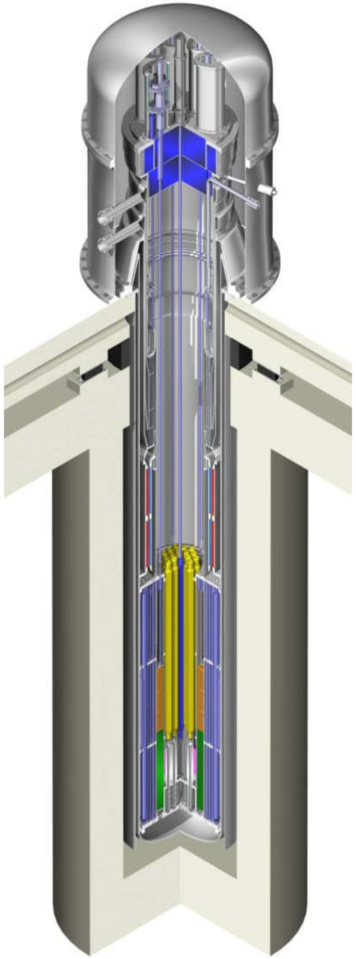


PBMR (Westinghouse)

Liquid-Metal-Cooled SMRs



PRISM (General Electric)



4S (Toshiba/W)

HPM (Hyperion)

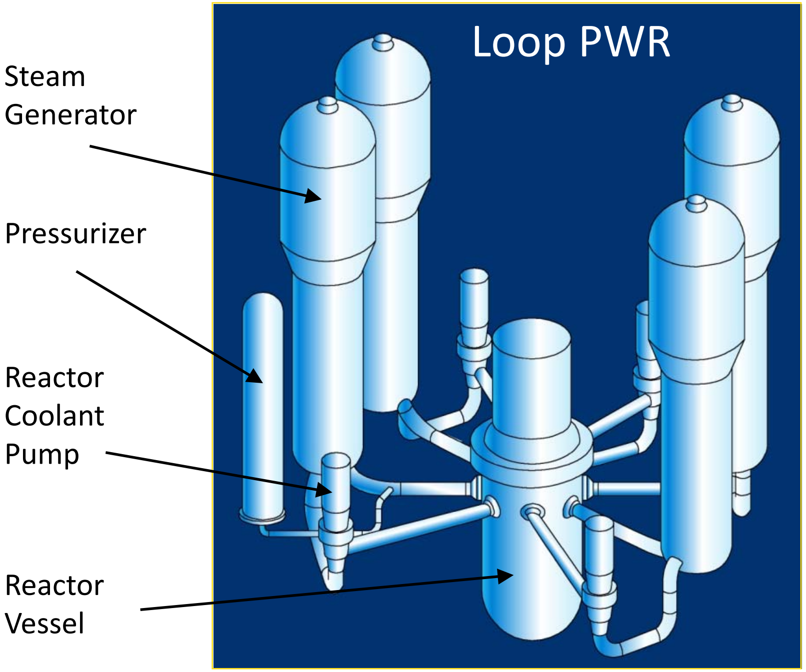
Interest in Smaller Sized Reactor Designs Are Beginning To (Re)Emerge

- Benefits
  - Cheaper (capital outlay)
  - Improved fabrication and construction logistics (especially domestic)
  - Enhanced safety (robustness)
  - Operational flexibilities (broader applications)
- Applications
  - Smaller utilities
  - Countries with financing or infrastructure constraints
  - Distributed power needs (e.g. military base islanding)
  - Non-electrical (process heat) customers

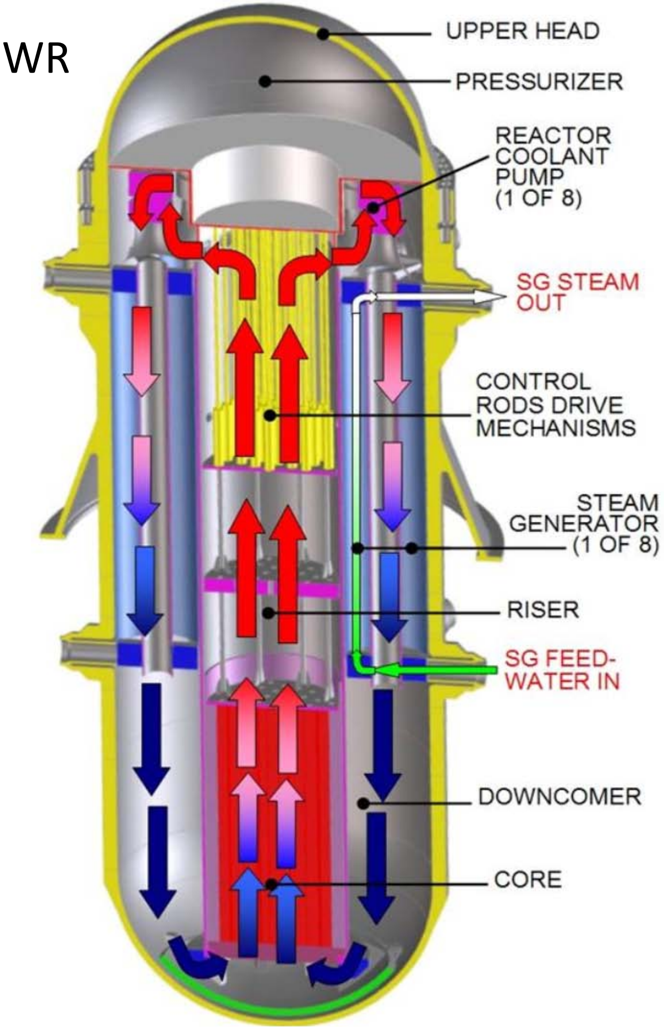
Safety Benefits of DSRs

- Reduced source term
  - Lower power means fewer fission products produced
  - Can allow for increased margin, or reduced shielding, site radius, emergency planning zone, etc.
- Improved decay heat removal
  - Lower decay heat generated in the reactor core
  - More efficient passive decay heat removal from reactor vessel (volume-to-surface area ratio effect)
- Elimination of accident initiators (e.g., integral designs)
  - No large pipes in primary circuit means no large-break loss-of-coolant accidents
  - Increased water inventory means slower system response to power transients

Integral Primary System Configuration



Integral PWR



- Enhances robustness by eliminating major classes of accidents (e.g., large pipe break).
- Simplifies design by eliminating unneeded safety systems, large piping and external vessels.
- Allows for compact containment (small plant footprint) to enhance economics and security.

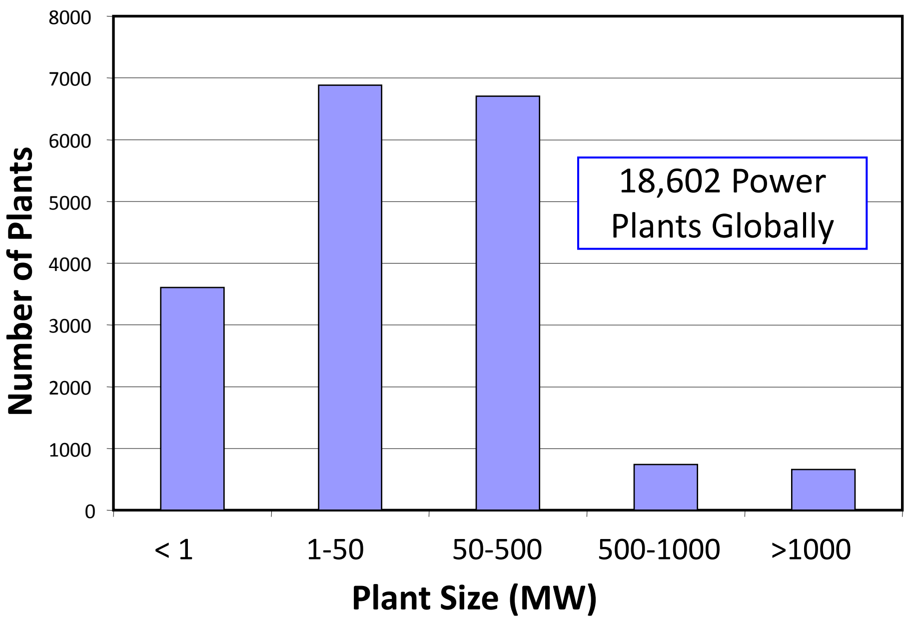
Fabrication and Construction Benefits

- Physically smaller components
  - Eliminate or reduce number of large forgings
  - More in-factory fabrication; less site-assembly
    - Reduces schedule uncertainty
    - Improves safety
    - Reduces cost (as much as 8-fold)
  - Reduce size and weight for easier transport to site
    - Access to a greater number of sites
    - Well suited for remote or undeveloped sites
- Smaller plant footprint
  - Place nuclear system further below grade to improve resistance to external events and sabotage

Operational Flexibilities

- Site selection
  - Potentially reduced emergency planning zone
  - Use of seismic isolators
  - Lower water usage
- Load demand
  - Better match to power needs for many non-electrical applications
- Grid stability
  - Closer match to traditional power generators
  - Smaller fraction of total grid capacity
- **Demand growth**
  - **Ability to add (and pay for) capacity as demand dictates**

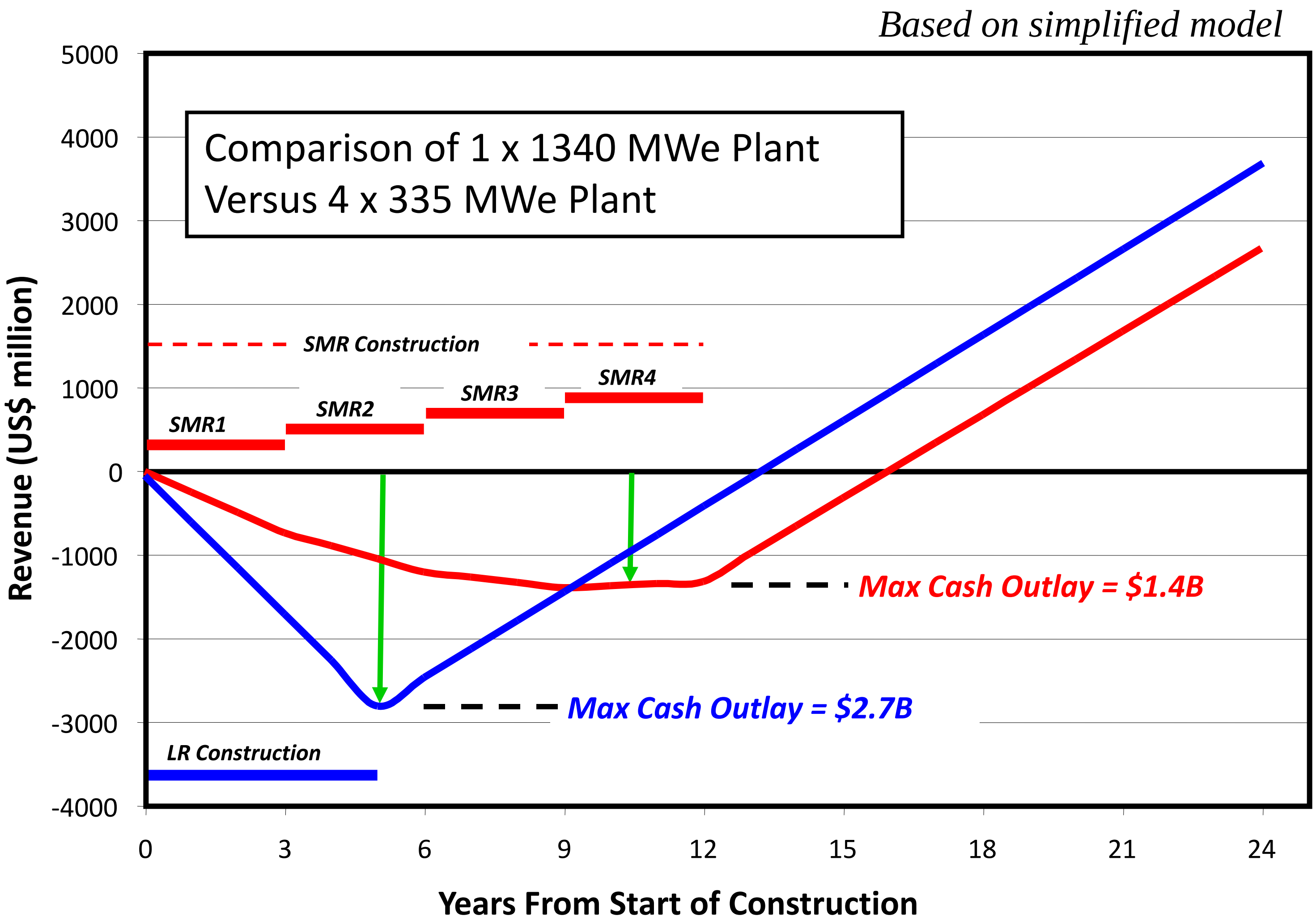
93% of all generating units in the world have capacities < 500 MWe



Economic Benefits

- Total project cost
  - Smaller plants should be cheaper
  - Improves financing options and lowers financing cost
  - May be the driving consideration in some circumstances
- Cost of electricity
  - Economy-of-scale (EOS) works against smaller plants but can be mitigated by other economic factors
    - Accelerated learning, shared infrastructure, design simplification, factory replication
- Investment risk
  - Maximum cash outlay is lower and more predictable
  - Maximum cash outlay can be lower even for the same generating capacity

Staggered Build of SMRs Reduces Maximum Cash Outlay (*Source: B. Petrovic, GaTech*)



Economy-of-Scale Is Only One Of Many Economic Factors To Consider

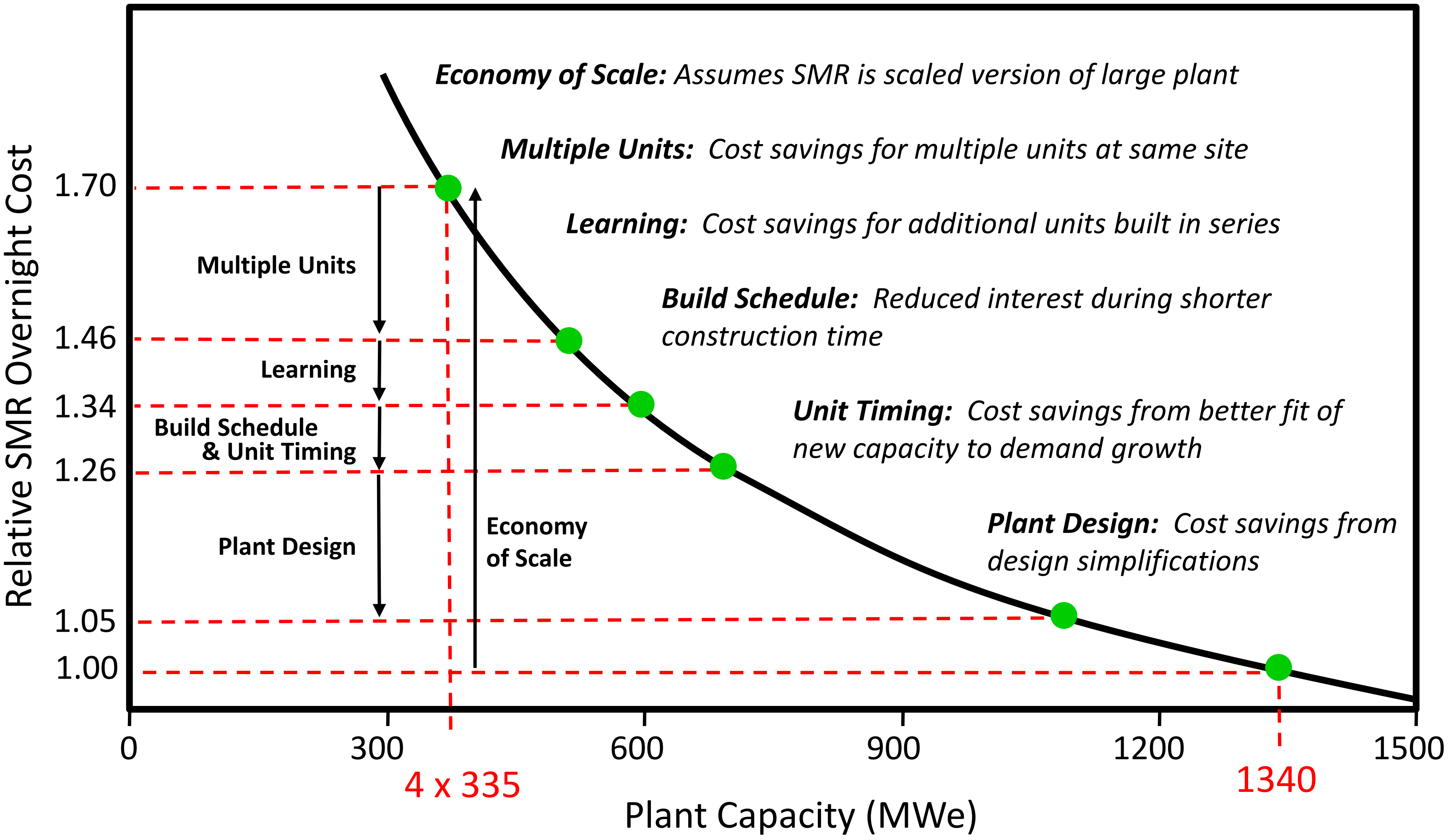
Example: the family car

A bus offers the lowest transportation cost per person

But…

- ***More capacity than needed***
- ***Very costly to purchase***
- ***Very costly to operate and maintain***
- ***Too big for the garage***

Factors Offsetting the Economy of Scale Penalty (Source: C. Mycoff, WEC)



Economy of Scale: *Assumes SMR is scaled version of large plant*

Multiple Units: *Cost savings for multiple units at same site*

Learning: *Cost savings for additional units built in series*

Build Schedule: *Reduced interest during shorter construction time*

Unit Timing: *Cost savings from better fit of new capacity to demand growth*

Plant Design: *Cost savings from design simplifications*

SMR Applications

- Electricity generation
  - Smaller utilities with low demand growth
  - Regions/countries with small grid capacity
  - Installations requiring independent power
  - Non-baseload possibilities
- Non-electrical power needs
  - Potable water production (desalinations)
  - Advanced oil recovery for tar sands and oil shale
  - Hydrogen production
  - Advanced energy conversion such as coal-to-liquids conversion or synfuels
  - District heating

SMR Challenges – Technical

- All designs have some degree of innovation in components, systems, and engineering, e.g.
  - Integral primary system configuration
  - Internal control rod drive mechanisms and pumps
  - Multiplexed control systems/interface
- Longer-term systems strive for increased utility/security
  - Long-lived fuels and materials for extended operation
  - Advanced designs for load-following and co-generation
- Sensors, instrumentation and controls development are likely needed for all designs
  - Power and flow monitoring in integral systems
  - Advance prognostics and diagnostics for remote operations
  - Control systems for co-generation plants

SMR Challenges – Institutional

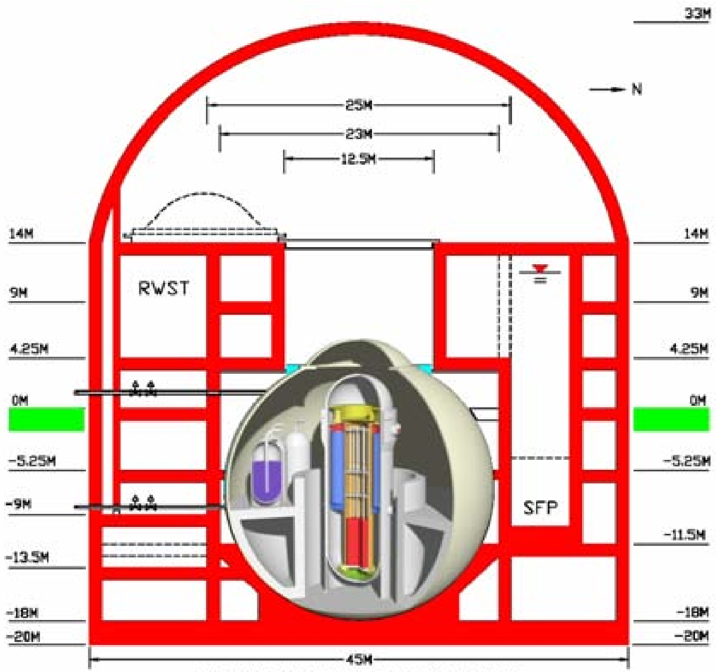
- Too many competing designs
- Mindset for large, centralized plants
  - Fixation on economy-of-scale
  - Economy-of-hassle drivers
  - Perceived risk factors for nuclear plants
- Traditional focus of regulators on large, LWR plants
  - Standard 10-mile radius EPZ (in the U.S.)
  - Staffing and security force size
  - Plant vs module licensing
- Fear of first-of-a-kind
  - New business model as well as new design must be compelling

Summary

- The U.S. started commercial nuclear power using smaller sized plants
- After initial experience with small units, plant size and complexity grew rapidly
- New SMRs offer many potential benefits
- SMRs do not compete directly with large plants—they offer customers a greater range of options

IRIS – International Reactor Innovative and Secure

- Advanced integral light water reactor
- 335 MWe/module
- Innovative, simple design
- Enhanced Safety-by-Design™
- International team
- Recognized by Global Nuclear Energy Partnership (GNEP) as Grid Appropriate Reactor
- Anticipated competitive economics
- Cogeneration (desalination, district heating, bio-fuel)
- NRC pre-application underway
- Design Certification testing program underway
- Interest expressed by several countries
- Projected deployment target: 2015 to 2017

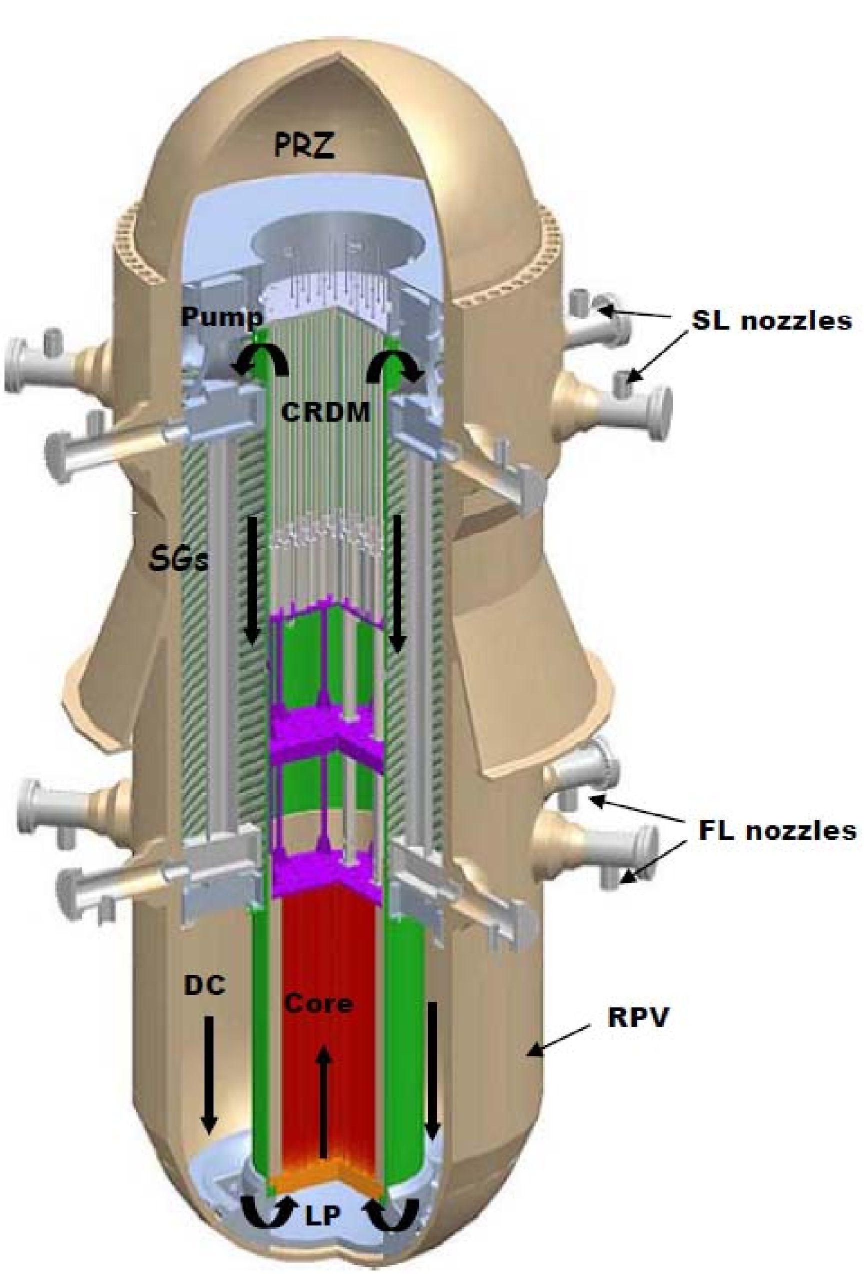


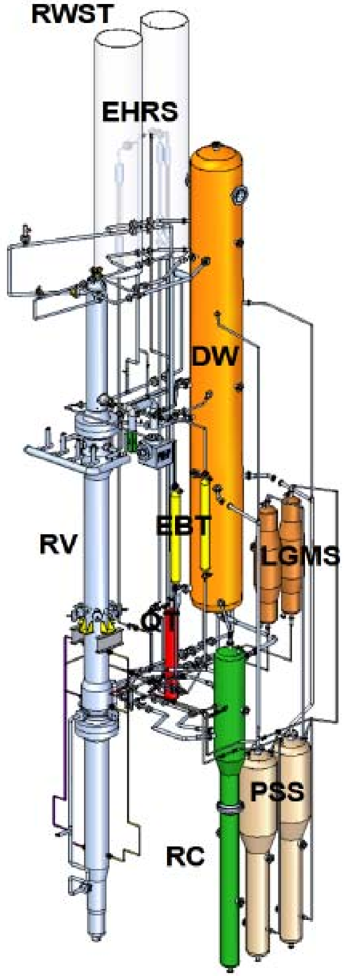
IRIS AUXILIARY BUILDING ELEVATION VIEW

The IRIS Team

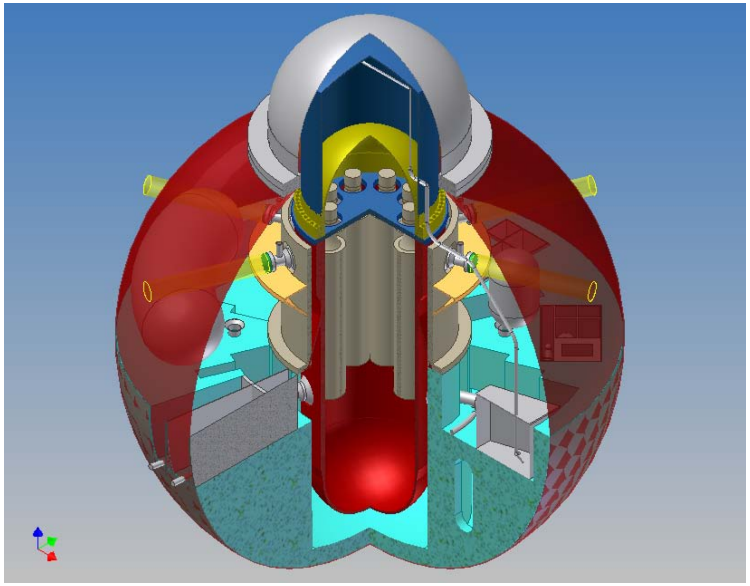
- 9 Countries
  - Brazil
  - Croatia
  - Italy
  - Japan
  - Lithuania
  - Mexico
  - Spain
  - United Kingdom
  - United States
- 18 Organizations
  - Industry
  - Power Producers
  - Laboratories
  - Universities

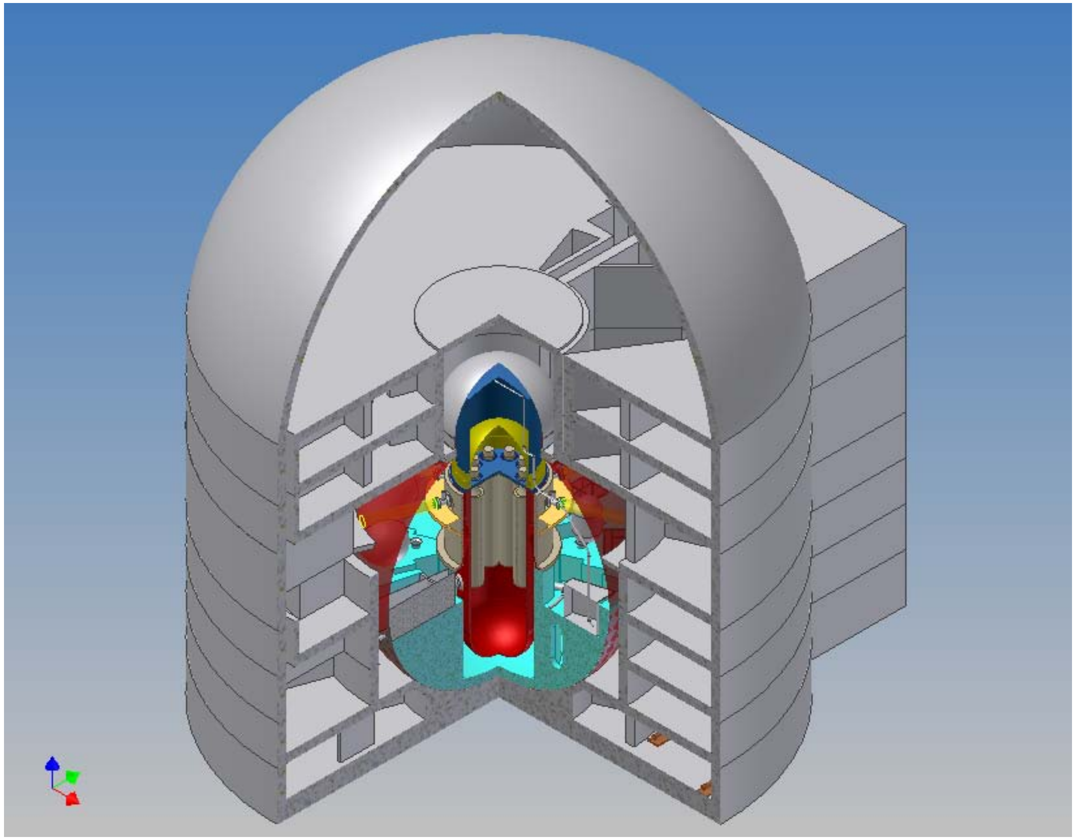
IRIS Integral layout
SPES-3 facility





IRIS containmnet and building



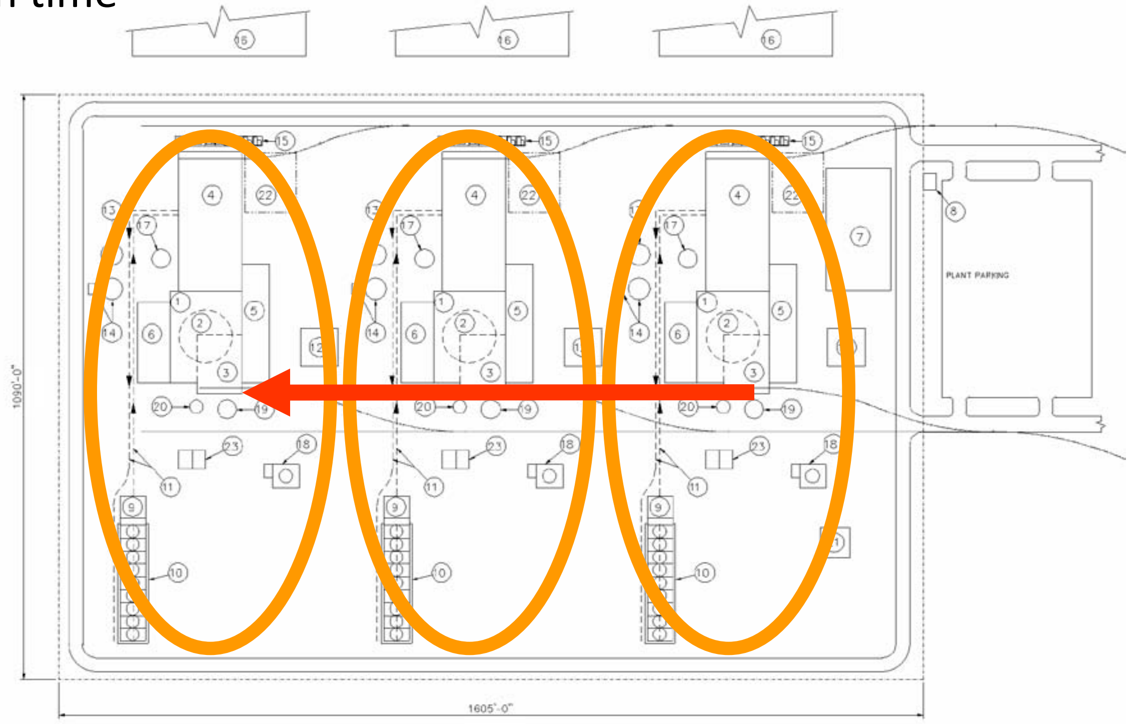


IRIS Plant Layout

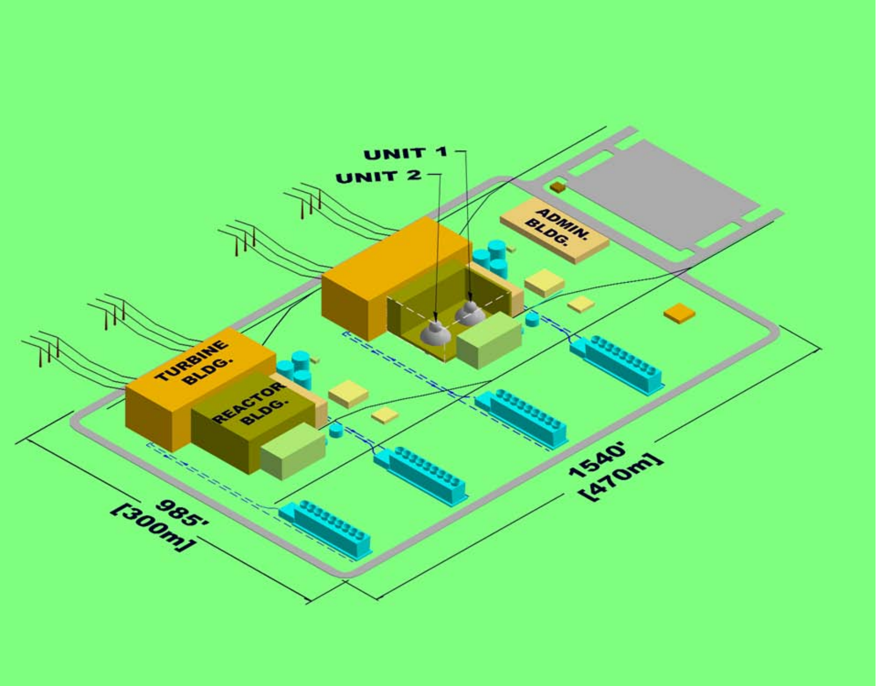
- Developed in response to US utilities as part of the Early Site Permit Program
- Basic configurations:
  - Single module (335 MWe)
  - Twin units (670 MWe)
  - Offered individually or in multiples
- For utilities requiring at least 1000 MWe, IRIS offers three single modules or two twin units
- For better growth match (and spin reserve), smaller power increments from multiple units will be more practical

IRIS - Multiple Single Unit Site Plot Plan

- Shared structures and systems are minimized
- Units constructed in “slide-along” manner with first unit(s) put into operation while subsequent unit(s) under construction
- Compact footprint (330m-by-480m site for 3 modules, 1005 MWe)
- Minimizes construction time and provides generating capability ASAP
- Maximizes workforce efficiency and significantly shortens 2nd and 3rd unit construction time



IRIS – Site Plot Arrangement Example

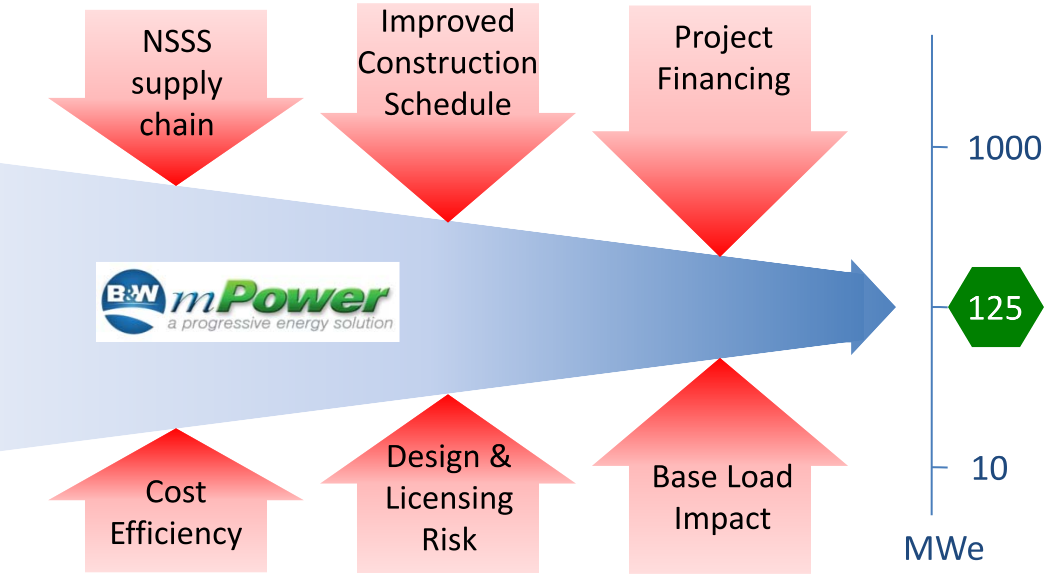


Multiple twin-units
(2 twin-units, 1340 MWe)

B&W mPower

- 125 MWe integral modular LWR (PWR) reactor
- Well known reactor/power components vendor

The Drivers Behind a Modular Reactor



NSSS supply chain

Improved Construction Schedule

Project Financing

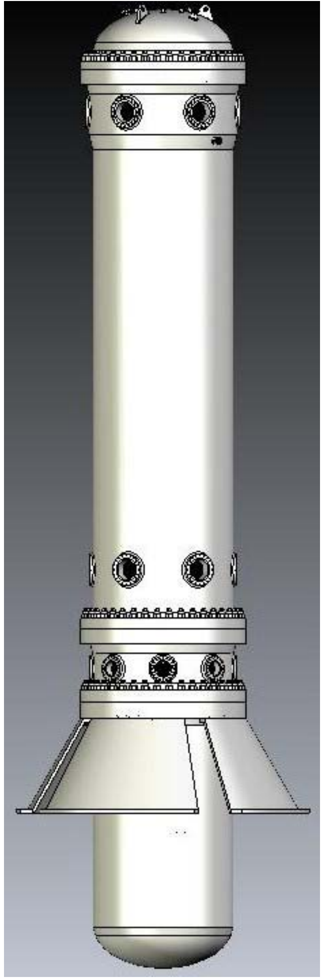
Cost Efficiency

Design & Licensing Risk

Base Load Impact

Real-world issues are shaping the optimal size.

Solution: B&W's *mPower*™ Reactor Modular Approach



- **Flexible and scalable to customer requirements**
  - Integrated reactor modules
  - 100 percent shop manufactured
  - Multi-unit (1-10+) plant
  - Rail-shippable

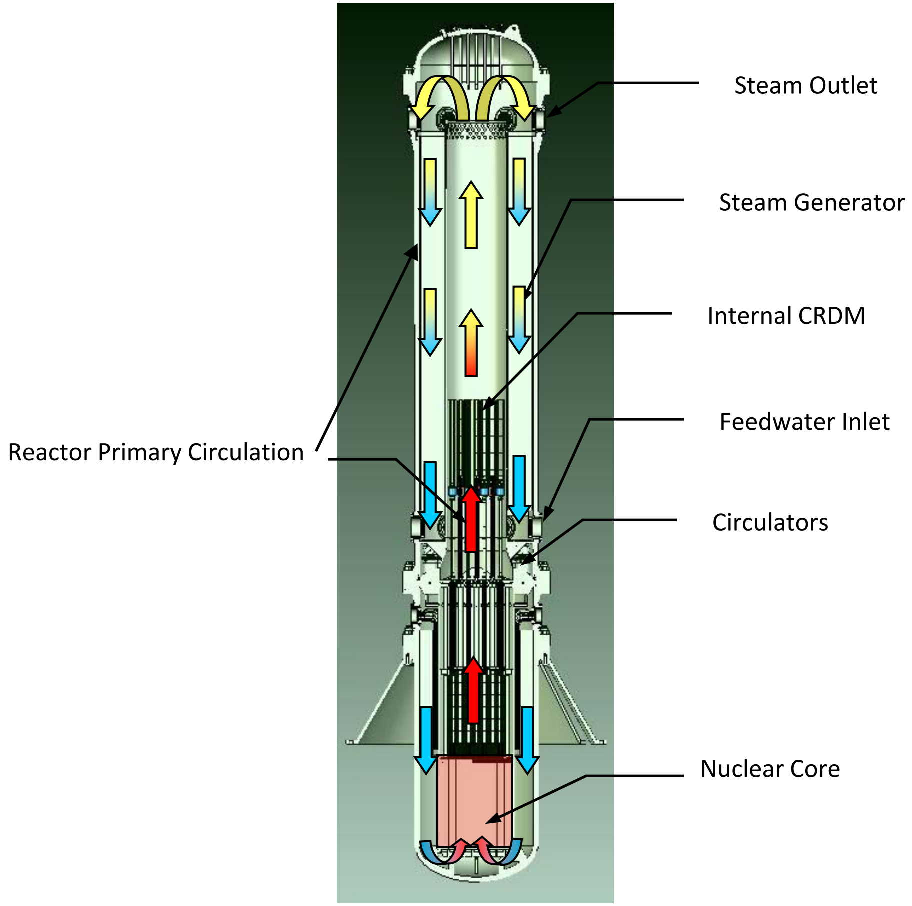
- **Reduced licensing risk, construction cost, & schedule**
  - Evolved PWR-type concepts
  - No on-site NSSS construction
  - Passive safety
  - Three years to start-up

- **Integrated and simplified NSSS with fewer components**
  - Internal helical coil SG
  - No external pressurizer
  - No need for safety-grade backup power
  - Conventional core and standard fuel

- **Simplified operations and maintenance**
  - Four plus-year core design
  - Standardized BOP
  - Sequential partial-plant outages

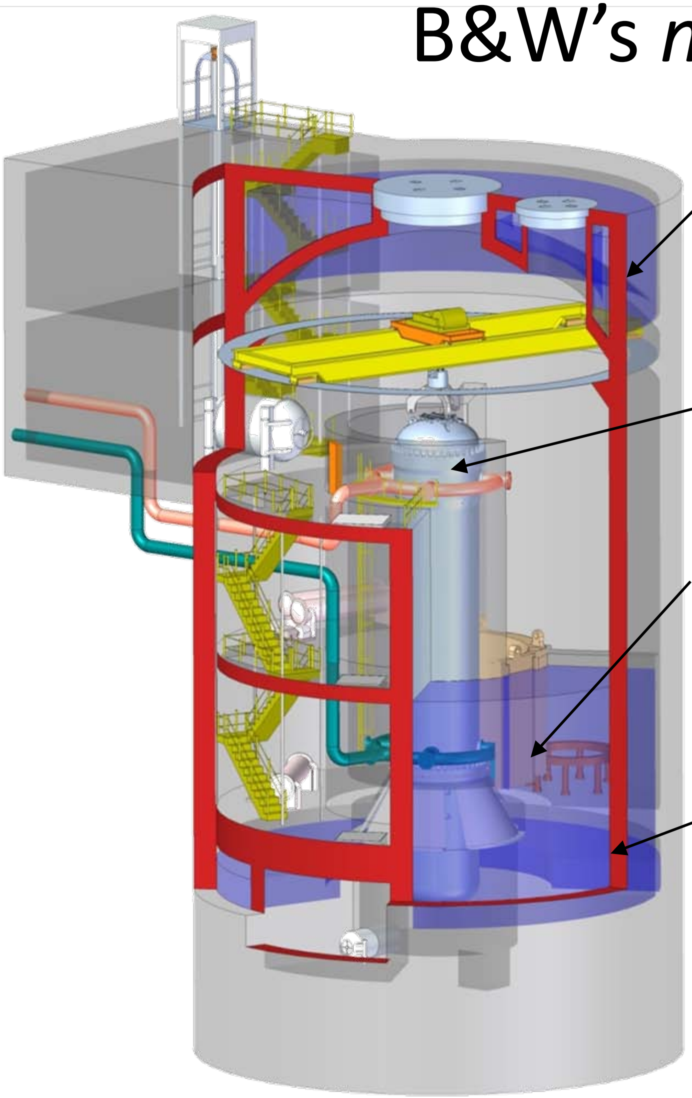
Lower risk and cost solution…

B&W's *mPower* Reactor



- **125 Mwe integral reactor**
- **Internal steam generator**
- **Standard PWR fuel**
- **Large primary coolant inventory**
- **SA508 RPV with SS clad**
- **Small penetrations into Primary Coolant System at TOP of RPV**
- **Diverse, redundant internal CRDMs**
- **No boron in primary coolant**

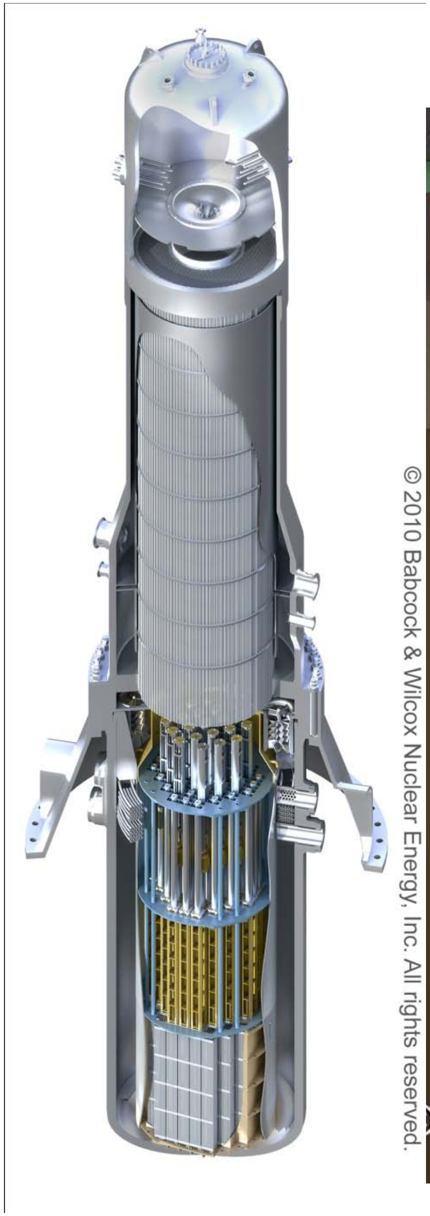
B&W's *mPower* Reactor Features



- **Underground containment**
- **Used fuel stored in spent fuel pool for life**
- **Natural circulation decay heat removal system for emergency/refueling cooling**
- **Primary coolant treatment system within containment**
- **Steam generator inspection within containment**

Independent, self contained modules

Single module in containment



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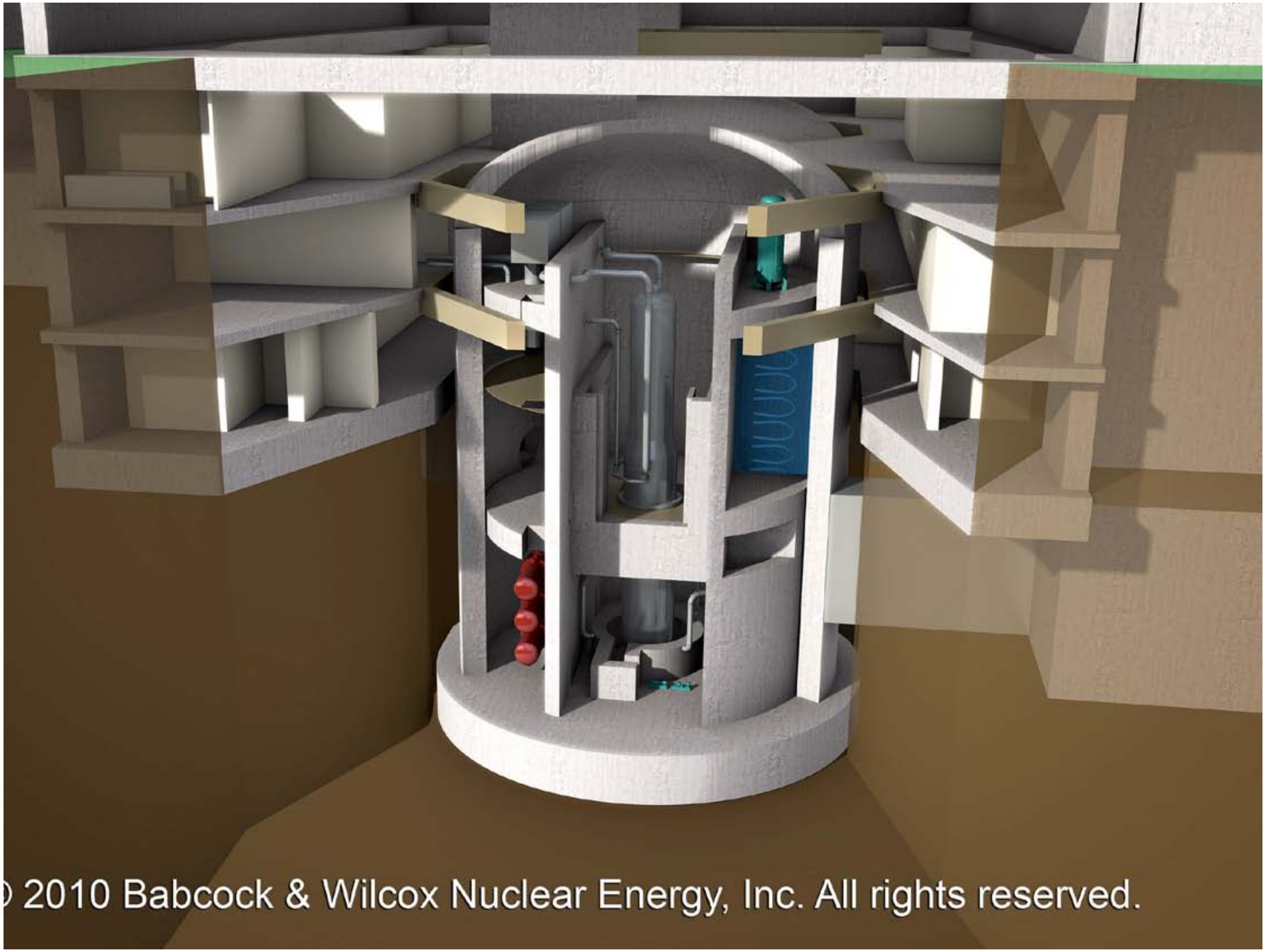

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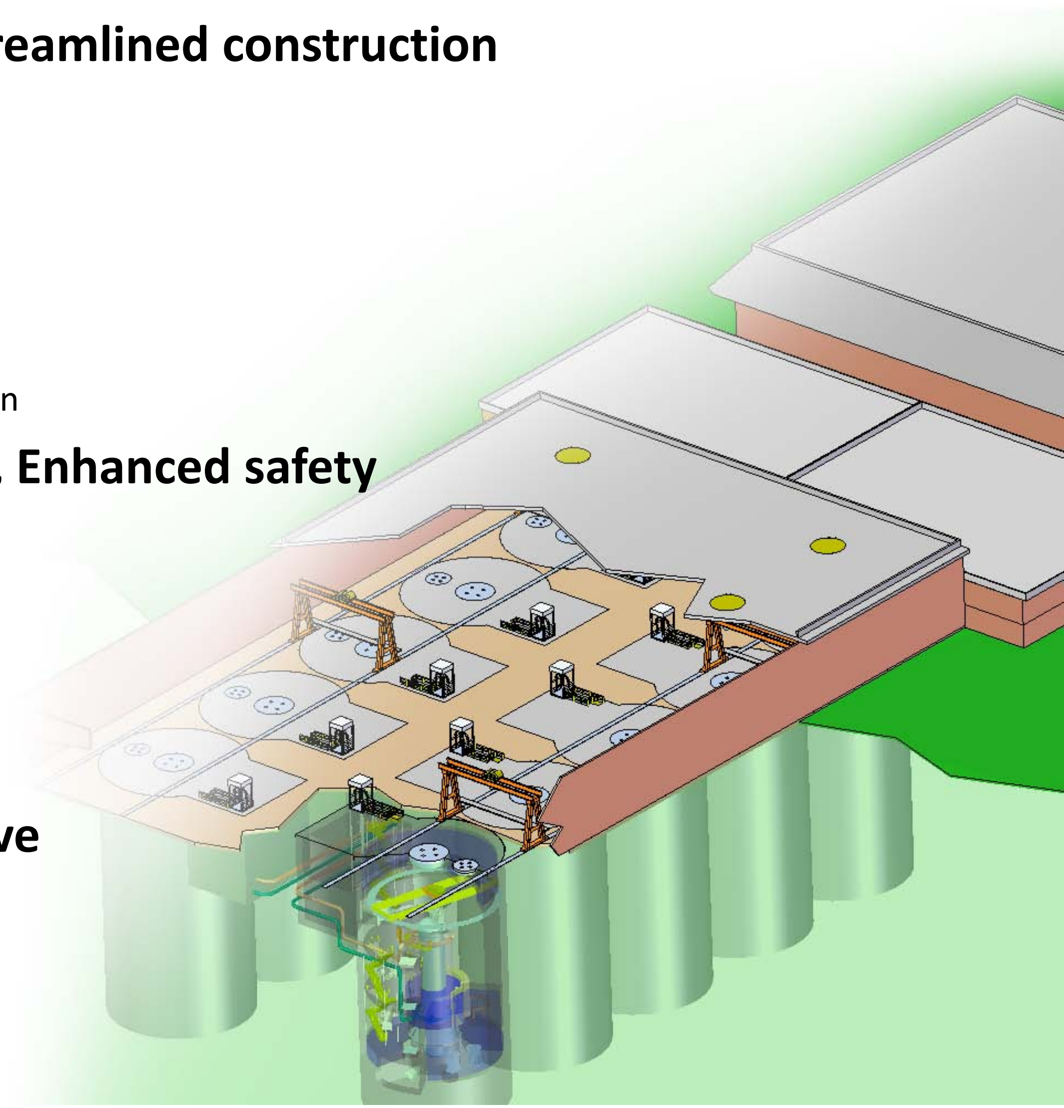
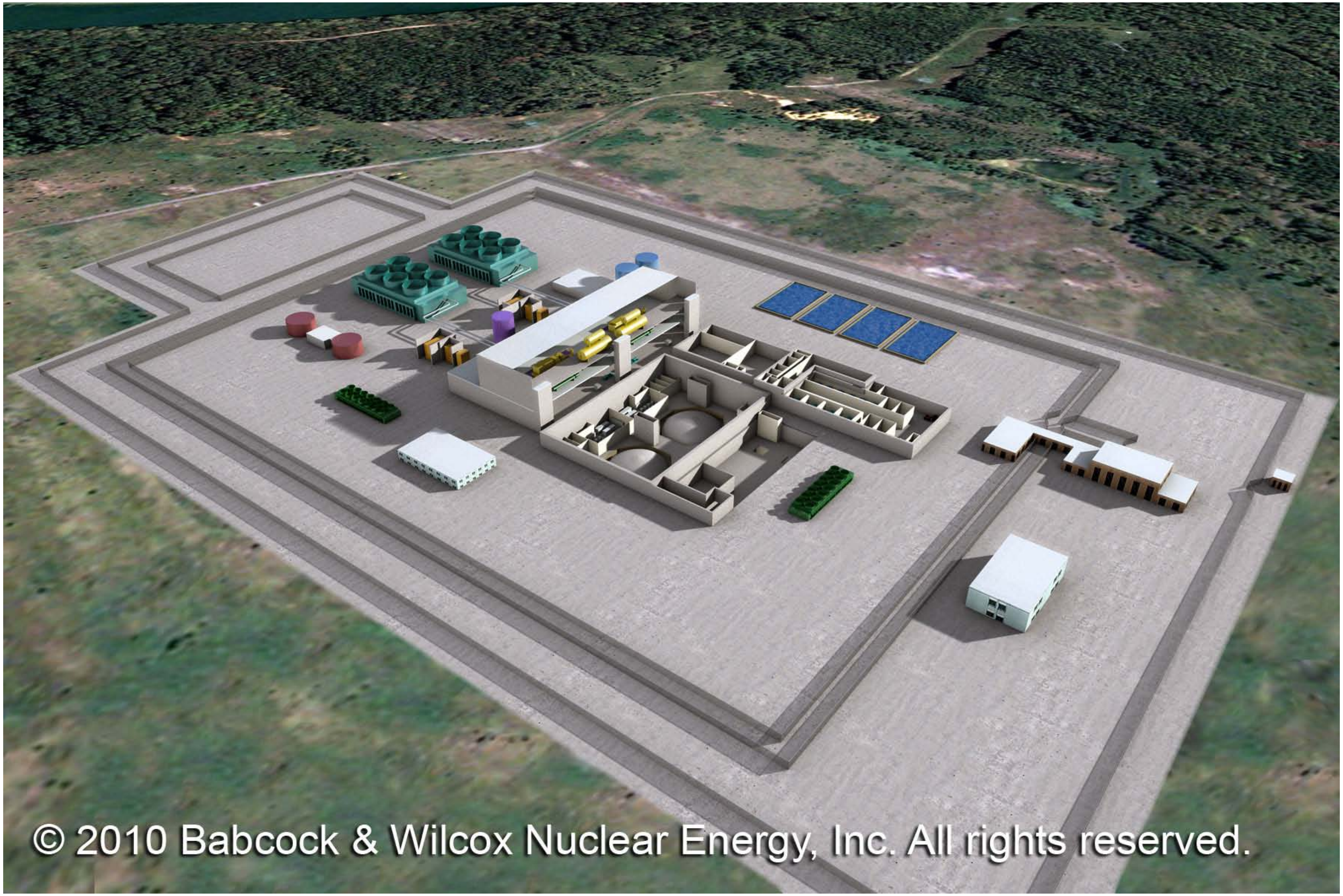
The B&W mPower Plant Design Features

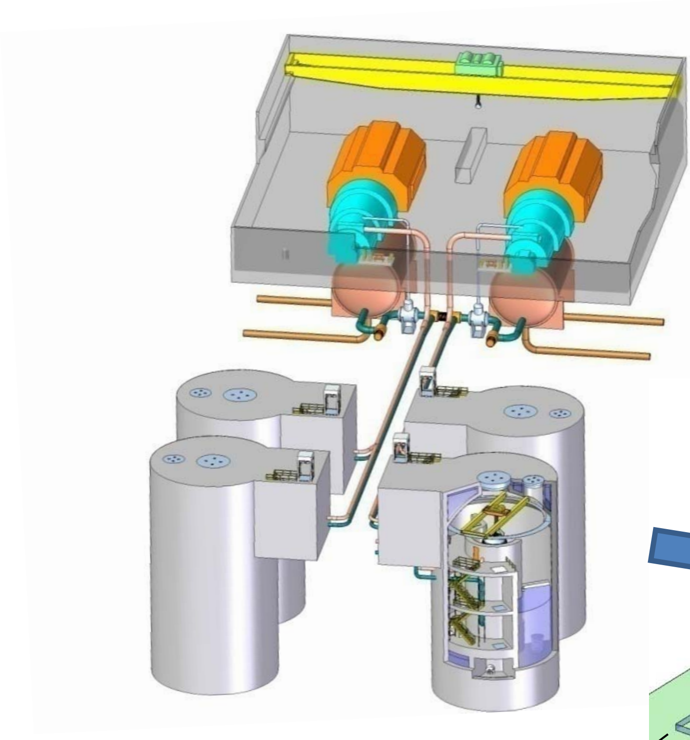
- **Prefabricated components, Streamlined construction**
  - NSSS
  - Steam turbine
  - Control room containment
- **Limited Module Interaction**
  - Independent controls
  - "Local" responses minimizes interaction
- **Underground reactor building, Enhanced safety**
  - Missile penetrations
  - Seismic advantages
  - Non-proliferation support
- **Reliable**
  - Sequential outages
- **Minimize options, Cost effective**
  - Condenser cooling (air or water)
  - Seismic design (2 zones?)
  - Number of modules

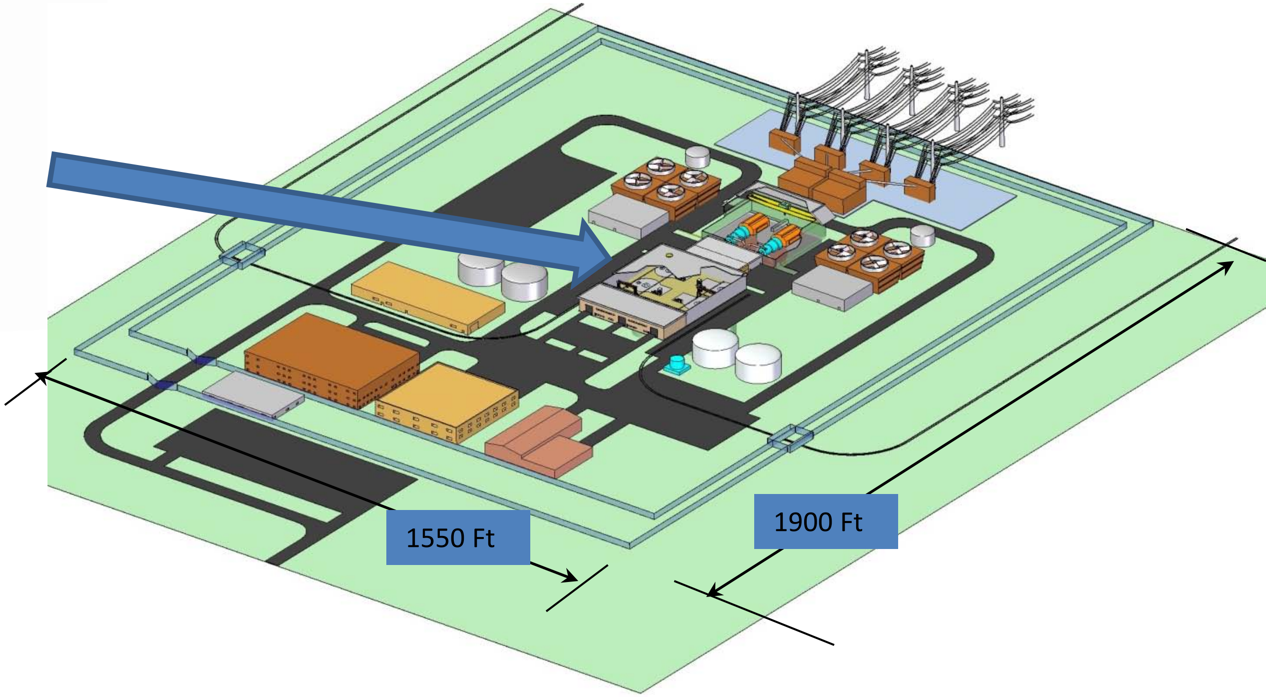


2 modules



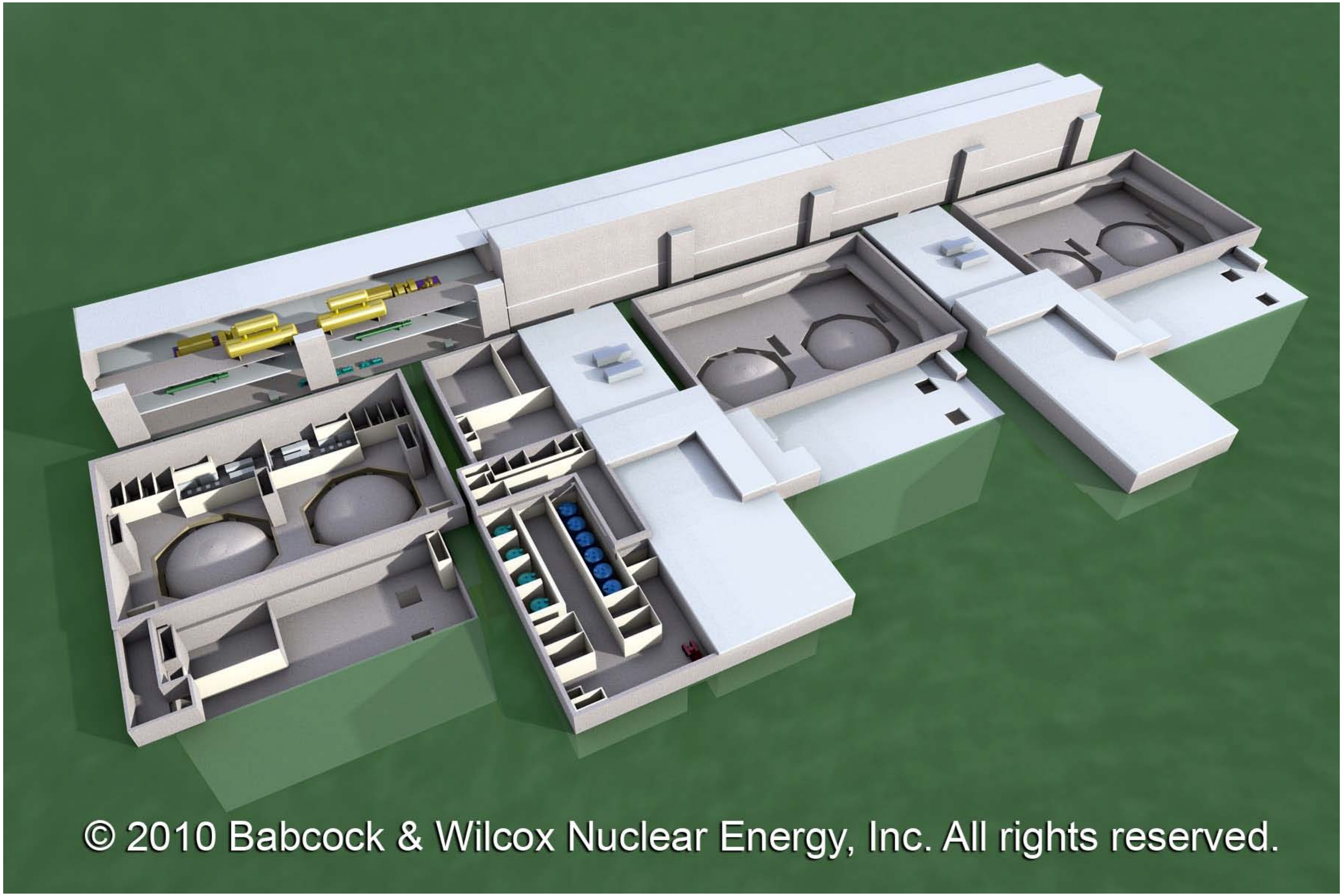
500 MWe Plant Using 125 MWe Modules





- *Compact footprint*
- *Self-contained*
- *Location flexibility*

6 modules



Adaptability to Government Installations

- Small compact standardized design
- Passively safe
- Scalable
- Long refueling cycle
  - 5+ years at <5% enriched U^{235}
  - ~10 years at <10% enriched U^{235}
- Built in the USA
  - Heavy forgings from Lehigh Heavy Forge
  - Component fabrication at B&W’s Mt. Vernon, Indiana facility
  - Fuel fabrication at B&W’s Lynchburg, VA facility
  - Modular construction techniques
  - Transportable size

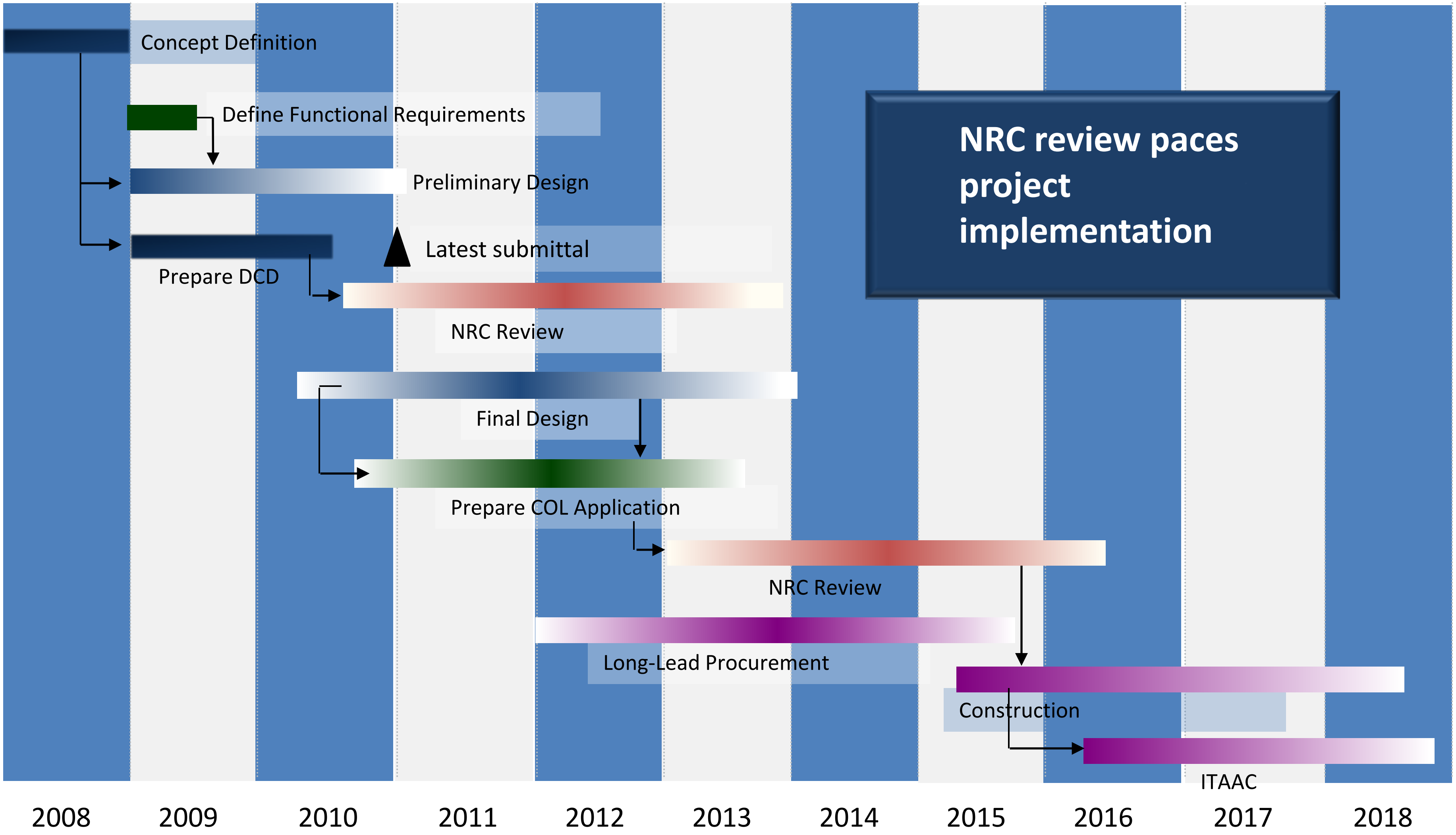
Adaptability to Government Installations

- Potential for Co-Generation
  - Steam
  - Desalination
  - Electrolysis for hydrogen and oxygen production
    - Fischer-Tropsch?
- Sell Excess Electricity to Secondary Market

Public-Private Partnerships

- To be Successful Program Must:
  - Select appropriate sites for reactor deployments
    - Critical missions
    - Strategic offensive and defensive capabilities
    - High energy costs and usage
      - Production tax credits and loan guarantees could make nuclear power more competitive at more sites
  - Develop a long-term land lease agreement (EUL?)
    - Win-Win arrangement for Air Force and commercial developer
  - Develop a long-term power purchase agreement
    - Mechanism for third-party financing
    - Minimizes market risks for initial units

First Plant Deployment



NRC review paces project implementation

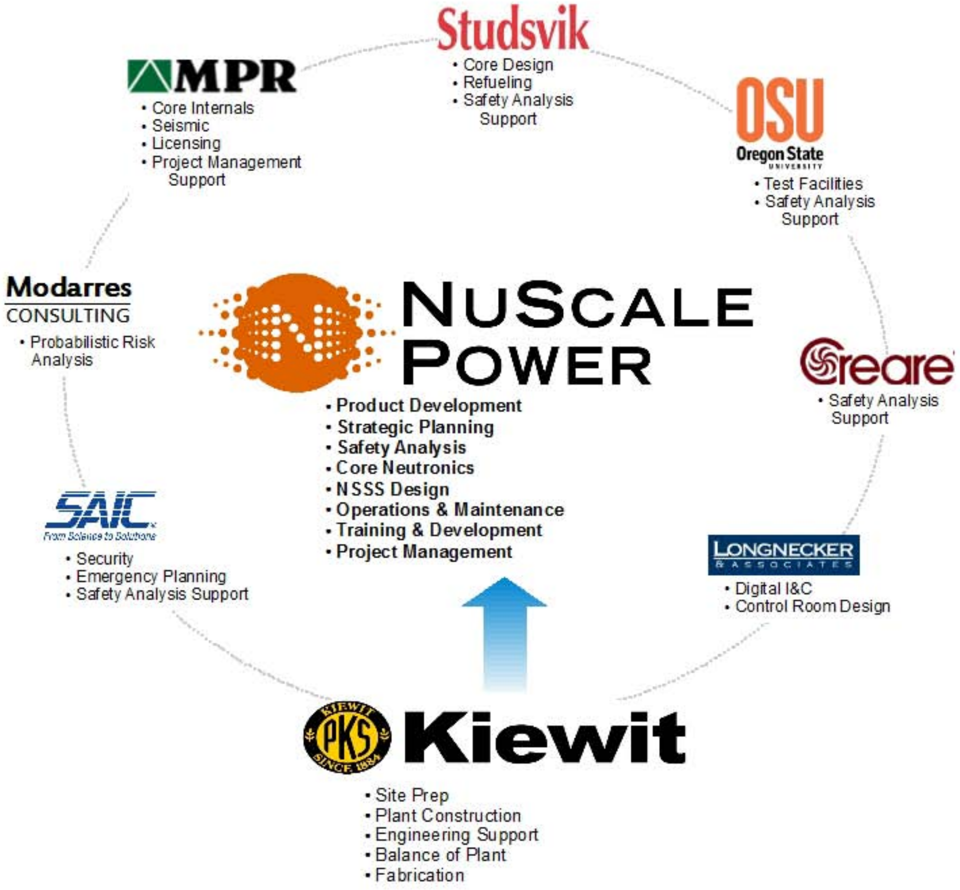
NuScale Power

- 45 MWe integral modular LWR (PWR) reactor
- New company with mixed types of organizations

The Team:

Best In Class” Industry Partners and Contractors

- In addition to Kiewit, NuScale is working with industry partners, contractors, and suppliers to build a first class product delivery team.



Studsvik
- Core Design
- Refueling
- Safety Analysis Support

OSU Oregon State University
- Test Facilities
- Safety Analysis Support

MPR
- Core Internals
- Seismic
- Licensing
- Project Management Support

Modarres Consulting
- Probabilistic Risk Analysis

NuScale Power
- Product Development
- Strategic Planning
- Safety Analysis
- Core Neutronics
- NSSS Design
- Operations & Maintenance
- Training & Development
- Project Management

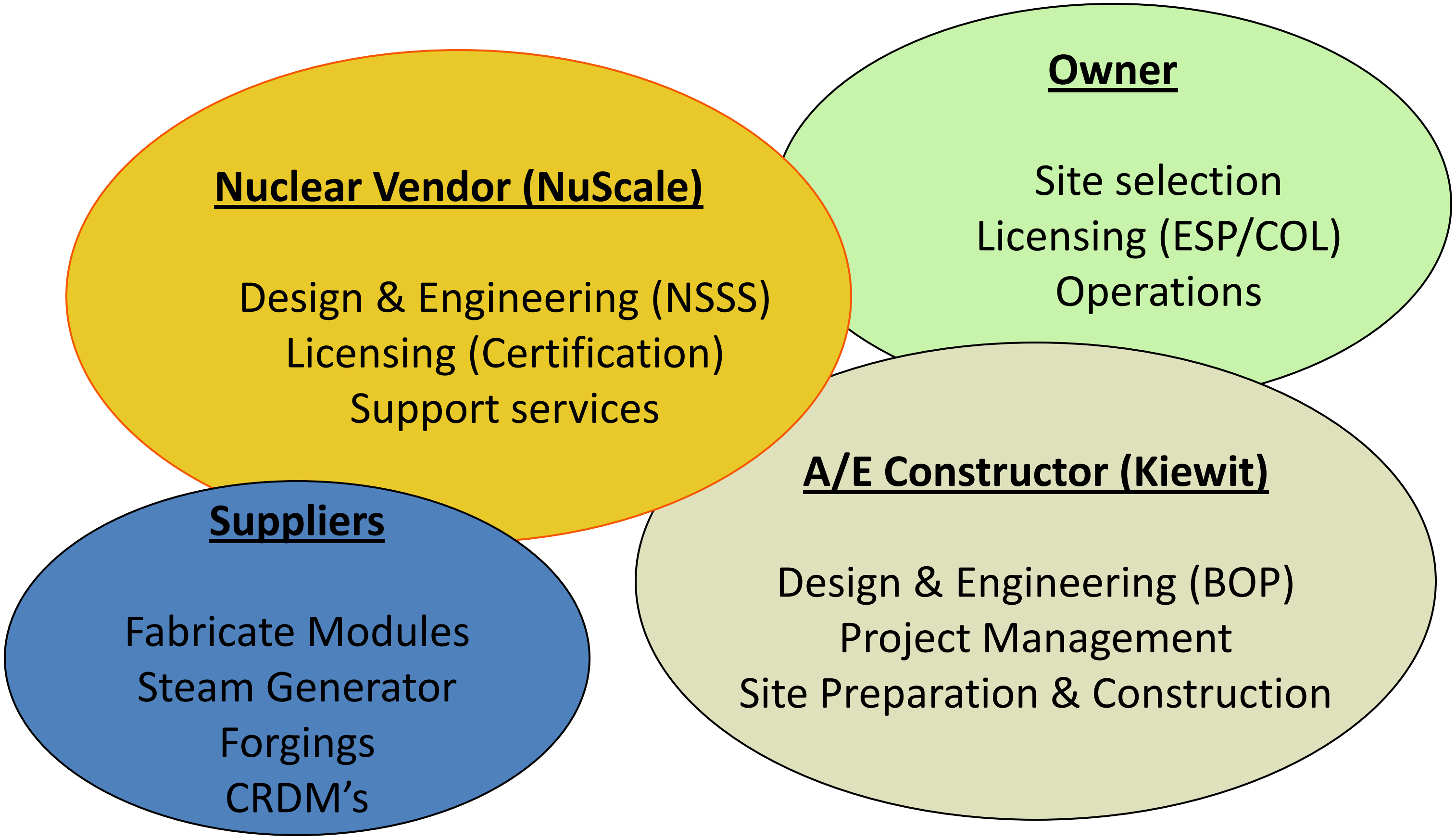
Creare
- Safety Analysis Support

SAIC From Science to Solutions
- Security
- Emergency Planning
- Safety Analysis Support

Longnecker & Associates
- Digital I&C
- Control Room Design

Kiewit
- Site Prep
- Plant Construction
- Engineering Support
- Balance of Plant
- Fabrication

NuScale Power Project Organization



Nuclear Vendor (NuScale)

Design & Engineering (NSSS)
Licensing (Certification)
Support services

Owner

Site selection
Licensing (ESP/COL)
Operations

A/E Constructor (Kiewit)

Design & Engineering (BOP)
Project Management
Site Preparation & Construction

Suppliers

Fabricate Modules
Steam Generator
Forgings
CRDM's

NuScale Nuclear Power Plant
- Quick Facts

45 MWe, 150 MWt per module

Light Water Reactor technology - known, proven

Cooled by natural circulation

Steam generators integrated into reactor pressure vessel which is integrated into containment vessel

Compact and pre-manufactured - containment vessel is 60 feet by 14 feet

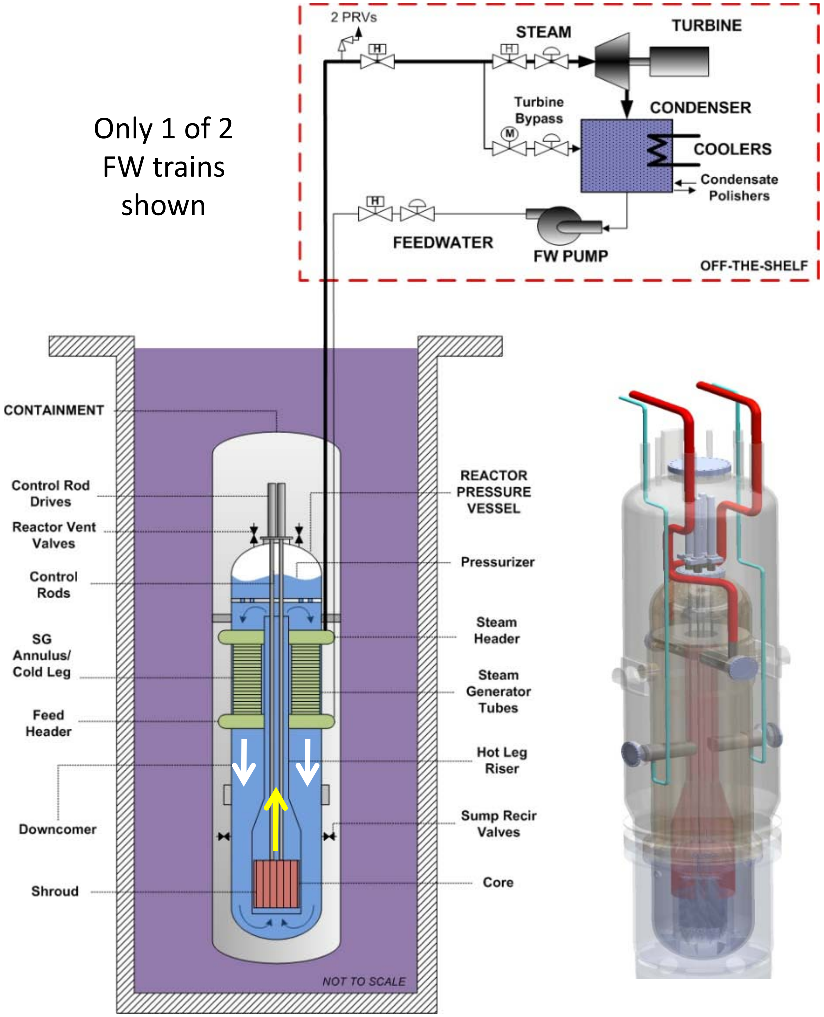
Standard LWR fuel assembly design - 6 feet in length

24 -30 month refueling cycle

Scalable: 1 to 24 modules per plant

The Product:

Prefabricated, Simple, Safe…



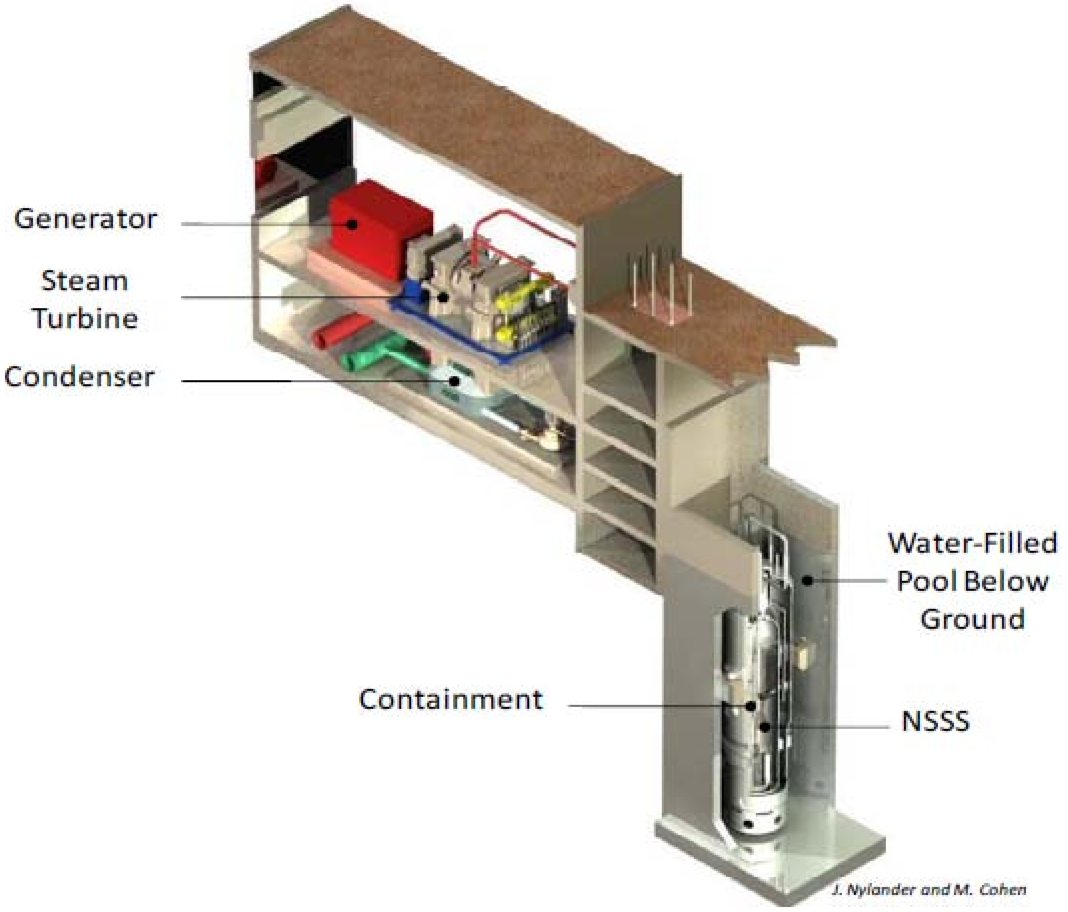
Only 1 of 2 FW trains shown

- Construction Simplicity:
  - Entire NSSS is 60’ x 15’. P*<u>refabricated and shipped by rail, truck or barge</u>*
- Natural Circulation cooling:
  - *<u>Enhances safety</u>* – eliminates large break LOCA; strengthens passive safety
  - *<u>Improves economics</u>* -- eliminates pumps, pipes, auxiliary equipment
- Below grade configuration enhances security
- Flexibility:
  - Capacity additions match demand growth
  - On-line refueling improves reliability

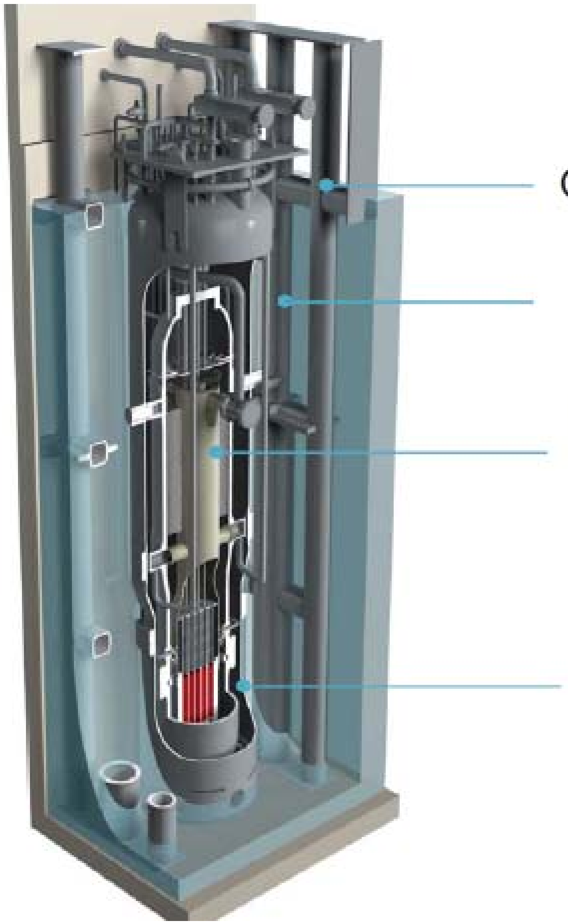
… *While relying on proven LWR technology*

- Light water technology utilizes large existing base of R&D
- NuScale can be licensed within existing regulatory framework
- Fully integrated prototype test facility available for licensing
- “Off-the-shelf” systems (turbine-generators; fuel) facilitate commercialization

Each module is an independent power module



J. Nylander and M. Cohen



Containment

Reactor
Vessel

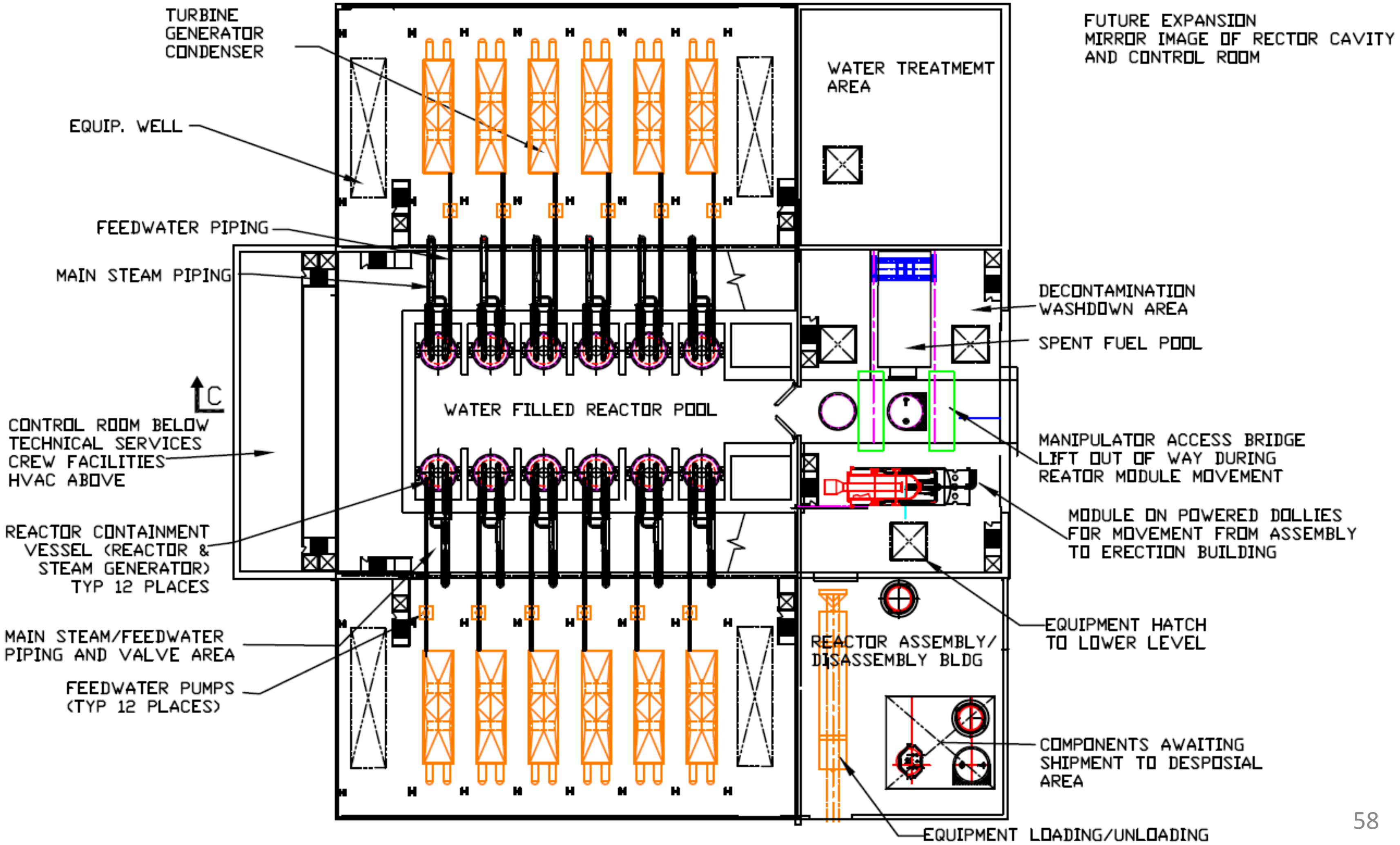
Helical Coil
Steam
Generator

Nuclear
Core

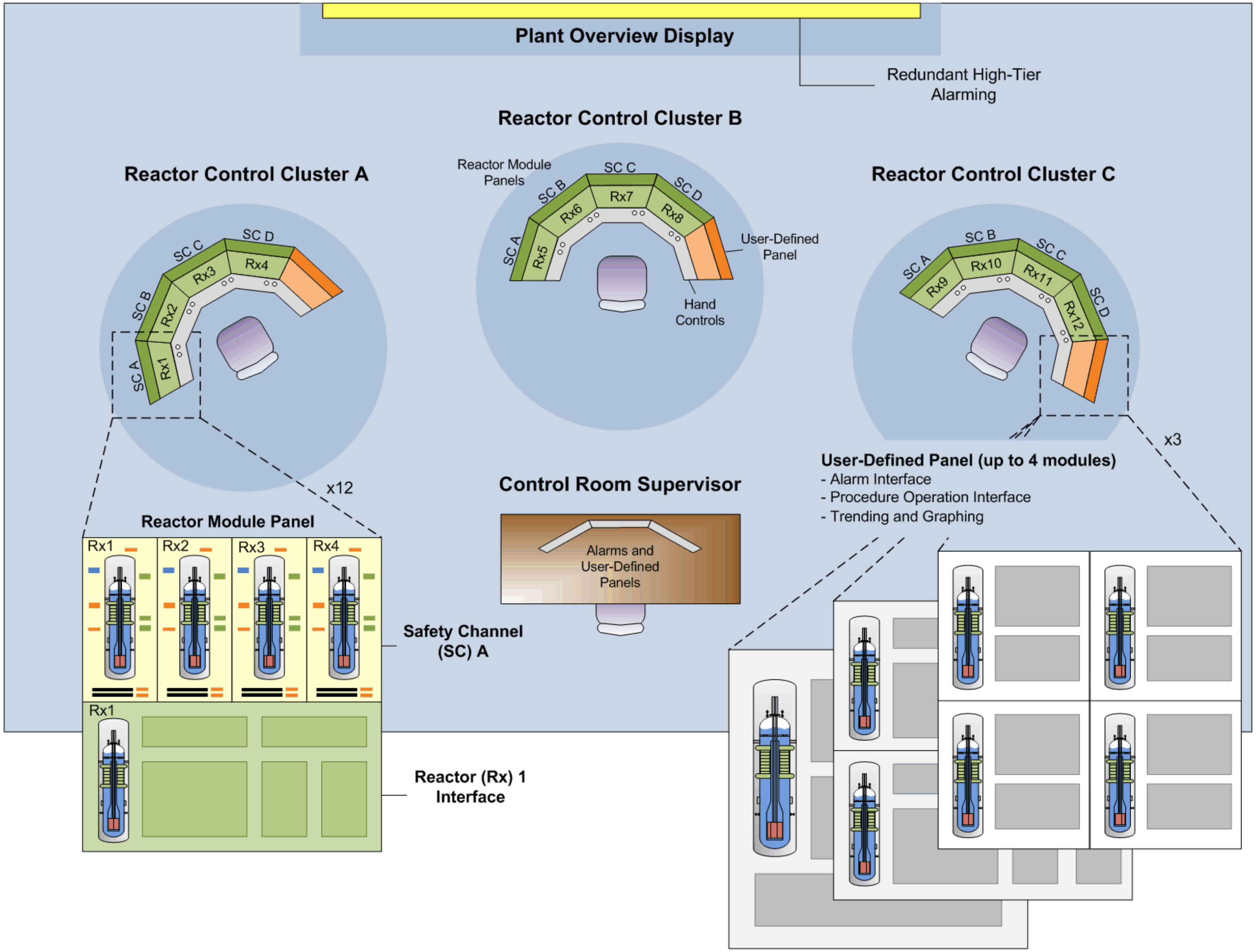
Containment
Trunnion

Multiple-Module Complex – Flexible Capacity

(12 modules – 540 MWe)

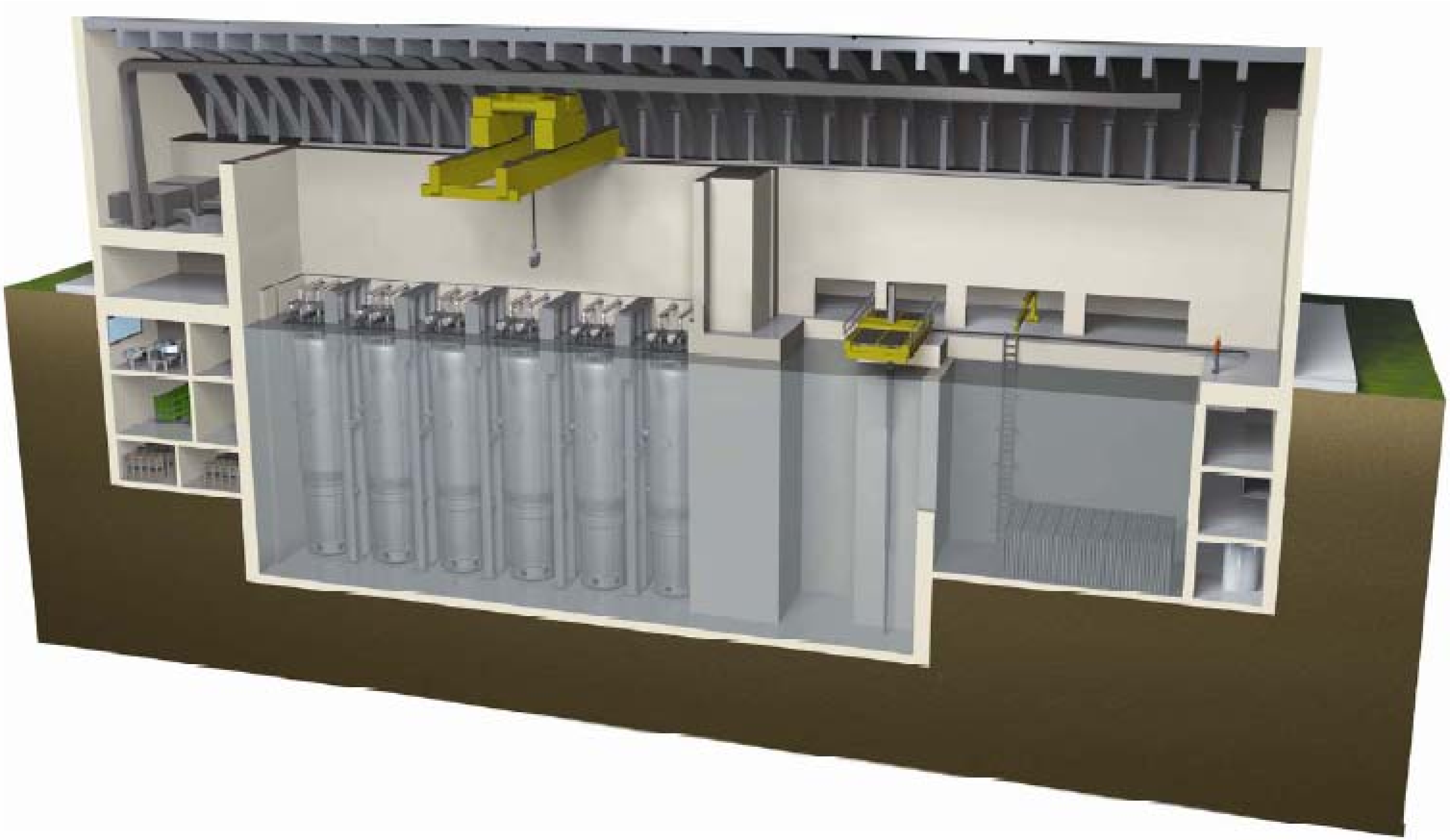


Multi-Module Control Room



User-Defined Panel (up to 4 modules)
- Alarm Interface
- Procedure Operation Interface
- Trending and Graphing

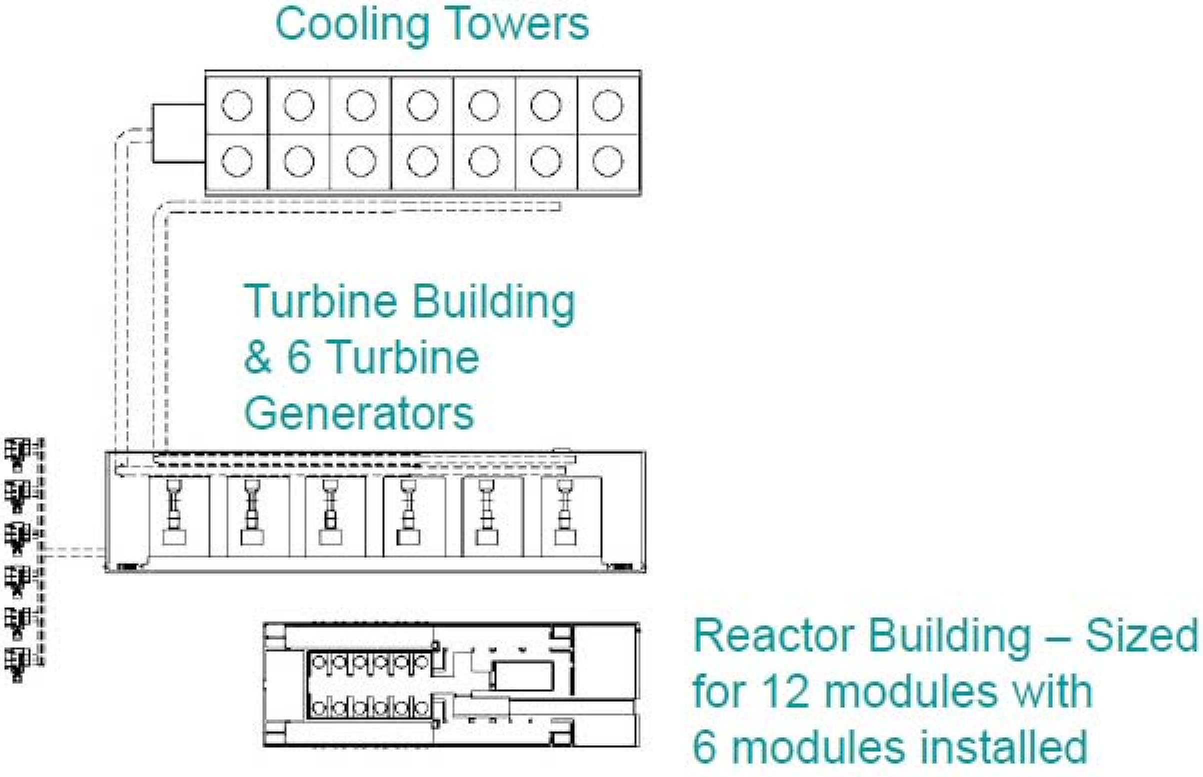
Modularity = Scaling to Any Size



12 modules, 45 Mwe each produces 540 MWe

Incremental Buildout

Initial installation 270 MWe



Cooling Towers

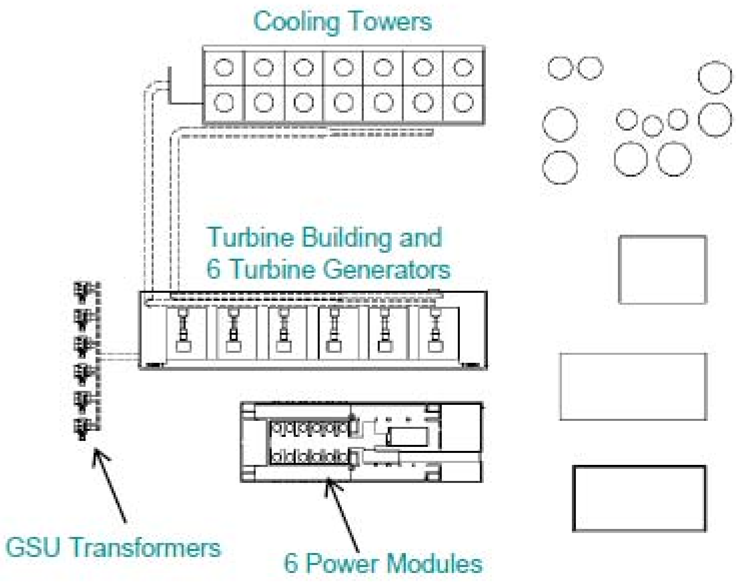
Turbine Building & 6 Turbine Generators

Reactor Building – Sized for 12 modules with 6 modules installed

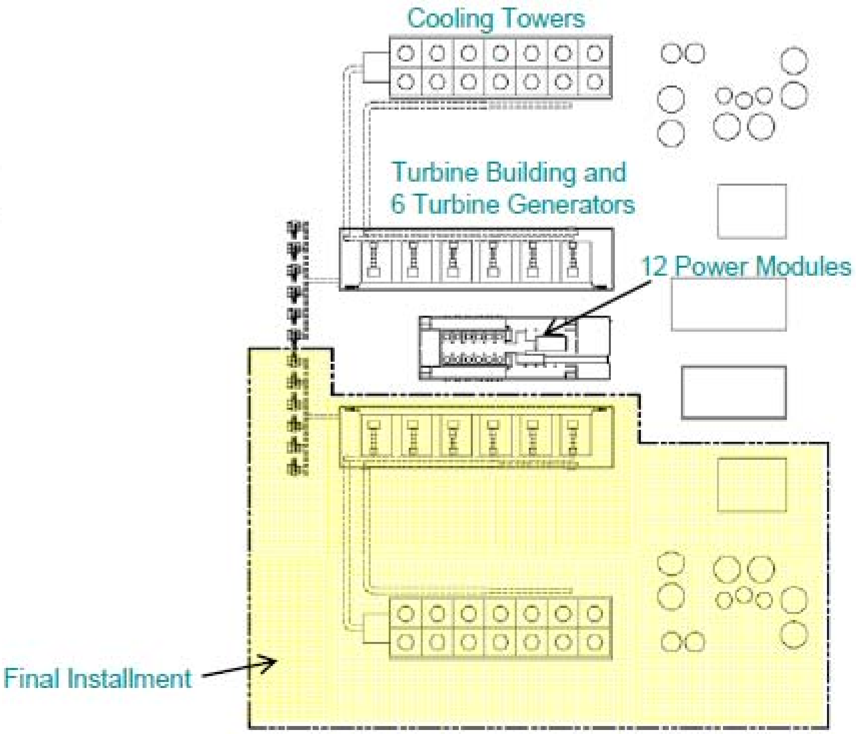
Incremental Buildout (cont)

Incremental build out minimizes financial risk, matches demand growth

Initial installment (270 Mwe)



Final Installment (540 Mwe)



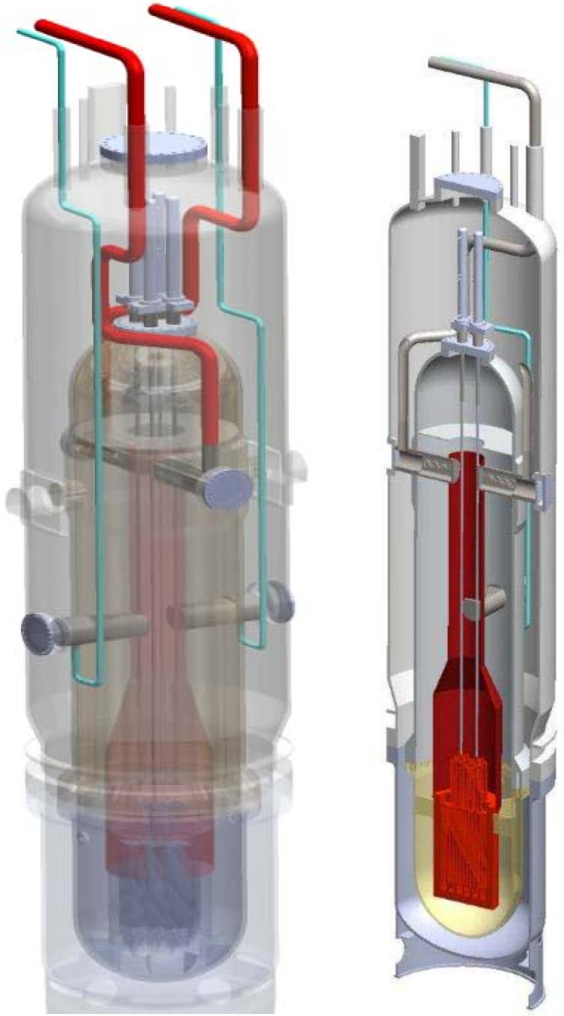
NuScale Site Perspective

Engineered Safety Features

- High Pressure Containment Vessel
- Shutdown Accumulator System (SAS)
- Passive Safety Systems
  - Decay Heat Removal System (DHRS)
  - Containment Heat Removal System (CHRS)
- Severe Accident Mitigation and Prevention Design Features

High Pressure Containment

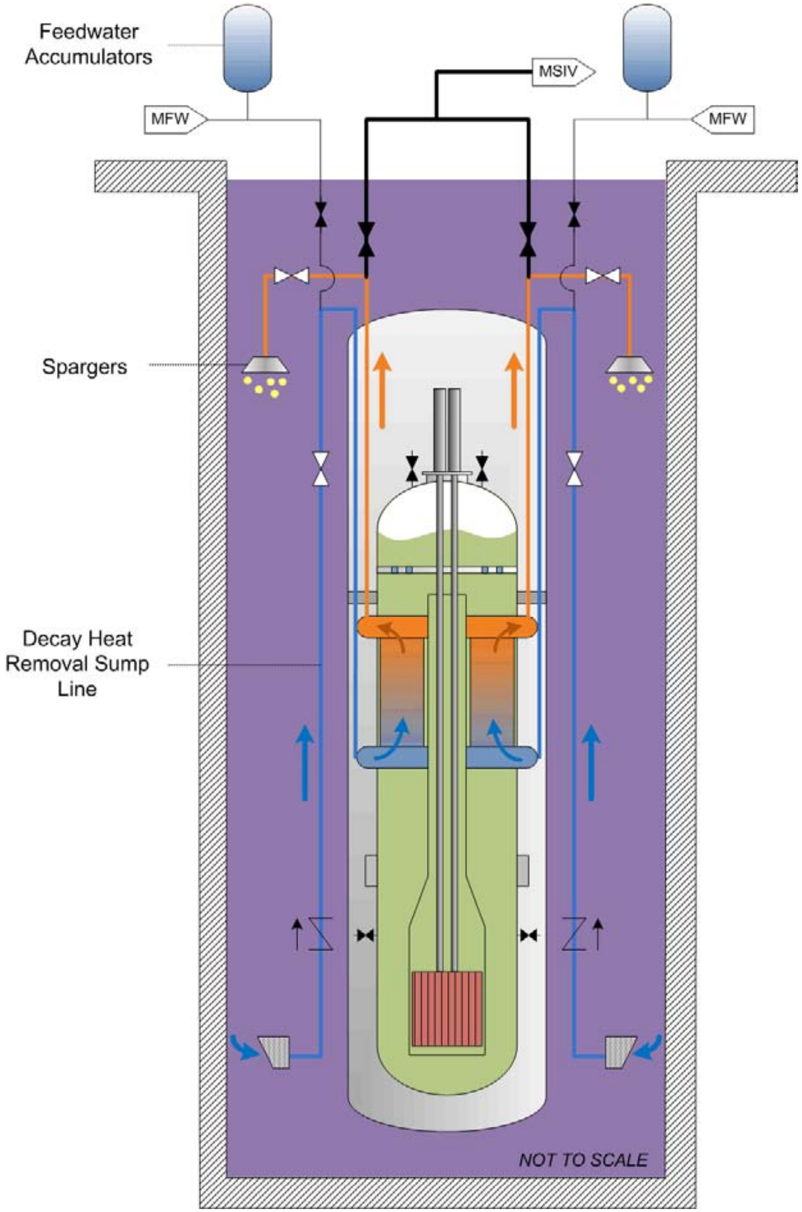
Enhanced Safety



- **Capable of 3.1 MPa (450 psia)**
  - Equilibrium pressure between reactor and containment following any LOCA is always below containment design pressure.
- **Insulating Vacuum**
  - Significantly reduces convection heat transfer during normal operation.
  - No insulation on reactor vessel. ELIMINATES SUMP SCREEN BLOCKAGE ISSUE (GSI-191).
  - Improves steam condensation rates during a LOCA by eliminating air.
  - Prevents combustible hydrogen mixture in the unlikely event of a severe accident (i.e., no oxygen).
  - Eliminates corrosion and humidity problems inside containment.

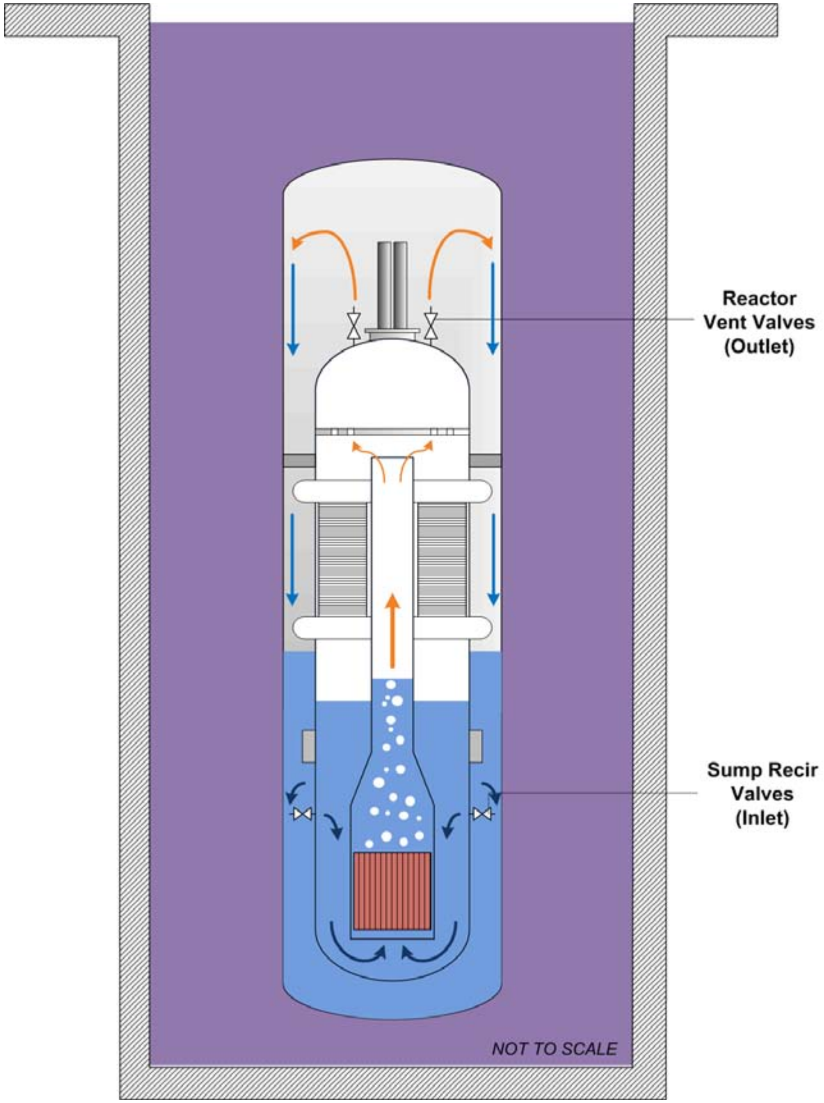
Decay Heat Removal System (DHRS)

- Two independent trains of emergency feedwater to the steam generator tube bundles.
- Water is drawn from the containment cooling pool through a sump screen.
- Steam is vented through spargers and condensed in the pool.
- Feedwater Accumulators provide initial feed flow while DHRS transitions to natural circulation flow.
- Pool provides a 3 day cooling supply for decay heat removal.

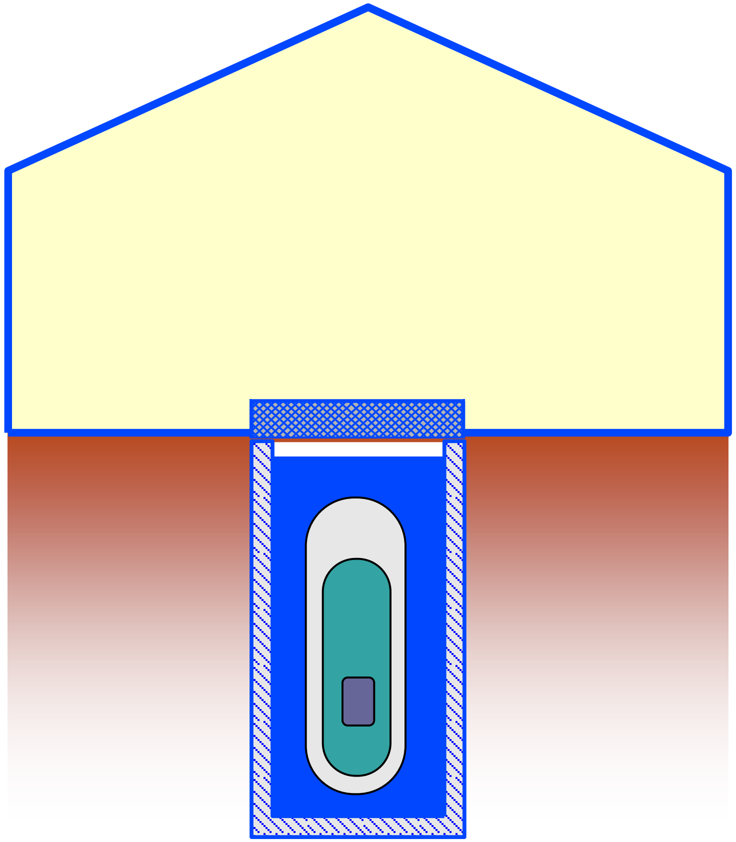


Containment Heat Removal System (CHRS)

- 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 (sump).
- Sump valves open to provide recirculation path through the core.



Additional Fission Product Barriers



- Fuel Pellet and Cladding
- Reactor Vessel
- Containment
- **Containment Cooling Pool Water**
- **Containment Pool Structure**
- **Biological Shield**
- **Reactor Building**

NOT TO SCALE

Expert panel review confirms safety

- June 2-3, 2008, a panel of experts convened to develop a Thermal-Hydraulics/Neutronics Phenomena Identification and Ranking Table (PIRT) for the NuScale module.
  - Large-break LOCA eliminated by design
  - Since all water "lost" out of the primary system can be recovered by opening the sump recirculation valves, it is *impossible* to uncover the core during design bases LOCAs
  - Therefore even a small-break LOCA does not challenge the safety of the reactor

Enhanced Public Safety

- Greater seismic resistance
- Fewer accident scenarios - no LOCA, inability to uncover core
- Simplified operations and safety systems
- Multiple barriers and greater security
- Smaller Emergency Planning Zone

Reduced licensing and technology risks

- Relies on existing LWR technology and licensing base
- Prototype integral test facility existing and available
- Plant simplicity and safety advantages reduce licensing challenges

Security and Safeguards Advantages

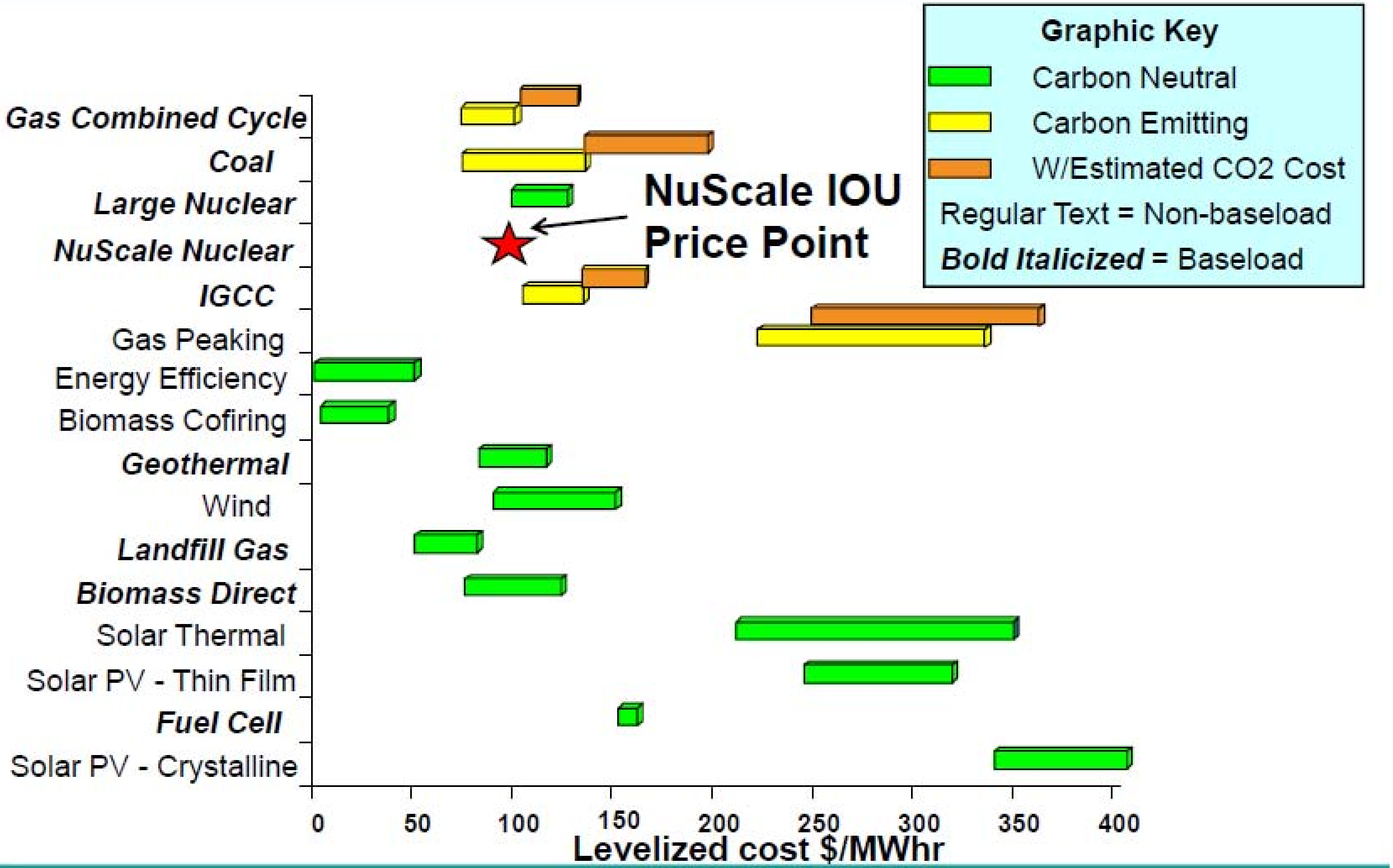
- Safety maintained without external power
- Below-grade
  - Power Module (NSSS and Containment)
  - Control Room
  - Spent Fuel Pool
- Low profile building
- Containment pool Impact Shield for aircraft

Capturing the Economies of “small”

- Smaller unit size reduces financial exposure
- Can be built faster in a series of smaller units
  - Interest during construction reduced
  - Better regulatory treatment
  - Moves NSSS construction off-site
- Upfront capital requirements reduced
- Capacity added to meet demand growth
- Less generation per shaft – avoids large “single shaft risk.”
- “Pinch Points” avoided

Forgings for conventional nuclear plants done by Japan Steel Works.

Generation Levelized Cost Comparison (1)



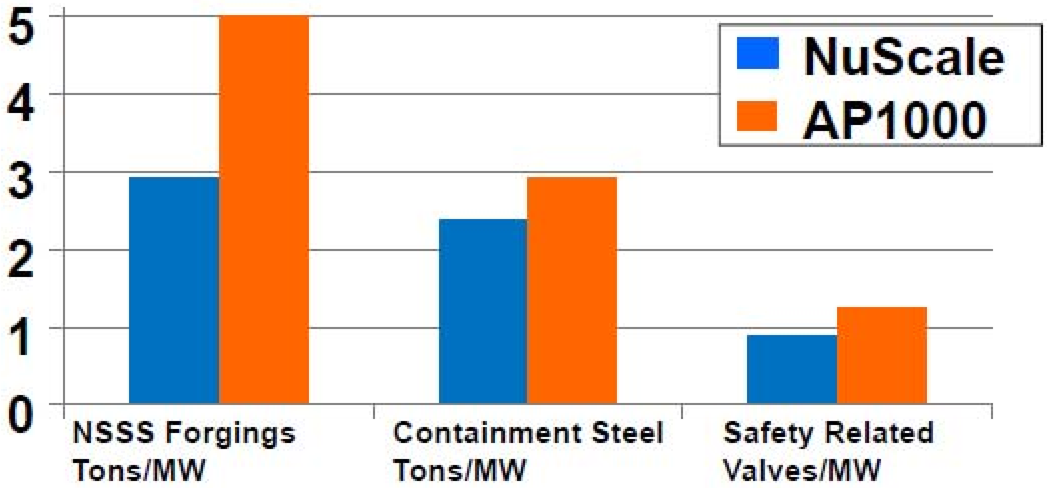
NuScale IOU Price Point

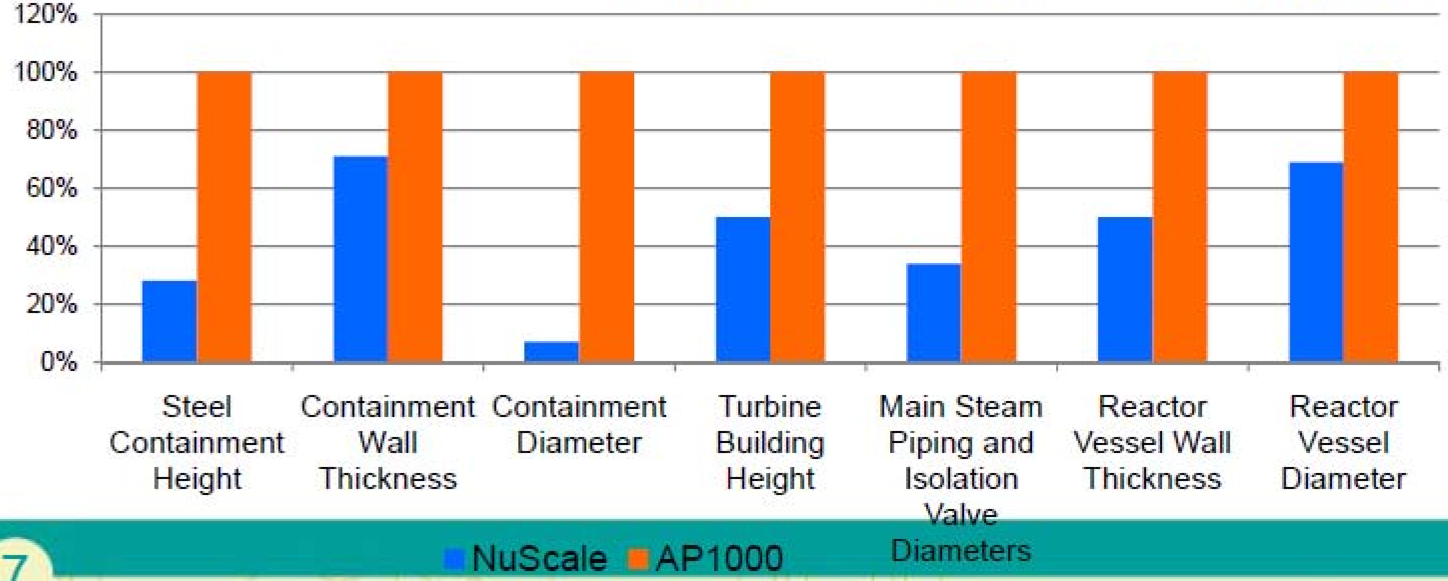
(1) June, 2008 Lazard "Levelized Cost of Energy Analysis – Version 2.0." Case presented assumes no federal tax incentives for any technologies. CO2 Costs estimated from Study by Brattle Group for Connecticut Light & Power

NuScale Power

How Can Smaller Be Cheaper?

- Simplicity eliminates equipment
- Modularity reduces size
- Smaller sizes less costly to manufacture
- Factory modular manufacturing vs. on-site

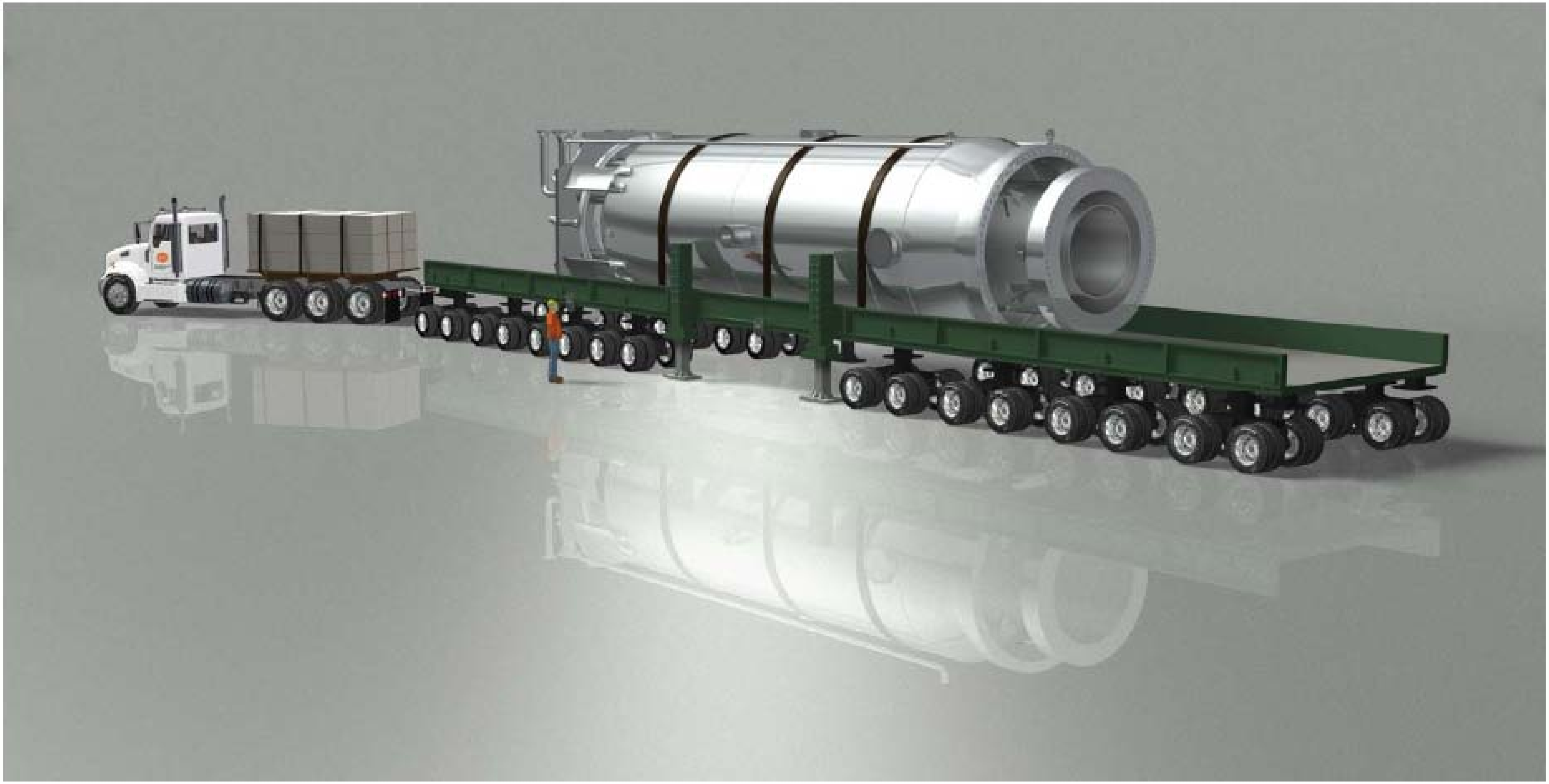




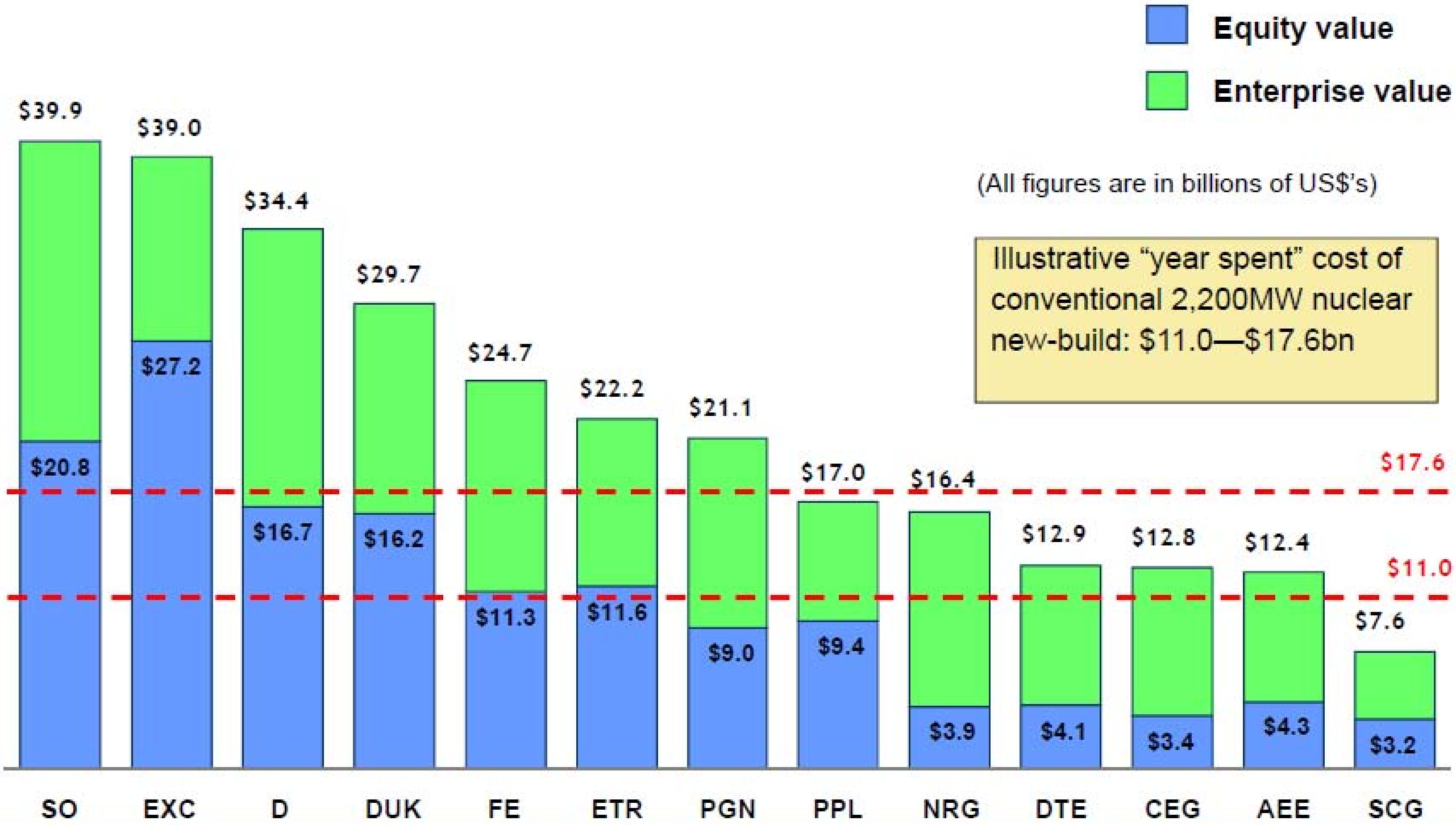
Simpler Design More Cost Effective

	AP1000	NuScale
Nuclear Steam Supply System (NSSS) Components	4 Reactor Coolant Pumps	None
	4 Cold Legs	None
	2 Hot Legs	None
	1 Pressurizer Surge Line	None
Passive Safety Systems	2 Core Make-up Tanks and Piping (2000 ft^{3} each)	None
	2 Direct Vessel Injection Lines	None
	2 Passive Residual Heat Removal Heat Exchangers	None
	In-Containment Storage Tank	None
	Hydrogen Recombiners	None

Modular Advantages



Financial Risks in Large Nuclear Plants



(All figures are in billions of US$'s)

Illustrative "year spent" cost of conventional 2,200MW nuclear new-build: $11.0—$17.6bn

Source: JPMorgan; FactSet as of 3/13/09

System-integrated Modular Advanced Reactor SMART

Smart is a 330 MWt pressurised water reactor with integral steam generators and advanced safety features.
The unit is designed for electricity generation (up to 100 MWe) as well as thermal applications such as seawater desalination, with a 60-year design life and three-year refuelling cycle.

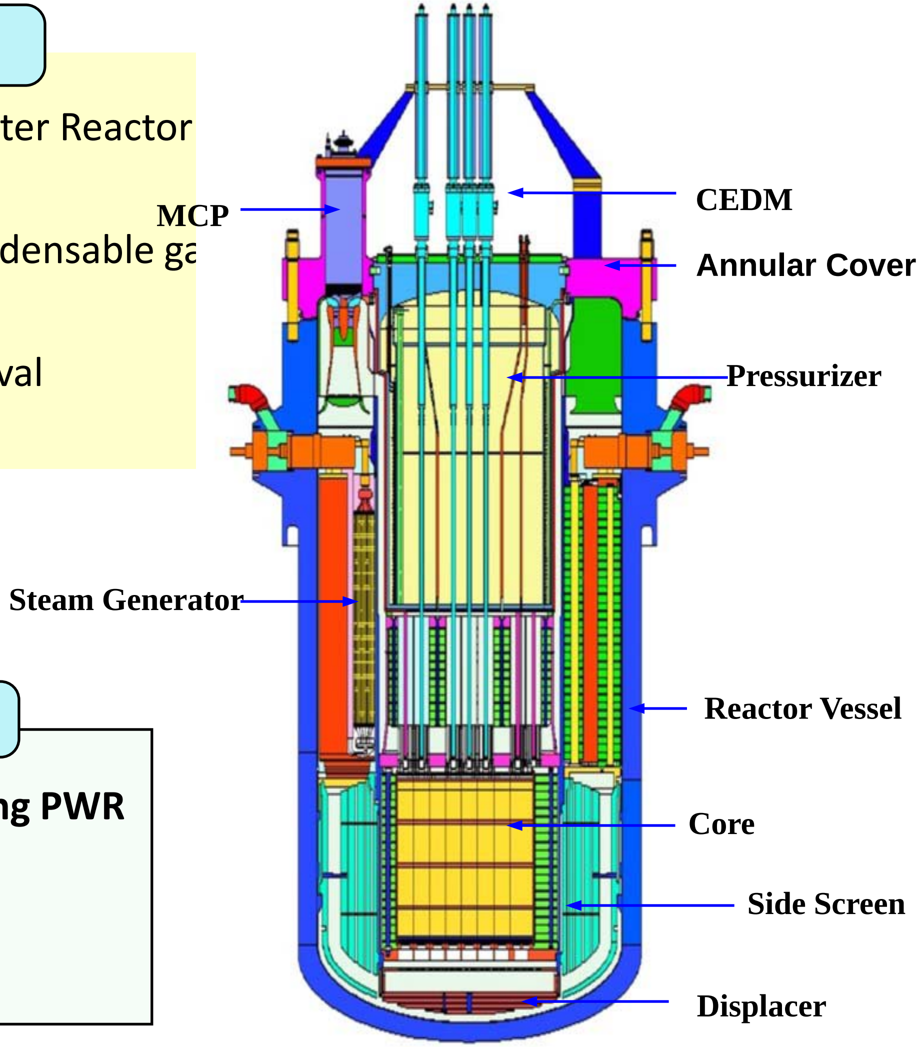
INTRODUCTION – SMART Plant

SMART DESIGN

- Small sized integral type Pressurized Water Reactor
- Elimination of the possibility of LBLOCA
- Self controlled pressurizer by a non-condensable ga
- Low power density and Boron free core
- Passive system for the decay heat removal
- Simplification of system/components

CHARACTERISTICS

- **Enhance safety comparing with existing PWR**
- **Shorten construction period**
- **Reduce liquid radioactive wastes**



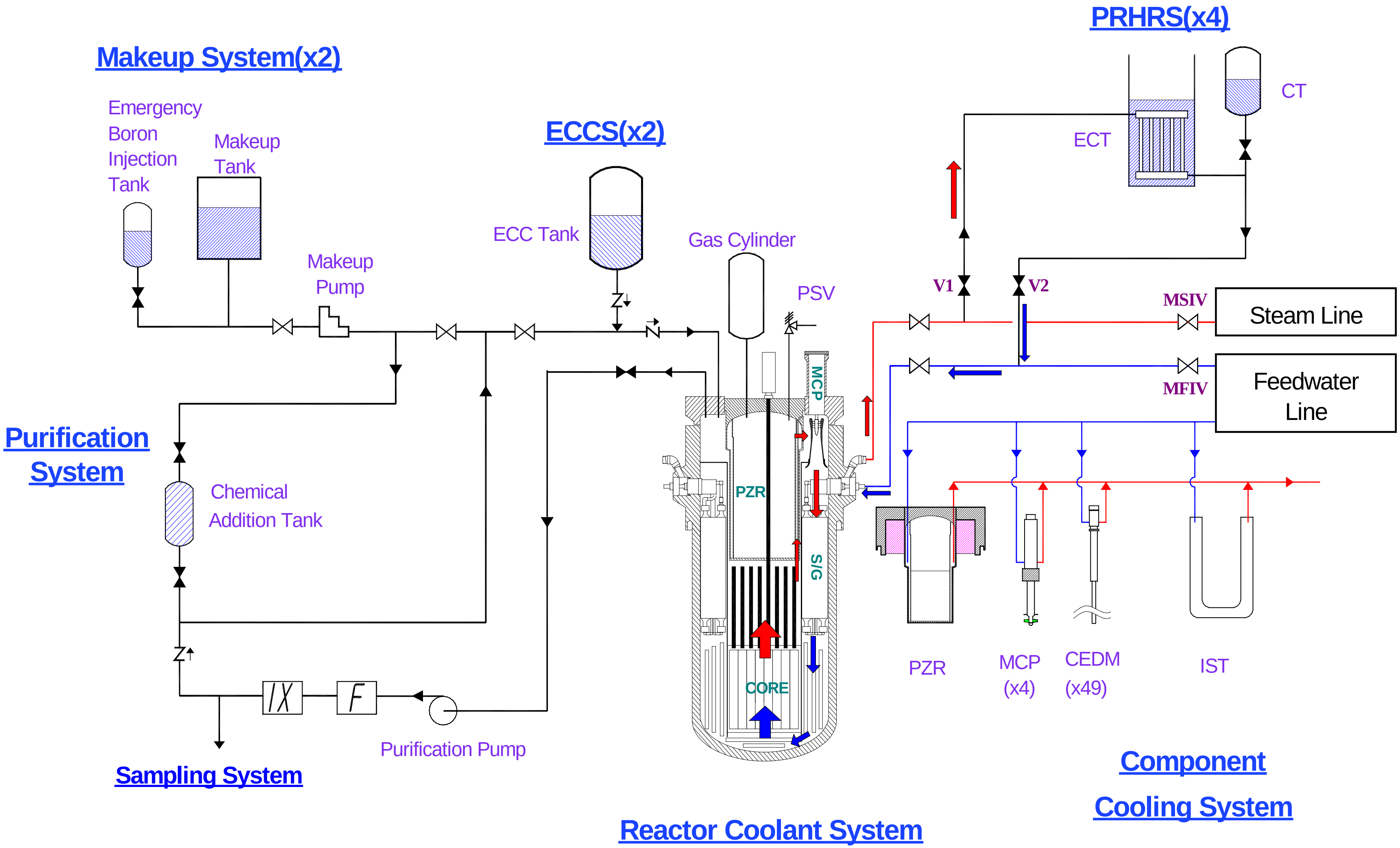
INTRODUCTION – SMART Plant

- SMART Plant
  - Multi-purposed plant; sea water desalination and power generation
  - Designed to supply 40,000 ton of water and 90 MW of electricity
  - Major components
    - Vessel :Height-10.6m, Outer diameter-4.6m
    - 12 SG cassettes, 49 CEDMs, 4 MCPs
    - 4 independent train of PRHRS
  - Nominal operation conditions
    - Core power : 330 MWt
    - Primary pressure : 15 MPa
    - Primary mass flow : 1540 kg/s
    - Secondary mass flow : 152.7 kg/s
    - SG in/out liquid Temp : 310, 270 °C
    - Linear heat gen. : 12.0 kW/m (commercial: 17 kW/m)
    - Heat flux : 394.1 kw/m^2 (commercial: 567 kw/m^2)

INTRODUCTION – SMART Plant

- Core
  - 17x17 rectangular arrays of Korea Optimized Fuel Assembly
  - Soluble boron free operation with large negative MTC
  - Long cycle operation with a single batch reload scheme
- Steam Generator
  - 12 steam generator cassettes located between Rv and barrel
  - Primary coolant flows the shell side and secondary fluid flows tube side
  - Reduce the possibility of the SGTR accident
- Pressurizer
  - Self controlled in-vessel pressurizer located in the upper space of Rv
  - Annular cavity, intermediate cavity, and end cavity
  - Control the pressure by a partial pressure of the non-condensable gas
  - Eliminate the active system such as spray and heater

INTRODUCTION – SMART-P Plant

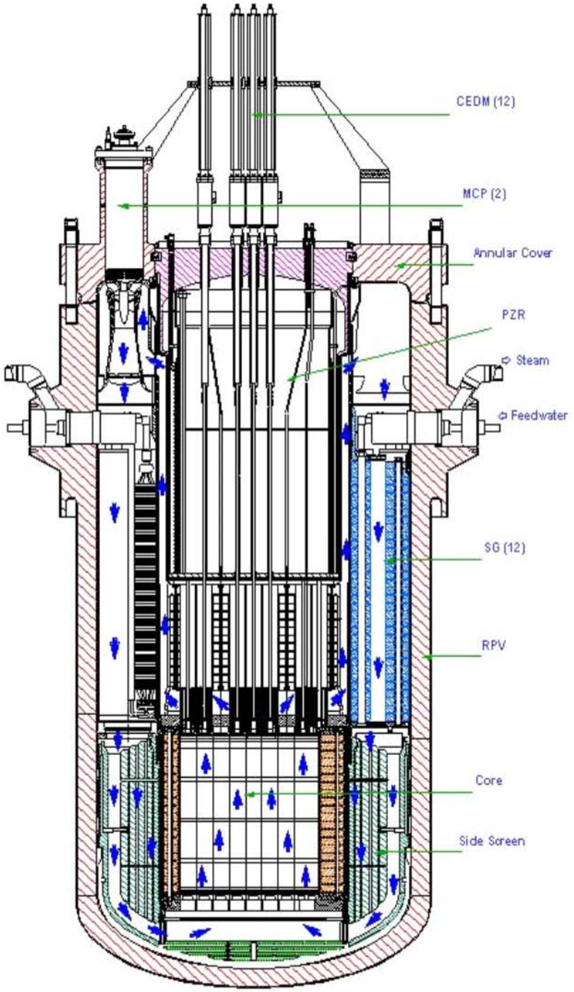


INTRODUCTION – SMART Plant

- Natural circulation circuit in the SMART Plant
  - Three natural circulation circuit are involved in the PRHRS operation
    - Reactor coolant system
    - Passive residual heat removal system
    - Emergency cooldown tank
  - Passive residual heat removal system is designed to remove the decay heat
    - The system can remove the decay heat for 72 hours without operator action
  - Emergency cooldown tank is a final heat sink for the decay heat
    - The heat exchanger is submerged the water in the ECT

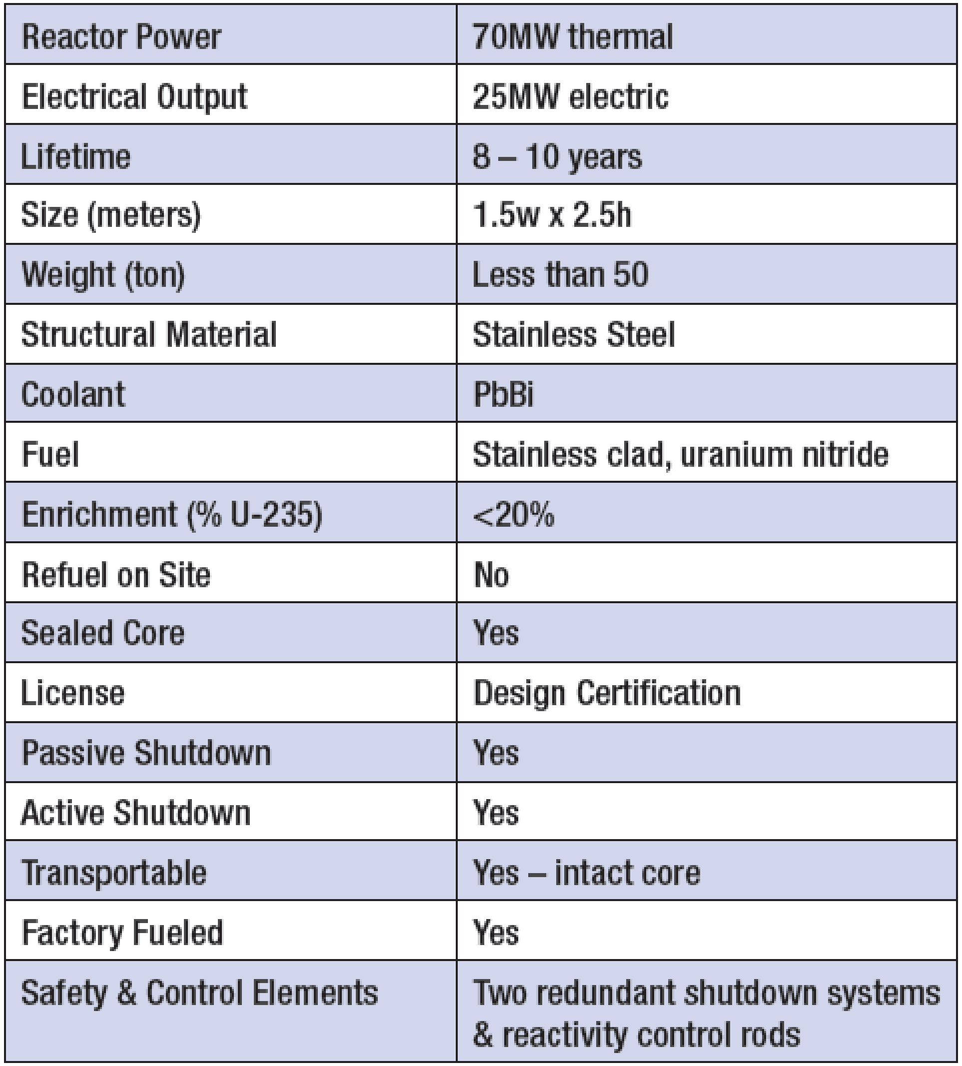
Natural Circulation of the SMART

- Description of the reactor coolant system
  - System
    - Consist of core, upper guide structure, MCP, SG primary side, downcomer
  - Initiation of natural circulation in the RCS
    - MCP trip signal is initiated by the LOOP signal or operator action manually
  - Characteristics
    - the SMART can operate 25% of nominal power by natural circulation operation mode
    - Natural circulation is established by hydraulic head and density difference between the core and the SG
    - Heat generated in the core is transported to the SG by natural circulation flow



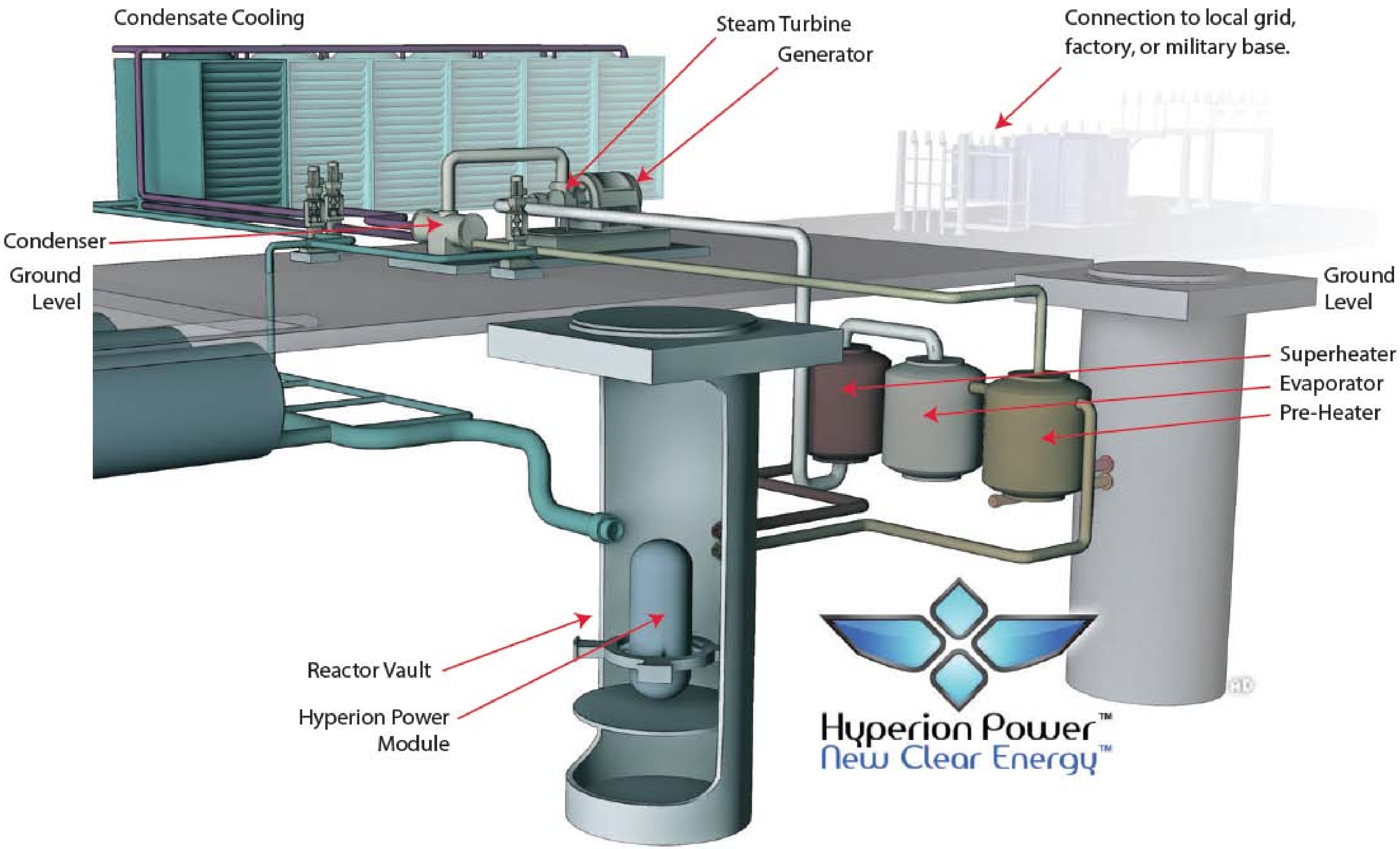
Hyperion Power

- 25 MWe fast PbBi cooled reactor
- Originated from LANL



Reactor Power	70MW thermal
Electrical Output	25MW electric
Lifetime	8 – 10 years
Size (meters)	1.5w x 2.5h
Weight (ton)	Less than 50
Structural Material	Stainless Steel
Coolant	PbBi
Fuel	Stainless clad, uranium nitride
Enrichment (% U-235)	<20%
Refuel on Site	No
Sealed Core	Yes
License	Design Certification
Passive Shutdown	Yes
Active Shutdown	Yes
Transportable	Yes – intact core
Factory Fueled	Yes
Safety & Control Elements	Two redundant shutdown systems & reactivity control rods

Hyperion Power Module (HPM)



HPM Characteristics

1. Transportable

- Unit will measure approximately 1.5m wide x 2.5m tall
- Fits into a standard fuel transport container
- Transported via ship, rail, or truck
- Modular design for easy and safe transport

2. Sealed Core – Safe and Secure

- Factory sealed; no in-field refueling, closed fuel cycle
- Returned to the factory for fuel and waste disposition

3. Safety

- System will handle any accident through a combination of inherent and engineered features
- Inherent negative feedback keeps the reactor stable and operating at a constant temperature
- Sited underground, out of sight
- Proliferation-resistant; never opened once installed

HPM Characteristics

4. Operational Simplicity

- Operation limited to reactivity adjustments to maintain constant temperature output of 500C
- Produces power for 8 to 10 years depending on use

5. Minimal In-Core Mechanical Components

- Operational reliability is greatly enhanced by the reduction of moving mechanical parts

6. Isolated Power Production

- Electric generation components requiring maintenance are completely separated from the reactor
- Allows existing generation facilities to be retrofitted

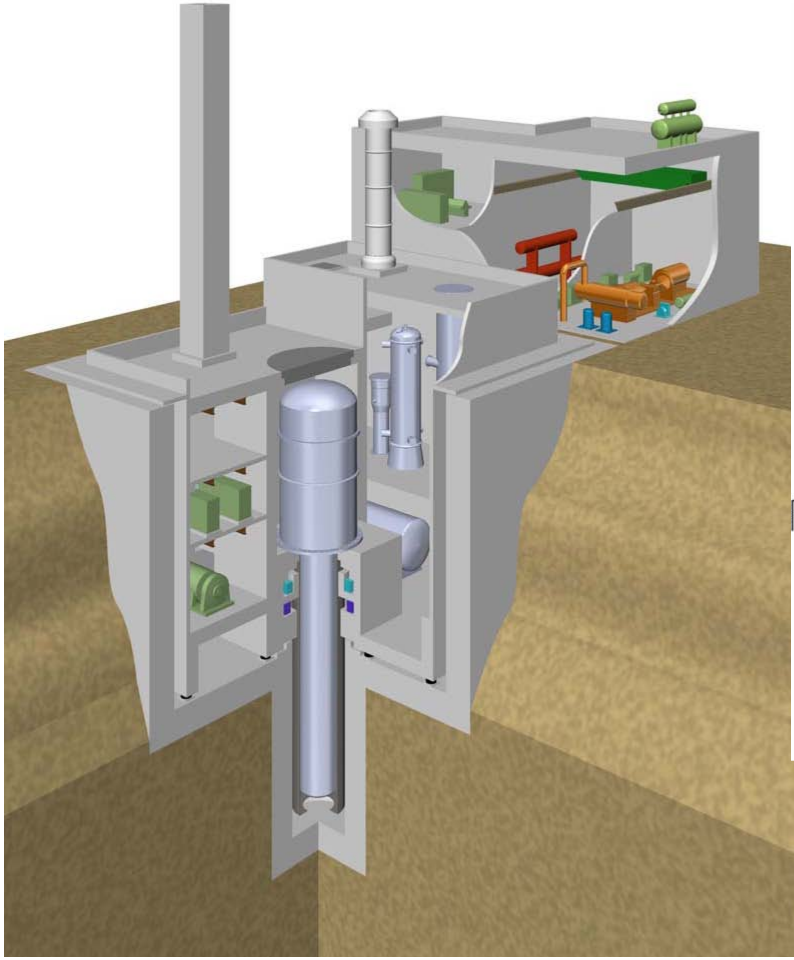
7. Licensing

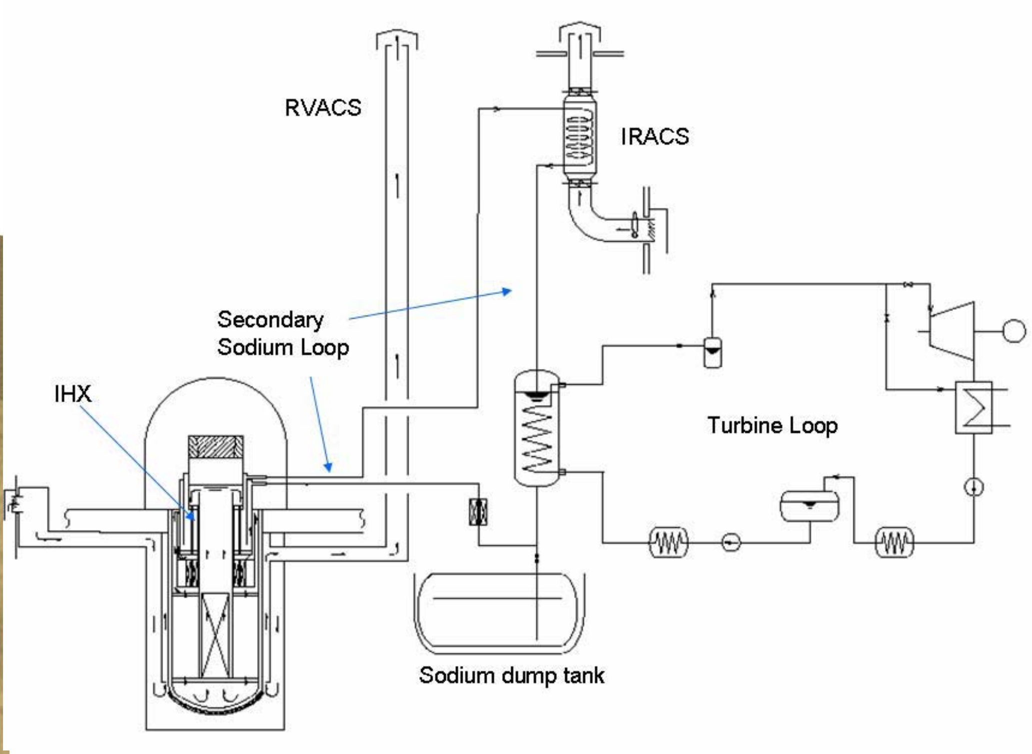
- The Hyperion Power Module will be licensed by national and international regulatory authorities.

Toshiba 4S (Super Safe, Small and Simple)

- 10 MWe liquid sodium cooled fast reactor (nuclear battery type)
- Galena, Alaska USA (700 residents)
- Land use 190x90 ft
- The overall plant equivalent availability factor shall equal or exceed 90 % for the standard design and is targeted at > 95% for the Galena facility.
- The nuclear steam supply system (NSSS) shall be designed to operate for 30 years. Any NSSS component not capable of meeting the 30-year design life will be designed to be replaceable.
- The reactor module shall be designed to be replaceable in order to provide the capability of extending the plant life beyond 30 years.
- The reactor module shall be capable of being installed and ready for sodium fill within 6 months after site delivery.
- The standard plant shall be capable of being in operation from 2 to 4 years from the start of site work, with the duration of the construction period depending on of site-specific weather conditions.
- The capital and operating costs shall be competitive with projected busbar costs for other power sources to the remote customers.

Plant layout, primary + secondary sodium loops

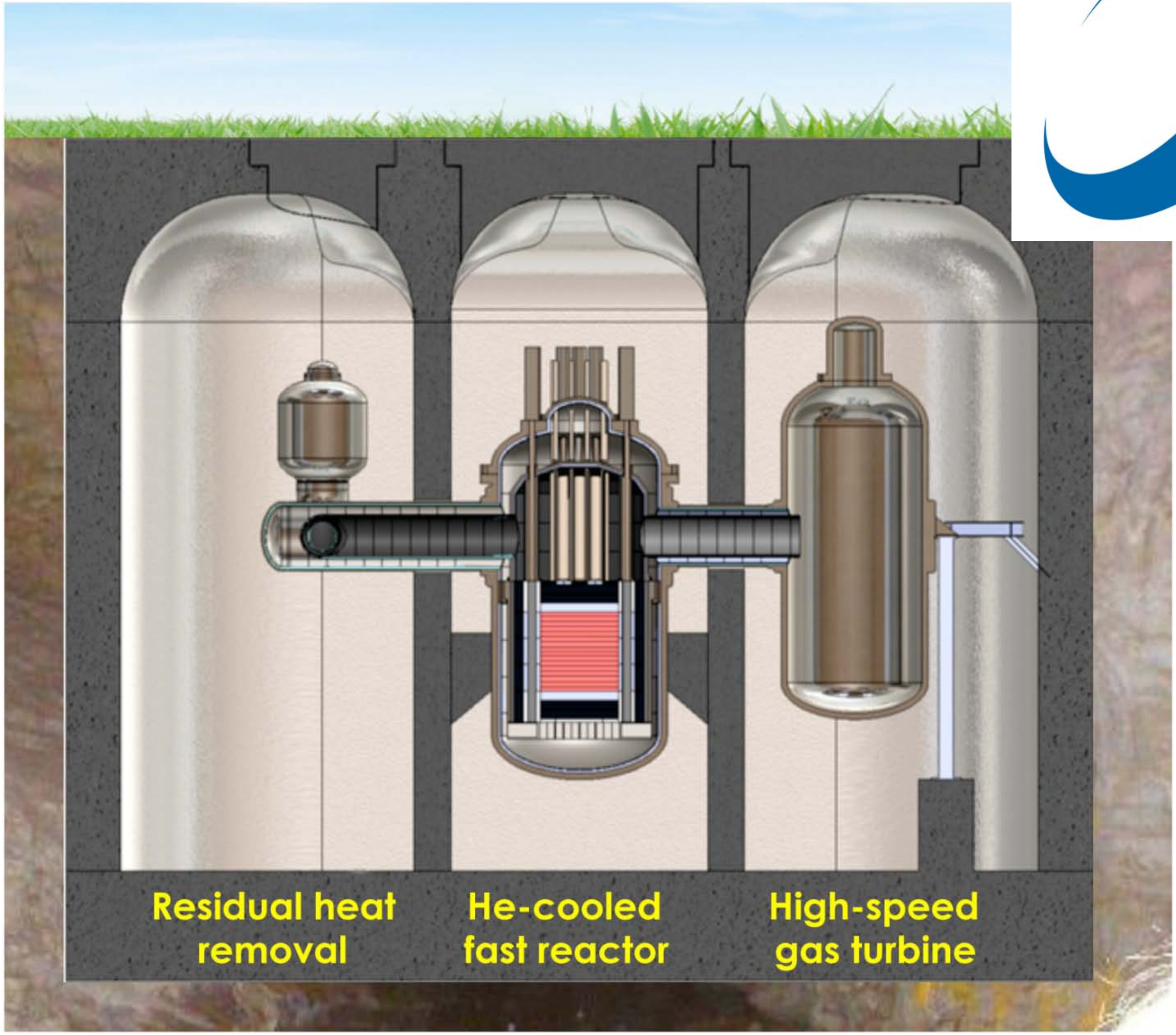




GA Energy Multiplier Module (EM^2)

- The EM^2 is a modified version of General Atomics' high-temperature, helium-cooled reactor and is capable of converting used nuclear fuel into electricity and industrial process heat, without conventional reprocessing.
- Each module would produce about 240 MWe (500 MWt) of power at 850^oC.
- 30yrs fuel cycle
- Sealed below grade

EM^2 Module


Residual heat removal
He-cooled fast reactor
High-speed gas turbine

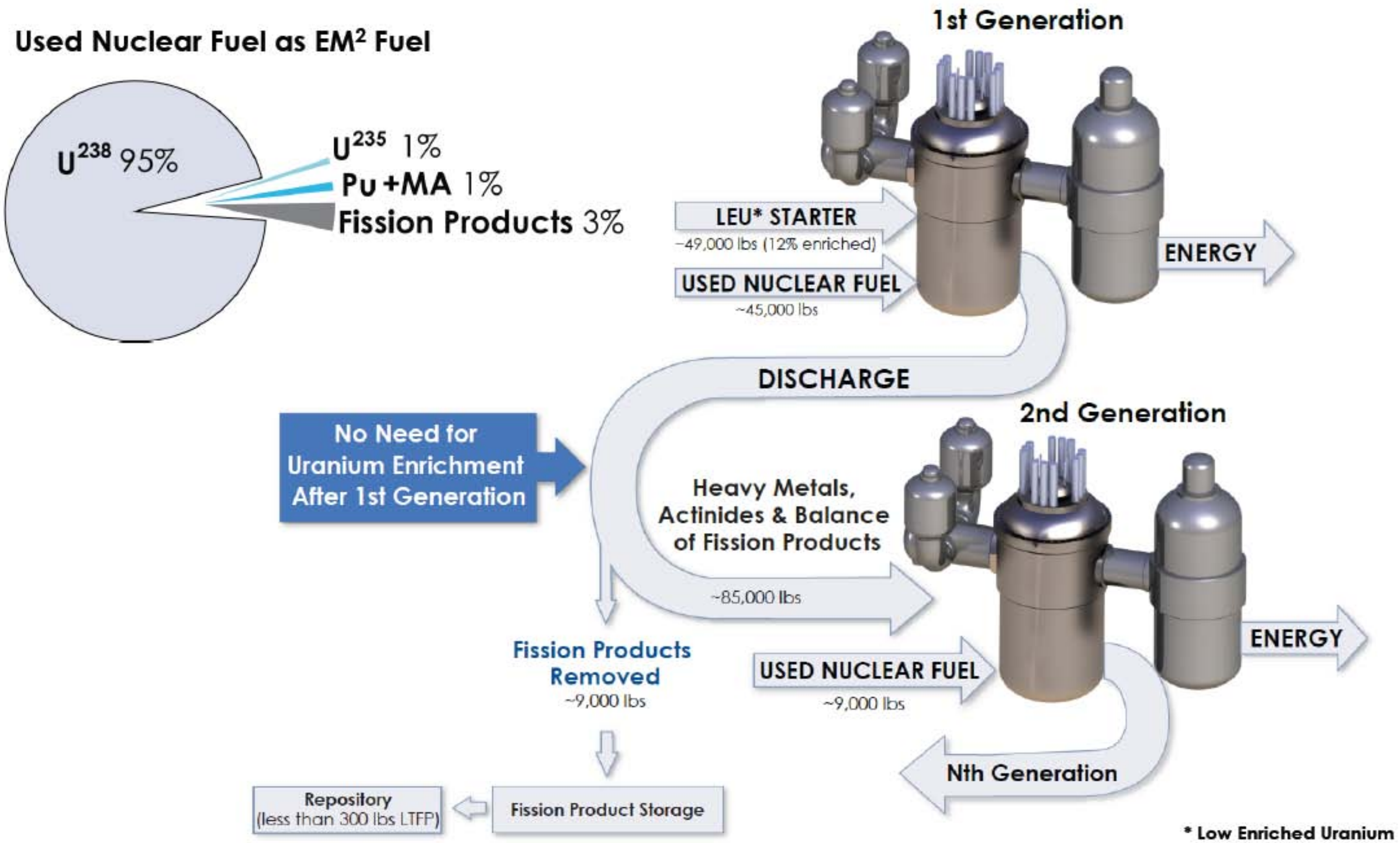
EM^2 Characteristics

- Reduces initial capital investment and power costs
- Uses used nuclear fuel, depleted uranium or weapons plutonium
- **Minimizes need for long-term repositories**
- **Reduces need for uranium enrichment**
- **Eliminates conventional fuel reprocessing**
- Burns used nuclear fuel w/o conventional reprocessing
- - Spent fuel cladding removed, fuel meat pulverized and AIROX dry process employed to remove fission products
- EM2 discharge is recycled
- - Uses modified dry AIROX to remove some fission products
- - AIROX cannot remove heavy metals
- - Waste stream contains only fission products

EM^2 Characteristics

- Site flexibility for electricity generation and process heat applications
- Grid capable
- Gas-cooled fast reactor
- Passively safe, underground sited
- Factory manufactured, shipped by rail or commercial truck
- No greenhouse gas emissions
- No refueling for 30 years

Closed Nuclear Fuel Cycle



Used Nuclear Fuel as EM² Fuel

U^{238} 95%

U^{235} 1%

Pu +MA 1%

Fission Products 3%

1st Generation

LEU* STARTER
~49,000 lbs (12% enriched)

USED NUCLEAR FUEL
~45,000 lbs

ENERGY

DISCHARGE

2nd Generation

No Need for Uranium Enrichment After 1st Generation

Heavy Metals, Actinides & Balance of Fission Products
~85,000 lbs

Fission Products Removed
~9,000 lbs

USED NUCLEAR FUEL
~9,000 lbs

ENERGY

Nth Generation

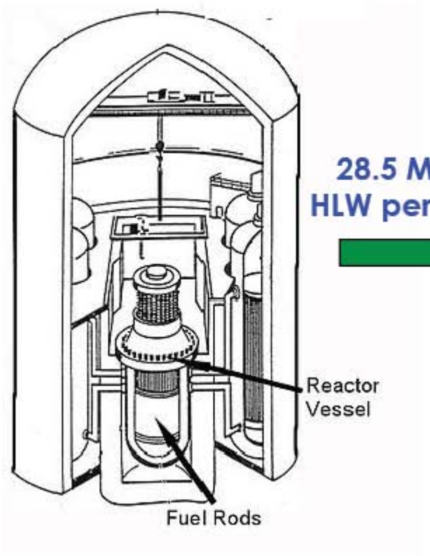
Fission Product Storage

Repository
(less than 300 lbs LTFP)

* Low Enriched Uranium

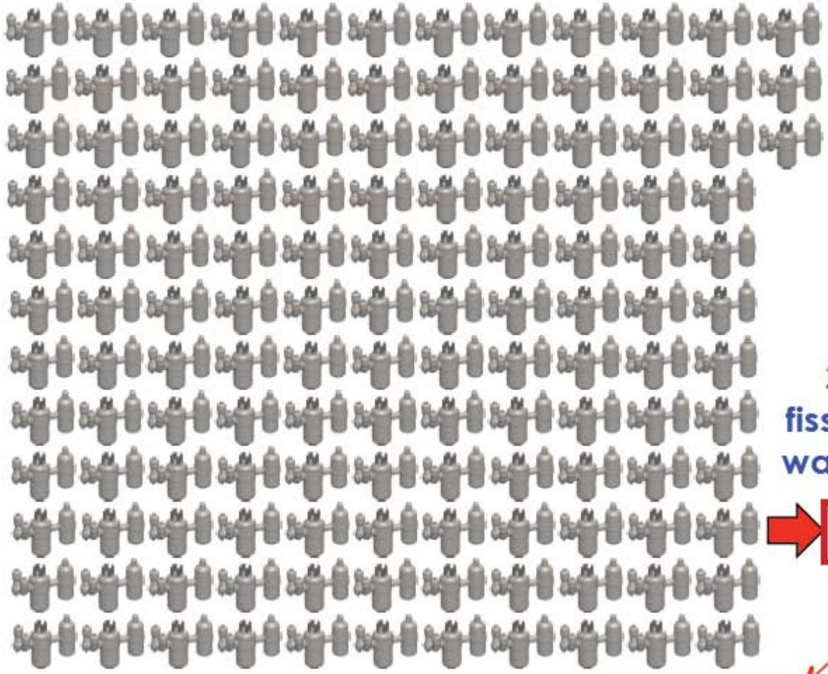
Multiplication of Energy Extracted from LWR Spent Fuel (27x)

Pressurized water reactor – 1.2 GWe



28.5 MT of HLW per year

Provides annual fuel consumed by 135 EM^2 to produce 32.5 GWe



28.5 MT of fission product waste per year

Disposition

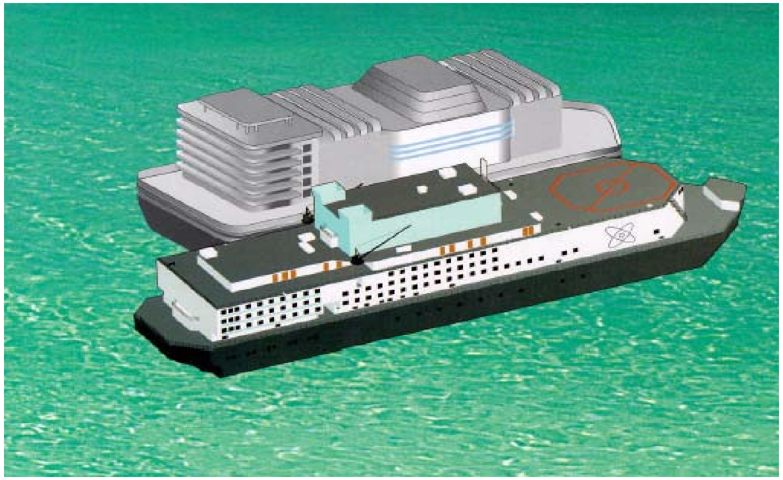
- 2.9 MT Class C
- 24.7 MT "beyond Class C"
- 0.9 MT of long lived isotopes (e.g., ^{99}Tc, ^{129}I)

or

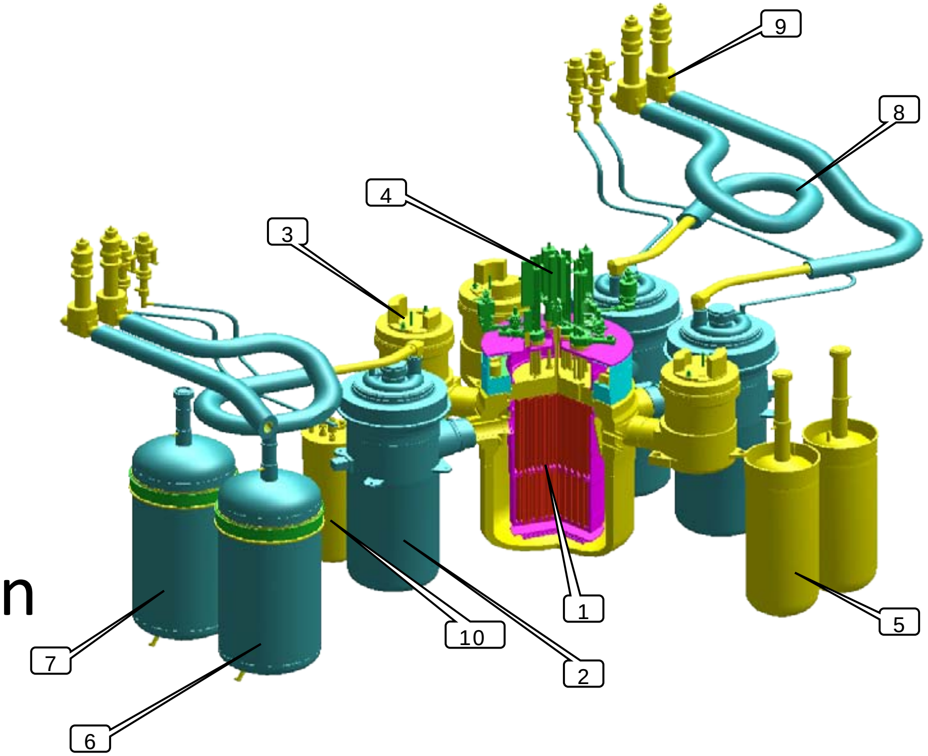
disposition

28.5 MT HLW per year

KLT-40 (OKBM)



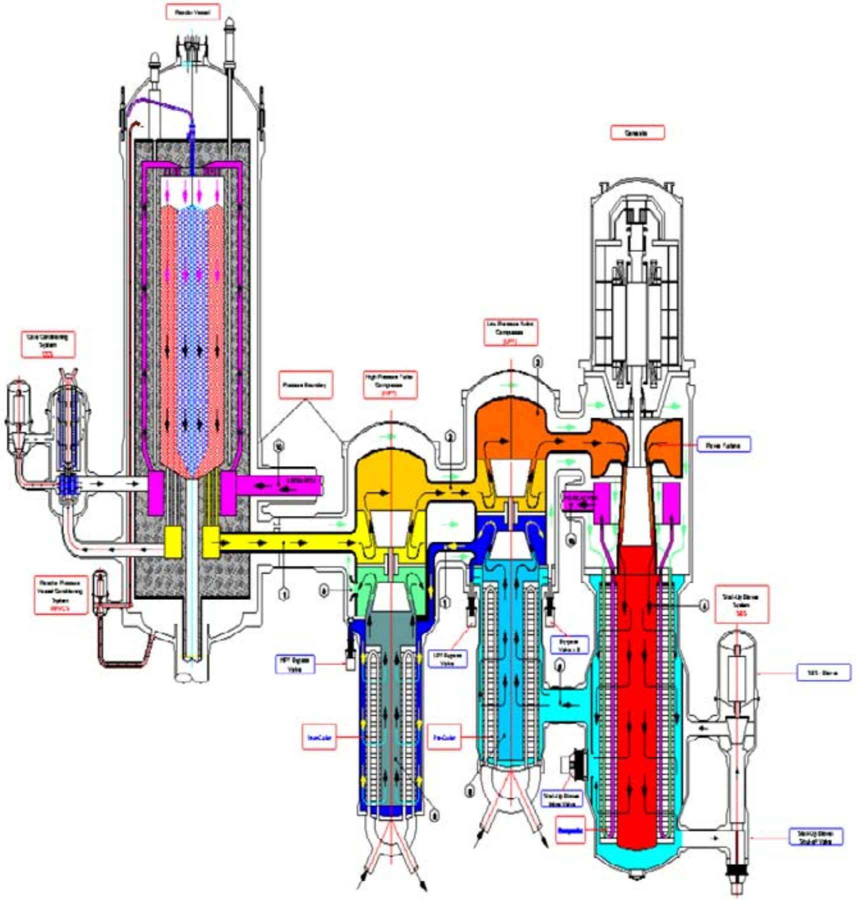
- floating small NPP design for electricity and heat
- Construction of pilot plant (2 units) started 4.2007



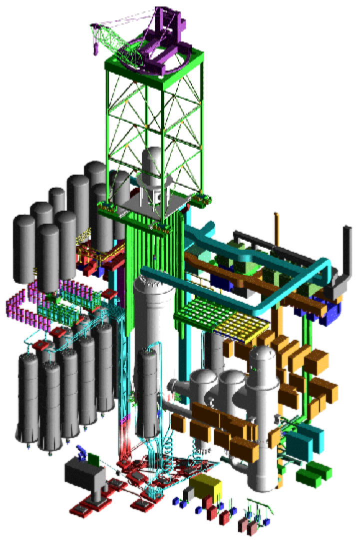
1 Reactor; 6&7 Pressurizers; 2 Steam generator; 8 Steam lines; 3 Main circulating pump; 9 Localizing valves;

4 CPS drives; 10 Heat exchanger of purification and cooldown system; 5 ECCS accumulator

The South African “Pebble Bed Modular Reactor” (PBMR) promises high thermal efficiency and safety



- being developed by Eskom, SA’s Industrial Development Corporation, and Westinghouse
- a direct cycle helium turbine provides thermal efficiency of ~ 41- 43%
- inherent features provide a high safety level



Small and Medium Reactors (SMRs): the cases for and against

(written by Jason Deign on 09.02.2011)

- Challenges in getting large nuclear projects off the ground seems to have renewed interest in small modular reactors. But not everyone is convinced there is a market for smaller plants. Can the SMR developers play ball with the big boys of nuclear?
- This year the nuclear energy industry is thinking small, or at least a segment of it is. Everyone from the International Atomic Energy Agency (IAEA) to Nuclear Energy Insider is staging an event or carrying out a study into small modular reactors (SMRs), while manufacturers are gearing up new product designs.
- Is the hype justified? It depends who you ask.

Initial Position

- SMRs (the acronym also stands for small and medium reactors, defined by the IAEA as having ratings of under 300MW and up to 700MW, respectively) have been around for a long time and have not exactly shown great commercial promise throughout their existence.
- Take the Pebble Bed Modular Reactor being planned in South Africa by the company of the same name, in association with African electrical giant Eskom. After six years of development the project was shelved last September, allegedly due to a lack of customers and investors.
- “SMRs have been tried many times before,” says Steve Kidd, deputy director general of the World Nuclear Association. “If they are so fantastic, why don’t we have them out there already? There is no SMR that has been licensed. I think it is a blind alley.
- “If you have gone through the hurdles to build a nuclear plant then the economics probably suggest you should build it big. We don’t know the economics of SMRs. The whole area of their economies is a grey area.”

Smaller utilities

- However, Kidd acknowledges that it is probably economics that is driving current interest in SMRs: “You don’t need such a large dollop of cap-ex to get a programme underway,” he accepts.
- Adrian Heymer, executive director of strategic programs at the USA’s Nuclear Energy Institute, adds: “Interest is being driven in part by smaller utilities looking at different types of energy generation and which cannot afford a large nuclear plant.
- “If you add capacity in 100MW to 300MW increments it’s easier on the planning. And you can bring them on in stages, so you are still getting 600MW to 700MW in a 10 to 15-year period but you can finance it as you go forward.”

Smaller utilities

- Another advantage of an SMR design, he says, is that because most of the components can be shipped ready-built from the manufacturer, “it doesn’t take as long to build. You can assemble most of the plant in a factory.”
- According to Jay Harris, an independent consultant, a further reason why some utilities might be keen on SMRs is because they provide greater base load flexibility as intermittent renewable energy sources are increasingly integrated into the grid.
- The danger for a utility that is bound by regulation to accept renewable energy is that if most of its base load comes from a single nuclear source then a peak in renewables could mean a portion of the base is no longer profitable, and there may be further costs if the plant has to shut.

Power pricing

- “A utility does not want to be tied into a fixed base load,” he says. “If renewables are putting out a lot of power it puts you into a position of negative power pricing, so the constant base load is a problem,” Harris explains.
- Clearly, having an array of SMRs instead of a single large plant, could help the utility cope with the peaks and troughs associated with renewable energy production. And an added advantage, Harris says, is that many SMRs are being designed with load-following capacity in mind.

Power pricing

- However, most experts agree the SMR concept still has to jump through a few hoops before its feasibility is established.
- Heymer echoes Kidd’s concerns about plant financials: “If you’re looking at a 60-year lifespan you’ll need to know about the operations and maintenance costs, because you have got more reactor vessels, more pipes and so on.”
- In addition, SMRs are unlikely to be viable in countries such as the United States unless there are changes to the current regulatory regime, Heymer says.

Island states

- For these reasons, most experts agree that the immediate market for SMRs is in developing countries or island states where placing a small reactor still might make more economic sense than building a large one.
- “Initially, it’s a developing country thing,” says Geoff Bolton, principal consultant at Geoff B Associates. And while manufacturers worldwide are readying a host of SMRs for the market, in practical terms it could be some time before they see the light of day.
- “I think they’re probably a fair way down the road still,” Bolton says. “In the 2020s, maybe, verging on the 2030s.”

Summary

- Modern Small Reactors are simplified efficient designs, can be mass produced economically, and will dramatically reduce siting costs.
- The high level of passive safety technology combined with the lack of an environmental impact makes SMRs a wise choice for certain future energy needs.
- Their introduction still is not certain and simple.
- LWR versions are closer to the deployment but other more advanced technologies could be in production in next 10 years.
- SMRs can be applied in both big and small electricity grids and some advanced power control capabilities will be needed except in special isolated applications.
- SMRs do not compete directly with large plants—they offer customers a greater range of options, but they will share some of the common destiny.

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