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2nd International Summer School on Early-deployable SMRs,
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Advances in Technology Developments of Small Modular Reactors including Microreactors

Prospects and Challenges

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OUTLINE

- Statement of DG Mr. Grossi in the 67th General Conference (2023)
- Driving Factors & Opportunities for SMRs
- SMR: Categorization and First 10 Years of Deployment
- SMR: Major Technology Lines
- Marine-based SMRs, Microreactors and MSRs
- Advantages, Issues & Challenges
- Issues and Actions for Deployments

DG IAEA Statement to the 67-th Regular Session of the IAEA General Conference 25.09.2023

Nuclear power capacity will need to grow significantly if the world is to meet its climate goals.

Part of that growth could come from Small Modular Reactors (SMRs).

The *IAEA Platform on SMRs and their Applications* provides Member States with enhanced Agency support on this important emerging technology whose modular design allows for a more gradual scaling up of power capacity making SMRs especially relevant for developing countries.

To further support the global deployment of safe and secure advanced reactors such as SMRs, I launched the Nuclear Harmonization and Standardization Initiative (NHSI). It works towards enhancing the harmonization of regulatory approaches and also the wider standardization of industrial approaches. I am pleased to report that, since we started work a year ago, progress has been made on the two tracks of this key initiative, including the recent publishing of a white paper outlining why serially manufactured industrial products are crucial for the reliable deployment of SMRs.

Driving Factors & Opportunities for SMRs

Cost Affordability

Small Power, Innovation, Standardization

Short Construction Span

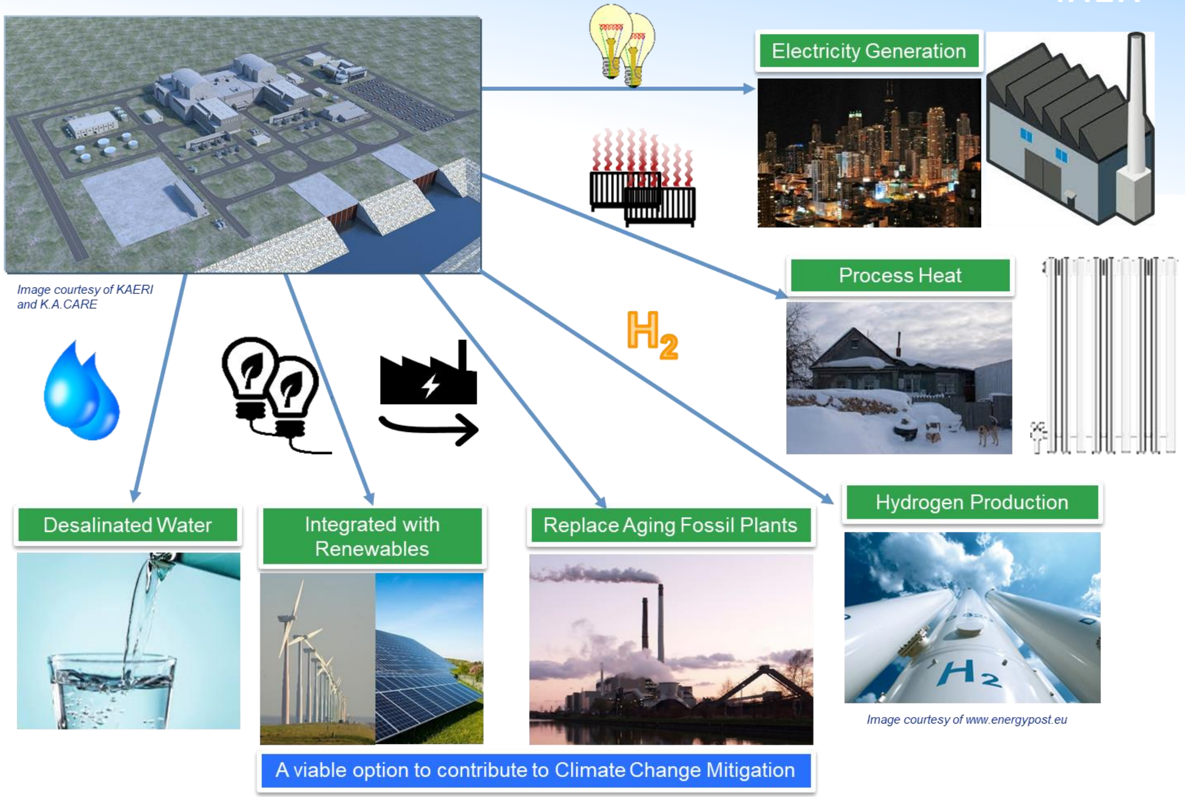
Design Simplification, Modularization

Energy Resilience

Flexibility and ensured energy supply

Energy Sustainability

Hybrid with Renewables,
Replace Retiring Fossil Plants



Typically up to 300 MWe, High Degree of Modularity, Option to Energy Supply in Countries with Smaller Grids; Contribute to Climate Change Mitigation

Development Objectives of Small Modular Reactors

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Enhanced Safety

Versatile

Modular

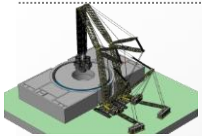
Enhanced Constructability

Affordable

Non-electric applications

Economic
- Lower Upfront capital cost
- Economy of serial production

Better Affordability



Modularization
- Multi-module
- Modular Construction

Shorter construction time

Flexible Application
- Remote regions
- Small grids

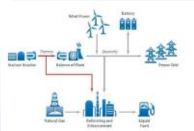
Wider range of Users

Smaller footprint
- Reduced Emergency planning zone

Site flexibility

Replacement for aging fossil-fired plants

Reduced CO_2 production



Potential Hybrid Energy System

Integration with Renewables

How SMRs answer the challenges?

Some Key Challenges for SMRs	Key Drivers for SMRs
First-of-a-Kind Technology Risks	Shorter construction period ($)
Time and cost of getting to market and/or proven technology	Design simplification thru standardization
Newcomers need Reference Plant	Modularization, factory construction and enhanced transportability
National programmatic cost for newcomers vs project cost for the unit	Lower upfront capital cost ($)
Regulatory preparedness to license FOAK and/or advanced designs	Smaller site footprint
Prediction of the level of demand, generating cost versus alternative ($)	Scalability through multi-module ($)
Which funding and financing models?	Non-Electric Apps, grid suitability and flexible operation

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*

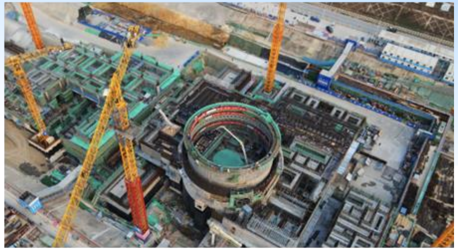
HTR-PM

- *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)*
- *Operation expected in 2030s*

Deployment and Development Status in Brief (2/3)

Advanced stage of licensing

RITM-200N

- *Russian Federation*
- *Integral PWR, 55 MW(e)*
- *License permit for construction received in Apri 2023*
- *Commissioning expected in 2028*

HERMES

- *United States of America*
- *Molten salt reactor with TRISO fuel, 35 MW(t)*
- *Construction permit approved by the NRC in December 2023*
- *Commissioning expected in 2026*

VOYGR

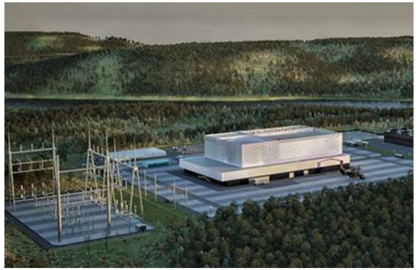
- *United States of America*
- *Integral PWR, 77 MW(e) per unit*
- *Certified by the NRC in January 2023*
- *Submitted construction application in August 2023*

NATRIUM™

- *United States of America*
- *Sodium fast reactor coupled with a molten salt-based integrated energy storage system, 345 MW(e)*
- *Pre-application activities interactions with NRC*
- *Submitted construction application in March 2024*

BWRX-300

- *United States of America*
- *Boiling water reactor, 290 MW(e)*
- *Construction permit expected to be received by the end of 2024*
- *Commissioning expected in 2029*



Deployment and Development Status in Brief (3/3)

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The Call France 2030 has fostered the AMR activity

- Several different Gen4 technologies are being considered:
  - LFR (Newcleo, Sparta)
  - SFR (Hexana, Otrera,)
  - MSR (Naarea, Stellaria)
  - HTR (Jimmy, Blue Capsule)
- Some SU are reaching considerable team size and are investing in the supply chain (M&A; collaborations)
- More and more SU are targeting markets beyond electricity

newcleo
Futurable Energy

- LFR design
- 400+ staff
- 3b€ investment announced by 2030

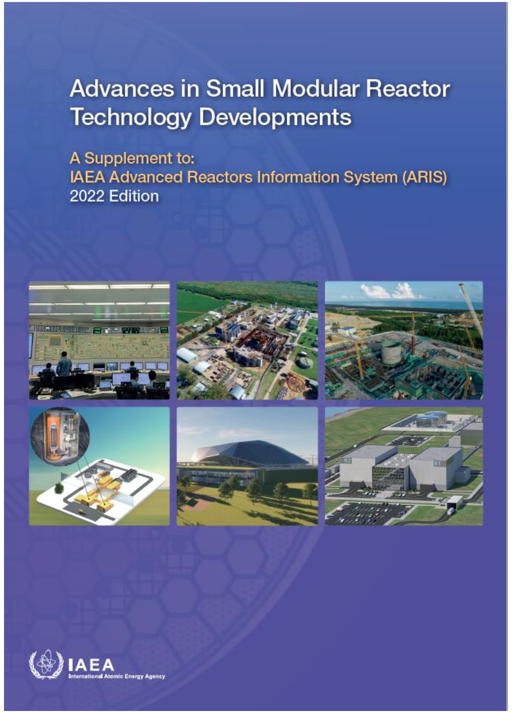
naarea

- MSR design
- 140+ staff
- Digital Twin

Jimmy SPARTA HEXANA STELLARIA otrera RENAISSANCE FUSION BLUE CAPSULE

cea

IAEA ARIS SMR Booklet 2022



IAEA SMR Booklet, 2022 Edition	
Number of reactor designs:	**83**
Member states involved:	**18**
Reactor types	1.1. Water-cooled Land Based – **25** 1.2. Water-cooled Marine Based – **8** 2. High temperature Gas-cooled – **17,** including **3** HTGR-type test reactors 3. Liquid Metal-cooled Fast Neutron Spectrum – **8** 4. Molten Salt – **13** 5. Microreactors – **12**
Distinguishing features	• New annexes on **economic challenges, decommissioning, and experimental testing for design verification and validation** • Insightful annexes with various charts and tables
Status	Finished, submitted for publication.
Downloadable version	Coming soon.

The 2022 IAEA SMR ARIS Booklet is a biennial publication as a supplement to the IAEA Advanced Reactor Information System (ARIS) Database. It provides a brief yet comprehensive design description of 83 different reactor designs. The 2022 version is an updated version of the 2020 booklet. It includes 11 more designs and a more comprehensive set of annexes.

Growing Interest in SMRs

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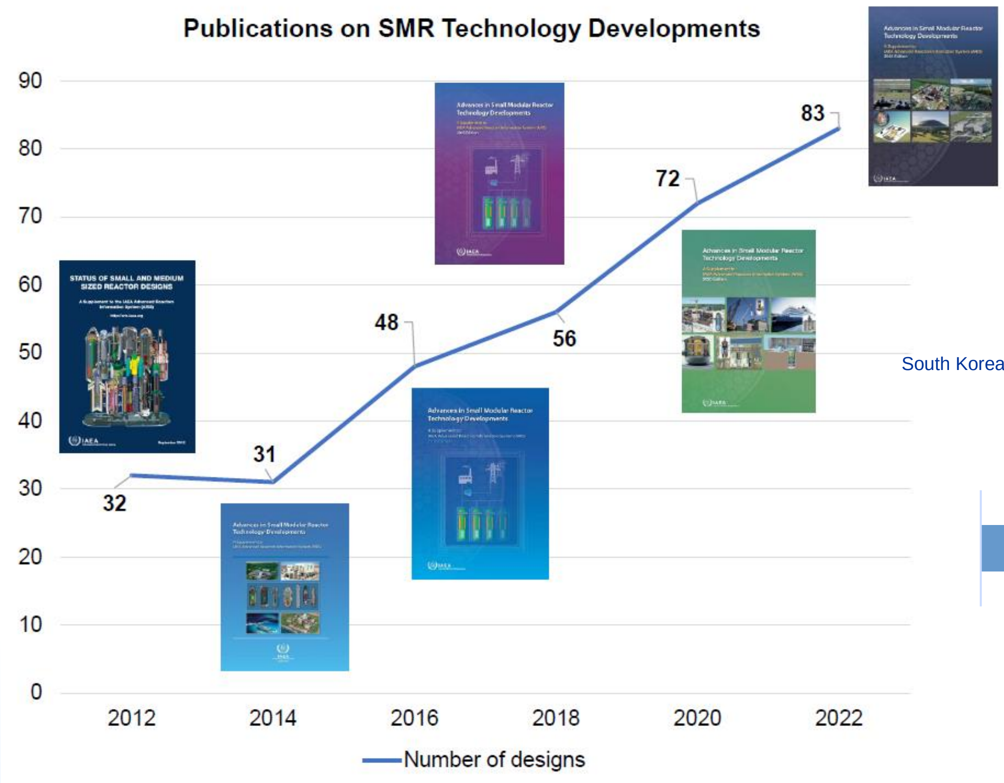
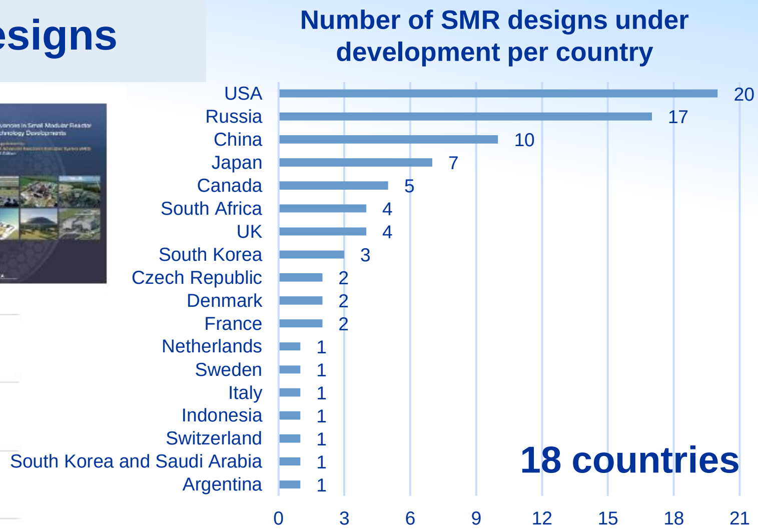
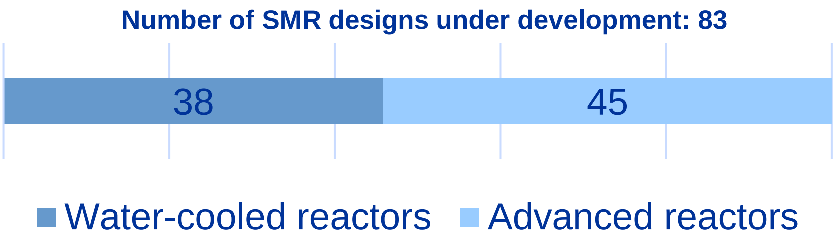
Comprehensive Collections of Designs

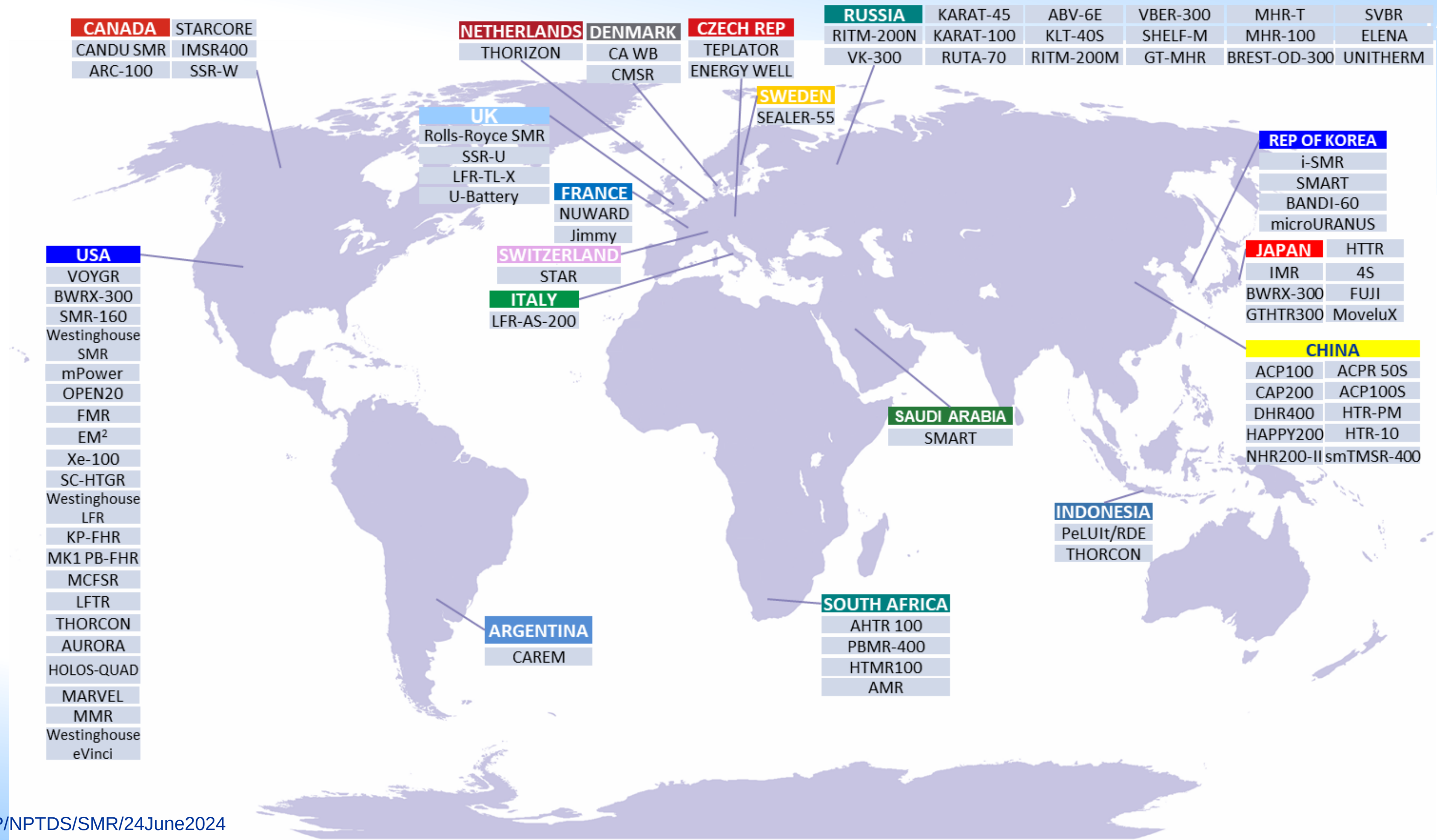




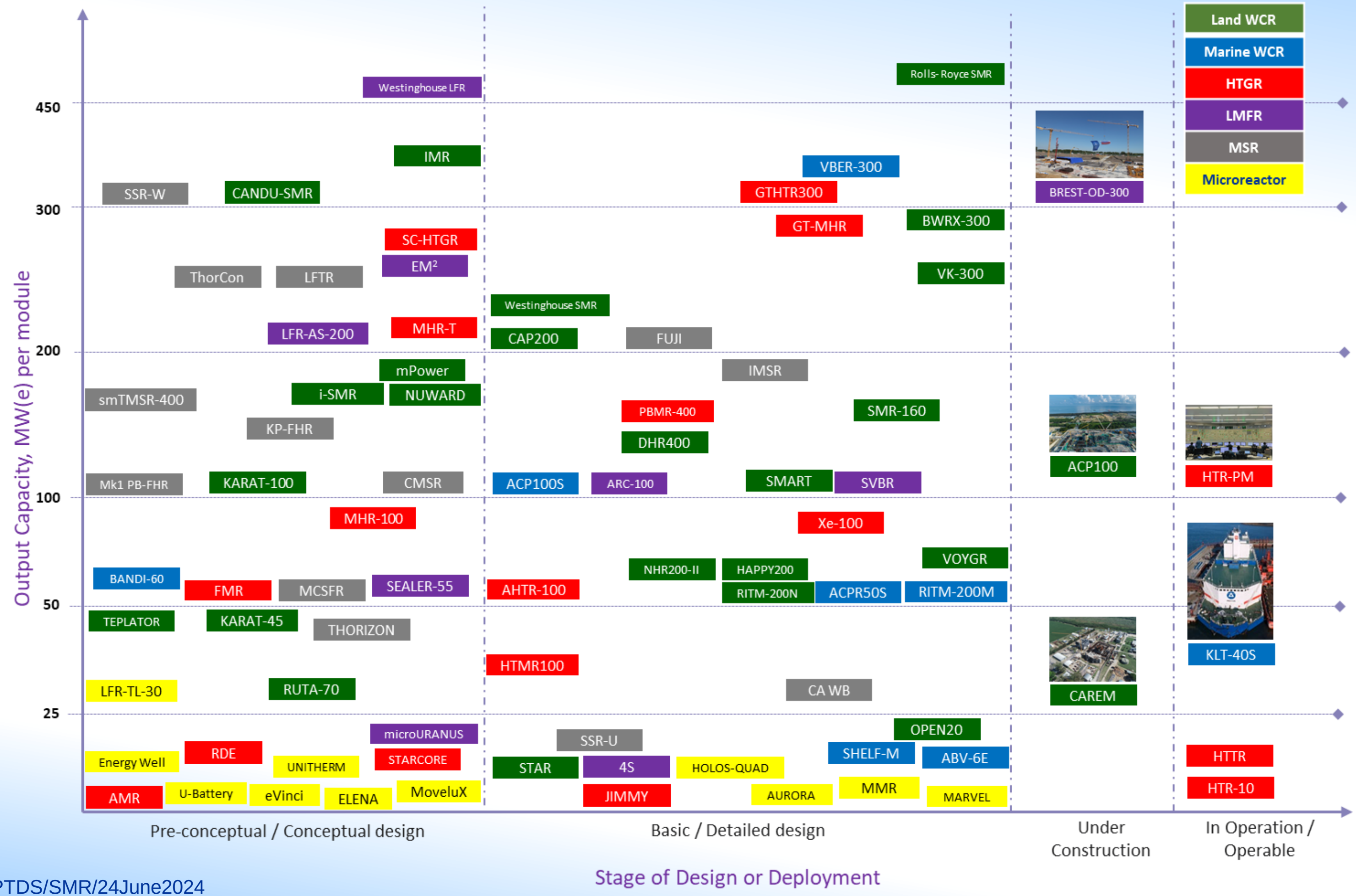


HTGR 21
MSR 13
LFR 8
SFR 3

Global map of SMR Technology Development (2022)



Stage of development or deployment of SMRs



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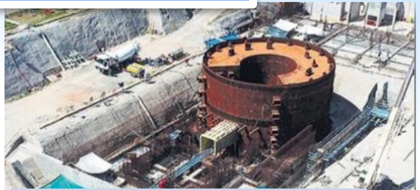
First 10-year Deployment Horizon

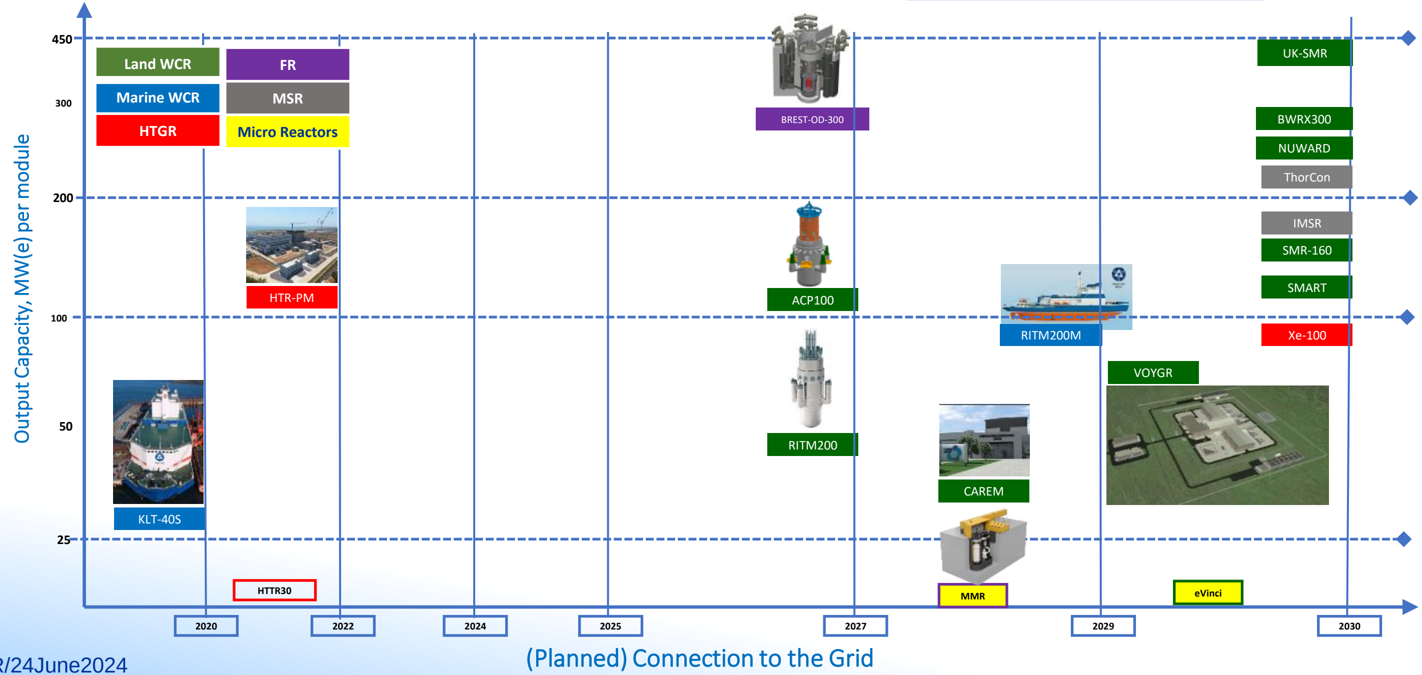
SMR Forerunners: 2 in operation, 4 in advanced stage of construction

KLT-40S in **operation,** Dec 2019

HTR-PM started **operation 2021**



CAREM to start **operation in 2028**

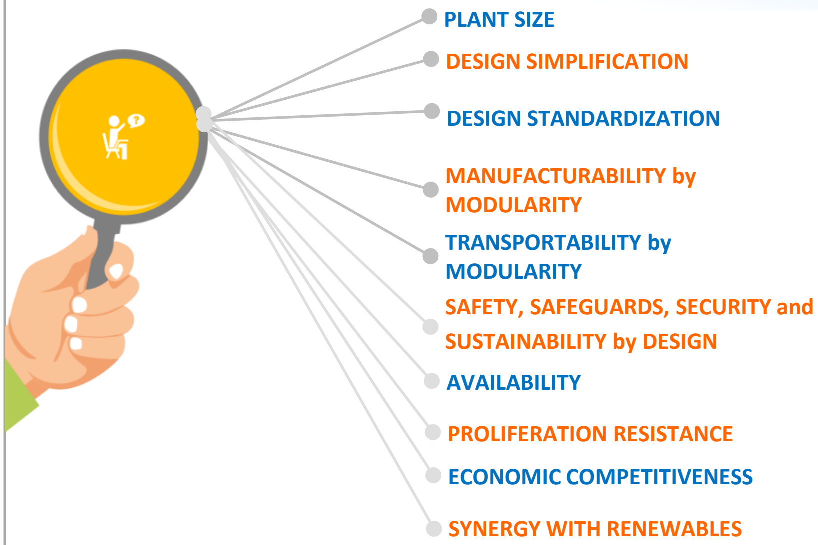


SMRs: Development Objectives & Attributes

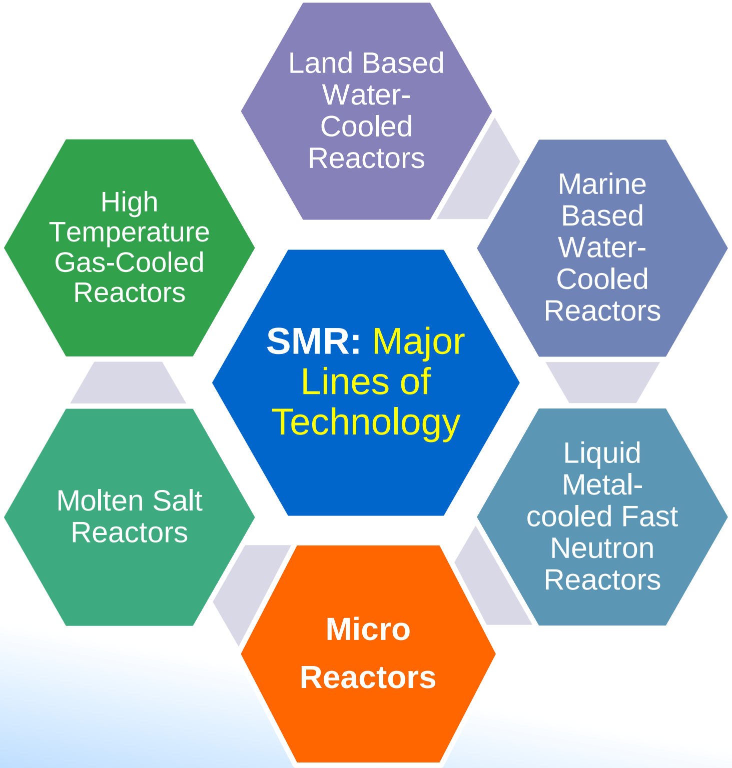
Developmental Objectives

- Smaller power, simplified design, deployed with high modularity
- Cost benefit, e.g., lower upfront capital cost and risk; economy of multiple
- Flexible to meet higher demand using multiple-module power plants
- Various applications for electric and non-electric, including H_2 production
- Salient features comparing to Large NPPs
- A value proposition for enhancing social acceptance by public

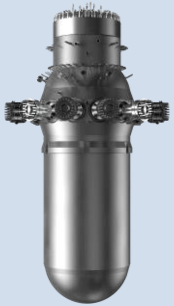
Key Attributes and Requirements



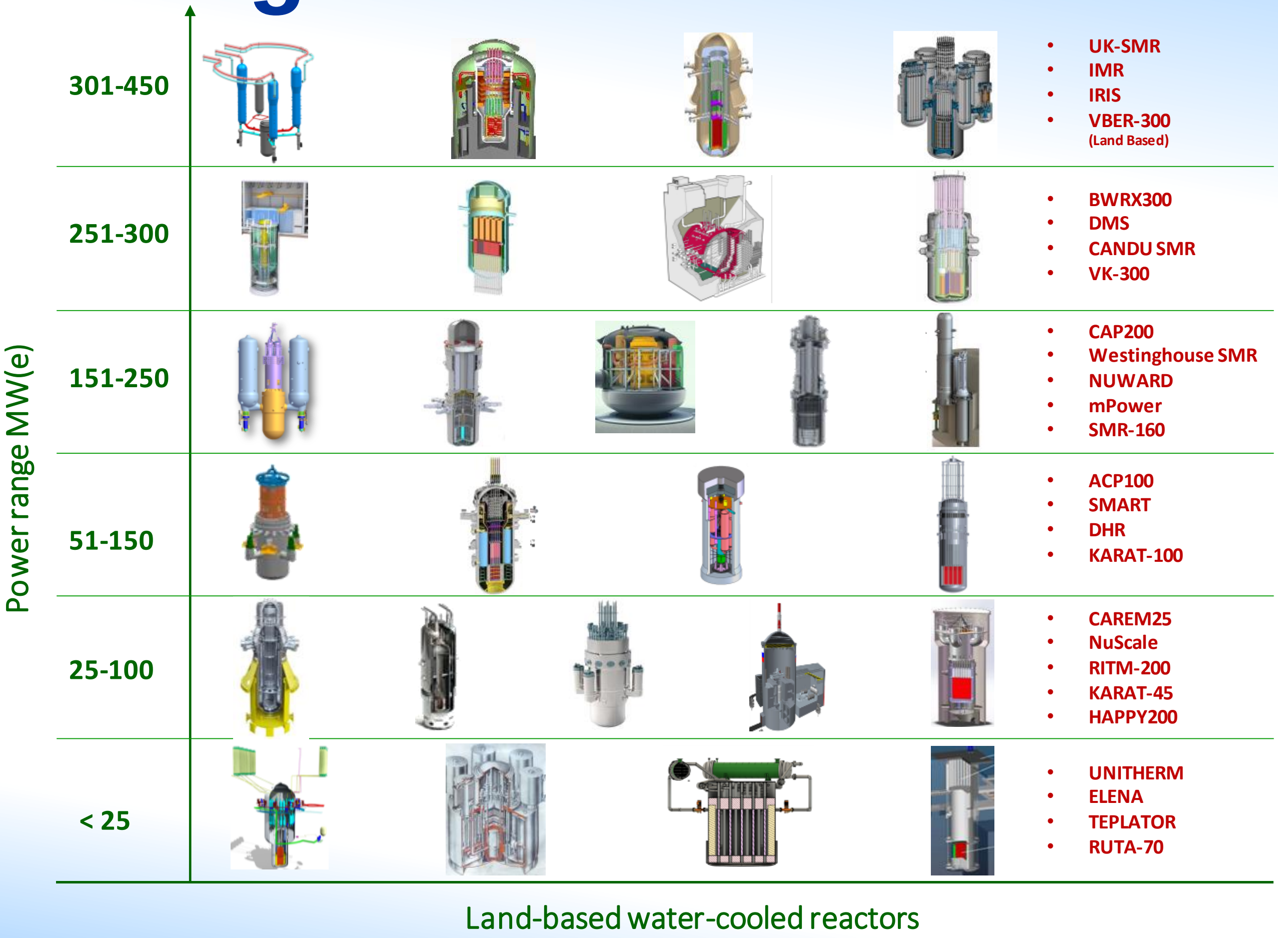
A categorization of SMR Technology



LWR-type SMRs (Examples)

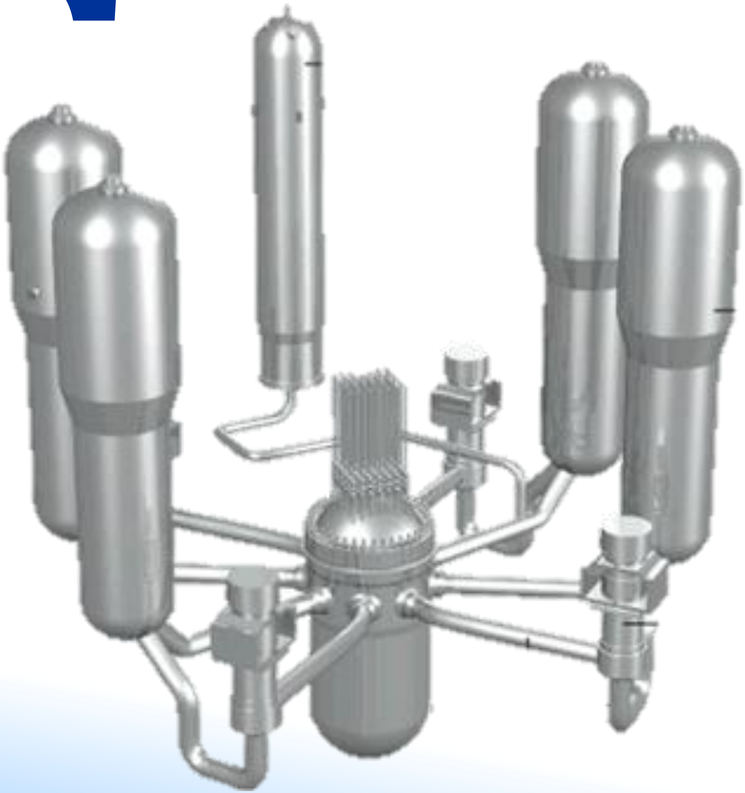
CAREM	ACP100	NUWARD	SMART	NuScale	BWRX-300
					
Design Status: Advanced stage of construction in Atucha site, Argentina	Design Status: Received license for construction in July 2019; site excavation for FCD in 2021	Design Status: Conceptual design; Consortium launched in September 2019	Design Status: Licensed/Standard Design Approval (July 2012), Pre-Project Engineering completed	Design Status: Design Certification Approval received in September 2020, to start construction by 2023	Design Status: Pre-licensing initiated in UK, Canada, US, aiming for construction start in 2024, operation in 2027
• **CNEA, Argentina** • Integral-PWR • 100 MWt / 30 MWe • Natural Circulation • Core Outlet Temp: 326ºC • Enrichment: 3.1% (prototype) • Refuel interval: 14 months (prototype)	• **CNNC, China** • Integral-PWR • 385 MWt / 125 MWe • Forced circulation • Core Outlet Temp: 319.5ºC • 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: 307ºC • 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: 322ºC • 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: 321ºC • 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: 287ºC • Enrichment: <4.95% • Refuel interval: 24 months

Power Range of LWR-based SMRs



Design Example 1: Integral-PWR type SMR

∫ (2000 – 4500) MWth



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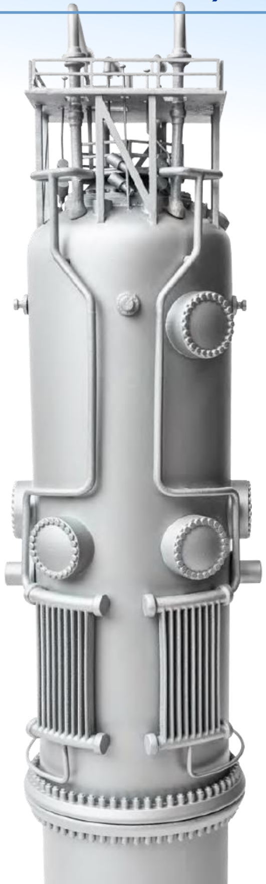
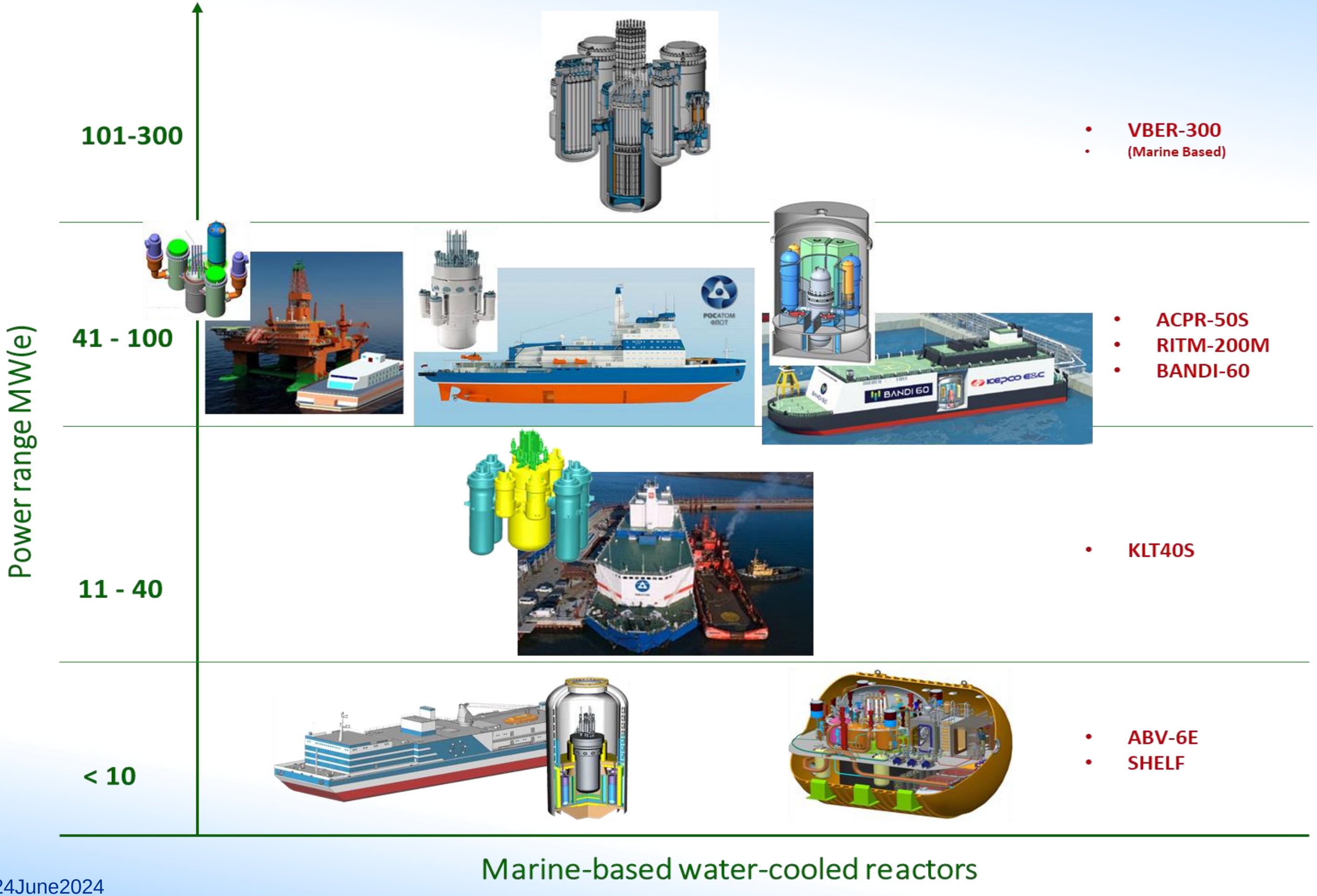
(100 – 1000) MWth



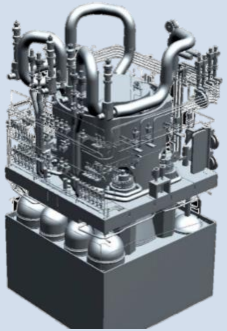
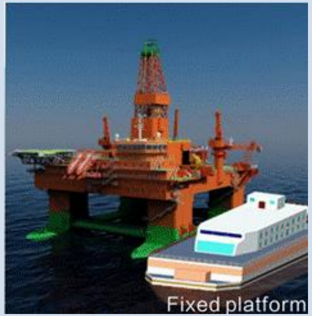
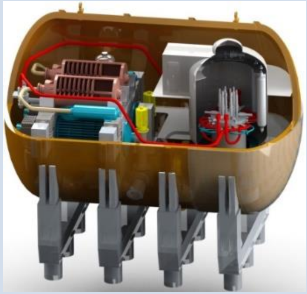
iPWRs: Safety Advantages & Challenges

Advantages	Issues / Challenges
No large piping connected to RPV → No Large-LOCA	Increased numbers of small-bore piping connections to the RPV
Coolant Pumps connected to RPV → Reduced leakage probability	Structural strength of RPV and joints; mechanical vibration; flow stability
Internal Control Rod Drive Mechanism → No CRD ejection accident	In-service inspection approach for in-vessel components
Wide use of Passive Safety Systems → Independence of power source	Passive system has lower driving heads; ADS reliability is critical
Modularization and NSSS components integration → compact reactor building	Larger and taller RPV to house NSSS components: steam generators, etc.

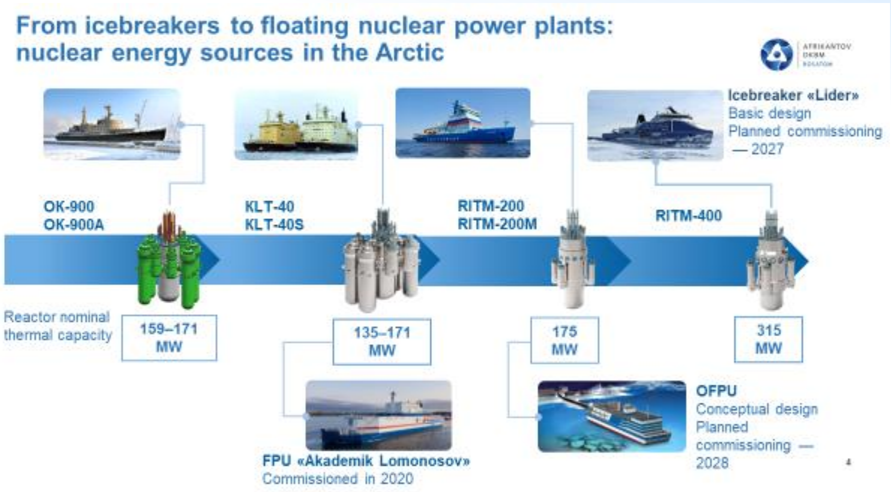
Power Range of Marine-based SMRs

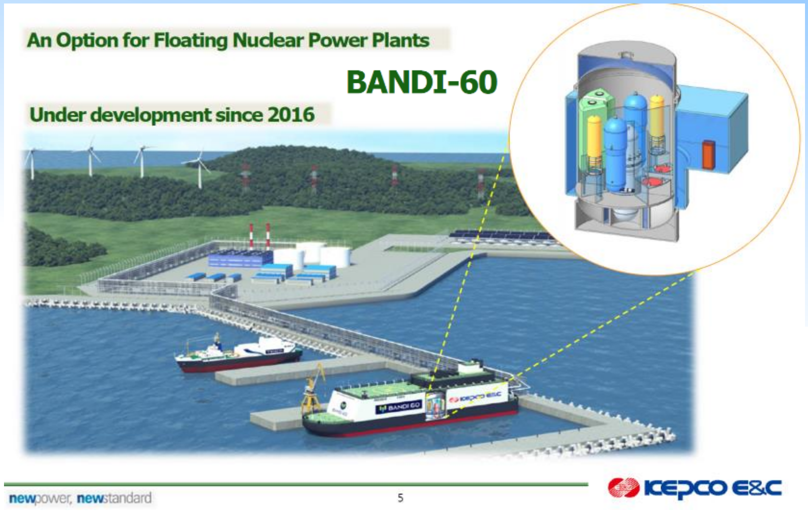


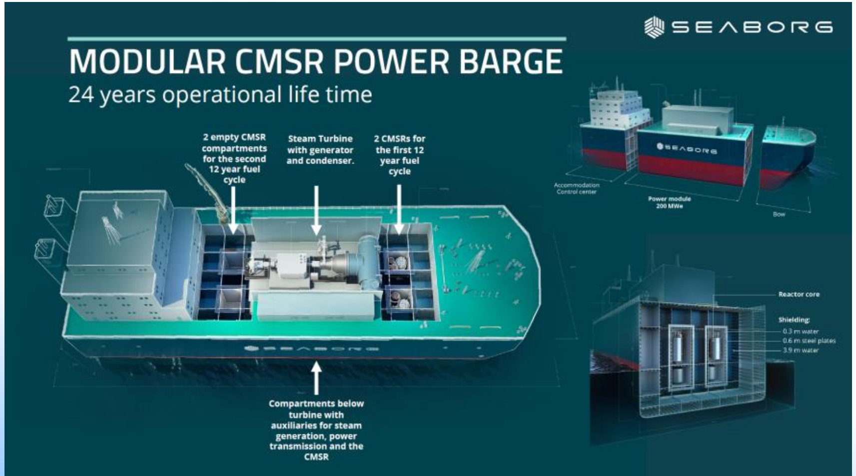
Marine-Based SMRs (Examples)

On-Shore Deployment		Off-Shore Deployment	
KLT-40S	**RITM-200M**	**ACPR-50S**	**SHELF**
			
Design Status: Full Commercial Operation since May 2020 in the Akademik Lomonosov Floating NPP	Design Status: 6 prototype reactors were manufactured and installed on icebreakers (2 ones are in the process of testing)	Design Status: Completion of conceptual/ program design, preparation of project design.	Design Status: Detailed design underway
• OKBM Afrikantov, Russian Federation • Compact Loop PWR • 150 MWt / 35 MWe per module x 2 modules for the FNPP • Core Outlet Temp: 316ºC • Enrichment: 18.6% • Refuel interval: 36 months • Without onsite refuelling • Spent fuel take back	• OKBM Afrikantov, Russian Federation • Integral-PWR • 175 MWt / 50 MWe per module • Core Outlet Temp: 318ºC • Enrichment: <20% • Refuel interval: Up to 120 months • Without onsite refuelling • Spent fuel take back	• CGNPC, China • Integral-PWR • 200 MWt / 50 MWe per module • Core Outlet Temp: 321.8ºC • Enrichment: <5% • Refuel interval: 30 months • Whole heap refuelling	• NIKIET, Russian Federation • Integral-PWR • 28.4 MWt / 6.6 MWe per module • Core Outlet Temp: 310ºC • Enrichment: 19.7% • Refuel interval: 6 years (8 for SHELF-M) • Without onsite refuelling • Spent fuel take back

FNPP R&D and deployment progress



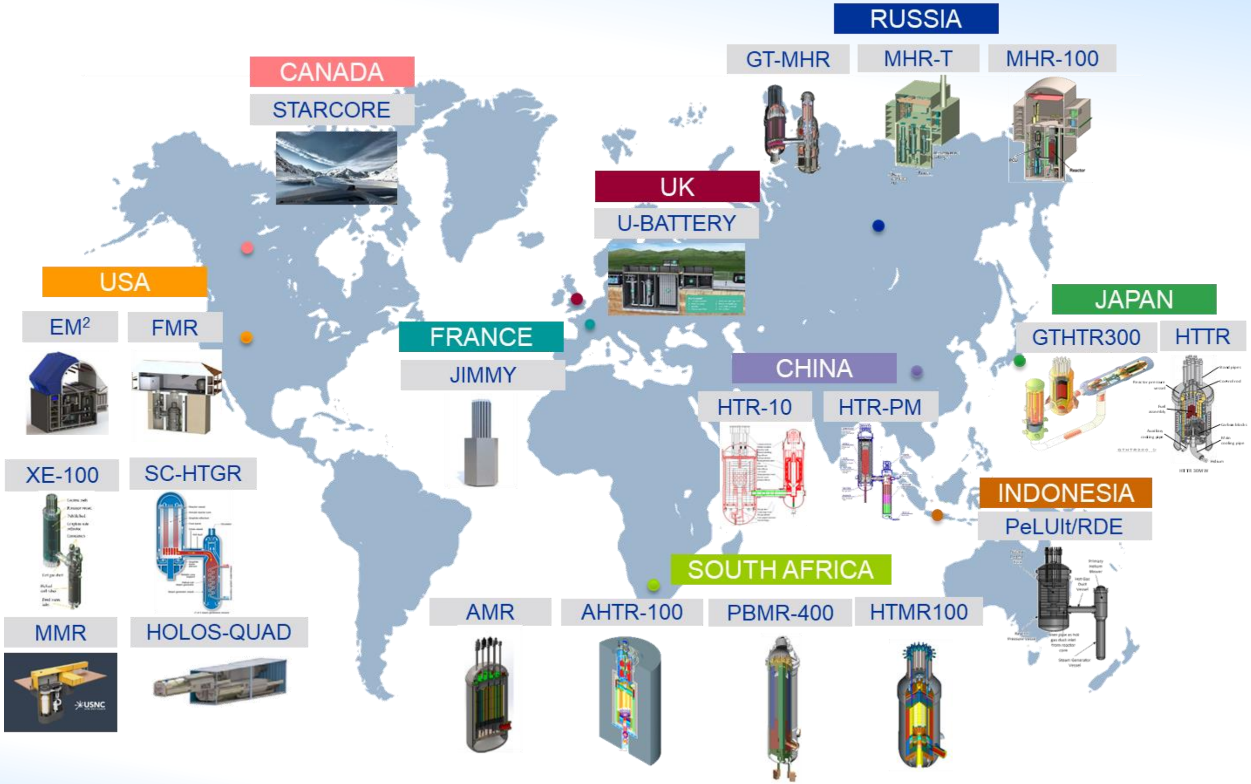




Market Potential of Marine-based SMRs

- East and South-East Asia
  - high seismicity and tsunami risk, high coastal population density, and limited domestic energy resources
- Middle East
  - Massive water desalination plants
- Africa and South America
  - small grids, high prices of electricity, water desalination, no incentives to develop large domestic nuclear infrastructure
- Russian Federation and northern Europe
  - Remote Arctic region power and heat supply, large mining operations, large offshore oil/gas operations

Global Activities on HTGR-SMR development



Under wide-range of development and deployment stages

Key organizations with HTGR development

IAEA

TSINGHUA UNIVERSITY 1911

Jimmy

JAEA

PBMR

STEENKAMPSKRAAL ThO_2RIUM STL NUCLEAR (PTY) LTD

OKBM AFRIKANTOV A SC "ROSATOM" COMPANY

GENERAL ATOMICS

X energy

HolosGen™

framatome

BRIN BADAN RISET DAN INOVASI NASIONAL

ULTRA SAFE NUCLEAR

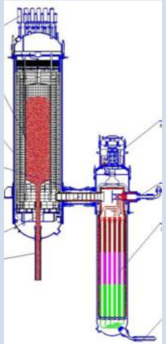
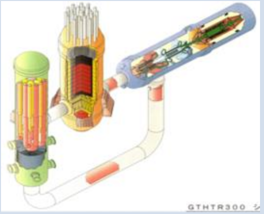
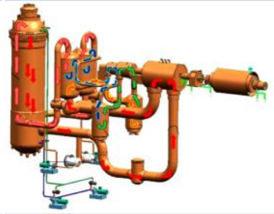
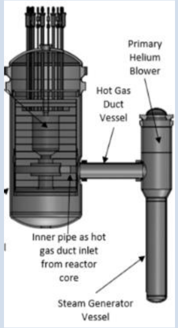
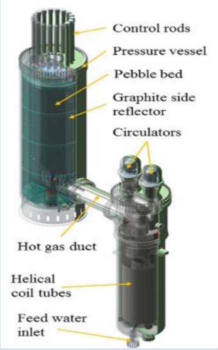
STARCORE NUCLEAR

urenco The Energy to Succeed

Eskom

Industries and National Laboratories in 9 Member States

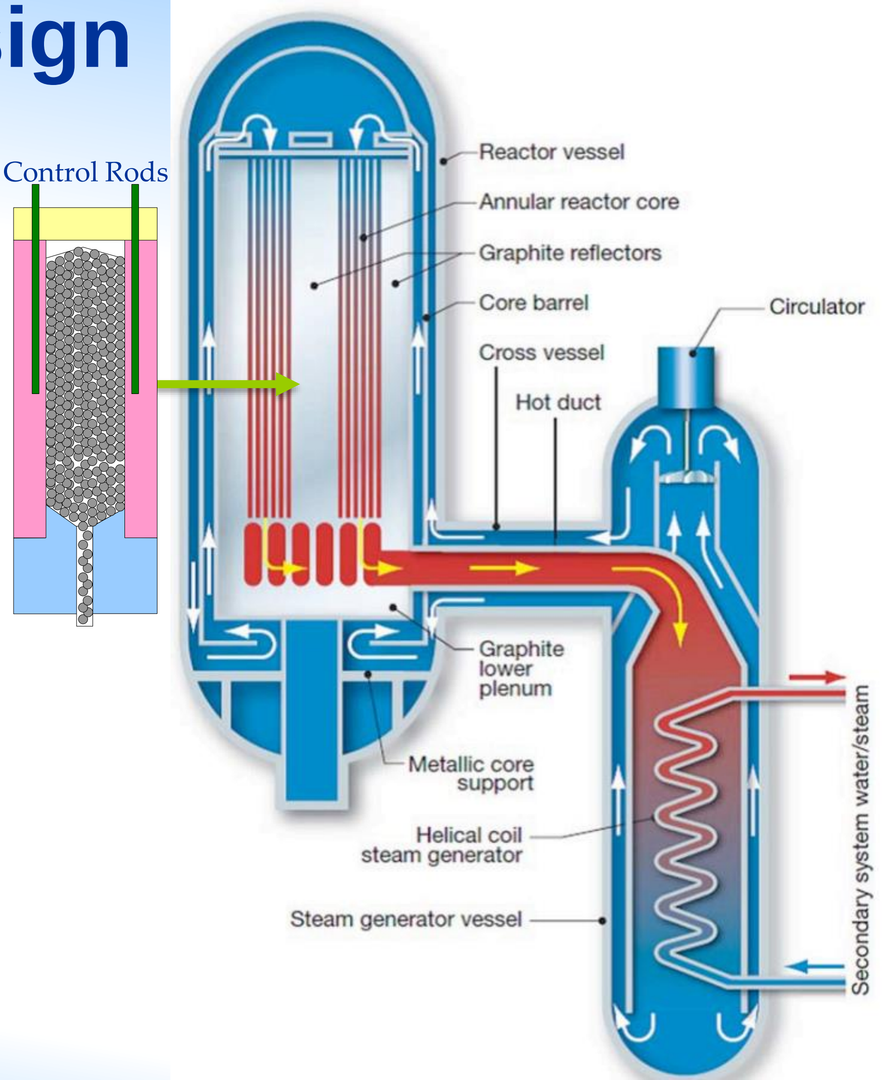
HTGR-type SMRs (Examples)

HTR-PM (China)	SC-HTGR (France)	GTHTR300 (Japan)	PBMR-400 (South Africa)	Xe-100 (X Energy, United States)
				
<u>Design Status</u>: Achieved first criticality on 13 Sept 2021 in Shidao Bay, planned grid connection by end of 2021	<u>Design Status</u>: Conceptual Design	<u>Design Status</u>: Pre-Licensing; Basic Design Completed	<u>Design Status</u>: Preliminary Design Completed, Test Facilities Demonstration	<u>Design Status</u>: Basic design development . Applied for VDR in July 2020. To submit design certification to the U.S. NRC in 2021 for construction in 2025 - -2026
• INET Tsinghua University, China • Modular pebble-Bed HTGR • 250 MWt / 210 MWe x 2 modules • Forced Circulation • Core Outlet Temp: 750ºC • Enrichment: 8.5% • Refuel interval: Online refuelling	• Framatome Inc ,United States, France • Prismatic-bloc HTGR • 625 MWt / 272 MWe per module • Forced convection • Core Outlet Temp: 750ºC • Enrichment: <14.5% avg, 18.5% max • Refuel interval: ½ core replaced every 18 months	• JAEA, Japan • Prismatic HTGR • <600 MWt / 100~300 MWe • Core Outlet Temp: 850-950ºC • Enrichment: <14% • Refuel interval: 48 months • Multiple applications	• PBMR SOC, Ltd, South Africa • Pebble-Bed HTGR • Forced Circulation • 400 MWt / 165 MWe per module • Core Outlet Temp: 900ºC • Enrichment: 9.5% • Refuel interval: Online refuelling	• X Energy, LLC, United States of America • Modular HTGR • Forced Helium Circulation • 200 MWt / 82.5 MWe • Core Outlet Temp: 750ºC • Enrichment: 15.5% • Refuel interval: Online refuelling

Pebble-bed Reactor design parameters

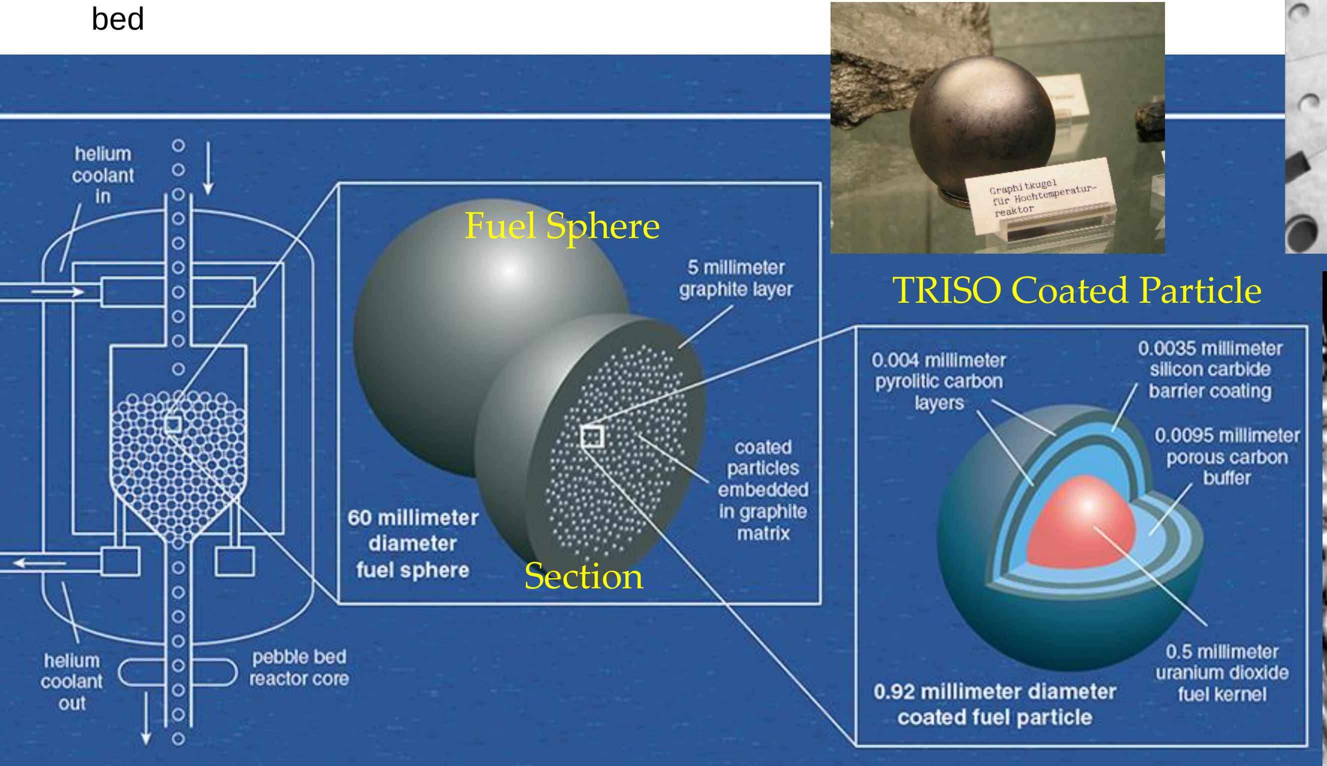
Example: HTR-PM Parameters

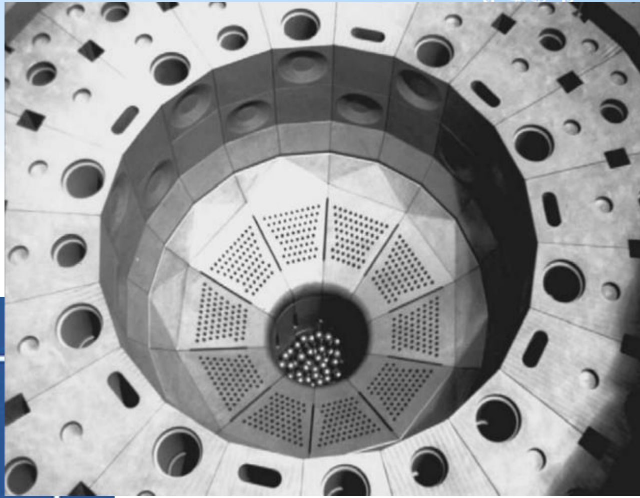
Plant electrical power, MWe	210
Core thermal power, MW (one module)	250
Number of NSSS Modules	2
Core diameter, m	3
Core height, m	11
Primary helium pressure, MPa	7
Core outlet temperature, °C	750
Core inlet temperature, °C	250
Fuel enrichment, %	8.5
Steam pressure at turbine, Mpa	13.25
Steam temperature at turbine, °C	566
Efficiency, %	42



Design Example 2: Pebble-bed type HTGRs

- Spherical graphite fuel element with coated particles fuel
- On-line / continuous fuel loading and circulation
- Fuel loaded in cavity formed by graphite to form a pebble bed





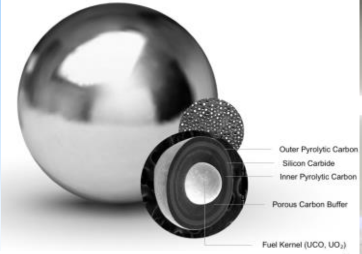
Comparison of Main Characteristics among Some HTGR-type SMR Designs

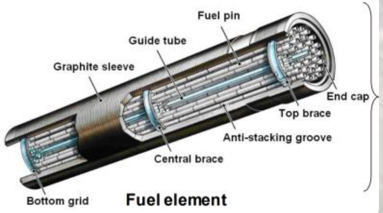
	HTR-PM	GTHTR300	GT-MHR	HTMR100	Xe-100	SC-HTGR	EM^2
Country of Origin	China	Japan	Russian Federation	South Africa	USA	USA	USA
Design organization(s)	INET, Tsinghua University	JAEA	JSC "Afrikantov OKBM"	STL Nuclear (Pty) Ltd.	X-energy, LLC	Framatome Inc.	General Atomics
Reactor type	Modular pebble bed HTGR	Prismatic HTGR	Modular Helium Reactor	Pebble-bed HTGR	Modular HTGR	Prismatic HTGR	Modular high temperature gas-cooled fast reactor
Fuel materials	TRISO spherical elements with coated particle fuel	UO_2 TRISO ceramic coated particle	Coated particle fuel in compacts, hexagonal prism graphite blocks	TRISO particles in pebbles; LEU/Th	UCO TRISO/pebbles	UCO TRISO particle fuel in hexagonal graphite blocks	UC pellet / hexagon
Coolant	Helium	Helium	Helium	Helium	Helium	Helium	Helium
Moderator	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	N/A
Thermal output, MW(t)	2 x 250	< 600	600	100	200	625	500
Electrical output, MW(e)	210	100 - 300	288	35	82.5	272	265
Core inlet temp., ºC	250	587 - 633	490	250	260	325	550
Core outlet temp., ºC	750	850 - 950	850	750	750	750	850
Enrichment, %	8.5	14	14-18% LEU or WPu	10%	15.5	14.5 (avg) 18.5 (max)	~14.5 (LEU)
Core Discharge Burnup (GWd/ton)	90	120	100-720 (depends on fuel type)	80 - 90	165	165	~130
Refuelling cycle, months	Online refuelling	48	25	Online fuel loading	Online fuel loading	½ core replaced every 18 months	360
Reactivity control	Control rods	Control rods	Control rods	Control rods in the reflector	Control rods	Control rods	Control rods
Reactor Vessel's height/diameter, (m)	25 / 5.7 (inner)	23 / 8	29 / 8.2	15.7 / 5.6	16.4 / 4.88	24 / 8.5	12.5 / 4.6
Design status	In operation	Basic design	Preliminary Design completed	Basic Design	Basic Design	Preliminary Design	Conceptual design

HTGR – Benefits

FEATURES

- ✓ Non-electric applications
- ✓ Walk away safe
- ✓ Inert gas coolant
- ✓ High efficiency
- ✓ High Burnup possible

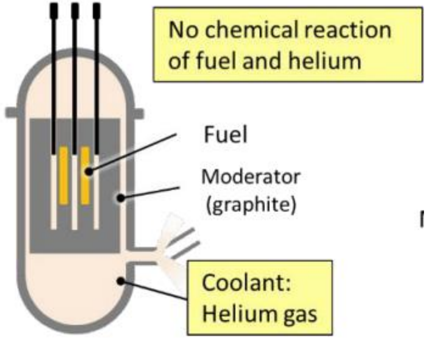




- Very different from first generation gas cooled graphite moderated reactors
  - Different fuel type (coated particle) – retain radioactive material at 1600 °C
  - Different coolant (Helium) – stable at high temperatures
  - (similar) Graphite core structure – high thermal inertia

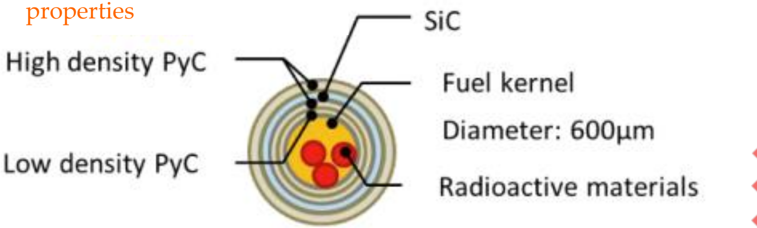
Image: X-energy, JAEA, Wikipedia

Chemically inert



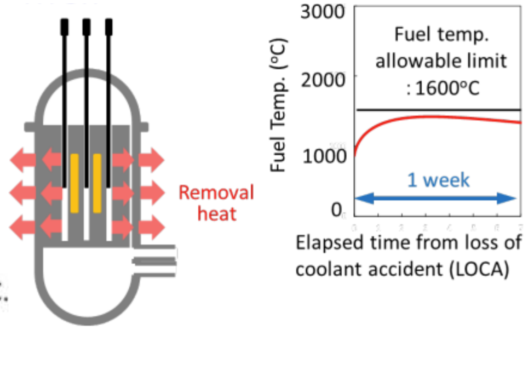
In case of vapor or air ingress accident, the surface of graphite oxidizes but safety of the core never be lost

Excellent heat resistant properties



Fission products is released from intact particles over 2200 °C.
(Fuel is recyclable under 1600 °C)
In case of a loss of coolant accident, reactor can be cooled passively and fuel temperature never exceeds 1600 °C.

No immediate accident management



In case of a loss of coolant accident, large heat capacity and high thermal conductivity of graphite absorbs heat.

HTGRs – Challenges

- The low power density leads to large reactor pressure vessels (but site requirements not larger)
  - Forging capability can also set limit on RPV diameter and power (e.g. Φ6.7 m → < 350 MWth in South Korea)
- Helium coolant has low density and thus requires high pressurization
- Helium coolant is non-condensable – so a traditional containment cannot be used
- Coated particle fuel costs are expected to be higher
- Availability of licensing framework
- Supply Chain

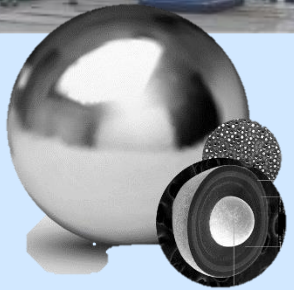
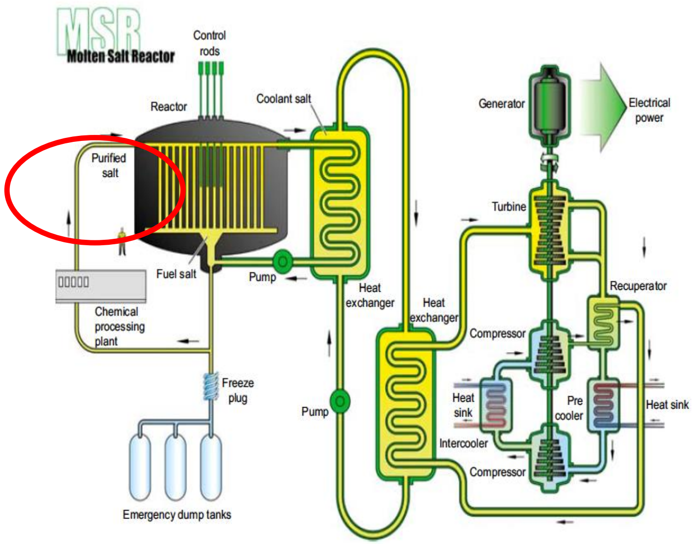


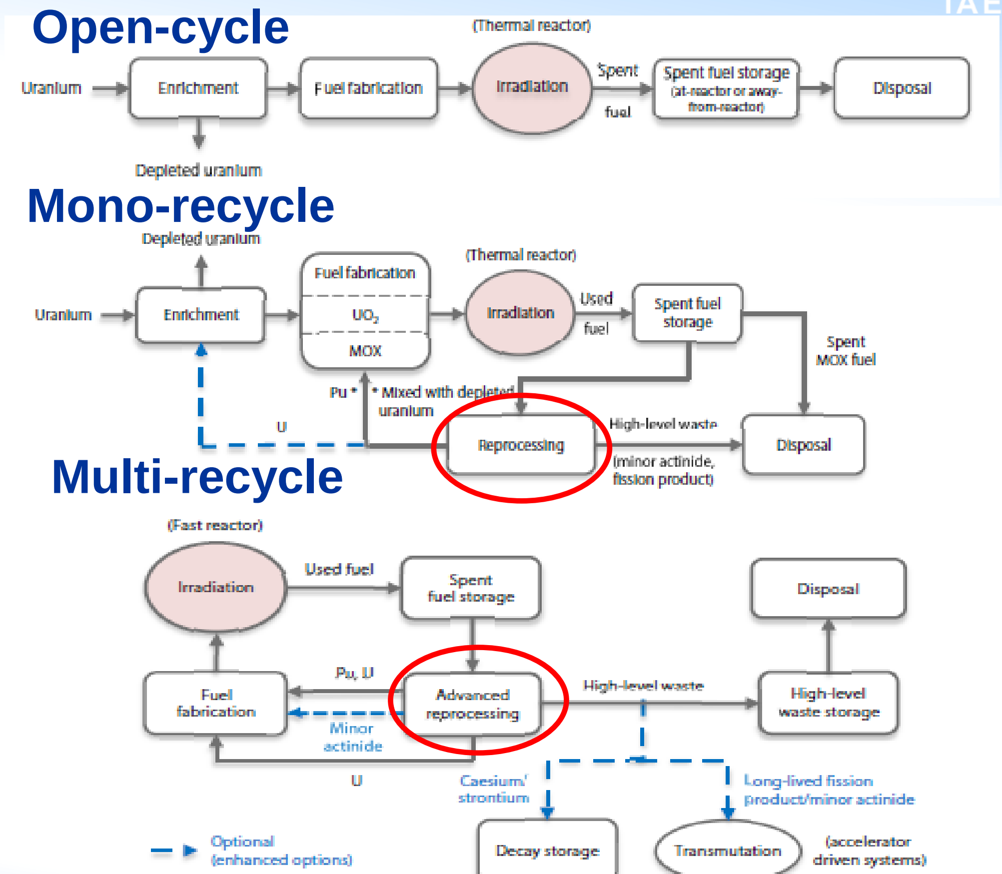
Image: HTR=PM, X-energy

Advances in Molten Salt Reactor development

Features/Incentives for MSR Development: Online reprocessing

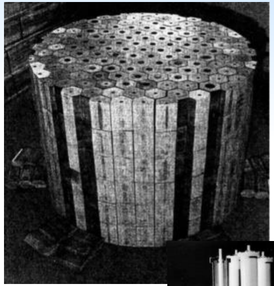


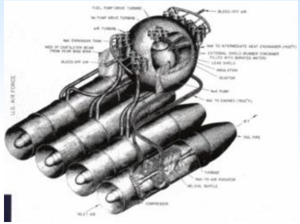
On-line refuelling / reprocessing
(multirecycling in a single facility)



Strategies and Considerations for the Back End of the Fuel Cycle, OECD/NEA 2021

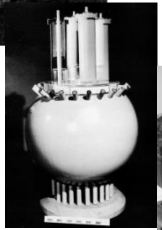
On the History of MSRs





Some early experience:

- ORNL aircraft power plant 1953
- Aircraft reactor experiment (ARE) – 1954
- Aircraft reactor test (ART) - 1956



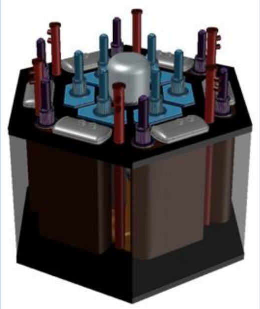
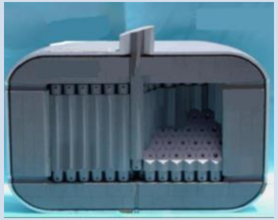
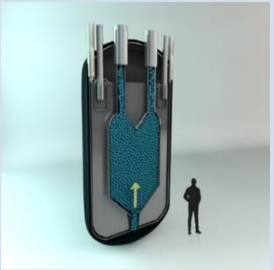
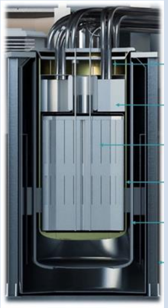
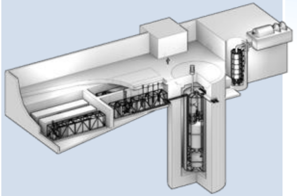
- Molten Salt Reactor Experiment – MSRE (1965-1969)
  - 8 MWt
  - Single region core
  - Graphite moderated
  - Also used U-233 and mixed U/Pu salt fuel
  - On-line refueling
  - >13,000 full power hours

MSRE Experience

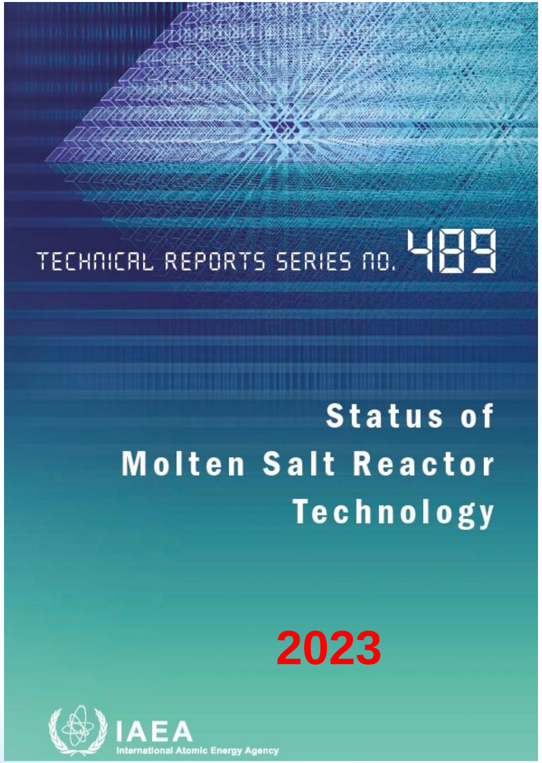
- Keeping salt molten was not difficult
- Moving salt among tanks was routine
- No salt leaks during operation (corrosion as expected)
- Adding enriching salt during operation was uneventful
- Static nuclear properties were accurately predicted
- Excellent dynamic stability with both ^{235}U and ^{233}U as predicted
- Reactivity change with time was as expected
- Heat transfer and hydraulic performance as predicted
- No pump maintenance required
- Stripping of noble gas fission products was effective
- Effective oxide stripping. Good UF_6 recovery

Power range of MSRs in the Category of SMRs

Molten Salt SMRs (Examples)

MCSFR	FUJI	KP-FHR	IMSR	ThorCon
				
Design Status: Conceptual design in progress, fuel development in testing	Design Status: 3 experimental MSRs were built. Detail design not started	Design Status: Conceptual design in progress	Design Status: Conceptual design complete – basic engineering in progress	Design Status: Complete basic design
• Elysium Industries, Canada and United States • Molten-salt cooled • 100 MWt / 50 MWe • Forced Circulation • Core Outlet Temp: 610°C • Enrichment: fuel salt contain 10-20% fissile actinide fraction and consume 100% actinide • Refuel interval: Online refuelling	• ITMSF, Japan-led consortium • Molten-salt cooled • 450 MWt / 200 MWe • Forced Circulation • Core Outlet Temp: 704°C • Enrichment: 2% • Refuel interval: Continuous operation possible	• Kairos Power, LLC, United States • Modular, pebble bed, high temperature, salt-cooled reactor • 320 MWt / 140 MWe • Core Outlet Temp: 650°C • Enrichment: 19.75% • Refuel interval: Online refuelling	• Terrestrial Energy Inc, United States • Molten salt reactor • Forced Circulation • 440 MWt / 195 MWe • Core Outlet Temp: 700°C • Enrichment: <5% • Refuel interval: 84 months	• ThorCon International, United States • Thermal molten salt reactor • Forced Circulation • 557 MWt / 250 MWe per module • Core Outlet Temp: 704°C • Enrichment: 5 – 19.7% • Refuel interval: 48 months

IAEA Publication on MSR Technology



220 pages

Section 1: Introduction	• Background, Objective, Scope, Structure
Section 2: History of MSR technology	• Development efforts of several member states on MSR technologies since the 1940s
Section 3: Advantages and technical challenges of MSR technology	• Potential safety and economic advantages of MSRs and technical challenges for deploying MSRs
Section 4: Classification of MSRs	• Taxonomy of MSRs based on the major reactor types and technological similarities: Classes, Families, Types
Section 5: Research and Development activities	• R&D activities in Member states with major programmes for MSR technology
Section 6: Current challenges to deploying MSRs	• Non-technical challenges associated with the deployment MSRs and potential solutions to these challenges
Section 7: Summary and conclusions	• Summary and main conclusions regarding the status of the MSR technology

Taxonomy of Molten Salt Reactor

IAEA

Courtesy of J. Křepel, Paul Scherrer Institute, Switzerland

Category / **Class** / **Family** / **Type**

- **Molten Salt Reactors**
  - Graphite based MSRs
    - Fluoride salt cooled
      - Salt cooled reactor with pebble bed fuel
      - Salt cooled reactor with fixed fuel
    - Graphite moderated
      - Single-fluid Th-U breeder
      - Two-fluids Th-U breeder
      - Uranium converters and other concepts
  - Homogeneous MSRs
    - Homogeneous fluoride fast MSRs
      - Fluoride fast Th-U breeder
      - Pu containing fluoride fast reactor
    - Homogeneous chloride fast MSRs
      - Chloride fast breeder reactor
      - Chloride fast B&B reactor
  - Heterogeneous MSRs
    - Non-graphite moderated MSRs
      - Solid moderator heterogeneous MSR
      - Liquid moderator heterogeneous MSR
    - Heterogeneous chloride fast MSRs
      - Heterogeneous salt cooled fast MSR
      - Heterogeneous lead cooled fast MSR
  - Other MSRs
    - Directly cooled MSRs
    - Subcritical MSRs
    - Hybrid moderator MSRs
    - Chloride salt cooled fast reactors
    - Frozen salt reactors
    - Hybrid spectrum MSRs
    - Heterogeneous gas cooled MSRs

- TRS-489 presented the MSR taxonomy in terms of class, family and type.
- Uranium converters and other concepts under the graphite moderated family has the most designs.

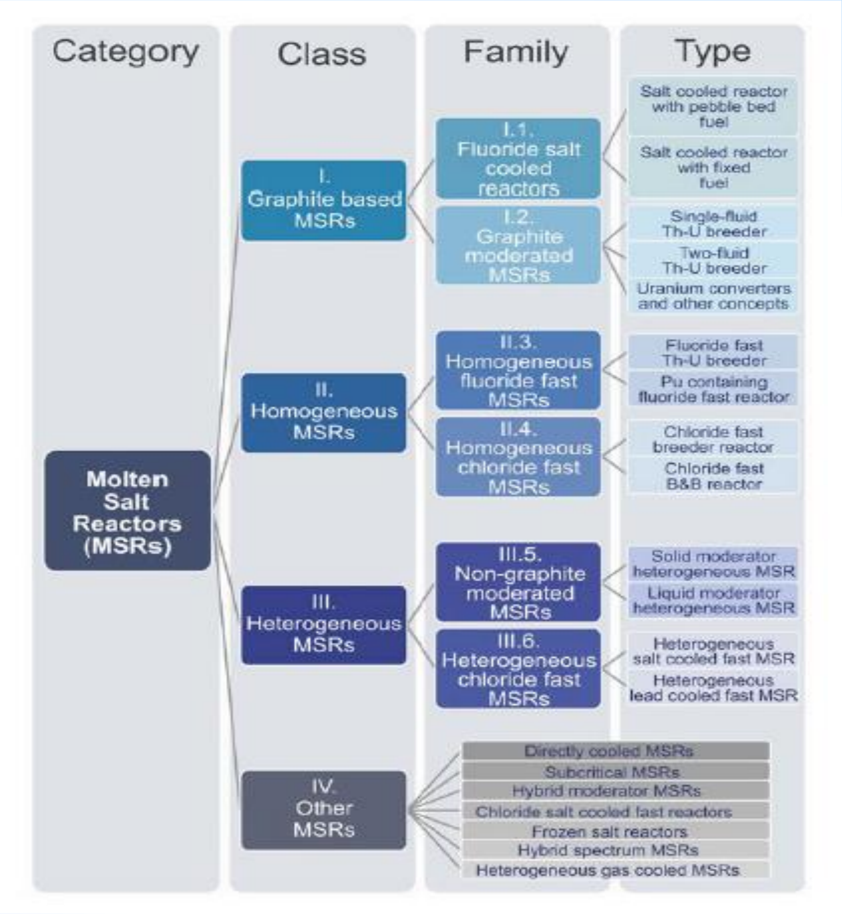
Advantages & Taxonomy

Near atmospheric operating pressure

No irradiation damage or mechanical failure of fuel

Strong negative reactivity temperature feedback.

On-line removal of gaseous fission products.



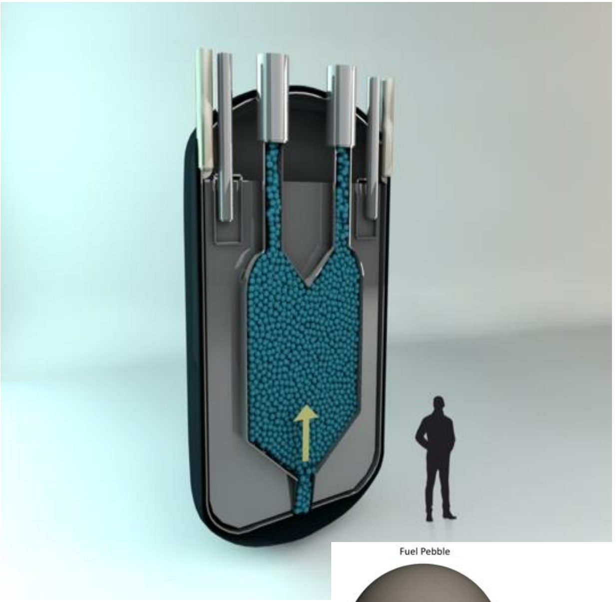
Courtesy of J. Křepel, Paul Scherrer Institute, Switzerland

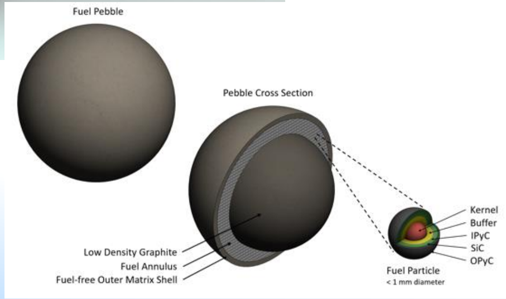
Integral Molten Salt Reactor

(Terrestrial Energy Inc., Canada)

Major Technical Parameters	
Reactor Type	Molten Salt Reactor
Coolant / Moderator	Fluoride fuel salt/graphite
Thermal / Electrical Capacity	440 MWt / 195 MWe
Operating Pressure (primary / Secondary)	< 0.4 (hydrostatic)
Core Inlet/Outlet Coolant Temperature	620^{o}C / 700^{o}C
Fuel Type	Molten salt fuel
Fuel enrichment	< 5% (LEU)
Design Status	Conceptual Design complete, VDR with CNSC

KP-FHR (Kairos Power, United States of America)

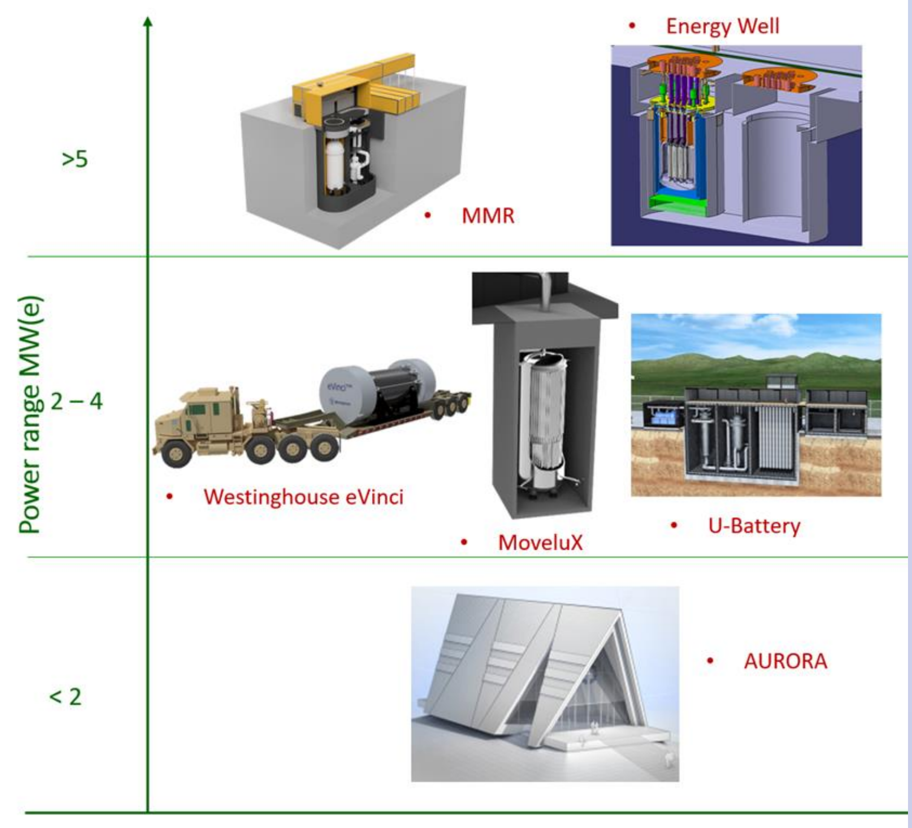




Major Technical Parameters	
Reactor Type	Modular, pebble bed, high temp, salt-cooled reactor
Coolant / Moderator	Li_2BeF_4 / graphite
Thermal / Electrical Capacity	320 MWt / 140 MWe
Operating Pressure (primary / Secondary)	< 0.2 (hydrostatic)
Core Inlet/Outlet Coolant Temperature	550°C / 650°C
Fuel Type	TRISO particles in graphite pebble matrix / pebble bed
Fuel enrichment	< 19.75% (LEU)
Design Status	Conceptual Design in progress

Emerging: Microreactors

Micro Reactors



- 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.

Microreactors (others, in organizations' website)

Technology Category
• Subcritical power modules in ISO container
• UCO TRISO fuel with gas/steam turbine generator
• Self cooling heat pipe
• Sodium Potassium eutectic-cooled, UZrH, HALEU
• lightweight fission power system to fuel deep-space exploration

Factors in Microreactors Development

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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

Specificities of Microreactors

04

Heat-pipe technology
proven by LANL for space application

03

Transportability
Within standard shipping containers

05

Compact and simplified

02

Multi-applications

- Energy generation; or
- Production of heat and electricity

06

Manufactured and fueled in a factory

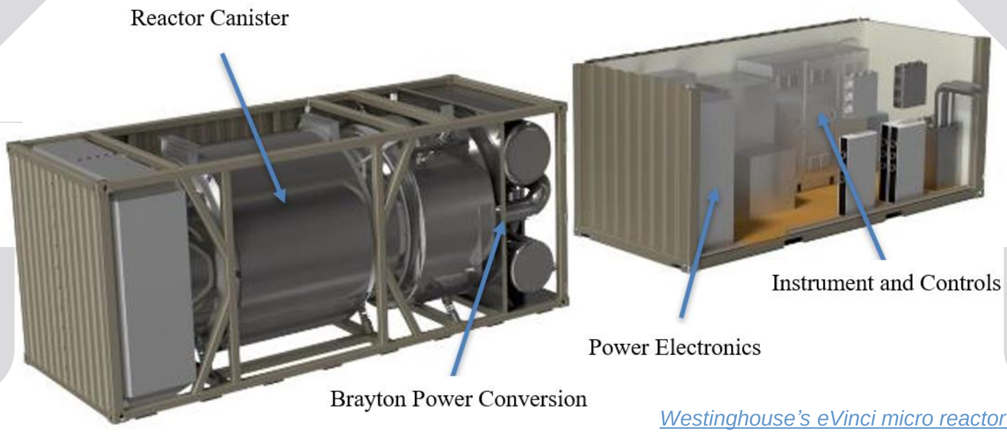
01

Specifically designed to serve

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

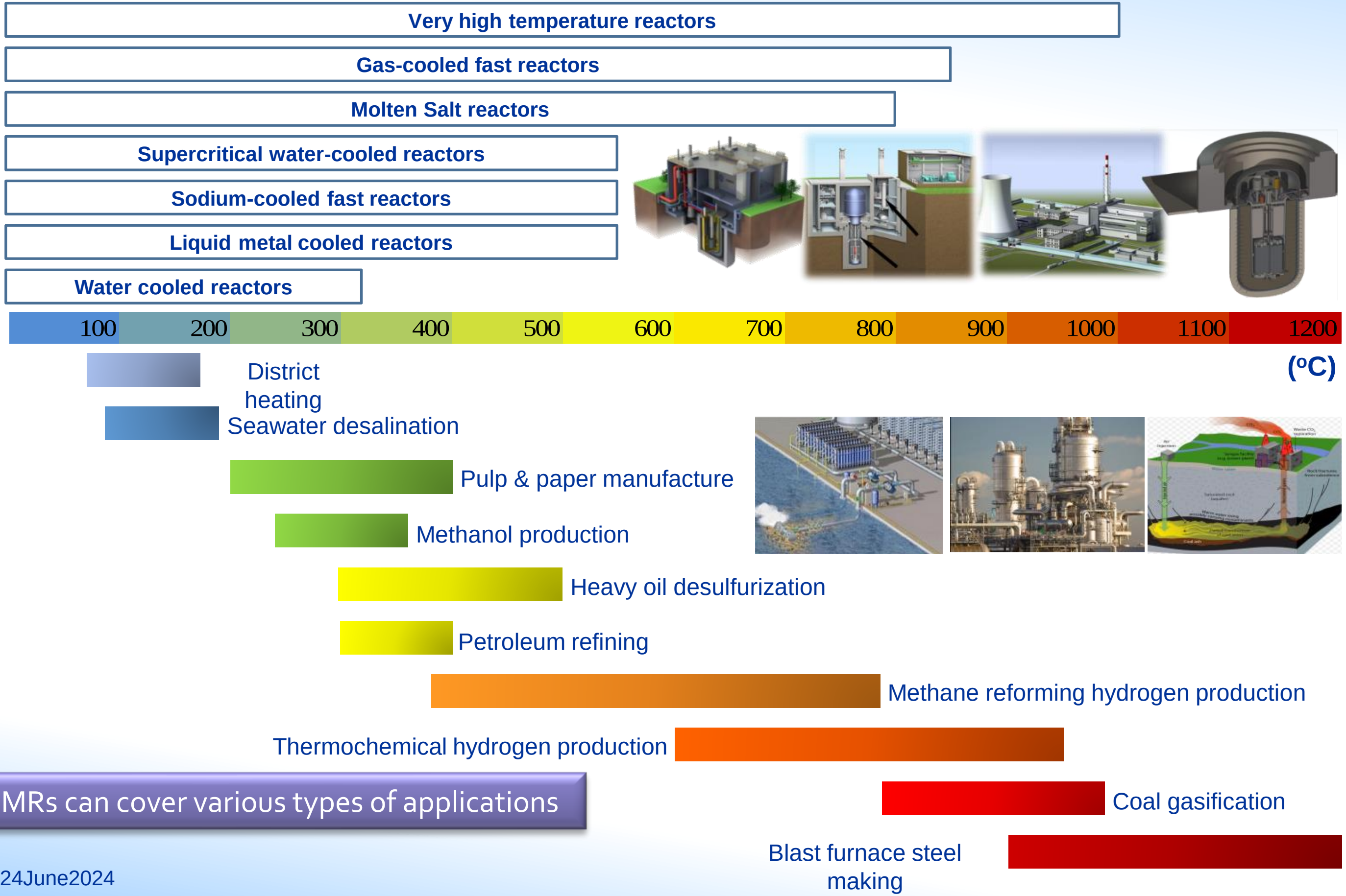
07

Packageable
in standard transport containers



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

SMR for Non-Electric Applications



Wide spectrum of SMRs can cover various types of applications

Values of Nuclear Cogeneration

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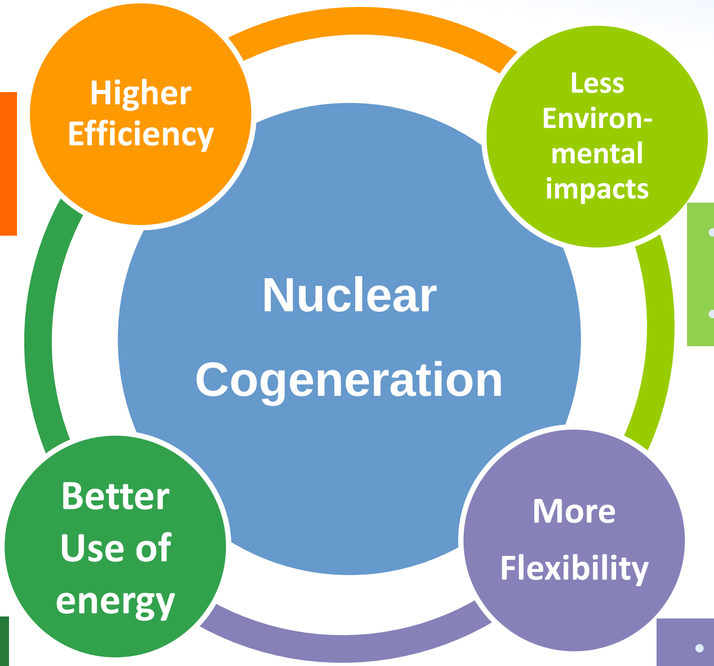

- Up to 80% energy efficiency
- Open new sectors for nuclear power

- Reduce the waste heat dumped to environment
- Additional heat sink

- Optimize energy efficiency
- Match industrial application needs at the right temperature

- In future energy planning
- In operating NPPs & Grid
- In diversifying energy outputs

Waste Management and Disposal Plan adopted by SMR Designs

- Volume Reduction and Conditioning:

  Coated particle separation from graphite will reduce volume by up to a factor of 100.
- Waste Processing:

  - Low and intermediate level waste from plant operation will be conditioned by different process technologies.

  - Possible graphite recycling, ^{14}C separation process
- Storage Approach, Spent Fuel Pool Cooling Mechanism:

  - With higher thermal efficiencies the radiotoxicity and decay heat will be lessened by 50% for HTGRs as compared to LWRs.

  - Dry storage with natural convection after short material active cooling.

  - Facilities for long-term storage of spent fuel and solid radwaste are in the NPP complex
- Spent Fuel Take-back Option: to date not considered in HTGRs.

Potential Challenges on Safeguards on SMRs

Reference: Jeremy Whitlock, SH-CA, SGCP, 2 November 2021

- **New fuels and fuel cycles:** pebble-bed, molten salt, Th/U-233, MOX, transuranic (TRU) fuels, fast reactors, higher enrichment (HALEU), pyroprocessing, other new processes
- **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
- **Spent fuel management:** storage configurations, waste forms
- **Diverse operational roles:** district heating, desalination, hydrogen + electricity
- **Remote, distributed locations:** access issues, accessibility of nuclear material for verification, cost-benefit issues

IAEA independent verification capabilities must be ready

Challenges facing
Successful Deployment of novel SMR designs

- **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**

Advantages, Issues & Challenges

IAEA

Technology aspects

- Shorter construction period (modularization)
- Potential for enhanced safety and reliability
- Design simplicity
- Suitability for non-electric application (desalination, etc.).
- Replacement for aging fossil plants, reducing GHG emissions

Non-Techno aspects

- Fitness for smaller electricity grids
- Options to match demand growth by incremental capacity increase
- Site flexibility
- Reduced emergency planning zone
- Lower upfront capital cost (better affordability)
- Easier financing scheme

Technology issues

- Licensing of FOAK designs, particularly non-LWR technologies
- Prove of operability and maintainability
- Staffing for multi-module plant;
- Supply chain for multi-modules
- Optimum plant/module size
- Advanced R&D needs

Non-technology issues

- Time from design-to-deployment
- Highly competitive budget source for design development
- Economic competitiveness: affordability & generation cost
- Availability of *off-the-shelf* design for newcomers
- Operating scheme in an integration with renewables

Prospects and Actions for Deployments

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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

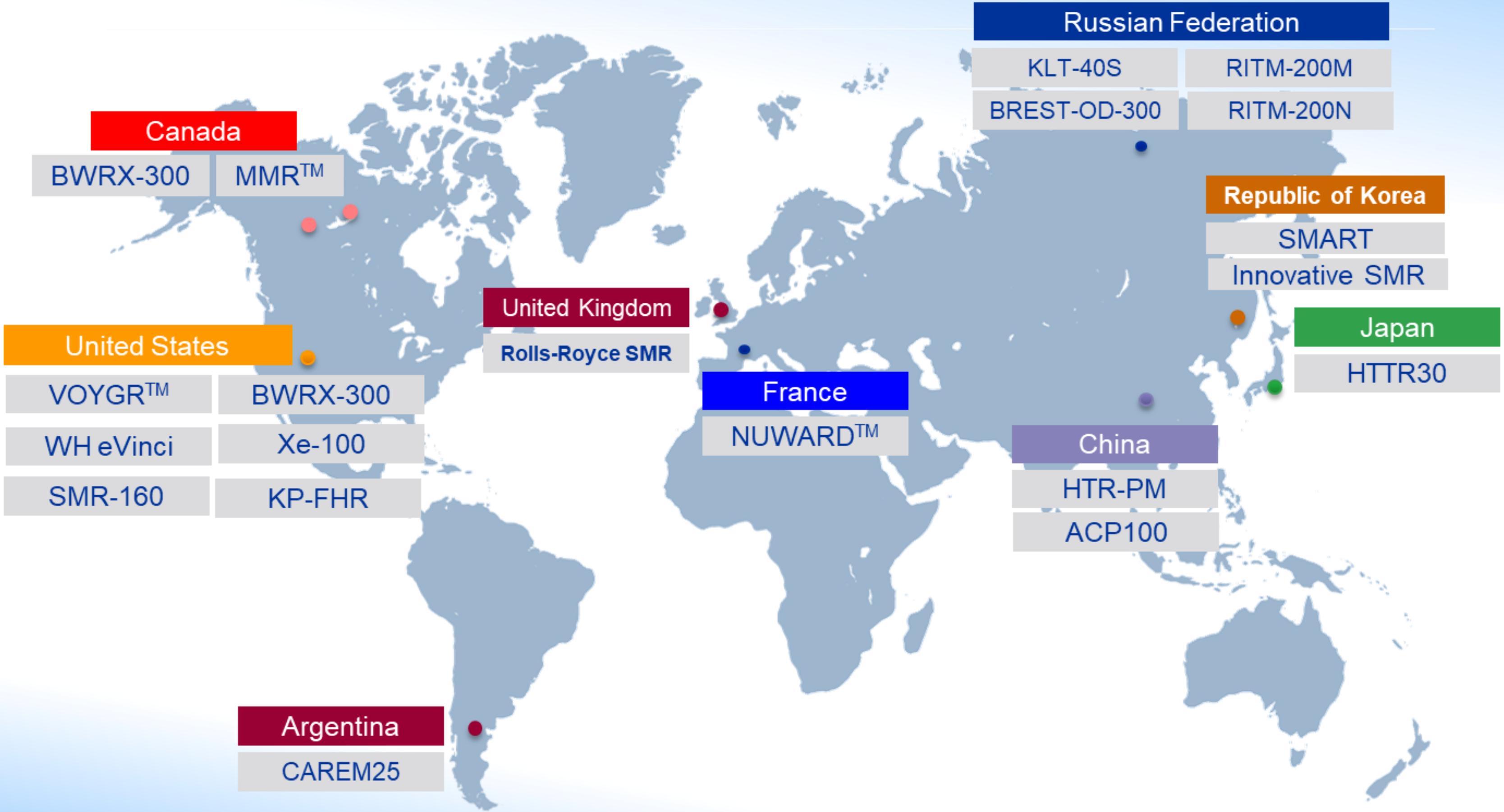
Regulatory framework, licensing pathways: global deployment,

need of harmonization?

Development of Nuclear Infrastructure for near-term deployment particularly

in Embarking countries

Status and Prospect of Deployment (2020 – 2030s)



TWG-SMR Second Term 2022-2025

Members of TWG-SMR 2018-2021

Members of TWG-SMR 2022-2025

Functions of the TWG – New ToR

- To provide advice to DDG-NE on specific topics of relevance to the IAEA's programmatic activities on SMR;
- To share information and knowledge on national and international programmes on SMR;
- To contribute to the development and/or review of selected IAEA publications, in particular from the IAEA NE Series, assess existing gaps and advise on the preparation of new publications or e-learning materials;
- Upon request, to present to the Standing Advisory Group on Nuclear Energy (SAGNE) the key findings of the TWG meeting; and
- To share experience and advice on increasing the participation of young professionals and improving the gender balance in the nuclear sector

Recommendations from TWG-SMR 2022-2025 term

IAEA

Key recommendations from the 20 members of TWG-SMR

- Addressing standardization on requirements and specifications
- Facilitate suppliers to ensure the supply chain for SMRs in the near term
- Programs to share test facilities for design validation and verification purposes
- Update/improve the NE Series on Technology Roadmap for SMR Deployment
- Develop risk matrix of SMRs technology
- Provide economics indexes compare to present NPPs and other generation sources
- Economic analysis and development of Financing Tools
- Review past studies on non-electrical applications. Organizing issues to be considered in safety point of views
- Approach to evaluate technology readiness level of SMRs
- Safety standards for SMRs and Gen-4 reactors
- … and so forth …

Formulation of 3 Topical Groups in TWG-SMR

Topical Group-1: SMR Technology Roadmap

- ✓ Revision of the NE Series No. NR-T.1.18 on Technology Roadmap for SMR Deployment (2021) for 2025 edition
- ✓ Good practices and approaches to evaluate technology readiness level of advanced reactors and SMRs

Topical Group-2: R&D, Codes & Standards and Operation Preparation

- ✓ Research & Development of Innovative Designs; Codes & Standards for Design and Construction; and Approach and Preparation for Demonstration Operation of SMRs

Topical Group-3: SMR Technology Deployment for Cogeneration

- ✓ SMR Technology Deployment for Cogeneration and Interaction with end-users of various applications of SMRs

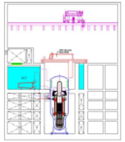
Key IAEA Activities on SMRs

Technology Development and Deployment
- TWG-SMR/GCR
- ARIS Database
- SMR Booklet

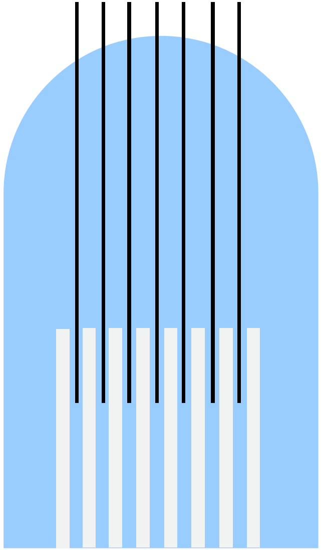
Reactor Technology Assessment
- Updated Method incorporates SMR

Fuel, Safe management of Spent Fuel, Radioactive Waste and Decommissioning

Approaches to Commissioning and Operation
- Issues on the conduct of operation, OLC and MCR for multi-unit plant



Economics
- Economic Appraisal of SMR Projects: Methodologies and Applications



Technical Cooperation for MS Capacity Building

Legal Frameworks for safety, security, safeguards and civil liability for nuclear damage

Safety & Security
- Applicability of Safety Standards and Security Guides
- Emergency Preparedness and Response

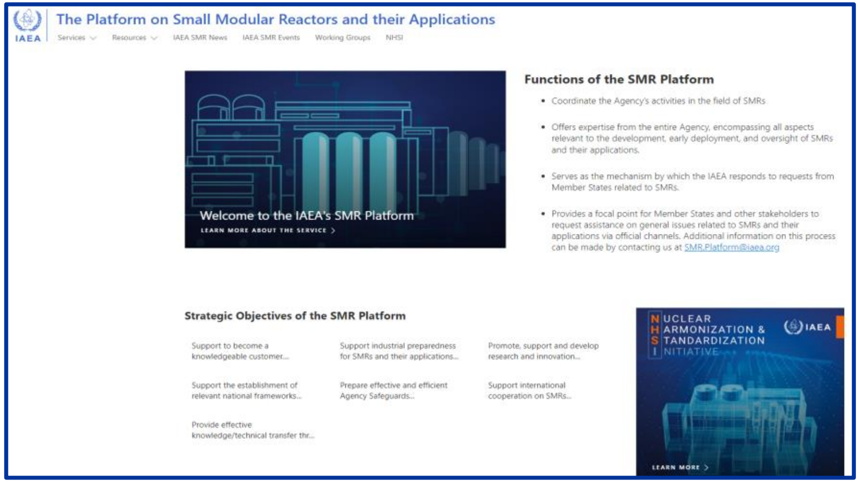
Nuclear Harmonization and Standardization Initiative
- Industry Track
- Regulatory Track

Safeguards-by-Design
- Facilitation of safeguards inspection early in reactor design stage

Infrastructure Development
- IAEA Milestones Approach applicable to SMR
- New deployment models

SMR Platform

- Provides **coordinated support from across the entire Agency on** the development, early deployment, and oversight of SMRs
- **SMR Portal smr.iaea.org** provides latest news, IAEA events, and publications on SMRs



- Enquiries and requests for assistance: **SMR.Platform@iaea.org**

Assistance to address MS requests

- **Expert mission** to review prefeasibility study reports on desalination for Jordan
- **Training** on Reactor Technology Assessment
- Ongoing delivery of support to address **requests from Member States and other stakeholders**
  - Brazil, India, Poland, Venezuela
  - World Association of Nuclear Operators

IAEA
International Atomic Energy Agency


8 December 1953


1 to 23 October 1957


11 December 1957


1959


10 December 2005

1958 to 1979



23 August 1979

Atoms for peace and Development…

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