GEN IV International Forum℠

OVERVIEW OF SMALL MODULAR REACTOR TECHNOLOGY DEVELOPMENT

Mr. Frederik Reitsma
IAEA

29 July 2020

Meet the Presenter

Mr. Frederik Reitsma…. is the Team Leader for SMRs in the Nuclear Power Technology Development Section of the International Atomic Energy Agency (IAEA) in Vienna. He joined the IAEA nearly 7 years ago and manages, coordinates and supervises the projects in this area. He provides technical and programme leadership by identifying key future trends and technology development needs in cooperation with Member States. Before he was head of the High Temperature Gas Cooled Reactor project.
Frederik holds a master's degree in Reactor Science and has published more than 90 papers. He has been invited as a speaker to many international workshops and conferences and led several international cooperation projects (such as OECD/NEA and GIF). He is a reactor physicist by training with extensive experience in SMRs and HTGRs nuclear engineering and analysis with core neutronics design and safety as focus areas. He worked on the South African PBMR project in different leadership positions for 13 years. For the first 10 years of his career, he contributed to the OSCAR reactor calculational system development and performed cycle and reload analysis.

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IAEA
International Atomic Energy Agency
Atoms for Peace and Development

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BIG or small

What would you want for breakfast?

Economy of scale

Economy of multiples

What is the best?

It depends .....

Small Modular Reactor Technology Development

- The International Atomic Energy Agency (IAEA)
- What is SMRs?
- Specific Characteristics
- Flexible application
- Economics
- Challenges to deployment
- Conclusions

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IAEA

International Atomic Energy Agency

Atoms for Peace and Development

The IAEA

Established in 1957

171 Member States

~ 2,560 multidisciplinary professional and support staff from more than 100 countries

ATOMS FOR PEACE AND DEVELOPMENT

- Article II of the IAEA Statute (Objectives): *The Agency shall seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world*
- Article III of the IAEA Statute (Functions): *The Agency is authorised to encourage and assist research on, and development and practical application of, atomic energy for peaceful uses throughout the world…*

International Atomic Energy Agency

UN's scientific forum for cooperation in the nuclear field
maximizing contribution of nuclear technology to the world, while verifying its peaceful use

ORGANIZATIONAL STRUCTURE

Offices Reporting to the Director General

- Management
- Technical Cooperation
- Nuclear Energy
- Nuclear Safety and Security
- Nuclear Sciences and Applications
- Safeguards

6 Departments

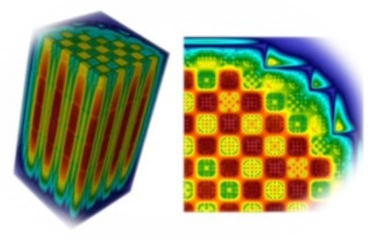
Fosters sustainable nuclear energy development by supporting existing and new nuclear programmes and provides technical support on the nuclear fuel cycle and the life cycle of nuclear facilities

- Nuclear Power Engineering Section
- Nuclear Infrastructure Development Section
- Nuclear Power Technology Development Section
- International Project on Innovative Nuclear Reactors and Fuel Cycle Section

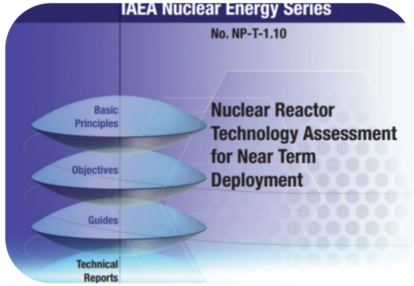
Macro Areas for Each Reactor Line and Non-Electric Applications

Assist MSs with national nuclear programmes; Support innovations in nuclear power deployment; Facilitate and assist international R&D collaborations

Information Exchange



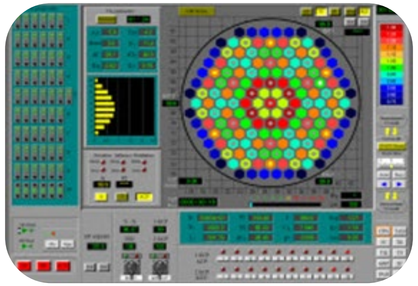
Modelling and Simulations



Development of Methodologies

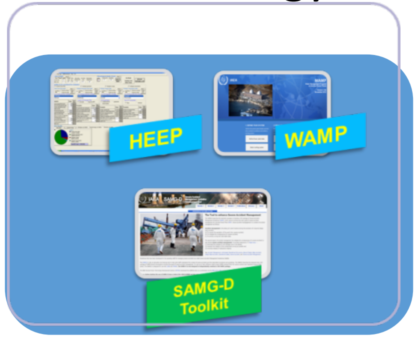
Safety - Technology

Technology Support



Education and Training

Knowledge Preservation



Tool-kits

Embarking Countries interested in SMR and IAEA support

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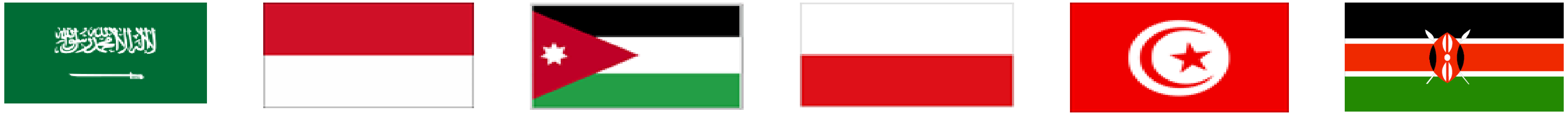
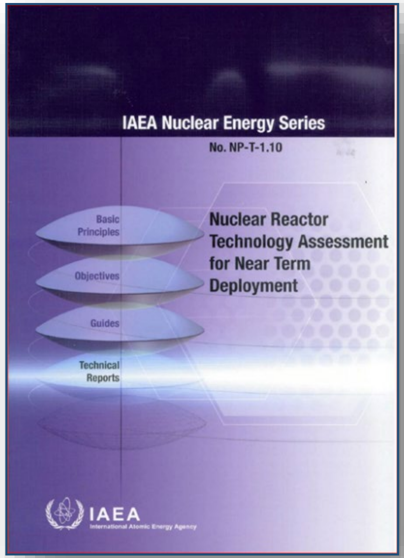


Reactor Technology Assessment



IAEA

TOOLKIT FOR REACTOR TECHNOLOGY ASSESSMENT

Developed by the Nuclear Power Technology Development Section

Division of Nuclear Power, Department of Nuclear Energy

INTERNATIONAL ATOMIC ENERGY AGENCY

* Form completed: 2019-05-30

EVALUATOR INFORMATION

Name

Organisation/Country

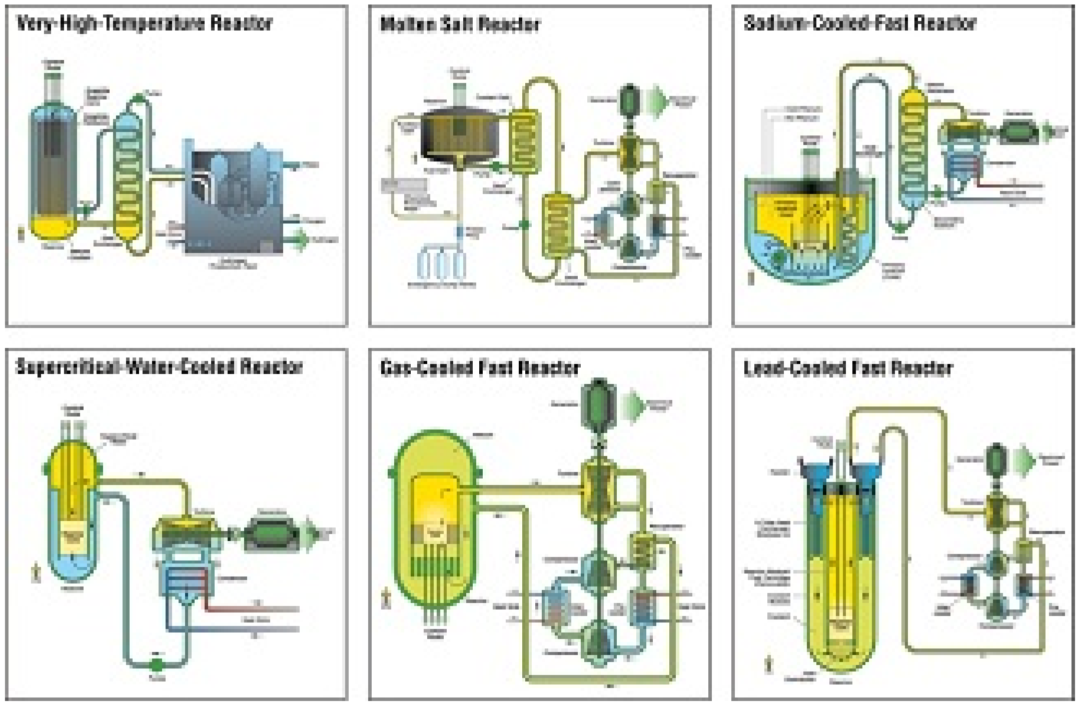
Go Next

- IAEA RTA methodology is under revision
- New Toolkit framework is developed to help embarking countries in applying the IAEA RTA methodology

IAEA-GIF Interface

- Avoid duplication and cooperate in all areas:
  - The six systems
  - Risk & Safety Working Group
  - Proliferation Resistance & Physical Protection Working Group
  - Economics

- Yearly interface meeting to coordinate activities



What is SMRs

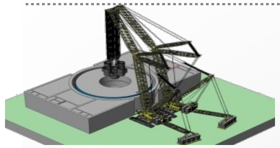
Small Modular Reactors (What is it?)

Advanced NPP that produces up to 300 MW(e). Individual modules built in factories and transported to sites for installation as demand arises.

A nuclear option to meet the need for flexible power generation for a wide range of users and 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

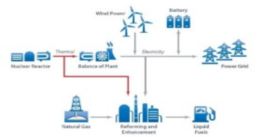
Wider range of Users

Smaller footprint
- Reduced Emergency planning zone

Site flexibility

Replacement for aging fossil-fired plants

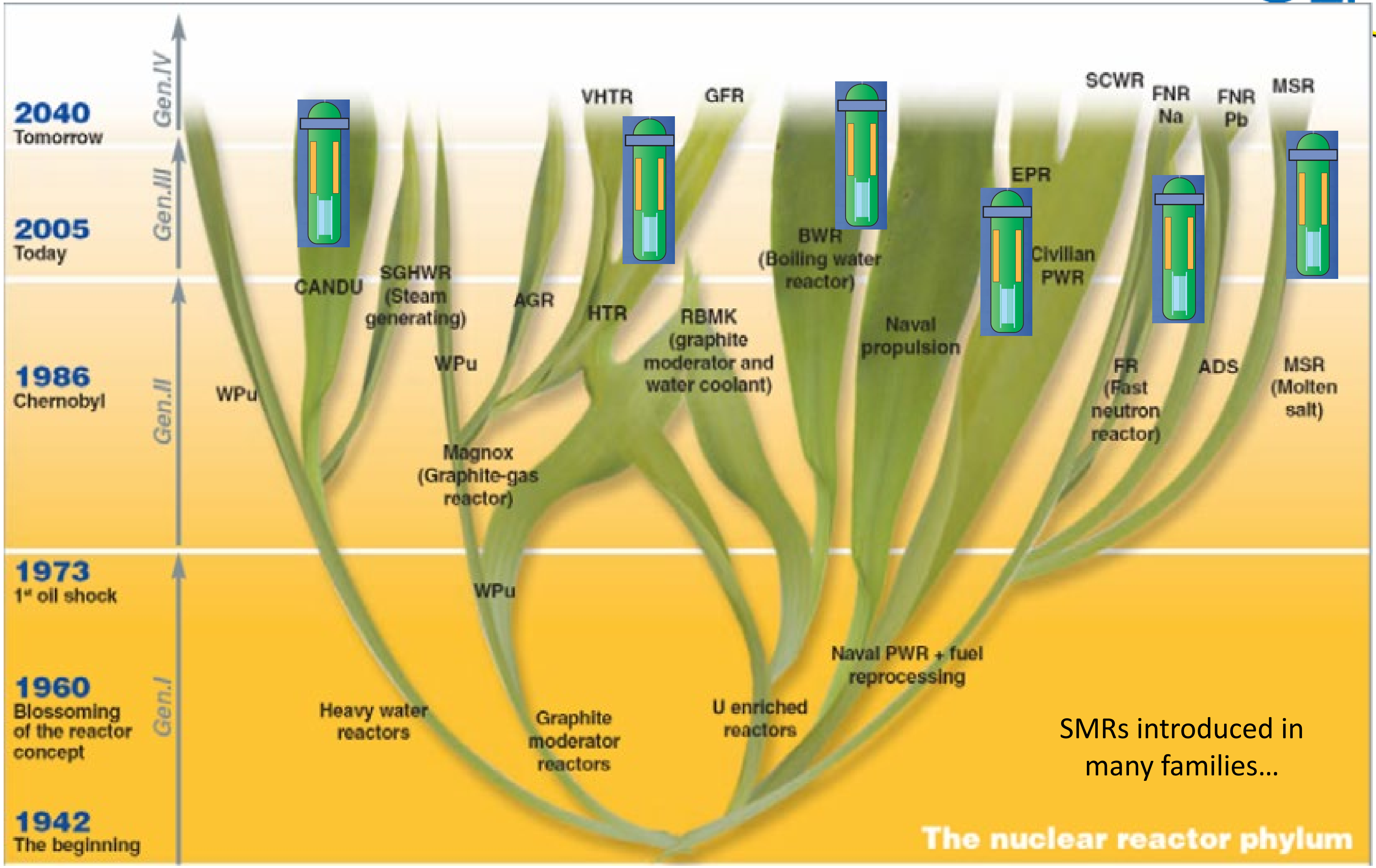
Reduced CO_2 production



Potential Hybrid Energy System

Integration with Renewables

Reactor Classification through Decades of Development:
Nuclear Tree



http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/44/078/44078364.pdf

Salient Design Characteristics

Simplification by Modularization and System Integration

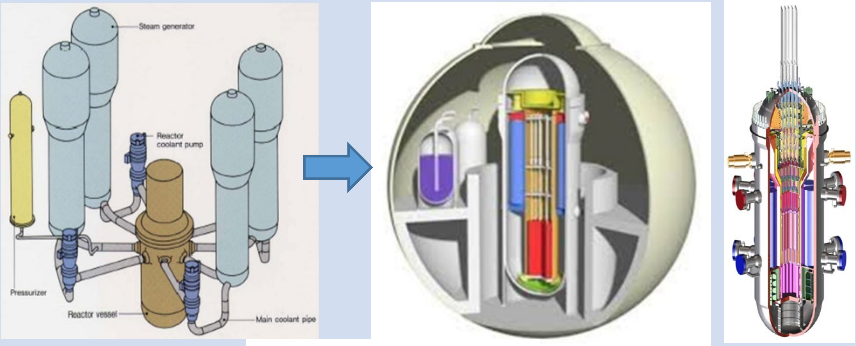


Image courtesy of IRIS 7 .

Multi-module Plant Layout Configuration

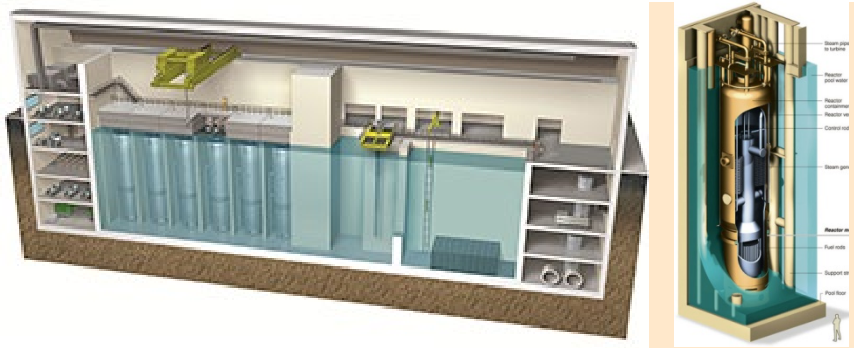


Image courtesy of NuScale Power Inc.

Underground construction for enhanced security and seismic

Image courtesy of BWX Technology, Inc.

Enhanced Safety Performance through Passive System

- Enhanced severe accident features
- Passive containment cooling system
- Pressure suppression containment

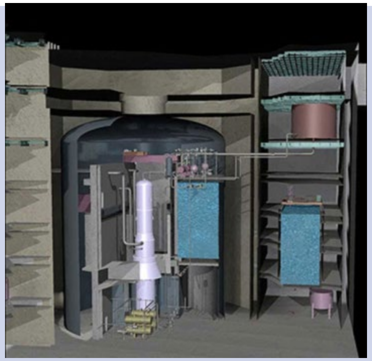


Image courtesy of BWX Technology, Inc.

SMRs deployed and under construction

KLT-40S: Rosatom OKBM Afrikantov, Russian Federation

The FNPP arrived at its final mooring in the city of Pevek, Chukotka Automomous Region in mid-September. The **Akademik-Lomonosov Floating NPP** with 2 modules of **KLT-40S** were connected to the grid and provided first electricity on 19 December 2019. Commercial operation since May 2020.

KLT-40S is a compact-PWR to produce 35 MW(e) per module.

HTR-PM: Institute of Nuclear Energy Technology (INET), China

Civil construction of **HTR-PM** in the Shidao Bay site is completed, the two reactor pressure vessels were installed in 2016, and the two steam-generators hoisted in-place in July 2019. It targets initial criticality in 2021 with commercial demonstration to follow.

The **HTR-PM** is a Modular Pebble bed High Temperature Gas-cooled Reactor to produce 210 MW(e) from 2 modules of 250 MW(th).

CAREM25: CNEA, Argentina

CAREM25 is being constructed at the site of Atucha-II NPP. Initially it aims to start operations in 2023. Despite recent project delays due to funding from the government the project is back on track.

CAREM-25 is an integral-PWR to produce 27 MW(e), adopting advanced features that include an integral primary cooling system using natural circulation, in-vessel hydraulic control rod drive mechanisms and fully passive safety systems.

SMR Designs around the World

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Land Based Water Cooled Reactors

CAREM	SMART	RUTA-70	DHR400
ACP100	UNITHERM	NuScale	RITM-200
CAP200	VK-300	mPOWER	NUWARD
IRIS	KARAT-45	W-SMR	BWRX-300
DMS	KARAT-100	SMR-160	HAPPY200
IMR	ELENA	UK-SMR	CANDU SMR

Micro Reactors

IHTR	MMR-5
IMSBR	MMR-10
eVinci	AURORA
U-Battery	MoveluX

Fast Reactors

4S	W-LFR	SSTAR LFR
BREST-OD-300	SEALER	URANUS
SVBR-100	LFR-AS-200	ARC100
EM^2	LFR-TL-X	

High Temperature Gas-cooled Reactors

HTR-PM	MHR-100	XE-100	HTTR-30
DPP-200	PBMR-400	A-HTR 100	HTR-10
GT-MHR	HTMR-100	MMR	RDE
MHR-T	SC-HTGR	GTHTR300	StarCore

Marine Based Water Cooled Reactors

ACPR50S	VBER-300
KLT-40S	ABV-6E
RITM-200M	SHELF

Molten Salt Reactor

IMSR	SSR-WB	CA WB
CMSR	SSR-TS	KP-FHR
THORCON	LFTR REACTOR	MCSFR
FUJI ITMSF	MK1 PB-FHR	

IAEA SMR Booklet

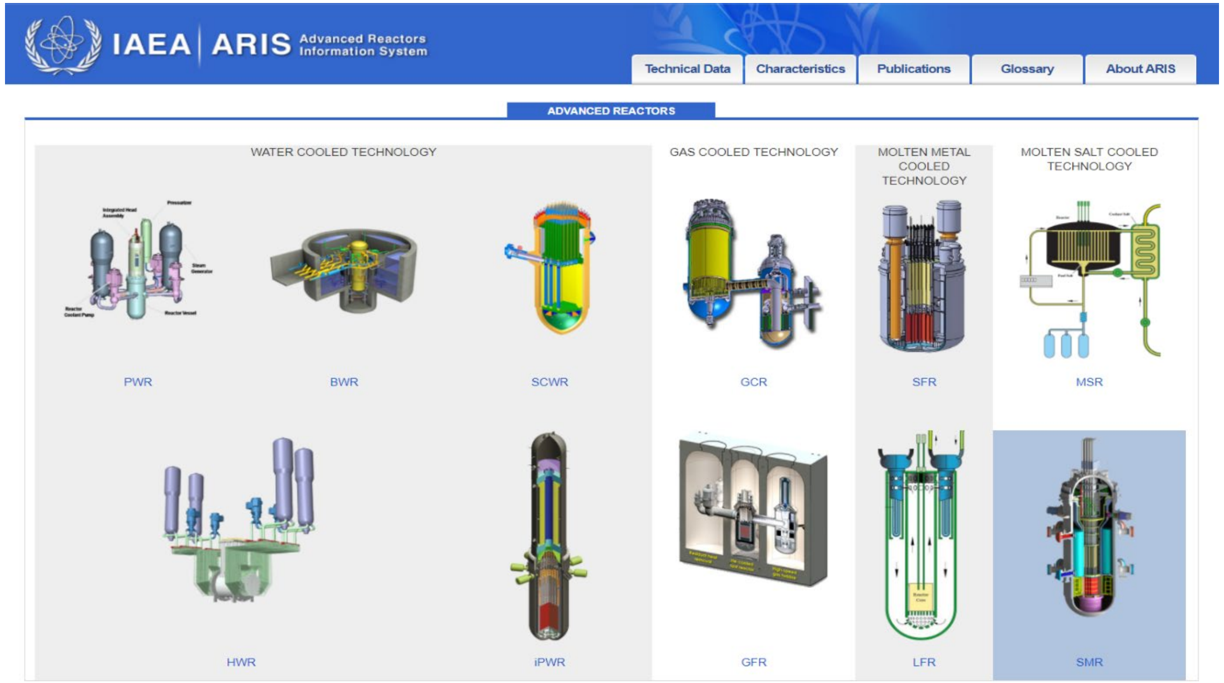
The booklet contains information provided by vendors and designers on their SMRs

2018 Edition

- SMRs are categorized in types based on coolant type/neutron spectrum:
  - Land Based WCRs
  - Marine Based WCRs
  - HTGRs
  - Fast Reactors
  - MSRs
  - Micro reactors
  - Test reactors (to be included with the types above as applicable)

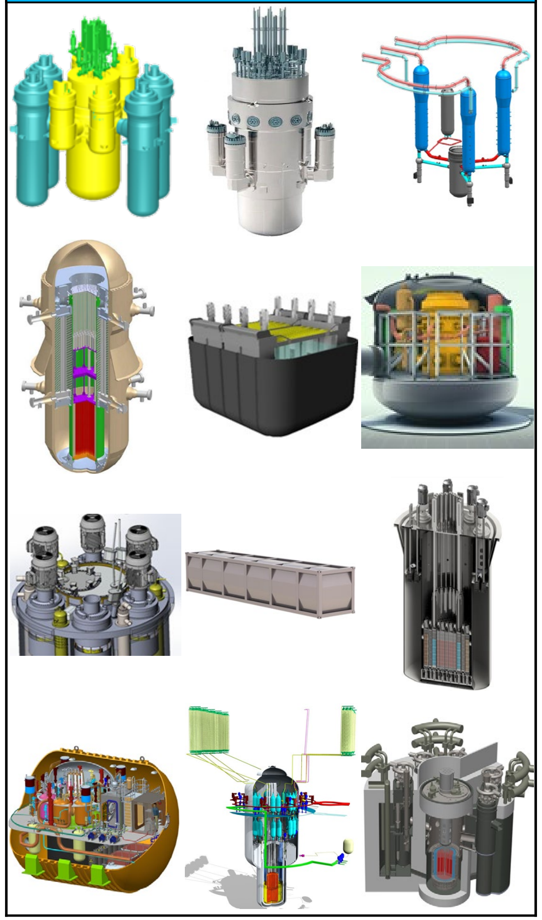
- Design description and main features of ~70 SMR designs being updated (56 in 2018)
- Include information on fuel cycle, decommissioning and final disposal (for the first time)

IAEA ARIS Database Includes SMR Designs

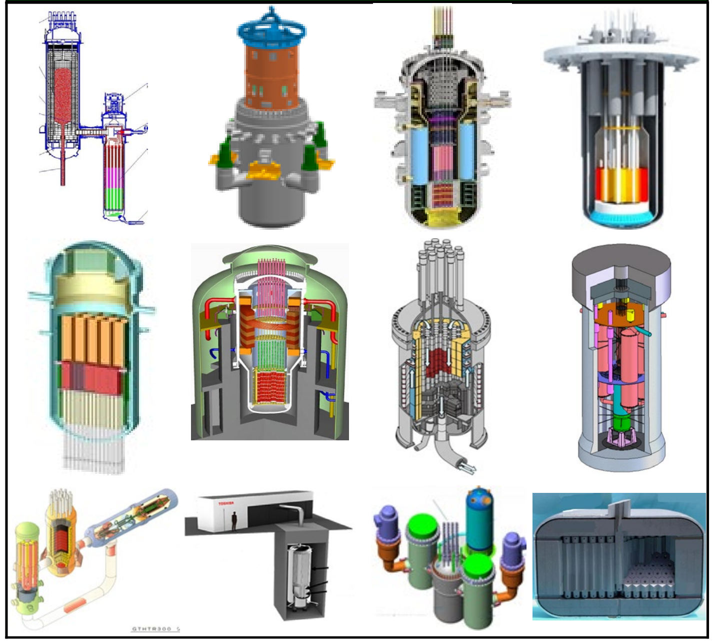


SMR Designs Across the World's Regions

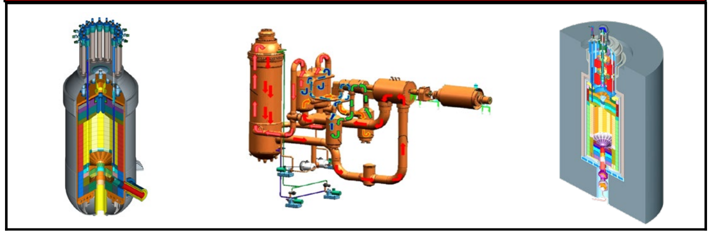
Europe, United Kingdom and Russian Federation



Asia



Africa



North America and South America

More than 70 designs of all major types in different stage of design development

SDGs & Paris Agreement

Sustainable Development Goals

Potential for NP in Future Energy System

08.10.2018_No199 / News in Brief

Major UN Climate Change Report Outlines Key Role For Nuclear

Policies & Politics

8 Oct (NucNet): The world's leading climate scientists have warned there is only a dozen years for global warming to be kept to a maximum of 1.5C, beyond which even half a degree will significantly worsen the risks of drought, floods, extreme heat and poverty for hundreds of millions of people.

The authors of the landmark report by the UN Intergovernmental Panel on Climate Change (IPCC) released today say urgent and unprecedented changes are needed to reach the target, which they say is affordable and feasible although it lies at the most ambitious end of the Paris agreement pledge to keep temperatures between 1.5C and 2C.

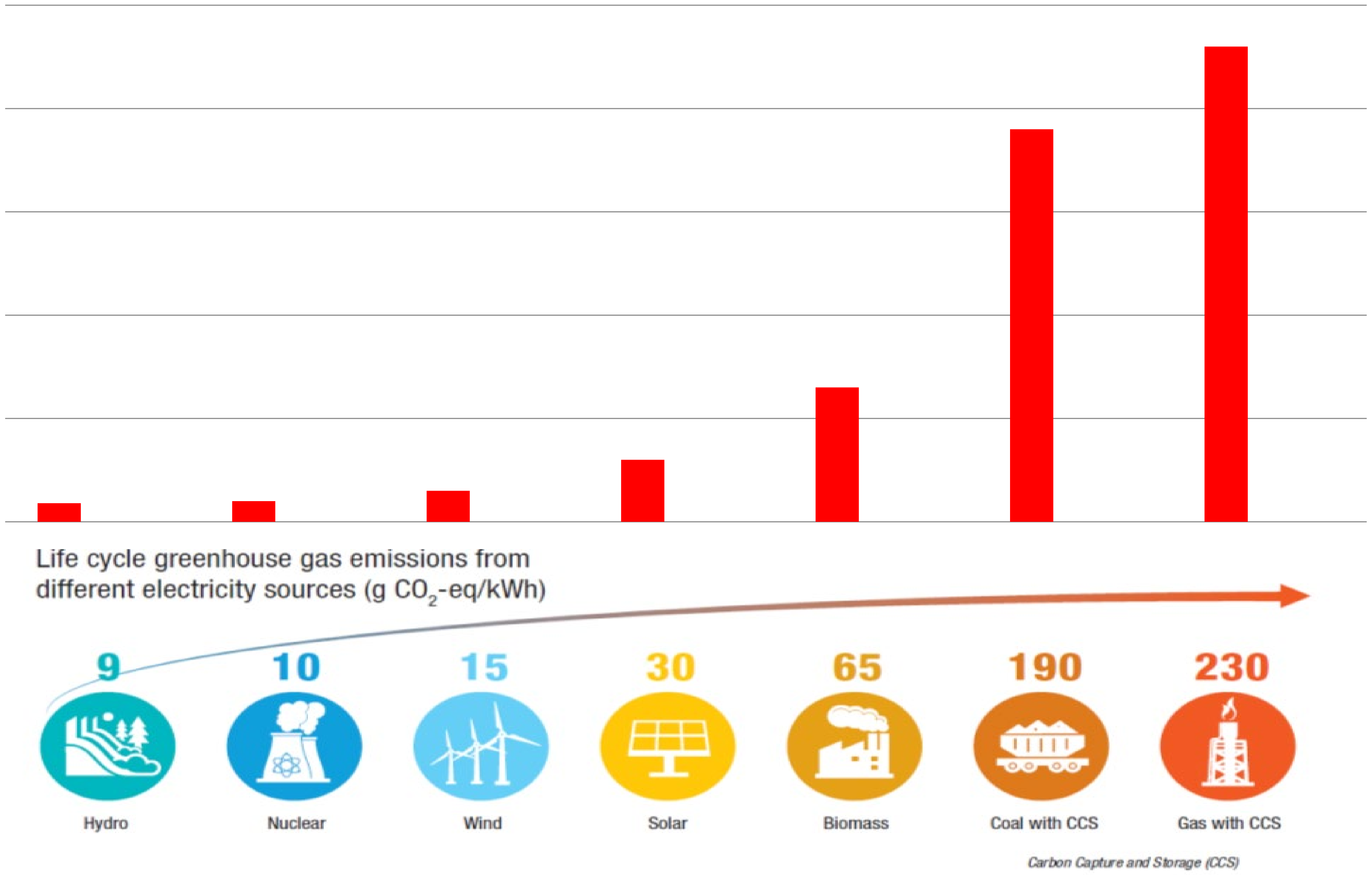
Limiting global warming to 1.5°C will require "far-reaching and unprecedented changes" such as ditching coal for electricity to slash carbon emissions, the report said.

In a number of "pathways" assessed in the report several energy supply characteristics are evident, including growth in the share of energy derived from low carbon-emitting sources including nuclear.

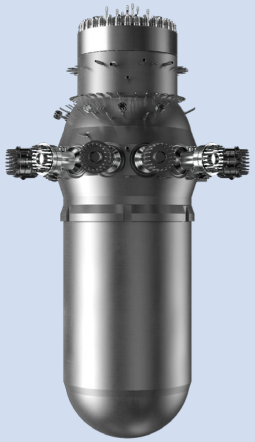
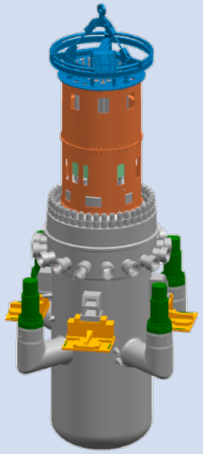
By mid-century, the majority of primary energy comes from non-fossil-fuels – essentially renewables and nuclear – in most 1.5°C pathways, the report said.

"It's a line in the sand and what it says to our species is that this is the moment and we must act now," said Debra Roberts, a co-chair of the working group on impacts. "This is the largest clarion bell from the science community and I hope it mobilises people and dents the mood of complacency."

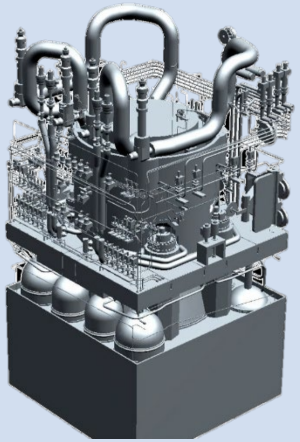
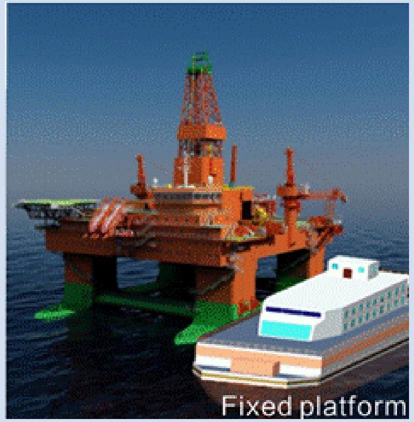
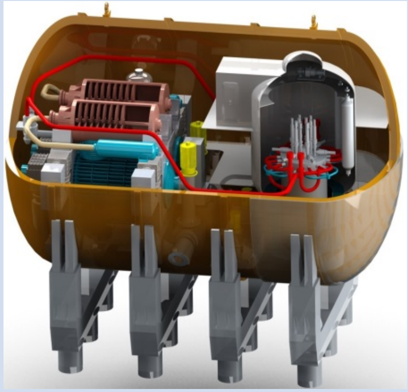
Life Cycle GHG Emissions



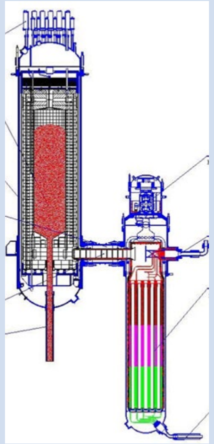
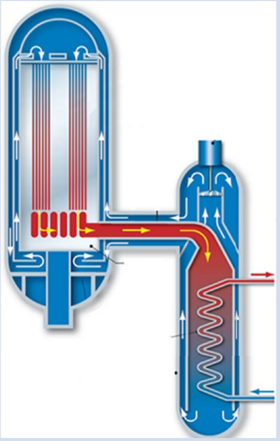
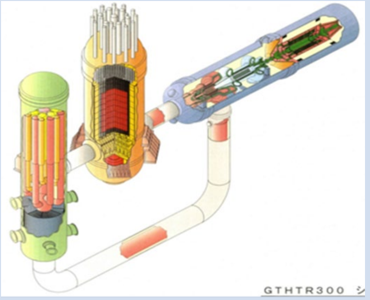
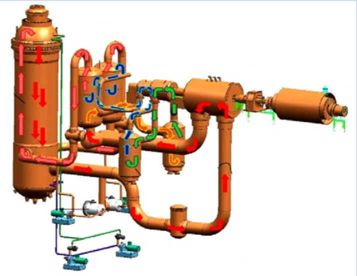
Land-based SMRs (Examples)

CAREM	ACP100	NUWARD	SMART	NuScale
				
Design Status: Advanced stage of construction in Atucha site, Argentina	Design Status: Detailed design; received license for construction in July 2019	Design Status: Conceptual design; Consortium launched in September 2019	Design Status: Standard Design Approval received in July 2012, Pre-Project Engineering completed	Design Status: Design Certification review completion in 2020, to start construction in 2023
• 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 / 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 Desalination	• 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

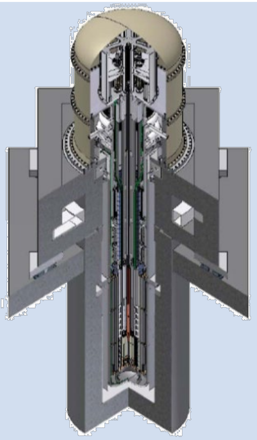
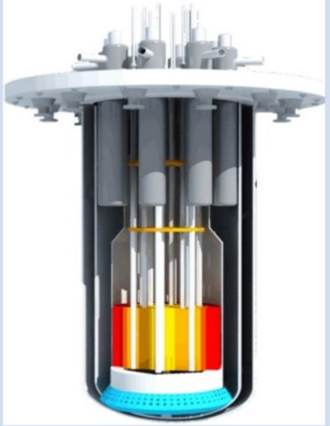
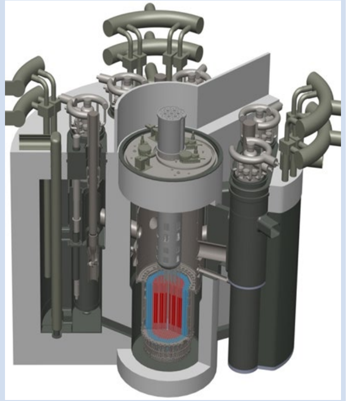
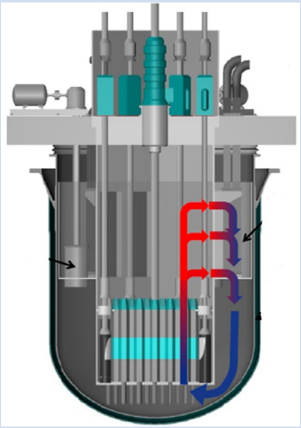
Marine-based SMRs (Examples)

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°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°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°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°C • Enrichment: 19.7% • Refuel interval: 6 years (8 for SHELF-M) • Without onsite refuelling • Spent fuel take back

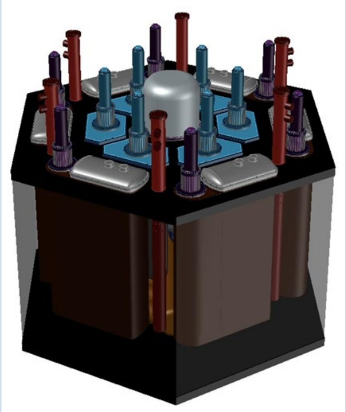
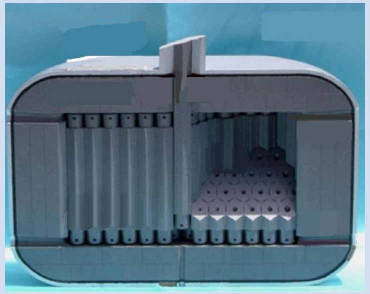
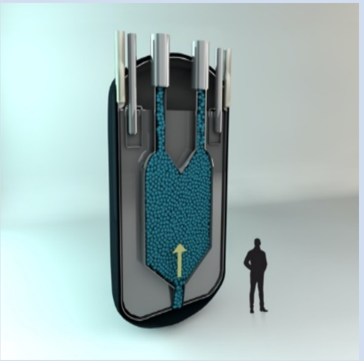
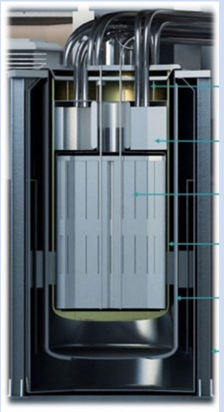
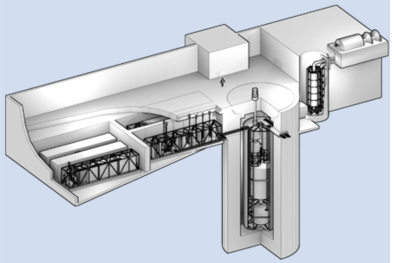
HTGR-type SMRs (Examples)

HTR-PM	SC-HTGR	GTHTR300	PBMR-400	Xe-100
				
Design Status: Finalizing construction in Shidao Bay for operation by 2021	Design Status: Conceptual Design	Design Status: Pre-Licensing; Basic Design Completed	Design Status: Preliminary Design Completed, Test Facilities Demonstration	Design Status: Conceptual design development
• 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, United States of America • Modular Pebble-Bed HTGR • Forced Circulation • 200 MWt / 75 MWe • Core Outlet Temp: 750ºC • Enrichment: <15.5% • Refuel interval: Online refuelling

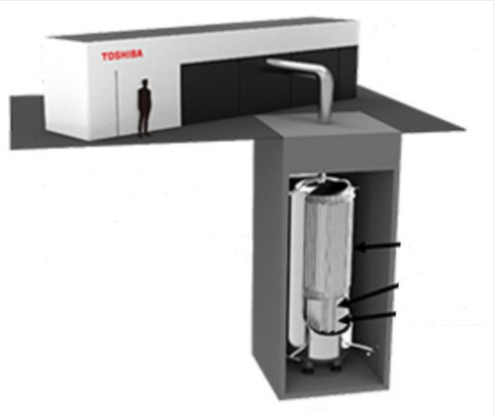
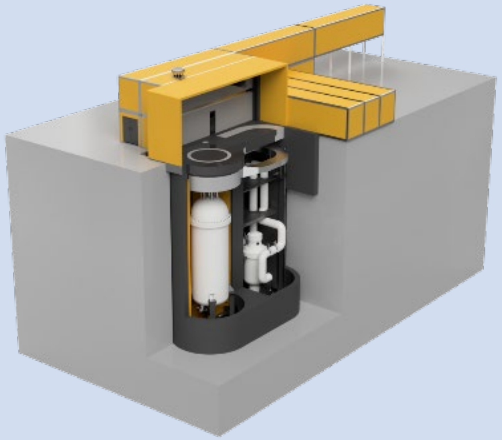
Liquid Metal, Fast-Neutron-Spectrum SMRs (Examples)

4S	URANUS	BREST-300-OD	EM^2	Westinghouse-LFR
				
Design Status: Detailed design	Design Status: Pre-conceptual design	Design Status: Detailed design with potential start-up in 2026	Design Status: Conceptual Design	Design Status: Conceptual design
• Toshiba, Japan • Liquid metal cooled fast reactor (pool type) • 30 MWt / 10 MWe • Forced Circulation • Core Outlet Temp: 510ºC • Enrichment: <20% • Refuel interval: N/A	• UNIST, Republic of Korea • Lead-bismuth cooled reactor • 60 MWt / 20 MWe • Electromagnetic pump • Core Outlet Temp: 350ºC • Enrichment: 3 radial zones (8, 10 and 12%) • Refuel interval: No refuelling	• NIKIET, Russian Federation • Liquid metal cooled fast reactor • 700MWt / 300MWe • Core Outlet Temp: 535ºC • Enrichment: <14.5% • Refuel interval: 900-1500 effective days	• General Atomics, United States of America • Modular high temperature gas-cooled fast reactor • 500 MWt / 265 MWe • Core Outlet Temp: 850ºC • Enrichment: <14.5% • Refuel interval: 360 months	• Westinghouse, United States of America • Liquid metal cooled fast reactor (pool type) • Forced Circulation • 950 MWt / 450 MWe • Core Outlet Temp: 600ºC • Enrichment: <19.75% • Refuel interval: 24 months

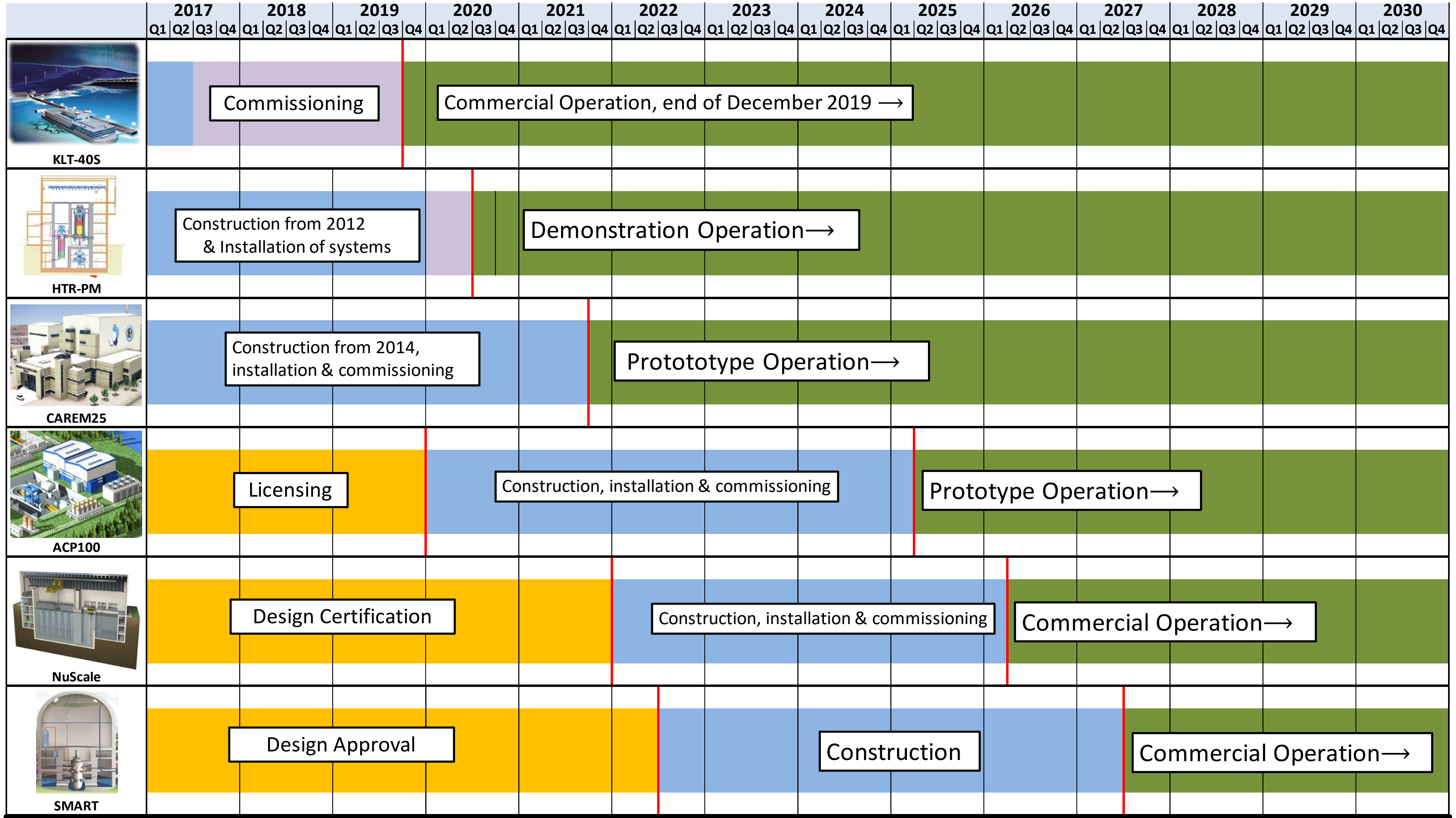
Molten Salt SMRs (Examples)

MCSFR	FUJI	KP-FHR	IMSR	ThorCon
				
<u>Design Status</u>: Conceptual design in progress, fuel development in testing	<u>Design Status</u>: 3 experimental MSRs were built. Detail design not started	<u>Design Status</u>: Conceptual design in progress	<u>Design Status</u>: Conceptual design complete – basic engineering in progress	<u>Design Status</u>: 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

Microreactors (Examples)

MoveluX	MMR	eVinci
		
Design Status: Conceptual design	Design Status: Preliminary Design, under vendor design review with the Canadian CNSC	Design Status: Conceptual Design
• Toshiba, Japan • Fast Reactor • 10 MWt / 3-4 MWe • Natural circulation • Core Outlet Temp: 680-685°C • Enrichment: <4.8-5% • Refuel interval: Continuous	• USNC, USA • HTGR / micro-reactor / nuclear battery • 15 MWt / 5 MWe • Core Outlet Temp: 630°C • Enrichment: <9-12% • Refuel interval: N/A	• Westinghouse, United States of America • Heat Pipe cooled • 7-12 MWt / 2-3.5 MWe per module • Core Outlet Temp: 800°C • Enrichment: 5-19.75% • Refuel interval: 36+ months

Status of Deployment Timeline as of Spring 2020

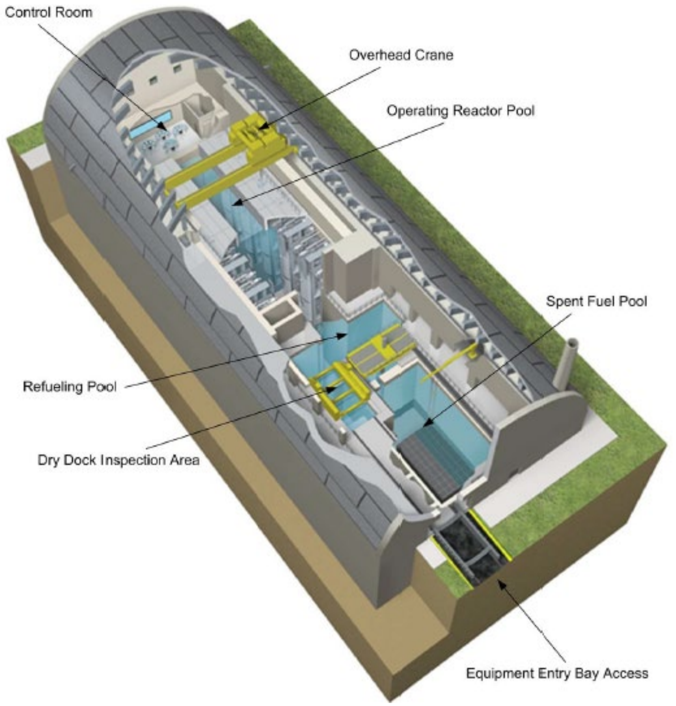


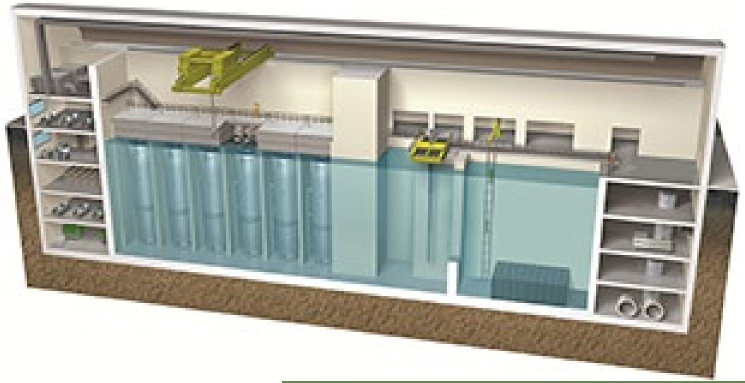
Floating NPP, HTGR, integral-PWRs, and multi-module plants

Specific Characteristics

SMR Key Design Features: Modular

- Multi modules configuration
  - Two or more modules located in one location/reactor building and controlled by single control room
    - → reduced staff
    - → new approach for I&C system





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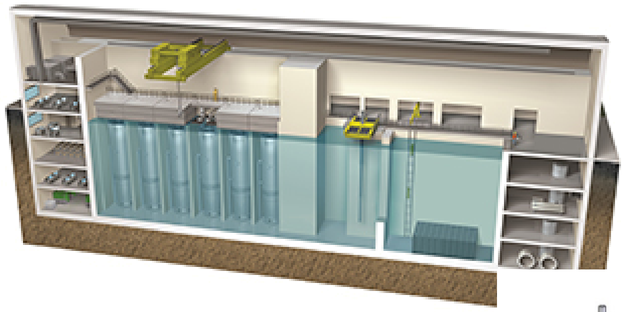
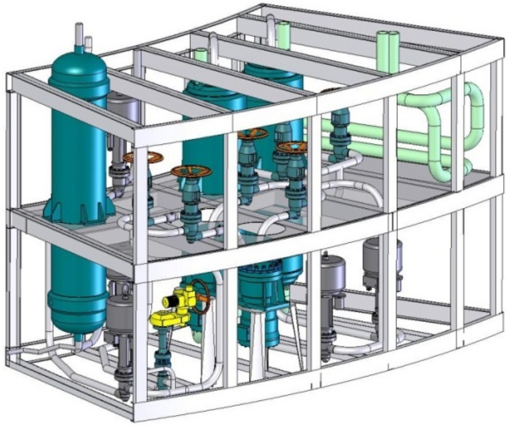
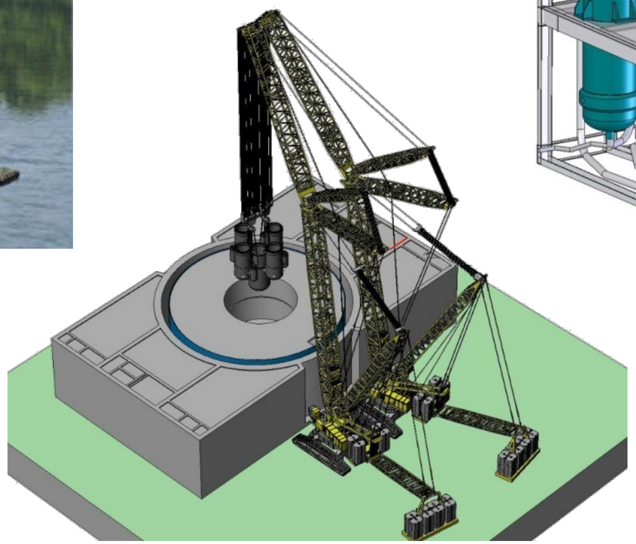
Modularization

Modularization (construction technology)

- Factory manufactured, tested and Q.A.
- Heavy truck, rail, and barge shipping
- Faster construction
- Incremental increase of capacity addition as needed
- (Construction principle is also applied to large LWRs)







Images reproduced courtesy of NuScale Power Inc. and BWX Technology, Inc., USA.

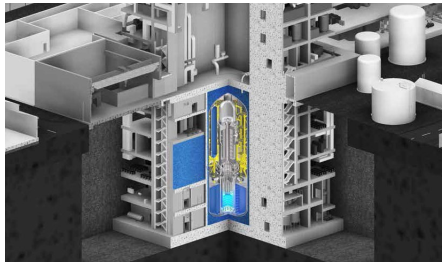
SMR Site Specific Considerations

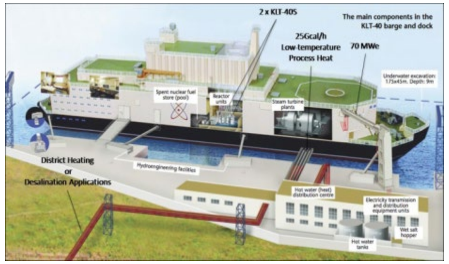
- SMRs promise much smaller sites
  - EPZ can possible be reduced
  - Located close to population centers / end users
  - Located next to heat users / industries
- The first SMRs currently built / to be deployed has selected existing NPP / nuclear sites (HTR-PM, CAREM, NuScale plan)
- Important factor is physical security (smaller site and close proximity of other buildings / industries will present new challenges)

The HTR-PM - (Two-reactor unit) = 210MWe
The Vogtle 3 and 4 Nuclear power plant USA - 2 units = 2220 MWe

Design Features offered by SMR: Site and building

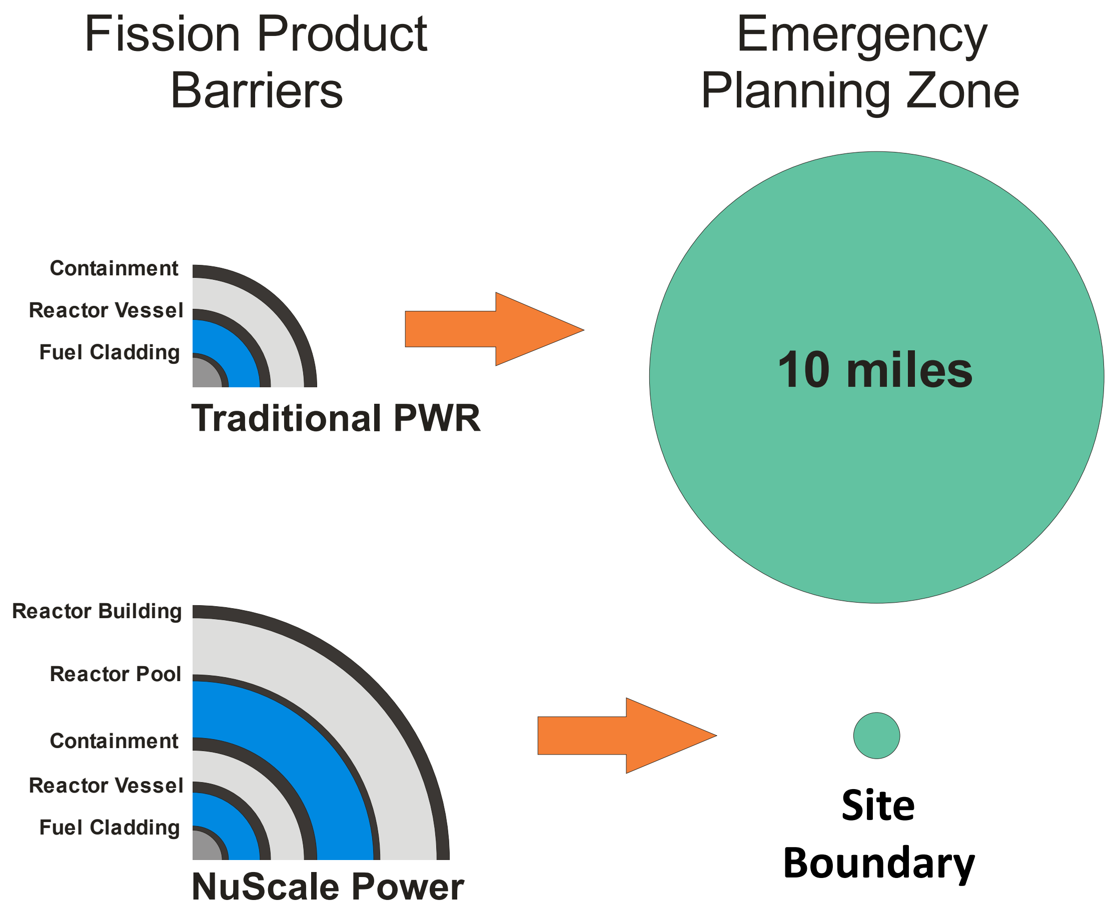
- Underground and marine based deployment
  - Underground sites offer:
    - Better protection against the impacts of severe weather
    - Better seismic strength
    - Enhanced protection against fission product release
    - Improved physical security, aircraft impacts and conventional warfare
  - Marine based deployments offer:
    - Infinite heat sink (sea)
    - Site flexibility
    - Alternative owner / operator options



Example: Basis for Reducing EPZ

- **Greater safety margin**
  - Elimination of many accident initiators
  - Passive and active accident prevention
  - Low power density
- **Slower event sequences**
  - Larger water inventory
  - Larger pressurizer volume
  - Huge core graphite mass
- **Reduced core damage frequency**
  - >3,000 times lower than operating reactors
  - Risk-informed design process
  - No core melt (mHTGRs)
- **Better accident mitigation**
  - Smaller fuel inventory
  - More design features to reduce and delay radionuclide release



Progress made in applying a graded approach

- Nuclear Regulatory Commission staff agreed with the Tennessee Valley Authority that scalable emergency planning zones (EPZs) for small modular reactors are feasible

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US regulators discuss smaller SMR emergency zones

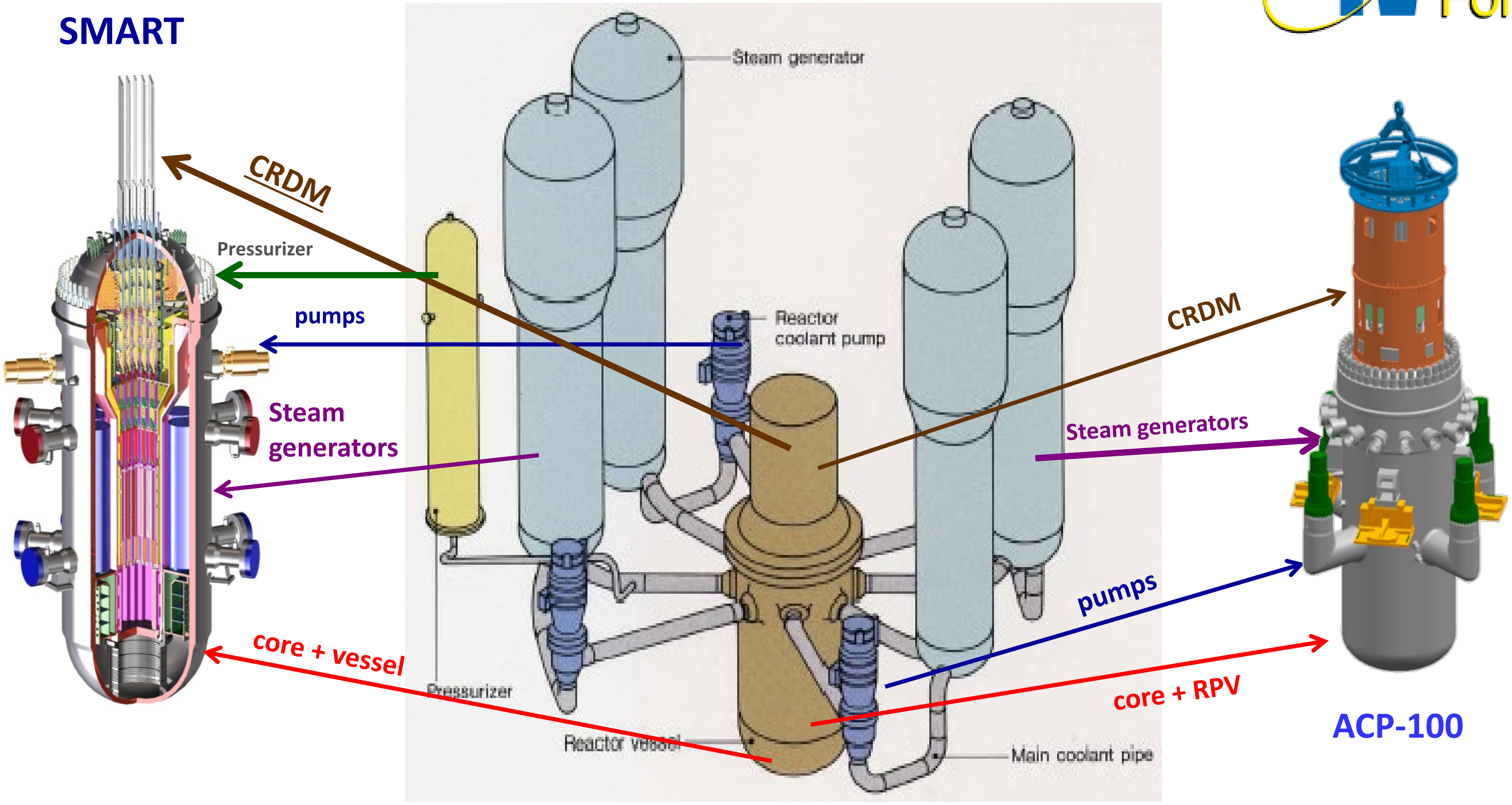
28 August 2018

Share

CLARIFICATION: NRC staff have concluded the TVA methodology can be used in the future to determine if a reduced emergency planning zones is justified, and has not made a decision on EPZ criteria for small modular reactors.

The US Nuclear Regulatory Commission (NRC) has concluded that Tennessee Valley Authority's (TVA's) methodology can be used in the future to determine if a reduced emergency planning zone is justified for small modular reactors, a spokesman for the Commission told *World Nuclear News* today. It has not yet agreed that an EPZ around small modular reactors can be scaled to reflect their reduced risks rather than the mandatory ten-mile EPZ required for the USA's current light-water reactor fleet.

Integral-PWR type SMR

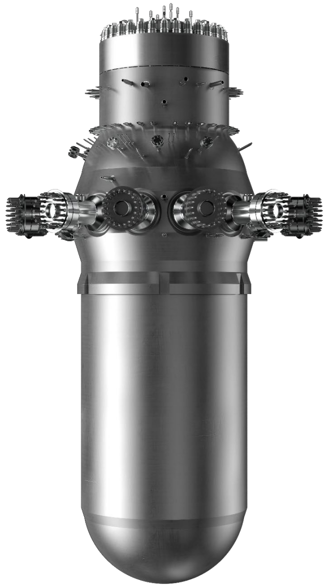
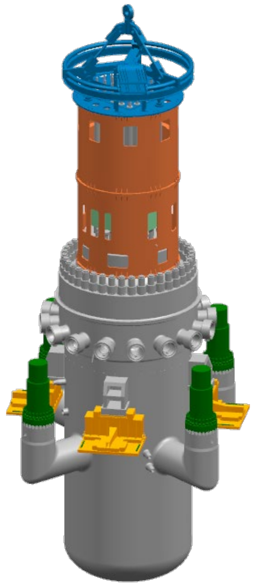


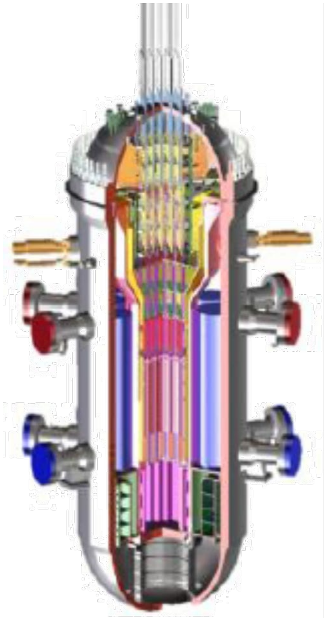
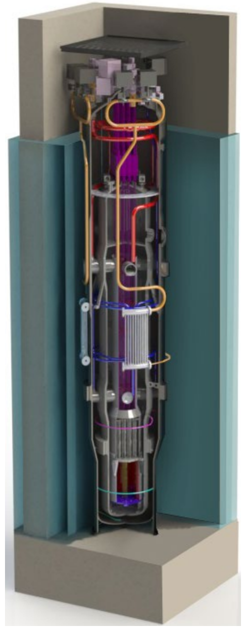
Integration of major components to be within the reactor pressure vessel:

- Eliminates loop piping and external components, thus making the nuclear island smaller and compact
- Eliminates the possibility of large break LOCA

Design Features offered by SMR: Integrated iPWR

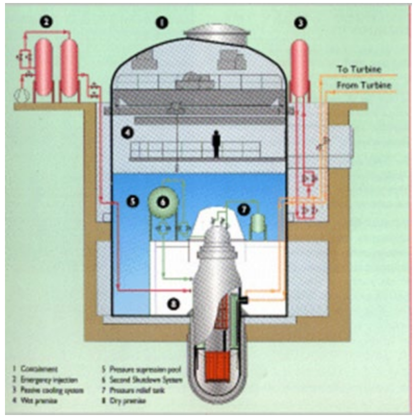
- Major components within nuclear steam supply system installed inside the reactor vessel (e.g. CAREM, ACP100, NUWARD, SMART, NuScale, etc)
  - → **Large LOCA eliminated**
- Pressurizer within the vessel / Pressurizer outside the vessel (ACP100)
- Enable multi-module plant arrangement

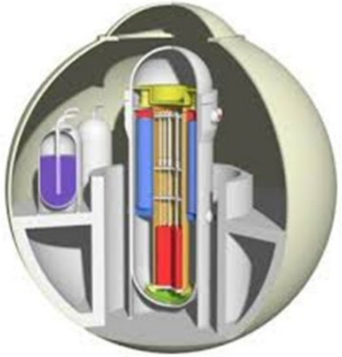



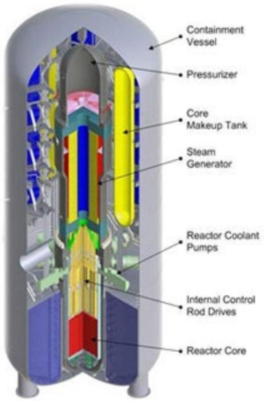



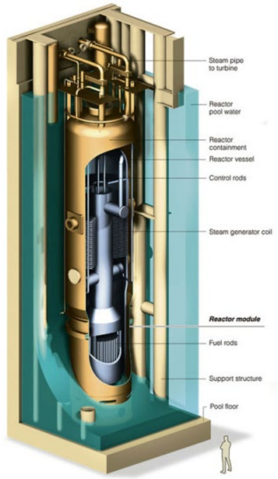
Design Features offered by iPWR-SMRs

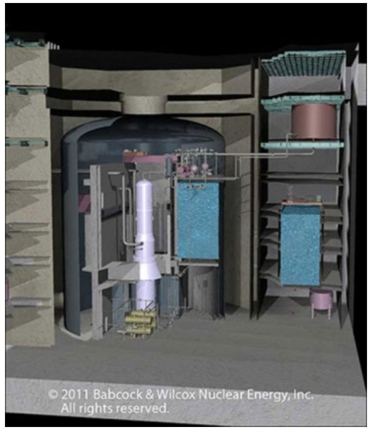
- Containment
  - Passively cooled Containment :
    - Submerged Containment (Convection and condensation of steam inside containment, the heat transferred to external pool) (NuScale, W-SMR)
    - Steel containment (mPower)
  - Concrete containment with spray system (SMART)
  - Pressure suppression containment (CAREM, IRIS)
- Severe Accident Feature
  - In-vessel Corium retention (IRIS, Westinghouse SMR, mPower, NuScale, CAREM)
  - Hydrogen passive autocatalytic recombiner (CAREM, SMART)
  - Inerted containment (IRIS)











Typical LWR Safety Systems

GEN IV International Forum

Systems and components needed to protect the core:

- Reactor pressure vessel
- Containment vessel
- Reactor coolant system
- Decay heat removal system
- Emergency core cooling system
- Reactor protection system
- Containment isolation system
- Ultimate heat sink
- Residual heat removal system
- Safety injection system
- Refueling water storage tank
- Condensate storage tank
- Auxiliary feedwater system
- Emergency service water system
- Hydrogen recombiner or ignition system
- Containment spray system
- Reactor coolant pumps
- Safety related electrical distribution systems
- Alternative off-site power
- Emergency diesel generators
- Safety related 1E battery system
- Anticipated transient without scram (ATWS) system

NuScale Safety Systems

GEN IV International Forum℠

Systems and components needed to protect the core:

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- Alternative off-site power
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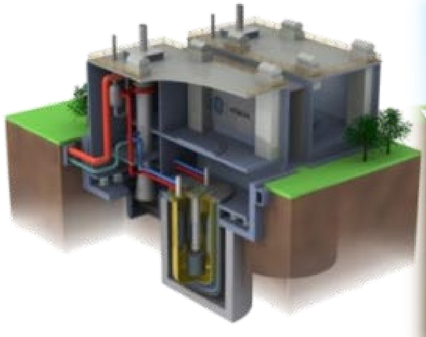
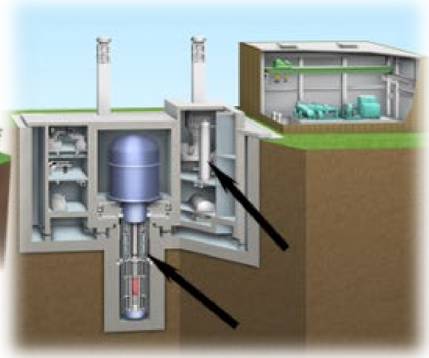
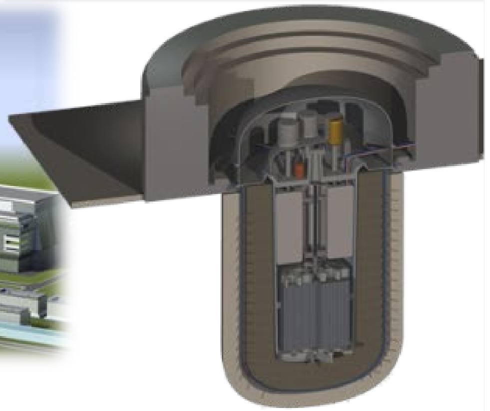
Example:
Innovative Nuclear Systems
Revolutionary designs
(Very) High Temperature Gas Cooled Reactors

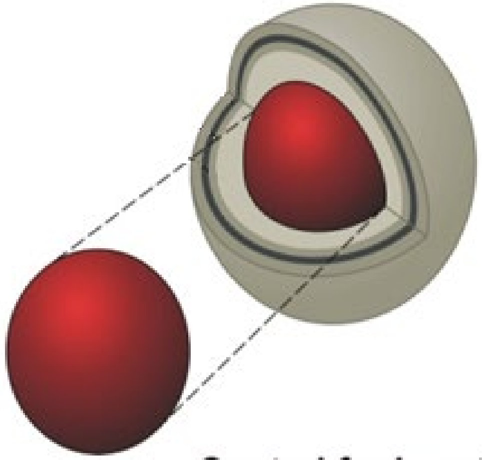





VHTRs; HTRs; HTGRs

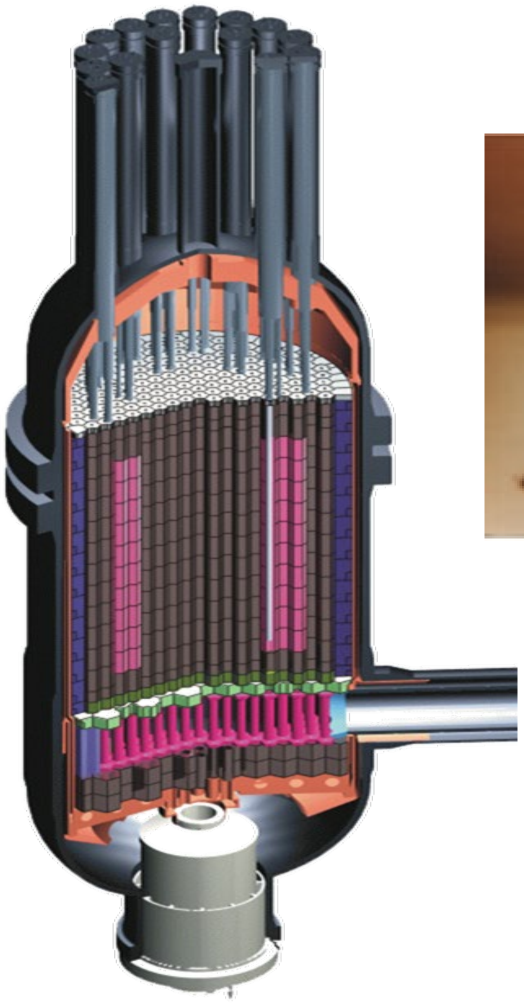
HTGRs Characteristics

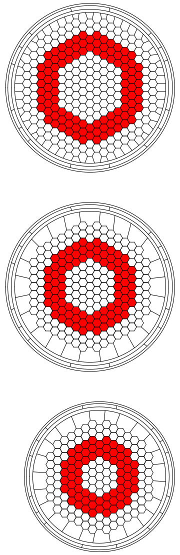
- High Temperature Gas Cooled Reactors is an advanced reactor system (part of GEN-IV) with the following main characteristics:
  - High temperatures (750-1000°C)
  - Use of coated particle fuel
  - Helium coolant
  - Graphite moderated
  - Small reactor units (~100 - 600 MWth)
  - To be deployed as multiple modules
  - Low power density (typically 3-6 W/cc compared to 60-100W/cc for LWRs)
  - Two basic design variations – Prismatic and pebble bed design

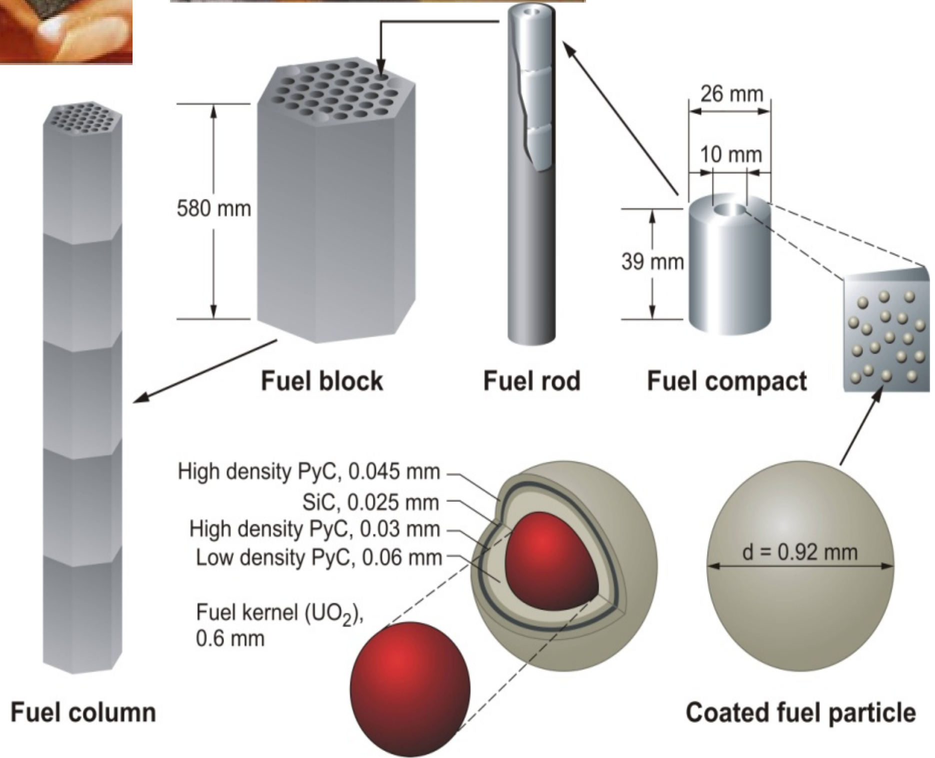


Coated fuel particle

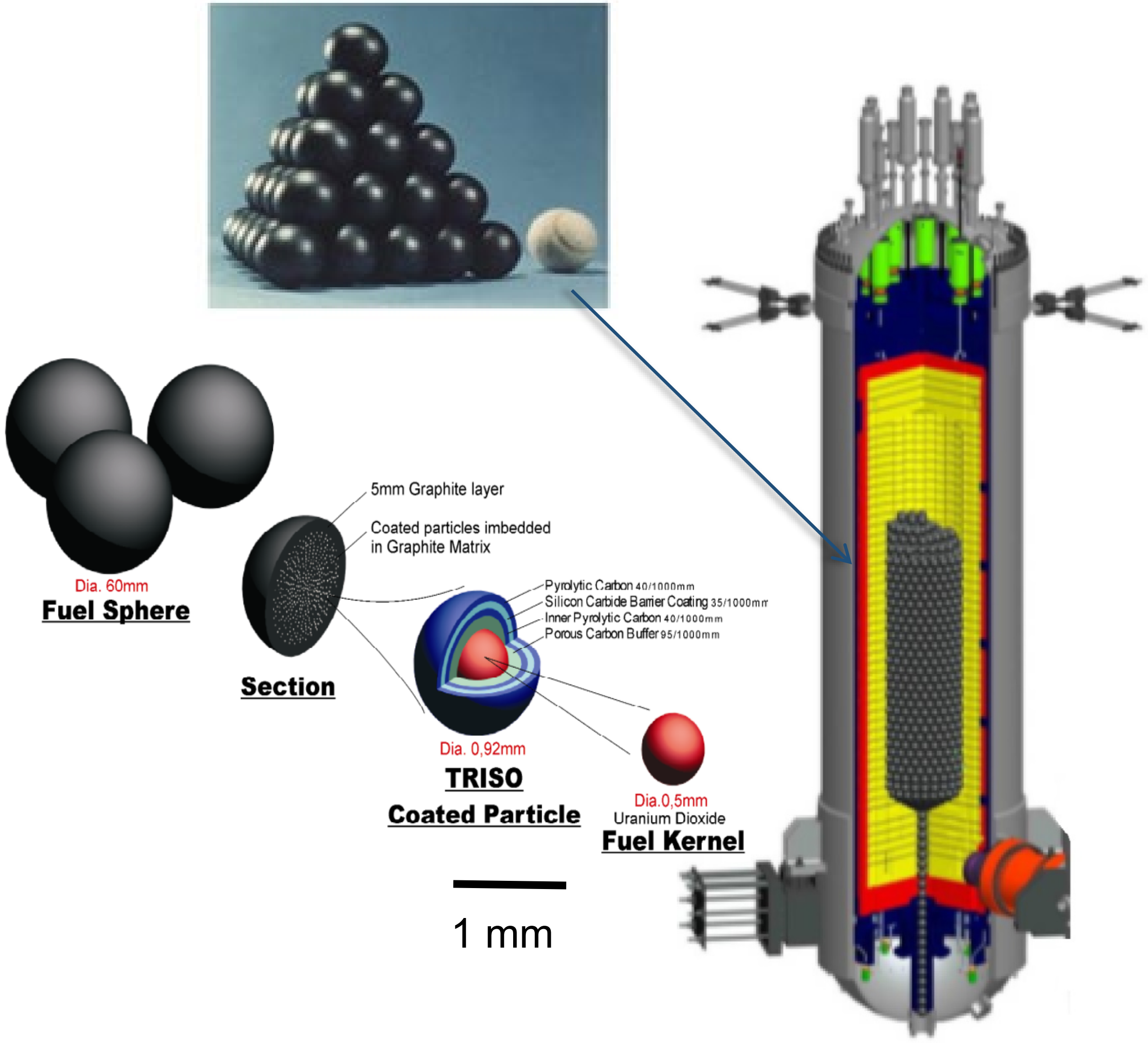
Prismatic (block-type) HTGRs







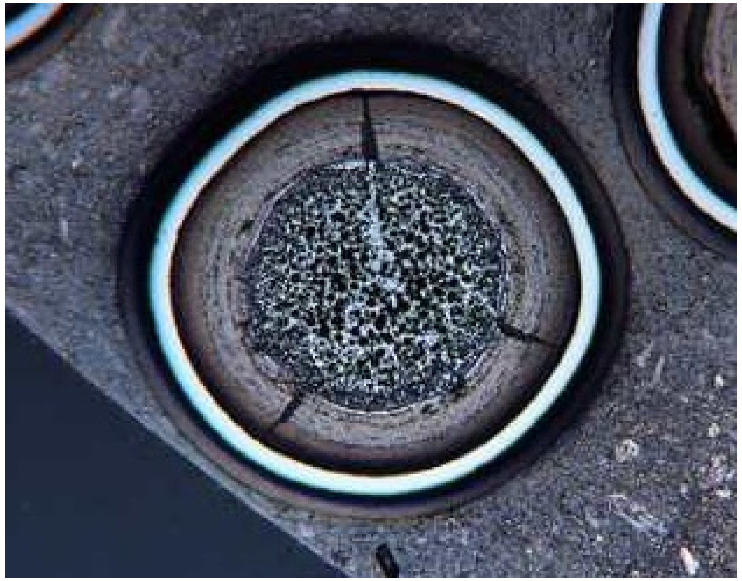
Pebble type HTGRs



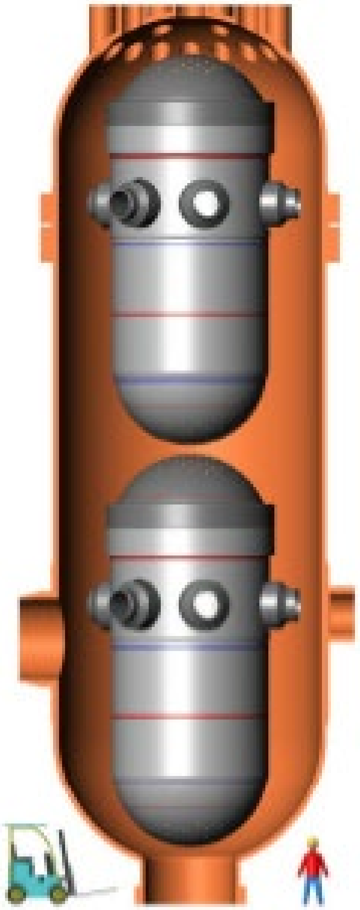
- Spherical graphite fuel element with coated particles fuel
- On-line / continuous fuel loading and circulation
- Fuel loaded in cavity formed by graphite to form a pebble bed

HTGRs - Benefits

- Higher (↑20-50%) efficiency in electricity generation than conventional nuclear plants due to higher coolant outlet temperatures
- Potential to participate in the complete energy market with cogeneration and high temperature process heat application
  - Process steam for petro-chemical industry and future hydrogen production
  - Market potential substantial and larger than the electricity market
  - Allows flexibility of operation switching between electricity and process heat
- Significantly improved safety
  - Decay heat removal by natural means only, i.e. no meltdown
  - No large release - radioactivity contained in coated particle fuel
  - EPZ can be at the site boundary
- Position close to markets or heat users
  - Savings in transmission costs
- Can achieve higher fuel burnup (80-200 GWd/t)
  - Flexible fuel cycle and can burn plutonium very effectively



HTGRs - Challenges



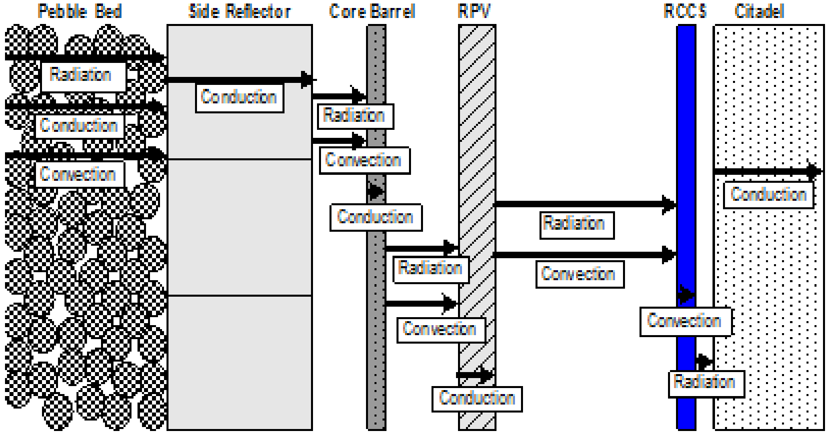
600 MWt HTGR RPV
vs
PWR RPV

- 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. ∅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

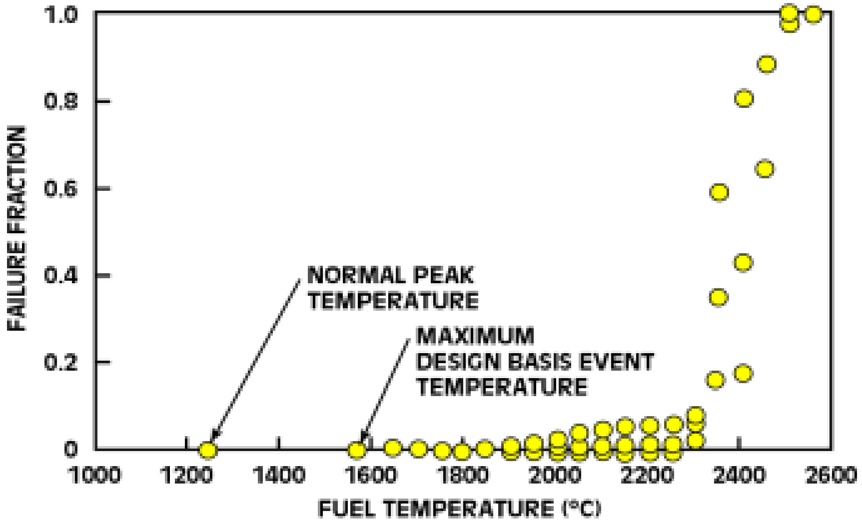
No early or large FP release

Ceramic fuel retains radioactive materials up to and above 1800˚C

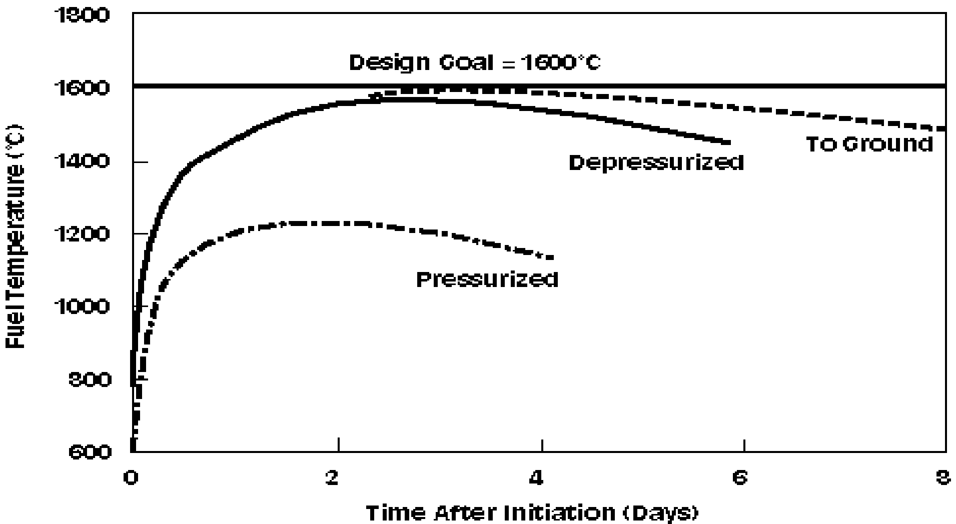
Heat removed passively without primary coolant – all natural means



Coated particles stable to beyond maximum accident temperatures



Fuel temperatures remain below design limits during loss-of-cooling events



No early or large FP release

GEN IV International Forum

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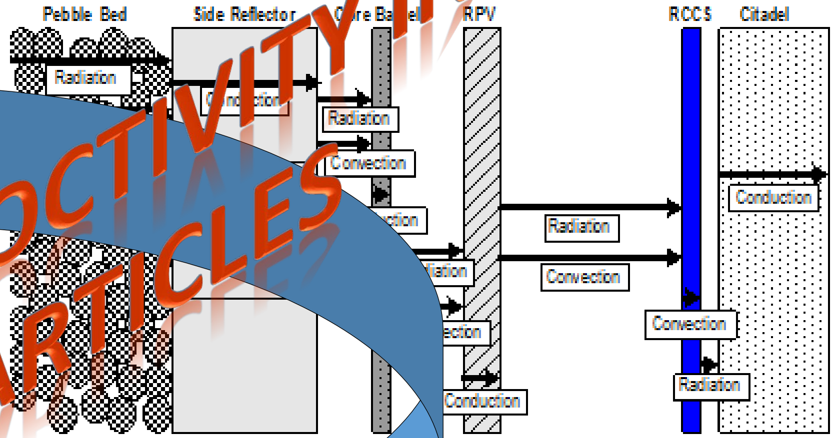
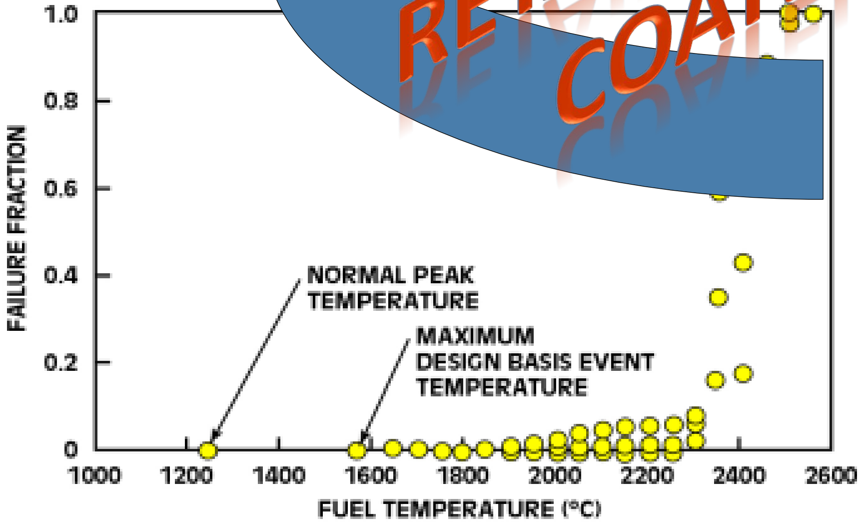


RETAINS RADIOCTIVITY IN COATED PARTICLES

Coated particles stable to beyond maximum accident temperatures



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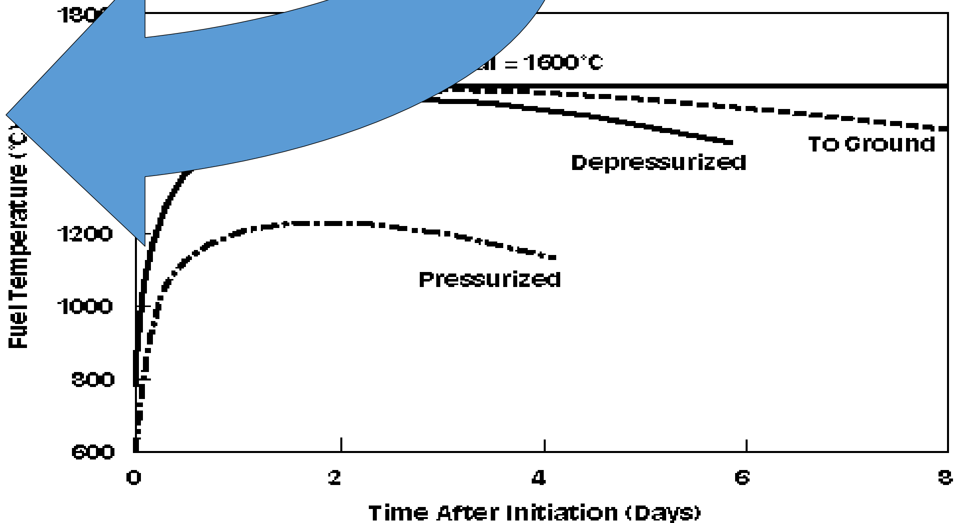
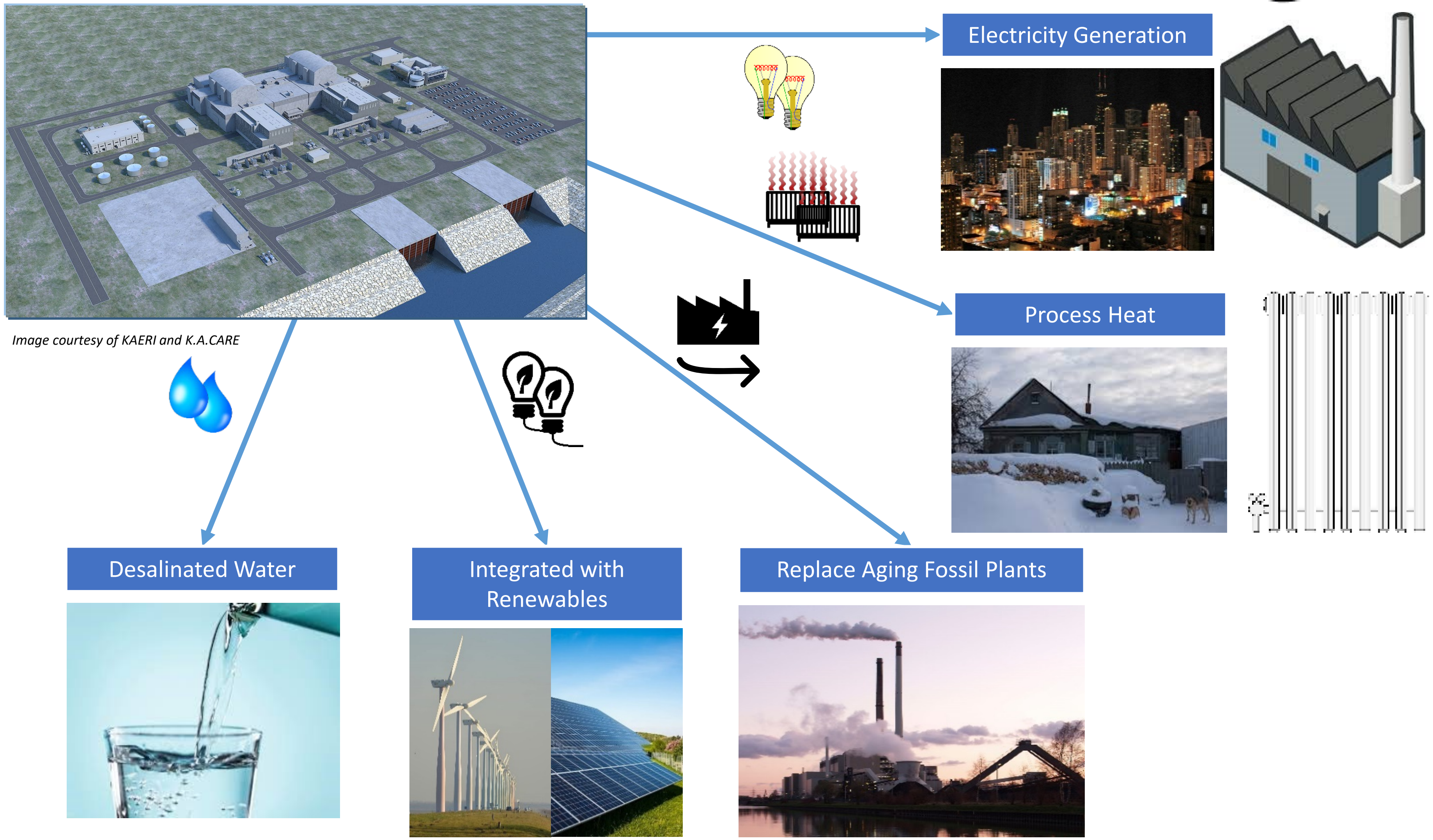


FLEXIBLE APPLICATIONS

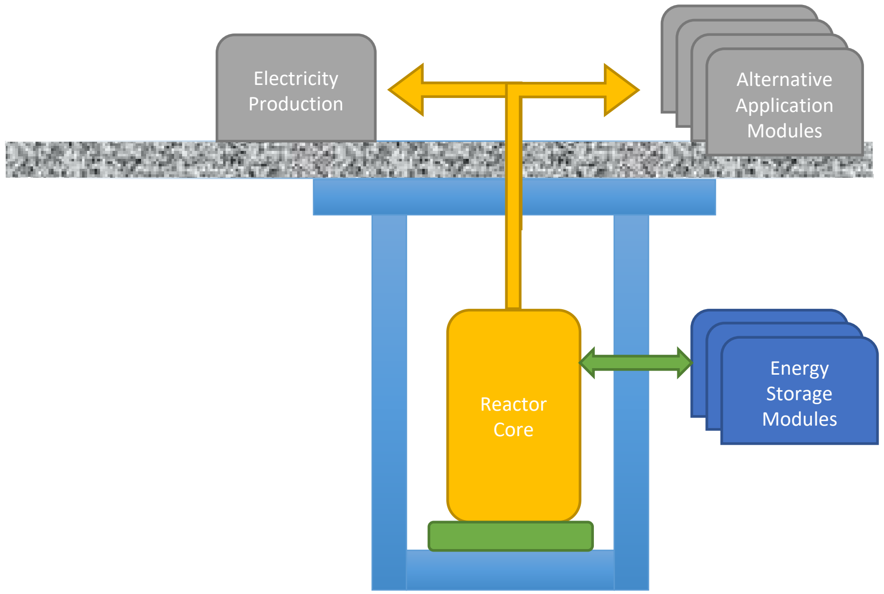
Viable Applications of SMRs



A viable option to contribute to Climate Change Mitigation

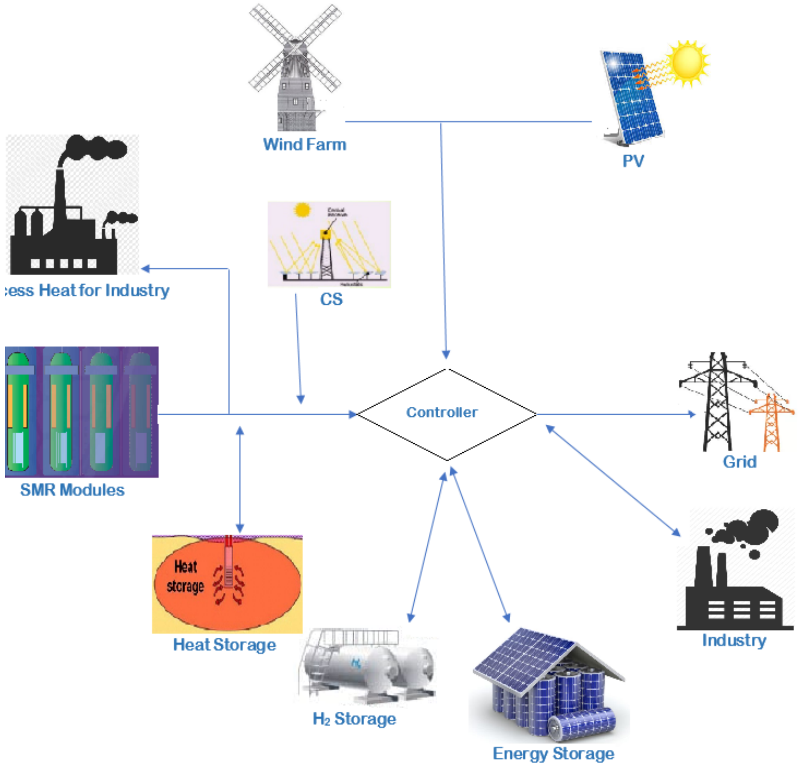
Role of SMRs in Climate Change

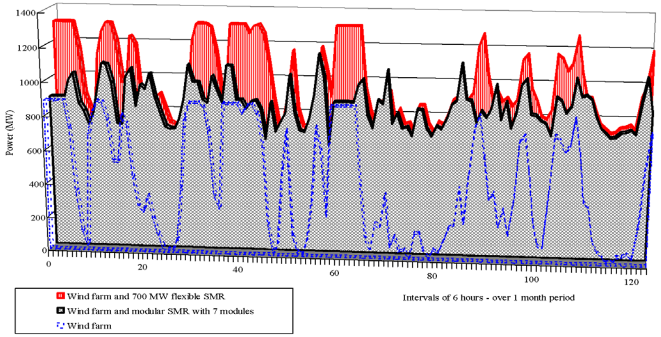
SMR Renewables Hybrid Energy System to Reduce GHG Emission



Modules:

- Electricity production
- Process heat
  - Petro-chemical industry
  - Desalination plant
  - Oil and gas reforming
  - Hydrogen production
  - Ammonia production
  - District heating / cooling
  - Waste reforming
- Energy storage
- Load follow capabilities
  - Switch between applications

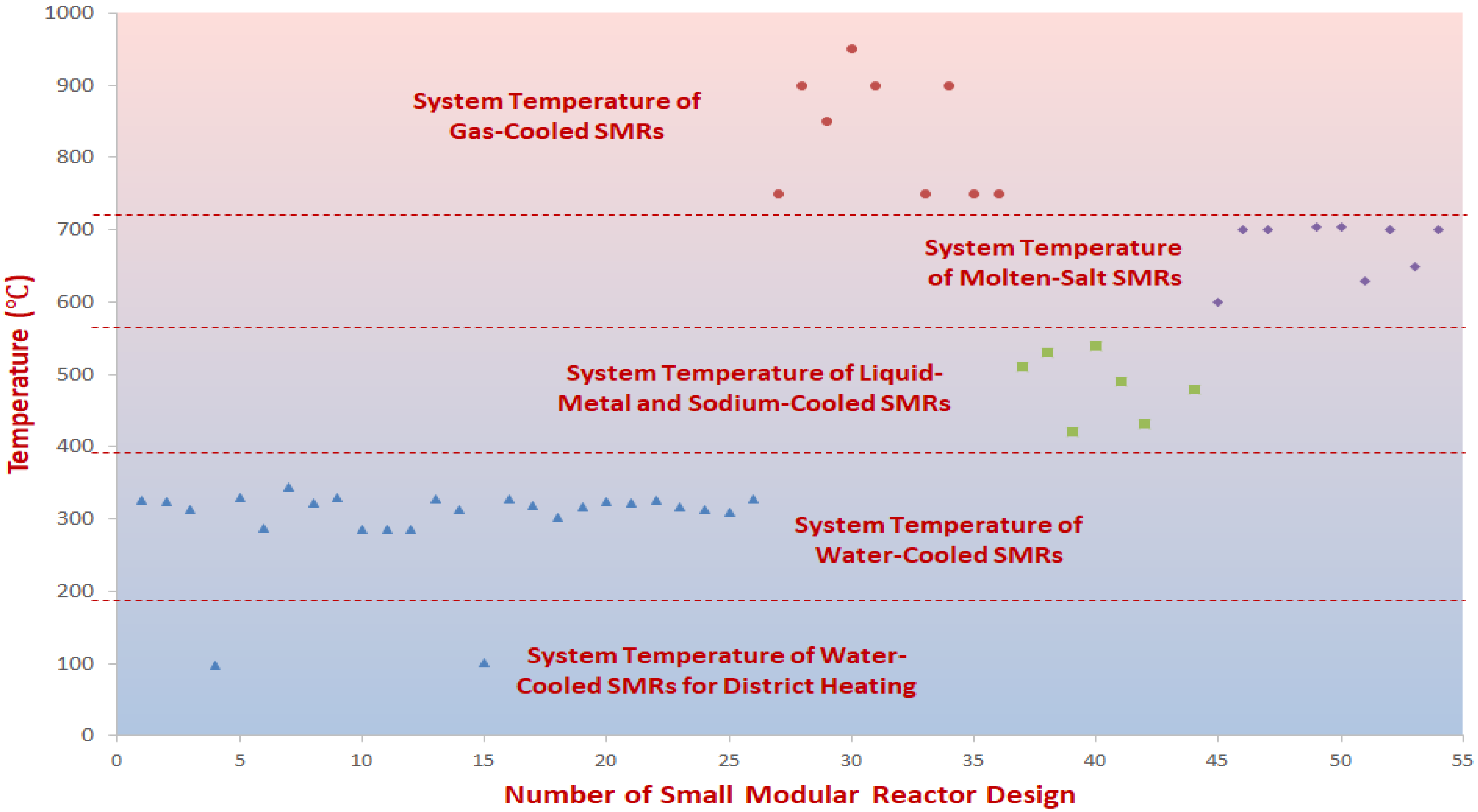




Example of load follow with renewables

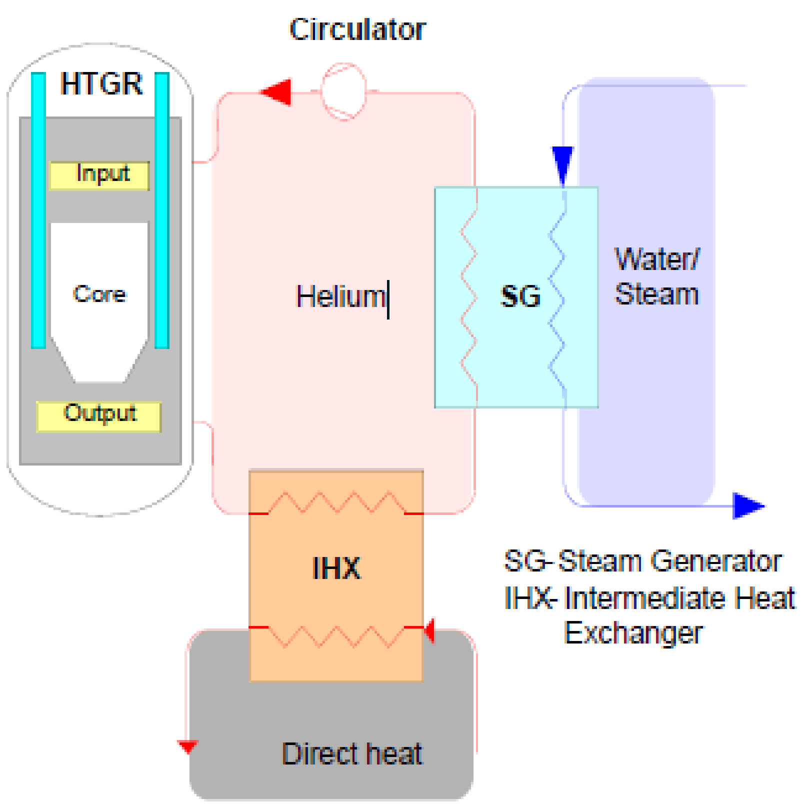
TECDOC:
Options to Enhance Energy Supply Security using Hybrid Energy Systems based on SMR;
being finalised in 2020

SMR Designs Based on Core Exit Temperature

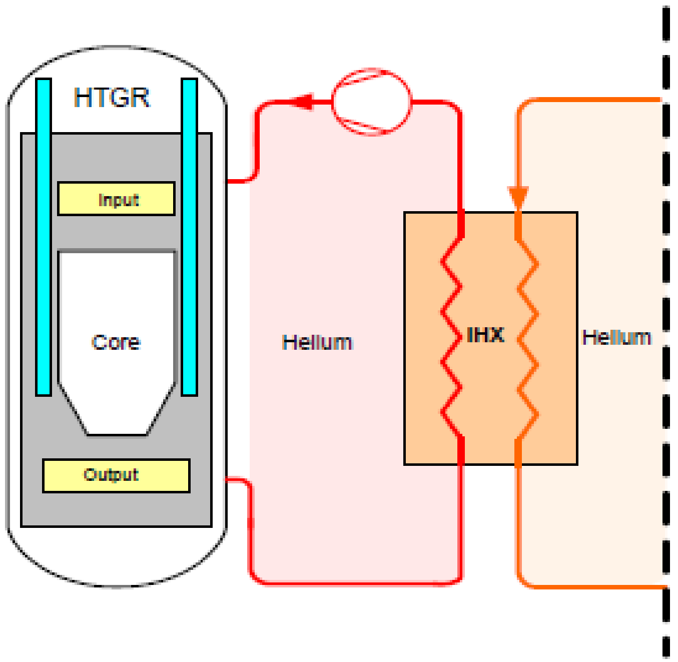


Coupling examples

Illustrative Configurations for Direct Heat, Higher Temperature Applications

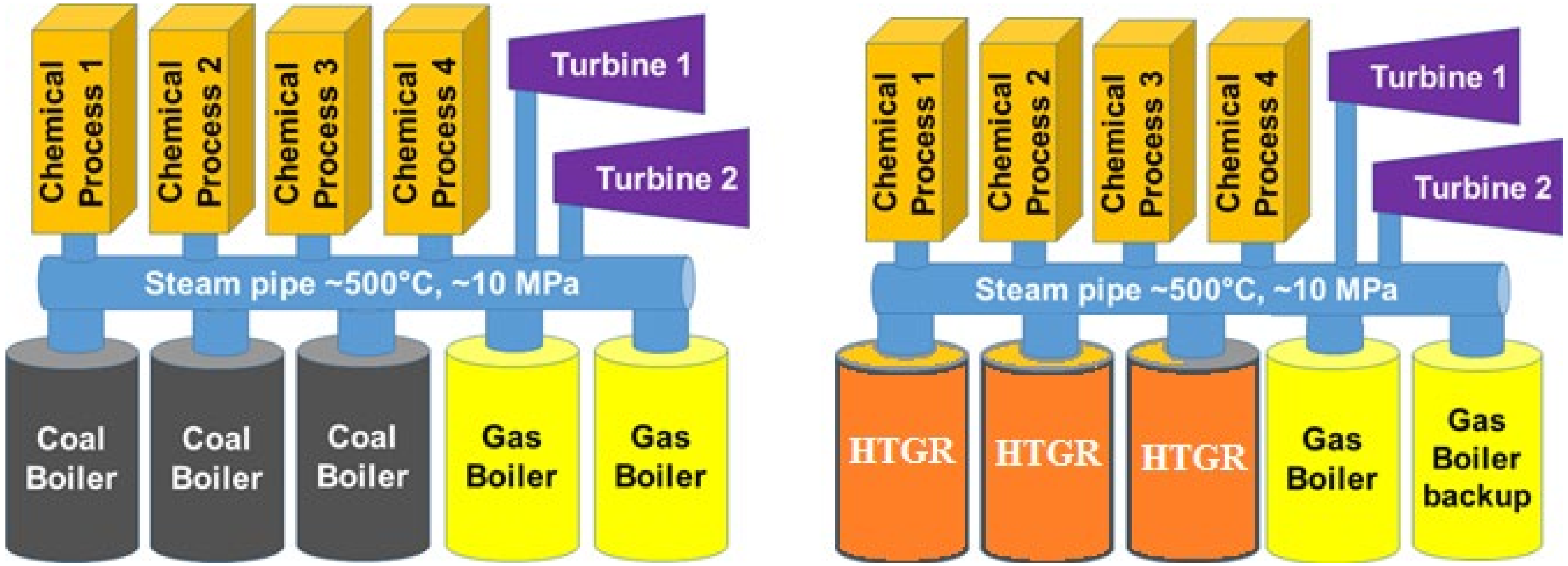


SG-Steam Generator
IHX- Intermediate Heat Exchanger



HTGRs and Poland

- Industrial Heat Market in Poland
  - 13 largest chemical plants need 6500 MW of heat at T=400-550°C
  - Construction of experimental reactor of ~10 MW_{th} in Swierk
  - Target to construct the first commercial reactor of 150-300 MW_{th} (165 MWth was determined to be optimum size for Poland)
  - Huge potential: Foresee 10, 100, 1000 reactors for Poland, Europe and the world …



Benefits from HTGR deployment for economy & society in Poland*

- ***Decreasing dependence on fossil fuel import.*** *HTGR is the only practical alternative to replace fossil fuels for industrial heat production. With expected growth of CO2 tax and low discount rate, the cost of the steam from HTGR could be comparable to that from gas, while having more secure availability and more predictable prices.*
- ***Decreasing sensitivity of economy to environmental regulations.*** *Industry dependent on fossil fuels might become less competitive in case of stronger environmental regulations (CO2 tax, emission limits, etc.). HTGR being a zero emission technology is immune to that.*
- ***Boost for economy growth based on high added value.*** *HTGR deployment is a large, innovative project, opening a new branch of economy, leading to high-tech reindustrialization and creating more attractive jobs.*
- ***Synergy with multi-GW LWR program.*** *Increasing scientific and industrial potential, upgrading the regulatory framework, developing human resources and creating a supply chain, will be beneficial for both HTGR and LWR projects.*
- ***Large export potential.*** *Very high safety level, favorable output parameters (>500°C) and relatively small size makes HTGR a very attractive export product.*
- *Most of those benefits are valid for other countries. You are invited to cooperate.*

* From 2017 IAEA GC Side Event – Poland Ministry of Energy

Process heat / co-generation

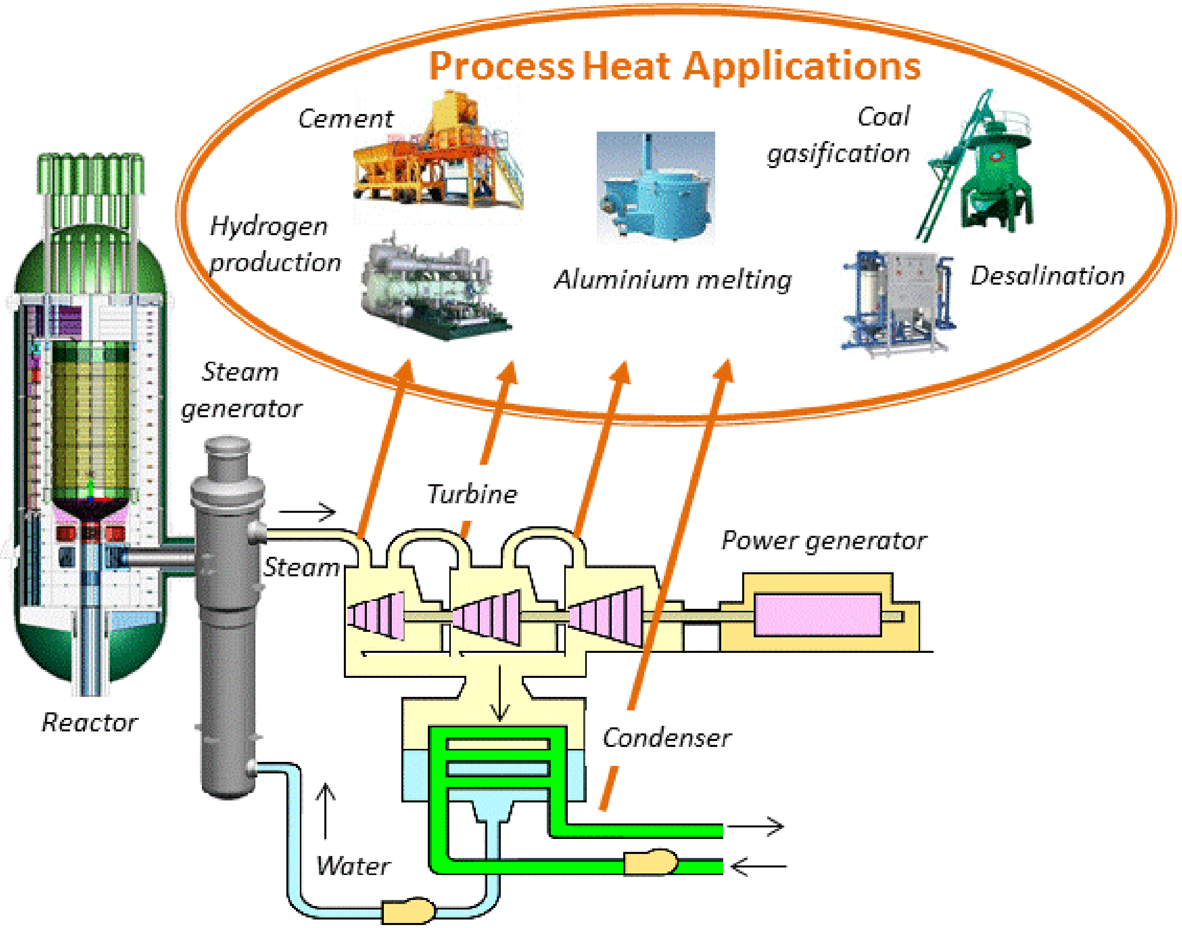
* Survey of HTGR Process Energy Applications, NGNP Project, MPR-3181 Rev 0, May 2008

Near term market potential
North America / USA only:

250-500°C = 75,000MWt
(or 150-300 reactors)
Mostly Petroleum products:

500-700°C = 65,000MWt
(or 130 – 260 reactors)
(Petroleum + Ammonia)

Easily achievable today

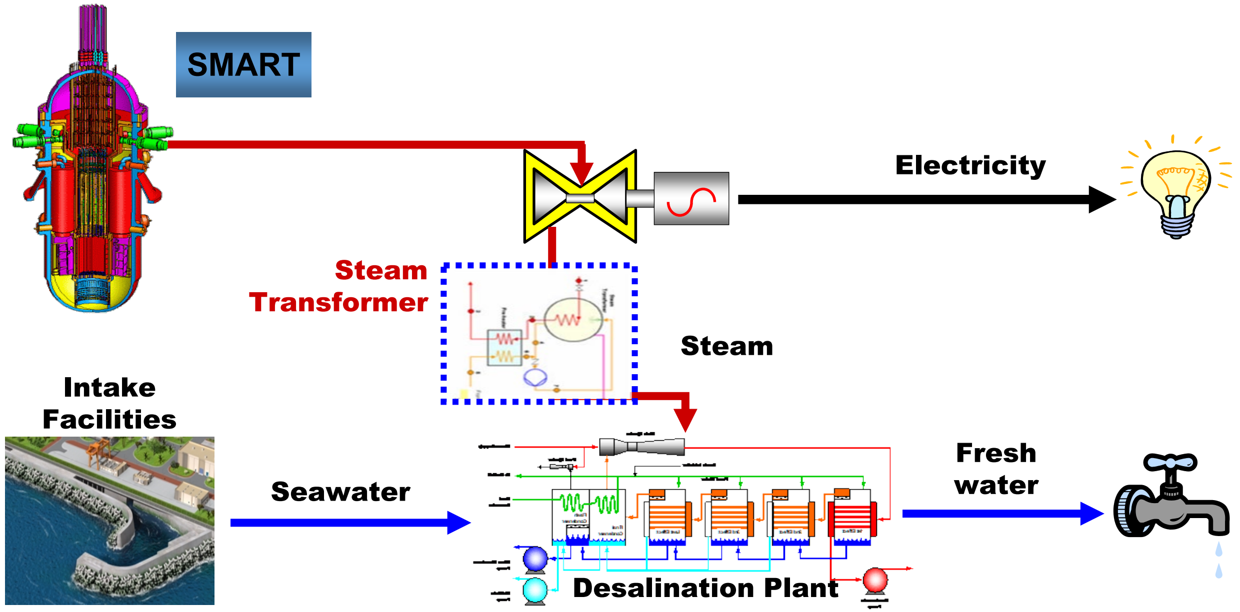


Allows flexibility of operation switching between electricity and process heat

Cogeneration Concept of SMART

330 MW$_{th}$ integral-PWR

Electricity Generation, Desalination and/or District Heating



Plant Data

- Power : 330 MWt
- Water : 40,000 t/day
- Electricity : 90 MWe

System-integrated Modular Advanced ReacTor

- ❑ Electricity and Fresh Water Supply for a City of 100,000 Population
- ❑ Suitable for Small Grid Size or Distributed Power System

Images courtesy of KAERI, Republic of Korea

Value of Non-Electric Applications

- **Better Efficiency**

Over 80% energy efficiency
Open new sectors for nuclear power

- **Better Use of energy**

Optimize energy efficiency
Match industrial application needs at the right temperature

- **Better Flexibility**

In future energy planning
In operating nuclear power plants/and electrical Grid
In diversifying energy outputs

- **Reduced environmental impact**

Reduced waste heat dumped to the environment
Additional heat sink

Save Energy

Recover waste heat
Open new utilization of nuclear power

Save Environment

Reduce CO_2 emissions
Reduce nuclear waste

Save Money

Get cheaper energy
Reduce the need for fossil fuels

- **Feasible**

On all reactor types
Existing nuclear reactors can be <u>retrofitted</u>

- **Safe**

Minimal impact on reactor safety
Product outputs is free of radioactive contamination

- **Value added**

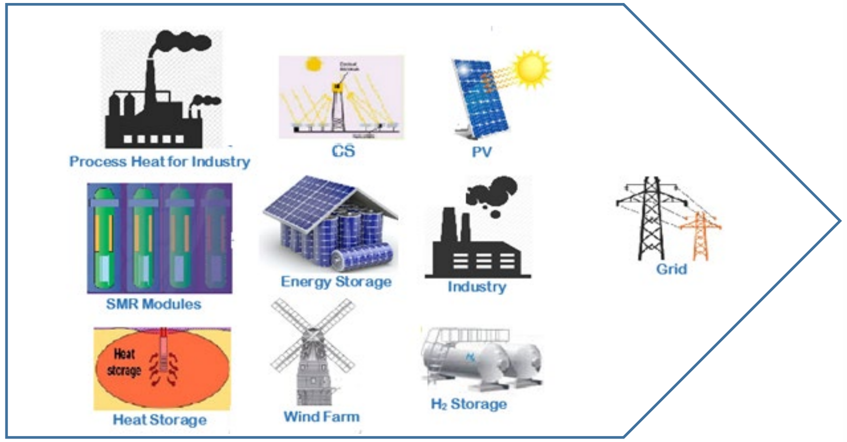
For pubic use: Drinking Water, District heating/cooling
For industrial use : Steam, Synthetic Fuels, Hydrogen

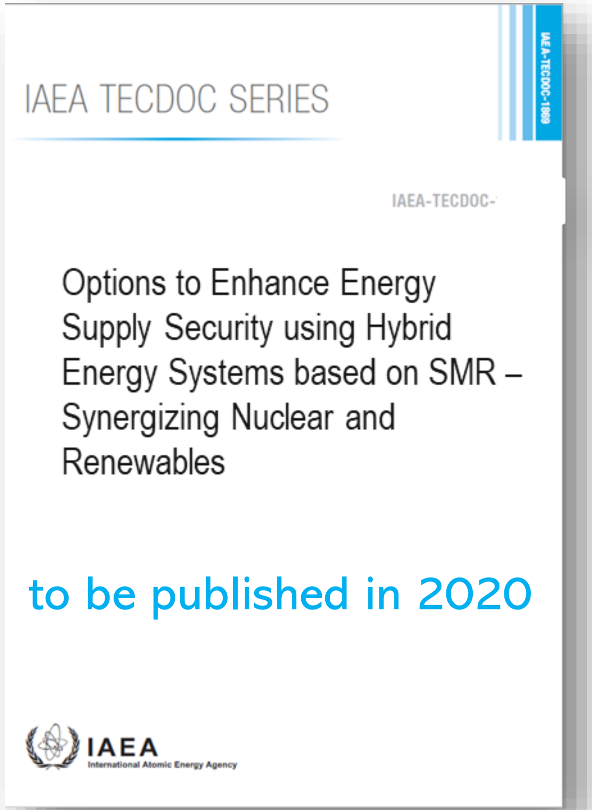
Technology development for SMRs & HTGRs

SMR Renewables Hybrid Energy System to Reduce GHG Emission

Case Studies

- IRIS
- SMR, biomass and wind
- NuScale and wind
- Capacity factor studies



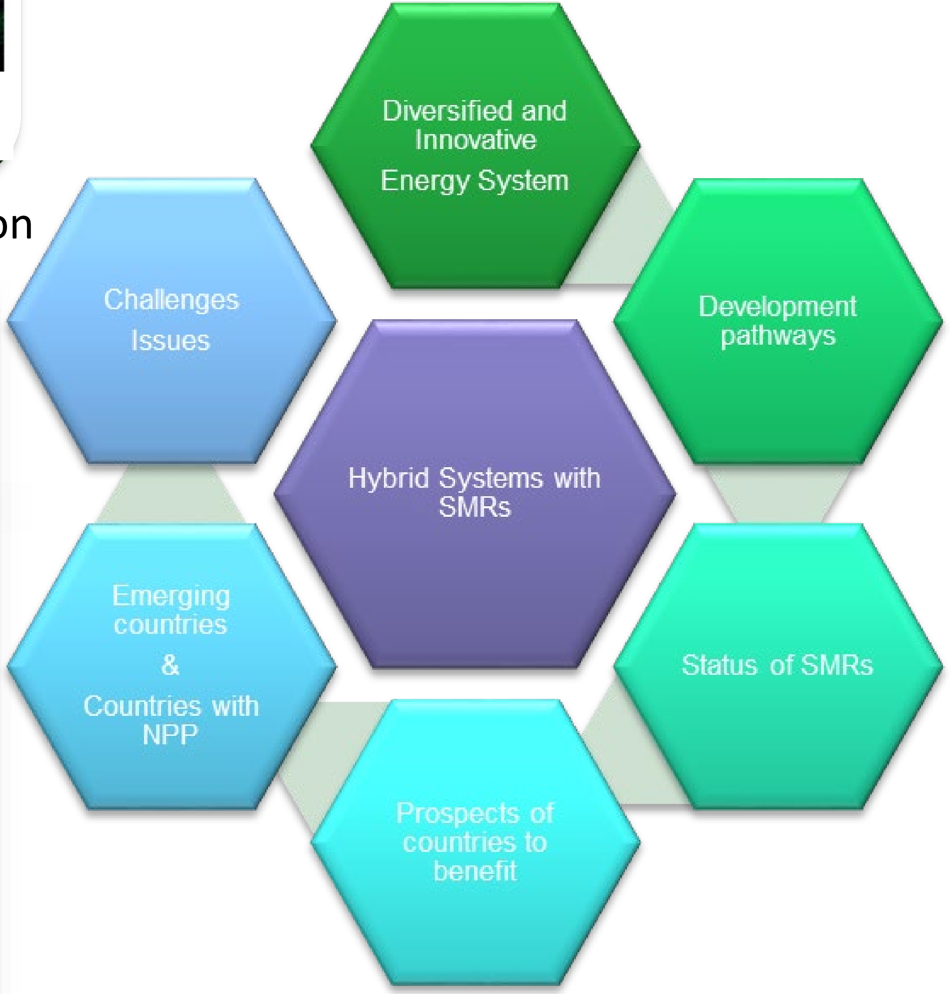

IAEA TECDOC SERIES

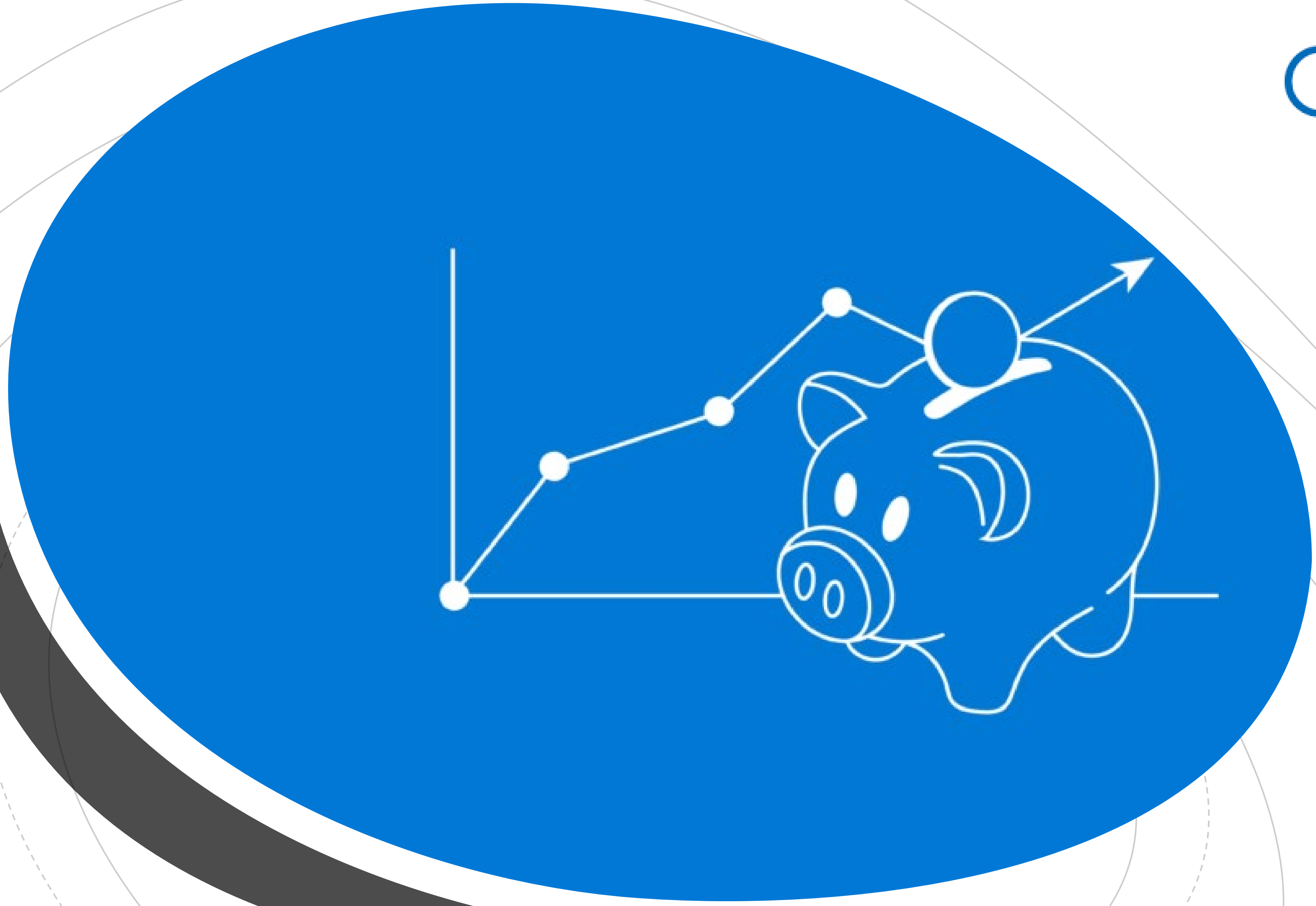
IAEA-TECDOC-

Options to Enhance Energy Supply Security using Hybrid Energy Systems based on SMR – Synergizing Nuclear and Renewables

to be published in 2020

IAEA
International Atomic Energy Agency





Economics

Economy of scale

Economy of multiples

What is the best?

or micro reactors

It depends …..

Enhanced Safety and Economics

- Can the improved safety characteristics lead to improve economics?
  - Need fewer safety systems
  - Less expensive safety class high equipment
- Safety achieved by:
  - Low power density = large vessel and relatively large buildings
  - Coated particle fuel = higher manufacturing cost compared to LWR fuel
  - Integrated designs and passive systems
- Cost saving can perhaps be achieved by:
  - Simplicity and decreased number of safety systems
  - Other quantifiable / indirect savings due to safety?
  - Reduced insurance premiums?
  - …. or public acceptance?

Benefits of SMRs and Modularity

- Less total capital funds at risk during construction period
- Reduced interest during construction expense
- Capability to better match generation capacity to load growth
  - Potential to operate fewer modules should load growth not materialize
  - Potential to add more modules should load demand increase

Capital costs for SMRs

Key Topics	Prospects	Impediments
Capital component of levelized cost of power	Potential decrease in case of large scale and serial production	Require large initial order *(e.g. 50 – 80 modules)*
Comparison of material quantities	Design saving	Standardization of new structure, system, components and materials
Impact of local labour and productivity	○ Reduced construction time for proven design ○ Lesser work force required with modular construction (case by case)	FOAK deployment of multi-module plant with modular construction technology versus stick-build
Cost of licensing	Based on LWRs technology - easier licensing, but still could take long in established nuclear regulators	First of a kind; Time required for modifying the existing regulatory and legal frameworks
Ensuring all necessary equipment is included in the cost estimate, e.g. there is no 'missing equipment'	Learning curve: the higher the number of SMR built on the same site is, the better the cost effectiveness of construction activities on site	Cost impact by delayed component delivery or defect during shipping
Assurance of reliable estimates of technology holder equipment prices	Similar among vendors	Manufacturing of FOAK components

- **What are the major material quantities?**
- **Do they align with the projection of expected capital costs?**
- **What is the expected capital cost of the *n*th of a kind (NOAK) unit versus the cost of the first of a kind (FOAK) unit?**

We will only know after we build and operate SMRs

Challenges to deployment

Advantages, Issues & Challenges

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

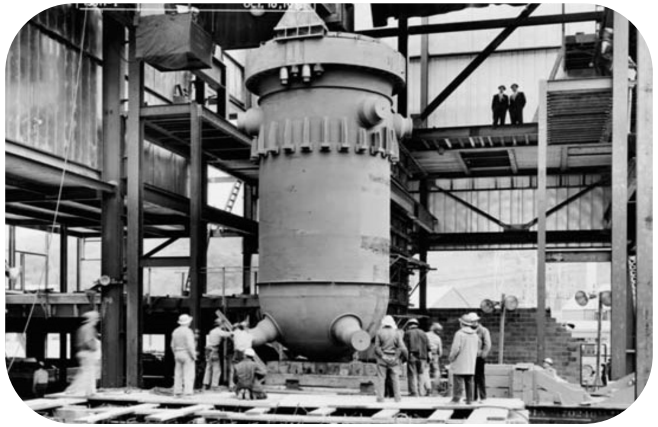
Technology issues

- 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

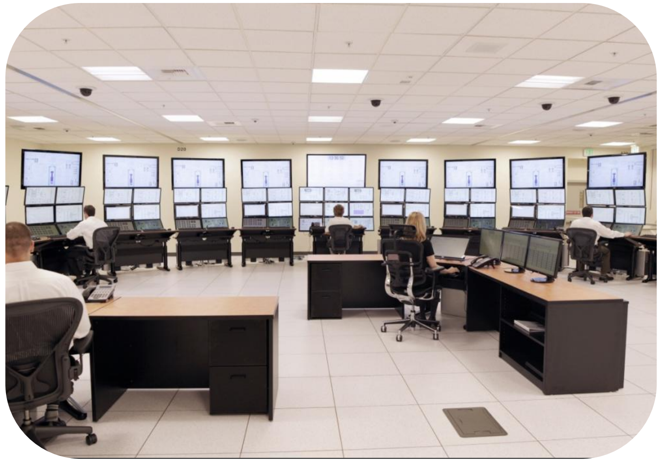
- Time from design-to-deployment
- Highly competitive budget source for design development
- Economic competitiveness: affordability & generation cost
- Availability of *off-the-shelf* design for newcomers
- Operating scheme in an integration with renewables

SMR Challenges

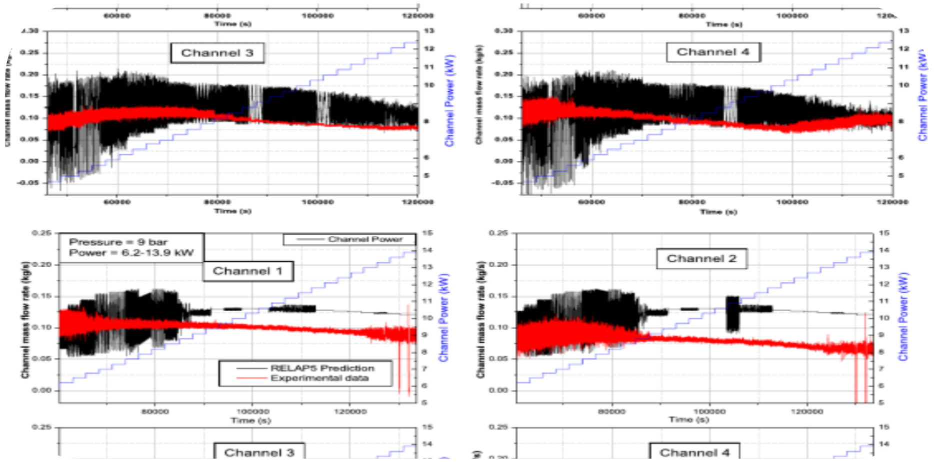


Standardization of first-of-a-kind engineering structure, systems and components

Defining source term for **multi-module** SMR Plants with regards to determining **emergency planning zone**

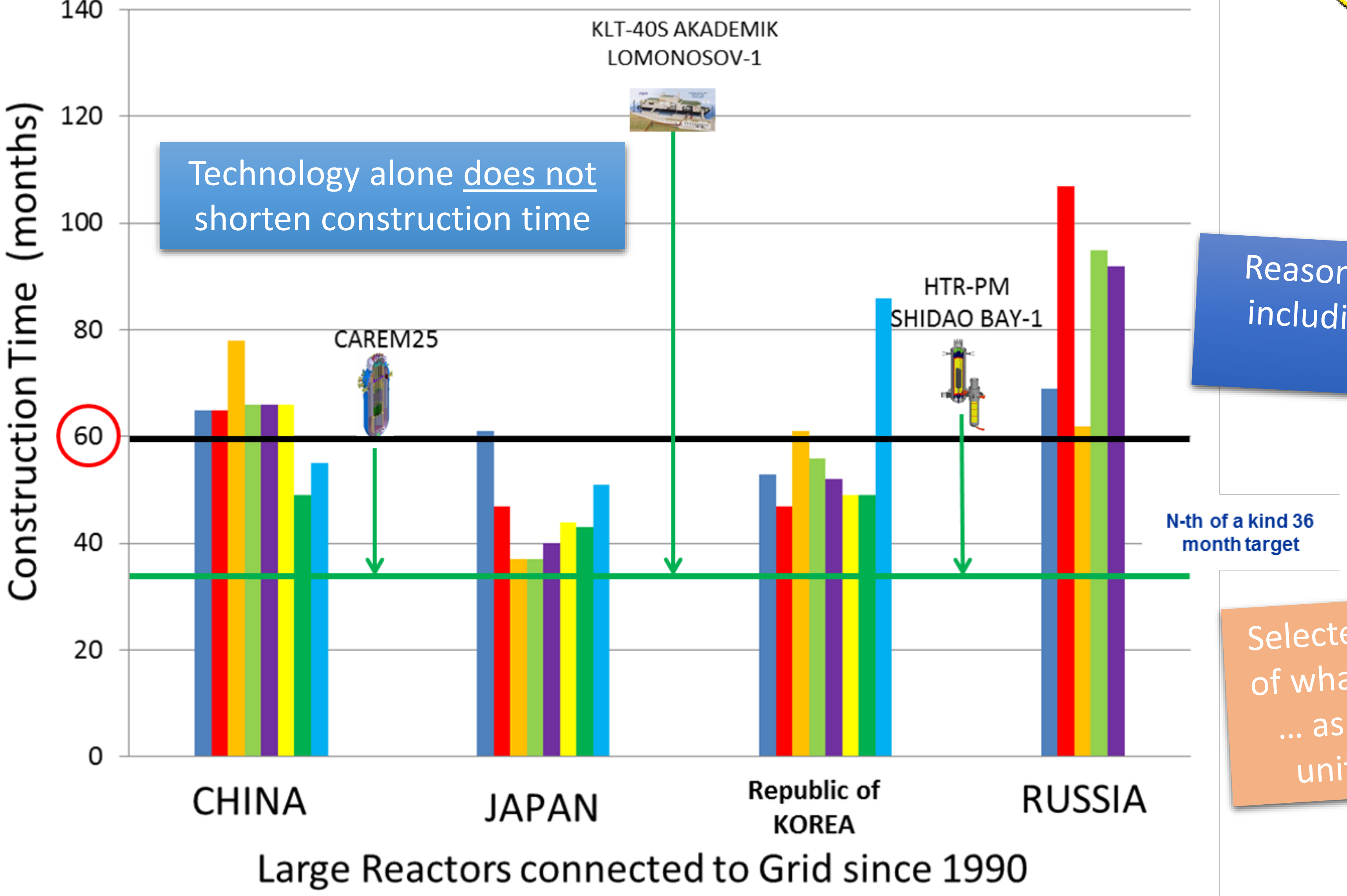


Control room staffing for **multi-module** SMR Plants



Rational **start-up procedure** for **natural circulation** integral PWR designs

Key Challenge: Construction Time



Reasons for delayed are varied, including to incorporate safety lessons learned.

Selected the best examples of what large NPP can offer … as NOAK and multiple units on the same site

Key Barriers/Challenges to Deployment

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- Limited ***near-term commercial availability***
- Technology developers ability to secure investors for design development and deployment: *first domestically, then international markets*
  - *may be an opportunity to cooperate*
- **Economic** competitiveness
  - Need economy of numbers (vs economy of scale) …
- Regulatory, licensing and **safety issues**.
  - *FOAK, passive features, integrated designs, different technologies*
- Technology Maturity
  - Water cooled SMRs (iPWR and BWRs) based on mature technology
  - HTGR mature technology (with steam generator and Tout < 850 ^{o}C)
  - MSR has limited operation experience –some challenges to be solved

NEED GOVERNMENT COMMITMENT TO REALIZE DEMONSTRATIONS PROJECTS!

One example…
Status of SMR pre-licensing in Canada

Vendor	Name / cooling type	(MWe)	Applied for	Review start date	Status
Terrestrial Energy Inc.	IMSR Integral Molten Salt Reactor	200	Phase 1	April 2016	Phase 1 complete
			Phase 2	December 2018	Phase 2 assessment in progress
NuScale Power, LLC	NuScale Integral Pressurized Water Reactor	60	Phase 2*	January 2020	Phase 2 assessment in progress
Ultra Safe Nuclear Corporation / Global First Power	MMR-5 and MMR-10 High Temperature Gas	5-10	Phase 1	December 2016	Phase 1 complete
			Phase 2	Pending	Project start pending
X Energy, LLC	Xe-100 High-temperature gas	75	Phase 2*	July 2020	Project start pending
LeadCold Nuclear Inc.	SEALER Molten Lead	3	Phase 1	January 2017	Phase 1 on hold at vendor's request
Advanced Reactor Concepts Ltd.	ARC-100 Liquid Sodium	100	Phase 1	Fall 2017	Assessment in progress
U-Battery Canada Ltd.	U-Battery High-Temperature Gas	4	Phase 1	Pending end 2019	Project start pending
Moltex Energy	Moltex Energy Stable Salt Reactor Molten Salt	300	Series Phase 1 and 2	December 2017	Phase 1 assessment in progress
SMR, LLC. (A Holtec International Company)	SMR-160 Pressurized Light Water	160	Phase 1	July 2018	Assessment in progress
GE-Hitachi Nuclear Energy	BWRX-300 boiling water reactor	300	Phase 2*	January 2020	Assessment in Progress

First Canadian SMR license application submitted

- **The Canadian Nuclear Safety Commission (CNSC) has received the first licence application for a small modular reactor.**
- **The application from Global First Power (GFP), with support from Ontario Power Generation and Ultra Safe Nuclear Corporation (USNC), supports a proposal to deploy a Micro Modular Reactor plant at Chalk River in Ontario.**
  - in response to an invitation issued in April 2018 by Canadian Nuclear Laboratories (CNL) to SMR project proponents for the construction and operation of an SMR demonstration unit at a CNL-managed site.
- **The MMR is a 15 MW (thermal), 5 MW (electrical) high-temperature gas reactor**
  - the reactor uses fuel in prismatic graphite blocks
  - TRISO coated particle fuel encased within a fully dense silicon carbide matrix
- **MMR technology would serve as a model for future off-grid SMR deployment in Canada, to provide low-carbon energy and heat to remote industry and northern communities**

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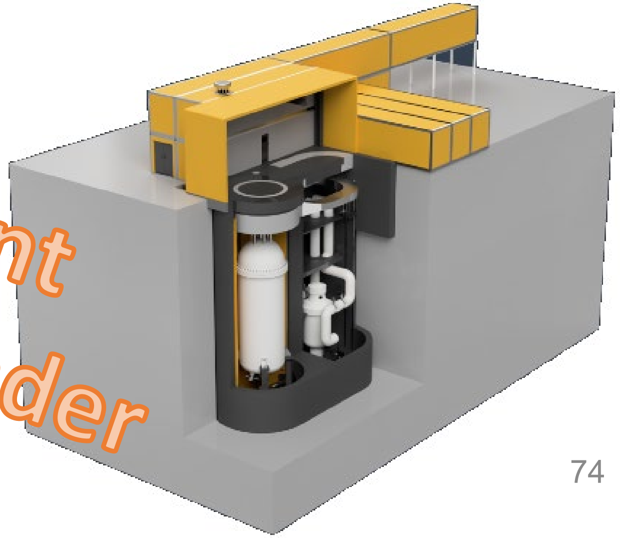
First Canadian SMR licence application submitted

02 April 2019

Share

The Canadian Nuclear Safety Commission (CNSC) has received the first licence application for a small modular reactor. The application from Global First Power (GFP), with support from Ontario Power Generation and Ultra Safe Nuclear Corporation (USNC), supports a proposal to deploy a Micro Modular Reactor plant at Chalk River in Ontario.

Environment Assessment under way



Paper reactors….

The Rickover Effect

UNIVERSITY OF LEEDS

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A paper reactor [new reactor concept] has the following characteristics:

- it is simple
- it is small
- it is cheap
- it is lightweight
- it can be built very quickly
- very little development is required and
- it will use off the shelf components; it is in the study phase and not being built now.

By contrast a real reactor has the following characteristics:

- it is complicated
- it is large; it is heavy
- it is being built now
- it is behind schedule
- requires an immense amount of development on apparently trivial items;
- takes a long time to build because of its engineering development problems.

MAY SMRs not only remain as paper reactors…

Hyman G. Rickover in pp. 158-159 *The Rickover Effect* (1992) by Theodore Rockwell, Naval Institute Press.

From: Cost-time project performance in megaprojects in general and nuclear in particular,

by Dr Giorgio Locatelli

Concluding Summary

Concluding Summary

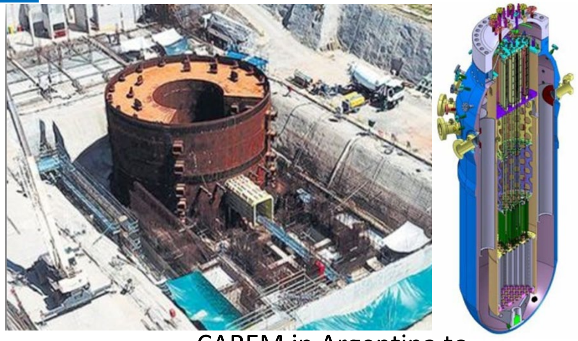
- The “SMR wave” is BIG…. with ever increasing interest and promise
- SMR is an attractive option to enhance energy supply security
  - **In newcomer countries with smaller grids and less-developed infrastructure**
  - **In advanced countries for power supplies in remote areas and/or specific applications**
- Innovative SMR concepts have common technology development challenges, including regulatory and licensing frameworks
- SMRs designed to be more flexible and could be the on-demand, carbon-free electricity generator in grid systems that contain large percentages of intermittent renewable energy.
- The potential impact on non-electric applications are even larger than the electricity market.
- We urgently need more demonstration units to come online to endure SMRs become a reality…

We have to build on the early successes

The 3 Forerunners: 1 design in operation, 2 in advanced stage of construction

KLT-40S in Russian Federation already in **commercial operation** since May 2020

HTR-PM in China to start **operation 2021**



CAREM in Argentina to start **operation by 2023**

Land Based Water Cooled Reactors

CAREM	SMART	RUTA-70	DHR400
ACP100	UNITHERM	NuScale	RITM-200
CAP200	VK-300	mPOWER	NUWARD
IRIS	KARAT-45	W-SMR	BWRX-300
DMS	KARAT-100	SMR-160	HAPPY200
IMR	ELENA	UK-SMR	CANDU SMR

Micro Reactors

IHTR	MMR-5
IMSBR	MMR-10
eVinci	AURORA
U-Battery	MoveluX

Fast Reactors

4S	W-LFR	SSTAR LFR
BREST-OD-300	SEALER	URANUS
SVBR-100	LFR-AS-200	ARC100
EM²	LFR-TL-X	

High Temperature Gas-cooled Reactors

HTR-PM	MHR-100	XE-100	HTTR-30
DPP-200	PBMR-400	A-HTR 100	HTR-10
GT-MHR	HTMR-100	MMR	RDE
MHR-T	SC-HTGR	GTHTR300	StarCore

Marine Based Water Cooled Reactors

ACPR50S	VBER-300
KLT-40S	ABV-6E
RITM-200M	SHELF

Molten Salt Reactor

IMSR	SSR-WB	CA WB
CMSR	SSR-TS	KP-FHR
THORCON	LFTR REACTOR	MCSFR
FUJI ITMSF	MK1 PB-FHR	

Paper -> Concrete

Thank You

Email: F.Reitsma@iaea.org

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Upcoming Webinars

26 August 2020	MSR Safety Evaluation in the US	Dr. David Holcomb, ORNL, USA
22 September 2020	Maximizing Clean Energy Integration: The Role of Nuclear Renewable Technologies in Integrated Energy Systems	Dr. Shannon Bragg-Sitton, INL, USA
28 October 2020	Global potential for small and micro reactor systems to provide electricity access	Prof. Amy Schweikert, Colorado School of Mines, USA