Small is Beautiful? A Review of the Small Modular Reactor (SMR) Designs

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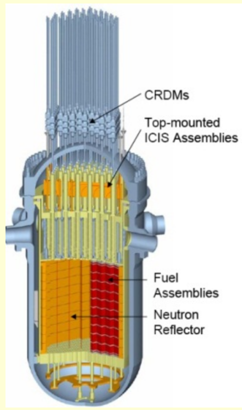
CENTER FOR ADVANCED NUCLEAR ENERGY SYSTEMS (CANES)

9 Advanced Reactor Designs Considered for New Construction in the US

All LWR-based systems

ABWR (GE-Hitachi)

US-APWR (Mitsubishi)

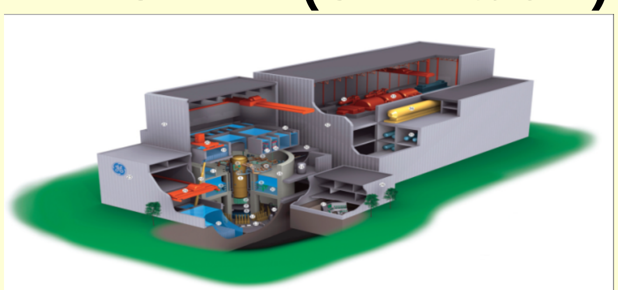


AP1000 (Toshiba-Westinghouse)

SMR-160 (Holtec)

US-EPR (AREVA)

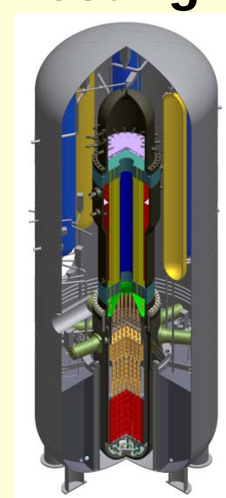
ESBWR (GE-Hitachi)



NuScale (NuScale Power)

mPower (B&W)

WSMR (Westinghouse)



U.S. NRC Certification of Advanced LWRs

Design	Applicant	Type	Design Certification Status
AP1000	Westinghouse-Toshiba	Advanced Passive PWR 1100 MWe	Certified*
ABWR	GE-Hitachi, Toshiba	Advanced BWR 1350 MWe	Certified, Constructed in Japan/Taiwan
ESBWR	GE-Hitachi	Advanced Passive BWR 1550 MWe	Expected 2013
US-EPR	AREVA	Advanced PWR 1600 MWe	Expected June 2013**
US-APWR	Mitsubishi	Advanced PWR 1700 MWe	Expected October 2014
mPower	Babcok & Wilcox	Small Modular PWR, 160 MWe	Pre-application
NuScale	NuScale Power	Small Modular PWR, 45 Mwe	Pre-application
WSMR	Westinghouse	Small Modular PWR, 200 Mwe	N/A
SMR-160	Holtec	Small Modular PWR, 160 MWe	N/A

* Under construction in China ** Euro version under construction in Finland, France and China

U.S. utilities have submitted 18 licensing applications (total 28 units); first license approved on 2/10/12

Why SMRs?

- Size of capital investment for large LWR plant is order of $10B, depending on number of units and plant type. The financial risk for most U.S. utilities (with market cap ~$10-20B) is too large, especially in deregulated markets.
- Small plant reduces absolute value of investment by an order of magnitude (though with likely higher cost per kW installed)
- Shorter construction schedule for smaller plant reduces interest costs + allows for precise matching of capacity and demand
- Economy of mass production vs economy of scale

Why SMRs? (2)

And also:

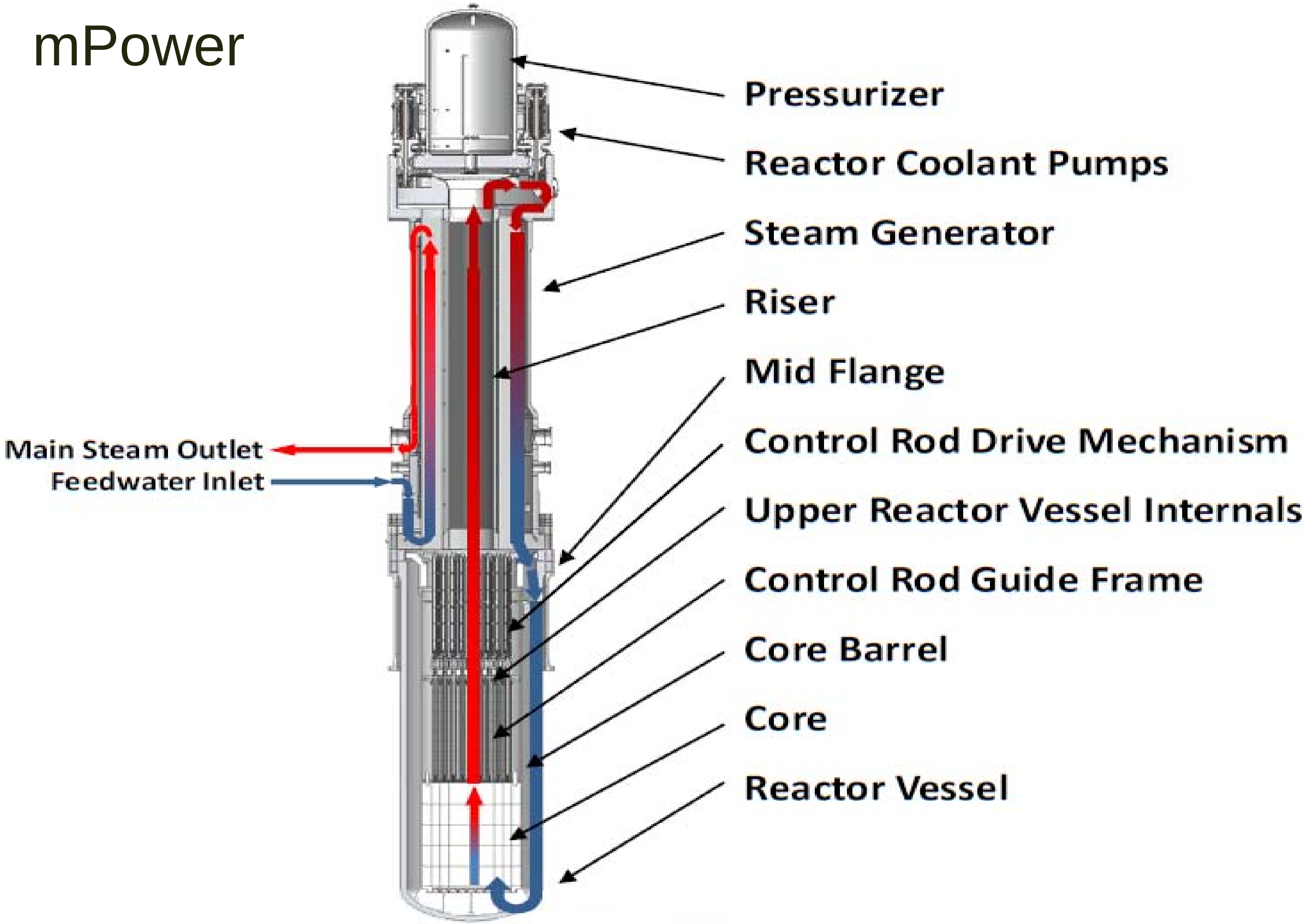
- Enhance physical protection: can put plant partially underground
- Enhance robustness wrt Fukushima-type scenarios
- Reclaim U.S. leadership in development of new nuclear reactor technology

Small Modular Reactors (SMRs)

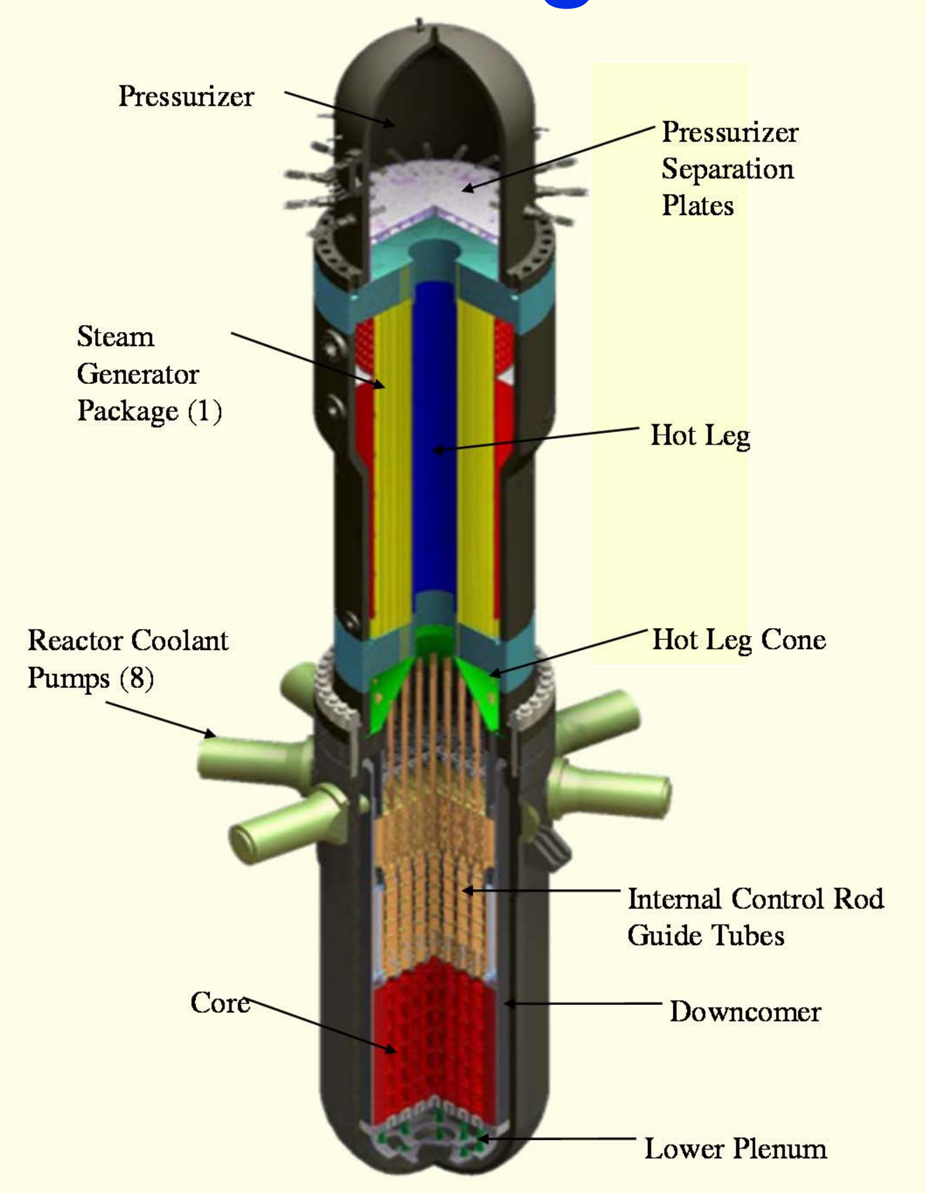
- 4 designs in the US: mPower (B&W), WSMR (Westinghouse), NuScale (Nuscale Power), SMR-160 (Holtec)
- All PWRs with an integral primary system design housed within the RPV (including control rod mechanisms)
- 50-200 MWe per module + 60-year plant design life
- Standard fuel (UO_2 enriched up to 5 wt% ^{235}U) and fuel assembly design (with shorter fuel pins)
- No boron + long irradiation cycle (up to 4 years)
- Passive safety systems
- Small high-pressure containment located underground
- Factory built in the US + rail shippable components

SMR Integral Primary System

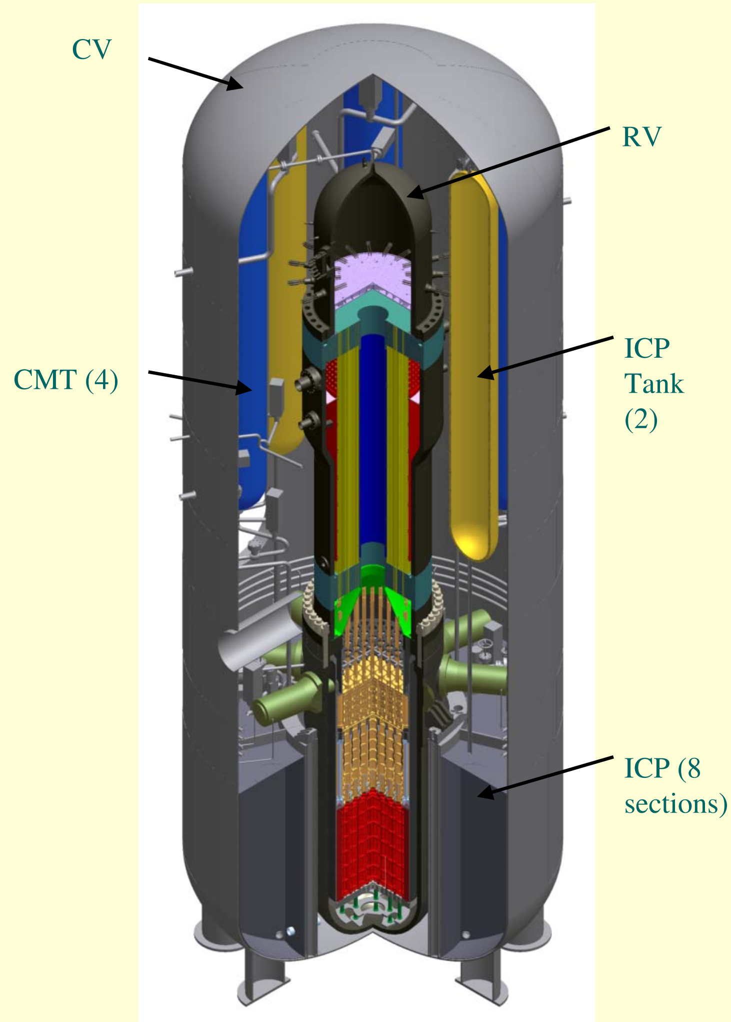
mPower



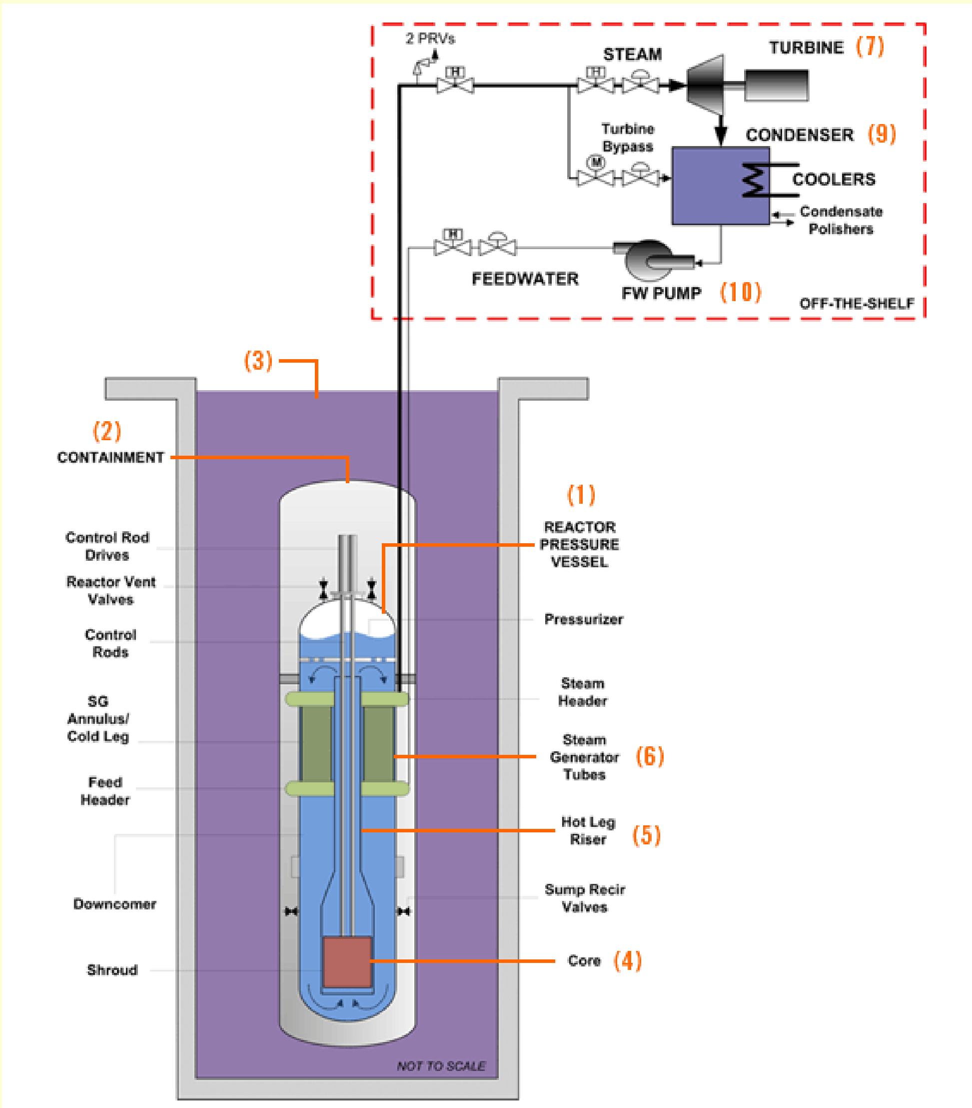
SMR Integral Primary System (2)



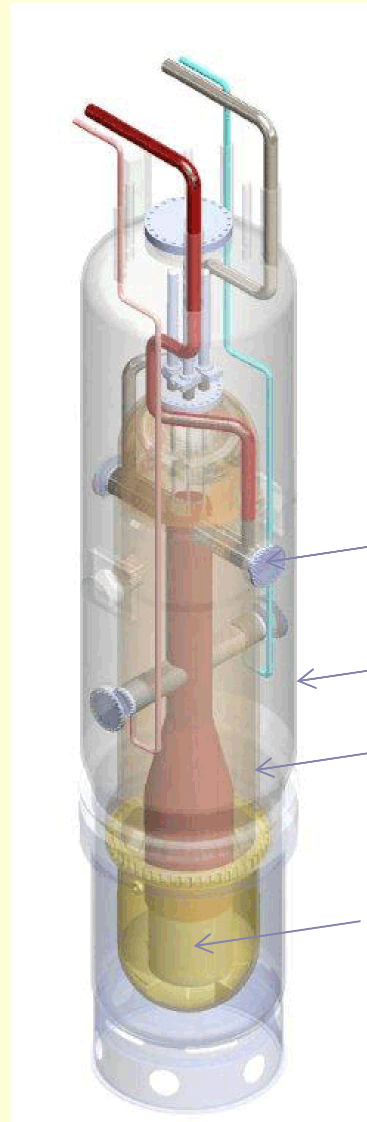
WSMR



SMR Integral Primary System (3)

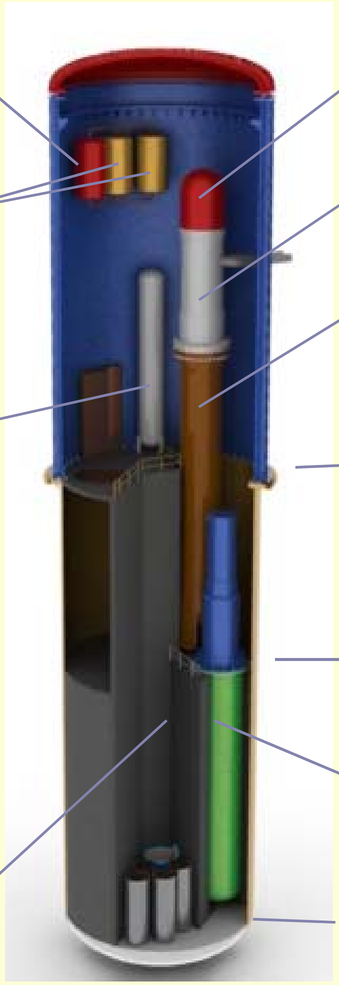


NuScale



SMR Integral Primary System (4)

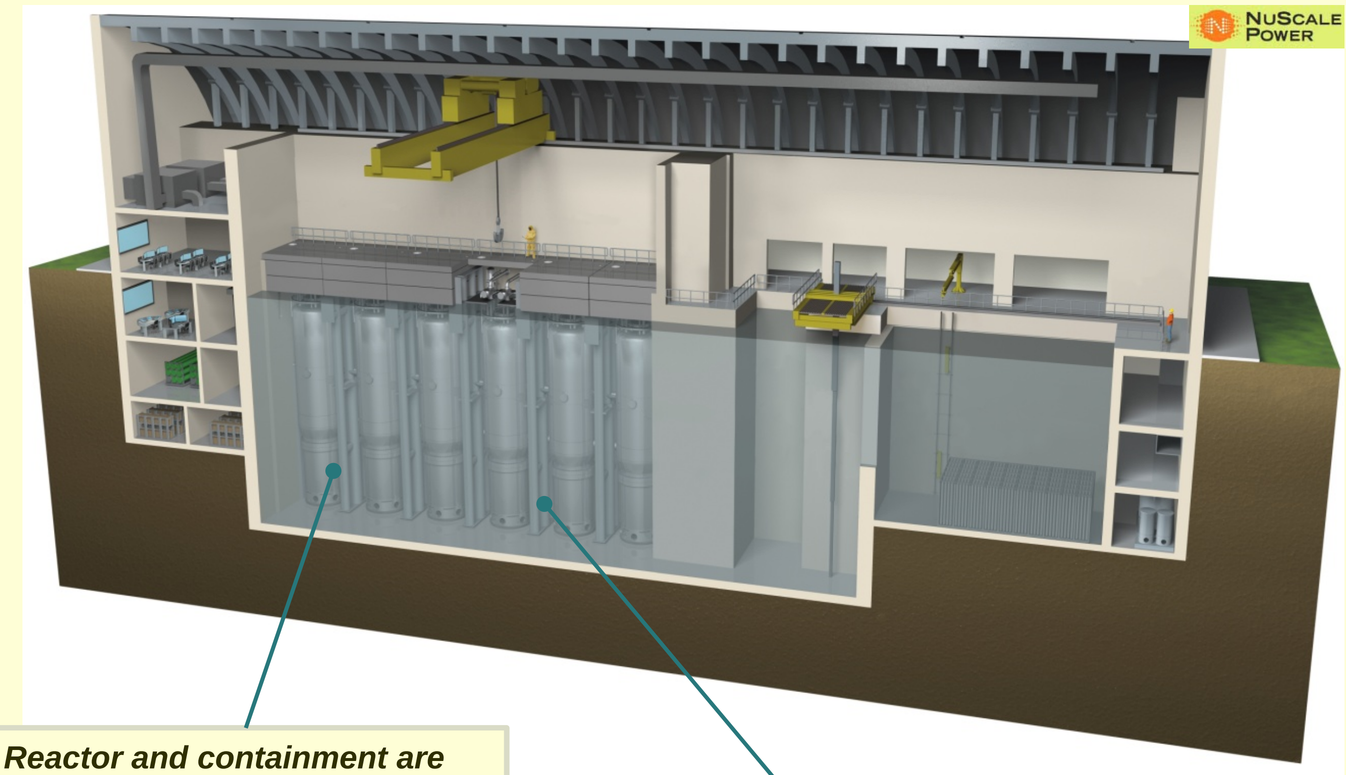
SMR-160



Single-batch cartridge core

SMR Modular Design

Multiple modules co-located at site to create mid- to large-size plant

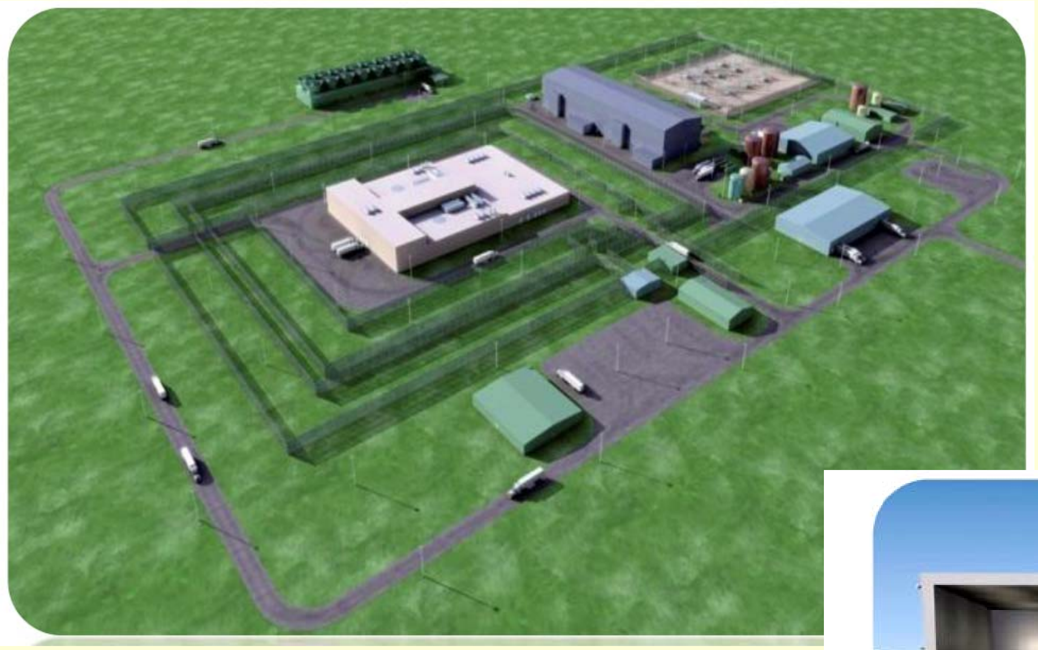


Reactor and containment are submerged in underground steel-lined concrete pool with 30-day supply of cooling water.

Any hydrogen released is trapped in containment vessel with little to no oxygen available to create a combustible mixture.

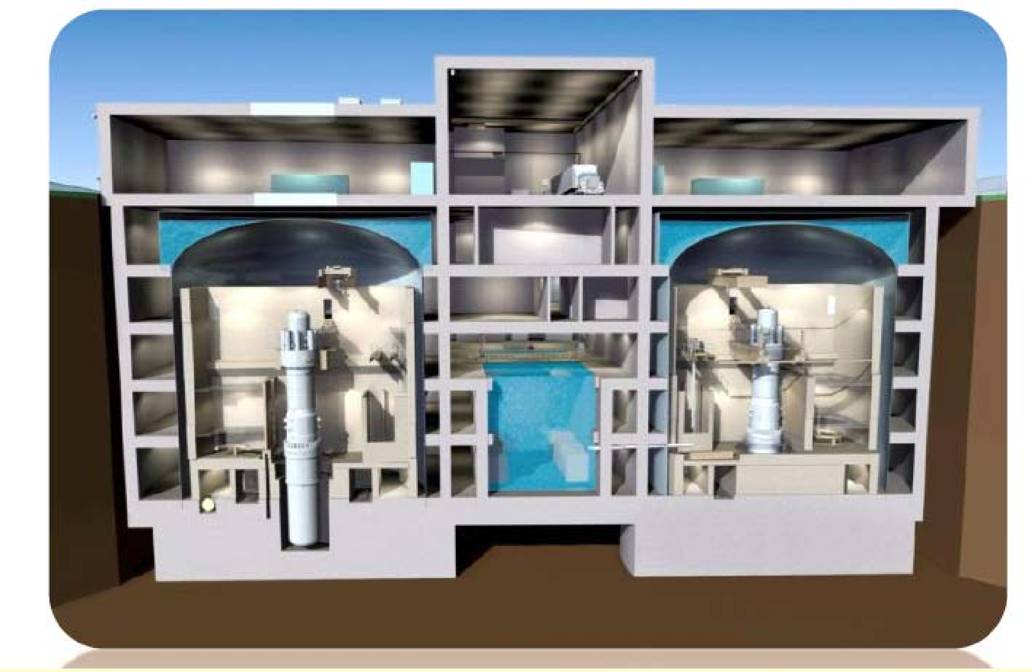
12-module, 540 MWe NuScale Plant

SMR Enhanced Physical Protection



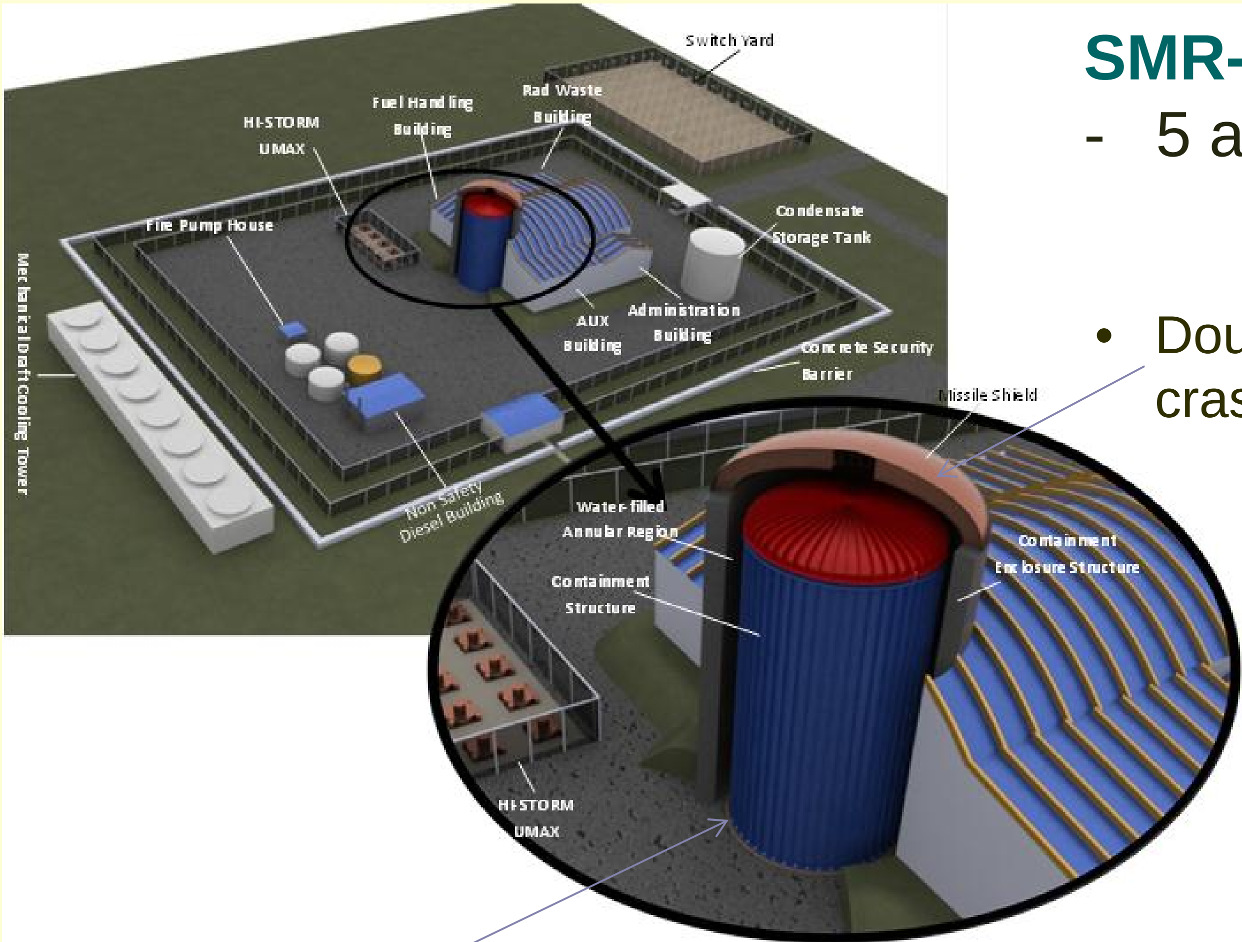
mPower example

- "Twin-pack" mPower plant configuration
- 40 acre site footprint



- Low profile architecture
- Enhanced security posture
- Underground containment
- Underground spent fuel pool

SMR Enhanced Physical Protection (2)



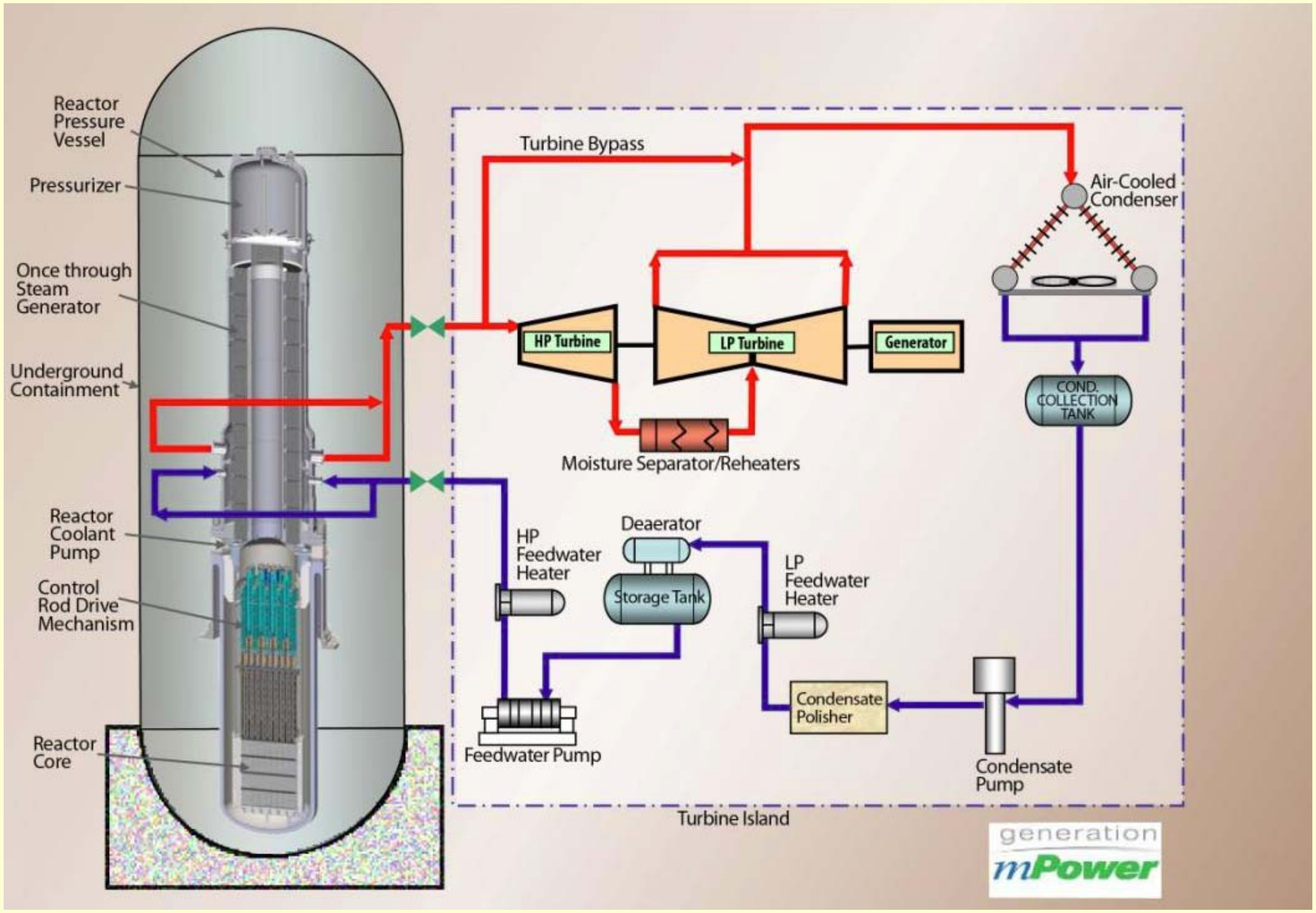
SMR-160 example

- 5 acre site footprint

- Double protection against crashing aircraft.

- Underground location of safety systems to provide:
  - Immunity from external natural events
  - Maximum protection from malevolent human intervention

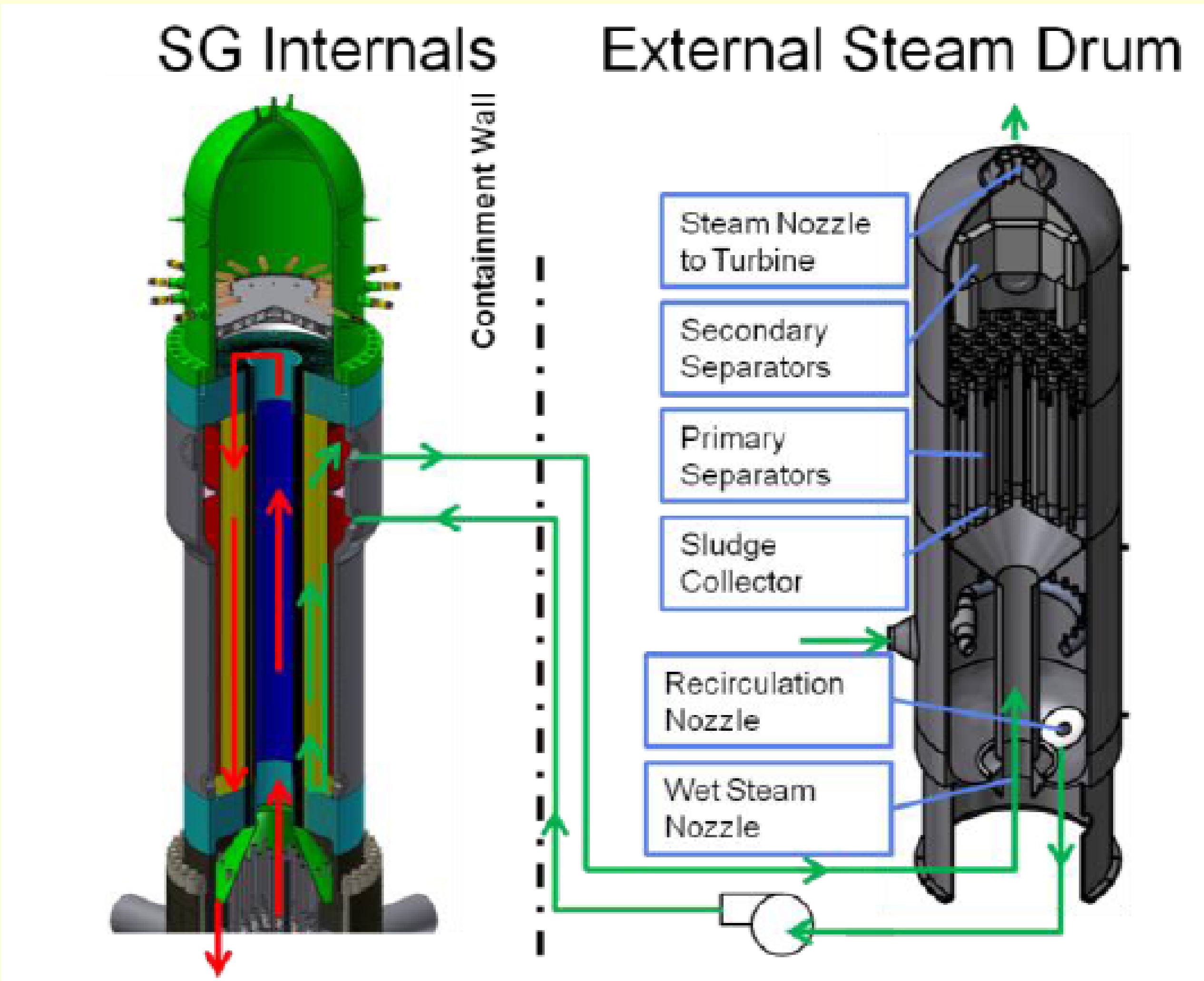
SMR Balance Of Plant



- Conventional steam cycle components
- Air-cooled condenser possible (at expense of efficiency and higher capital cost)

SMR Balance Of Plant (2)

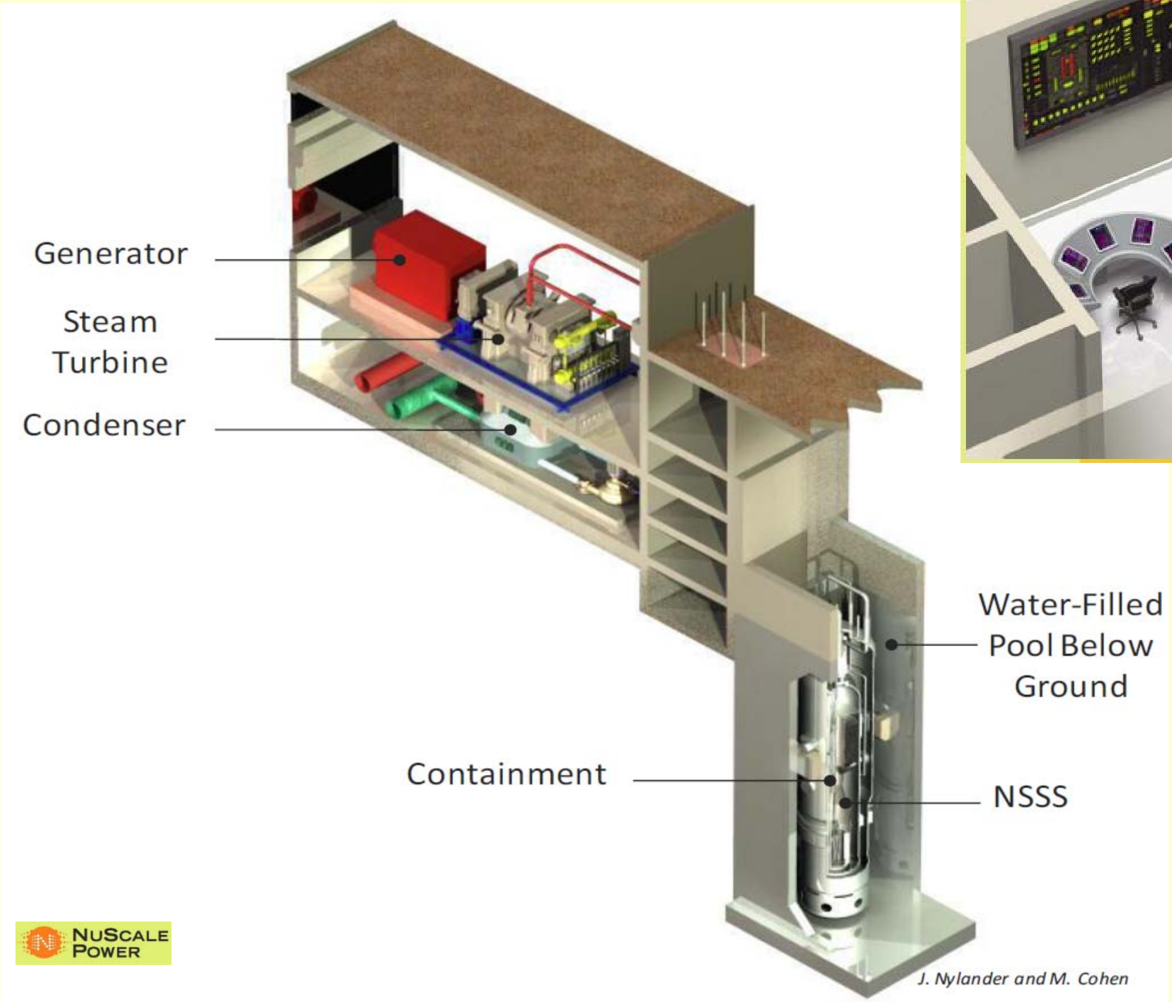
- **WSMR has an external steam drum**



- Eliminates dryout ⇒ allows compact SGs within RPV
- Increases water inventory on secondary side ⇒ lengthens heat removal through SGs in loss of feedwater event

SMR Balance Of Plant (3)

- **Each module has an independent BOP**



- **Multiple modules share control room**

SMR Plant Parameters NuScale Example

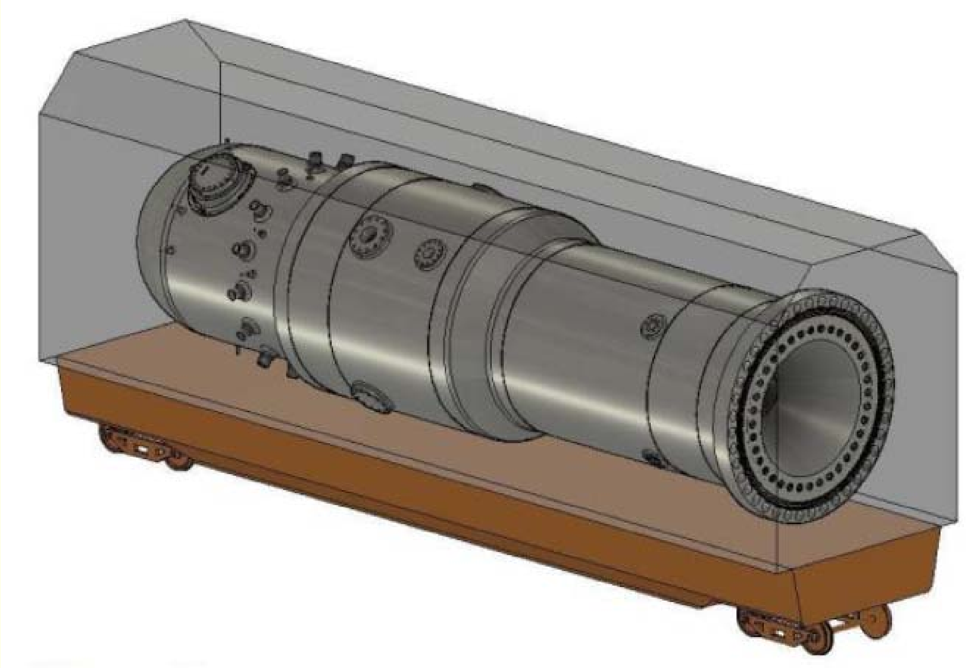
Overall Plant		
•	Net Electrical Output	540 MW(e)
•	Plant Thermal Efficiency	30%
•	Number of Power Generation Units	12
•	Nominal Plant Capacity Factor	> 90%
Power Generation Unit		
•	Number of Reactors	One
•	Net Electrical Output	45 MW(e)
•	Steam Generator Number	Two independent tube bundles
•	Steam 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 (1260 psia)
▪	Fuel	UO_2 (< 4.95% enrichment)
▪	Refueling Intervals	24 months

Lower pressure in primary and secondary sides ⇒ less expensive components, but also lower efficiency

SMR Plant Parameters

WSMR Example

Parameter	Value
Thermal Output	800 MWt
Electrical Output	>225 MWe
Passive Safety Systems	No operator intervention required for 7 days
Core Design	17x17 Robust Fuel Assembly 2.4 m (8.0 ft) Active Length < 5% Enriched U235 89 Assemblies Soluble Boron and 37 Internal CRDMs 24 month refueling cycle
Reactor Vessel	Max Diameter: 3.7m (12.0 ft) Height: 24.4m (80 ft)
Pressurizer and Steam Generator Assembly	2.54×10^5 kg (280 Tons)
Containment Vessel	Outer Diameter: 9.8 m (32 ft) Height: 27.1 m (89 ft) Fully Modular Construction
Reactor Coolant Pumps	8 External, Horizontally-Mounted Pumps Sealless Configuration
Steam Generator	Recirculating, Once-Through, Straight Tube
Pressurizer Instrumentation and Control	Integral to Vessel OVATION®-based Digital Control System



SMR Safety Features

- Low core linear power ⇒ low fuel and clad temperatures during accidents + lower flow velocities that minimize flow induced vibration effects
- Large coolant volume to core power ratio ⇒ more time for safety system response during accidents
- No large pipes connected to RPV ⇒ LB-LOCA eliminated by design

SMR Safety Features (2)

- Small penetrations at high elevation $\Rightarrow$ increased amount of coolant left in the RPV after a SB-LOCA
- Small penetrations $\Rightarrow$ reduced rate of energy release to containment resulting in lower containment pressures
- Automatic Depressurization Valves $\Rightarrow$ fast depressurization of the RPV to start low-pressure injection

SMR Safety Features (3)

mPower Example

Feature	B&W 177	Typical Gen 3 PWR	B&W mPower
Rated core power (MW_{th})	2568	3415	500
Core average linear heat rate (KW_{th}/m)	18.7	18.7	11.5
Average flow velocity through the core (m/s)	4.8	4.8	3.1
RCS volume (m^3)	325	272	92
RCS volume to power ratio (m^3/MW_{th})	0.14	0.08	0.18
Maximum LOCA area (m^2) *	1.3	1.0	0.0067
RCS volume/LOCA area ratio (m^3/m^2)	250	270	13,700

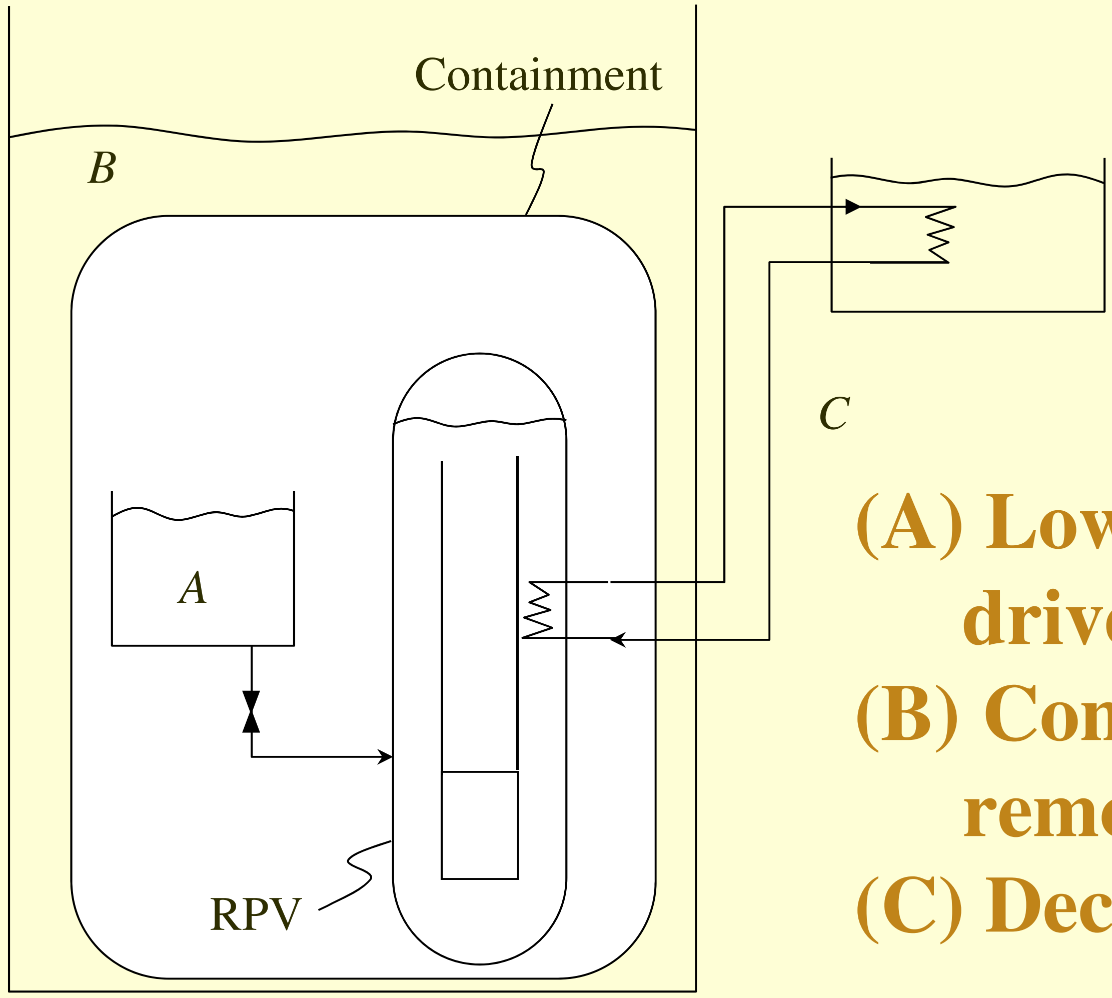
SMR Engineered Safety Systems

Key Functions

- Shut-down reactor = INTERNAL CONTROL RODS + STANDBY LIQUID CONTROL SYSTEM
- Remove decay heat = PASSIVE
- Relieve pressure = AUTOMATIC DEPRESSURIZATION SYSTEM
- Maintain (or replenish) reactor coolant inventory = PASSIVE

SMR Engineered Safety Systems (2)

All 4 designs share similar safety system concepts



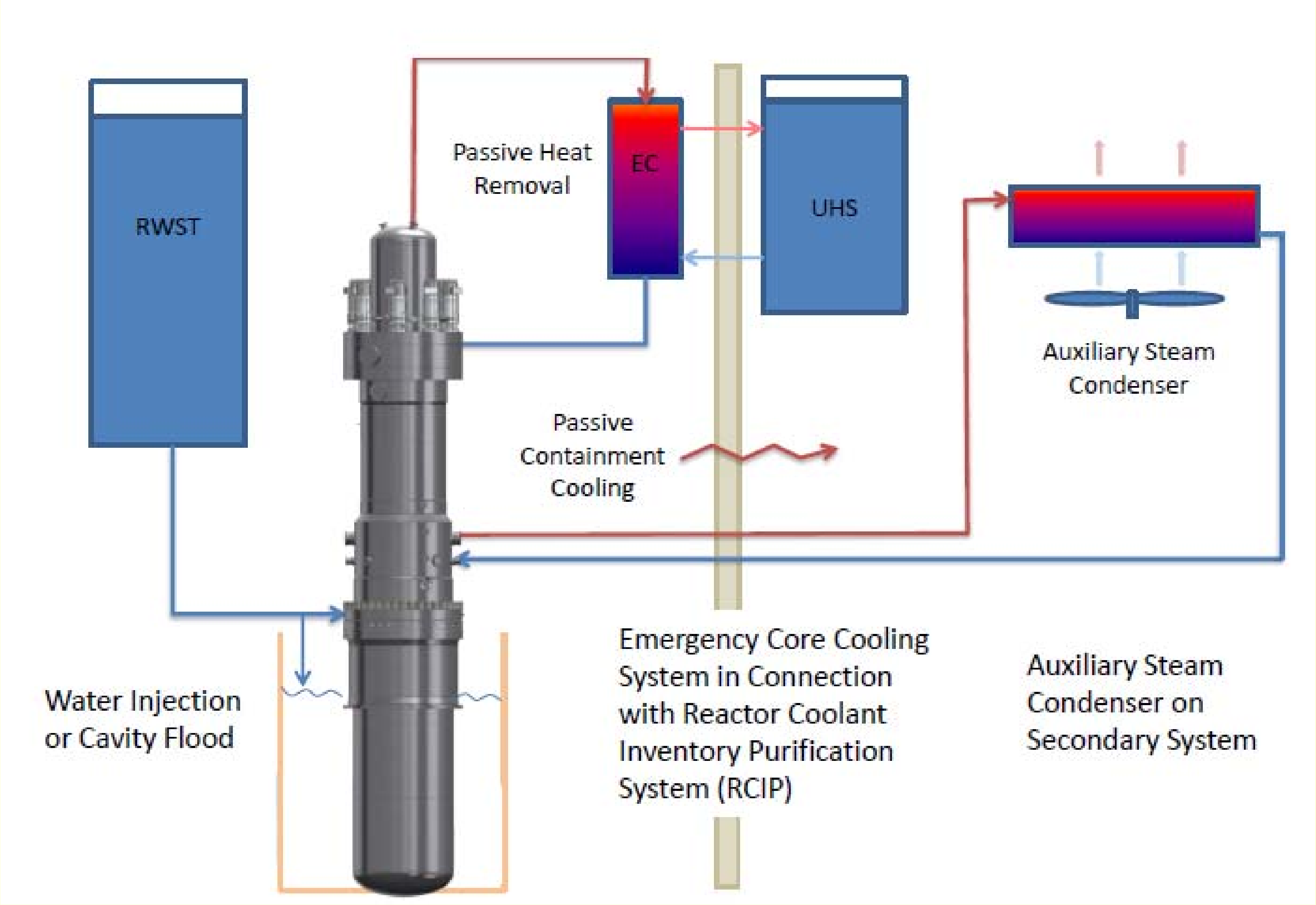
(A) Low-pressure gravity-driven injection

(B) Containment heat removal

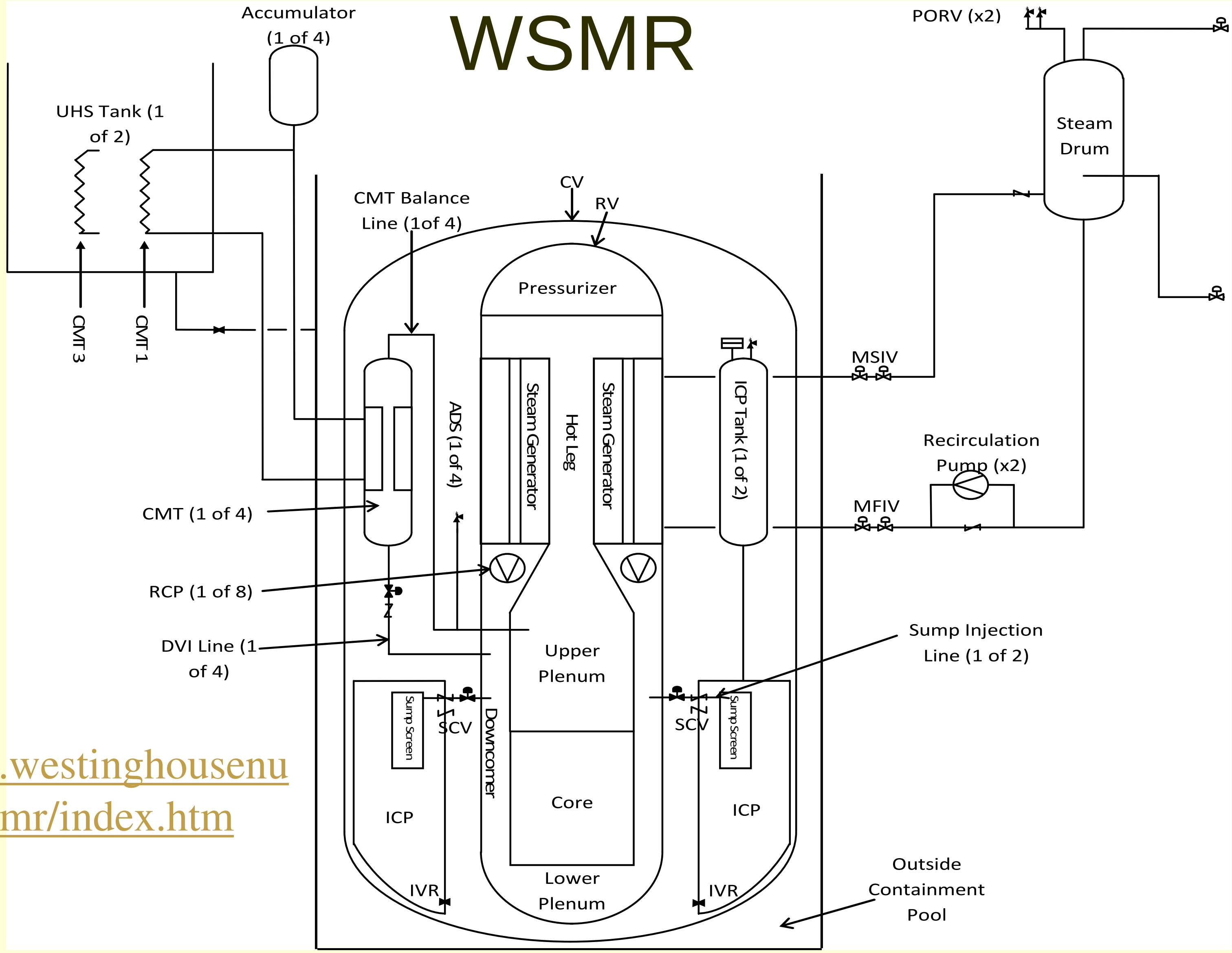
(C) Decay heat removal

SMR Engineered Safety Systems (3)

mPower



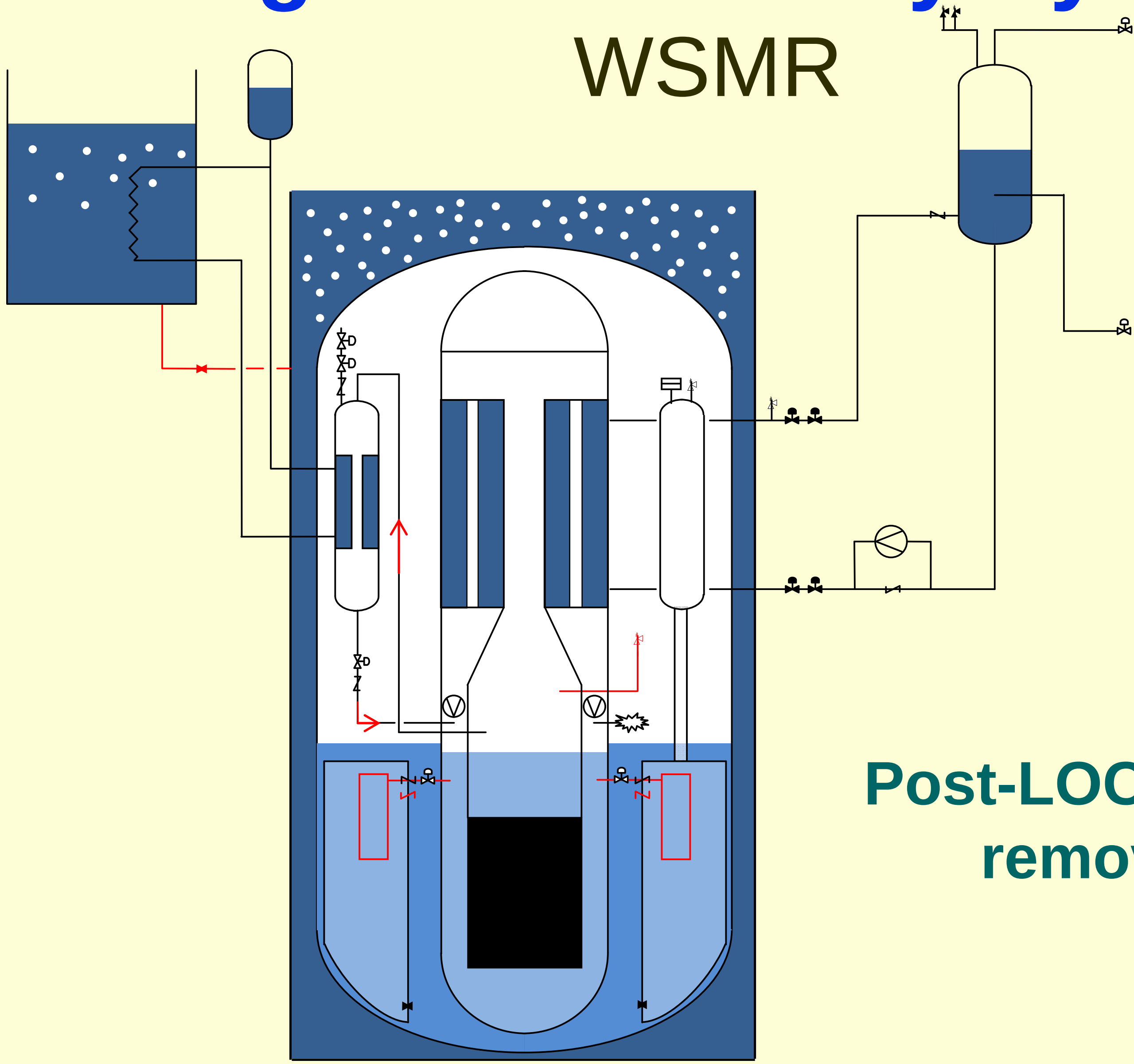
SMR Engineered Safety Systems (4)



http://www.westinghousenuclear.com/smr/index.htm

SMR Engineered Safety Systems (5)

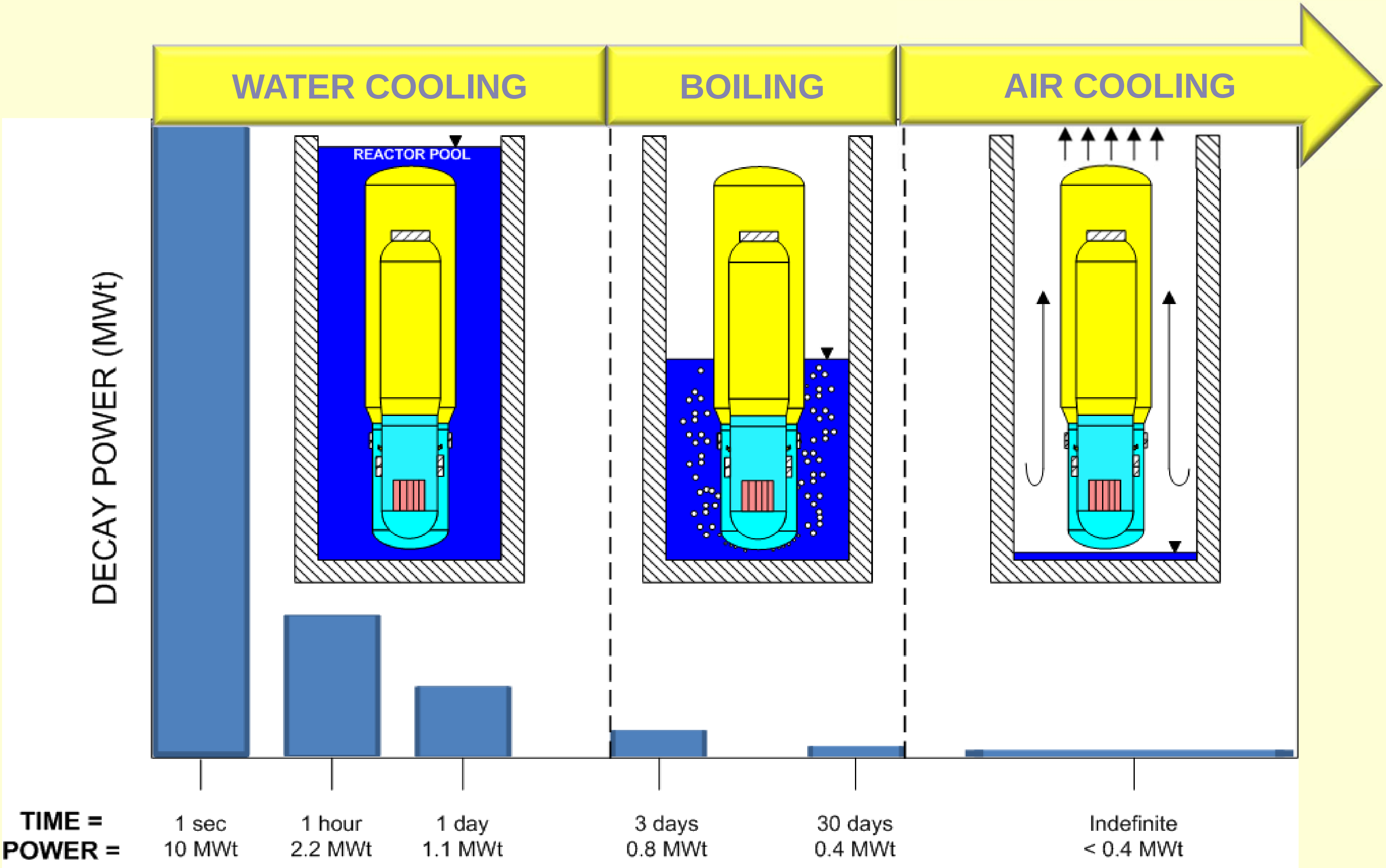
WSMR



Post-LOCA heat removal

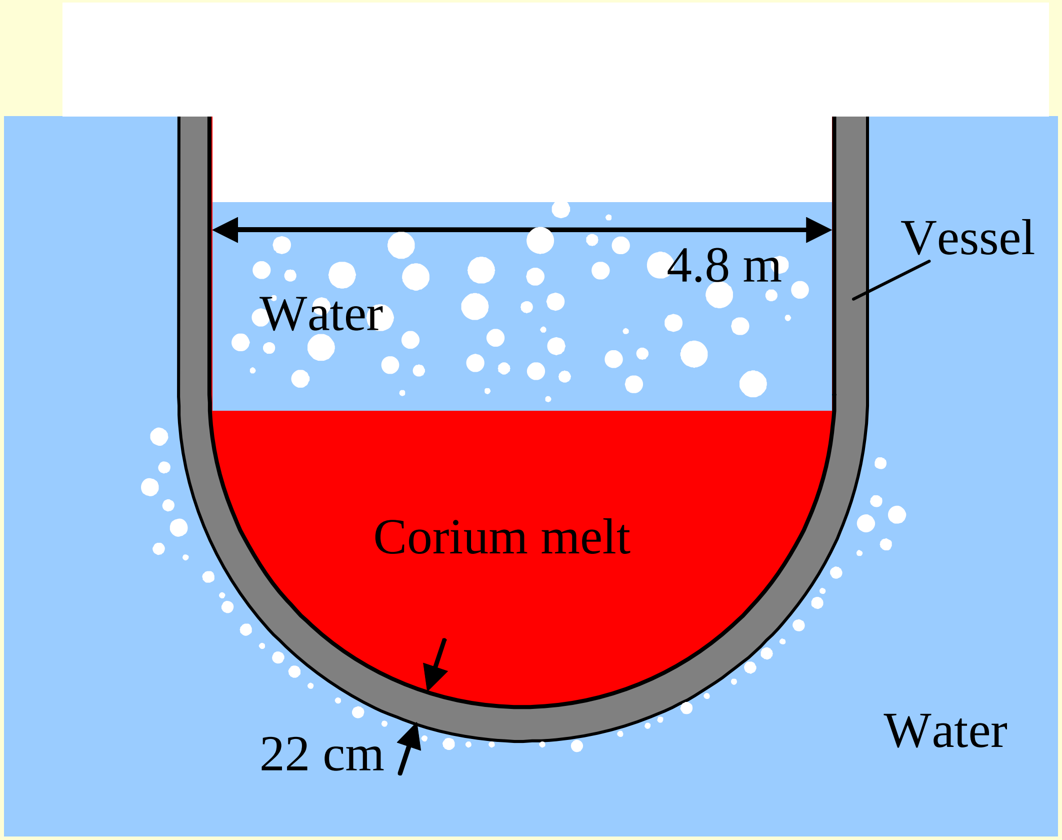
Long-term Containment Cooling

NuScale



SMR Mitigation of Severe Accidents

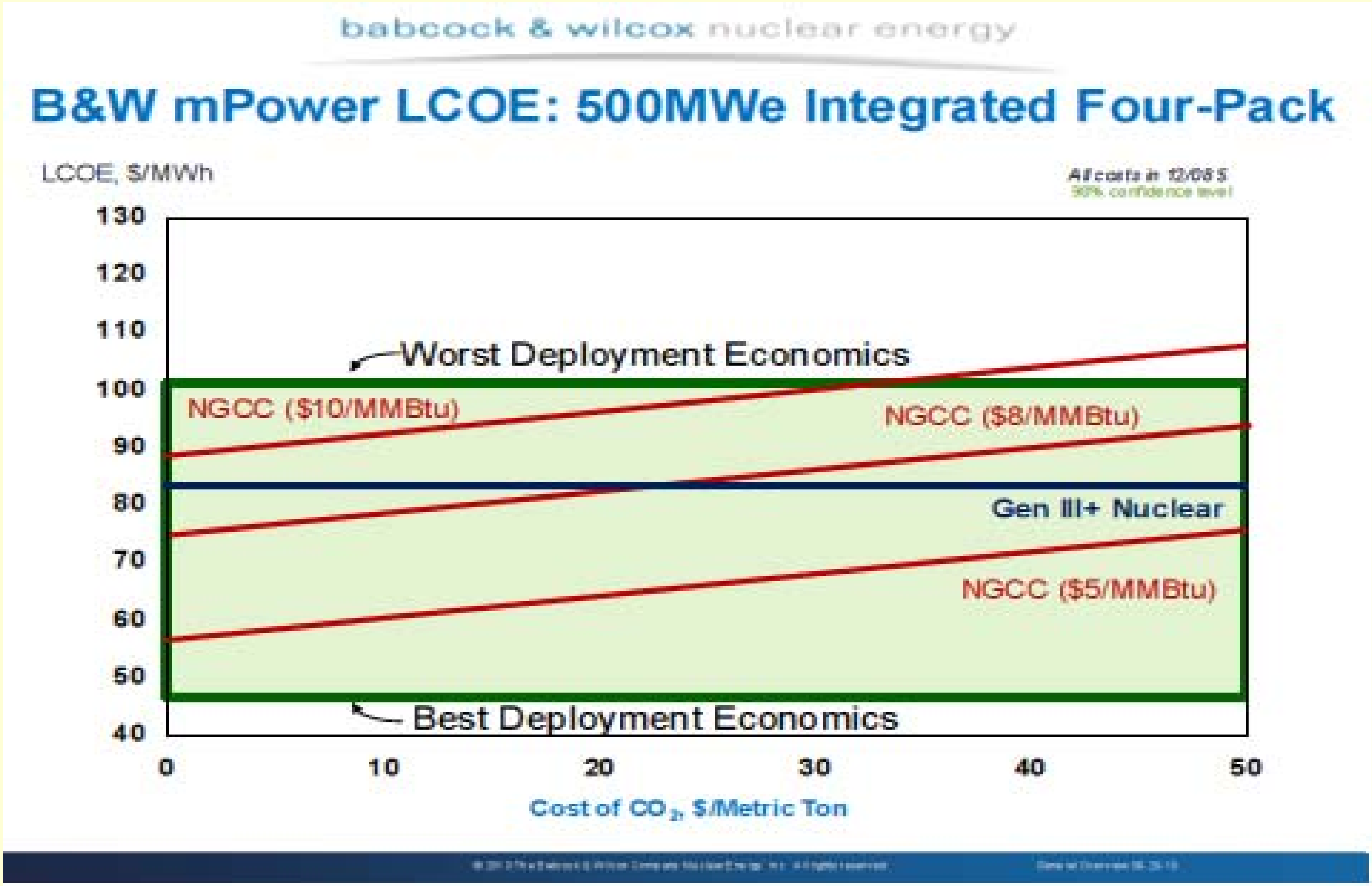
All SMRs use In-Vessel Retention (IVR) approach: flood RPV cavity + remove decay heat by boiling on outer surface of the RPV



IVR eliminates:

- Core-Concrete Interaction
- Steam Explosions
- High Pressure Core Melt
  - Eliminated by redundant, diverse ADS

Economic Potential of SMRs is good

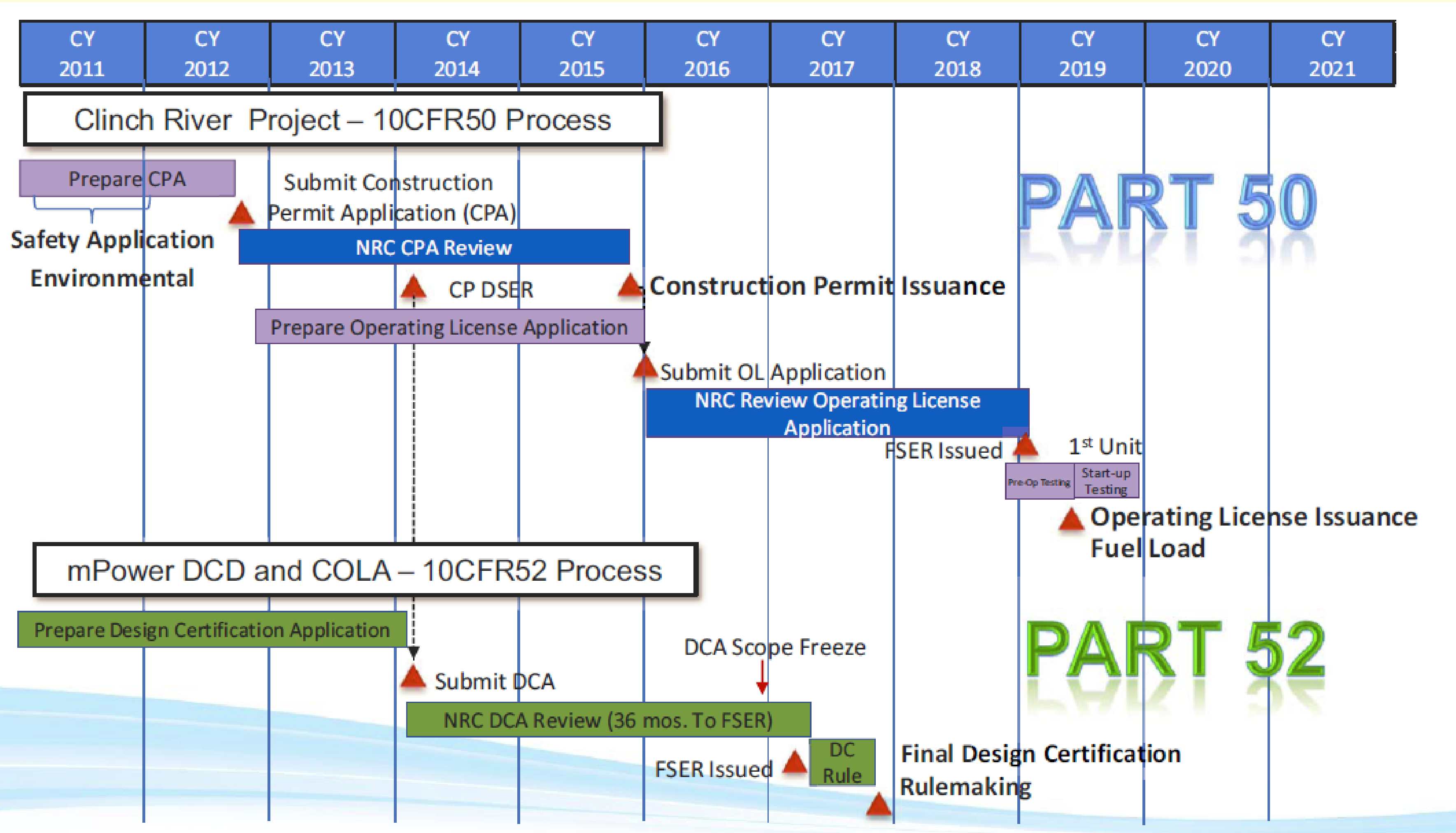


SMR RD&D

- Teams are testing novel separate systems (e.g. internal control rod drive mechanisms) and integral systems (e.g. gravity-driven emergency core cooling)
- B&W and Westinghouse have potential customers
- B&W seems somewhat ahead:
  - Joint development and pursuit of construction permit and operation license with TVA for up to six B&W mPower reactors at the Clinch River site in Roane County, Tennessee
  - Deploy first unit by 2020
  - Just won a $200M DOE grant to develop mPower
- Westinghouse has recently engaged Ameren (MO)

SMR RD&D (2)

Schedule for deployment of first mPower unit



Summary Features of Advanced LWRs

Reactor	US-EPR	US-APWR	AP1000	ABWR	ESBWR	mPower NuScale, WSMR, SMR-160
Neutron spectrum	Thermal	Thermal	Thermal	Thermal	Thermal	Thermal
Coolant/moderator	H_2O/H_2O	H_2O/H_2O	H_2O/H_2O	H_2O/H_2O	H_2O/H_2O	H_2O/H_2O
Fuel	LEU pins	LEU pins	LEU pins	LEU pins	LEU pins	LEU pins
Use of proven technology	++	++	+	++	+	+
Plant simplification			++		++	++
Modular construction			+		+	++
Economy of scale	++	++		+	++	
Economy of mass production						++
High thermal efficiency	+	+				
Passive safety			+		+	+
Mitigation of severe accidents	Core catcher	Core catcher	In-vessel retention		Core catcher	In-vessel retention

Potential Issues for Deployment of Advanced LWRs in the U.S.

- No capabilities for manufacturing very heavy components left. Need to buy from overseas. (Does not apply to SMRs)
- Shortage of specialized workforce experienced in nuclear construction (e.g., welders). (applies to all LWRs)
- Slow licensing process. (applies to all LWRs)
- Financial risk in deregulated markets. (Less of a problem for SMRs)

International SMR Designs

Name	MWe	Type	Company	Country
VK-300	300	PWR	Atomenergoproekt	Russia
CAREM	27	PWR	CNEA & INVAP	Argentina
KLT 40	35	PWR	OKBM	Russia
MRX	30-100	PWR	JAERI	Japan
IRIS-100	100	PWR	Westinghouse-led	International
SMART	100	PWR	KAERI	South Korea
NP-300	100-300	PWR	Technicatom (Areva)	France
PBMR	165	HTGR	Eskom et al.	South Africa
GT-MHR	285	HTGR	General Atomic Minatom et al.	USA Russia
BREST	300	LMR	RDIPE	Russia
FUJI	100	MSR	ITHMSO	Japan, Russia, USA

Include designs using other coolants like helium gas, liquid sodium, lead-bismuth or molten salt

Conclusions

- SMRs based on (relatively) proven LWR technology
- Can reduce financial risk
- Ultimate economic performance still unclear
- Superior degree of passive safety
- There is some interest from U.S. utilities