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Webinar on International Perspectives on SMR (Perspectivas Internacionais dos Reatores de Pequeno Porte - SMR) uma parceria do GESEL com a ABDAN e o Instituto ICT RESEL, 10 March 2022 – Virtual on WebEx

Advances in Small Modular Reactor Technology Developments for Near Term Deployment

Prospects and Challenges

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OUTLINE

- Challenges in the Member States on the Subject
- Driving Factors & Opportunities for SMRs
- SMR: Categorization and First 10 Years of Deployment
- SMR: Major Technology Lines
- Marine-based SMRs and Microreactors
- Advantages, Issues & Challenges
- Issues and Actions for Deployments

Challenges in Countries

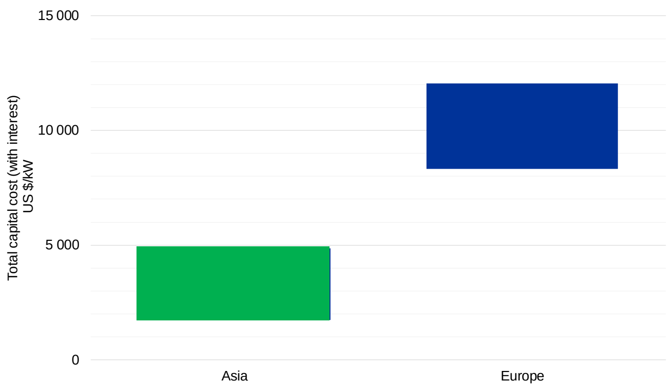
- Unless nuclear energy adapts to the new energy portfolios by being competitive and flexible, expansion of nuclear power will be hard
- Even more significant when the grid capacity and energy distribution is limited, such as in case of several embarking countries
- Dynamic energy market and governments' energy policies to increase share of renewables causes increasing need for NPPs to operate in "flexible" modes(*)
- SMRs and Microreactors will be a part of the nuclear generation from this decade

"Every new NPP is the first NPP for the grid"

(*) i.e. load following, frequency control, or abrupt changes to output upon requests from grid operators

De-risking NPP Newbuild Project

Long construction times, design and manufacturing complexity, and FOAK issues, are reasons behind the high construction costs and delivery times for nuclear newbuild.



Construction cost ranges for recent nuclear newbuild projects in Western Europe (France, Finland and the UK) and Asia (the UAE, Japan, Republic of Korea and China). Source: *Climate Change and Nuclear Power 2020, IAEA.*

Key success factors:

- Robust supply chain
- Simple and proven designs (with an operating 'reference plant');
- Close cooperation with the regulator;
- Sensible, risk informed contracting models;
- Proven contractors with experienced teams;
- 'Lessons learned' from other NPP projects;
- State of the art approaches to project and risk management;
- Reliance on IAEA peer review missions and advisory services

Driving Factors & Opportunities for SMRs

Cost Affordability

Small Power, Innovation, Standardization

Short Construction Span

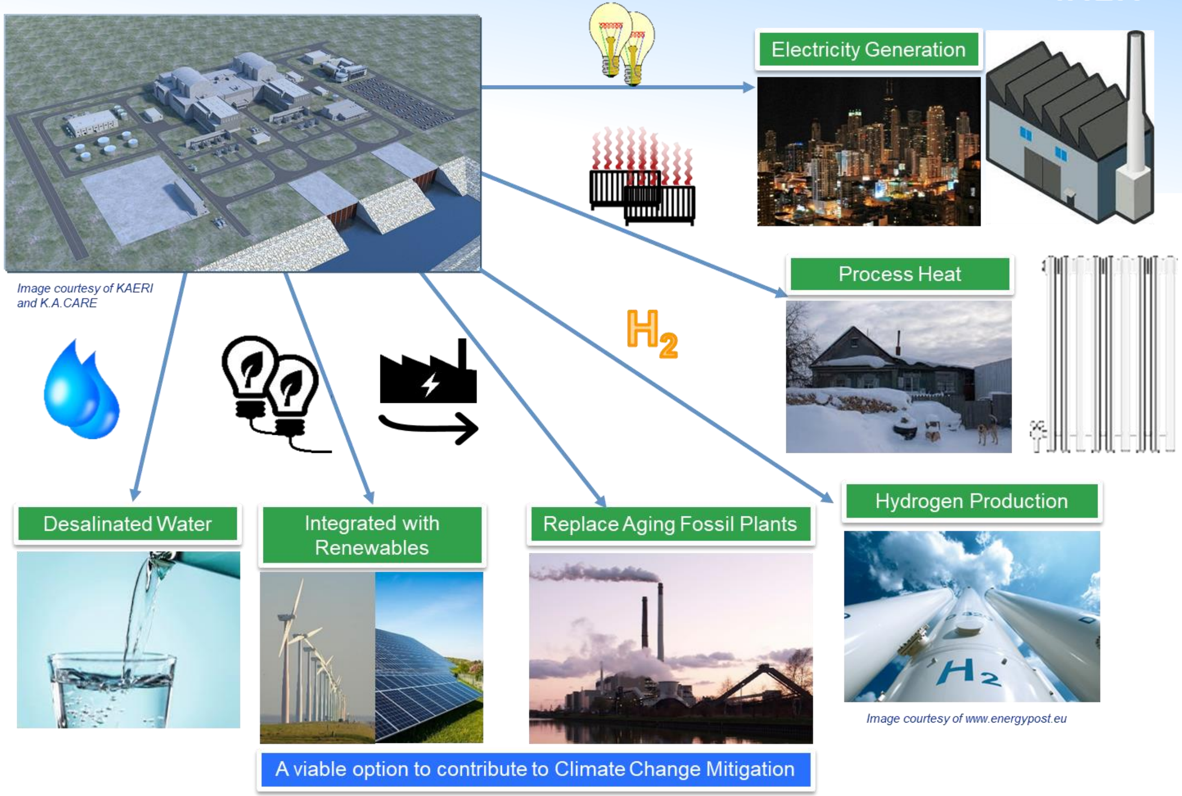
Design Simplification, Modularization

Energy Resilience

Flexibility and ensured energy supply

Energy Sustainability

Hybrid with Renewables,
Replace Retiring Fossil Plants



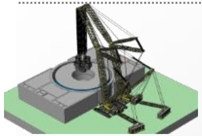
Typically up to 300 MWe, High Degree of Modularity, Option to Energy Supply in Countries with Smaller Grids; Contribute to Climate Change Mitigation

Development Objectives of Small Modular Reactors

- 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

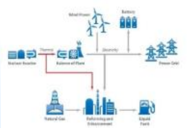
Wider range of Users

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
First-of-a-Kind Technology Risks
Time and cost of getting to market and/or proven technology
Newcomers need Reference Plant
National programmatic cost for newcomers vs project cost for the unit
Regulatory preparedness to license FOAK and/or advanced designs
Prediction of the level of demand, generating cost versus alternative ($)
Which funding and financing models?

Key Drivers for SMRs
Shorter construction period ($)
Design simplification thru standardization
Modularization, factory construction and enhanced transportability
Lower upfront capital cost ($)
Smaller site footprint
Scalability through multi-module ($)
Non-Electric Apps, grid suitability and flexible operation

A categorization of SMR Technology

SMR: Major Lines of Technology

- Land Based Water-Cooled Reactors
- Marine Based Water-Cooled Reactors
- Liquid Metal-cooled Fast Neutron Reactors
- **Micro Reactors**
- Molten Salt Reactors
- High Temperature Gas-Cooled Reactors

First 10-year Deployment Horizon

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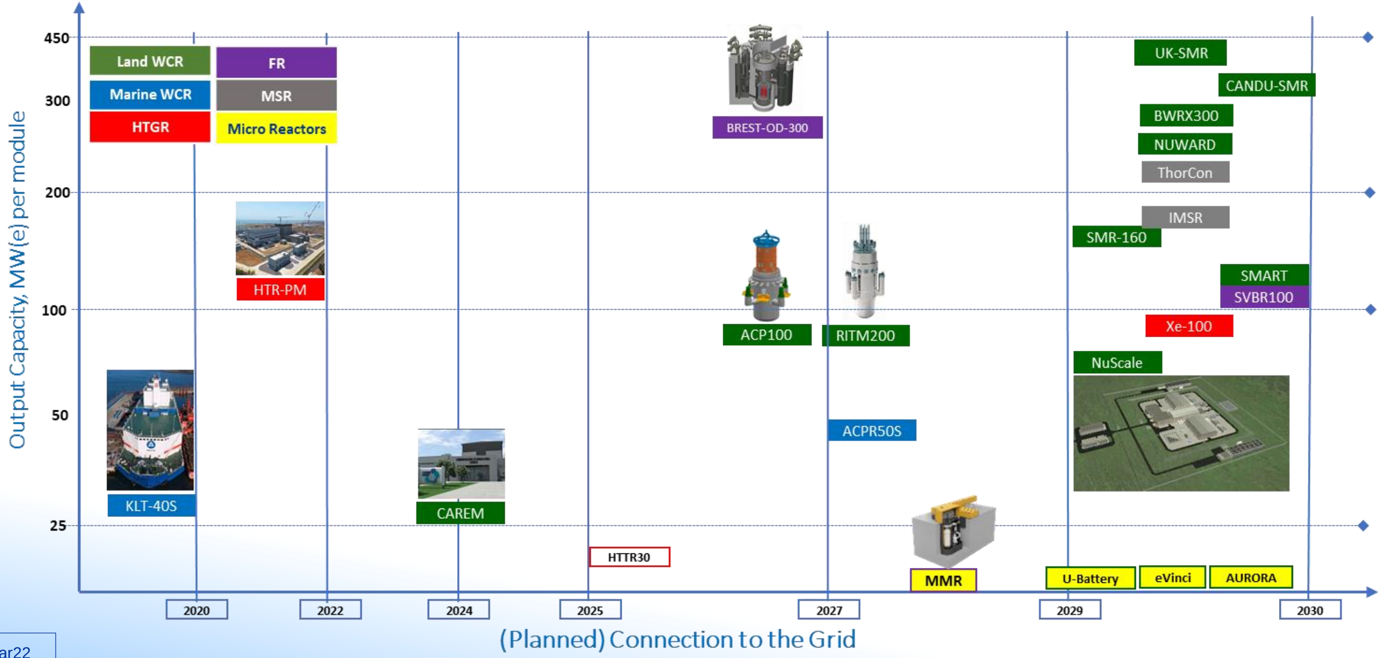
The four (4) SMR Forerunners: 2 in operation, 2 under construction

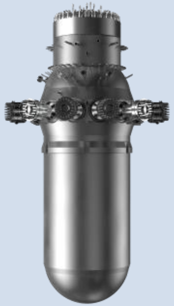
KLT-40S in **operation,** Dec 2019

HTR-PM **in operation, Dec 2021**

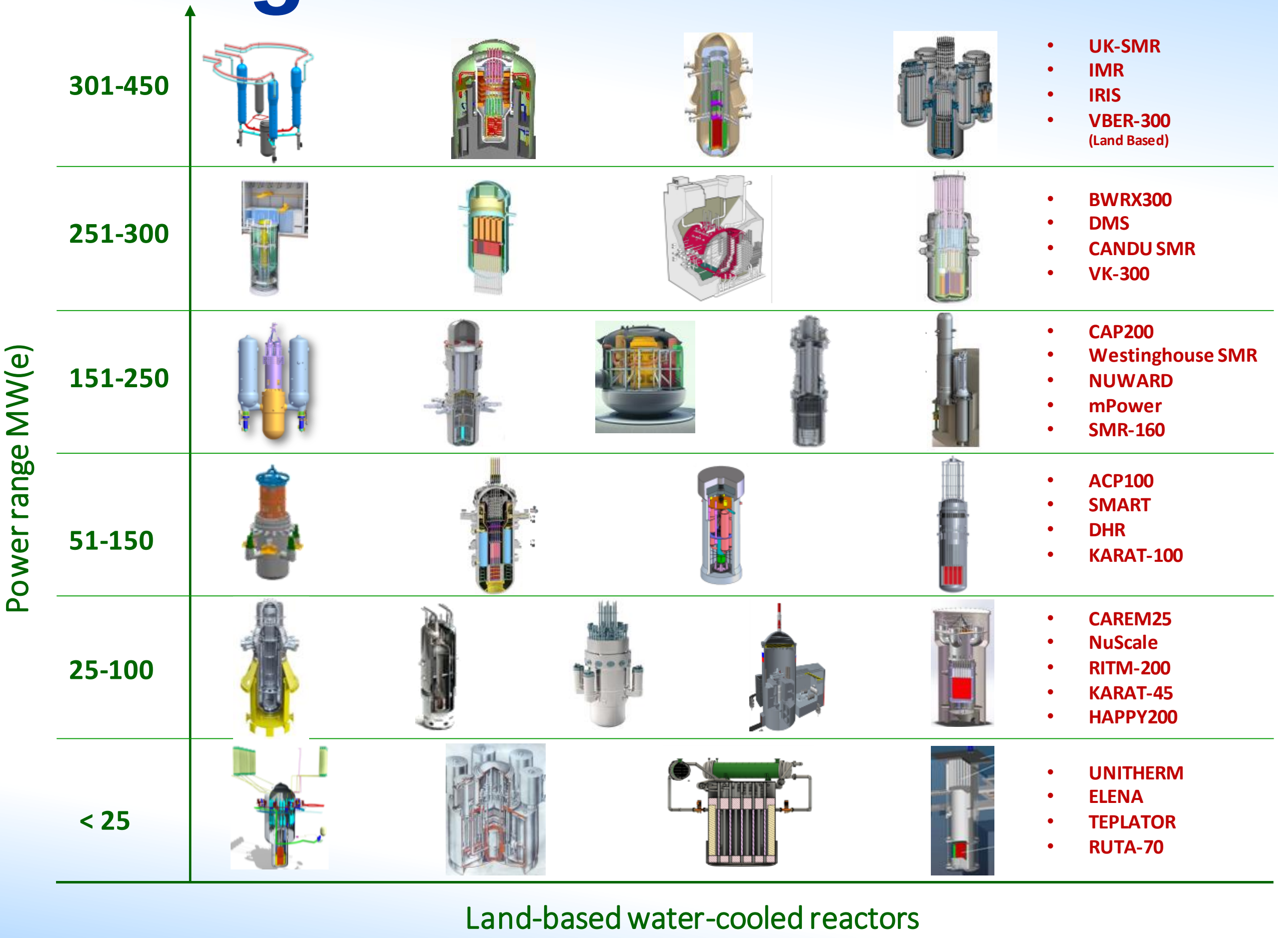
CAREM to start **operation in 2023**



LWR-type SMRs (Examples)

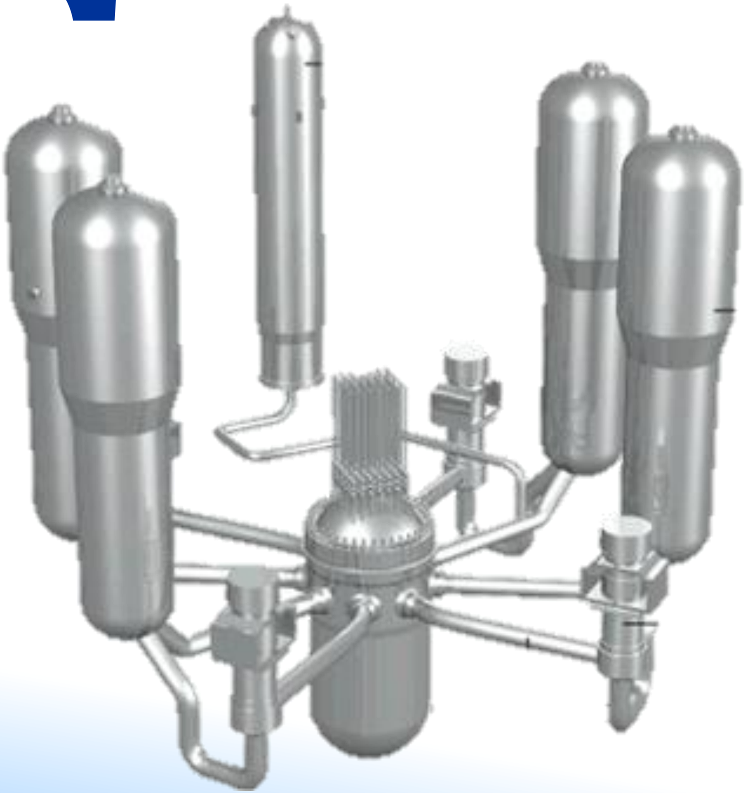
CAREM	ACP100	NUWARD	SMART	NuScale	BWRX-300
					
Design Status: Advanced stage of construction in Atucha site, Argentina	Design Status: Received license for construction in July 2019; site excavation for FCD in 2021	Design Status: Conceptual design; Consortium launched in September 2019	Design Status: 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

$\int$ (2000 – 4500) MWth



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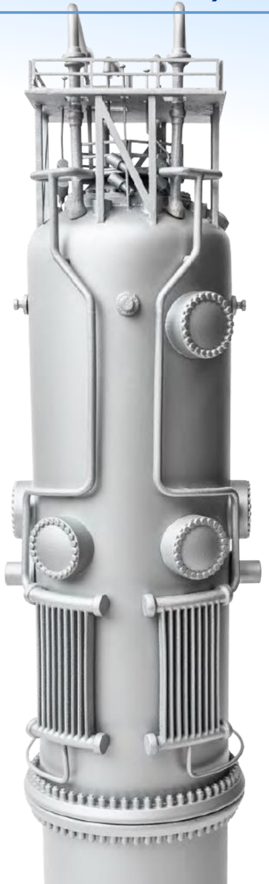
(100 – 1000) MWth



iPWRs: Safety Advantages & Challenges

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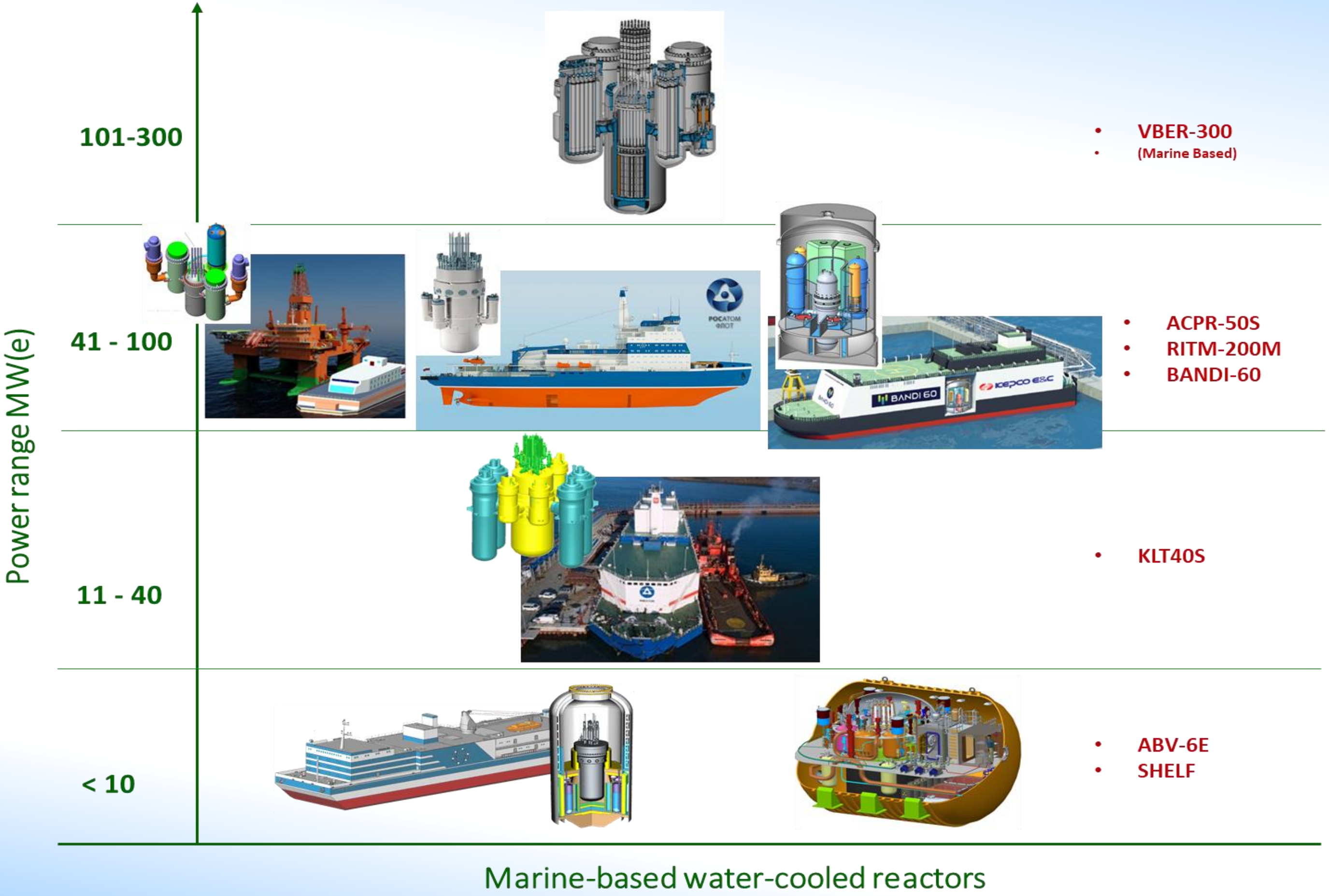
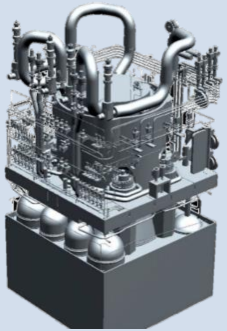
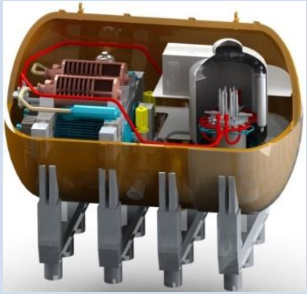
Advantages	Issues / Challenges
No large piping connected to RPV → No Large-LOCA	Increased numbers of small-bore piping connections to the RPV
Coolant Pumps connected to RPV → Reduced leakage probability	Structural strength of RPV and joints; mechanical vibration; flow stability
Internal Control Rod Drive 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



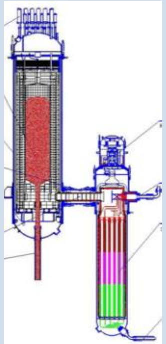
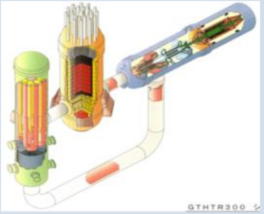
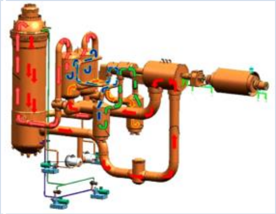
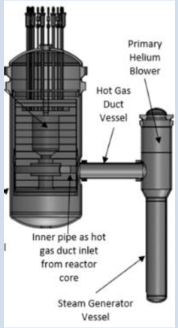
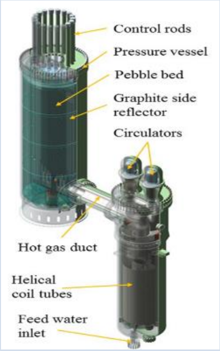
Marine-Based SMRs (Examples)

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: 316^{o}C • 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: 318^{o}C • 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: 321.8^{o}C • 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: 310^{o}C • Enrichment: 19.7% • Refuel interval: 6 years (8 for SHELF-M) • Without onsite refuelling • Spent fuel take back

Market Potential of Marine-based SMRs

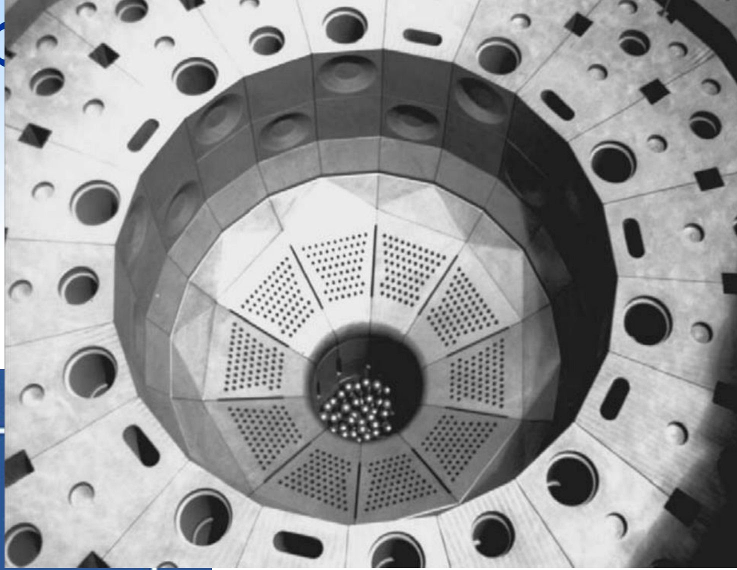
- East and South-East Asia
  - high seismicity and tsunami risk, high coastal population density, and limited domestic energy resources
- Middle East
  - Massive water desalination plants
- Africa and South America
  - small grids, high prices of electricity, water desalination, no incentives to develop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

HTGR-type SMRs (Examples)

HTR-PM (China)	SC-HTGR (France)	GTHTR300 (Japan)	PBMR-400 (South Africa)	Xe-100 (X Energy, United States)
				
Design Status: Achieved first criticality on 13 Sept 2021 in Shidao Bay, planned grid connection by end of 2021	Design Status: Conceptual Design	Design Status: Pre-Licensing; Basic Design Completed	Design Status: Preliminary Design Completed, Test Facilities Demonstration	Design Status: 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

Design Example 2: Pebble-b 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



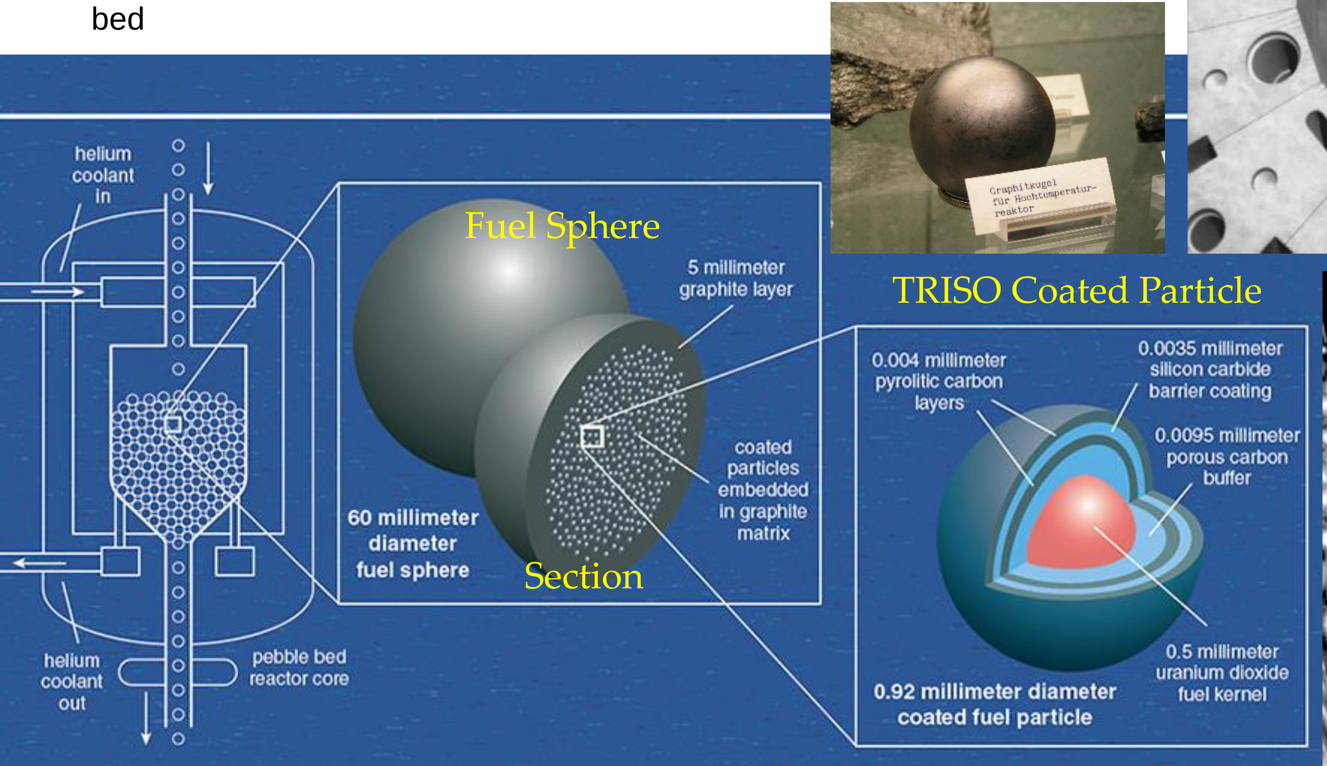
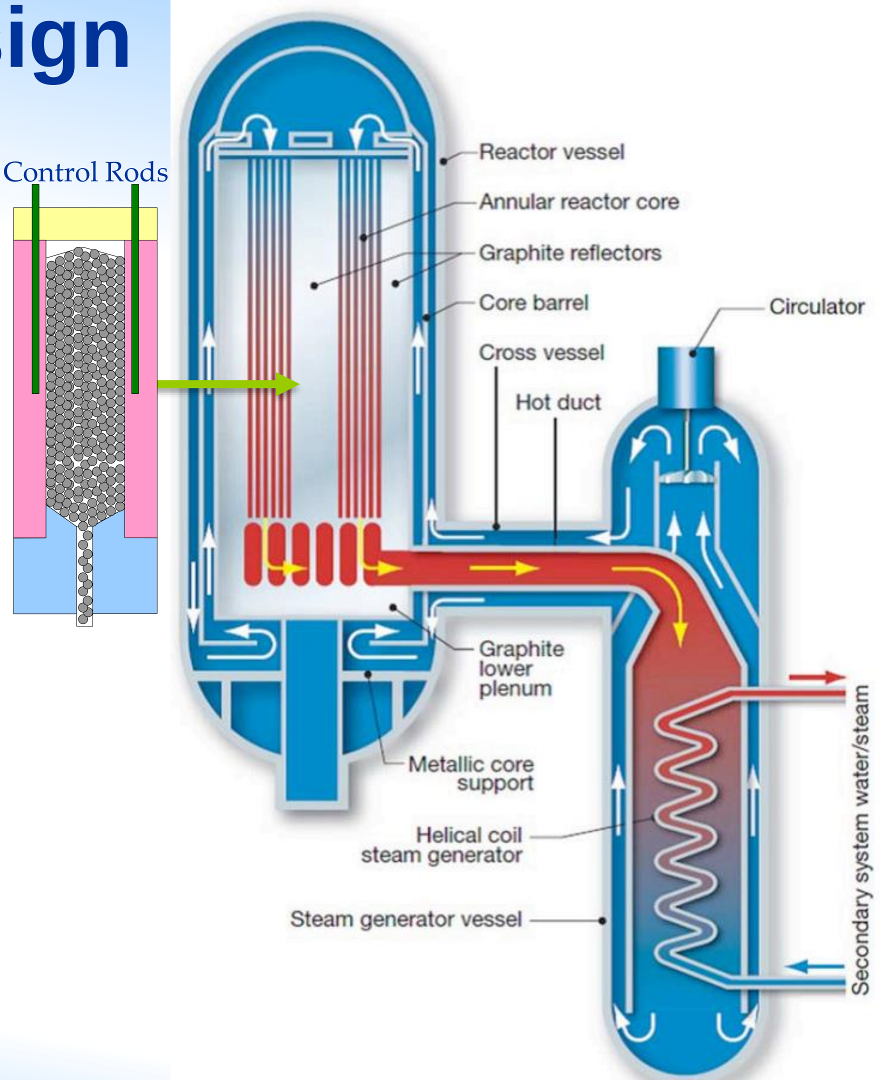


Image: American Scientist, HTR-10, THTR

Pebble-bed Reactor design parameters

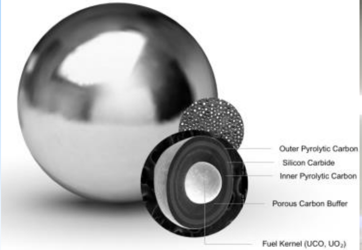
Example: HTR-PM Parameters

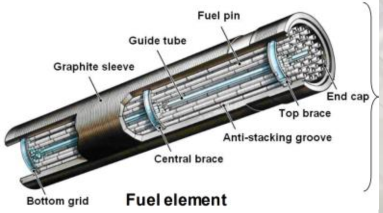
Plant electrical power, MWe	210
Core thermal power, MW (one module)	250
Number of NSSS Modules	2
Core diameter, m	3
Core height, m	11
Primary helium pressure, MPa	7
Core outlet temperature, °C	750
Core inlet temperature, °C	250
Fuel enrichment, %	8.5
Steam pressure at turbine, Mpa	13.25
Steam temperature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



HTGR – Benefits

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

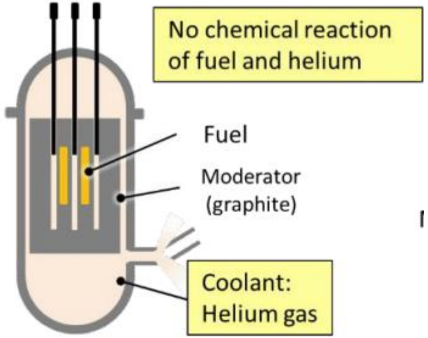




- Very different from first generation gas cooled graphite moderated reactors
  - Different fuel type (coated particle) – retain radioactive material at 1600 °C
  - Different coolant (Helium) – stable at high temperatures
  - (similar) Graphite core structure – high thermal inertia

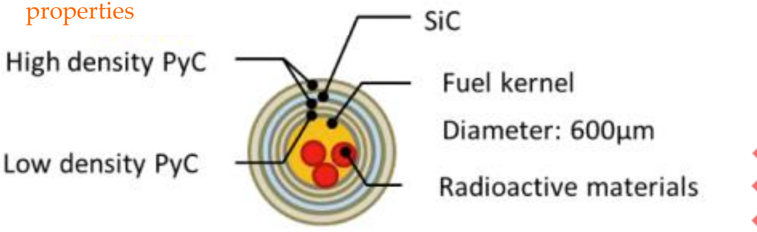
Image: X-energy, JAEA, Wikipedia

Chemically inert



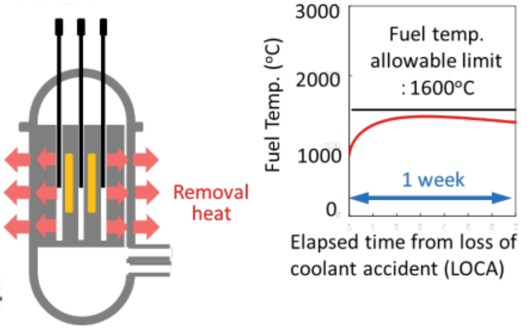
In case of vapor or air ingress accident, the surface of graphite oxidizes but safety of the core never be lost

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. $\Phi 6.7$ 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

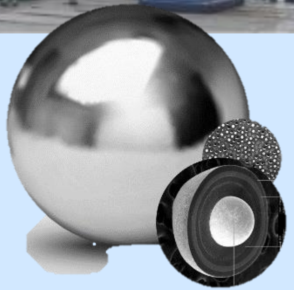
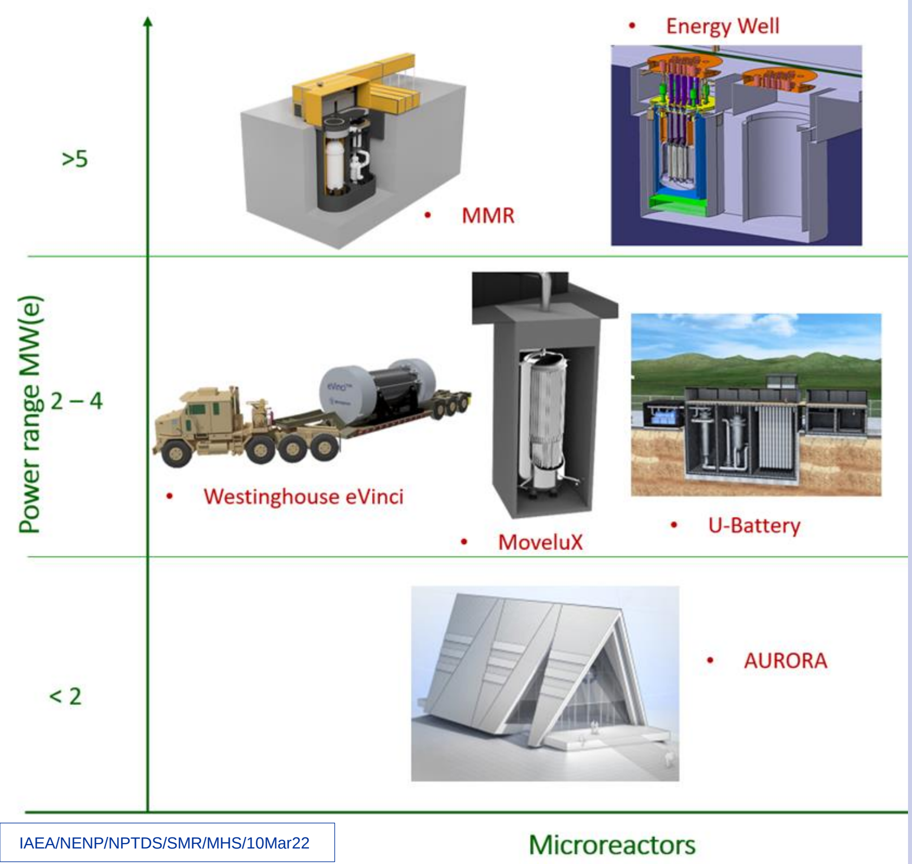


Image: HTR=PM, X-energy

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

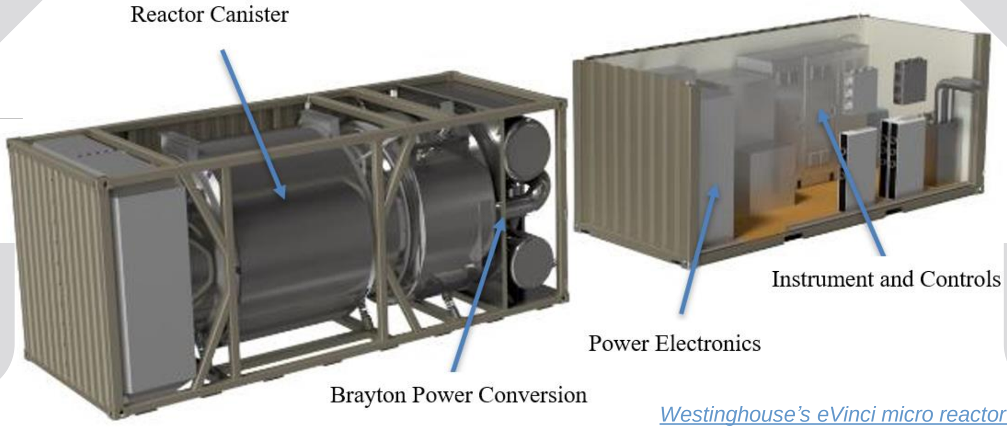
Manufactured and fueled in a factory

01

Specifically designed to serve
- Remote communities;
- Mining operations; or
- military installations.

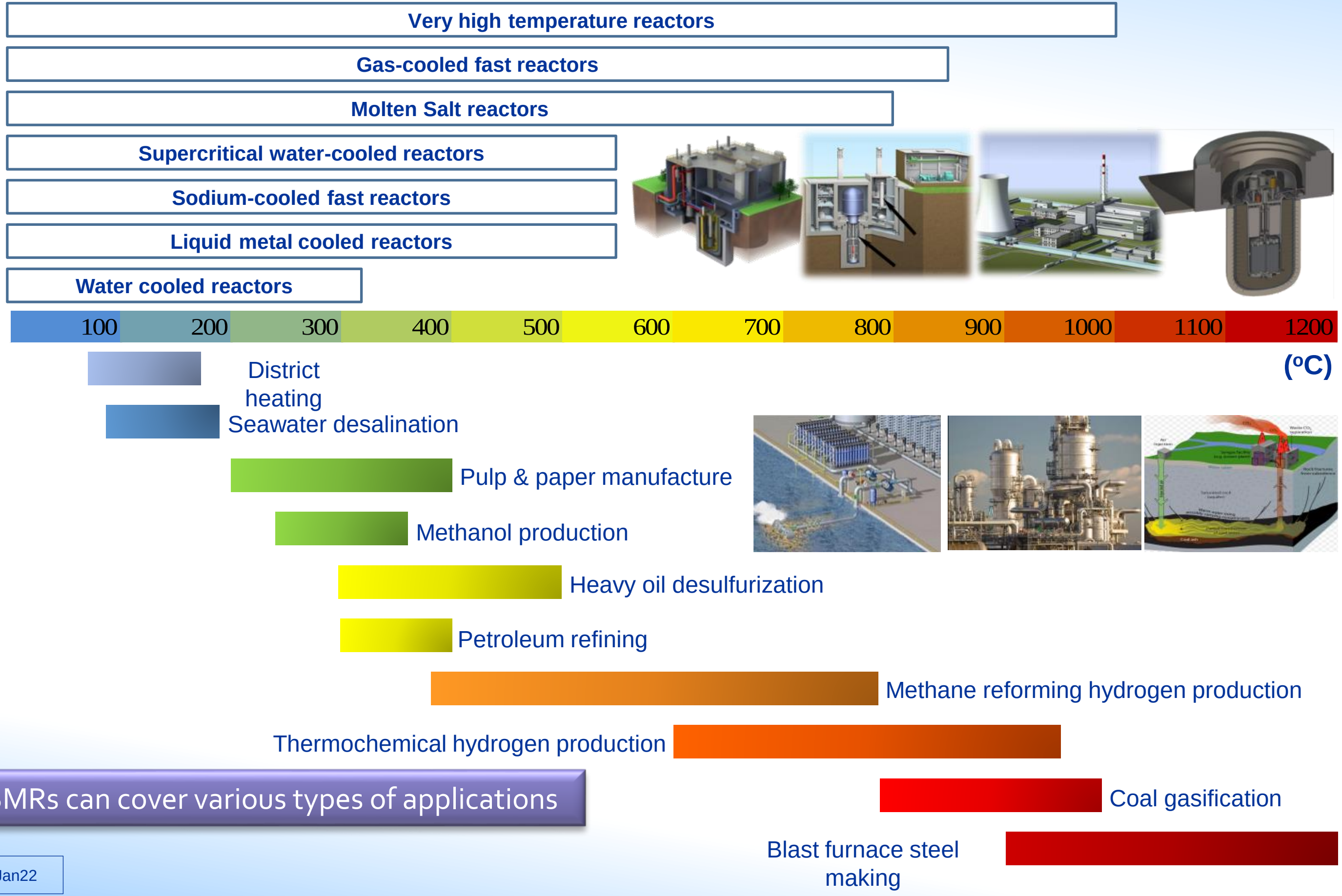
07

Packageable
in standard transport containers



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

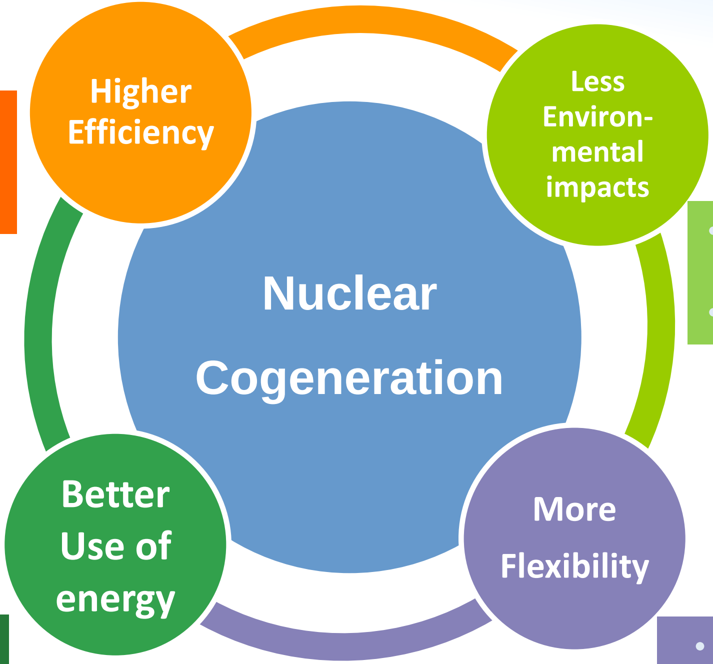
SMR for Non-Electric Applications



Wide spectrum of SMRs can cover various types of applications

Values of Nuclear Cogeneration

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



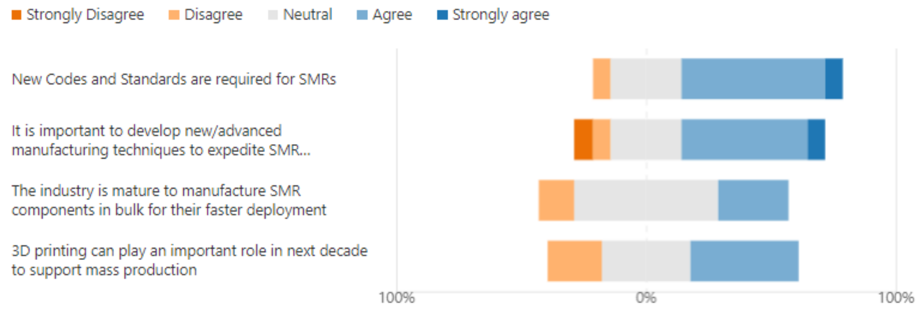
- Reduce the waste heat dumped to environment
- Additional heat sink

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

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

Codes and Standards for SMRs

- Key discussion points:
  - Are the existing international nuclear codes and standards adequate to facilitate the development and licensing of SMR technologies worldwide?
  - What are the key issues, prospects and impediments on design engineering, manufacturing process and technology qualification of novel components for SMRs?
  - How can SMR industries learn from other industrial sectors to support a diversified/ larger supply chain and enable factory modular construction?
  - What significant changes are foreseen for In-Service Inspection (ISI) and component In-Service Testing (IST) for SMRs compared to existing large reactors?



Experts' Survey result

Codes & Standards – Applicability to SMRs

Key Advantage #1: Enabling Design Simplification

- Minimized number of systems and components without compromising safety;
- Simplification to improve economics, maintainability and availability of components – without compromising safety.

Key Advantage #2: Confirm a robust supply chain:

- Assure ‘diverse’ supply for replacement by manufacturers other than the original manufacturers;
- Improve the assurance of sustainable operation of the nuclear power plant.

Findings on Standardization:

- Standardization alone will not solve all issues in advanced reactor product development;
- *Excellence* in applying *advanced manufacturing* and *NDE techniques* are often proprietary; not readily shareable or standardized because it would benefit competitors
- The biggest challenge to quality product is to having the capability of designing, manufacturing and delivering, within time and budget, products that meet the requirements

SMR Development should increasingly apply codification and standardization of Advanced Manufacturing Techniques to realize high degree of Modularity

Advantages, Issues & Challenges

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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

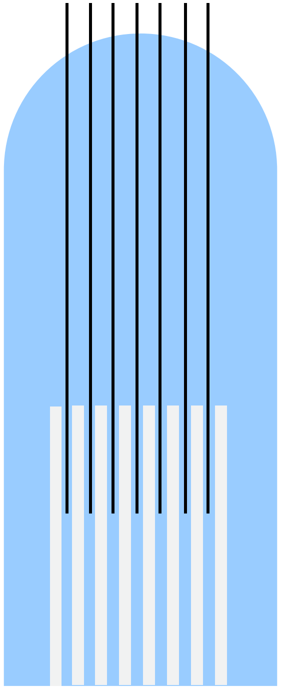
IAEA Activities on SMRs (key examples)

Development and Deployment Status
- ARIS Database
- SMR Booklet

Technology Roadmap
- Provide Member States with ‘model’ technology roadmaps for specific SMR projects

Economics
- Economic Appraisal of SMR Projects: Methodologies and Applications

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



Infrastructure Development
- The IAEA Milestones Approach applicable to SMR
- Integrated Work Plan for Embarking Countries

Safety
- SMR Regulators’ Forum
- Applicability of the IAEA Safety Standards to SMRs

Generic User Requirements and Criteria

- key policy of Member State on the expectations of its users on SMR technology

Reactor Technology Assessment
- Updated Method incorporate SMR

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!

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