

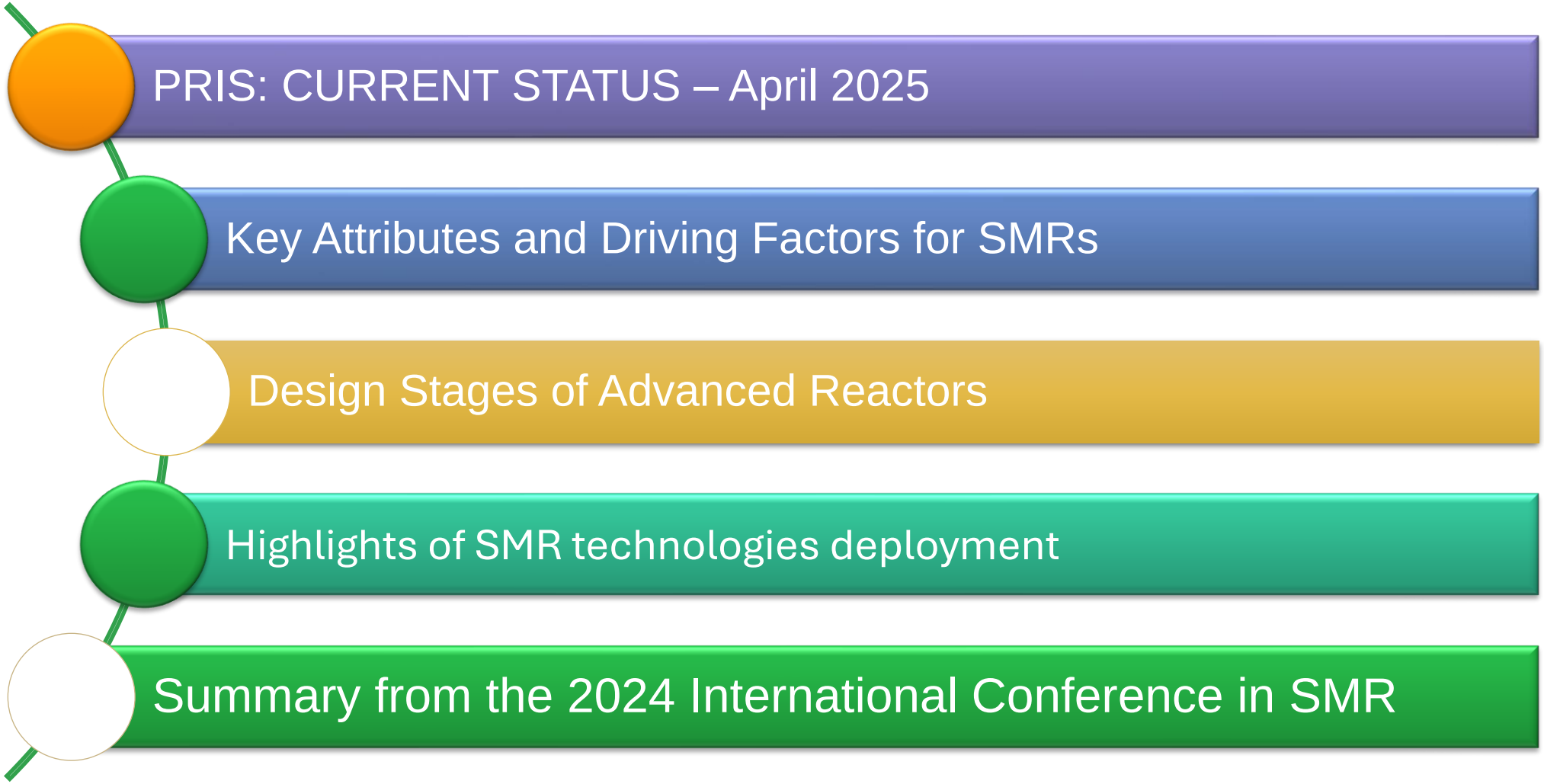
Advances in Small Modular Reactor Technology Developments

A. Constantin

Project Officer

Nuclear Power Technology Development Section,
Division of Nuclear Power,
IAEA Department of Nuclear Energy

OUTLINE of Presentation

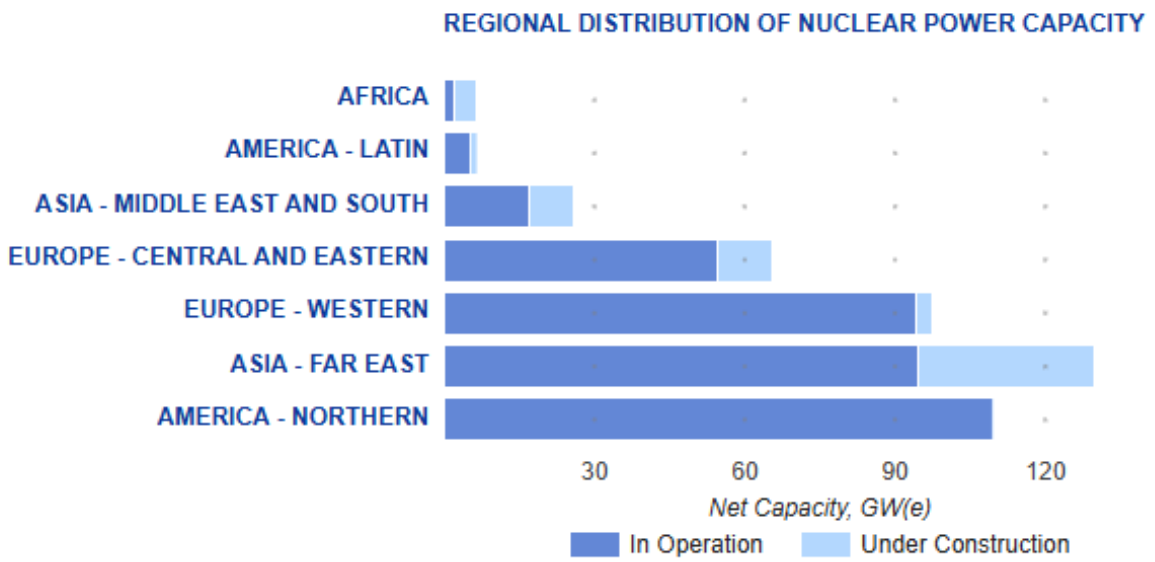


CURRENT STATUS – April 2025

Source:
IAEA Power Reactor Information System (**PRIS**), the database of nuclear power reactors,
https://pris.iaea.org/PRIS/home.aspx

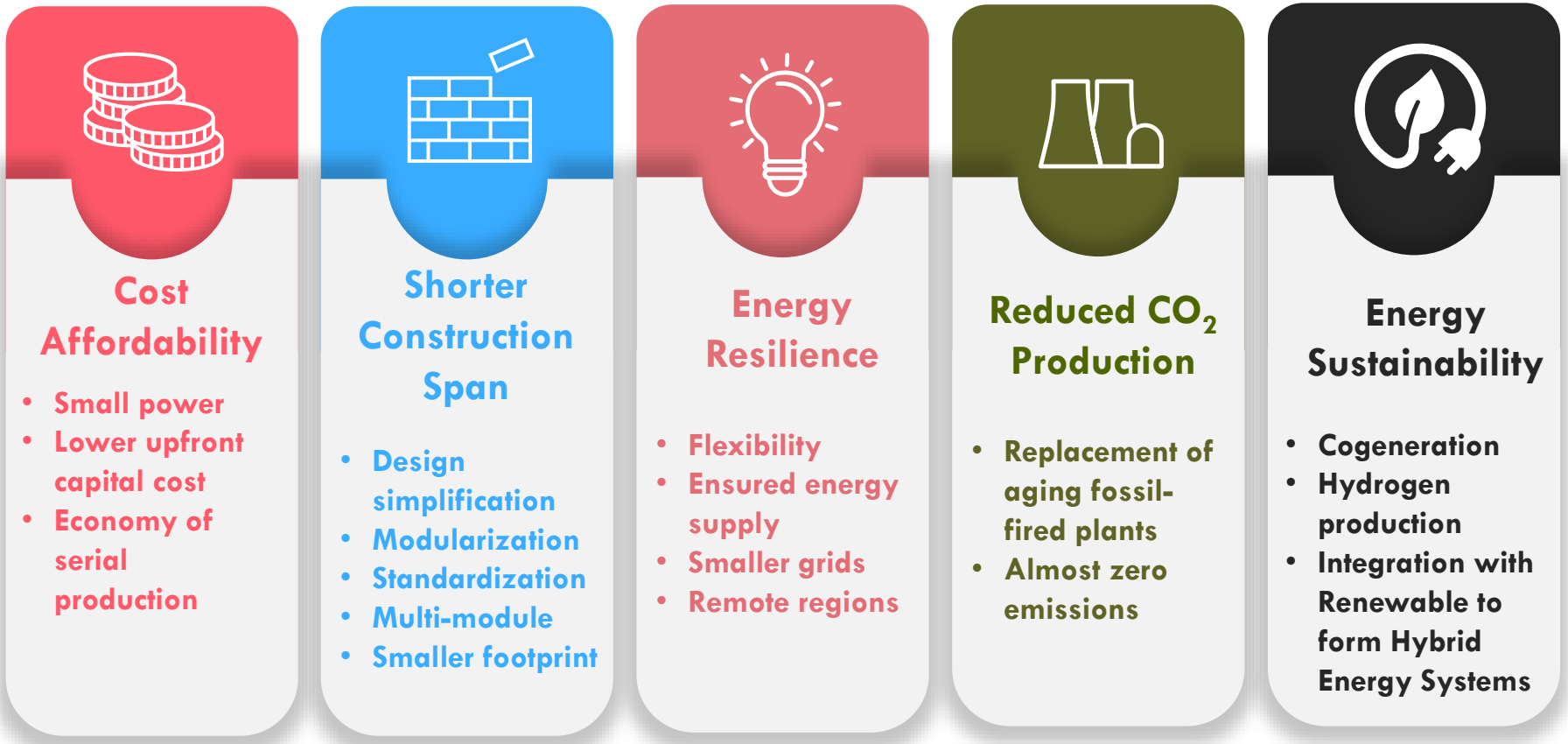
CURRENT STATUS

417	NUCLEAR POWER REACTORS IN OPERATION
377 221	MW_e TOTAL NET INSTALLED CAPACITY
23	NUCLEAR POWER REACTORS IN SUSPENDED OPERATION
19 687	MW_e TOTAL NET INSTALLED CAPACITY
61	NUCLEAR POWER REACTORS UNDER CONSTRUCTION
63 831	MW_e TOTAL NET INSTALLED CAPACITY
20 239	REACTOR-YEARS OF OPERATION



The operating reactors, include two (2) SMR NPPs in China and Russian Federation
NPPs under constructions, include four (4) SMR NPPs in Argentina, China, and Russia

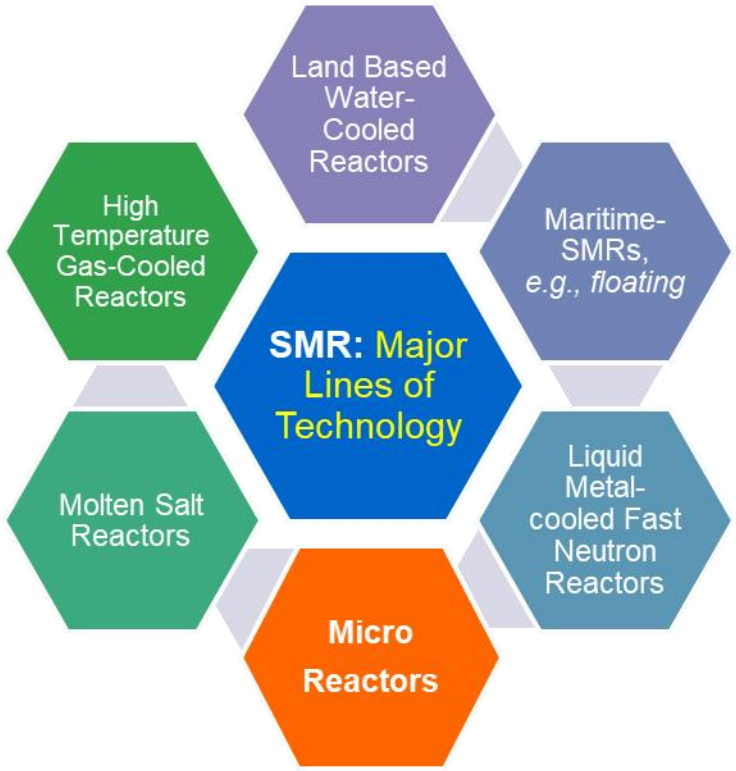
SMR Key Attributes and Driving Factors



Small Modular Reactors are designed and developed to be versatile with enhanced safety and reduced waste.

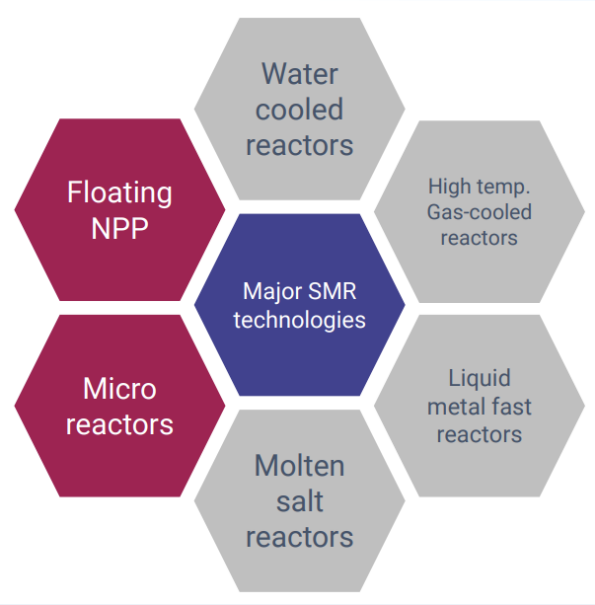
Definition and categorization of SMR technologies

Small Modular Reactors are advanced nuclear reactors with typical power up to 300 MW(e) of major lines of technology; whose systems and structures can be modularized in factory setting to shorten construction schedule thus reduce cost.

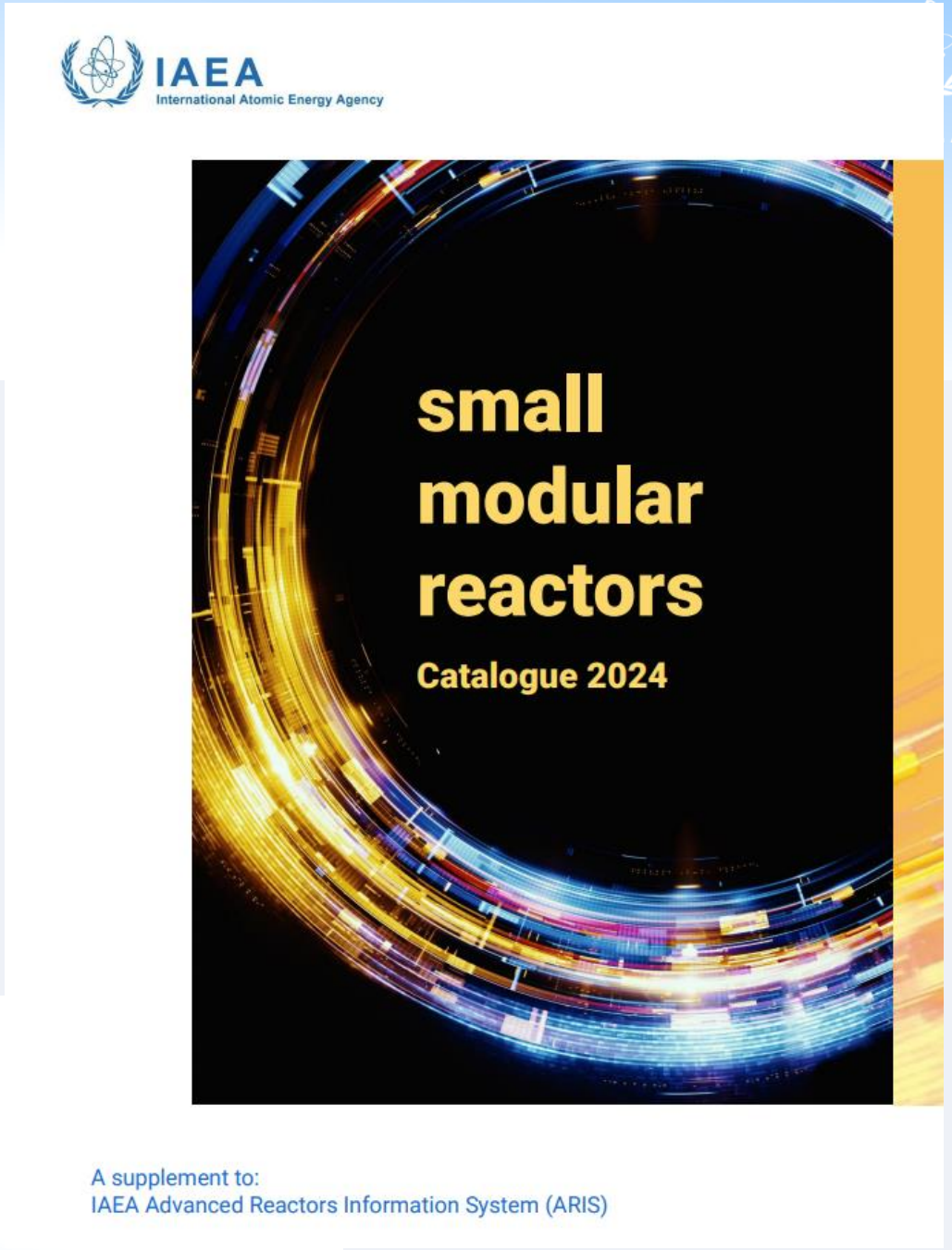




ARIS SMR Catalogue 2024

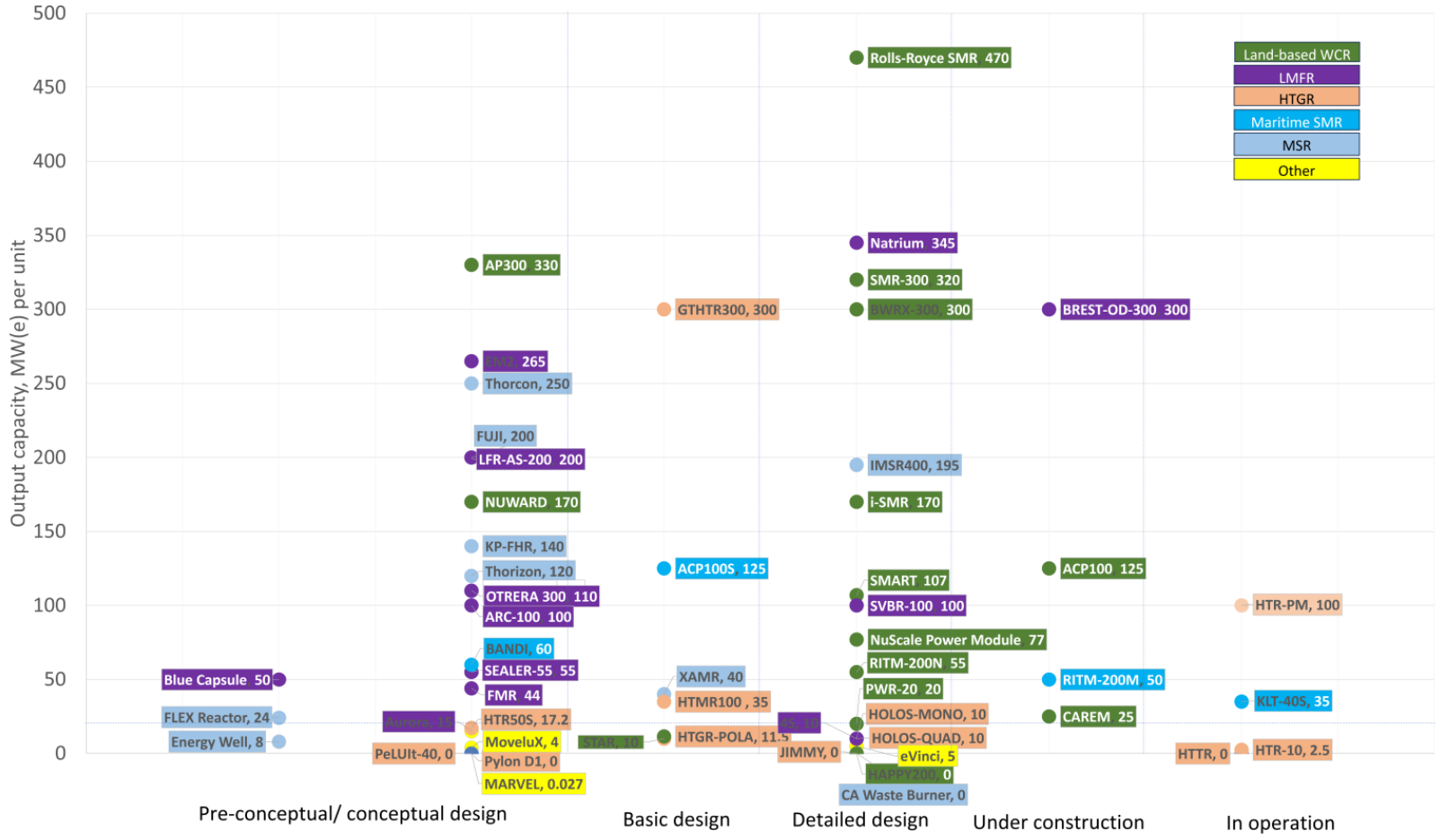


- **Available for download from this link:** https://aris.iaea.org/publications/SMR_catalogue_2024.pdf
- A supplement to ARIS Database, published biannually since
- 2012 with the objective to provide Member States with a concise overview of the latest status of SMR designs.
- The content is provided by the responsible institute or organization and is reproduced, with permission.
- For the 2024 SMR Catalogue, although close to 100 designs could have been listed, only active designs with demonstrated sustained development were reported in the catalogue.



Status of SMR Development and Deployment

Based on updates from technology developers to IAEA in 2024



Note: The value displayed with the design refers to the output capacity in MW(e) per unit.

Small Modular Reactors are advanced reactors that produce typically up to 300 MWe, built in factories and transported as *modules* to sites for installation to shorten construction span thus reduce the cost.

Deployment and Development Status in Brief (1/3)

In operation

Floating NPP "Akademik Lomonosov"

- *Russian Federation*
- *2 units of KLT-40S (PWR), 35 MW(e) per unit*
- *Commercial operation started May 2020, first fuel cycle completed*



HTR-PM

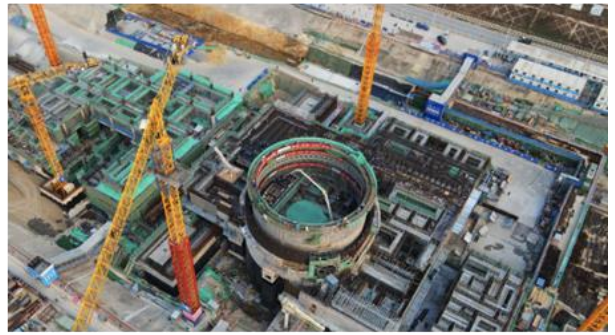
- *China*
- *2 units of high temperature gas cooled reactor pebbled-bed module, 200 MW(e) generated from single Turbine Island*
- *Operation started in 2023*



Under construction

ACP100

- *China*
- *Integral PWR, 125 MW(e)*
- *Operation expected in 2026*



BREST-OD-300

- *Russian Federation*
- *Lead-cooled fast reactor, 300 MW(e)*
- *Operation expected in 2026*



CAREM

- *Argentina*
- *Integral PWR, 32 MW(e)*



Deployment and Development Status in Brief (2/3)

Advanced stage of licensing

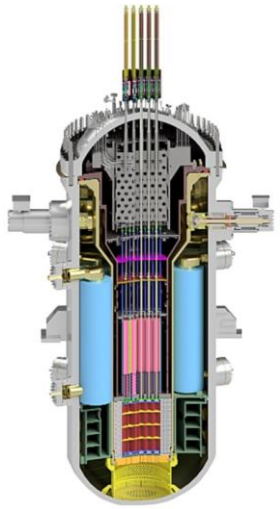
RITM-200N (Russian Federation)

- Integral PWR, 55 MWe
- License permit for construction received in April 2023
- Commissioning expected in 2028



i-SMR (Republic of Korea)

- Integral PWR, 170 MWe
- Completion of standard design expected by the end of 2025 and obtaining standard design approval in 2028
- **Simulator launched for development of i-SMR**



VOYGR (United States)

- Integral PWR, 77 MWe
- Certified by the US NRC in January 2023 (50 MWe)



NUWARD (France)

- In 2022 NUWARD was chosen as case study for a European Early Joint regulatory Review (JER), led by the French Safety Authority (ASN) with the participation of the Czech (SUJB) and Finnish (STUK) safety authorities
- EDF is refining its SMR strategy to fully meet the expectations of the utilities and industry, relying on well-known and mastered technological building blocks within the nuclear sector



BWRX-300 (United States)

- BWR, 290 MWe
- Contract awarded to BWXT to manufacture the RPV for the first BWRX-300 to be constructed at OPG's Darlington site.
- Commissioning expected in 2029



Deployment and Development Status in Brief (3/3)

Advanced stage of licensing

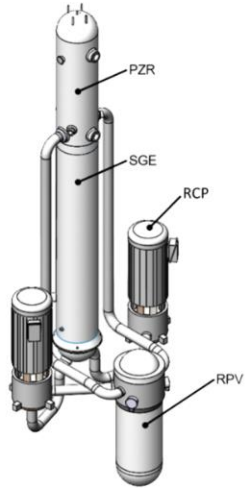
Xe-100 (USA)

- 80 MWe, HTGR technology
- X-energy announced plans in 2023 to build 4 Xe-100 SMRs at a Dow industrial site in Seadrift, Texas; expected to start construction in 2026
- X-energy has also signed a joint development agreement with utility Energy Northwest for the deployment of up to 12 Xe-100 plants in central Washington State
- Recent investment announcement by Amazon in X-energy for Xe-100 deployment



SMR-300 (United States)

- 2 loop PWR, 320 MWe
- In Feb 2024, SMR-300 FOAK site selection completed (Palisades site in MI, USA)
- Partner with Hyundai E&C for SMR-300 construction
- Completed first phase of UK Generic Design Assessment (GDA) process



AP300 (United States)

- Based on the licensed and operating AP1000 pressurized light water technology
- In 2024, received approval to enter the UK GDA
- Detailed design completion by 2027
- 2033 - target AP300 commercial operation



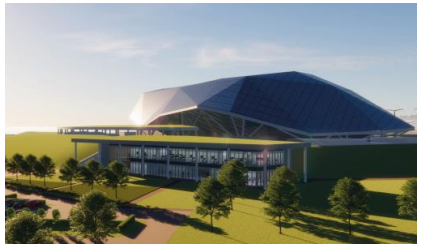
KP-FHR (USA)

- 320 MWt, 140 MWe (commercial plant)
- Power Purchase Agreement with Google to accelerate deployment with the aim to bring Kairos Power's first SMR online by 2030, followed by additional reactor deployments up to 500 MWe through 2035
- US NRC accepted the Hermes construction permit application (CPA) in Nov 2021
- In 2024, construction began on the Hermes demonstration reactor (15 MWt) in Oak Ridge, Tennessee; estimated to be operational in 2027
- Construction permit for the Hermes 2 test plant in Oak Ridge (2 X 28-MWt reactor units using the KP-FHR design)

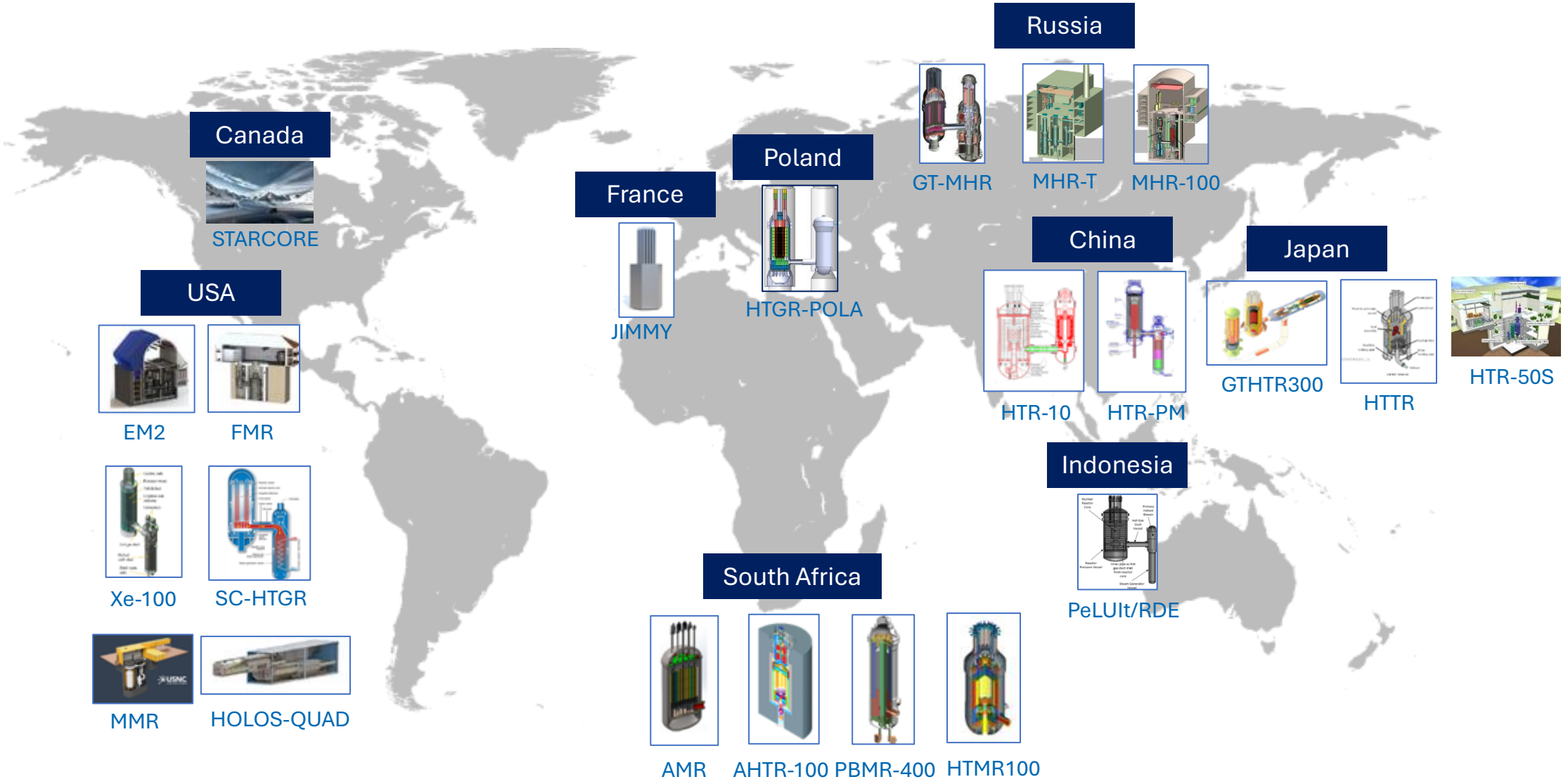


Rolls Royce SMR (UK)

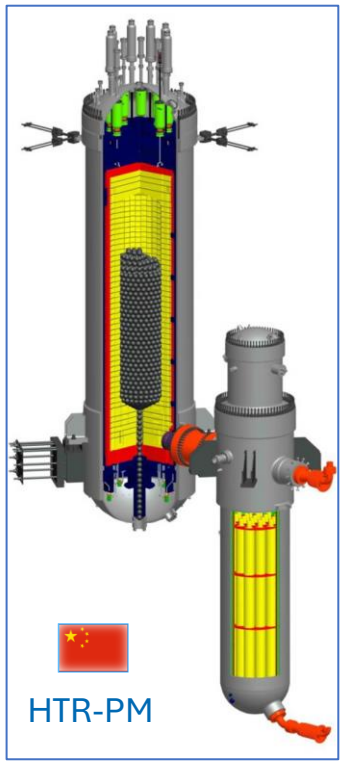
- Successfully completed Step 2 of the UK's Generic Design Assessment process and progressed to the third and final phase (expected completion in Aug 2026)
- 2027 planning start of construction and commercial operation early 2030s



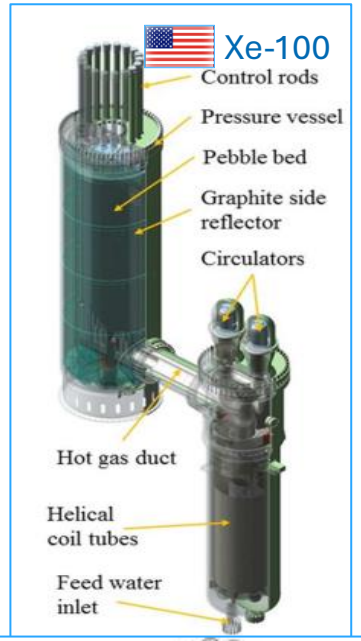
Global Activities on HTGR-SMR development

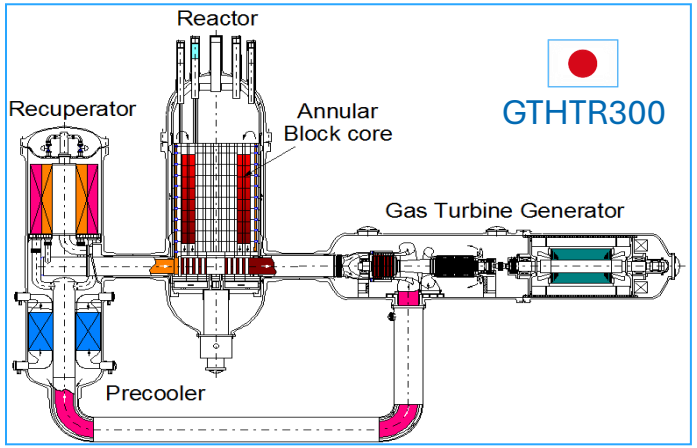


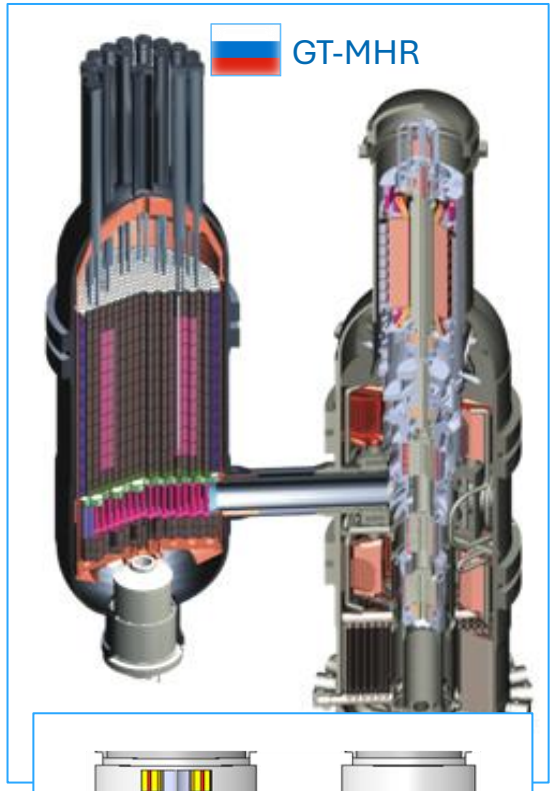
Multiple designs from Member States

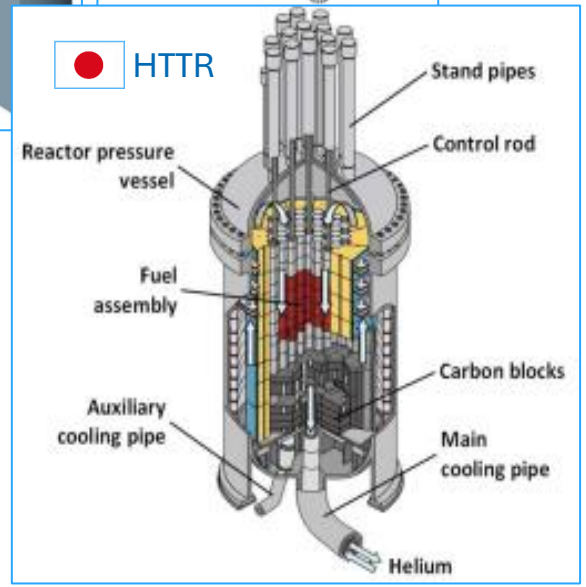


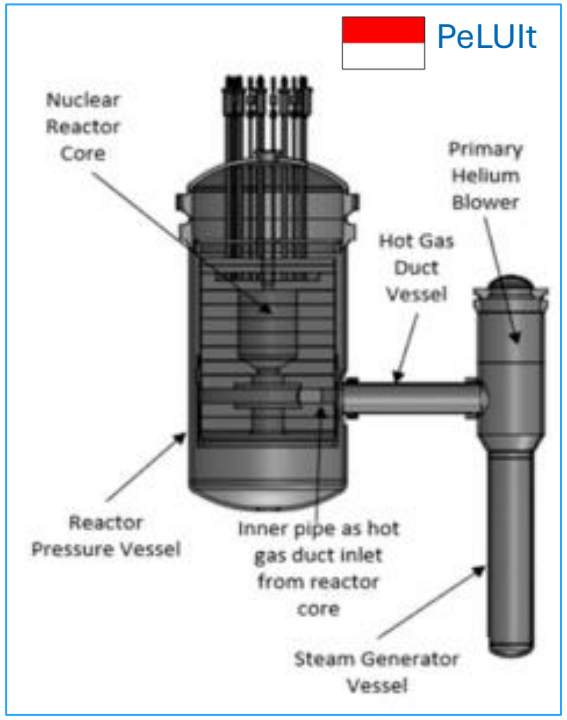


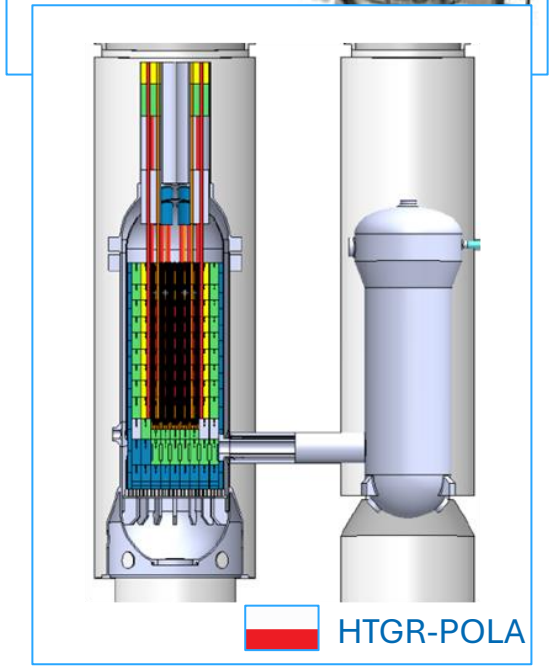












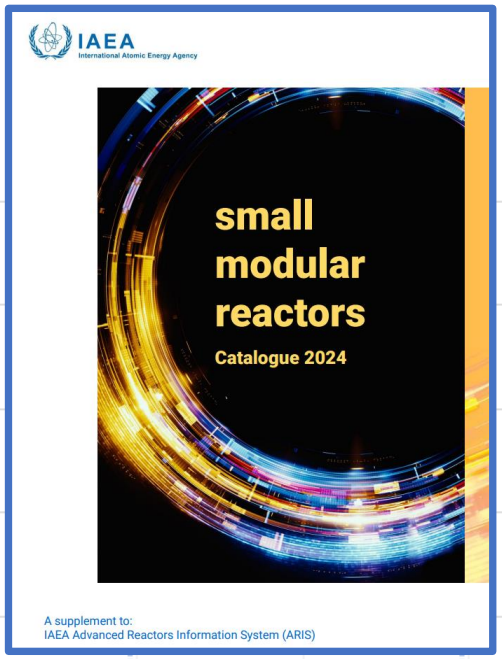


Number of SMR designs under development (2022)

- 38 Water-cooled
- 45 Non-water cooled
  - **HTGR 21**
  - MSR 13
  - LFR 8
  - SFR 3

SMR2024 Catalogue

https://aris.iaea.org/publications/SMR_catalogue_2024.pdf



18 designs

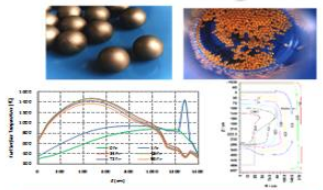
Note: The value displayed with the design refers to the output capacity in MW(e) per unit.

Specifications and history of HTGR technology development in China

Source: CNNC, Chinergy Co. Ltd at IAEA International Conference on Small Modular Reactors and their Applications (2024)

The development of HTGR in China can be divided into four stages

- Fuel
- Reactor physics
- Thermohydraulics
- Reactor structure etc.



Fundamental research (1980s)

- Know-how
- verified Inherent safety features
- Fuel tech
- Thermal application R&D



Test reactor (HTR-10, 1986)

- Fuel quantity production
- Modular reactor
- Engineering validation
- Equipment manufactures capacity
- Safety review tech
- Economic feasibility



Demonstration plant (HTR-PM, 2006)

- Inherent safety features
- Mature tech
- Modular and quantity production
- Economic competitiveness
- Achievable multi-use



Commercial plant (HTR-PM600, 2014)

Plant electrical power, MWe	200
Core thermal power, MW	250
Number of NSSS Modules	2
Core outlet temperature, ℃	750
Core inlet temperature, ℃	250
Steam pressure, MPa	13.2
Steam temperature, ℃	567

Milestones of Construction (HTR-PM, Shidao Bay, Shandong)



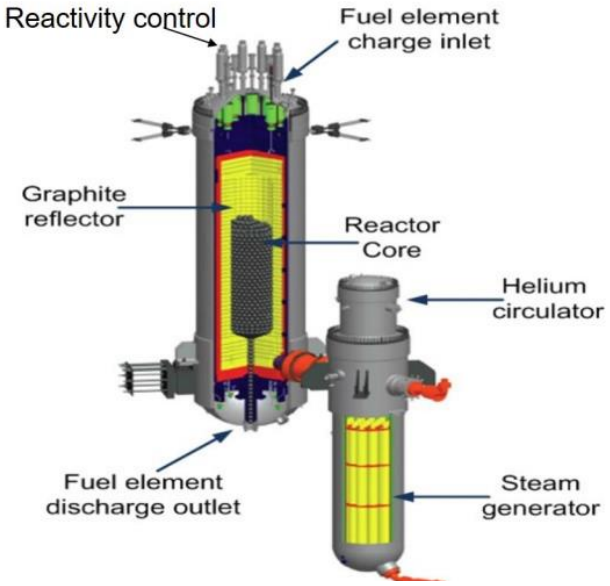
Development Milestones HTR-PM	
2001	Launch of commercial HTR-PM project
2004	Standard design of HTR-PM started
2006	HTR-PM demonstration power plant approved as one of the National Science and Technology major projects
2006	Huaneng Shandong Shidaowan Nuclear Power Co. Ltd., the owner of HTR-PM, established by the China Huaneng Group, the China Nuclear Engineering Group Co. and Tsinghua University
2006-2008	Basic design of HTR-PM completed
2009	Assessment of HTR-PM PSAR completed
2012	First pour of concrete of HTR-PM
2013	Fuel construction plant started
2014	Qualification irradiation tests of fuel elements completed
2015	Civil work of reactor building finished
2016	RPV and core barrel delivered, installation on main components
2017	Fuel plant achieved expected production capacity
2020	Startup commissioning test of primary circuit
Aug 2021	Operation license
Sept 2021	First criticality
Dec 2021	Grid connection
Dec 2022	Both 2 reactors initial full power operation
Dec 2023	Commercial operation

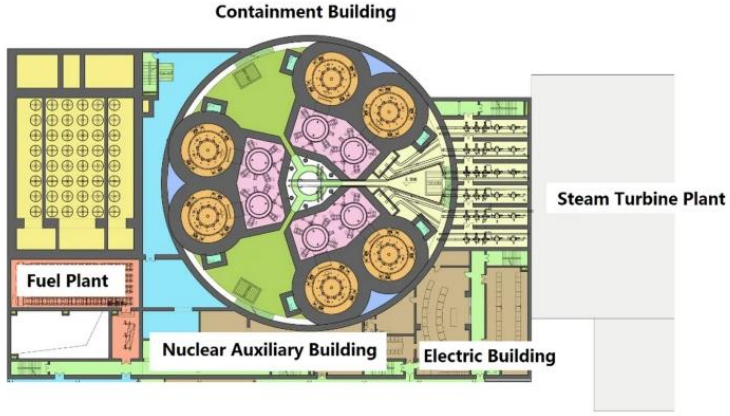
Source: IAEA ARIS

China

- HTGR basic research started in China in 1980s and in 1992 the government approved to construct HTR-10; its first criticality was achieved in 2000 and the full operation started in 2003.
- In 2006, HTR-PM project was listed as a major project in the national R&D programme for science and technology.
- In 2012, first concrete for HTR-PM was poured, 2016 first RPV was installed. Fuel loading started in August 2021 and the connection to the grid was done in December 2021. The commercial operation started in December 2023.
- An industrial scale fuel plant, capacity 300,000 fuel elements/ yr was built in Baotou. Construction was started in 2013 and production in 2016.
- April 2024: China's HTR-PM started heating project operation
- **HTR-PM600 will feature 6 modules connected to one single turbine to produce 650 MWe, building on the experience from the demonstration plant. Based on requirements from particular utilities, larger units with more modules can also be built that would enhance the economic competitiveness.**
  - **Since 2013, the HTR-PM600 has been jointly developed by INET and the Chinergy Co., Ltd of the China National Nuclear Corporation (CNNC).**
  - **The design of a standard HTR-PM600 was completed in 2016**
  - **HTR-PM600 vs HTR-PM Demo Plant: same safety features, same major components, same parameters**
  - **main tasks are to optimize manufacturing processes and standardize production in batches to minimize costs**
  - **SNERDI is manufacturing the RPVs → importance of preparation of long lead items**
- Another version is HTR-PM600S for cogeneration having HTR-PM modules with some minor changes.
- **August 2024: the Jiangsu Xuwei nuclear heat project was approved to build 2 Hualong 1 units and 1 HTR-PM600S unit.**
- Further development of HTR-PM for elevated temperatures is on-going (900-950C) looking at extending qualification of fuel performance and key component development.







LWR-type SMR: ACP100

ACP100



Design Status:
Under construction since July 2021

- CNNC, China
- Integral-PWR
- 385 MWt / 125 MWe
- Design life: 60 yr
- Forced circulation
- Coolant Outlet Temp: 320°C
- Enrichment: <4.95%
- Refuel interval: 24 months
- Main steam temp: >290C
- Main steam pressure: 4.5 MPa

1.2 Development Milestones

→ 2016 Generic reactor safety review for ACP100 by IAEA finished

First SMR to pass a safety review by IAEA

→ 2017 CNNC signed an agreement with the Changjiang municipal government in Hainan Province to host the first of a kind (FOAK) ACP100 demonstration unit

→ 2018 Preliminary safety assessment report (PSAR) finished

→ 2019 PSAR submitted to National Nuclear Safety Authority, site preparation started

→ 2020 Apply for authorize to Changjiang nuclear power site, Hainan, China

→ 2021 FCD on Changjiang nuclear power site, Hainan, China

→ 2026 Target commercial operation

Source: IAEA ARIS

2014: Preliminary design completed
July 2021: FCD (with a planned construction period of 58 months)
Dec 2022: Equipment installation work commenced
March 2023: Main internal structure of the reactor building completed
Feb 2024: Outer containment dome installed
Sept 2024: Lower part of the reactor internals installed at ACP100

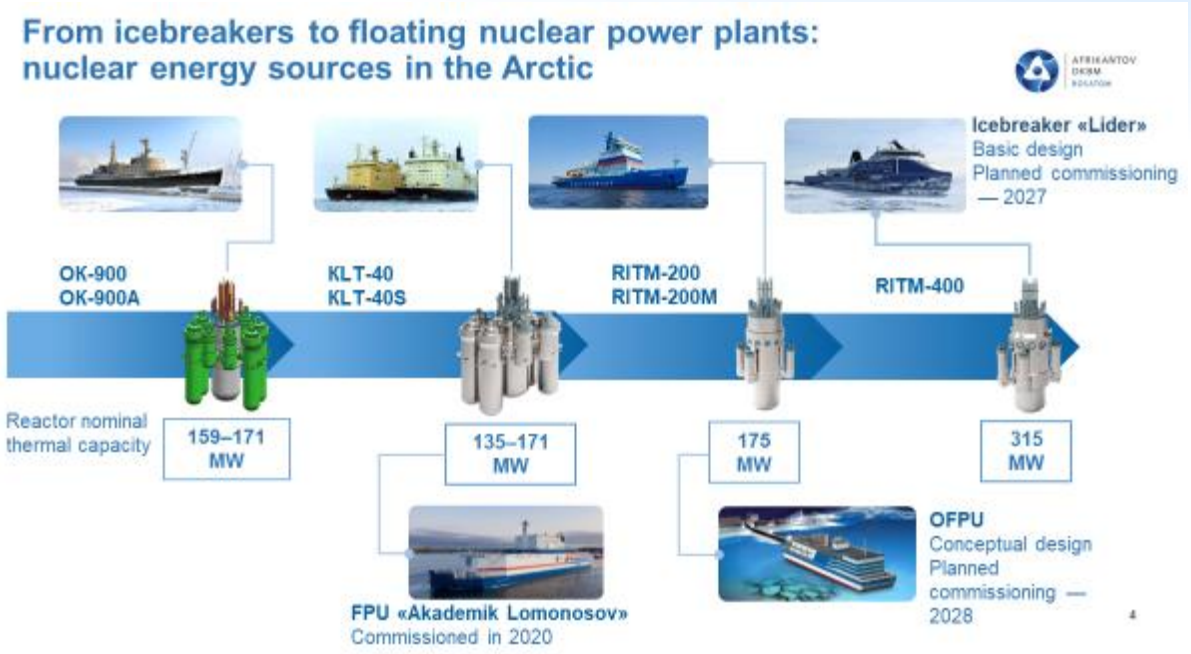
Source: WNN

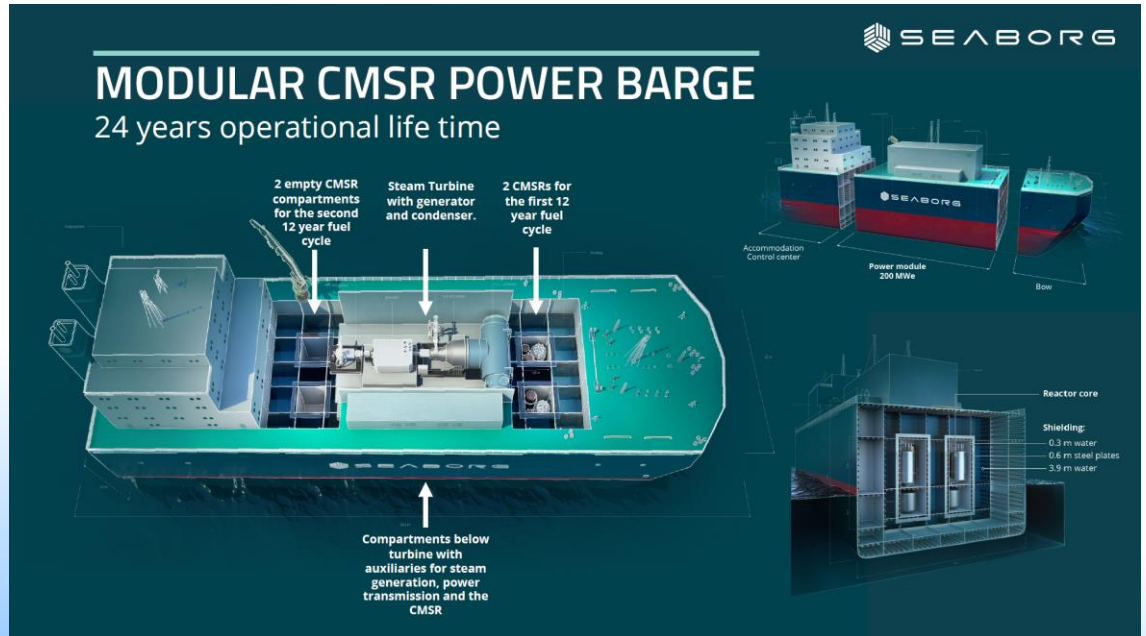


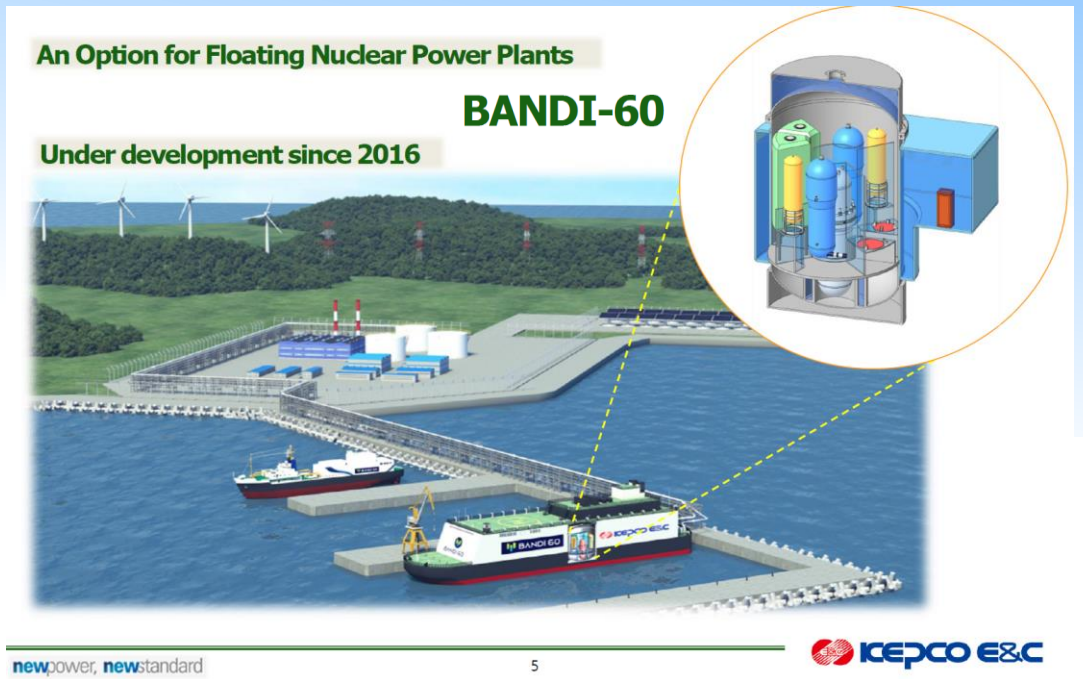


Images: CNNC

FNPP R&D and deployment progress





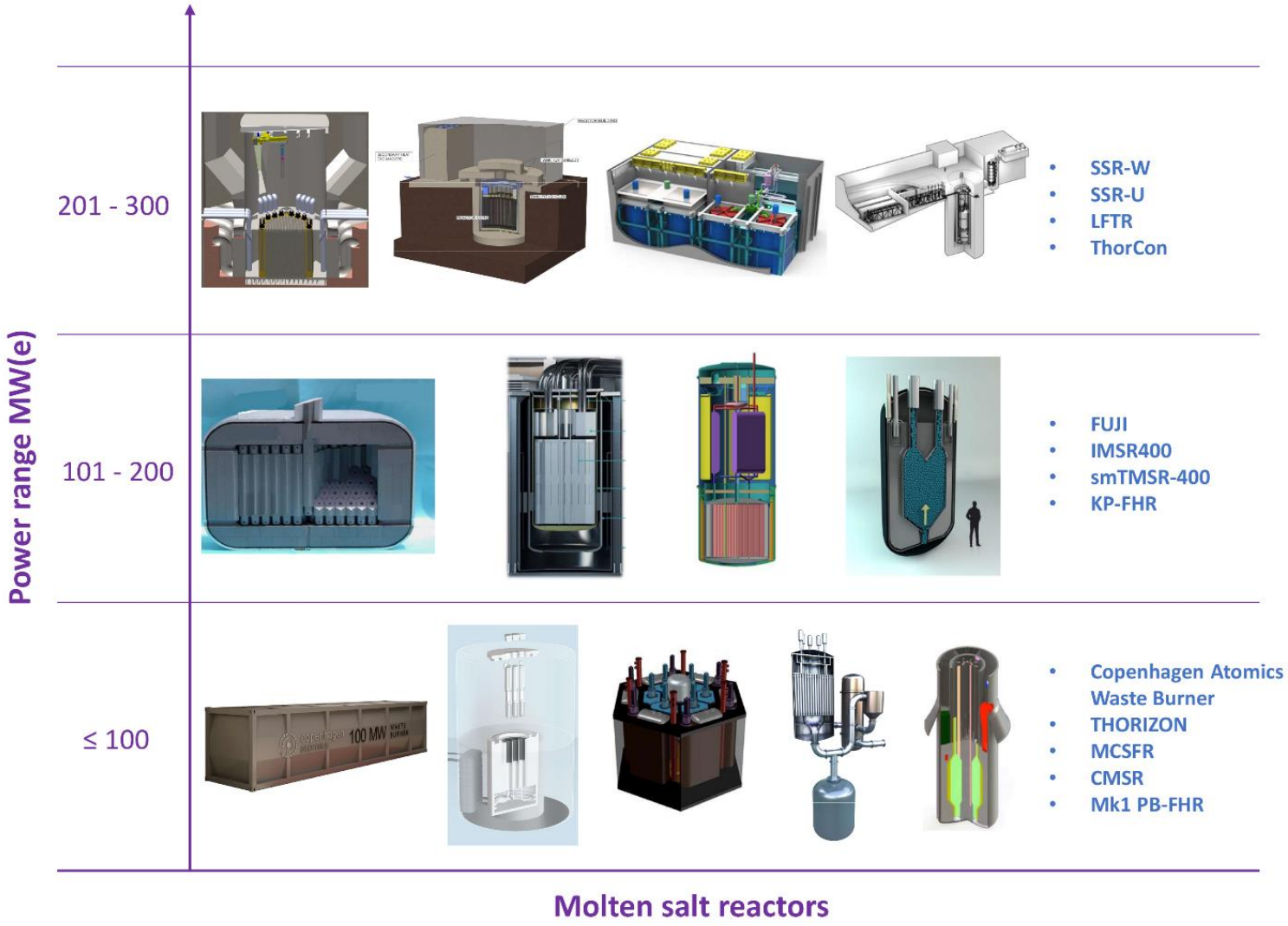




Advances in Molten Salt Reactors (examples)



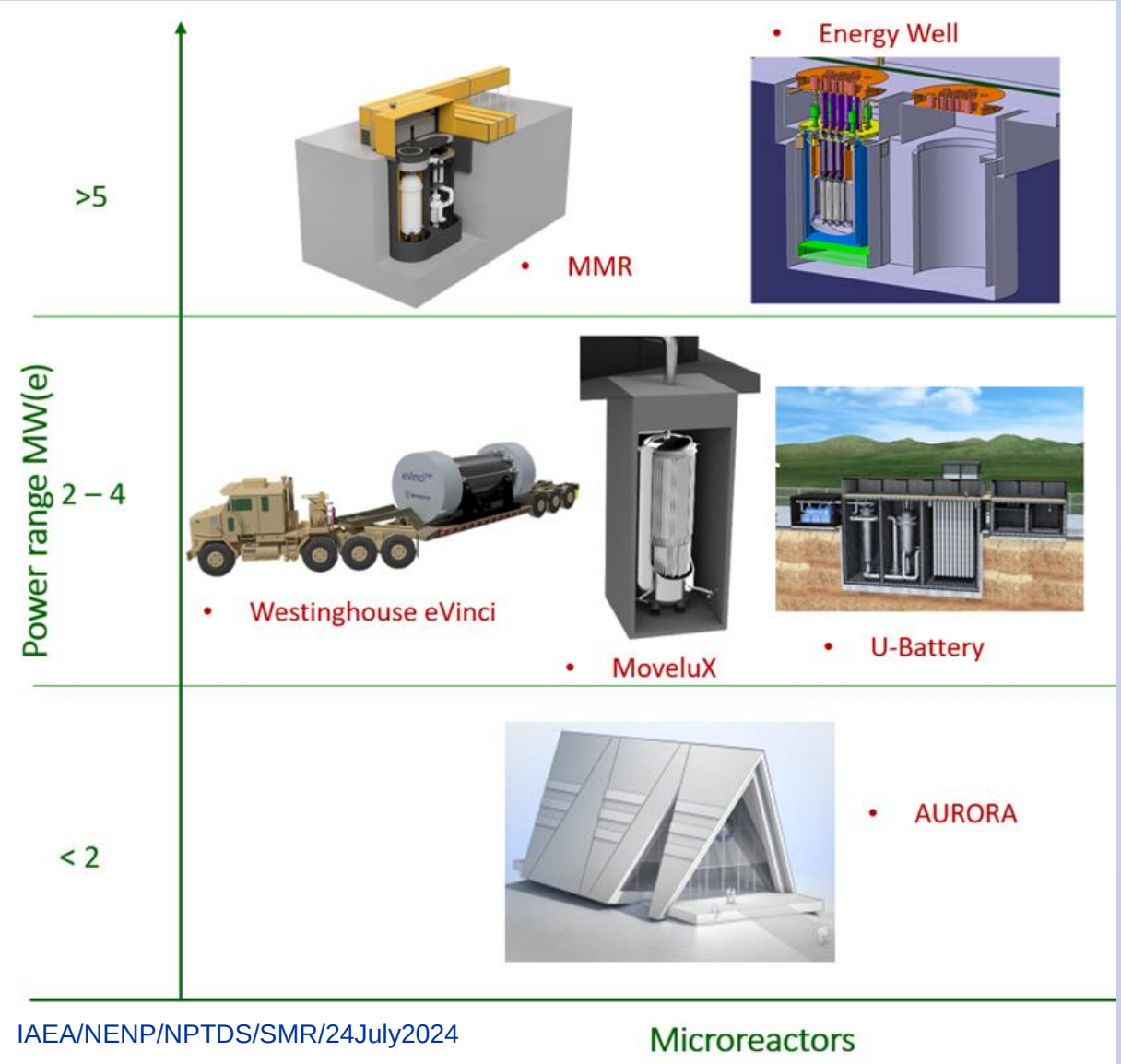
Power range of MSRs



IAEA
International Atomic Energy Agency

Micro Reactors

Emerging: Microreactors



- Several countries are developing Microreactors technology for potential deployment by 2030;
- *Typically* to generate from 1 to 10 MWe; designed for enhanced transportability to site by modularity;
- To supply power at remote sites with mining operations, island communities, oil platforms and maritime shipping.
- Deployment opportunities in remote areas in North America, Middle East, Africa, and the South-East Asian archipelagos.

Specificities of Microreactors

01

Specifically designed to serve

- Remote communities;
- Mining operations; or
- military installations.

02

Multi-applications

- Energy generation; or
- Production of heat and electricity

03

Transportability

Within standard shipping containers

04

Heat-pipe technology

proven by LANL for space application

05

Compact and simplified

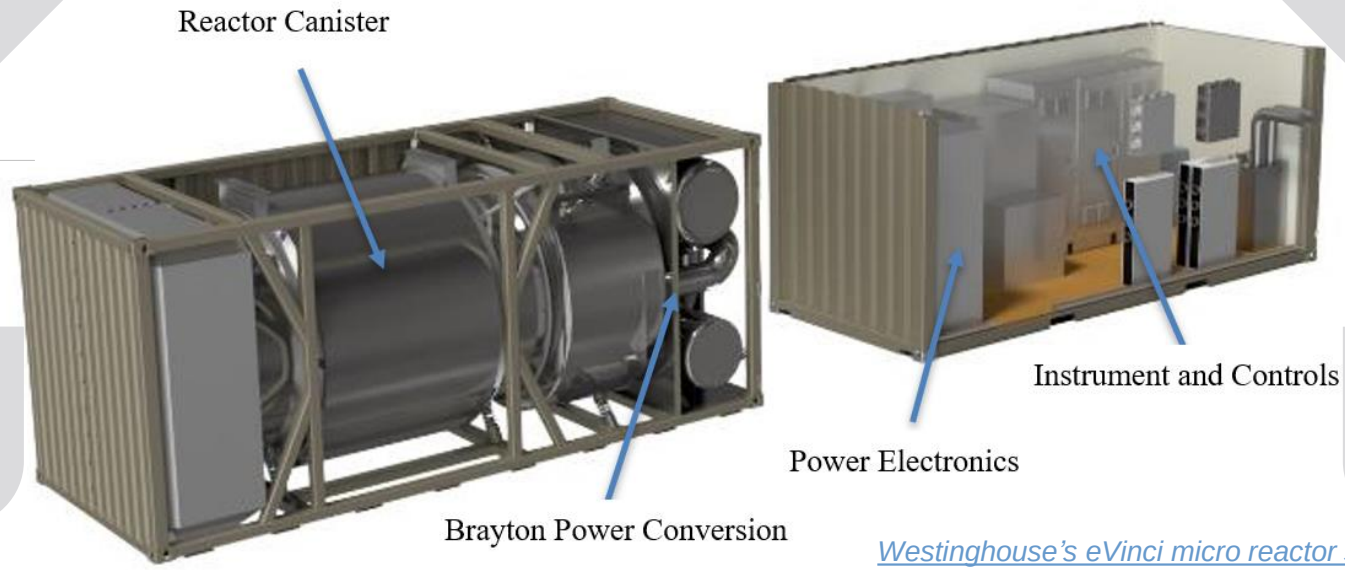
06

Manufactured and fueled in a factory

07

Packageable

in standard transport containers



Westinghouse's eVinci micro reactor schematic (Image: SMR Booklet edition 2020)

Factors in Microreactors Development

Rationales

- More specific nuclear portfolios beyond ‘known’ SMRs
- The need for energy resiliency
- Power needs in regions inaccessible by known power generators / plants
- Power needs in cities / techno parks

Pursued Advantages

- New technologies with innovative inherent safety features
- Substantially lower capital cost
- Modularity, mobility, more of “installation” than construction
- Long refueling interval or no refuel

Target Applications

- Microgrids for critical infrastructures
- Remote off-grid areas, minings
- Emergency power supply
- Wide spectrum non-electric apps
- Space and naval applications (UUV)

Potential Issues and Key Challenges

- Safeguards: *factory-sealed cores, new configs.*
- Security: *remote off grid areas, attractive theft target of new fuels / higher enrichment*
- Strategies for waste treatment and disposal
- Operator requirements, oversights / inspections

SMRs and associated challenges

- **Demonstration of safety and operating performance**
- **Secure deployment:** physical, cyber, transport security
- **Implementation of safeguards**
- **Demonstration of economic competitiveness**
  - Economies of serial construction with robust supply chain
- **Harmonization of licensing framework** for global deployment
- **Establishment of legal framework**
- **Workforce and skill gap**

Issues and impediments of SMR for cogeneration:

- Development of safety concept for the combined system is needed
- Different licenses and licensing approaches needed for the coupled plant
- Reference plant and demonstration of coupling
- Uncertainties in the compatibility with industrial processes
- Communication and collaboration between industrial players from different sectors, as well as a wide range of stakeholders

SMR Technical Features affecting Safeguards (1)

Source: J. Whitlock, SGCP, presentation at TWG-SMR Meeting, September 2022

- **New fuels and fuel cycles:** Th/U-233, RepU, MOX, TRU fuels, higher enrichment, pyroprocessing, other new processes
- **New reactor designs:** molten salt, fast reactors, pebble bed, …
- **Longer operation cycles:** continuity of knowledge between refuelling, high excess reactivity of core (target accommodation)
- **New supply arrangements:** factory sealed cores, transportable power plants, transnational arrangements (need for design verification and sealing)

SMR Technical Features affecting Safeguards (2)

Source: J. Whitlock, SGCP, presentation at TWG-SMR Meeting, September 2022

- **New spent fuel management:** storage configurations, waste forms
- **Diverse operational roles:** district heating, desalination, hydrogen + electricity
- **Remote, distributed locations:** access issues, lack of "unannounced" visit deterrence, cost-benefit issues

IAEA independent verification capabilities must be ready

Prospects and Actions for Deployments

Demonstration of Safety and Operational Performance of FOAK, Novel Designs & Technologies

Continuity of Orders, cost competitiveness against alternatives, robust supply chain, and viable financing Option

SMR Deployment Competitiveness

Regulatory framework, licensing pathways: global deployment, need of harmonization?

Development of Nuclear Infrastructure for near-term deployment particularly in Embarking countries

SMR Conference 2024

- **5** Topical Plenary Discussions
- **44** Parallel Technical Sessions
- **5** Side Events
- **6** Poster Sessions
- Plenary sessions live streamed
- Technical sessions streamed via the app

https://iaea.event.do/#/e/6461/f/47849



~1300 In-Person Participants

>1100 Virtual Participants

95 Member States

17 International Organizations

295 Presenters

Conference Topical Groups / Tracks

Topical Group A: SMR Design, Technology, Fuel Cycle and Applications **Lead: H. Subki, NENP**

- Track 1: Design and Technology Development of SMRs
- Track 2: Advanced fuels, reprocessing, waste management and decommissioning aspects for SMRs – Safety, Design and Technology
- Track 3: Engineering, Codes & Standards, Supply Chain, Operation and Maintenance of SMRs
- Track 4: Transportable SMRs
- Track 5: Non-Electric Applications for SMRs

Topical Group B: Legislative and Regulatory Frameworks **Lead: B. Rini, NSNI**

- Track 6: International and National Legal Frameworks and SMRs
- Track 7: Regulatory Considerations for SMRs

Topical Group C: Safety, Security and Safeguards **Lead: B. Rini, NSNI**

- Track 8: Demonstrating SMR's Safety Case
- Track 9: Emergency Preparedness and Response for SMRs
- Track 10: Safety, Security and Safeguards Interfaces related to SMRs
- Track 11: Security of SMR: Physical Protection and Computer Security
- Track 12: Safeguards for SMRs

Topical Group D: Considerations to Facilitate Deployment of SMRs **Lead: V. Artisiuk, NENP**

- Track 13: SMRs in Energy Planning for Climate Change Mitigation
- Track 14: Nuclear Infrastructure and Enabling Environment for SMRs
- Track 15: Financing, Cost & Economic Appraisals and Contracting Approaches for SMR Projects
- Track 16: Public and Stakeholder Engagements in SMR Development and Deployment
- Track 17: Cooperation for Harmonization and Standardization

Summary & Findings: Topical Group A
SMR Design, Technology and Fuel Cycle

- The development of SMRs highlights **diverse and innovative approaches** being taken to address safety, reliability, flexibility, and economic viability in nuclear energy.
- SMRs are poised to play an **essential role in near future energy markets**, particularly in their viability to **integrate with non-electric applications and renewable energy** sources.
- **Transportable SMRs,** either **floating** nuclear power units or **nuclear propelled ships**, could be a reliable and efficient source to meet the increasing energy demands in Member States and international shipping sector, and to achieve net-zero greenhouse gas emission targets.
- Fuel cycle developments and implementation are enablers for the SMR technologies to be deployed.
- Back-end of the SMR fuel cycle has to be considered already at the stage of design and planning.
- Focus would remain on simplifying reactor designs, to reduce the footprint and weight and foster safety system innovations; to ensure scalability and economic viability for both electricity production and industrial applications.

Summary & Findings: Topical Group A
SMR Design, Technology and Fuel Cycle

- Establish standardized codification processes for steel-concrete structures in SMR construction to ensure consistency and reliability.
- While cost is a key consideration, certain markets, such as mining and AI-data centres, can absorb higher energy costs.
- **Supply chain** for SMRs needs to be based on standard solutions – including products and services – to enable series production across the markets.
- Strengthen **international collaboration** among regulators, technology developers and nuclear component manufacturing to create standardized qualification schemes and streamline SMR deployment pathways.
- Encourage and foster IAEA and International Maritime Organization (IMO) collaboration for finding solutions for the maritime application of nuclear reactor technology.
- Achieving competitiveness requires delivering projects on budget and on time, with careful planning integrated into SMR development.

Summary & Findings: Topical Group D
Consideration to Facilitate Deployment of SMRs

- National sustainable energy planning strategies are increasingly **considering nuclear, including SMRs**, to achieve **net zero emission targets**
- **Reliable cost estimates, innovative financing and contracting approaches** are needed to improve confidence to support SMR near term deployment, especially within newcomer countries
- **Proactive, transparent, and inclusive** communication strategies, informed by lessons learned internationally, are essential for informing **societal aspects** in nuclear policymaking and engaging stakeholders to support SMR inclusion in their local energy portfolio
- The **Milestones Approach** remains the pivotal instrument to support the deployment of SMRs; in its latest revision it was accentuated that **early involvement of all stakeholders** including vendors and project sponsors could support the **acceleration of the deployment of SMRs**

Summary & Findings: Topical Group D
Consideration to Facilitate Deployment of SMRs

- There is an increasing number international cooperation initiatives, which brings regulatory bodies together to examine SMR designs and exchange their opinion, thus fostering harmonization (or at least understanding of equivalence) of licensing processes
- CNSC/U.S.-NRC cooperation on advanced designs and joint early review (JER) by six EU regulatory bodies are two such examples, commended by international organizations such as OECD-NEA, WNA and the IAEA through its NHSI initiative
- Shifting from economies of scale in large reactor development to economies of multiples for SMRs, and the potential for SMRs to have a higher learning rate per unit remain to be among the major advantageous factors for SMR deployment
- Standard Levelized Cost of Electricity (LCOE) is not enough for evaluating the full economic impact since in some Countries, urbanization and economic growth are driving demand for both electricity and heat

Take-aways

- SMRs encompass a variety of designs, including LWs, HTGRs, MSRs, FRs. This diversity allows for tailored applications beyond electricity production
- The modular nature of SMRs facilitates factory fabrication, which is expected to lead to reduced construction times and costs. This approach aims to make nuclear power more accessible and economically viable, especially for countries or regions with smaller energy demands
- More information of existing SMRs designs (including main design features, safety aspects, design and licensing status, fuel cycle approach and development milestones) are included in the IAEA ARIS database and SMR Catalogue 2024
- IAEA developed a IAEA Nuclear Energy Series No. NR-T-1.18 on Technology Roadmap for Small Modular Reactor Deployment; revision of this document is currently ongoing; Second IAEA Technical Meeting on Updating the Technology Roadmap for Small Modular Reactor Deployment (24-27 June 2025)
- An upcoming IAEA Technical Meeting on Approaches for Design and System Readiness Evaluation of Small Modular Reactors for Near-term Deployment (14-17 July 2025)

Thank you for your attention.

For inquiries, please contact:
Small Modular Reactor Technology Development Team
IAEA Division of Nuclear Power, Nuclear Power Technology Development Section
E-mail: SMR@iaea.org