Joint IAEA-ICTP Workshop on Reactor Physics, Thermal-hydraulics and Plant Design Engineering for SMRs, Trieste, Italy, 13 – 17 April 2026

Reactor Thermal-Hydraulics and System Engineering of integral PWR type SMRs

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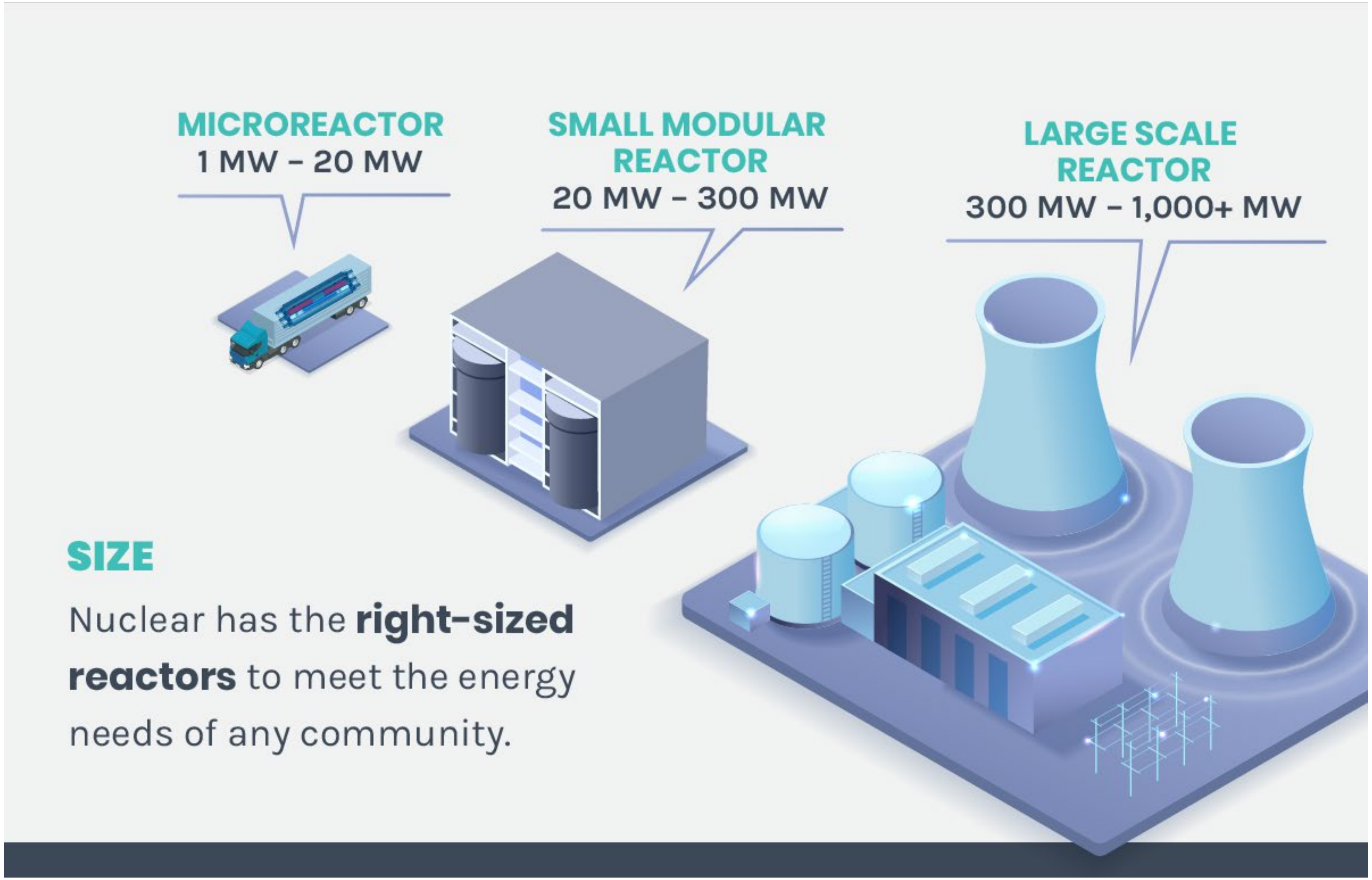
SMR – Definition not only by Size



SMR Design Characteristics

Simplified Design

- Modularization
- Compact
- Reduced Emergency Planning Zone

Affordability

- Reduced upfront capital cost
- Longer Design Life
- Enhanced Operability and Maintainability

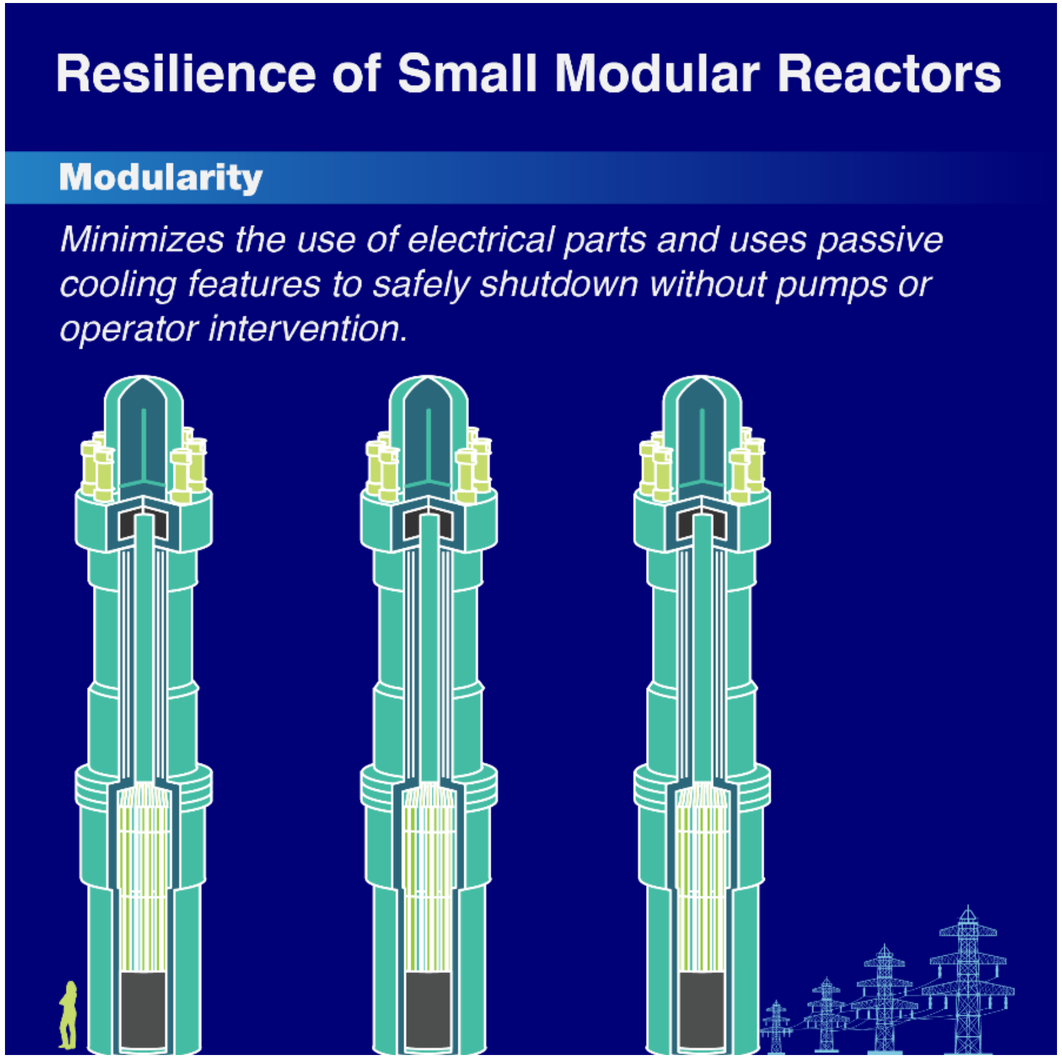
Enhanced Safety Features

- Enhanced Safety Margin
- Lower Core Damage Frequency
- Inherent and Passive Safety Features

Flexibility

- Load Following Capability
- Coping with the Intermittent Renewables
- Non-electric Applications

SMR Definition: Modularity



- Modular construction
- “Ability to fabricate major components of the nuclear steam supply system in a factory environment and ship to the point of use”
- Minimized on-site preparation
- Substantially reduce the lengthy construction times
- Multi- module as per energy demand

Modularity in IAEA Technology Roadmap for SMR

Reference: IAEA Nuclear Energy Series NR-T-1.18 (2021)

- **‘modular design’:** an approach whereby the design of a component, assembly or structure is subdivided into modules to be more easily assembled and may be replaced over time to facilitate ease of maintenance.
- **‘modular construction’:** a technique in which modules are constructed on-site or off-site and shipped to their final destination where they are assembled in a building.
- Modules can be **fabricated in parallel** with early site excavations and preparation work, reducing the overall construction time thus a reduction in costs
- For large nuclear installation, such construction approach **may necessitate large lift and rigging capabilities**, sometimes the building of temporary structures, and increased transportation costs (e.g. large trailers and barges).
- **Minimum information** disseminated by designers and builders on how the **safety of transporting modules** as well as fuelled modules is addressed

Recent Concepts of Modularity

- **'modular design'** for systems, structures, and components applying standardization, assuring repeatability in factory production line
- **'modular construction': size optimization** of modules, avoiding huge/large size modules that need to be dissembled for transportation (disbenefit)
- Modules are fully tested in factories to reduce activities at the sites
- Specific cases for SMRs for floating/transportable NPPs, microreactors for which the reactors with fuelled core are factory tested, sealed and transported to sites.
- For the latter: new startup designers and embarking countries need to have in-depth understanding on requirements that must be satisfied to ensure safety and to protect people, property, and the environment from harmful effects of ionizing radiation during the transport of radioactive material. This protection is achieved by requiring: (a) Containment of the radioactive contents; (b) Control of external dose rate; (c) Prevention of criticality; and (d) Prevention of damage caused by heat:

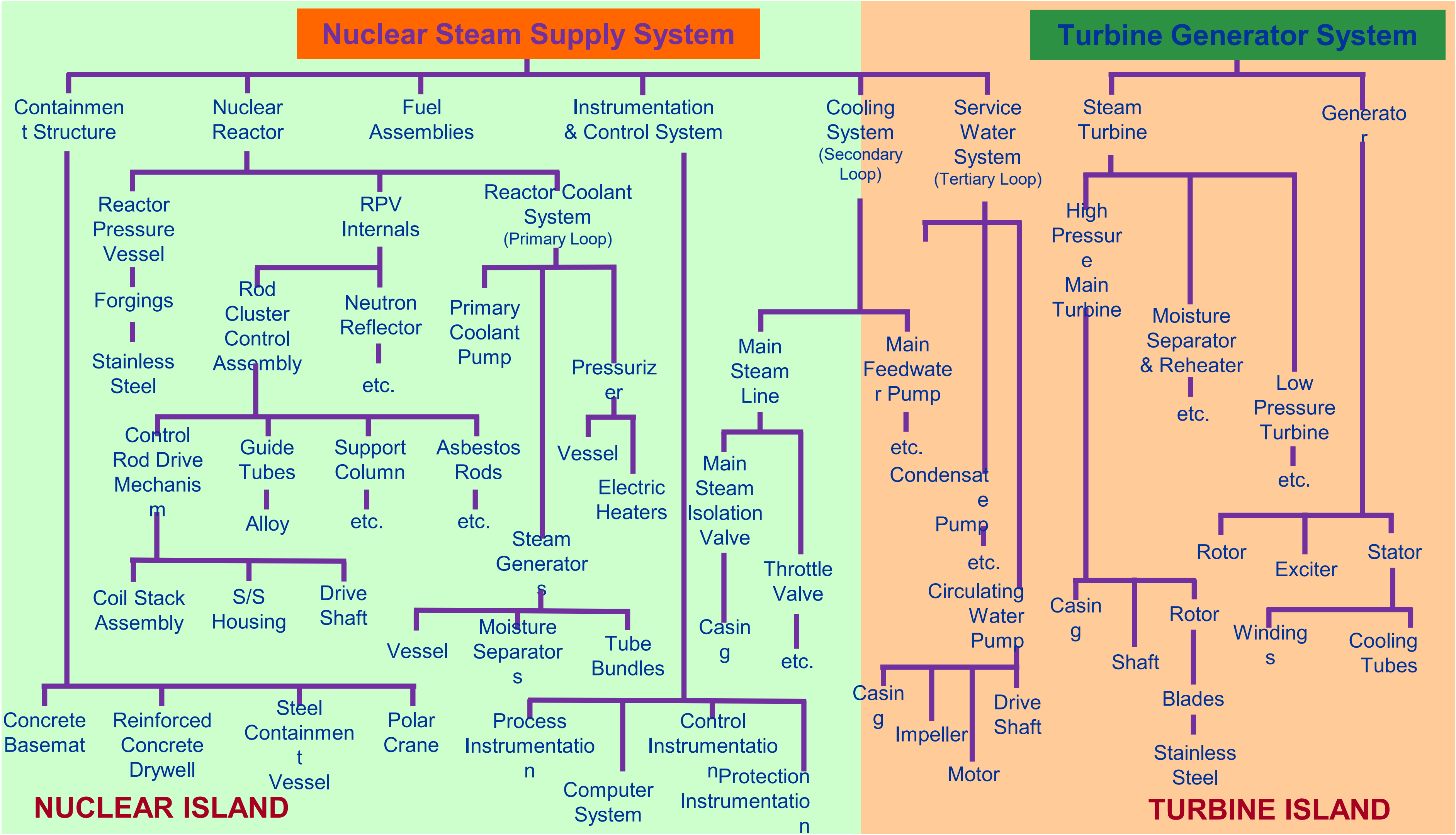
Specific Safety Requirements

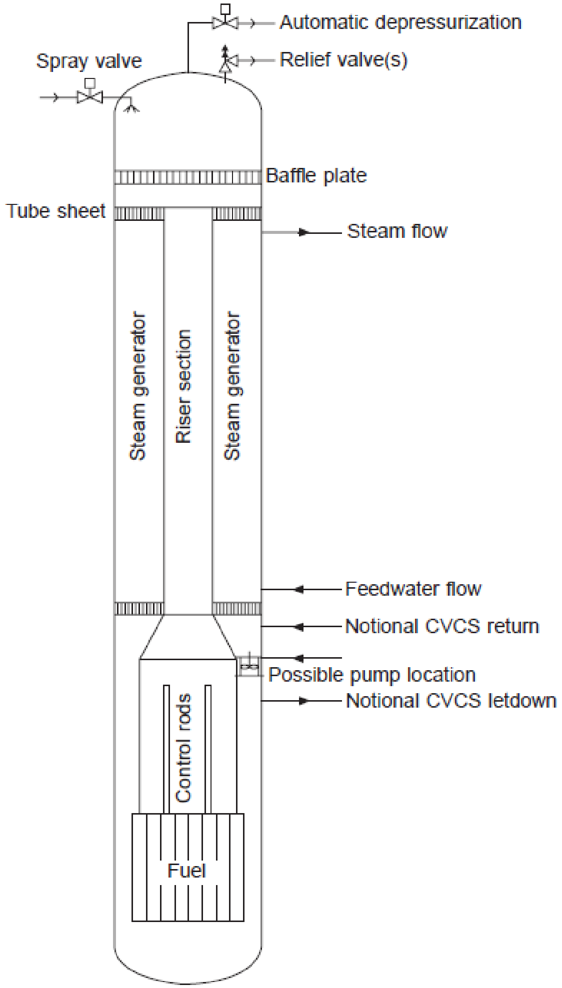
No. SSR-6 (Rev. 1)

Regulations for the Safe Transport of Radioactive Material

2018 Edition

Typical Trees of System Structure and Component - PWR



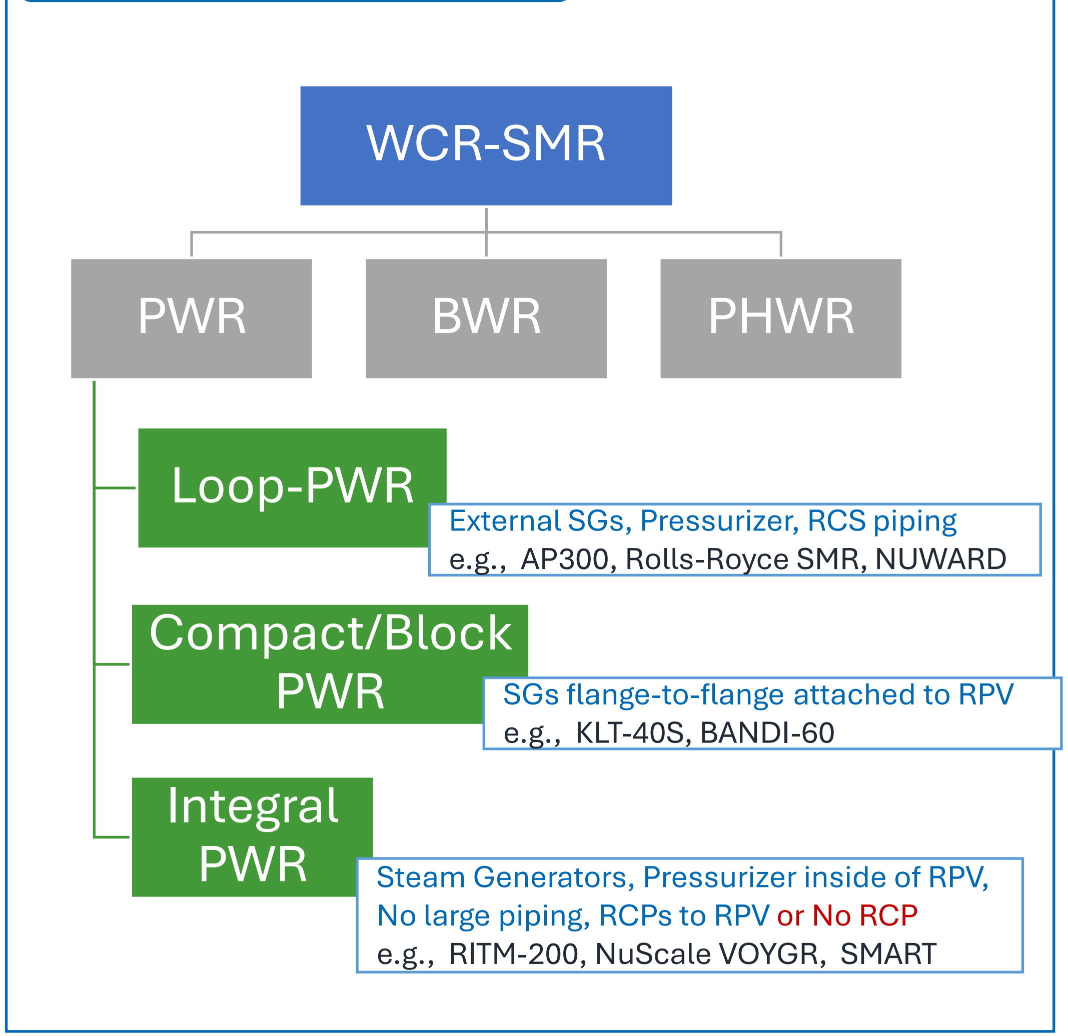


Integral PWR SMR

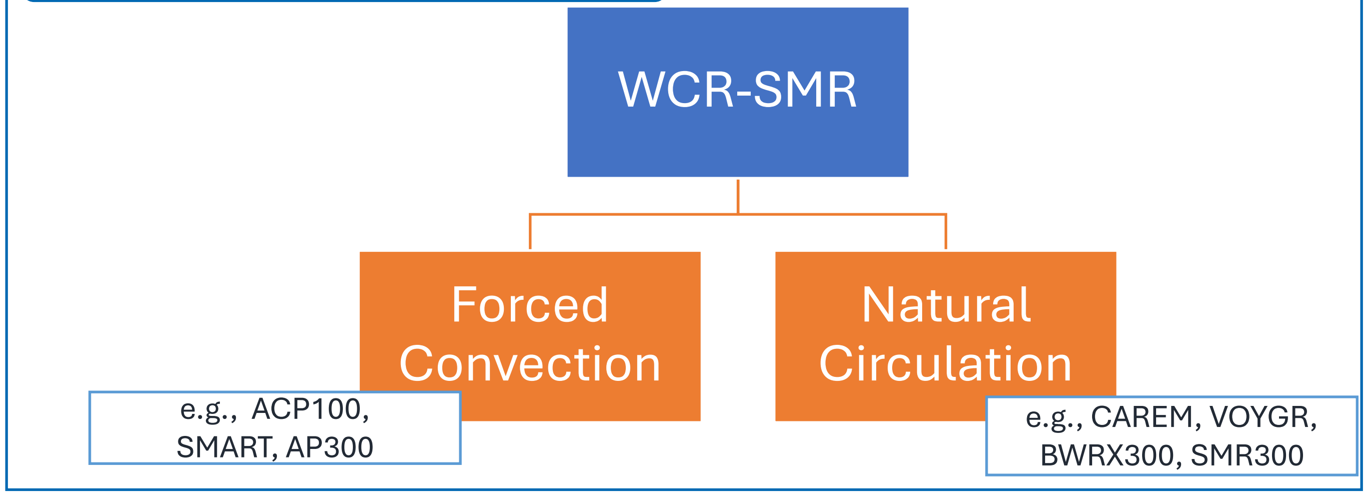
Source: Handbook of SMRs

Approach to the Taxonomy of the WCR-SMRs

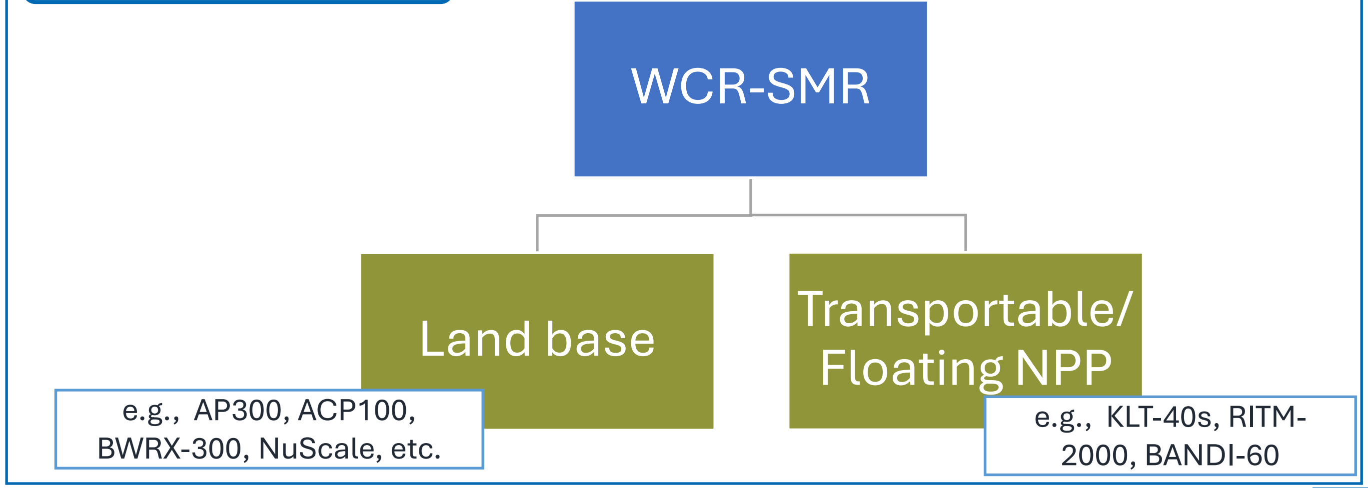
By RCS Configuration



By Heat Transport System

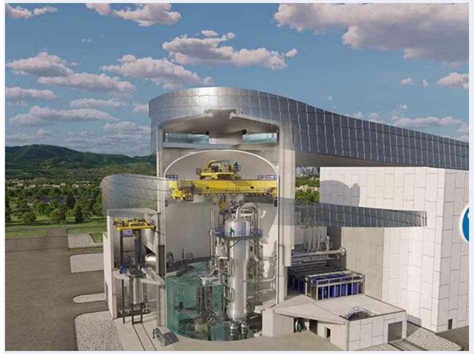
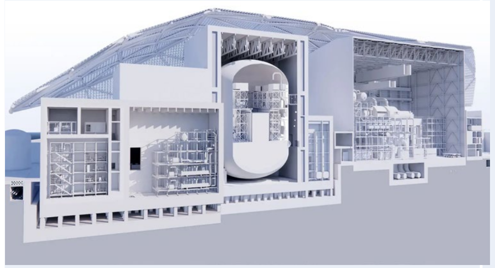
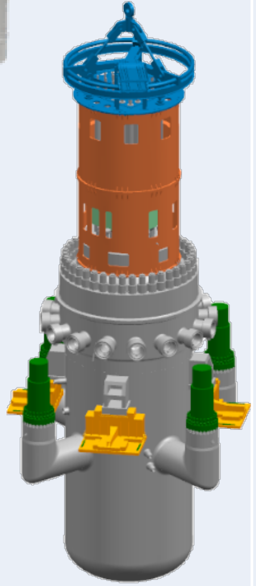
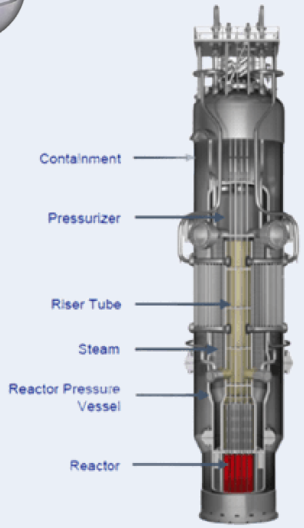
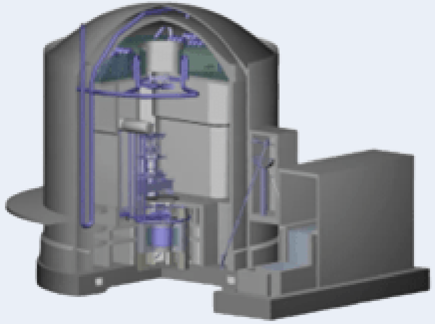
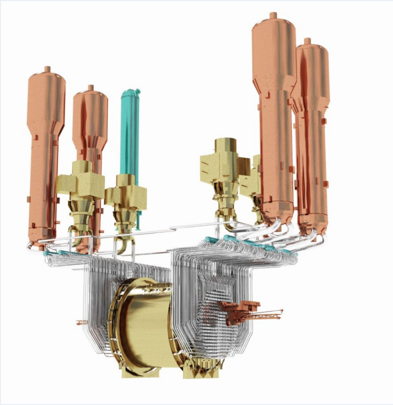


By Plant & Siting



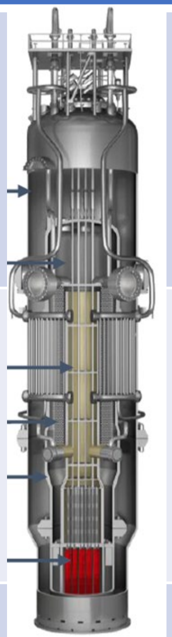
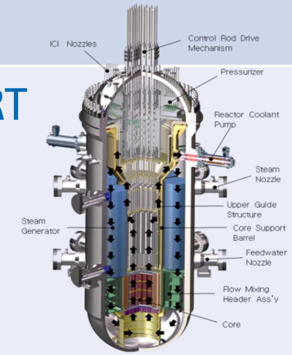
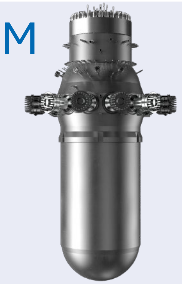
WCR-SMRs

By RCS Configuration

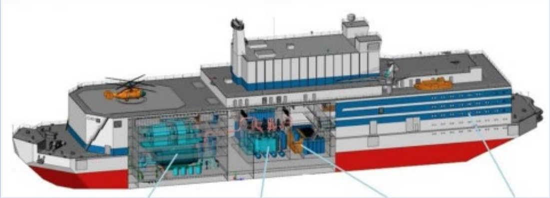
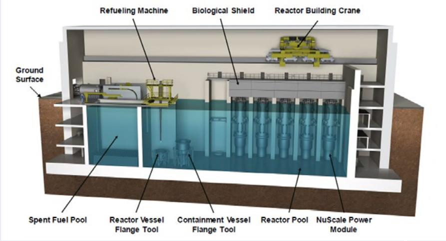
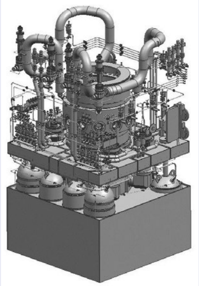
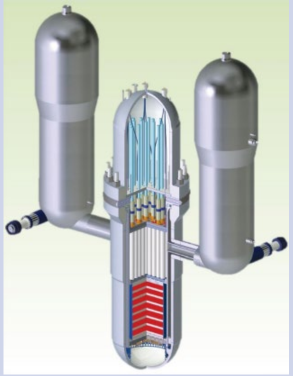
Loop-PWR	Compact/Block PWR	Integral PWR	BWR	PHWR
AP300  Rolls Royce SMR 	RITM-200N  ACP100 	SMART  VOYGR 	BWRX-300 	AHWR300-LEU  CANDU type SMR 

WCR-SMRs

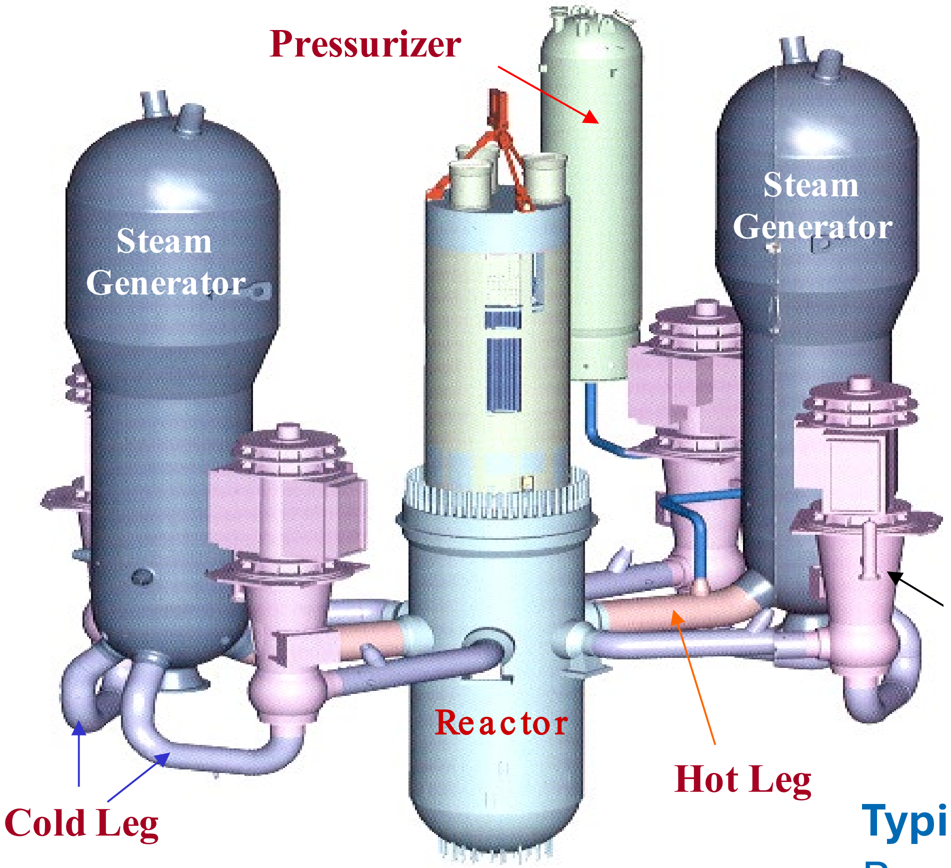
By Heat transfer system

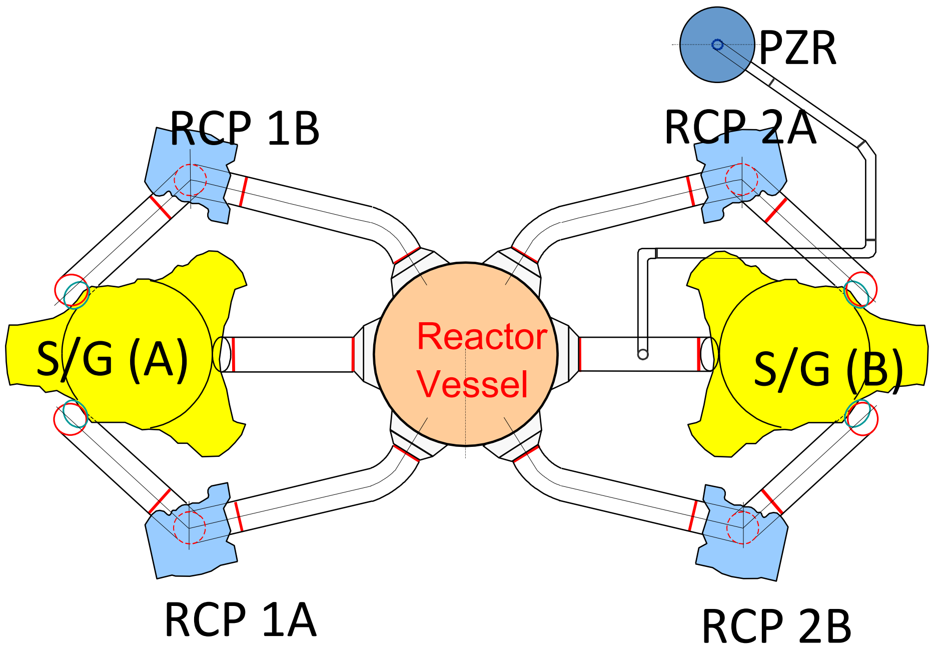
Forced circulation	Natural circulation
ACP100 	VOYGR 
SMART 	CAREM 
RITM-200N 	BWRX-300 

By Plant siting

Land base	Floating
AP300 	KLT-40S 
VOYGR 	RITM-200M 
0NRITM-200N 	BANDI-60 

Reactor Coolant System of PWR

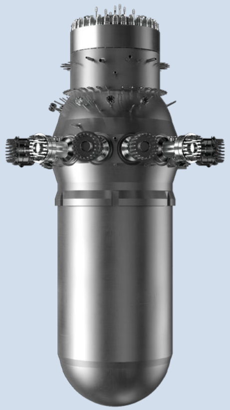
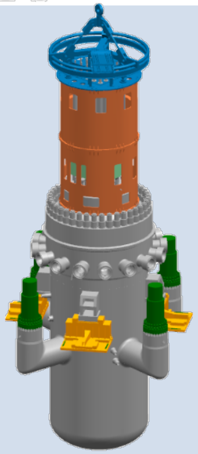




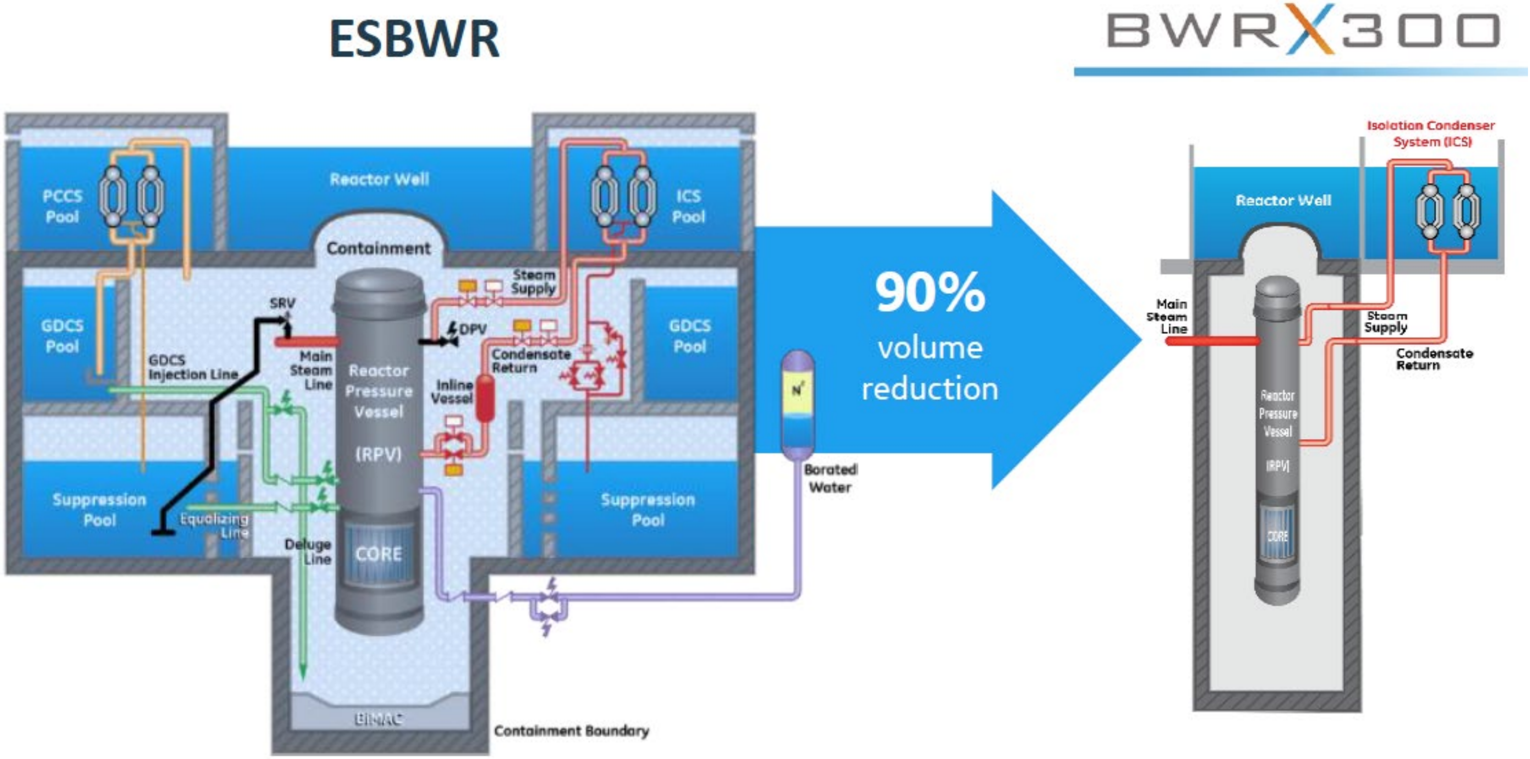
Typical loop-type RCS configuration:

Reactor Pressure Vessel, in each loop: steam generator, reactor coolant pump(s), interconnected legs between RPV and SG, pressurizer connected to one of the hot leg.

Water-cooled reactor type Small Modular Reactors (Examples)

CAREM	ACP100	NUWARD	SMART	NuScale	BWRX-300
					
Design Status: Advanced stage of construction in Atucha site, Argentina	Design Status: Detailed design; Started construction July 2021, connection to the grid by end 2025	Design Status: Conceptual design; Consortium launched in September 2019, Design Change applied in 2023.	Design Status: Licensed/Standard Design Approval (July 2012), Pre-Project Engineering completed	Design Status: Standard Design Approval received in Oct 2023, to start construction by end of 2030 in US or Europe	Design Status: Construction persmit issued in April 2025 for Darlington site, 4 units, operation by 2030
• CNEA, Argentina • Integral-PWR • 100 MWt / 30 MWe • Natural Circulation • Core Outlet Temp: 326°C • Enrichment: 3.1% (prototype) • Refuel interval: 14 months (prototype)	• CNNC, China • Integral-PWR • 385 MWt / 125 MWe • Forced circulation • Core Outlet Temp: 319.5°C • Enrichment: <4.95% • Refuel interval: 24 months	• EDF led consortium, France • Integral-PWR • 540 MWt x 2 / 170 MWe x 2 modules • Core Outlet Temp: 307°C • Enrichment: <5% • Refuel interval: 24 months	• Joint Design of KAERI, Republic of Korea with K.A.CARE, Saudi Arabia • Integral-PWR • 365 MWt / 107 MWe per module • Core Outlet Temp: 322°C • Enrichment: <5% • Refuel interval: 30 months • For cogeneration	• NuScale Power, LLC, United States of America • Integral-PWR • Natural Circulation • 200 MWt / 60 MWe per module x 12 Modules • Core Outlet Temp: 321°C • Enrichment: <4.95% • Refuel interval: 24 months	• GE-Hitachi & Hitachi-GE Nuclear Energy, USA and Japan • Boiling Water Reactor • Natural Circulation • 870 MWt / 290 MWe • Core Outlet Temp: 287°C • Enrichment: <4.95% • Refuel interval: 24 months

Approaches to Nuclear Island Design – Boiling Water Reactor



Systems/components eliminated:

- Suppression Pool
- GDCS Pool
- Safety Relieve Valves & Spargers
- Depressurization Valves
- BiMac (core catcher)

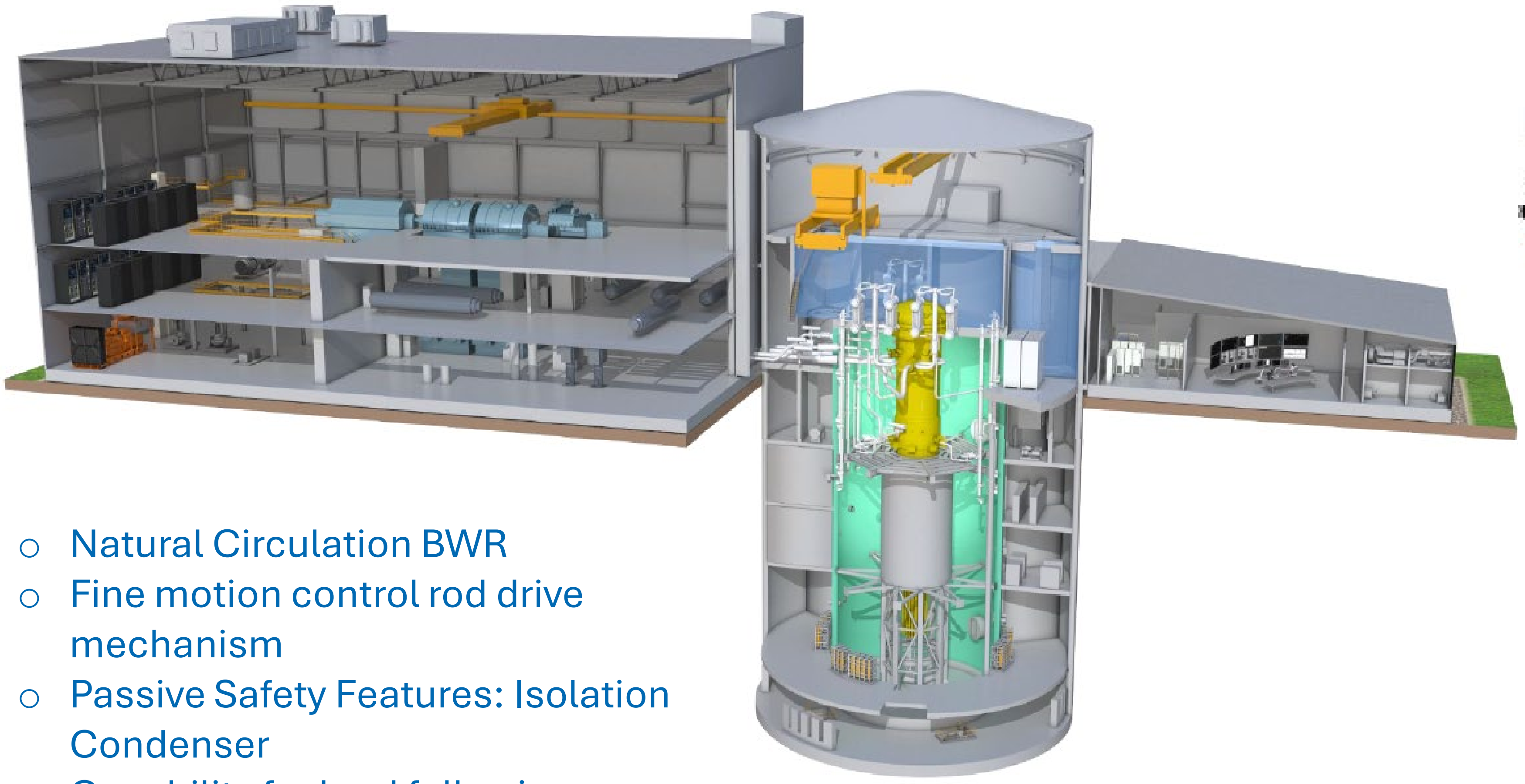
Systems/components simplified:

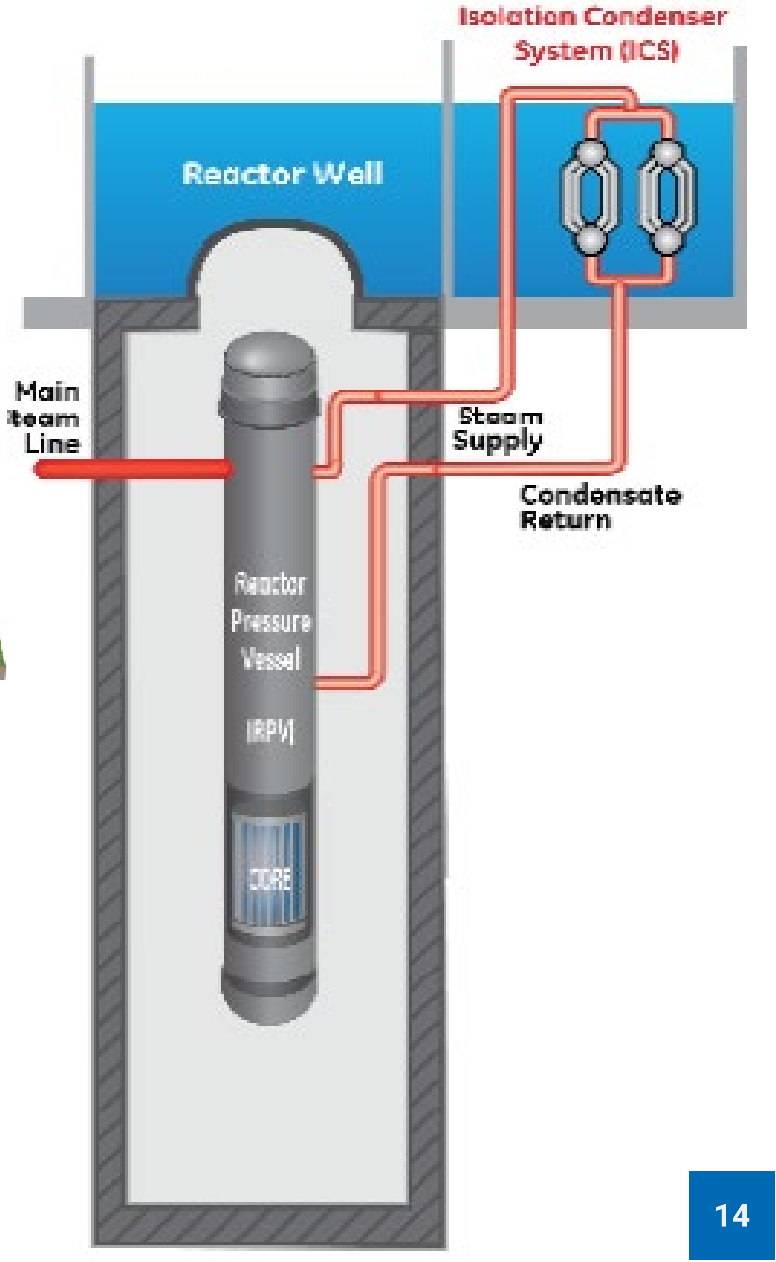
- Passive Containment Cooling
- Containment (use of SC)
- Boron injection
- Security (built into design)
- Turbine
- Generator (air cooled)

Outcome: Design Simplification

> 50% building volume reduction/MW and >50% less concrete/MW

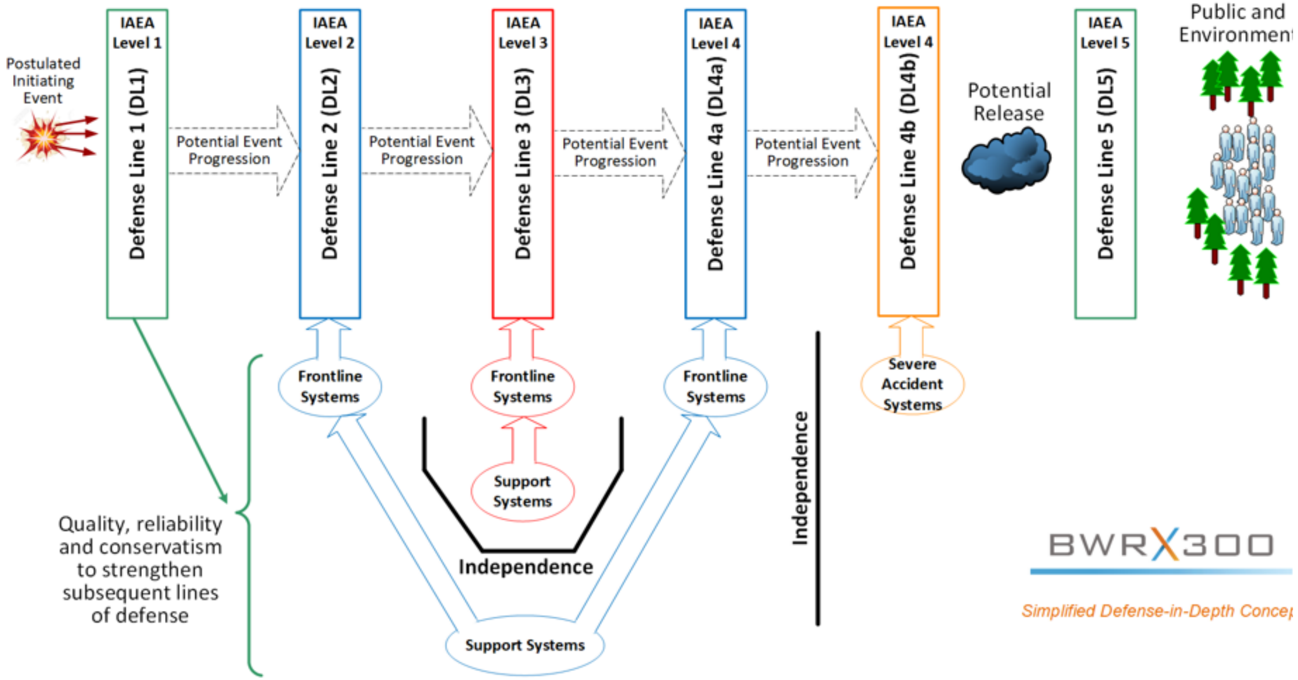
Approaches to Nuclear Island Design – Boiling Water Reactor

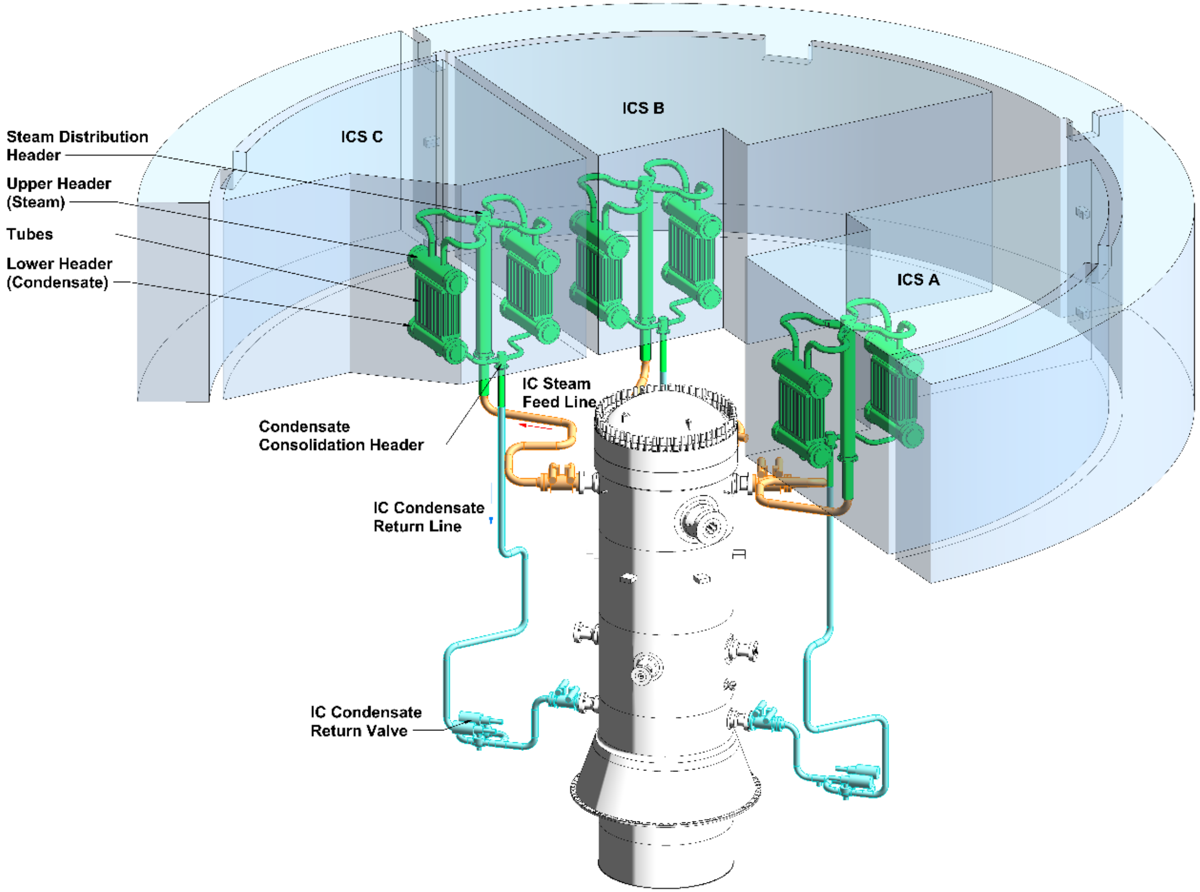




- Natural Circulation BWR
- Fine motion control rod drive mechanism
- Passive Safety Features: Isolation Condenser
- Capability for load following

Approaches to Engineered Safety Features – BWR





IAEA TECDOC 626 Category C Passive safety system

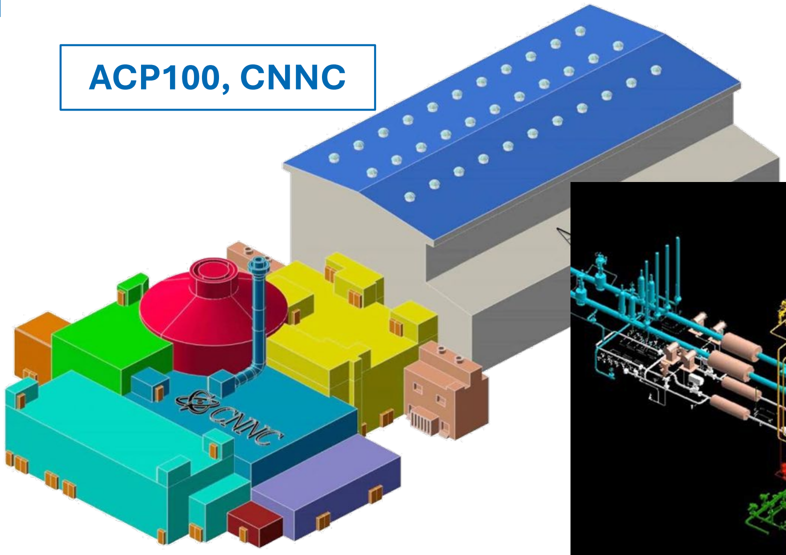
- Operates without power or external cooling
- Condensate return line opens on signal or low of power
- Steam generated in RPV and condensation in elevated heat exchanger drives flow

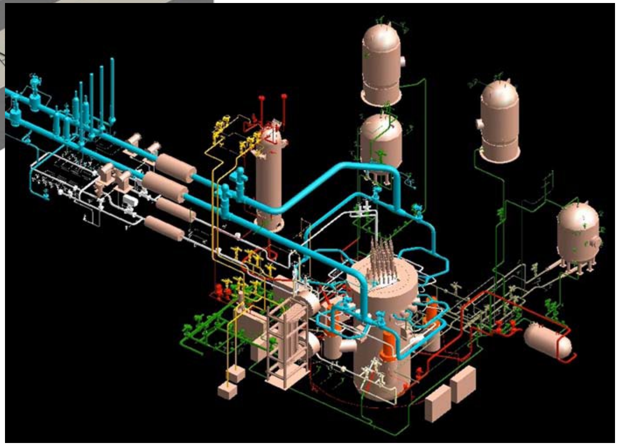
IAEA Defense in Depth approach through both redundancy and diversity

- 3 x 100% trains
- Mechanically diverse valves
- Instrumentation and controls are fail safe, with multiple redundant and diverse I&C platforms

Approaches to Nuclear Island Design – integral PWR

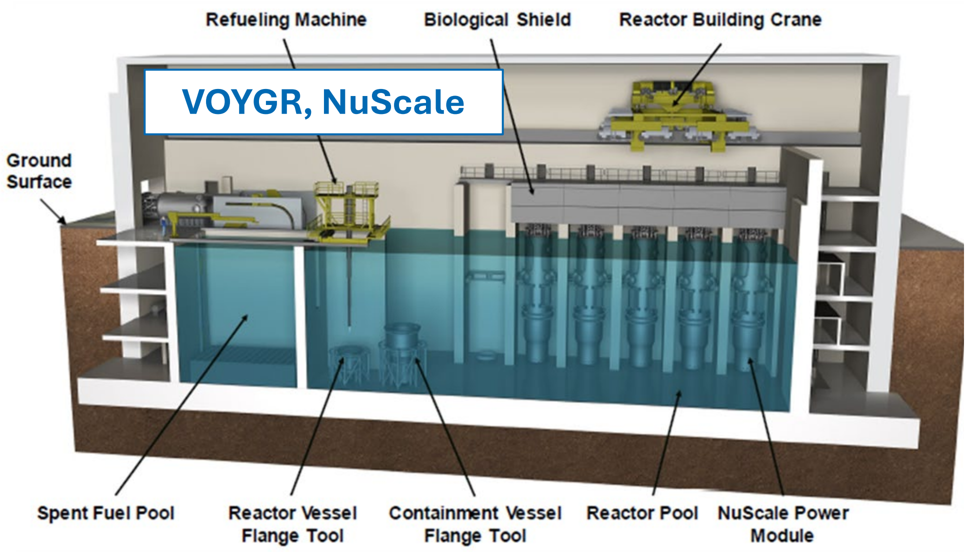
ACP100, CNNC

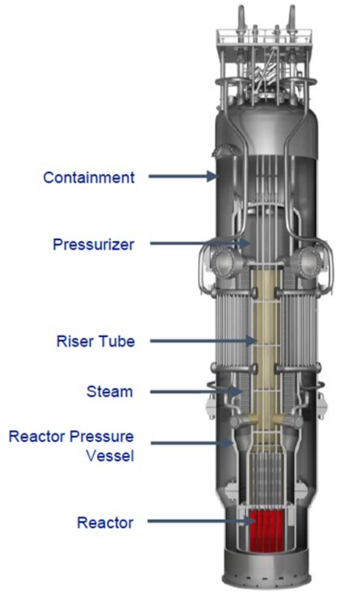


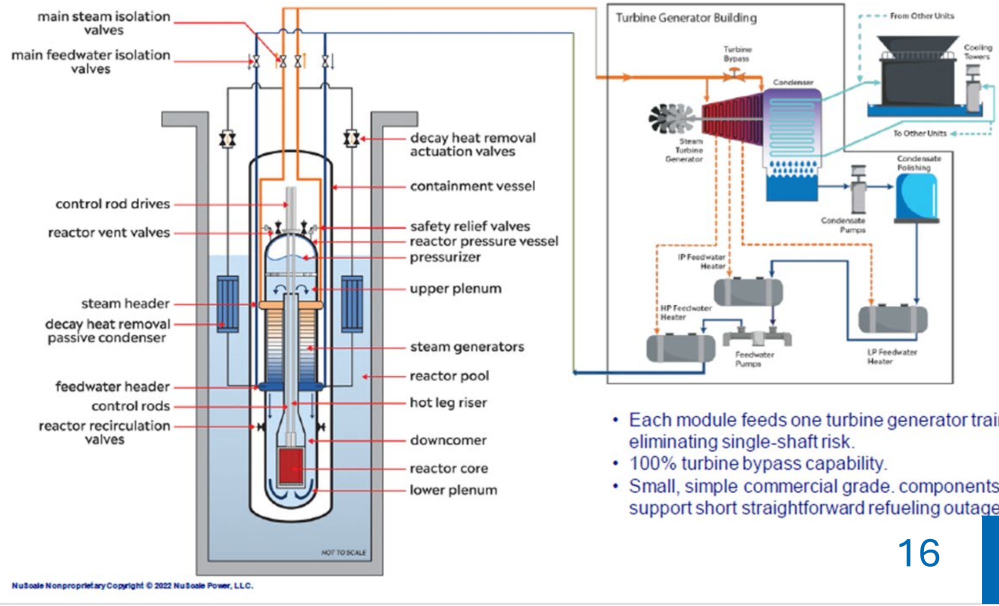


SMART, KAERI

VOYGR, NuScale



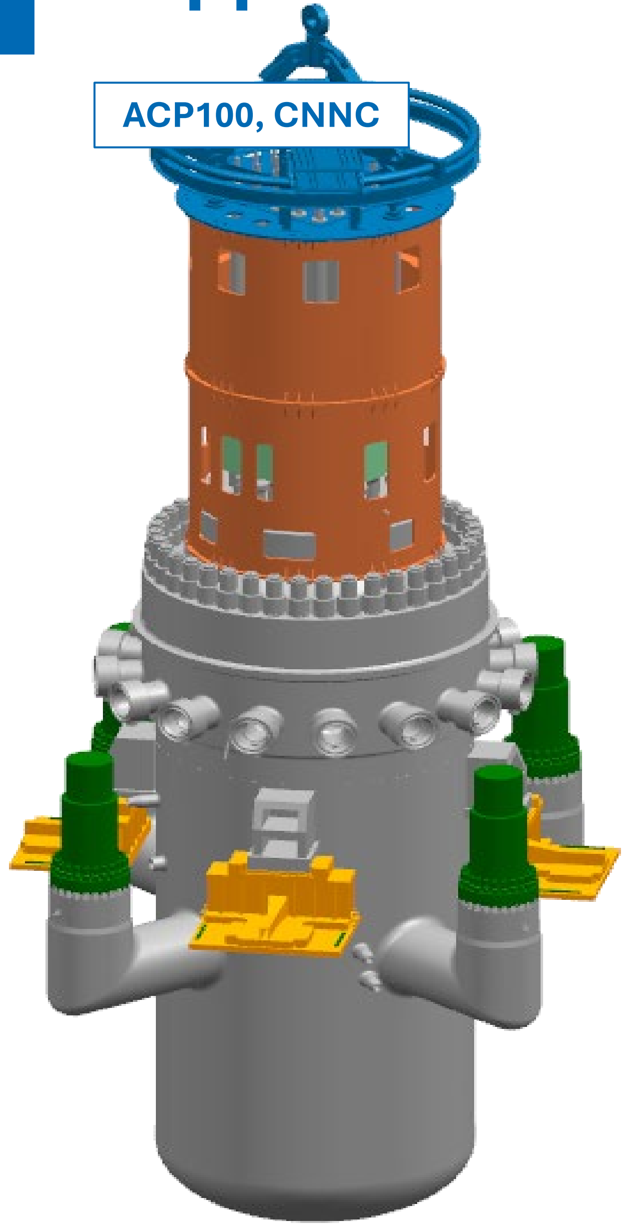




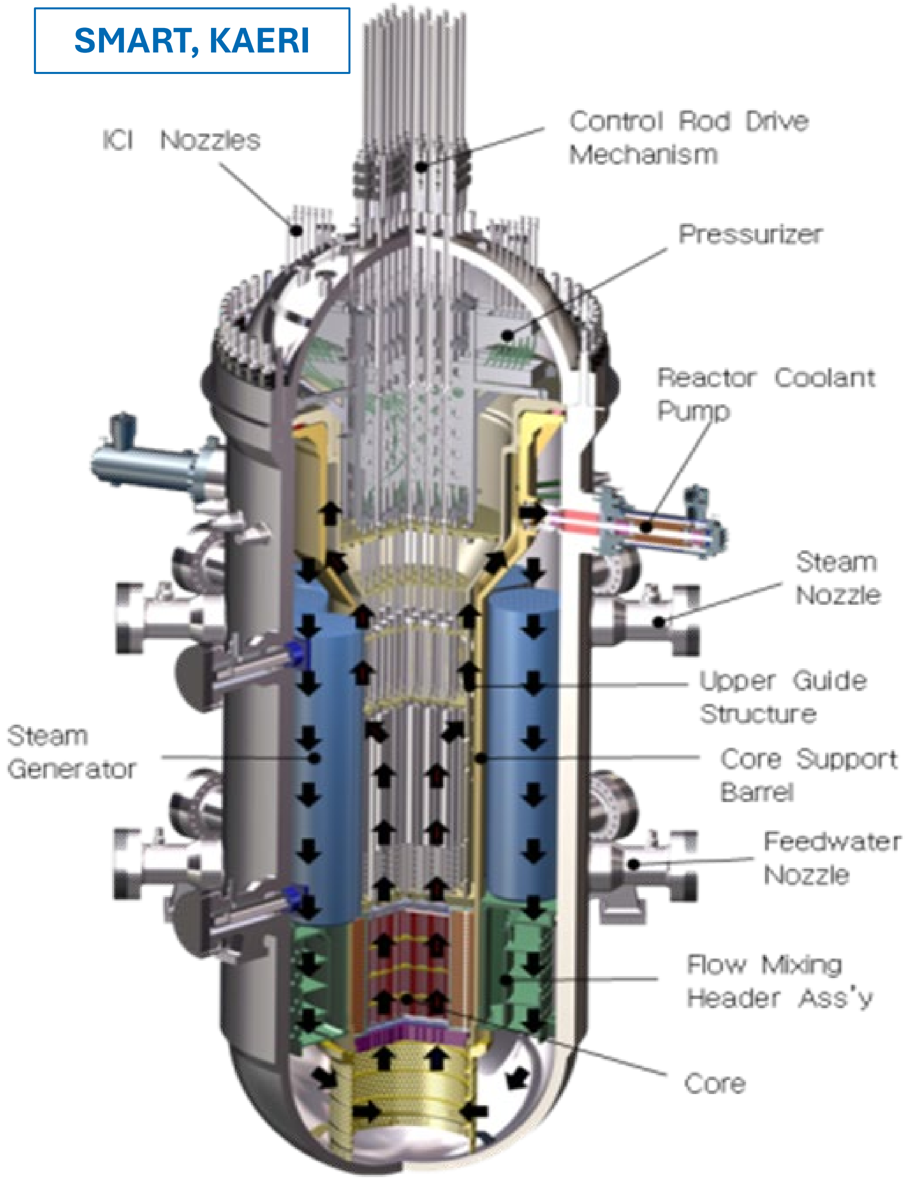
- Each module feeds one turbine generator train, eliminating single-shaft risk.
- 100% turbine bypass capability.
- Small, simple commercial grade. components support short straightforward refueling outages.

Approaches to integrated Reactor Coolant System (i-PWR)

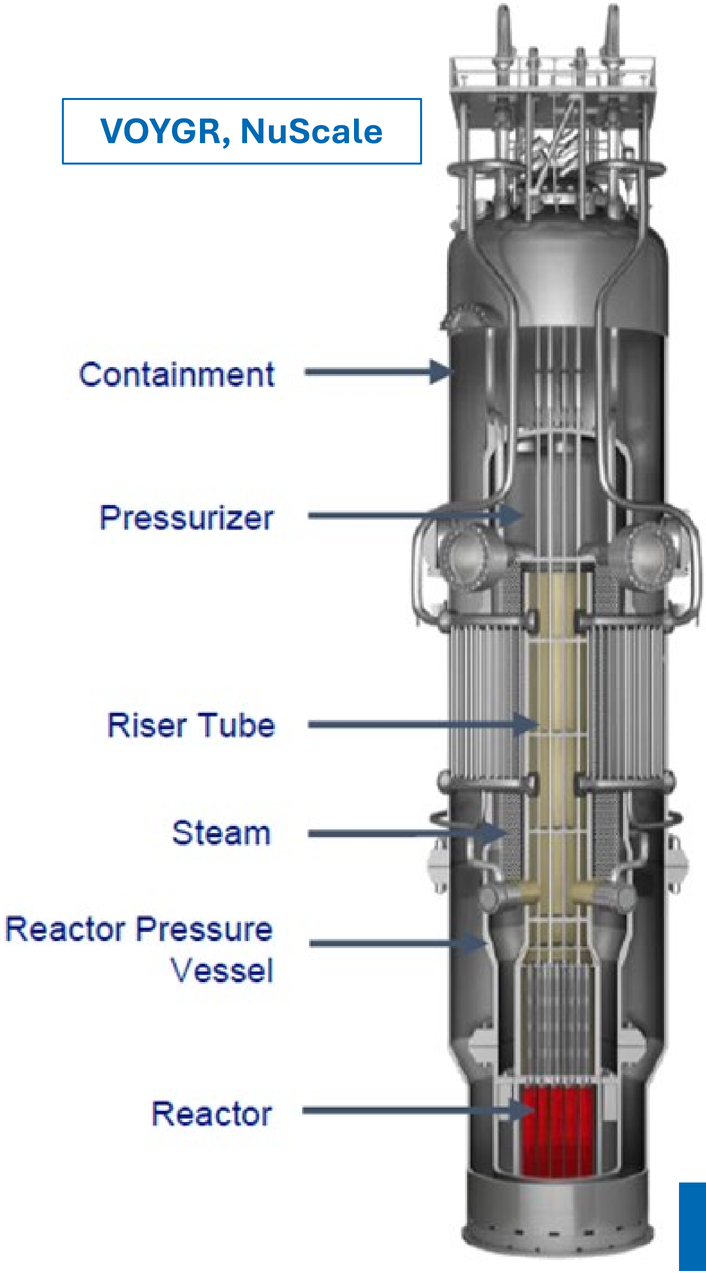
ACP100, CNNC



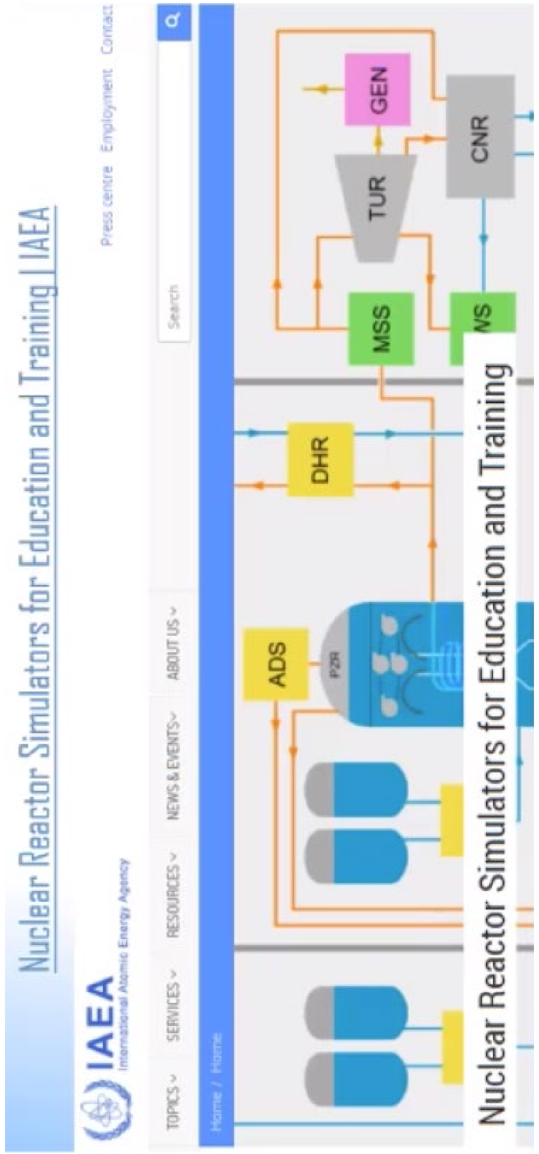
SMART, KAERI



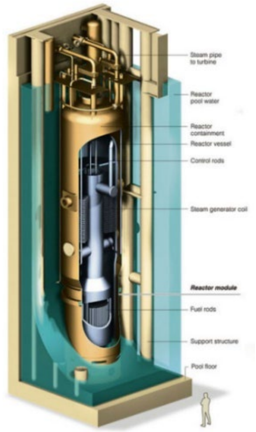
VOYGR, NuScale

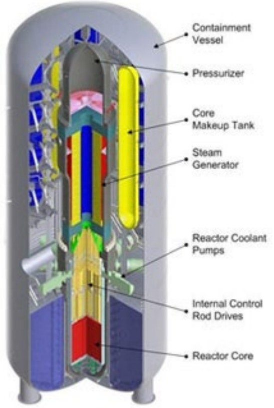


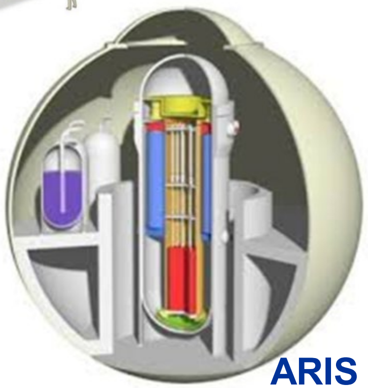
Approaches to Engineered Safety Features – integral PWR



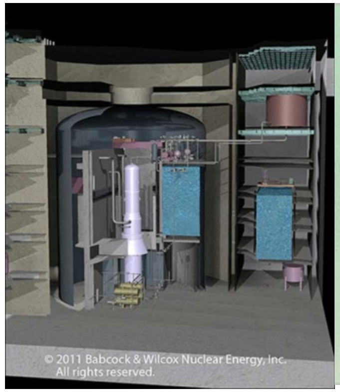
- Enhanced performance engineered safety features
  - Natural circulation primary flow
  - Reactivity control (internal CRDM, gravity driven secondary shutdown)
  - Residual heat removal system (passive heat removal systems)
  - Safety injection System (active and/or passive injection)
- Improved containment options
  - Passively cooled Containment
  - Concrete containment with spray system
  - Pressure suppression containment
- Severe accident mitigation features
  - In-vessel Corium retention
  - Hydrogen passive autocatalytic recombiner
  - Inerted containment

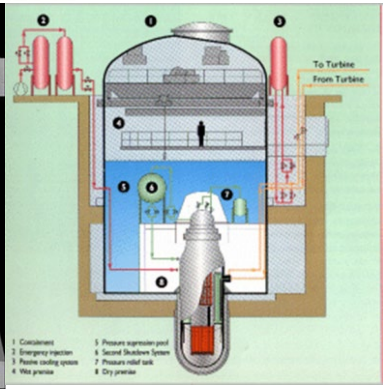






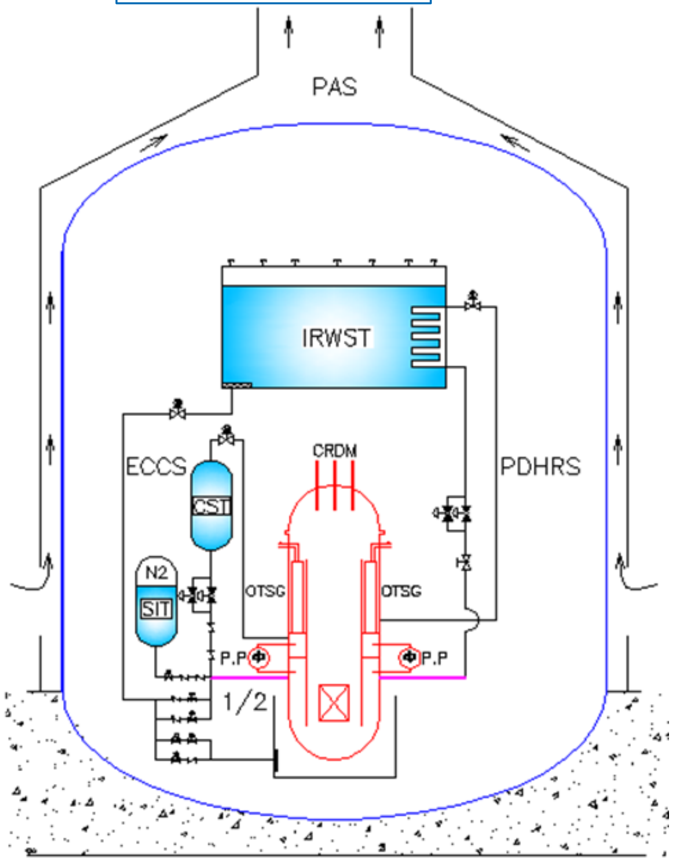
ARIS Database



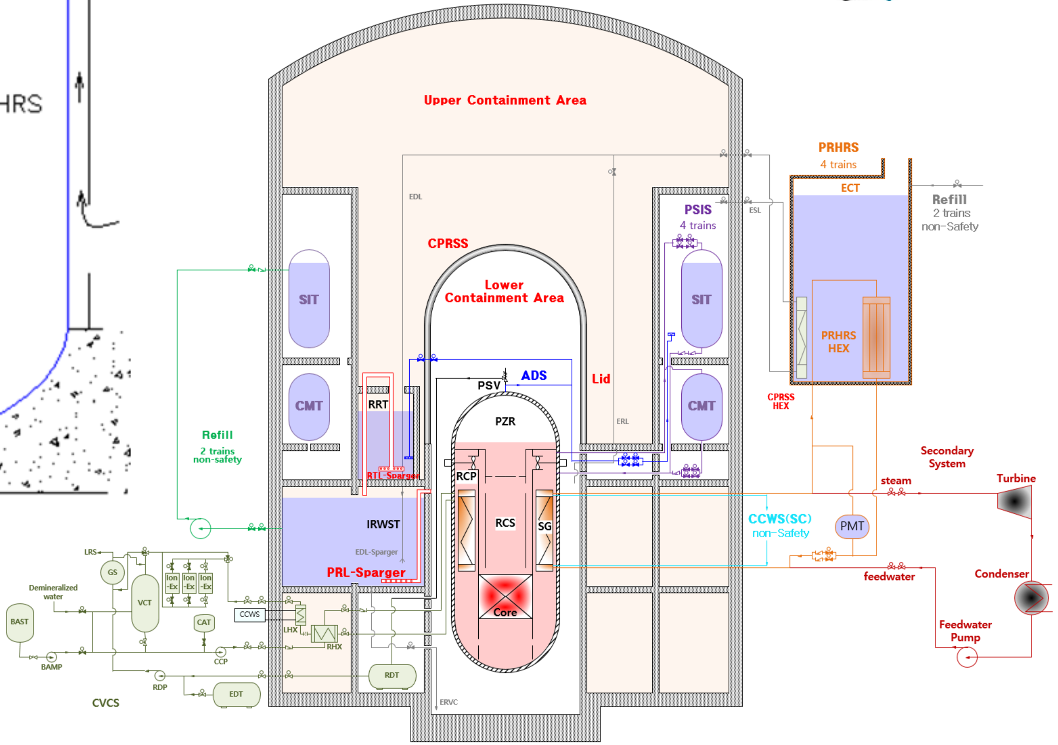


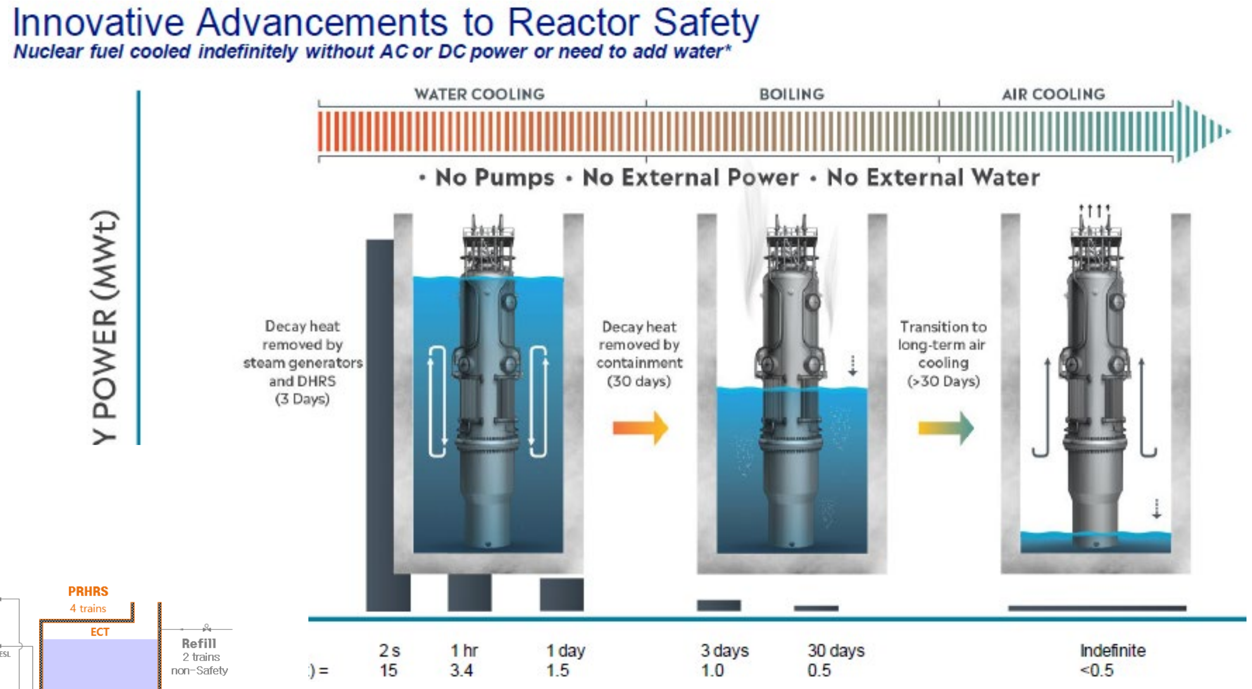
Approaches to Engineered Safety Features – integral PWR

ACP100, CNNC



SMART, KAERI

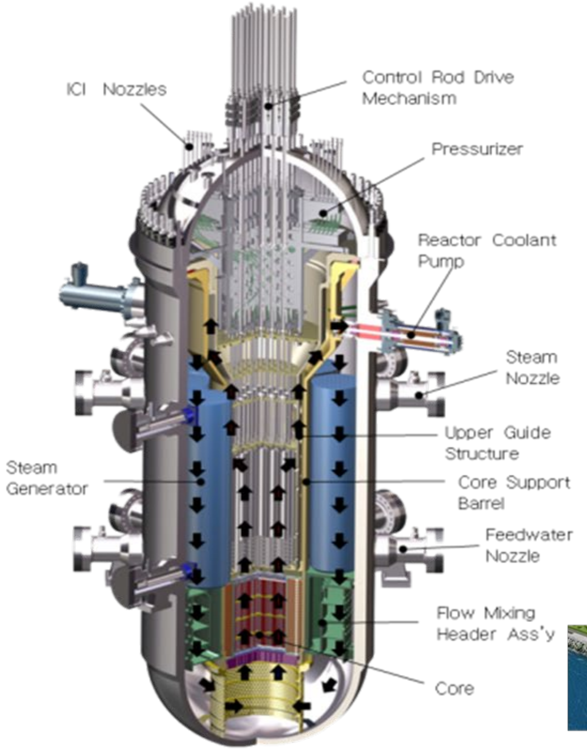


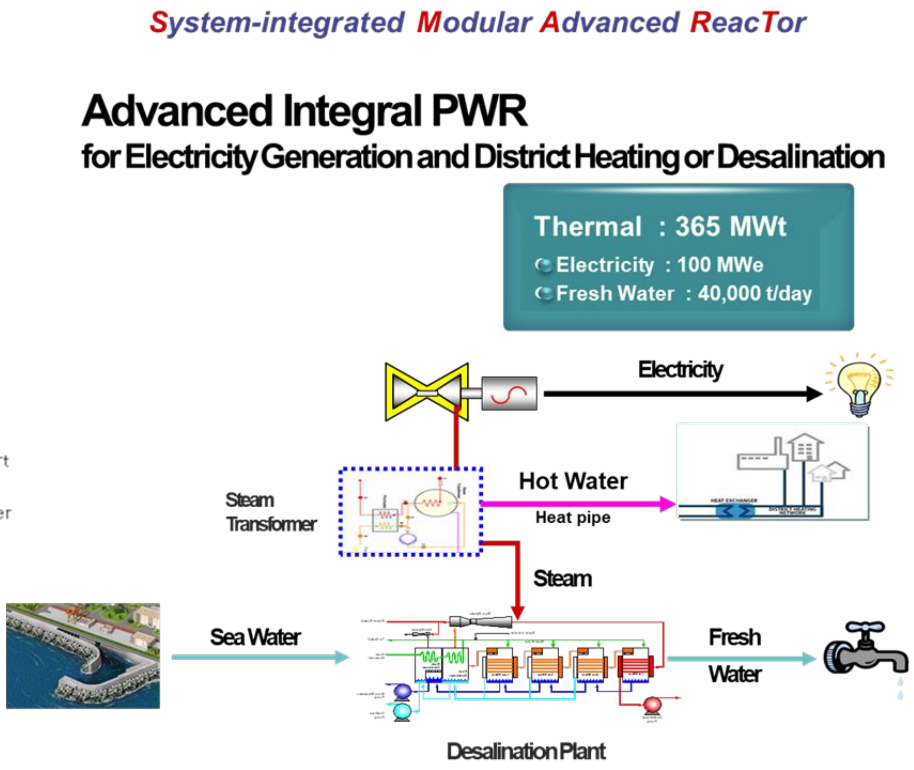


VOYGR, NuScale

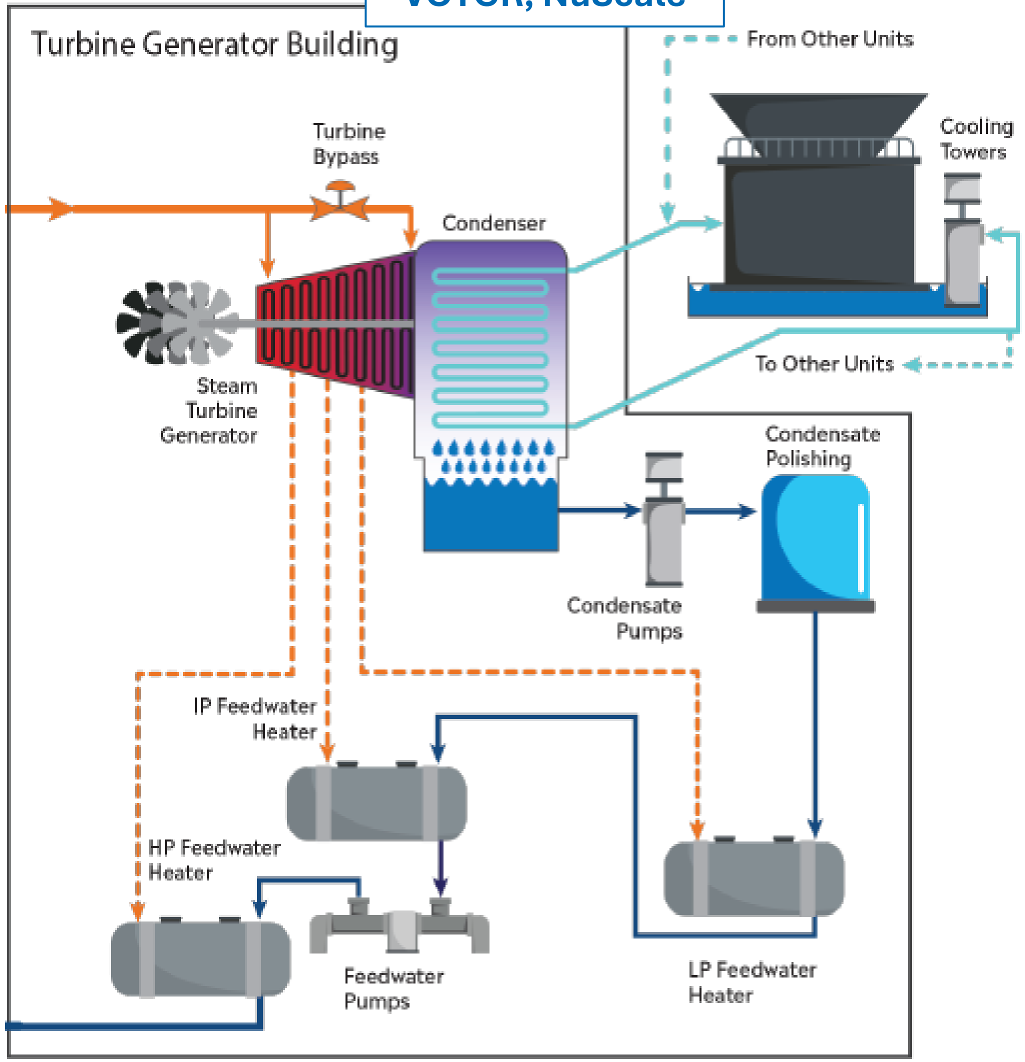
Approaches to Power Conversion System – integral PWR

SMART, KAERI

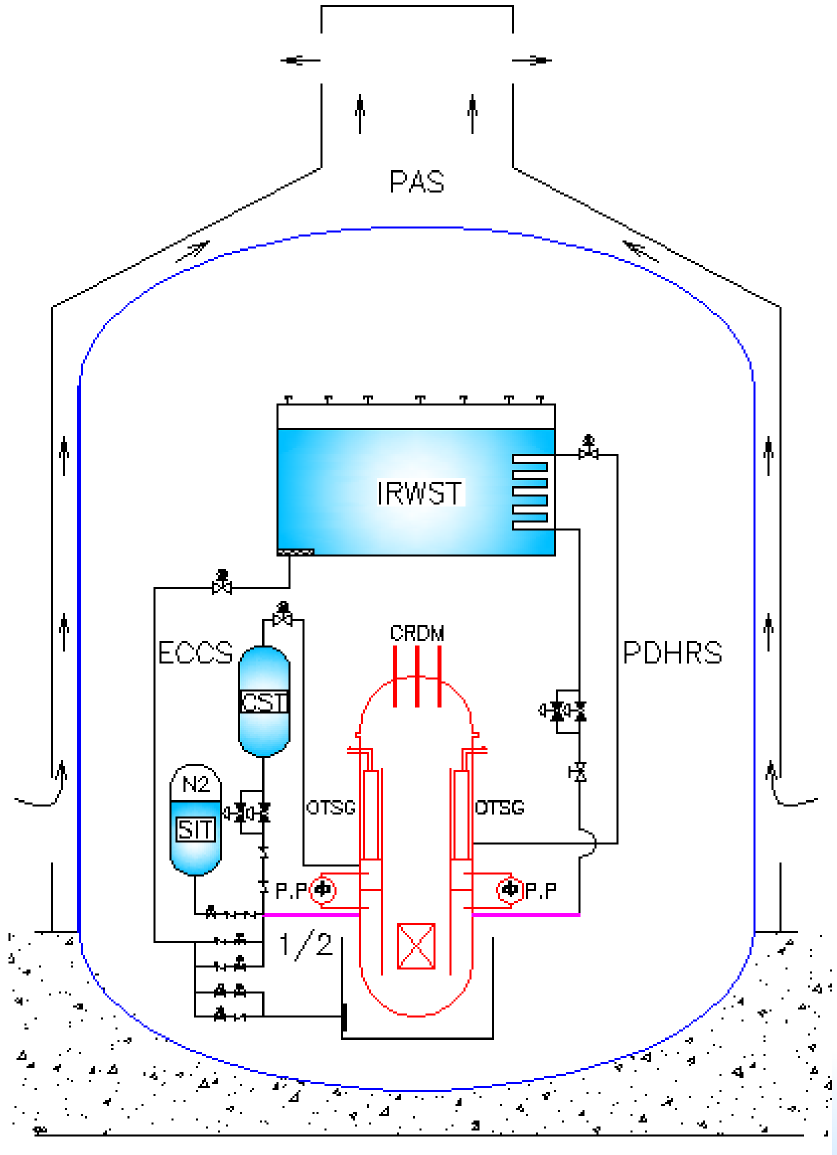




VOYGR, NuScale



Engineered Safety Features – ACP100



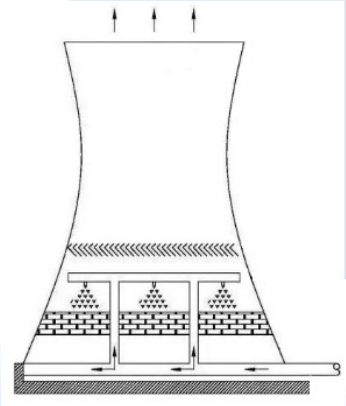
Safety System Configuration

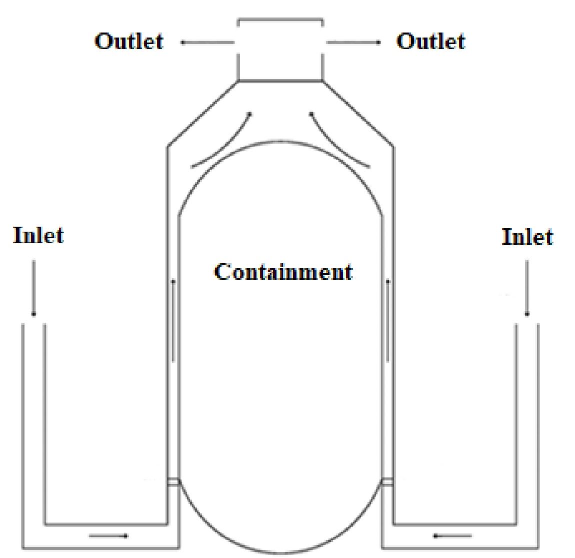
- ACP100 adopts full passive safety design concept to meet safety objectives through natural force, reduce dependence on external water and power sources and human intervention;
- The ACP100 passive system comprises: the passive decay heat removal system **(PDHRS)**, the passive emergency core cooling system **(ECCS)**, the passive containment air cooling system **(PAS)** and reactor automatic depressurization

Engineered Safety Features

Design of Ultimate Heat Sink

- In normal operation: the ACP100 plant is cooled by water; *for the sites with access to water*; cooling tower is the option *for inland sites*.
- During accident conditions, both **DBA** and **DEC**, the Passive Containment Air Cooling System (PAS) is activated to perform decay heat removal, for which the ultimate heat sink is ambient atmosphere, no water is required.





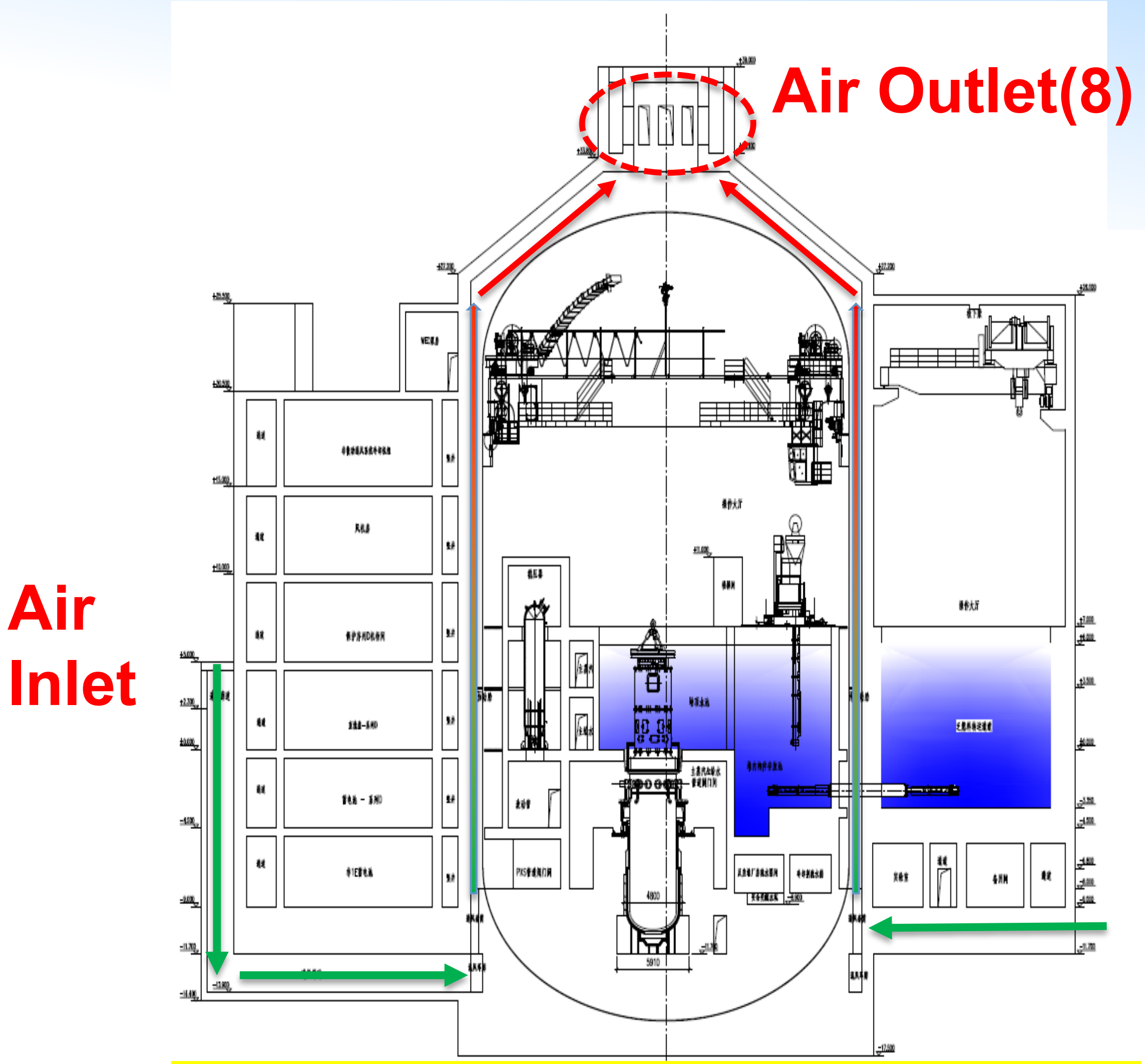
In normal operation conditions

Accident Conditions

Engineered Safety Features

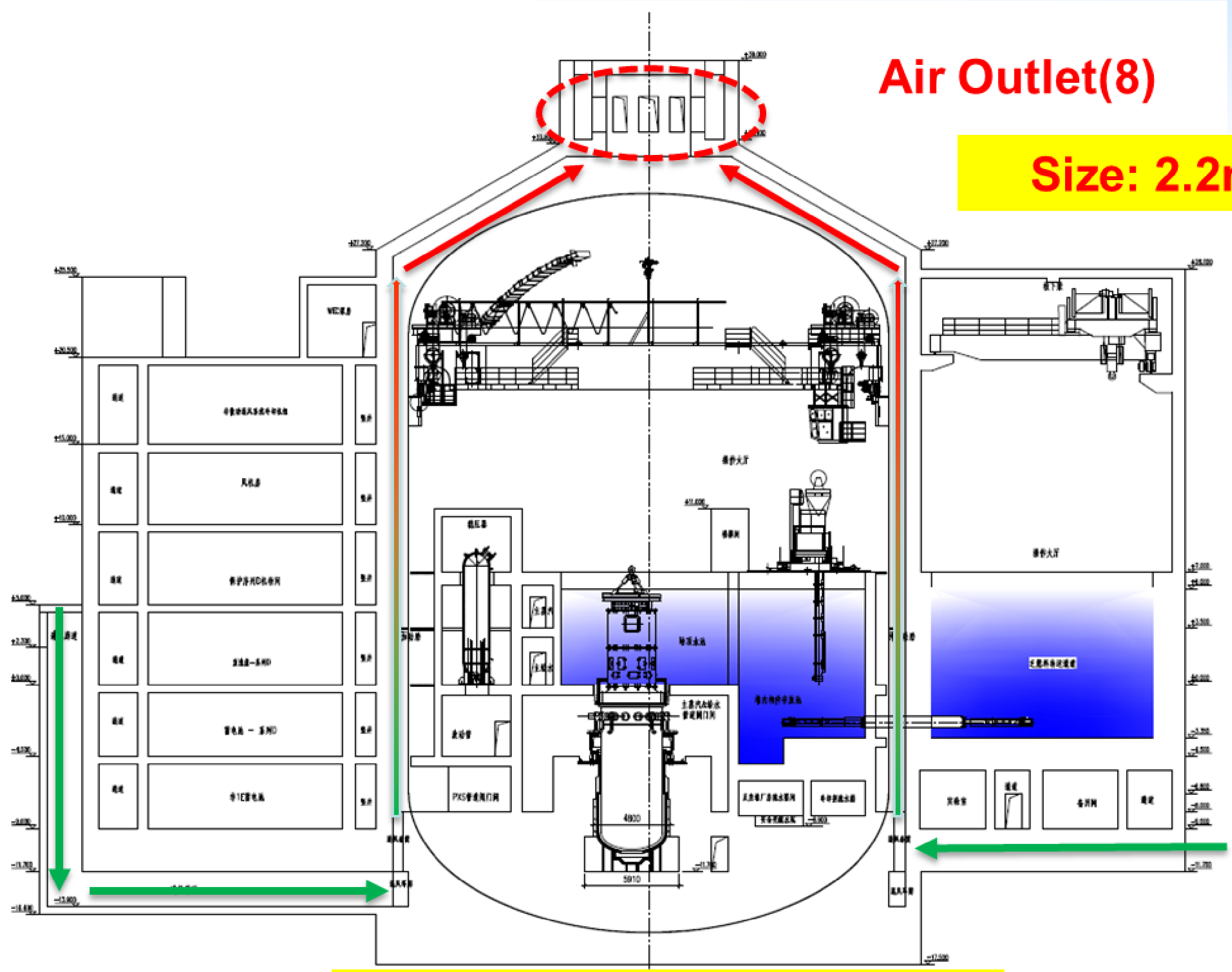
Design of Ultimate Heat Sink

- The Passive Containment Air Cooling System **(PAS)** in ACP100 is designed to remove the heat and reduce the containment pressure and temperature to acceptable level for maintaining the integrity of containment as the third barrier during both DBA and DEC.
- This function is accomplished by natural air convection coupled with thermal radiation – no water required.



ACP100 PAS Air Flow Path

Engineered Safety Features

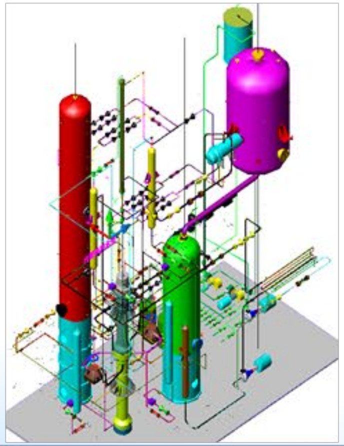


ACP100 PAS Air Flow Path

Experimental Testing for Novel Features

(3) Passive Safety Systems Tests:
A) Passive emergency core cooling system integration test
B) CMT and passive residual heat removal system test

Research results	
	Passive Safety System Test plays a key role in the safety analysis of the ACP100
	Validation and evaluation for the ACP100 passive safety systems design
	Support of License and Improvement of the ACP100
	Support of Code Development for natural circulation

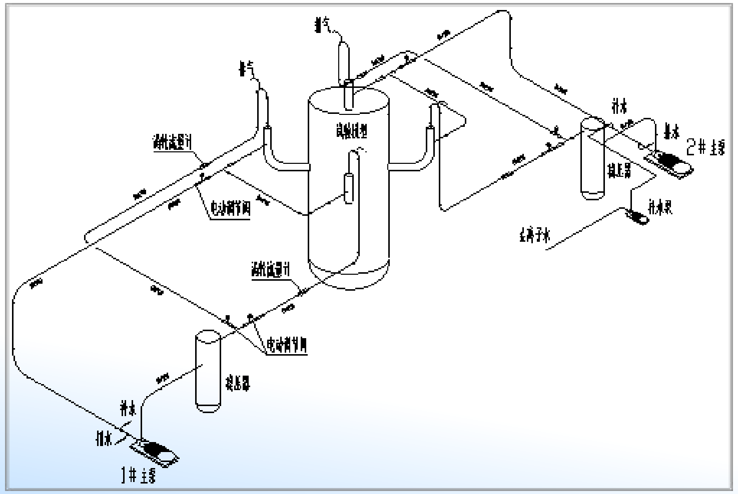


Experimental Testing for Novel Features

(4) Flow-induced Vibration Test

Research Results

- *The max stress was more less than high cycle fatigue allowable stress under 100% rated flow condition， so the design of ACP100 internals on flow induced vibration was safe*
- *The endurance test time under 100% rated flow condition was 50 hours, and the vibration numbers of key components exceeded 7 $\times 10^6$. Structure integrities check showed that: ACP100 internals were integrated and no obvious deformation, fasteners were not loose, structure's surfaces were not wear and tear*



Experimental Testing for Novel Features

(5) Fuel Assembly Critical Heat Flux Test

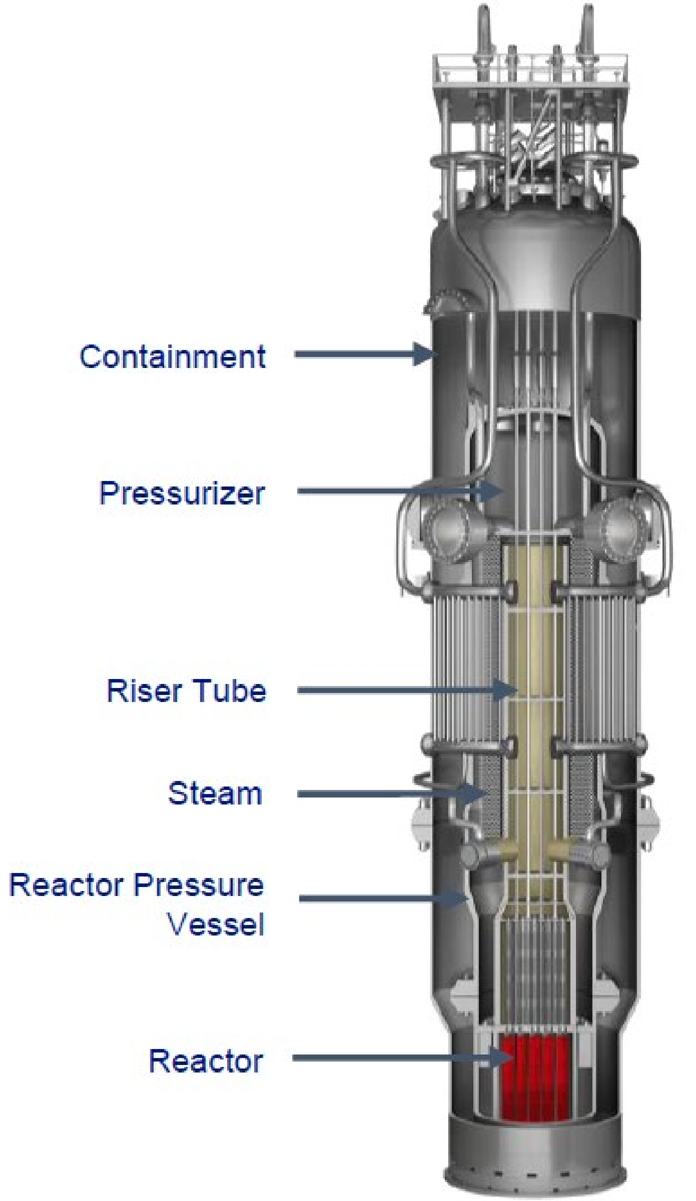
Research Content

- *CHF experiment in typical unit at uniform heat flux*
- *CHF experiment in typical unit at non-uniform heat flux*
- *CHF experiment in non-typical unit at non-uniform heat flux*

Brief Design Description and Key Parameters

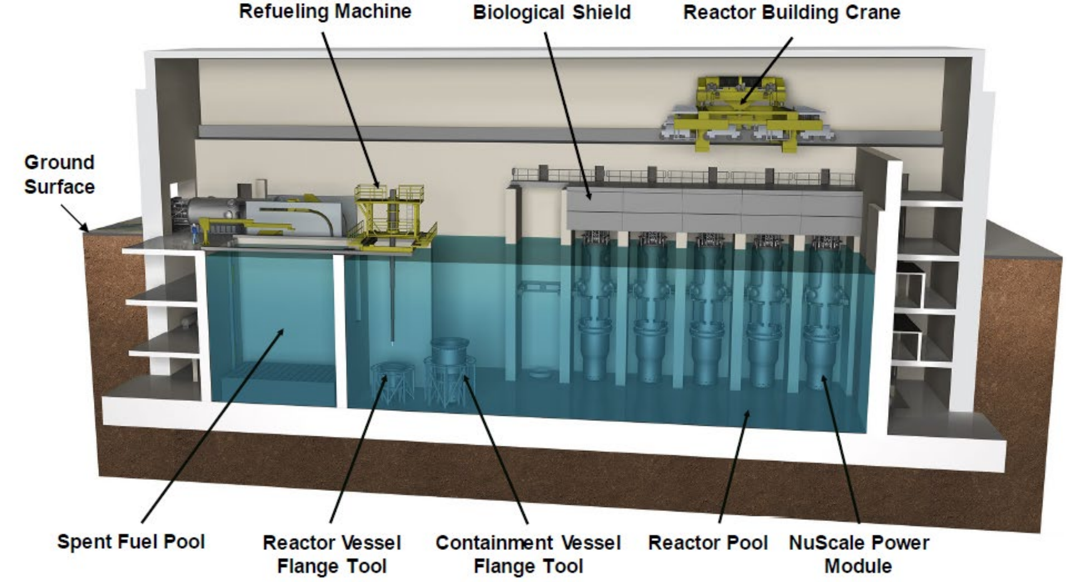
Core Technology: NuScale Power Module

- A NuScale Power Module™ (NPM) includes the reactor vessel, steam generators, pressurizer, and containment in an integral package
- Simple design that eliminates reactor coolant pumps, large bore piping and other systems and components found in large conventional reactors
- Each module produces up to 77 MWe
  - ✓ Small enough to be factory built for easy transport and installation
  - ✓ Dedicated power conversion system for flexible, independent operation
  - ✓ Incrementally added to match load growth
  - ✓ 12 module plant –up to 924 MWe gross
  - ✓ 6 module plant –up to 462 MWe gross
  - ✓ 4 module plant –up to 308 MWe gross



NuScale Description and Key Parameters

MAJOR TECHNICAL PARAMETERS	
Parameter	**Value**
Technology developer, country of origin	NuScale Power Corporation, USA
Reactor type	Integral PWR
Coolant/moderator	Light water / Light water
Thermal/electrical capacity, MW(t)/MW(e)	250 / 77 (gross)
Primary circulation	Natural circulation
NSSS Operating Pressure (primary/secondary), MPa	13.8 / 4.3
Core Inlet/Outlet Coolant Temperature (°C)	249 / 316
Fuel type/assembly array	UO_2 pellet / 17x17 square
Number of fuel assemblies in the core	37
Fuel enrichment (%)	≤ 4.95
Core Discharge Burnup (GWd/ton)	≥ 45
Refuelling Cycle (months)	Nominal 18
Reactivity control mechanism	Control rod drive, boron
Approach to safety systems	Passive
Design life (years)	60



Plant footprint (m^2)	140 000 (VOYGR™-12)
RPV height/diameter (m)	17.7 / 2.7
RPV weight (metric ton)	880
Seismic Design (SSE)	0.5g
Fuel cycle requirements / Approach	Nominal three-stage in-out refuelling scheme
Distinguishing features	Unlimited time for core cooling without AC or DC power, or water addition, or operator action
Design status	Equipment Manufacturing in Progress

NuScale Design Description and Key Parameters

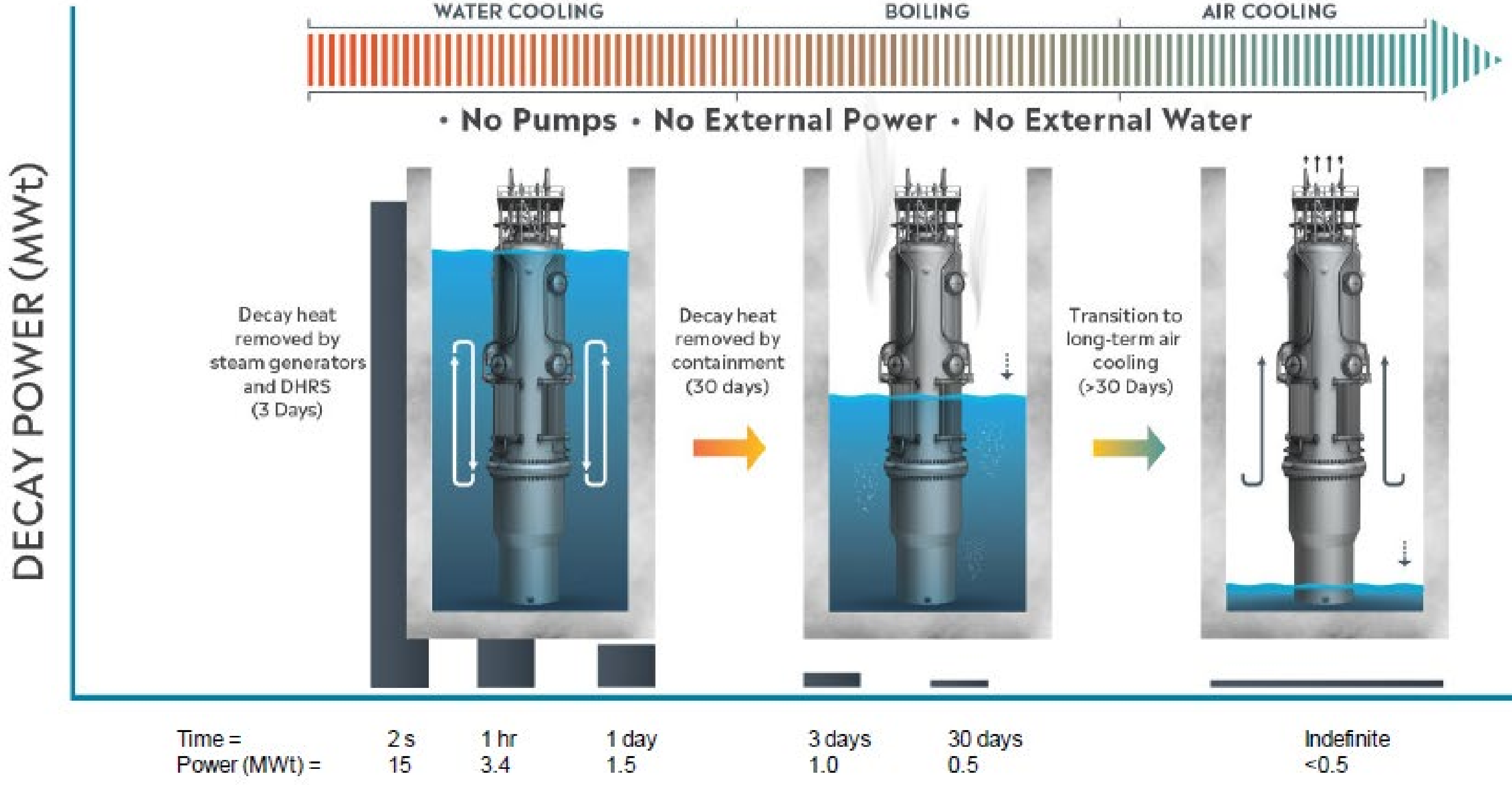
- The NuScale Power Module™ (NPM) is a small, light-water-cooled pressurized-water reactor (PWR).
- NuScale VOYGR™ SMR plants are scalable and can be built to accommodate a varying number of NPMs to meet customer's energy demands.
- NuScale standard plants include the VOYGR-4 at 308 MW(e), the VOYGR-6 at 462 MW(e), and the VOYGR-12 at 924 MW(e).
- A six-module configuration is the reference plant size for the Standard Plant Design Approval design and licensing activities.
- Each NPM is a self-contained module that operates independently of the other modules in a multi-module configuration.
- All modules are managed from a single control room.

Engineered Safety Features - VOYGR

Safety Approach and Configuration to Manage DBA/DEC

Innovative Advancements to Reactor Safety

Nuclear fuel cooled indefinitely without AC or DC power or need to add water*



*Alternate 1E power systemdesign eliminates the need for 1E qualified batteries to performESFAS protective functions – Patent Pending

NUSCALE Power for all humankind

Engineered Safety Features - VOYGR

IAEA

Safety System Configuration
• The NuScale VOYGR SMR plant adopts a set of engineered safety features designed to provide reliable long-term core cooling under all conditions, including severe accident mitigation. • They include integral primary system configuration, a containment vessel, passive heat removal systems, and severe accident mitigation features. • This fully passive safety design is rigorously proven by the NuScale Triple Crown for Nuclear Plant Safety™, which ensures that reactors will safely shut down and self-cool, indefinitely, and do so with no need for operator or computer action, AC or DC power, or the addition of water—a first for light water reactor technology. • Each NPM incorporates several simple, redundant, and independent safety features.

Engineered Safety Features - VOYGR

Safety Approach and Configuration to Manage DBC

- The decay heat removal system (DHRS) provides secondary side reactor cooling for non-LOCA events when normal feedwater is not available.
- The system is a closed-loop, two-phase natural circulation cooling system. Two trains of decay heat removal equipment are provided, one attached to each steam generator loop.
- Each train is capable of removing 100% of the decay heat load and cooling the primary coolant system. Each train has a passive condenser immersed in the reactor pool.

Engineered Safety Features - VOYGR

Safety Approach and Configuration to Manage DEC

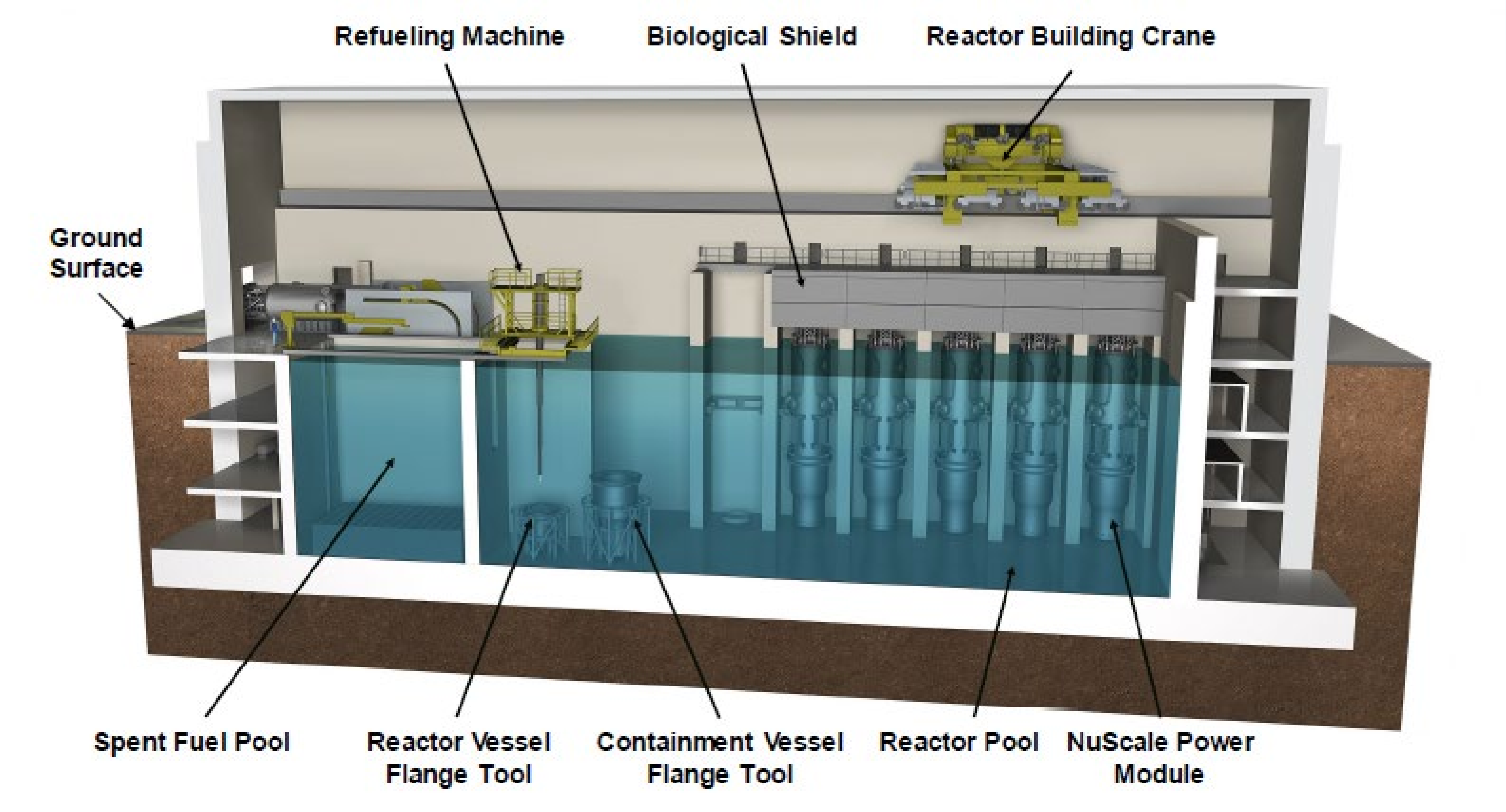
- Emergency core cooling system (ECCS) consists of three independent reactor vent valves (RVVs) and two independent reactor recirculation valves (RRVs).
- The ECCS provides decay heat removal in the unlikely event of a loss of feedwater flow, combined with the loss of both trains of the DHRS.
- The ECCS removes heat and limits containment pressure by steam condensation on, and convective heat transfer to, the inside surface of the CNV.

Engineered Safety Features - VOYGR

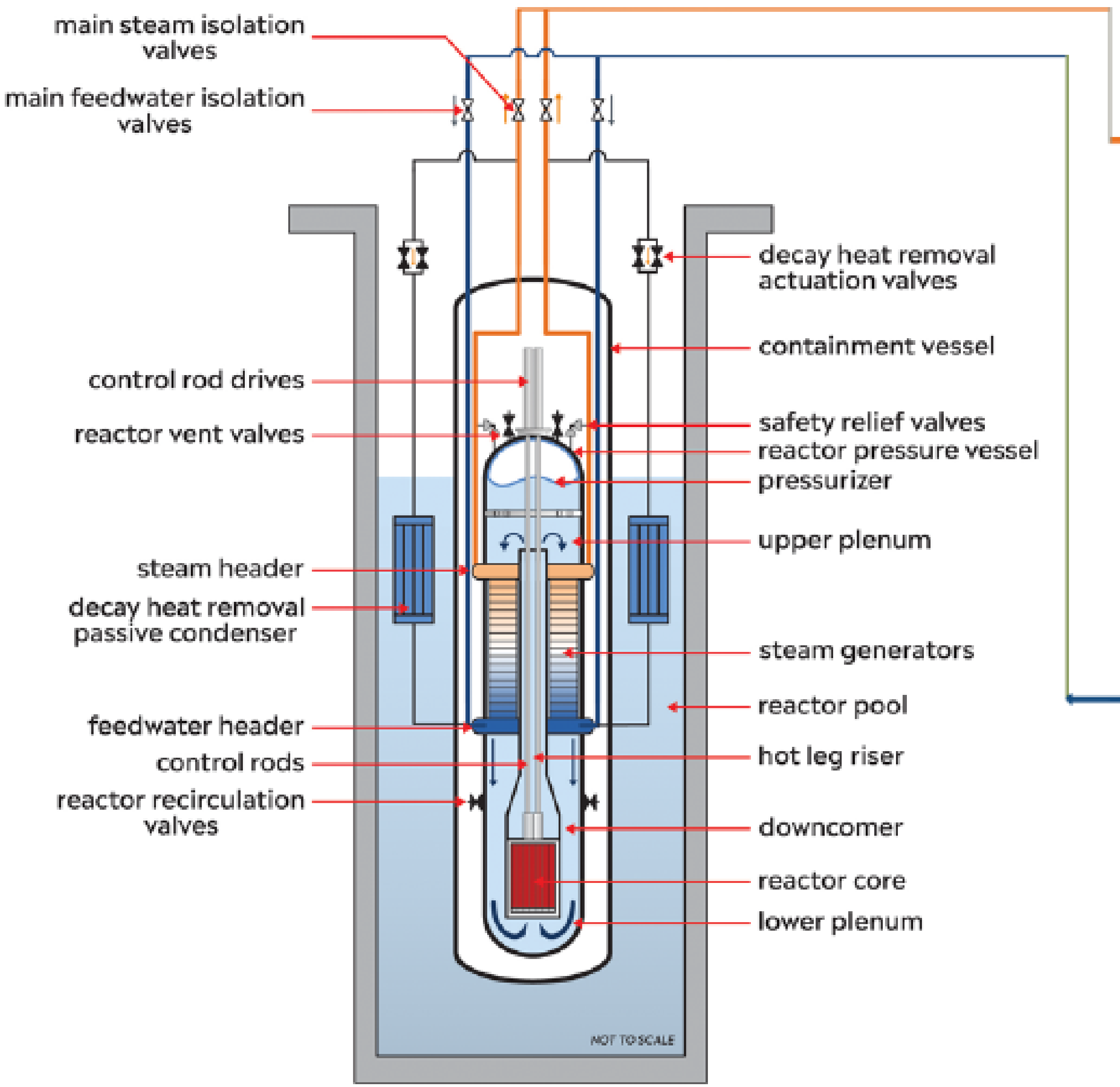
Containment System
• The functions of CNV are to contain the release of radioactivity following postulated accidents, protect the RPV from external hazards, and to provide heat rejection to the reactor pool following ECCS actuation. • Each CNV consists of a steel cylinder with an outside diameter of 4.5 m and an overall height of 23.1 m. • The CNV houses the RPV, control rod drive mechanisms, and associated piping and components of the NSSS. • The CNV is immersed in the reactor pool, which provides an assured passive heat sink for containment heat removal under LOCA condition.

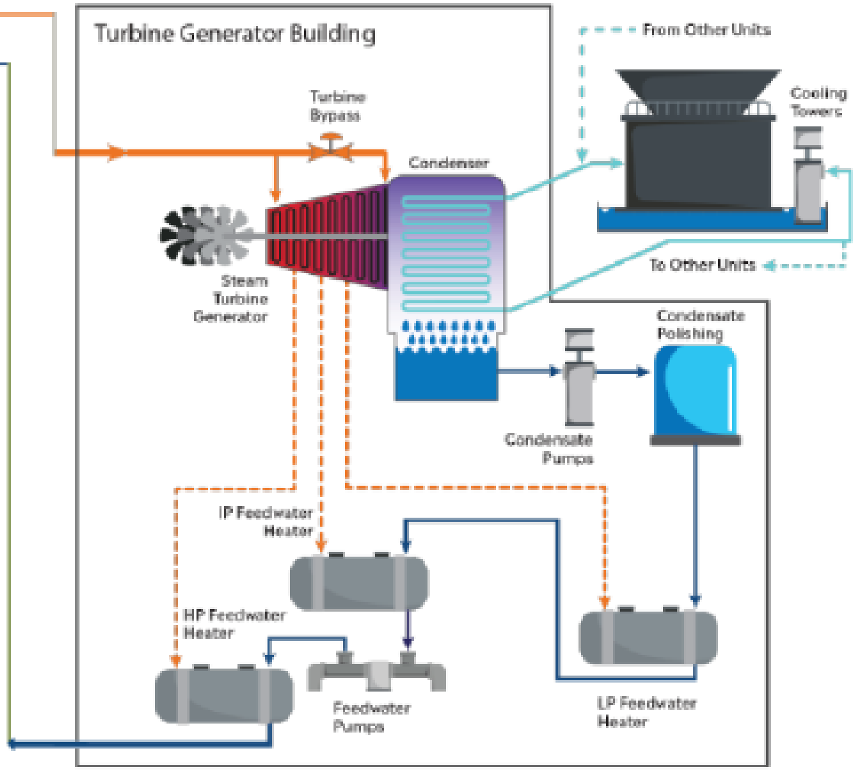
Nuclear Island Design

Reactor Building Houses NuScale Power Modules™, Spent Fuel Pool, and Reactor Pool



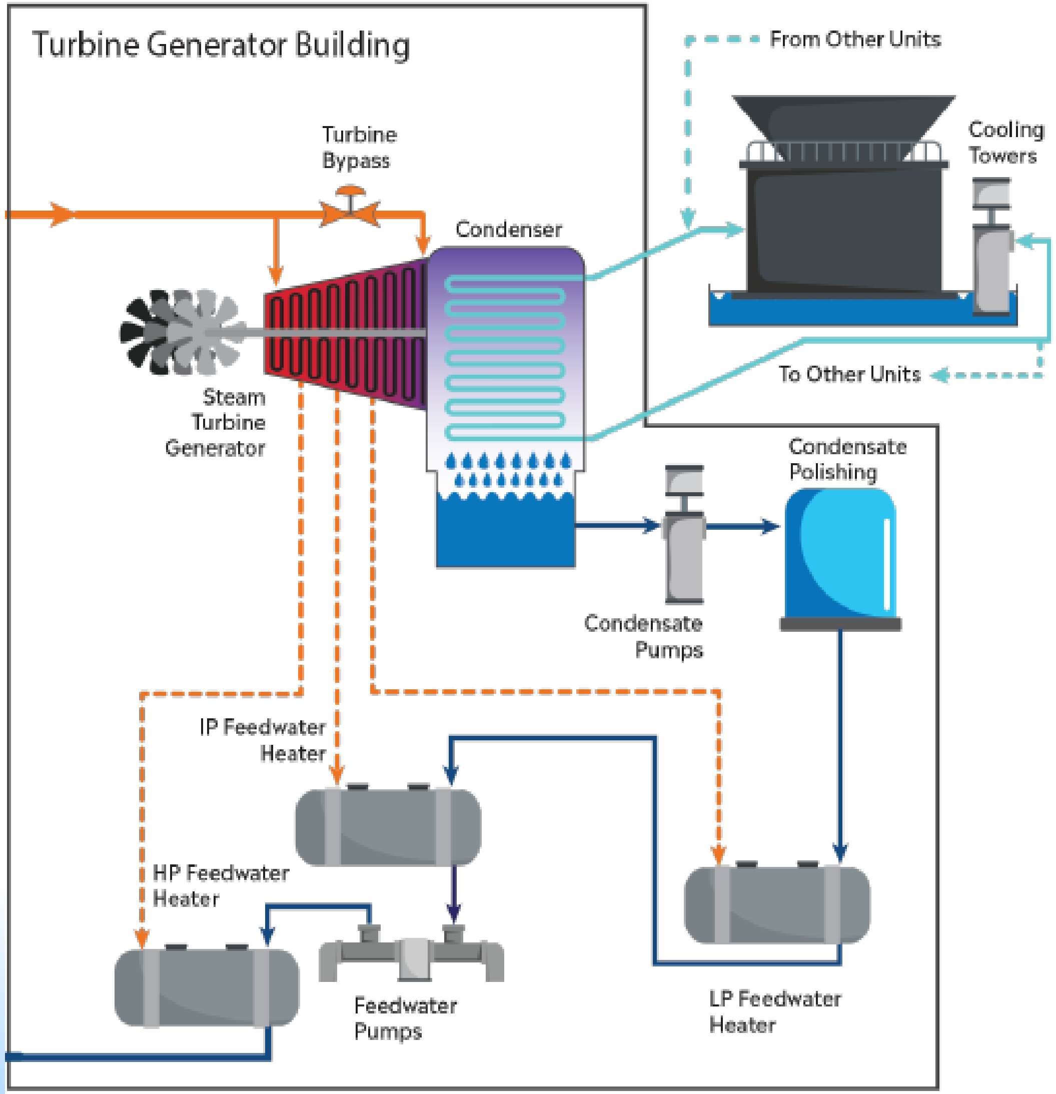
NuScale Power Train





- Each module feeds one turbine generator train, eliminating single-shaft risk.
- 100% turbine bypass capability.
- Small, simple commercial grade. components support short straightforward refueling outages.

BoP Design and Grid Integration



How the Secondary Side works?

- After the secondary coolant becomes steam, the energy is converted to electrical power in the turbine generator system.
- Each module is connected to its dedicated 60 MWe conventional steam turbine-generator system.
- The steam from the turbine flows through a condenser, and a succession of feedwater heaters before re-entering the S.
- The turbine and condenser units are designed to allow 100% steam bypass of the turbine, and the condenser can be cooled by either water or air (to reduce plant water consumption).
- In the case of cogeneration, the BoP can be configured differently for different modules, thus allowing the owner to optimize electricity and heat output from the plant

Experimental Testing for Novel Features

Technology Validation - VOYGR

- NuScale Integral System Test (NIST-1) facility located at Oregon State University in Corvallis, Oregon
- Critical Heat Flux testing at Stern Laboratories in Hamilton, Ontario Canada
- Helical Coil Steam Generator testing at SIET SpAin Piacenza, Italy
- Fuels Mechanical Testing at AREVA's Richland Test Facility (RTF) in Richland, WA, USA
- Critical Heat Flux testing at AREVA's KATHY loop in Karlstein, Germany
- Control Rod Assembly (CRA)drop / shaft alignment testing at AREVA's KOPRA facility in Erlangen, Germany
- Steam Generator Flow Induced Vibration (FIV) testing at SIET SpAin Piacenza, Italy
- Steam Generator Inlet Flow Restrictor Test at Alden Laboratory, Holden, MA, USA
- ECCS Valve Proof of Concept and Demonstration Tests, Target Rock, NY, USA

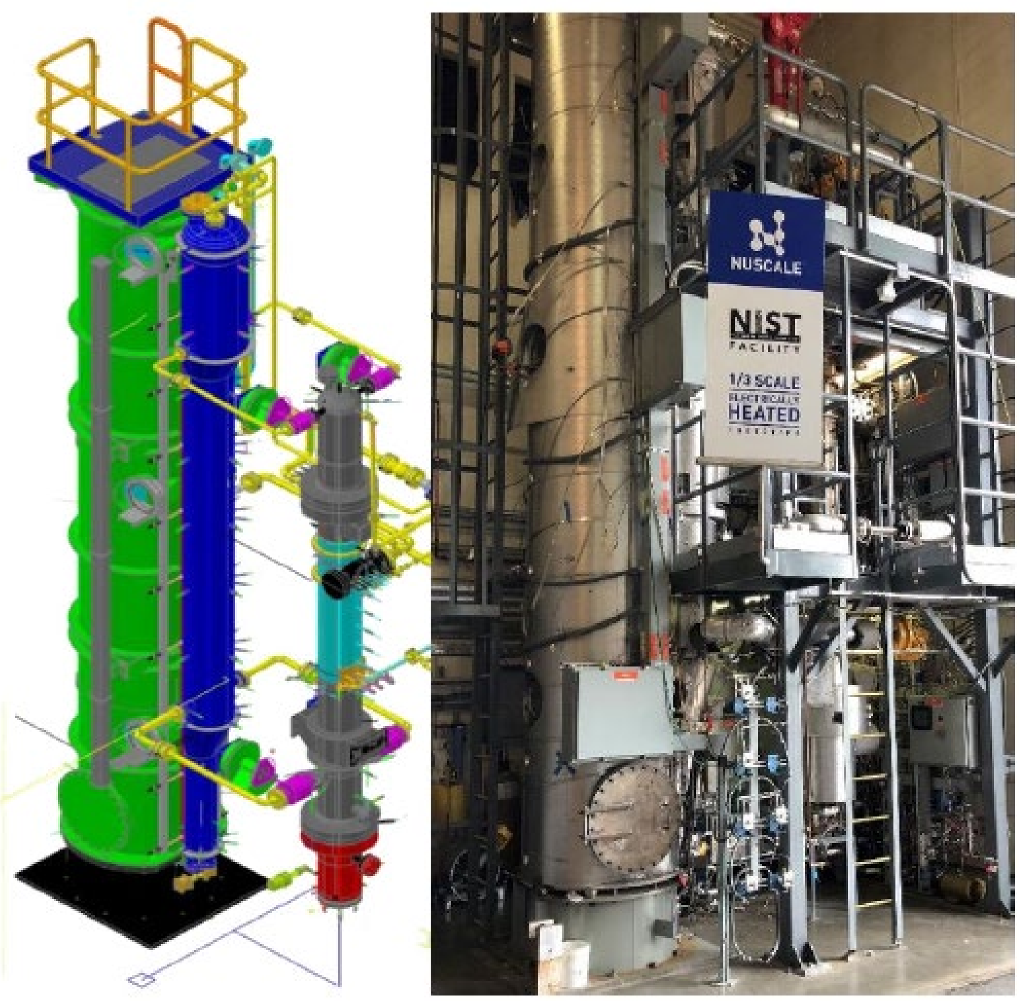


Figure 10. NuScale Integral System Test (NIST) facility

Key Take Aways

- Water-cooled type SMRs can be a loop-PWR, an integral-PWR, a compact PWR, a BWR, and also a PHWR with Calandria (not covered in this presentation)
- Integral PWR aims for compact nuclear power systems for enhanced safety, scalability, and simplified operation.
- Different from loop-type PWRs, iPWRs <u>in many cases</u> integrate the reactor core, steam generators, pressurizer, and primary coolant pumps within a single pressure vessel, eliminating large external piping and reducing the risk of loss-of-coolant accidents.
- iPWR type SMs typically produce 50–300 MWe per module, allowing flexible deployment in multi-unit configurations.
- Some iPWR adopts natural circulation cooling under normal and emergency conditions, minimizing dependence on active systems and external power sources.
- Overall, integral PWR emphasize safety, modularity, and economic viability, targeting cogenerations of electricity and industrial process heat, as well as remote or off-grid power supply.

THANK YOU