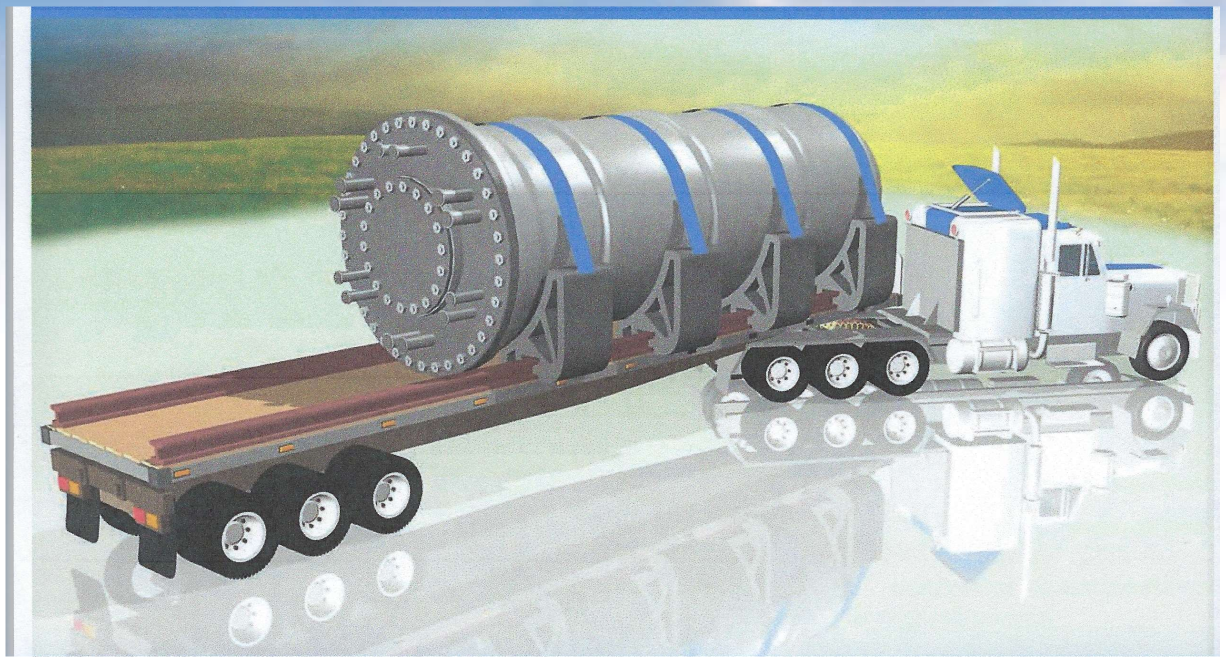
The Role of SMR's in Current and Future Energy Strategy Worldwide



Ted Quinn, tquinn@paragones.com
Past President, American Nuclear Society, Vice President, Licensing
Paragon Energy Solutions

February 21, 2024 ANS San Diego Local Section Meeting

Tonight's Discussion on SMR's

- Market Reasons for SMR
- World players in SMR
- Chinese HTR – Case Study
- American SMR – NuScale and Others
- SMR Economics
- Optimizing Manufacturing – Lessons Learned from Large Reactors and Other Industries
- Advanced Reactor Licensing
- Summary

Paragon Solution for Digital I&C

Paragon - A Complete I&C Solution Provider

Paragon can now fully execute digital upgrades

- Reactor Protection
- Neutron Flux Monitoring
- ESFAS
- Other Safety and Non-Safety Applications and Systems

Direct utility digital I&C engineering experience

- Digital I&C Initial Concept to Station Turnover Engineering
- Licensing Preparation and Coordination with NRC
- Specialized documents required including Defense-In-Depth (D3), reliability, time-response, safety analysis and failure analysis

Provide current bridging strategy through Repair and Reverse Engineering

Paragon

The Choice for Advanced Reactors

SHINE Technologies

- TSV Reactivity Protection System (TRPS)
- Engineered Safety Features Actuation System (ESFAS)
- Neutron Flux Monitoring System (NFMS)

NuScale Power

- Module Protection System (MPS)
- Plant Protection System (PPS)
- Safety Display and Indication System (SDIS)

X-Energy Xe-100

- Reactor Protection System (RPS)
- Neutron Flux Monitoring System (NFMS)

Kairos Power

- Hermes – KP-Shield, Reactor Protection System (RPS)
- KP-FHR – KP Shield, Rector Protection System (RPS)

DEC 2023 COP 28 TRIPLING NUCLEAR ENERGY

Nuclear Energy Makes History as Final COP28 Agreement Call Deployment

Jeffrey Donovan, IAEA Department of Nuclear Energy

DEC
13
2023

The annual UN Climate Change Conference (COP28) final agreement issued on 13 December 2023 called for accelerating the deployment of low-emission technologies including nuclear energy to help achieve deep decarbonization. (Photo: D. Calma/IAEA)

What are Small Modular Reactors?

As a class of reactors, SMRs are defined by their small size, but there is considerable variety within this class of reactors.   They vary by power output, temperature output, technology and fuel cycle. A number of SMRs are baed on existing commercially deployed light water reactor technologies, while others are based on advanced design concepts, offering a range of sizes – from 1MWe to over 300 MWe and a range of temperatures from 285 °C to more than 850°C, to meet the specific needs of industrial applications.

Small Modular Reactors (SMRs) for Net Zero

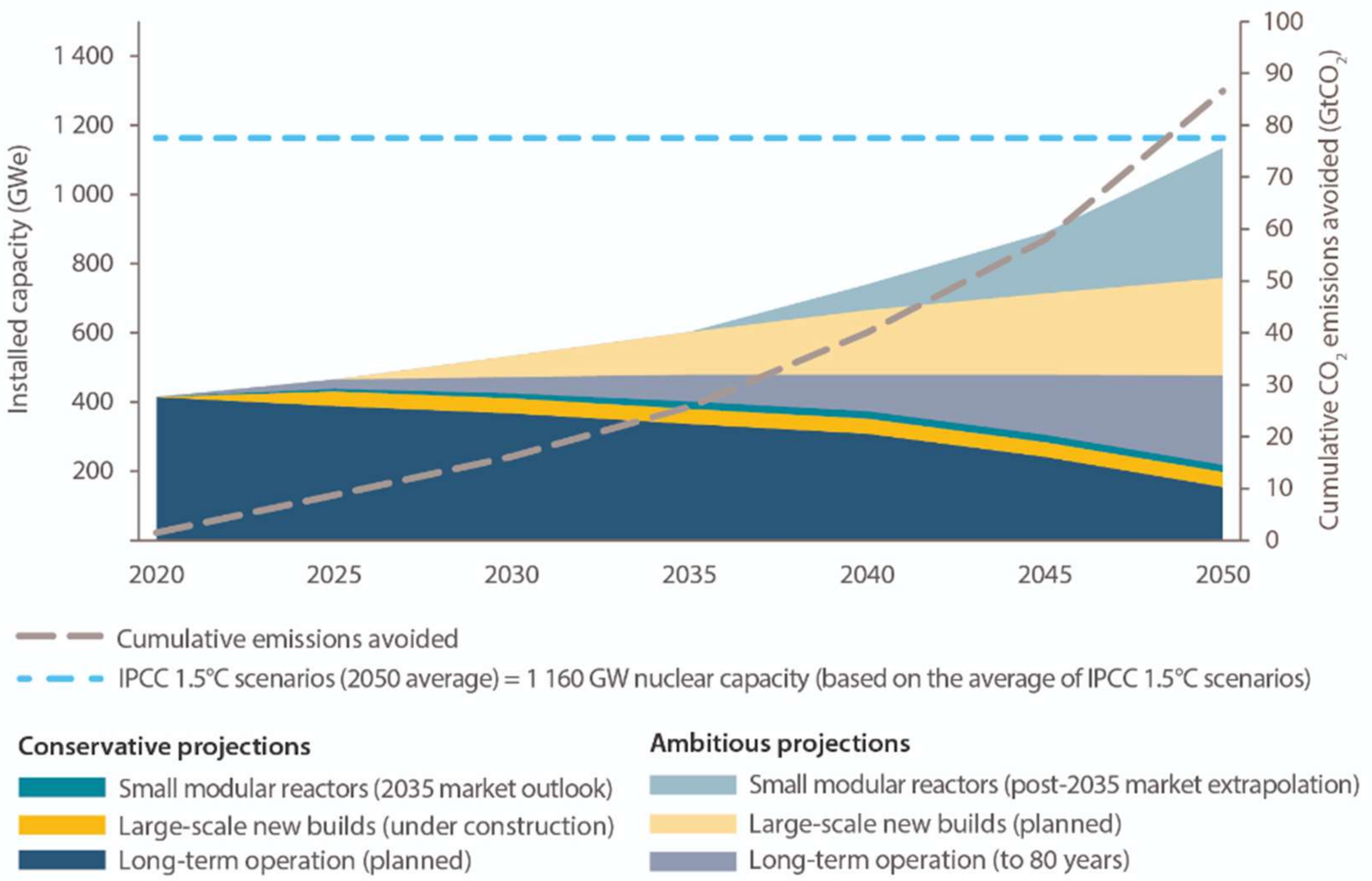
- SMRs are expected to have an essential and increasingly important role to play in supporting net zero targets, particularly for hard-to-abate industrial sectors like steel mills and oil refineries.
- There are a number of potential benefits to SMRs, ranging from enhanced and passive safety systems to more attractive financing options due to reduced construction schedules, fewer components and smaller plant footprints
- The first SMRs are expected to be built this decade, followed by accelerated deployment around the world in the 2030s.

Nuclear Energy Agency Worldwide

The Nuclear Energy Agency (NEA) tracks 42 SMRs around the world. Markets are signaling significant demand for on-grid power to replace coal plants, off-grid heat and power to replace diesel generators for remote mining operations; high-temperature heat to replace fossil fuel cogeneration in heavy industries such as chemical processing; and marine propulsion to replace heavy-fuel oil for merchant ships.

Contribution of Nuclear To Net Zero

Figure 2: Full potential of nuclear contributions to net zero



Source: NEA (2022)

Incentives for SMR Deployment

- Reduction of initial investment and associated financial risk
- Improved match to smaller electric power grids
- Effective protection of plant investment from the potential to achieve a reactor design with enhanced safety characteristics
- Possible reduction of the current 10-mile Emergency Planning Zone
- Reduction of transmission requirements and a more robust and reliable grid
- Use of components which do not require ultra-heavy forgings
- Suitability for load following, district heating and desalination

SMRs Under Construction Globally

Small reactor designs under construction

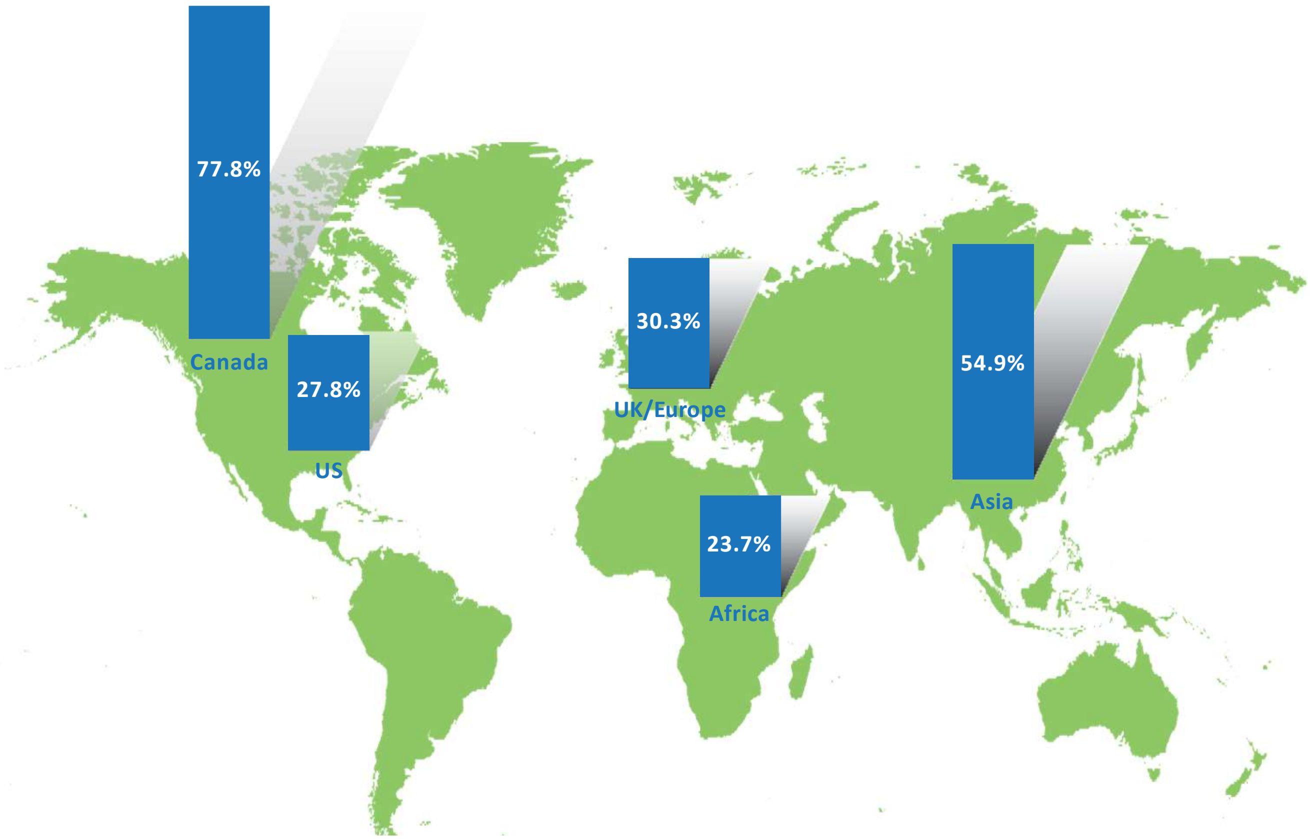
	Name	Capacity	Type	Developer
1	KLT-40S	35 MWe	PWR	OKBM, Russia
2	RITM-200	50 MWe	Integral PWR	OKBM, Russia
3	CAREM-25	27 MWe	integral PWR	CNEA & INVAP, Argentina
4	HTR-PM	2x250 MWt	HTR	INET, CNEC & Huaneng, China
5	ACPR50S	60 MWe	PWR	CGN, China

Source of info: World Nuclear Association www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx

Global SMR market value is approximately 65-86GW by 2035, valued at £250-400bn

Source www.rolls-royce.com/products-and-services/nuclear/small-modular-reactors.aspx?gclid=EAIaIQobChMIzu7s-rrD81gIV1wrTCh1jXQUMEAAYASAAEgLWcfD_BwE

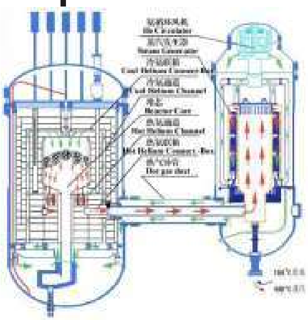
Nuclear Energy Insider poll: Which markets are most attractive for SMR deployment?



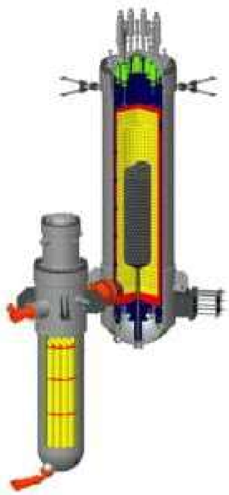
Chinese HTR-PM: a commercial NPP

- High Temperature Gas-cooled Reactor - Pebble-Bed Module
  - Total thermal power: 2*250MWth
  - Rated electrical power: 210MWe
  - Primary helium press: 7MPa
  - Temperature at inlet/outlet: 250/750℃
  - Commercial Op 2023

Chinese HTR-PM

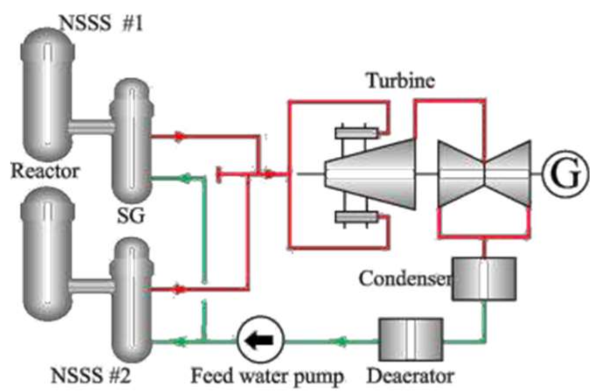


HTR-10



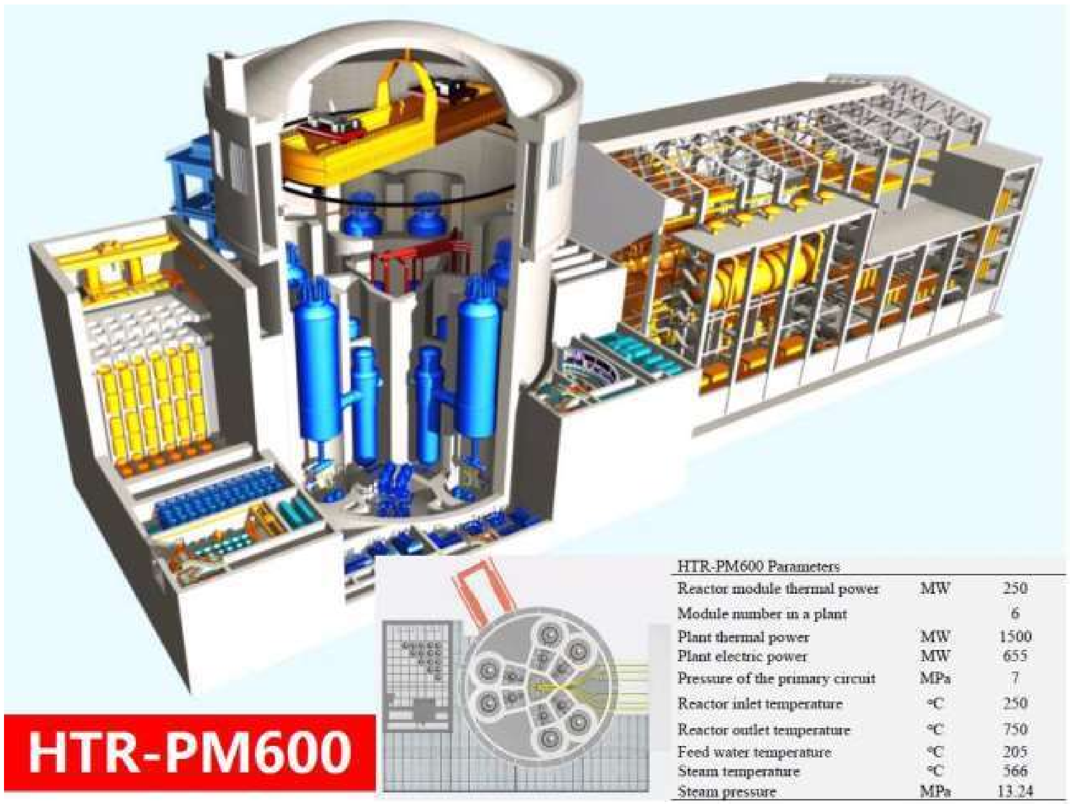
HTR-PM
(One module)

x2



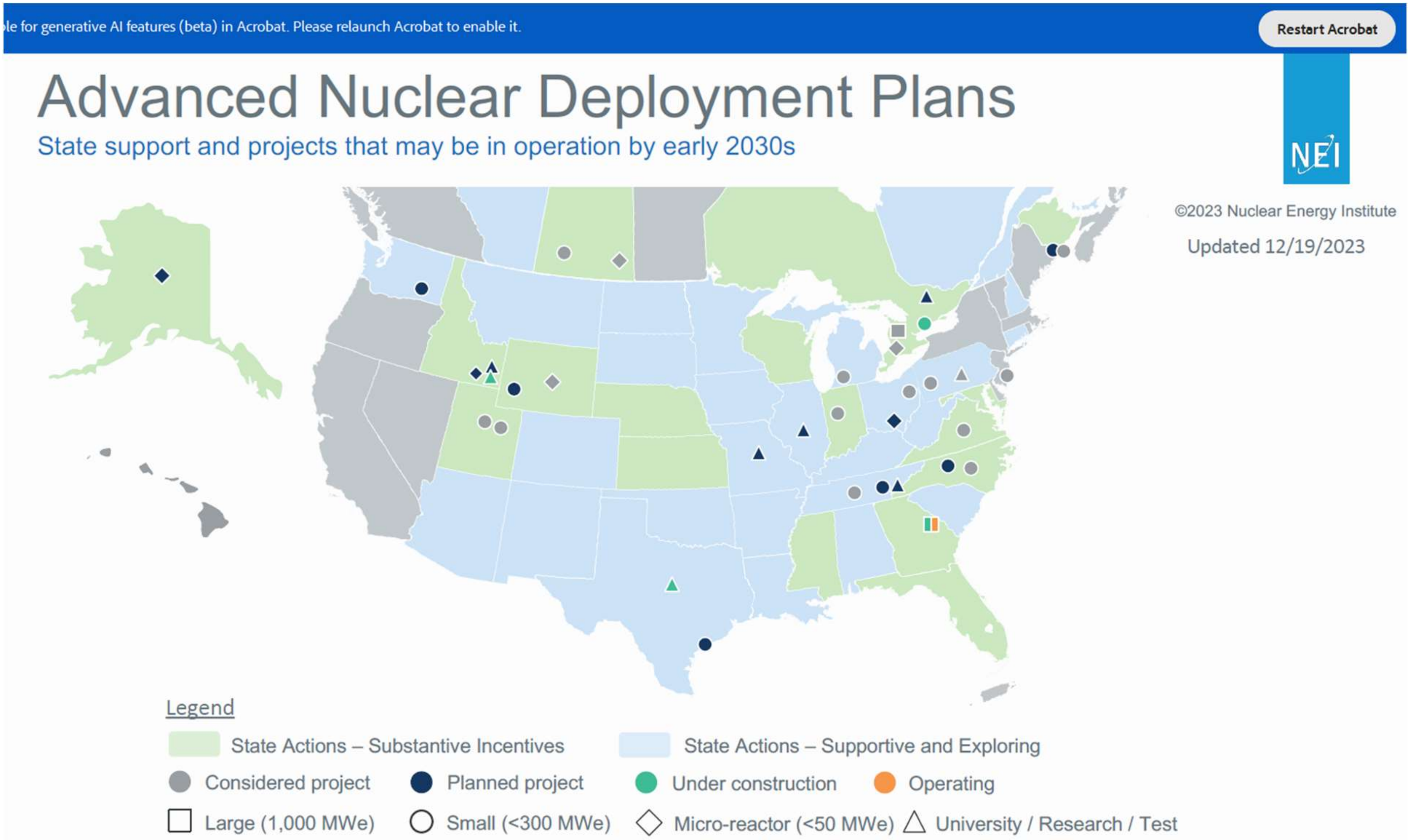
HTR-PM
(Two modules drive one steam turbine)

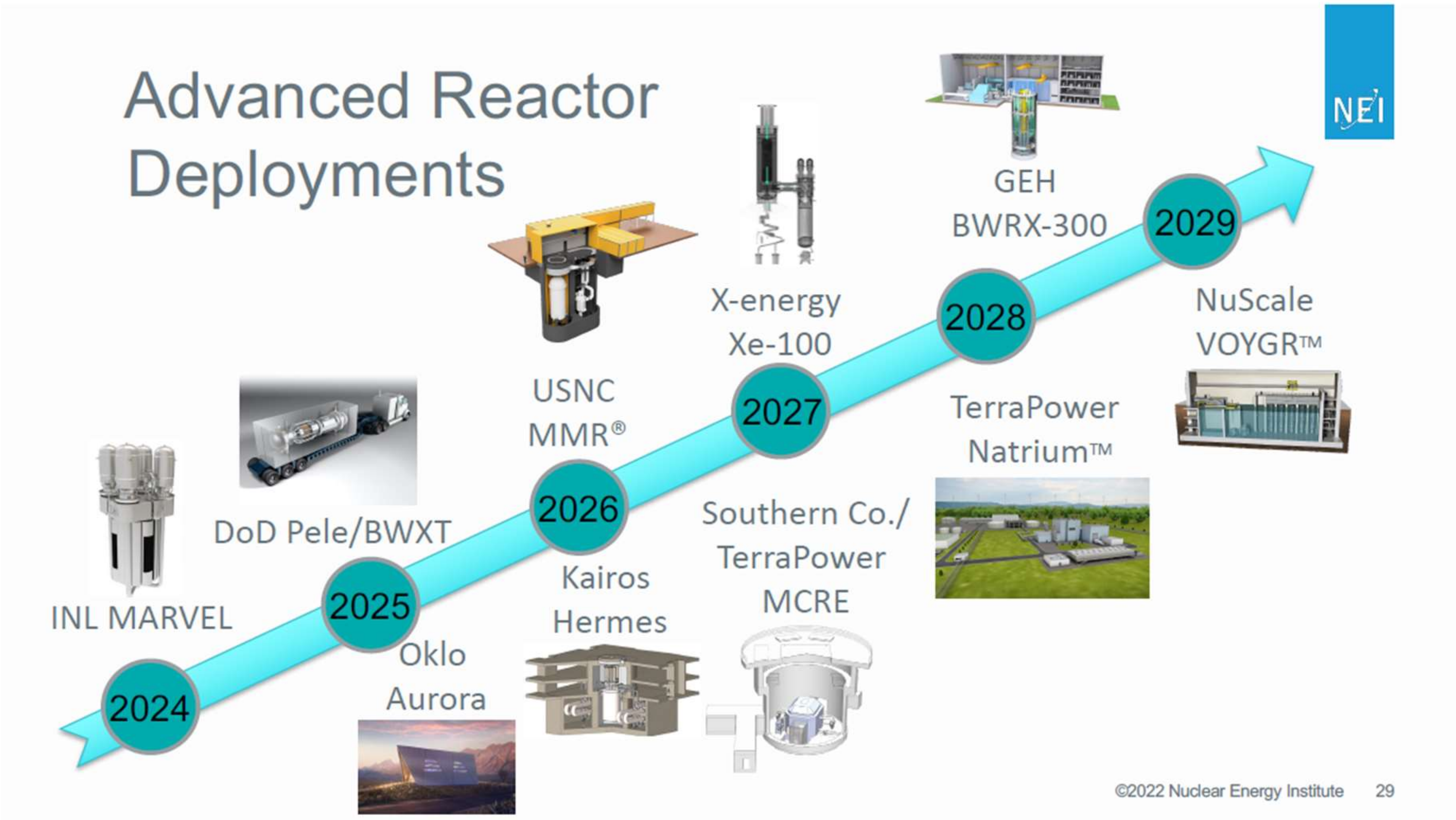
HTR-PM600 – Next Step



HTR-PM600 Parameters		
Reactor module thermal power	MW	250
Module number in a plant		6
Plant thermal power	MW	1500
Plant electric power	MW	655
Pressure of the primary circuit	MPa	7
Reactor inlet temperature	°C	250
Reactor outlet temperature	°C	750
Feed water temperature	°C	205
Steam temperature	°C	566
Steam pressure	MPa	13.24

American SMR's




Advanced Reactor Deployments
NEI
2024
INL MARVEL
2025
DoD Pele/BWXT
Oklo Aurora
2026
USNC MMR®
Kairos Hermes
2027
X-energy Xe-100
Southern Co./ TerraPower MCRE
2028
GEH BWRX-300
TerraPower Natrium™
2029
NuScale VOYGR™
©2022 Nuclear Energy Institute 29

Unique NuScale Design Features Approved by NRC

- No connection to the grid required for safety.
  - Permits siting at “end of line”; distributed generation applications, coal plant repowering; and for district heating.
- Island mode operation
  - Regulations permits “off-grid” operation - A very important feature for providing reliable power and process heat to industrial applications.
- NRC approved control room staffing. Three operators can safely operate 12 reactors in a single control room
- Eliminated Shift Technical Advisor (STA) position
- Unique cyber resistant FPGA based Module Protection and Plant Protection Systems.
- NuScale EPZ sizing methodology approved by NRC. Site boundary EPZ is achievable at most US sites surveyed.

NuScale at a Glance

1st
And Only SMR to Receive NRC Standard Design Approval

>$1.6B
Cumulative Capital Invested to Date

545
Employees with Unparalleled Nuclear Experience

28
PhDs

180
Masters in Engineering/ Science Degrees

686
Total Patents

505
Granted

181
Pending

Extensive Trade Secrets

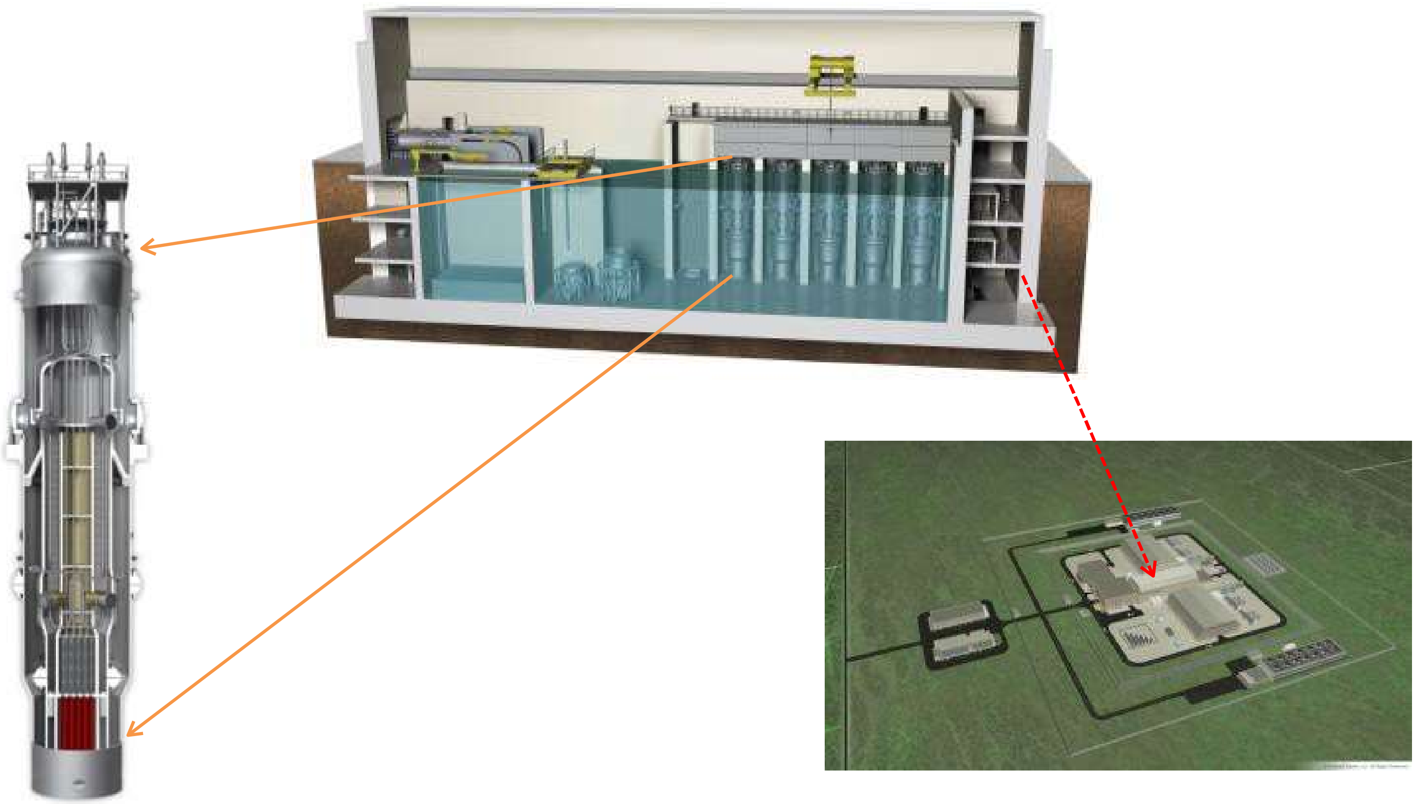
15
Years of R&D and Testing
Founded in 2007

9
Strategic Investors Supporting Global Customer Adoption[1]

Smarter | Cleaner | Safer | Cost Competitive

1. Established Supply Chain Network with Continued DOE Support

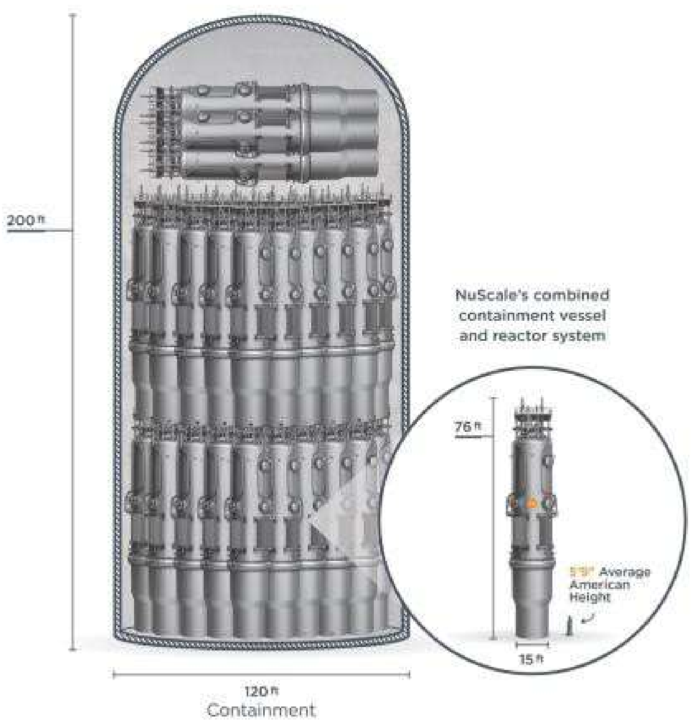
NuScale Power Plant - Overview



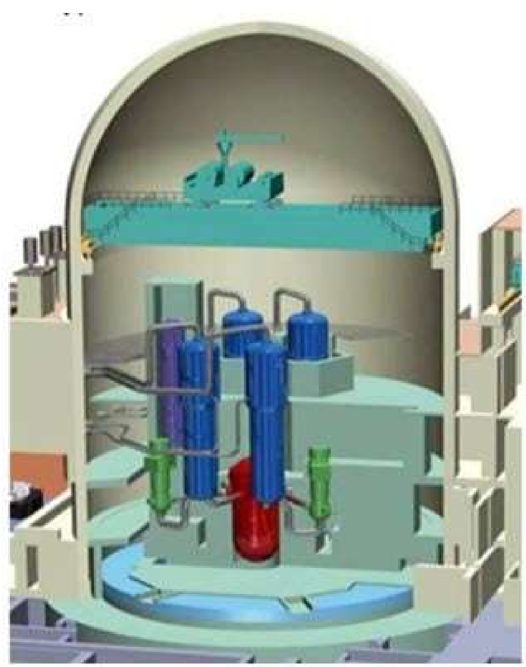
NuScale Nonproprietary

Size Comparison

Comparison size envelope of new nuclear plants currently under construction in the United States.



Typical Pressurized Water Reactor

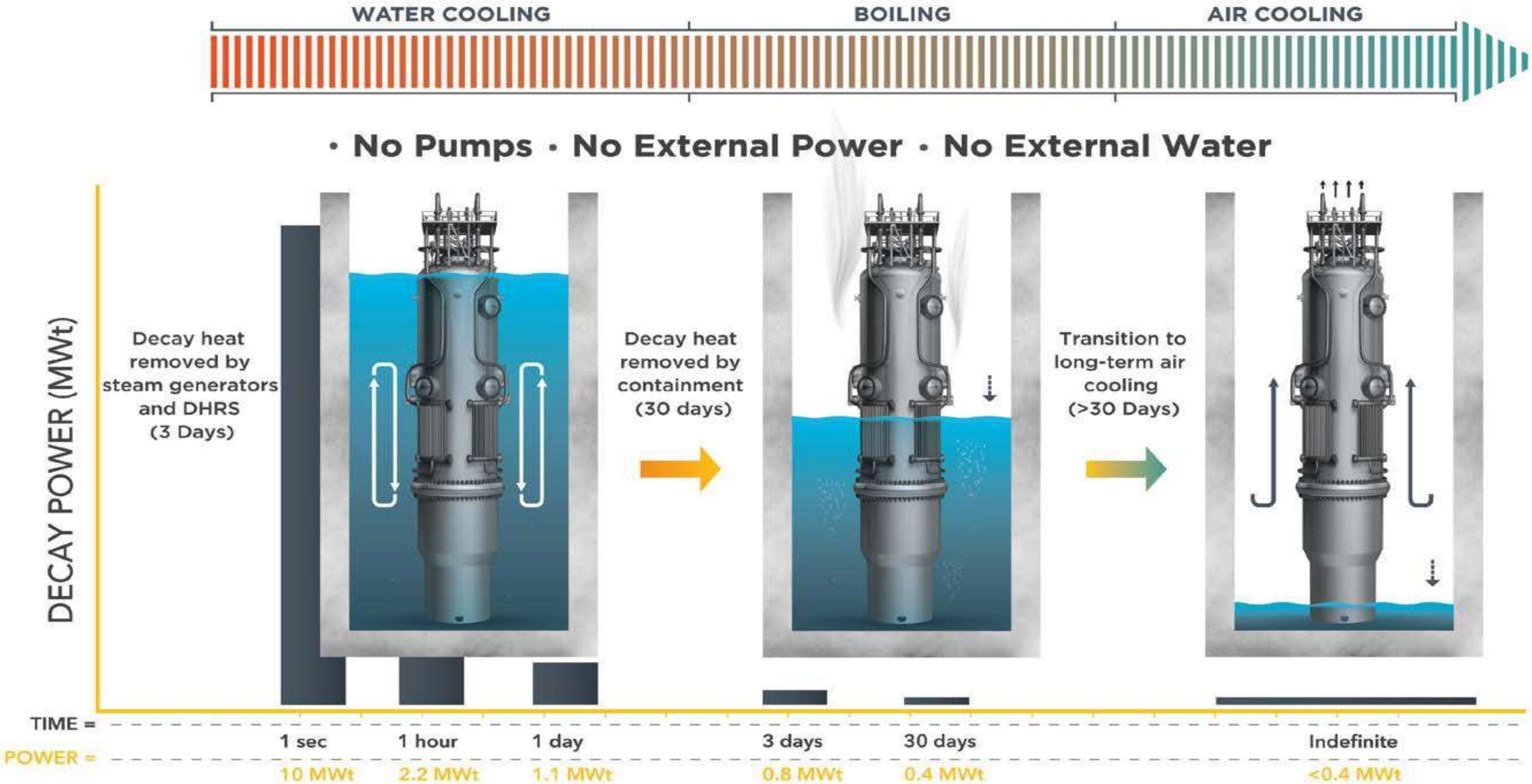


*Source: NRC

*Source: U.S. NRC

Innovative Advancements to Reactor Safety

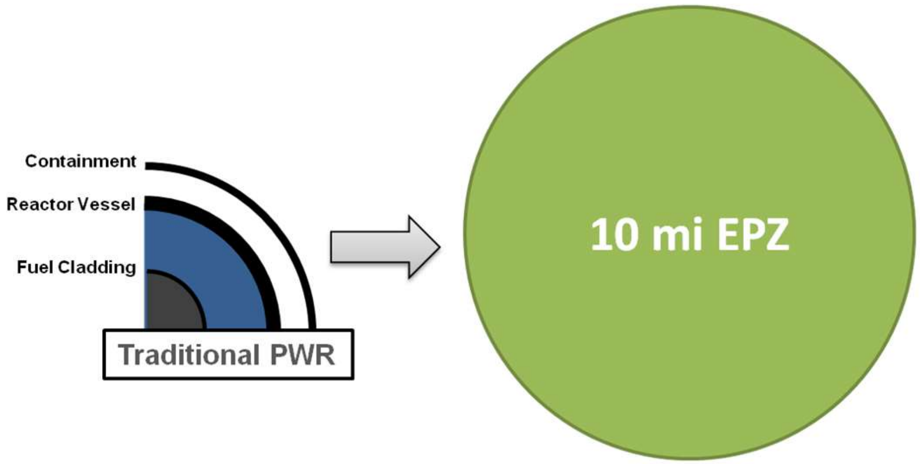
*Nuclear fuel cooled indefinitely without AC or DC power**



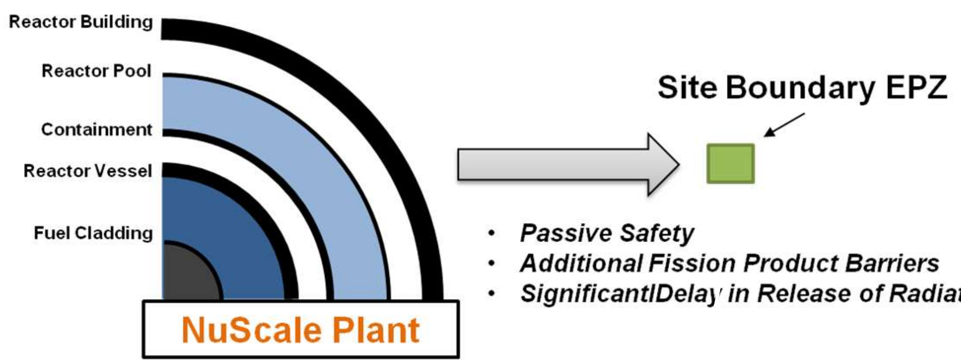
• ***30 days is a minimum based on very conservative estimates.***

****Alternate 1E power system design eliminates the need for 1E qualified batteries to perform ESFAS protective functions – Patent Pending***

Strong Safety Case - Smaller EPZ



The licensee must have pre-determined protective action plans in place for a large publicly accessible area.



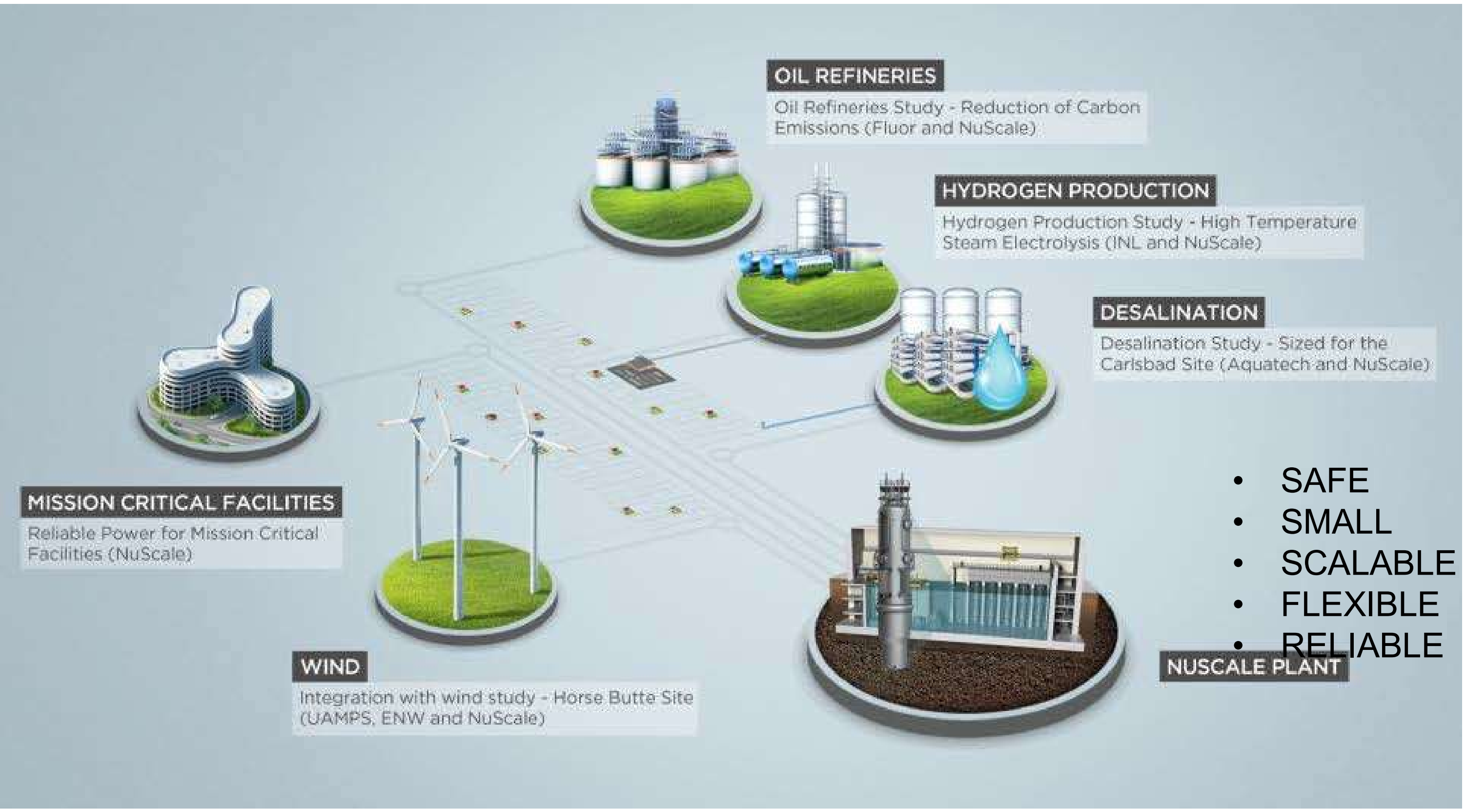
- *Passive Safety*
- *Additional Fission Product Barriers*
- *SignificantlDelay in Release of Radiation*

Virtually no publicly accessible area is subject to protective action planning by the licensee.

NuScale Control Room Simulator

Approved for 3 operators for 12 modules by NRC

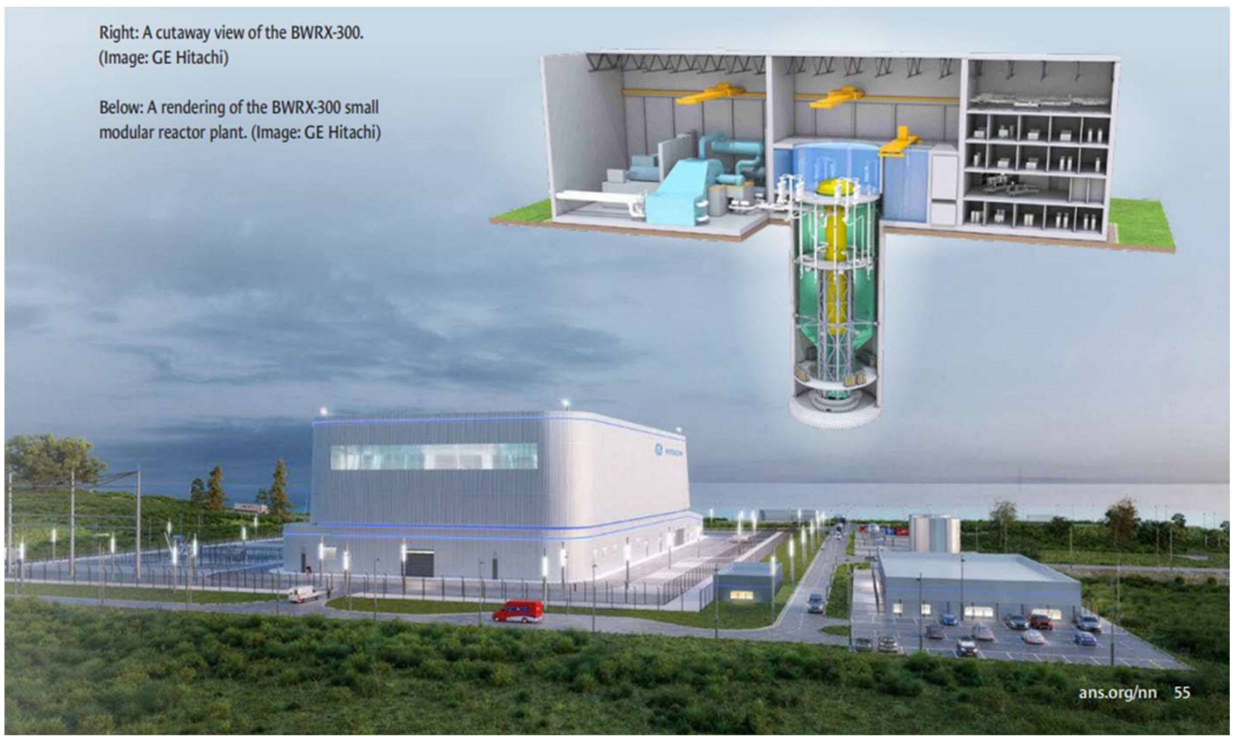
NuScale Diverse Energy Platform (NuDEP) Initiative



- SAFE
- SMALL
- SCALABLE
- FLEXIBLE
- RELIABLE

NuScale Power Corporation is a technology provider that specializes in **small modular reactor (SMR) technology**. Recently, **Standard Power**, a company offering infrastructure services to advanced data processing firms, announced its plans to develop two SMR-powered facilities in **Ohio and Pennsylvania**. These facilities are expected to produce nearly **2 gigawatts (GW)** of clean, carbon-free energy, with the aim of powering nearby data centers [1].

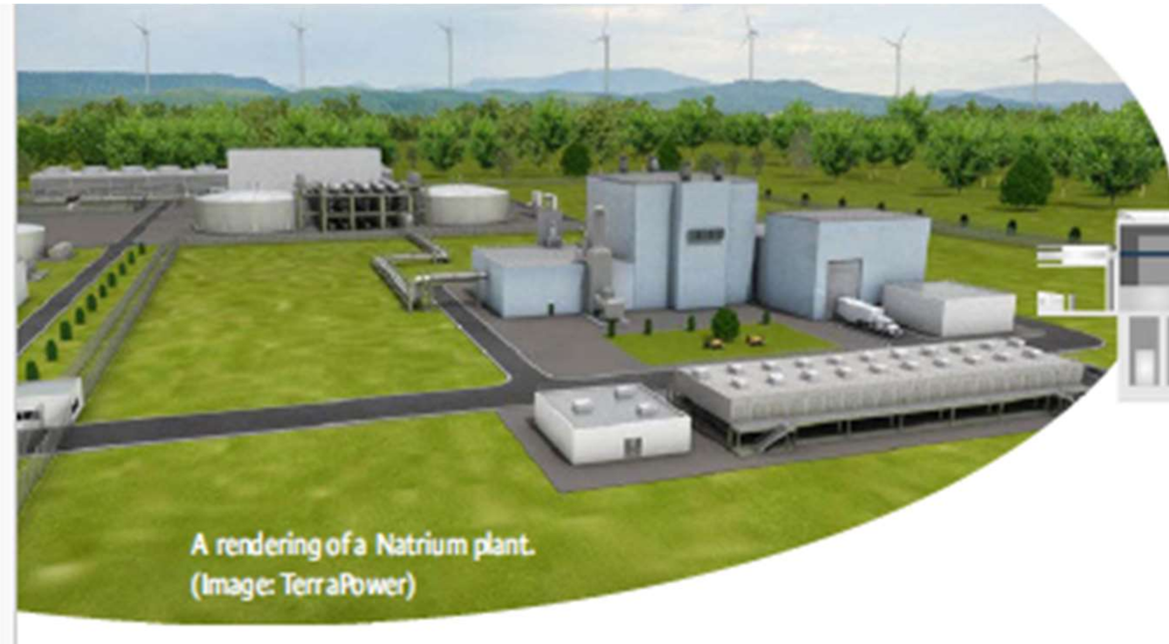
GE BWRX-300



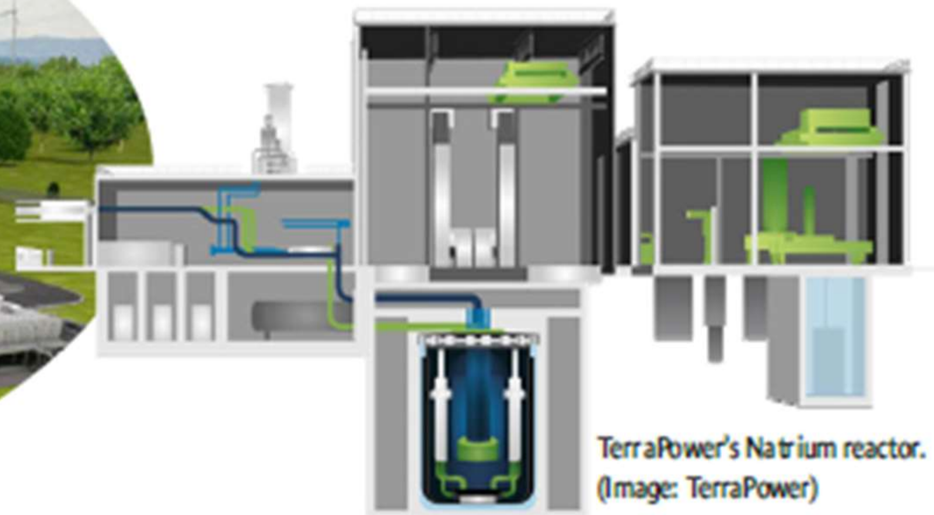
- Ontario Power Gen (OPG) 2023 announced plan to build three.
- Reactors to be completed by 2028.
- TVA next
- Synthos Green Energy of Poland Next

TerraPower “Bill Gates” Reactor Sponsor of Natrium-LMR and Molten Choloride Reactor Designs

TerraPower Natrium Reactor



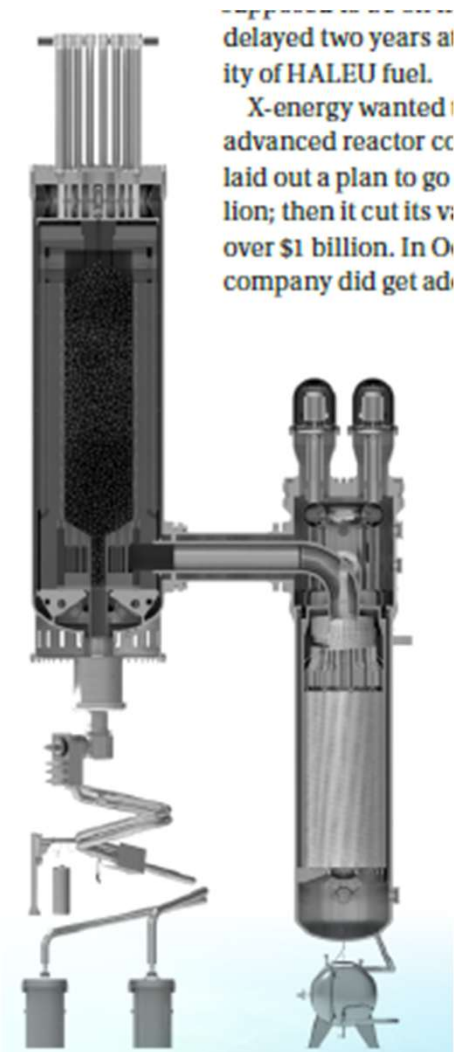
A rendering of a Natrium plant.
(Image: TerraPower)



TerraPower's Natrium reactor.
(Image: TerraPower)

- 345 MW electric liquid metal reactor
- Demonstration site – in Wyoming
- GEH/TerraPower build and sell to PacifiCorp
- Apply construction permit by March 2024
- Congress has appropriated $3.1B for this and X-Energy demonstration.

Xe-100

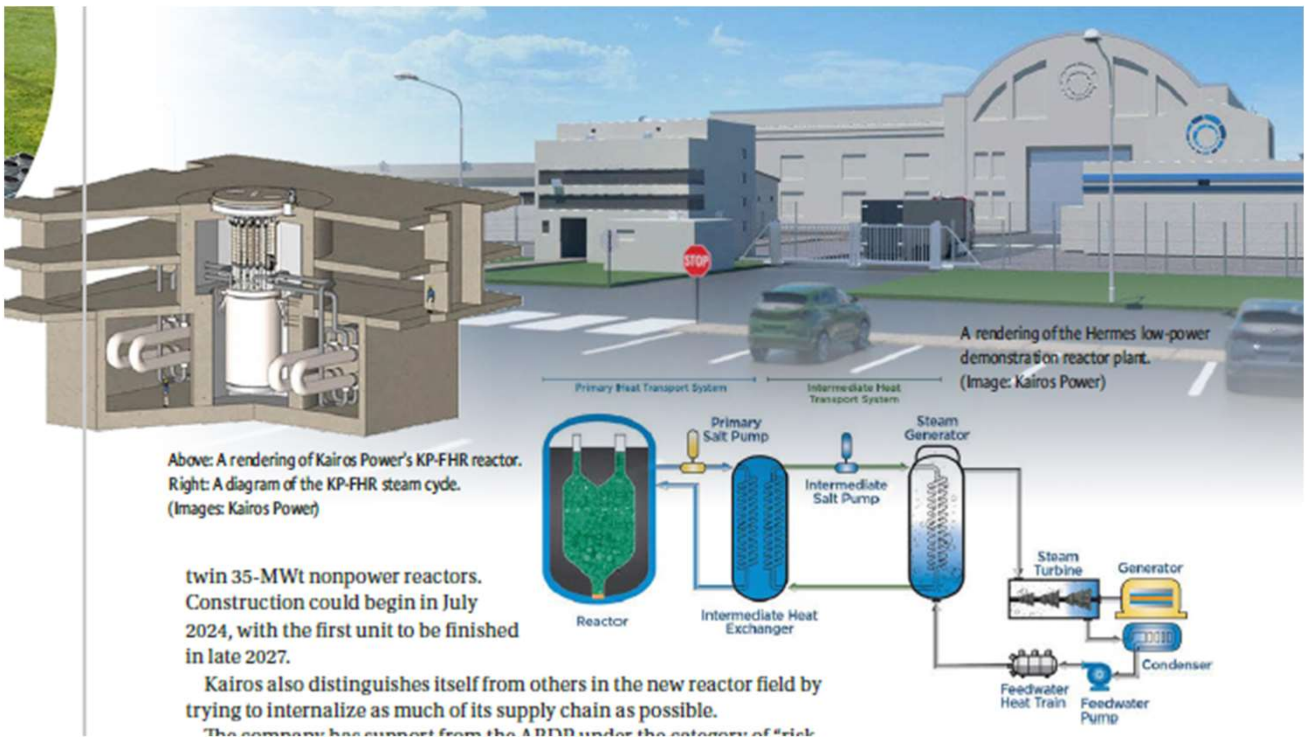


A cross-section view of X-energy's Xe-100 reactor. (Image: X-energy)

A rendering of the Dow/X-energy Xe-100 plant in Texas. (Image: X-energy)

Built as HTGR – 80 Mwe each module– pebble bad design
Dow Chemical announced in May 2023 – a cluster of four Xe-100s of 80 Mwe each in Texas for electricity and steam output.

Kairos Power KP-FHR



35 MWt non-power reactor Flouride salt-cooled, high temperature reactor – uses TRISO fuel pebbles.
TRISO spheres float in a low-pressure bath of fluoride salt coolant allowing for very high temperatures at low pressures.

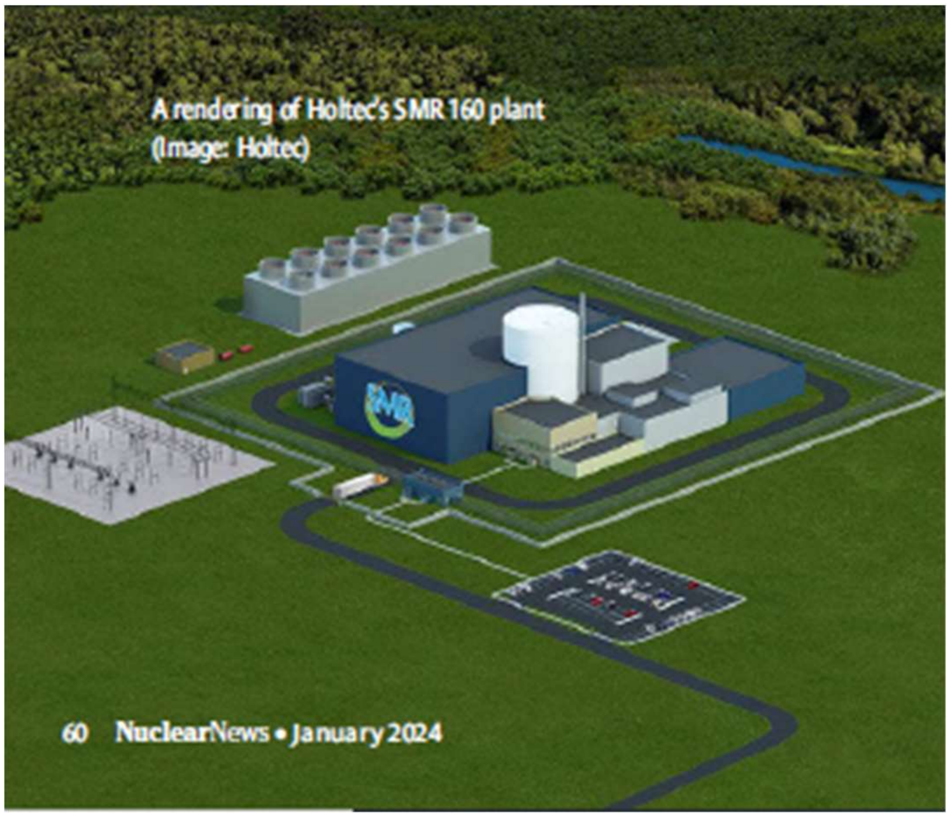
- Sibmitted Construction Permit application to NRC Sept 2021 for this test reactor. Licensed under ANS/ANSI-15.8

Westinghouse AP-300

¼ scale copy of the AP1000 which is licensed and built in Georgia – Vogtle 3&4

Smaller LWR vessel with one SG

HOLTEC SMR 160

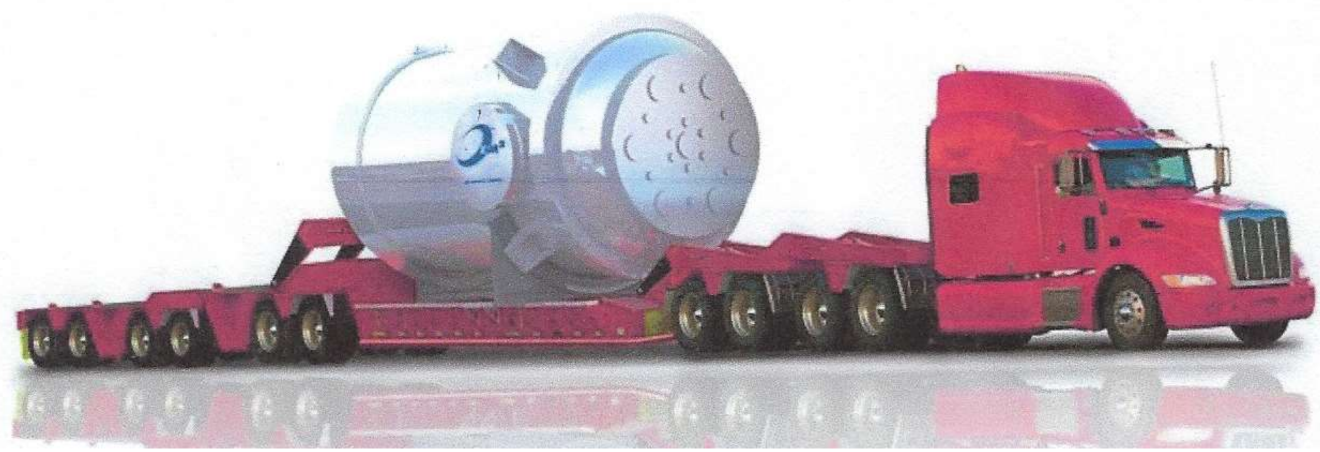


Heavy manufacturing experience
Candidate sites – Oyster Creek and Palisades
Also, have design for SMR-300
Seeking loan of $7.4B from DOE
Agreement with Energoatom to build in Ukraine

General Atomics EM-Squared Design

BUSINESS

Focus: For General Atomics, smaller nuclear plants are beautiful



Also, Micro-reactors and Demonstrations

Micro-reactors

- OKLO - Aurora Powerhouse
- BWXT Project Pele
- Westinghouse eVinci
- Ultra Safe Nuclear: Micro-Modular Reactor

Demonstrations and Experiments

- Molten Chloride Reactor Experiment – TerraPower- molten chloride
- Abilene Christian University – Molten salt reactor

Challenges Facing SMRs

However, being a pilot technology there are still several challenges that face SMRs' commercial deployment

Non-Exhaustive

Challenges facing SMR deployment

FOAK vs NOAK

To realize financial benefits SMRs require economies of scale and scalability, which will only be realized by NOAK

Supply Chain

Current supply chain network is geared towards large NPPs leaving SMR material difficult to source

Regulation/Licensing

Lack of SMR regulations governing enhanced passive safety systems and multi-modular deployment and components result in long and onerous licensing process

Electrical grid network

Electrical grid networks do not have the sufficient infrastructure to accommodate nuclear reactors

Know-how

There is a lack of technical know-how to manage multi-module plants and meet advanced R&D requirements, current technology not fully compatible with a factory assembly model

Source: IAEA,

NuScale Economics – Front and Center

- Simplicity of design provides competitive levelized cost of electricity compared to other low carbon options.
  - Lower up-front cost and lower operating cost as compared to large light-water nuclear reactors
    - Competitive overnight capital cost compared to large advanced nuclear
    - First plant target LCOE - $65/MWh

- Up to 12 modules can be added to a facility incrementally, in response to load growth, reducing initial capital costs

- First module in situ can generate and bring in revenue immediately

- NuScale Power Modules fabricated in an off site facility, bringing cost savings associated with repetitive manufacture
  - Realize benefits of factory fabrication

NuScale - Construction Cost Summary (U.S.) - 2018

Overall EPC Overnight Plant Costs For First Plant ($1,000,000)

ITEM	2014 Dollars	
Power Modules (FOAK Cost plus Fee, Transportation, & Site Assembly)	$	848
Home Office Engineering and Support	$	144
Site Infrastructure	$	60
Nuclear Island (RXB, RWB, MCR)	$	538
Turbine Island (2 buildings with 6 turbines each)	$	350
Balance of Plant (annex, cooling towers, etc)	$	225
Distributables (Temp. Bldgs., Field Staff, Const. Equip., etc.)	$	545
Other Costs	$	185
Total Overnight Price	**$**	**2,895**

$ 5,078 per kWe net

Note: NuScale website's latest estimate with uprated 60MWe modules is $3B for 12 module 684MWe net output with 54 month mobilization and 32 month critical path to commercial operation. ($4,385/kw)

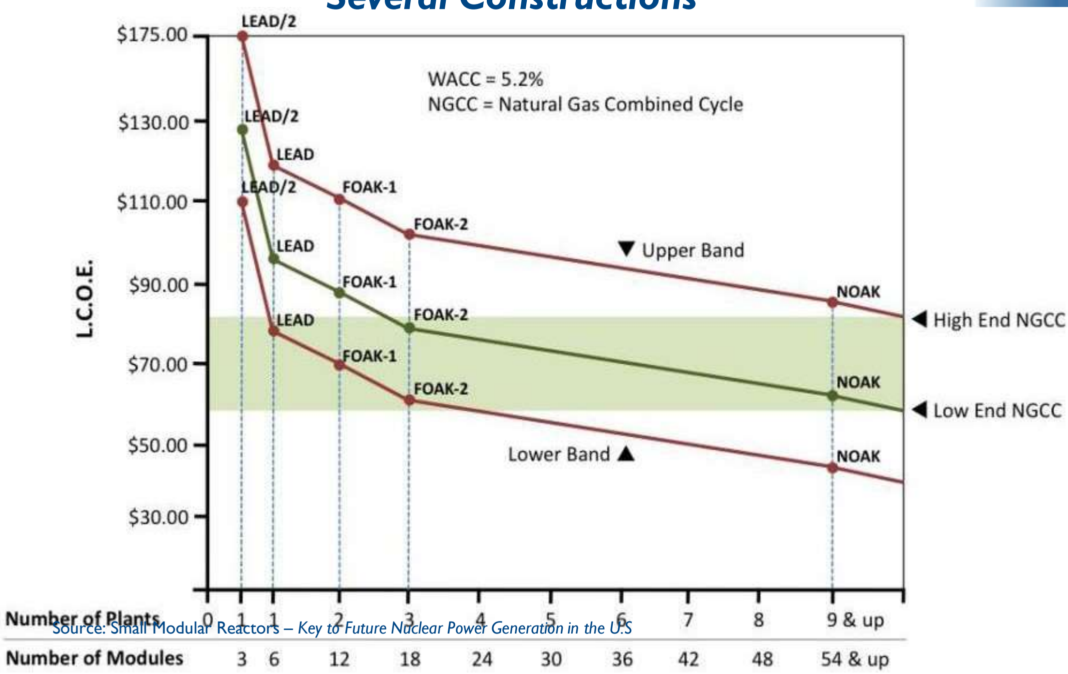
NuScale Nonproprietary

The electricity cost of SMR is expected to drop drastically driven by the learning achieved from repetitive construction and standardization of designs

Case Study

Costs Evolution of SMR and Natural Gas Plants

Expected Cost of SMR and NGCC After Several Constructions



Source: Small Modular Reactors – *Key to Future Nuclear Power Generation in the U.S*

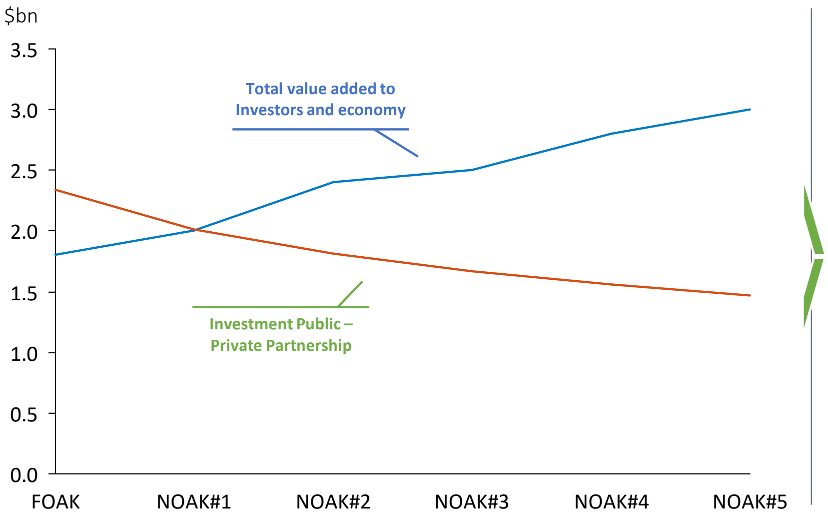
Comments

- The learning process will drive down costs through repetitive construction and manufacturing of standardized designs
- The upper and lower bound for prices reflect the uncertainties about learning rates
- The cost of electricity by building SMR after several repetitions is expected to be equal to or lower than the costs of electricity using Natural Gas Combined Cycle
- The prices considered, factor in owner's costs, contingencies, interest during construction, fuel, operations and maintenance costs

DOE advertising a $3600/kw price for electricity from NOAK SMR

INITIAL INVESTMENT VERSUS NET VALUE FOR SMR DEPLOYMENT

Net value added to USA economy from SMR Deployment



- Funding cost for initial FOAK comes from direct equity injection into VENDOR owner and from investors and govt and from lifetime NPV of VENDOR owner's funding gap (PPA tariff – LCOE)
- Total value added to economy derived from direct, indirect and induced benefits from SMR production and deployment
- Breakeven in net value added reached with NOAK#2 (3rd site)
- Net value added to USA economy can reach up to $ 1.5 bn by deployment of NOAK#5 (6th site)

- Options:
  - "Step of Faith"
  - State involvement – Fed help

Advanced Manufacturing for Nuclear

Model T Ford

Holtec Advanced Manufacturing Facility

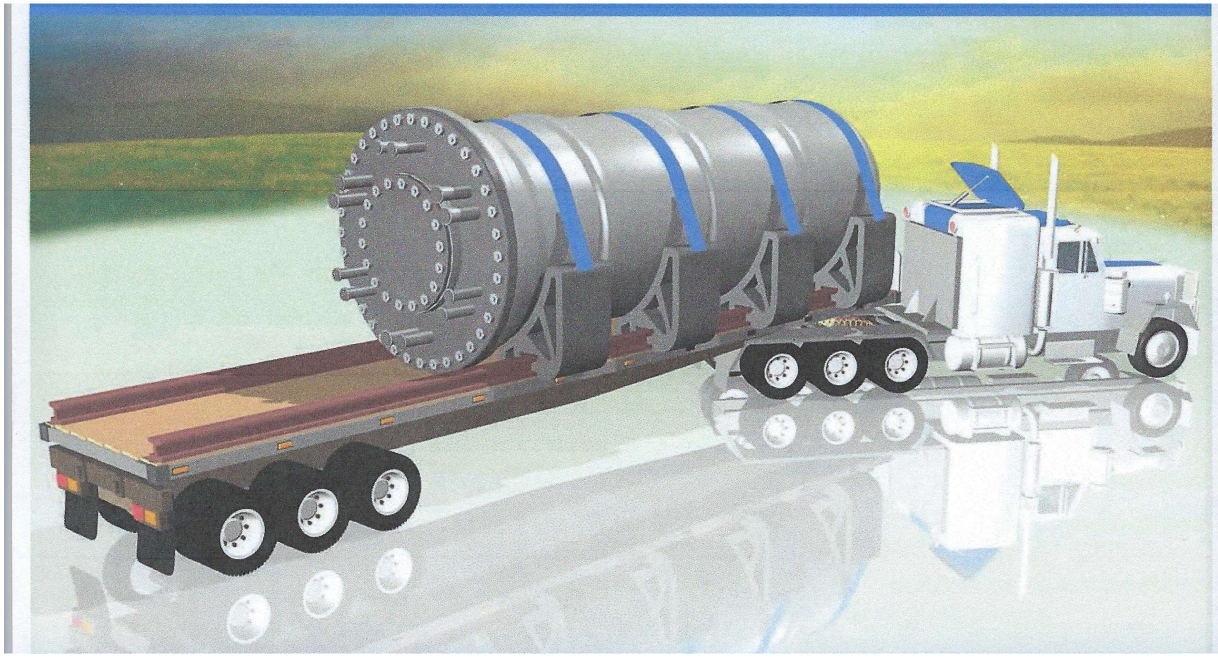
Advanced Manufacturing for Nuclear

Model T Ford

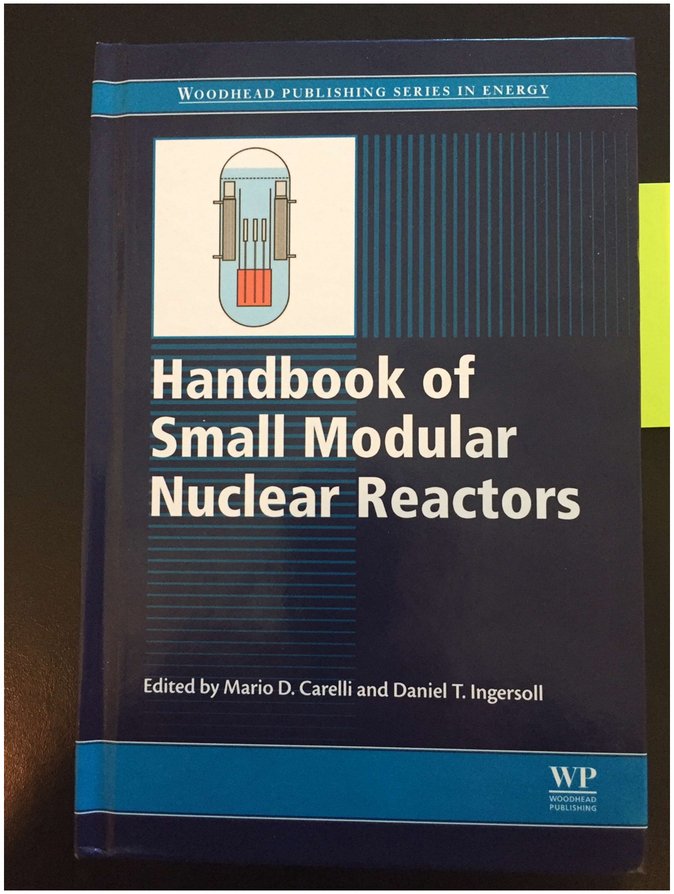
Holtec Advanced Manufacturing Facility

Methods of Reduction in Total Cost Must Address:

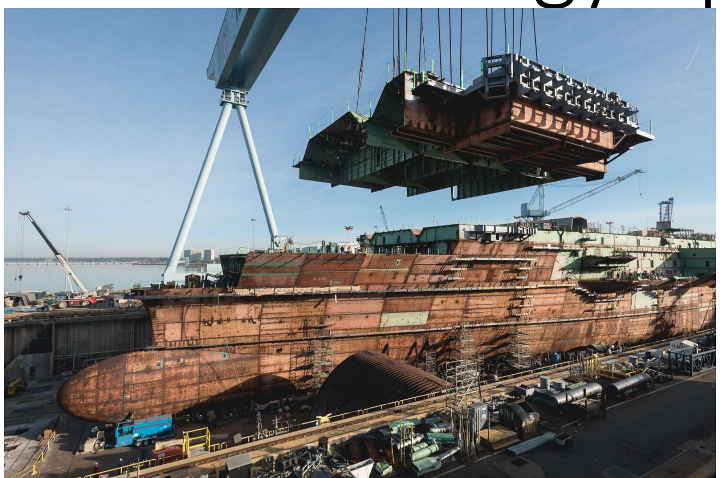
- Total capital costs
- Financing needs
- Manufacturing costs
- Transportation costs
- Construction costs
- Operating costs
- Maintenance costs

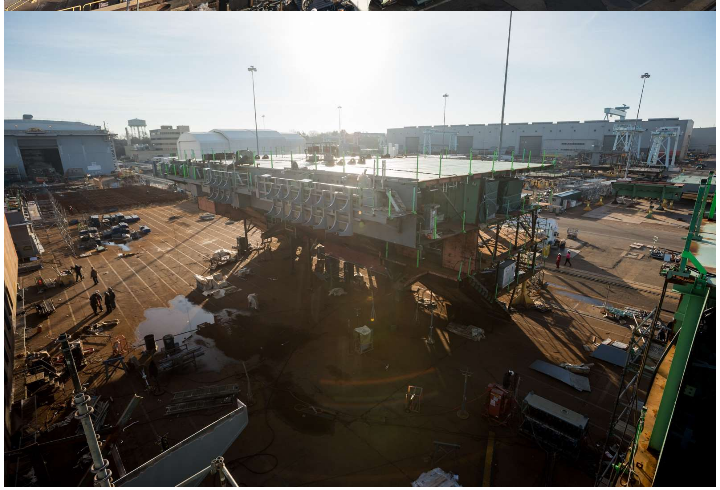


Many References to SMR Manufacturing



Flowline Technology Applications -Ships



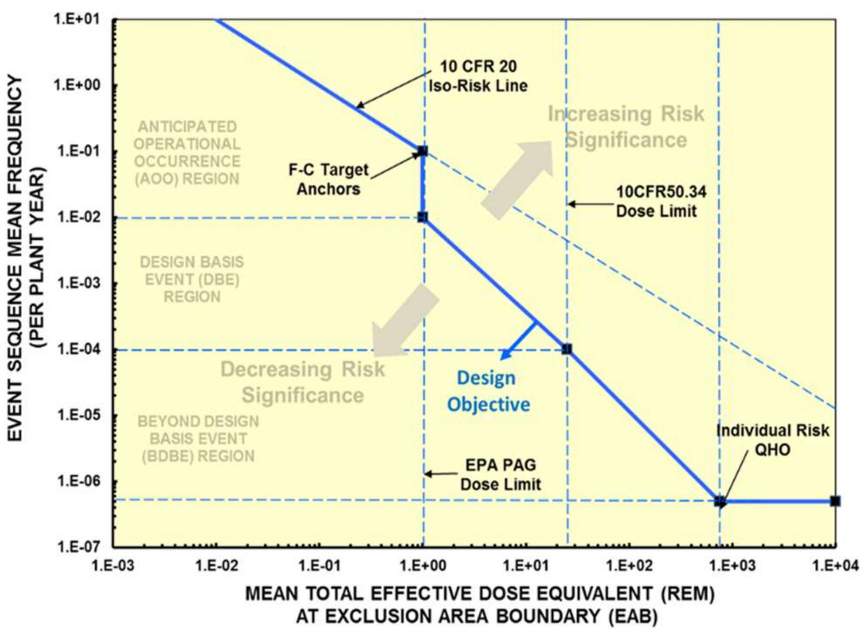


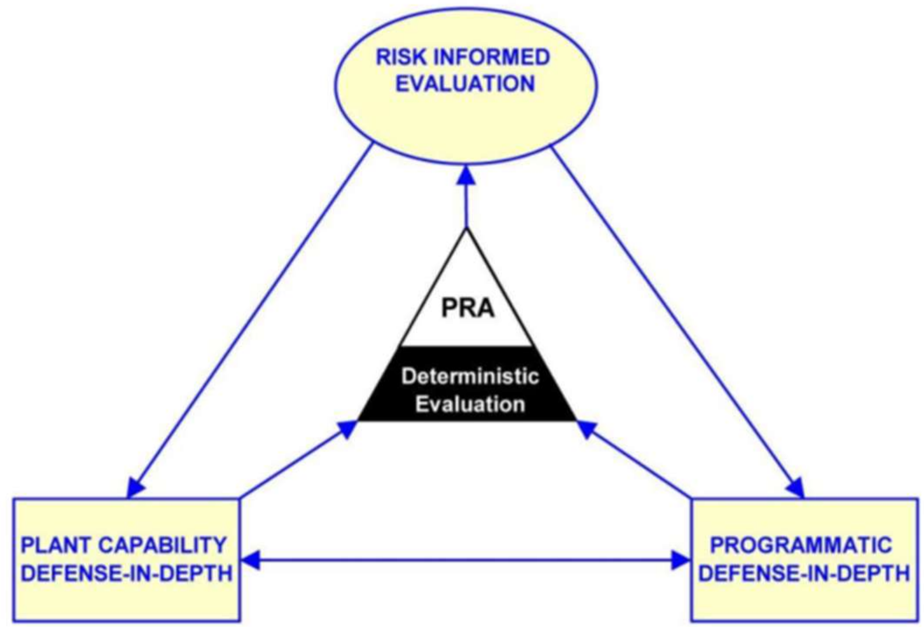
Flowline Technology Applications - SpaceX

Advanced Reactor Licensing – NEI 18-04

Licensing Modernization Project (LMP) (NEI 18-04 and RG 1.233)

- Licensing Basis Events
- SSC Classification and Special Treatment
- Defense-in-Depth Adequacy





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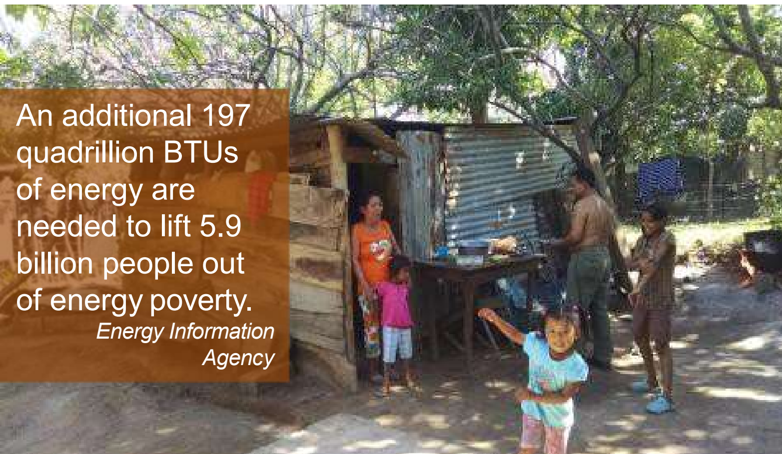
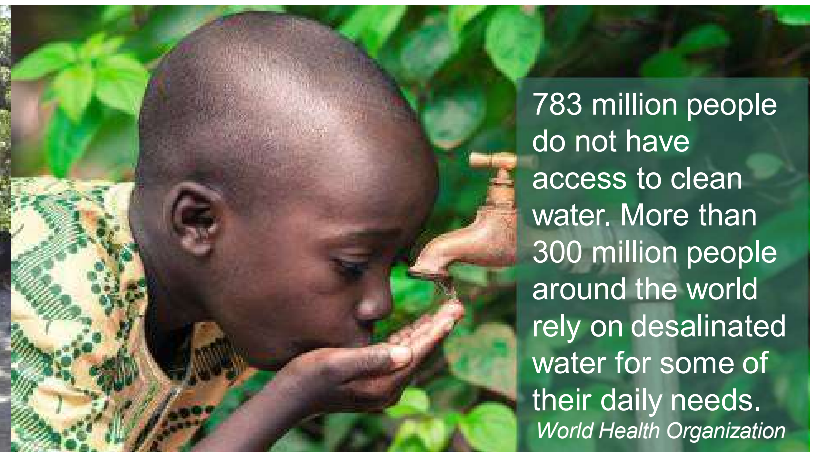
The Global Reality





Summary

Nuclear power has a major role to play in meeting our future energy needs in the U.S. and around the world

To be an economically attractive alternative, SMR's need to have a very strong modular construction methodology and deployment.

Goals for SMR Technology Advancement – U.S. and World

- Deploy SMRs in mid-2020's
- Develop and deploy advanced reactor non LWR technologies in the 2030's

Paper Reactors, Real Reactors

- **Characteristics of an Academic Plant**
  - It is simple
  - It is small
  - It is cheap
  - It is light
  - It can be built very quickly
  - It is very flexible in purpose.
  - Very little development is required. It will use mostly off the shelf components.
  - The reactor is in the study phase – it is not being built now.
- **Characteristics of a Practical Reactor Plant**
  - It is being built now.
  - It is behind schedule.
  - It is requiring an immense amount of development on apparently trivial items. Corrosion, in particular, is a problem.
  - It is very expensive
  - It takes a long time to build because of the engineering development problems.
  - It is large
  - It is heavy
  - It is complicated

(By Admiral Hyman Rickover, 1953)