IAEA 60 Years
Atoms for Peace and Development

ESI-CIL Nuclear Governance Project Conference Series
Small Modular Nuclear Reactors: The Outlook for Deployment
Jen Tanglin Hotel, Singapore, 8th November 2017

Advances in Small Modular Reactor Design and Technology Development for Near-term Deployment

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

Outline

Rationale of SMR Technology Development

Water-cooled Small Modular Reactors

High-temperature Gas-cooled and Gen IV Reactors

Status and major accomplishment in Member States

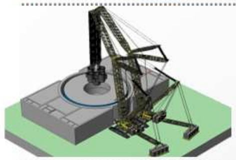
SMR: definition & rationale of developments

Advanced Reactors to produce up to 300 MW(e), built in factories and transported as modules to sites for installation as demand arises.

A nuclear option to meet the need for flexible power generation for wider 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

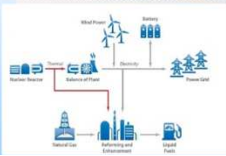
Wider range of Users

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

Salient Design Characteristics

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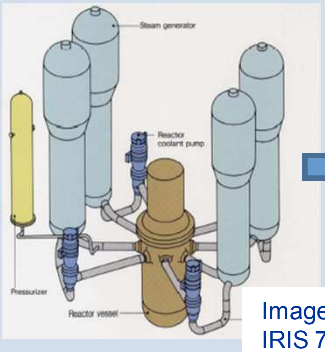
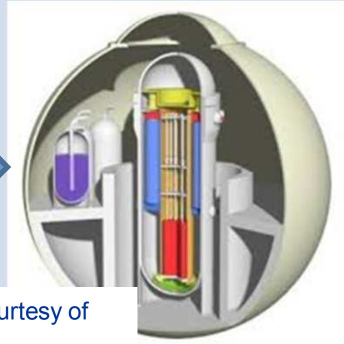
Simplification by Modularization and System Integration





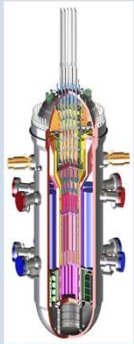
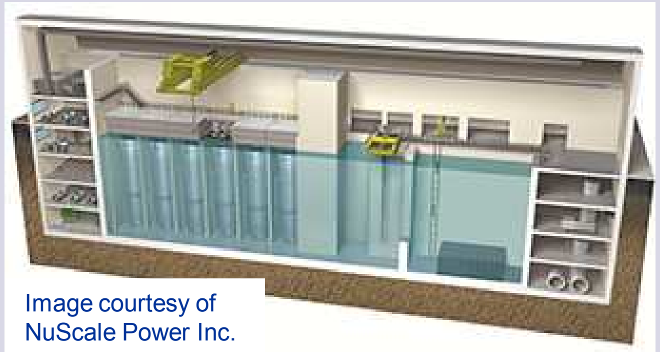


Image courtesy of IRIS 7 .

Multi-module Plant Layout Configuration



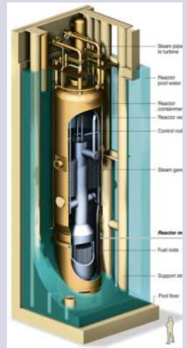


Image courtesy of NuScale Power Inc.

Underground construction for enhanced security and seismic

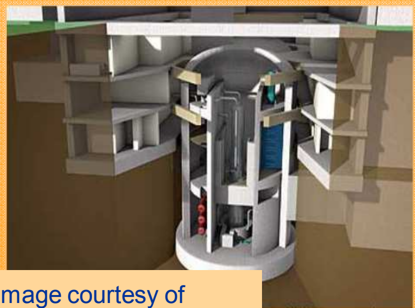


Image courtesy of BWX Technology, Inc.

Enhanced Safety Performance through Passive System

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

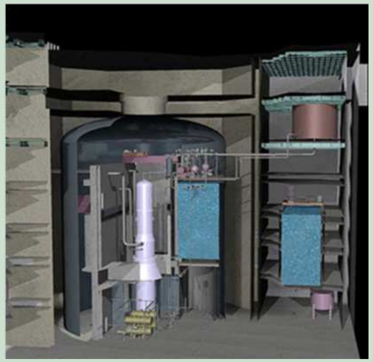


Image courtesy of BWX Technology, Inc.

SMRs for immediate & near term deployment

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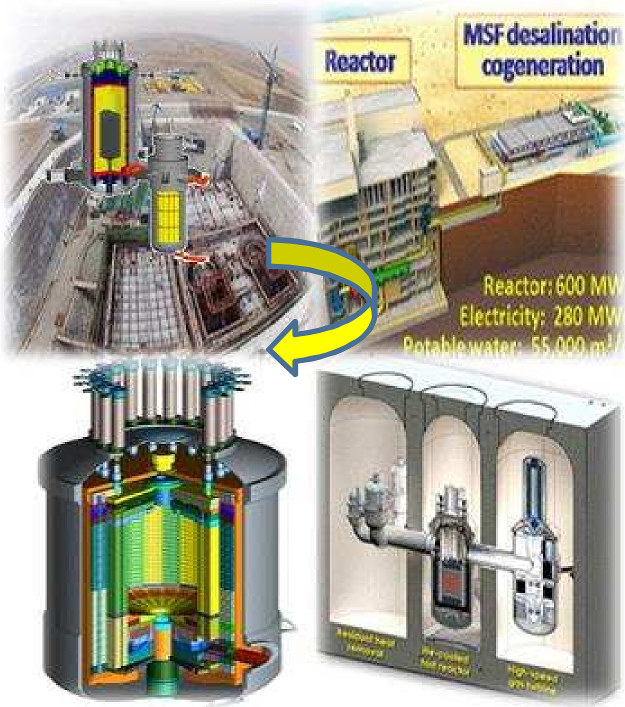
Water cooled SMRs

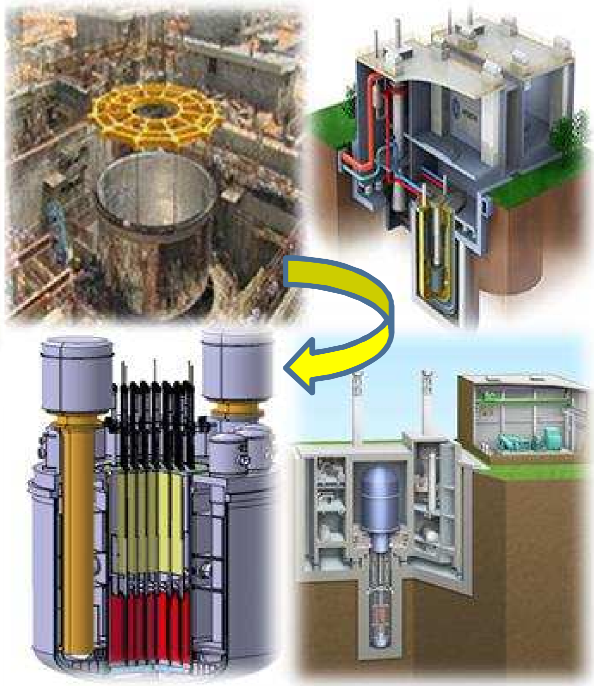
CAREM	
SMART	
ACP100	
NuScale	

Gas cooled SMRs



HTR-PM	
GTHTR300	
HTMR100	
EM^2	

Liquid metal cooled SMRs



PFBR	
PRISM	
SVBR	
4S	

Water cooled SMRs (Examples)

CAREM

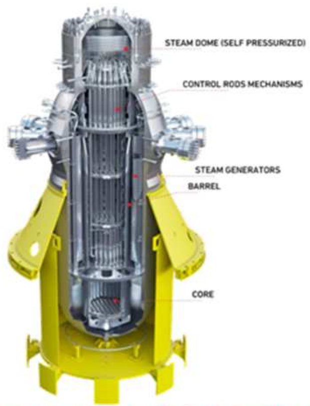


Image Courtesy of CNEA, Argentina

Under Construction

Integral PWR type SMR

Naturally circulation

- 30 MW(e) / 100 MW(th)
- Core Outlet Temp: 326°C
- Fuel Enrichment: 3.1% UO_2
- In-vessel control rod drive mechanisms
- Self-pressurized system
- Pressure suppression containment system
- Target commissioning: October 2018

SMART

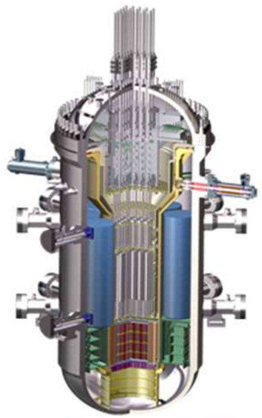


Image Courtesy of KAERI, Korea

Licensed/Certified

Integral PWR type SMR

Forced circulation

- 100 MW(e) / 330 MW(th)
- Core Outlet Temp: 323°C
- Fuel Enrichment: 5% UO_2
- Multi-purpose application: electricity production, sea water desalination, district heating and process heat for industries
- Passive safety systems along with severe accident mitigation features
- Standard Design Approval: 4 July 2012

ACP100

Image Courtesy of CNNC, China

Basic Design

Integral PWR type SMR

Forced circulation

- 100 MW(e) / 310 MW(th)
- Core Outlet Temp: 323°C
- Fuel Enrichment: (2-4)% UO_2
- Underground nuclear island and spent fuel pool-enhanced protection against external hazards
- Containment vessel installed in water pool with fully passive safety facilities
- Modules per plant: (1 – 8)
- Undertaking IAEA's Generic Reactor Safety Review.

NuScale

Image Courtesy of NuScale Power, USA

Under development

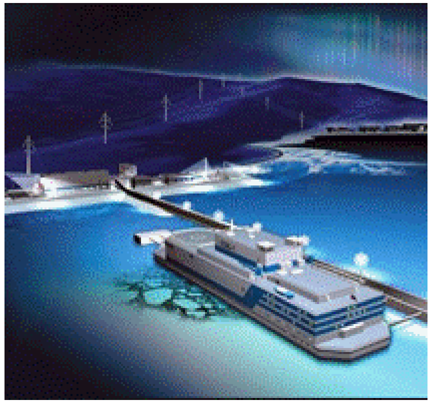
Integral PWR type SMR

Naturally circulation

- 50 MW(e) / 160 MW(th) per module
- Core Outlet Temp: 302°C
- Fuel Enrichment: 4.95% UO_2
- Modules per plant: 12
- Containment vessel immersed in reactor pool that provide unlimited coping time
- Underground installment of containment vessel
- Submit Design Certification Review Application: 12/2016

Marine-based SMRs *(Examples)*

KLT-40S

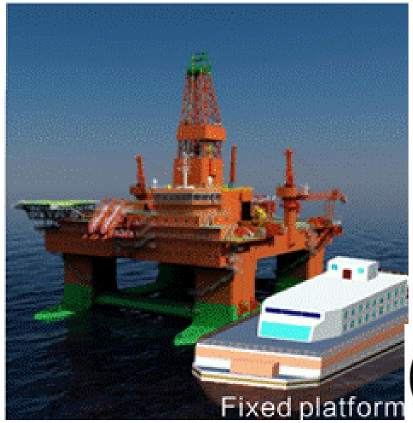


Floating Power Units (FPU)

Compact-loop PWR

- 35 MW(e) / 150 MW(th)
- Core Outlet Temp.: 316ºC
- Fuel Enrichment: 18.6%
- FPU for cogeneration
- Without Onsite Refuelling
- Fuel cycle: 36 months
- Spent fuel take back
- Advanced stage of construction, planned commercial start: 2019 – 2020

ACPR50S



FPU and Fixed Platform

Compact-loop PWR

- 60 MW(e) / 200 MW(th)
- Core Outlet Temp.: 322ºC
- Fuel Enrichment: < 5%
- FPU for cogeneration
- Once through SG, passive safety features
- Fuel cycle: 30 months
- To be moored to coastal or offshore facilities
- Completion of conceptual design programme

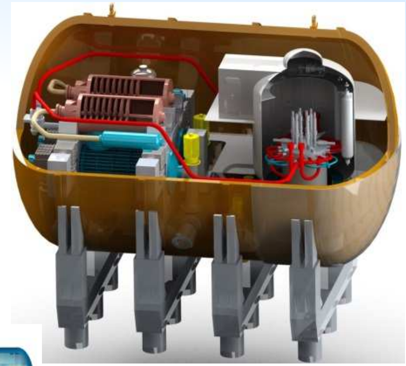
FLEXBLUE

Transportable, immersed nuclear power plant

PWR for Naval application

- 160 MW(e) / 530 MW(th)
- Core Outlet Temp.: 318ºC
- Fuel Enrichment 4.95%
- Fuel Cycle: 38 months
- passive safety features
- Transportable NPP, submerged operation
- Up to 6 module per on shore main control room

SHELF



Transportable, immersed NPP

Integral-PWR

- 6.4 MW(e) / 28 MW(th)
- 40,000 hours continuous operation period
- Fuel Enrichment: < 30%
- Combined active and passive safety features
- Power source for users in remote and hard-to-reach locations;
- Can be used for both floating and submerged NPPs

Images reproduced courtesy of OKBM Afrikantov, CGNPC, DCNS, and NIKIET

SMR for Non-Electric Applications

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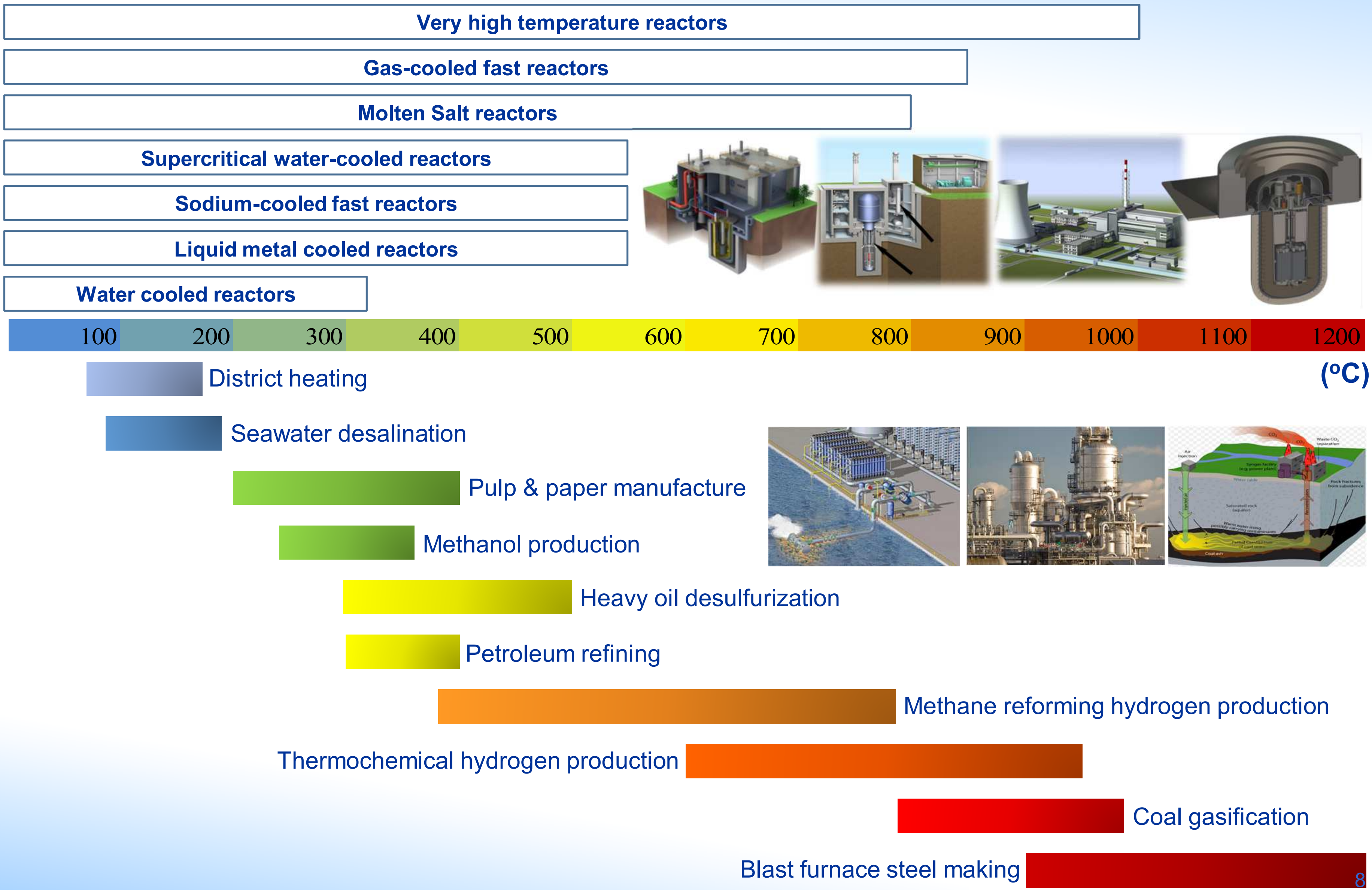
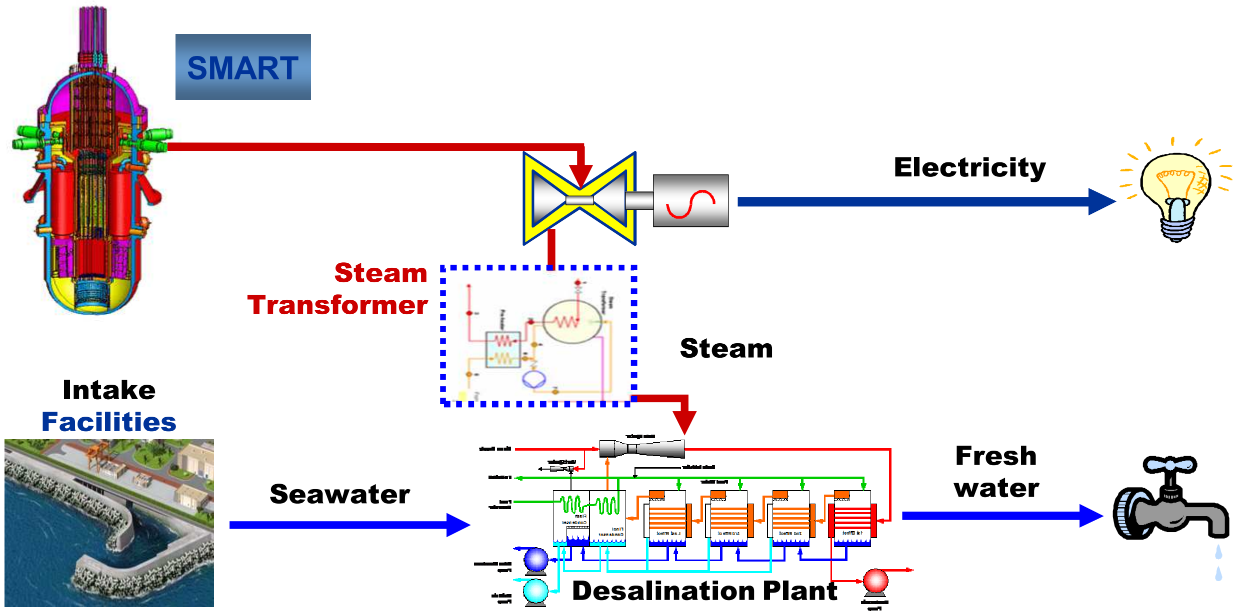


Cogeneration Concept

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 (SMART)

- ❑ 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

High Temperature Gas-cooled Reactor Technology Development for Near-term Deployment

High Temperature Gas Cooled SMRs (Examples)

HTR-PM

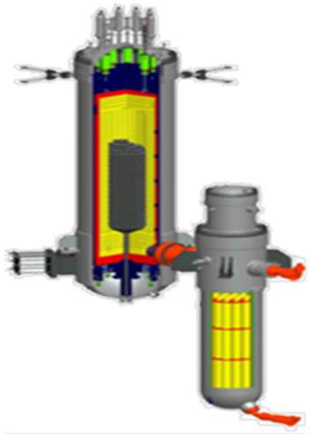


Image Courtesy of INET, China

Modular Pebble Bed High Temperature Gas Cooled Reactor

Helium/Graphite cooled

- 210 MW(e) / 500 MW(th)
- Core Outlet Temp: 750°C
- Fuel Enrichment: 8.5% UO_2 TRISO coated particle
- No. of fuel spheres: 420,000 /module
- Modules per plant: 2
- Advanced stage of construction- expected to be commissioned by 2018

GTHTR300

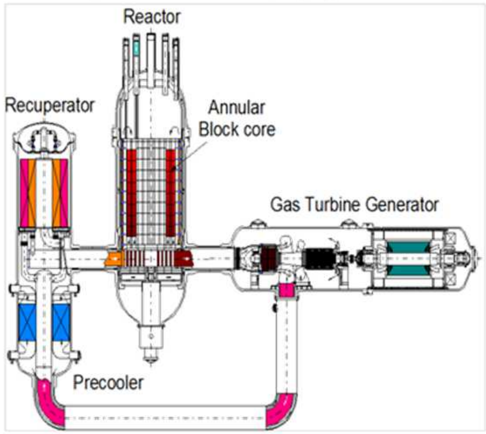


Image Courtesy of JAEA, Japan

Prismatic High Temperature Gas Cooled Reactor

Helium/Graphite cooled

- 100-300 MW(e) / 600 MW(th)
- Core Outlet Temp: 850-950°C
- Fuel Enrichment: 14 % UO_2 TRISO ceramic coated particle
- Fuel temperature limit: 1600°C
- Modules per plant: 4
- Inherent safety features
- Multi-purpose application: power generation, hydrogen production, process heat, steelmaking, desalination and district heating

HTMR100

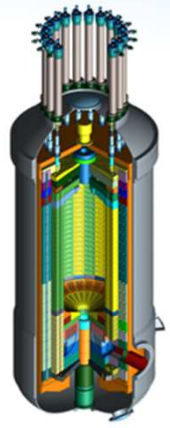


Image Courtesy of STL, South Africa

High temperature Gas Cooled Reactor

Helium cooled / graphite moderated

- 35 MW(e) / 100 MW(th) per module
- Core Outlet Temp: 750°C
- Fuel Enrichment: 15% Th/Pu, <10% U_{235} Th/LEU and Th/HEU
- Module per plant: (4-8) pack
- Number of Fuel units: ~150,000 pebbles
- Better load following capability and flexibility in multi-module configuration

EM^2

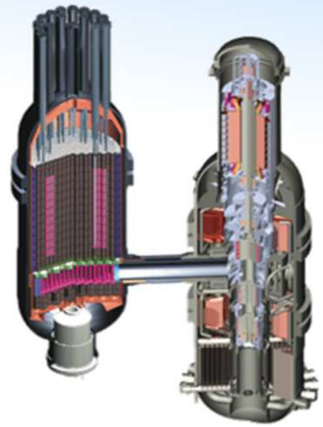


Image Courtesy of General Atomics, USA

High Temperature Gas Cooled Fast Reactor

Helium cooled

- 240 MW(e) and 500 MW(th)
- Refuelling cycle: 30 years
- Core Outlet Temp: 850°C
- Fuel enrichment: 1% U_{235} - 1% Pu, MA coated particle
- Efficiency: 48%
- Fully enclosed in an underground containment
- Utilization of spent fuel
- Simplified power conversion system and 30% reduction in material requirements than that of current NPPs

Other Generation IV SMRs
(Examples)

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PRISM

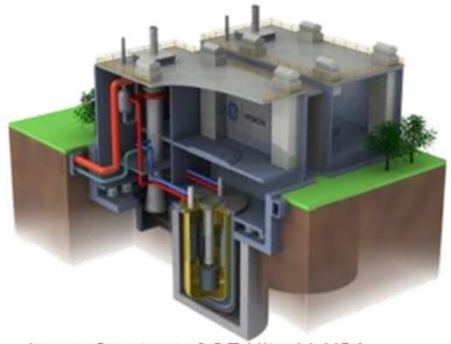

Image Courtesy of GE Hitachi, USA

Power Reactor Innovative Small Modular

Liquid Sodium-cooled Fast Breeder Reactor

- 311 MW(e) / 840 MW(th)
- Core Outlet Temp: 485°C
- Fuel Enrichment: 26% Pu, 10% Zr
- Underground containment on seismic isolators
- For complete recycling of plutonium and spent nuclear fuel

4S

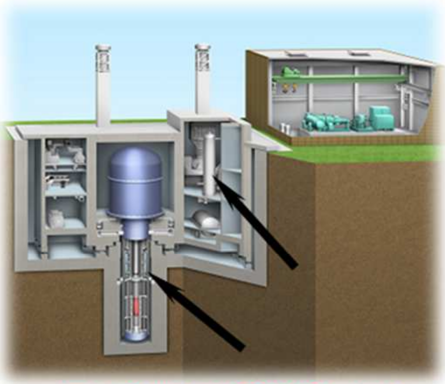

Image Courtesy of TOSHIBA, Japan

Super Safe Small Simple

Sodium-cooled Fast Reactor

- Fuel Cycle: 30 years
- 10 MW(e) / 30 MW(th)
- Core Outlet Temp: 510°C
- Fuel Enrichment < 20%
- Negative sodium void reactivity
- Hybrid of active and passive safety features
- Designed for remote locations and isolated islands, close to towns

SVBR100

Image Courtesy of AKME Engineering, Russia

Heavy Metal Liquid Cooled Fast Reactor 100 MW

Lead Bismuth Eutectic cooled Fast Reactor

- 101 MW(e) / 280 MW(th)
- Core Outlet Temp: 490°C
- Fuel Enrichment 16.5%
- Fuel Cycle: 8 years
- Hybrid of active and passive safety features
- Prototype nuclear cogeneration plant to be built in Dimitrovgrad, Ulyanovsk

IMSR

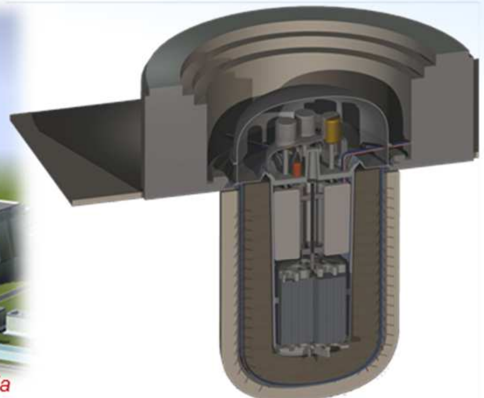

Image Courtesy of Terrestrial Energy, Canada

Integral Molten Salt Reactor

Molten Salt Reactor

- 80, 300 and 600 MW(th)
- Core Outlet Temp: 700°C
- Fuel Cycle: 7 years
- MSR-Burner: Efficient burner of LEU
- MSR-breeder: Thorium breeder
- Ideal system for consuming existing transuranic wastes (Long lived waste)
- Passive decay heat removal in situ without dump tanks

Development Status of HTGRs

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Wealth of past experience

- substantial technology basis
- test reactors in Japan and China
- ready for commercial deployment

Past Experience | **Current test reactors**

DRAGON	PB-1	AVR	FSR	THTR	HTTR	HTR-10
(1963-1976)	(1967-1974)	(1967-1988)	(1976-1989)	(1986-1989)	(since 1998)	(since 2000)

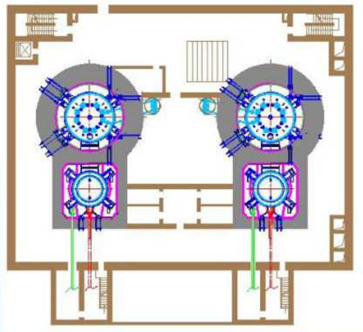
- HTR-PM construction of a commercial demonstration plant

  modular 2 x 250MWth

  operation in 2018

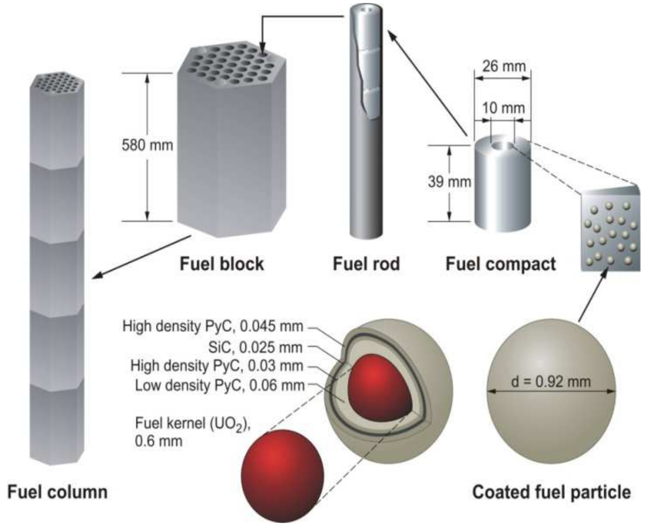
  Shidao Bay,

  Shandong province, China



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 characteristics with no early large release possible
  - 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



Inherent Safety Characteristics

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

Inherent Safety Characteristics

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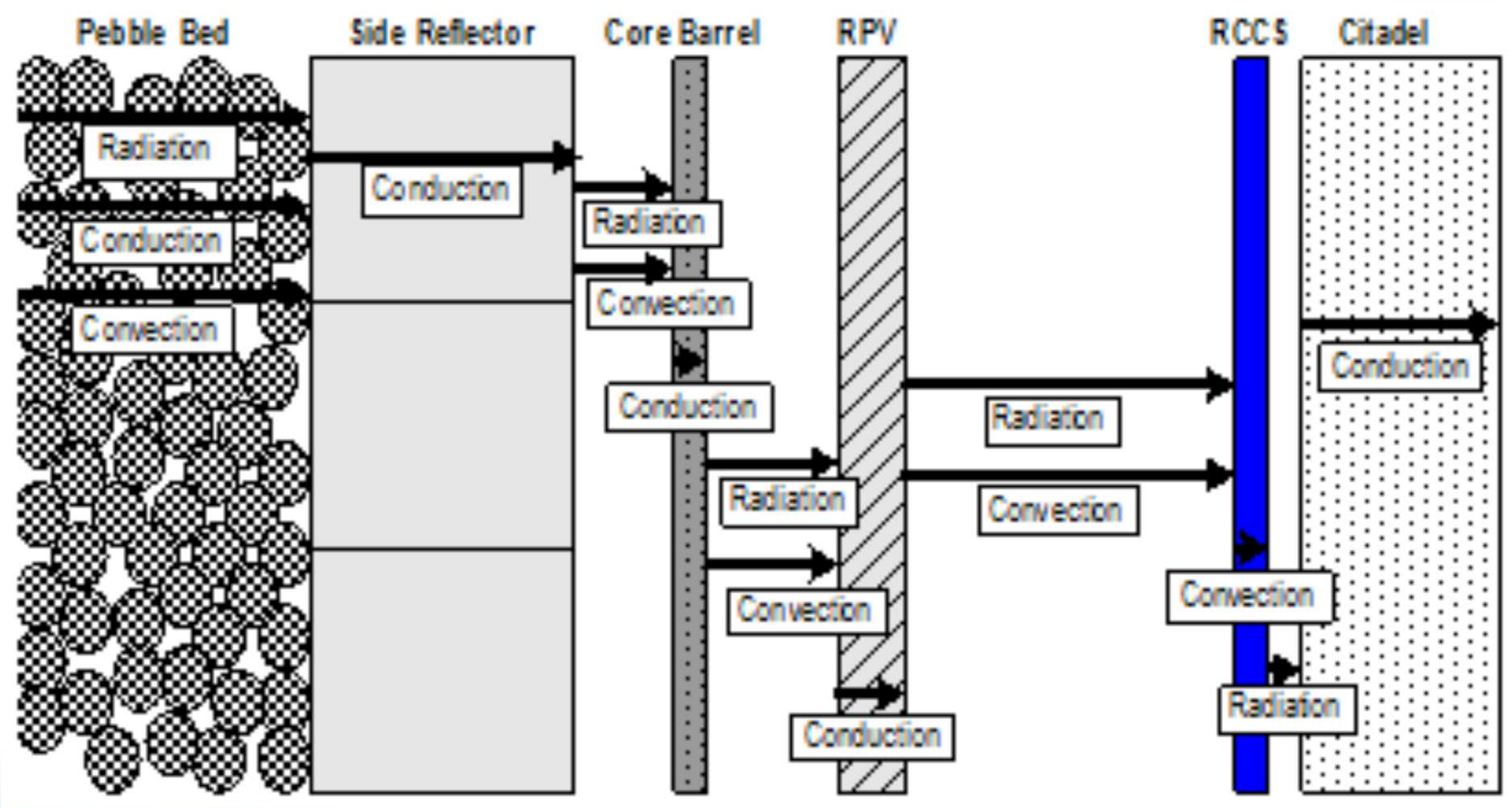
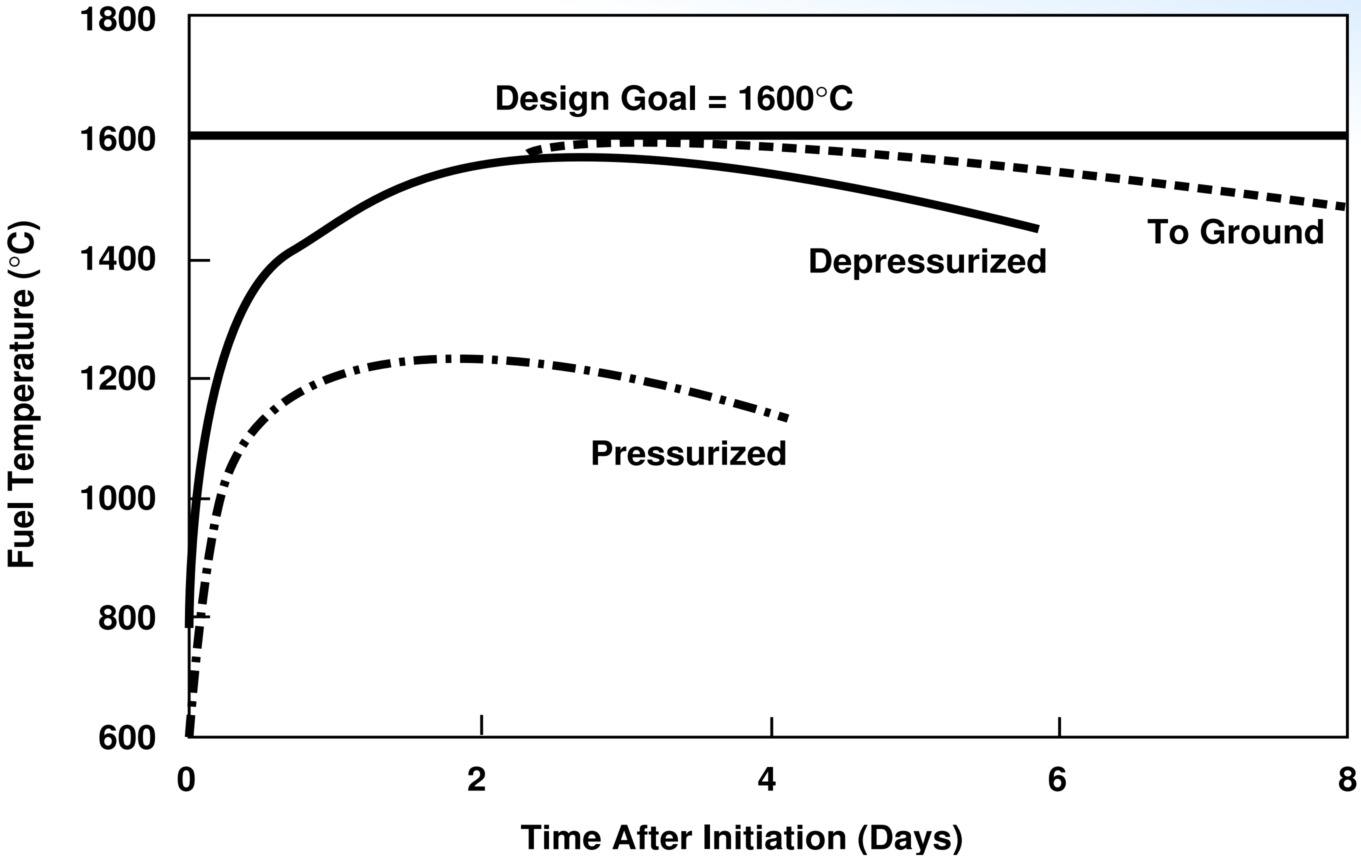
Heat removed passively without primary coolant – all natural means

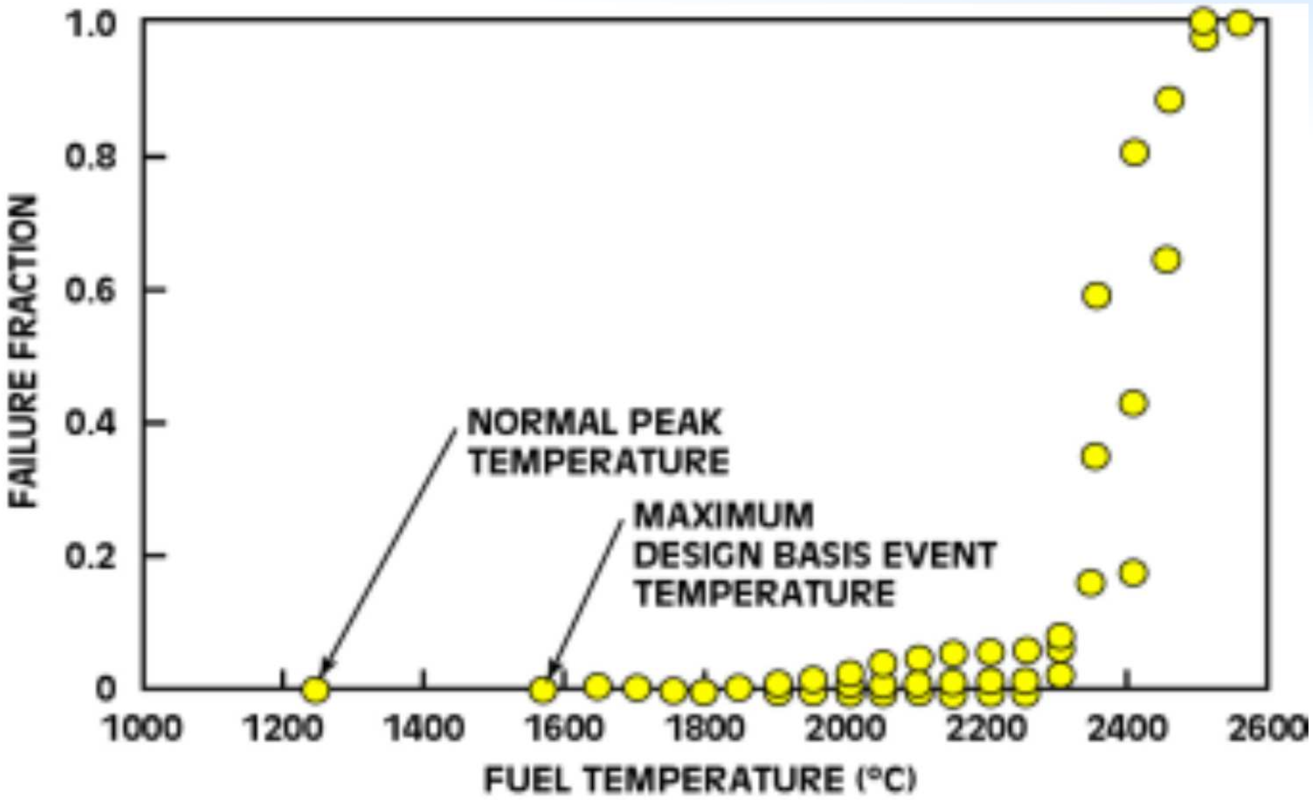


Inherent Safety Characteristics



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

Inherent Safety Characteristics

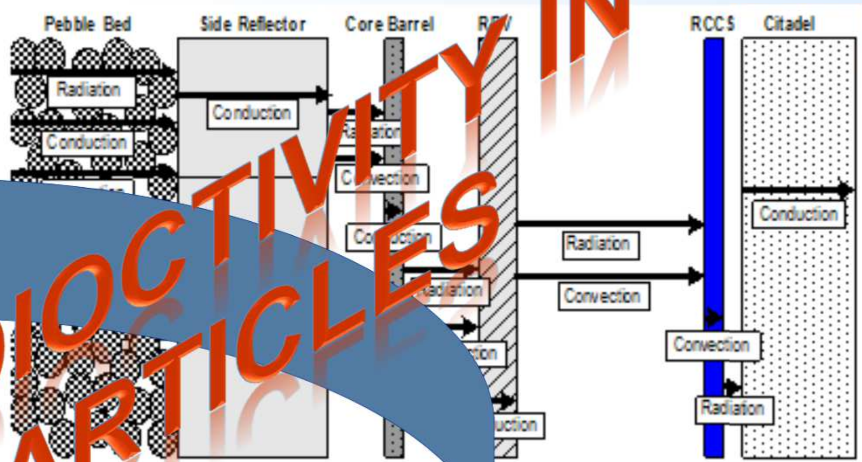


Coated particles stable to beyond maximum accident temperatures

NO Early or Large Radioactivity Release

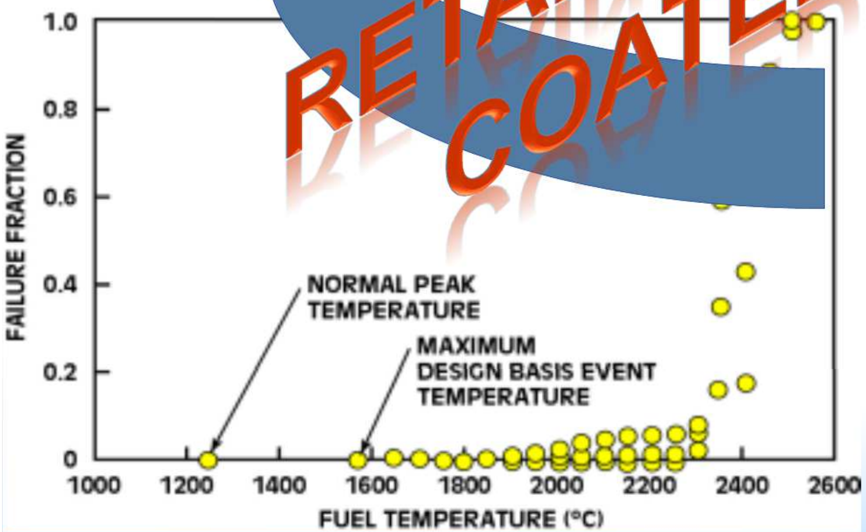
Ceramic fuel retains radioactive materials up to and above 1800˚C

Heat removed passively without primary coolant – all natural means

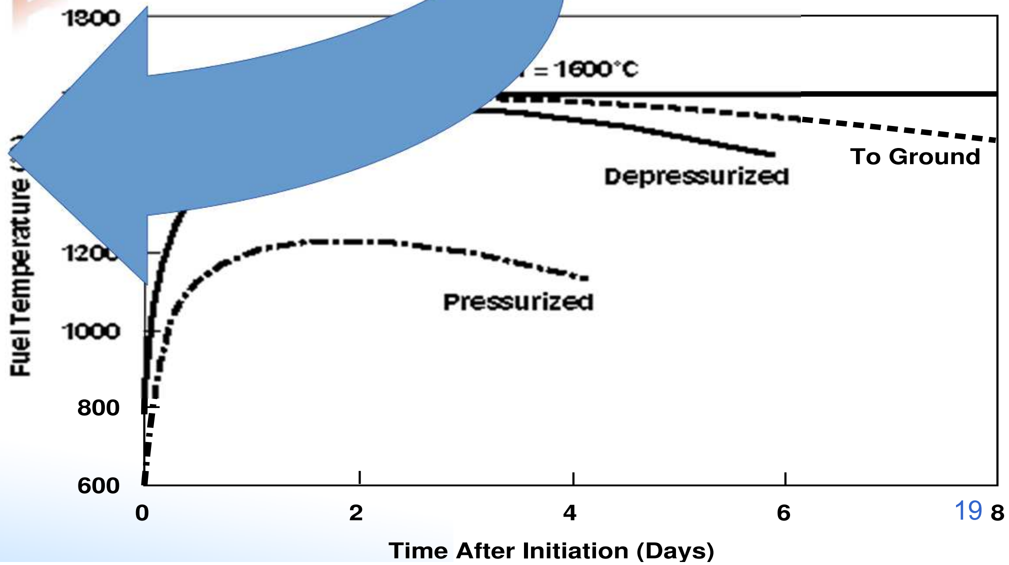


RETAINS RADIOACTIVITY IN COATED PARTICLES

Coated particles stable to beyond maximum accident temperatures



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



Interest in HTGRs

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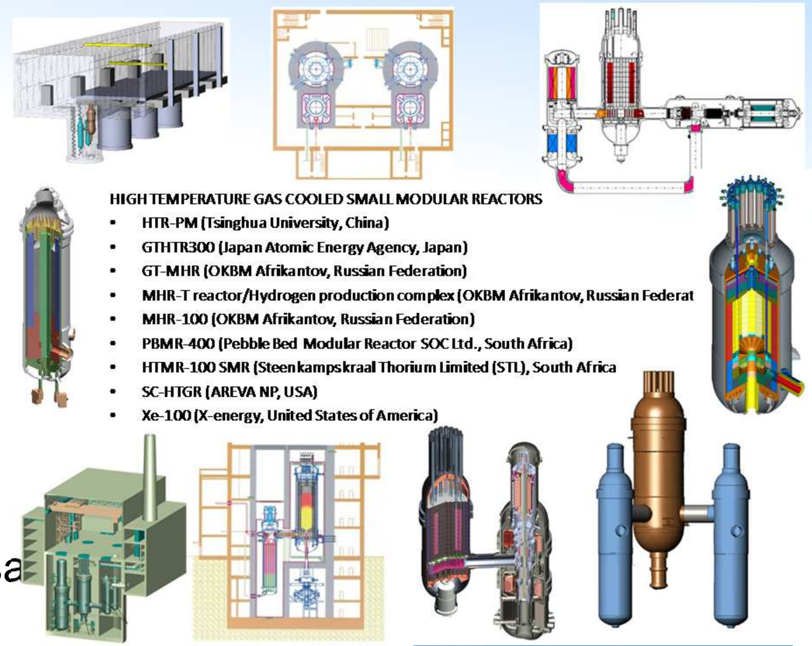
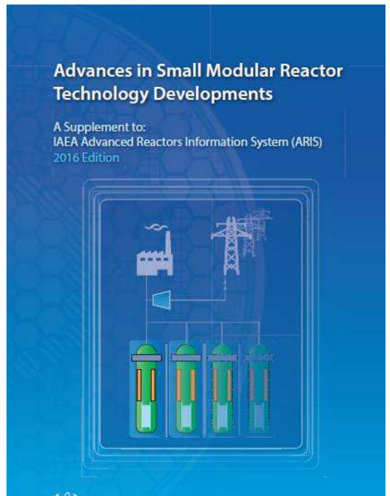
- 14 member states in the TWG-GCRs
- Active projects
  - China (HTR-10 and HTR-PM)
  - Japan (HTTR and hydrogen project)
  - USA, South Africa, Korea, Russian Federation
  - EU research projects

Newcomer countries:

- Indonesia
  - Indonesia completed the concept design and sa
    10MW(th) experimental power reactor
  - Ideal technology for deployment on remote areas / islands
- Saudi Arabia
  - signed an MoU with China for HTR-PM deployment
  - The use of 210 MW(e) HTGR for cogeneration of electricity and industrial process heat, e.g. hydrocarbon and petrochemicals
- Member states that recently expressed interest
  - Poland – new committee to prepare for the possible future implementation of HTGRs
  - Other countries in Asia-Pacific





For inquiries on HTGR, contact:
F.Reitsma@iaea.org

Advantages, Issues & Challenges

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Technology Issues

- 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 Issues

- 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

−

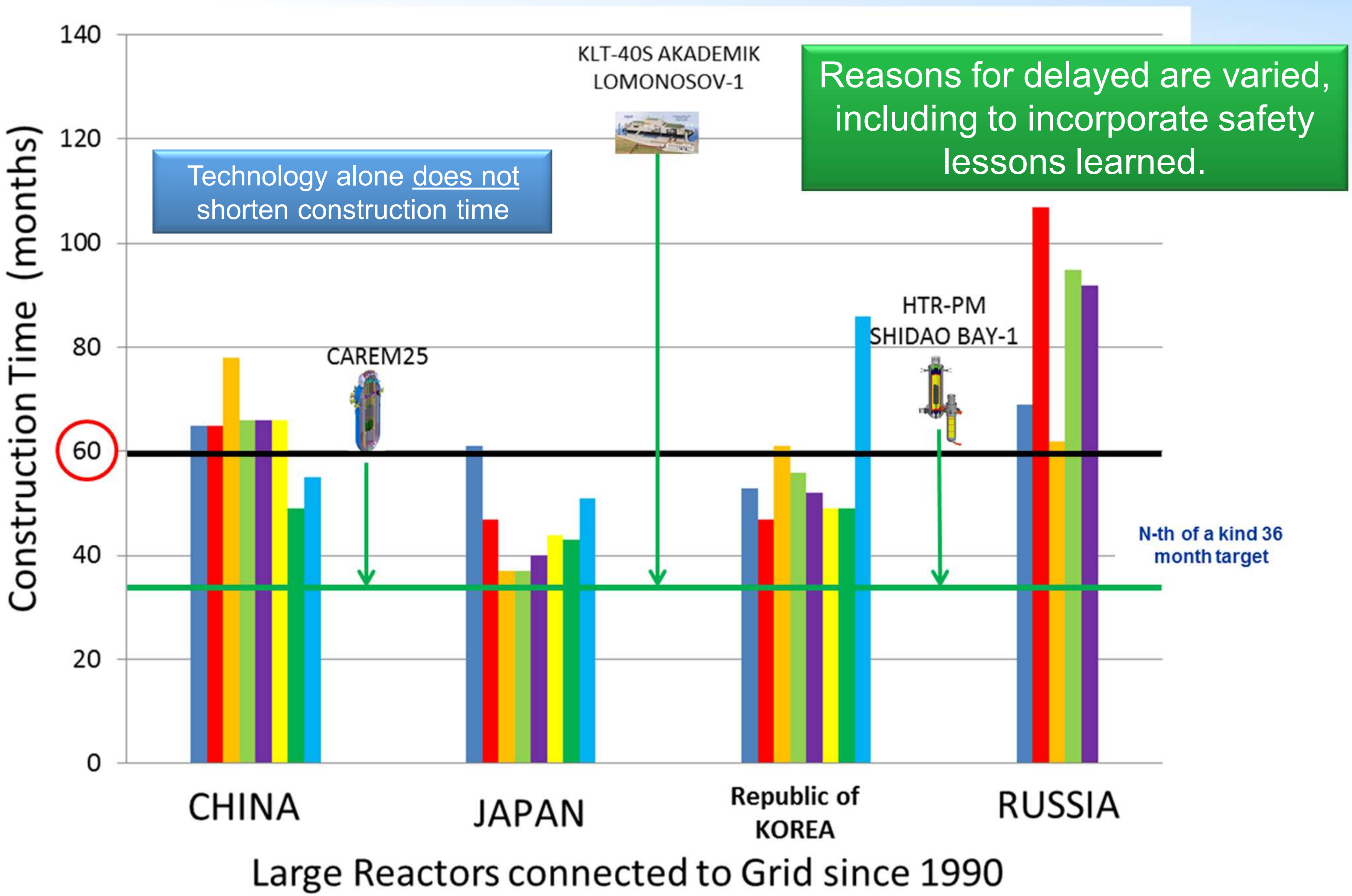
Technology Issues

- Licensability (FOAK designs)
- Non-LWR technologies
- Operability and Maintainability
- Staffing for multi-module plant; Human factor engineering;
- Supply Chain for multi-modules
- Advanced R&D needs

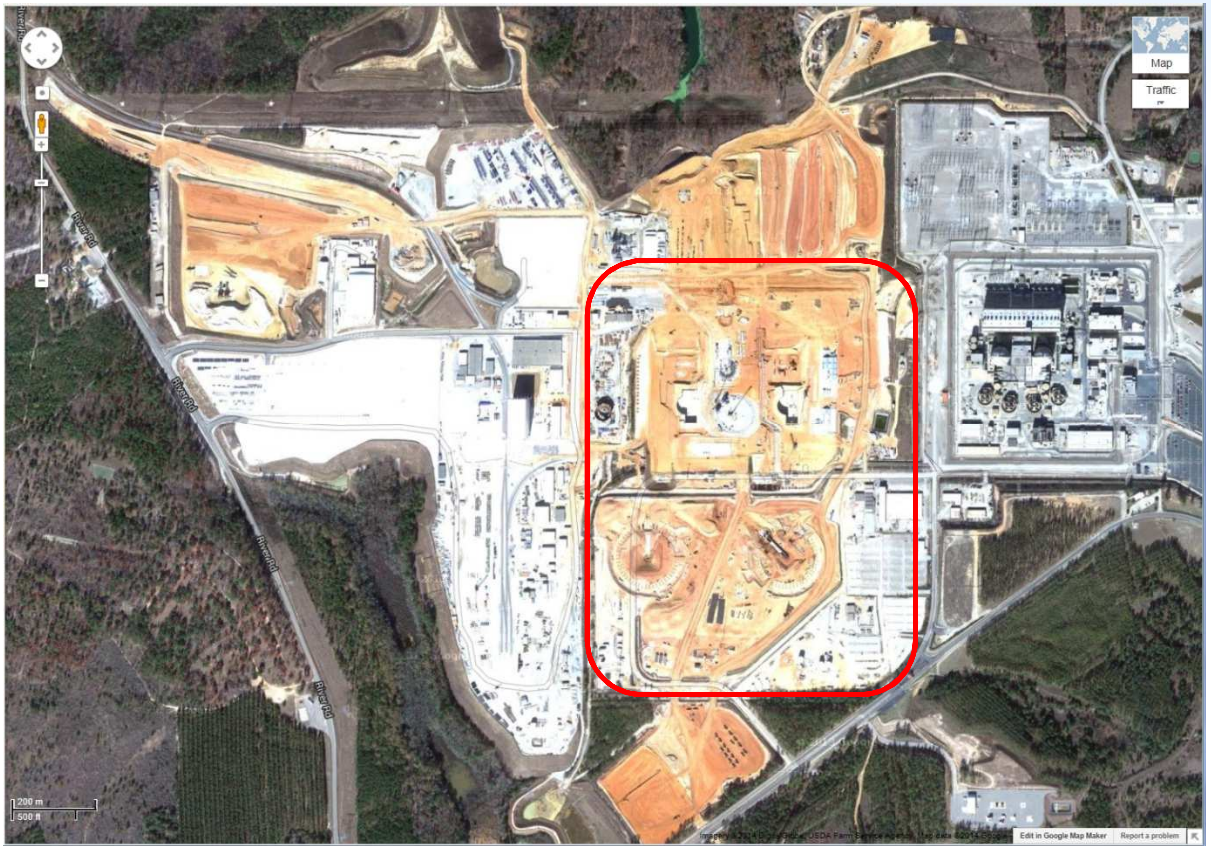
Non-Techno Issues

- Economic competitiveness
- Plant cost estimate
- Regulatory infrastructure
- Availability of design for newcomers
- Physical Security
- Post Fukushima action items on institutional issues and public acceptance

Key Challenge: Construction Management



Reactor footprints ??
Important to costs?

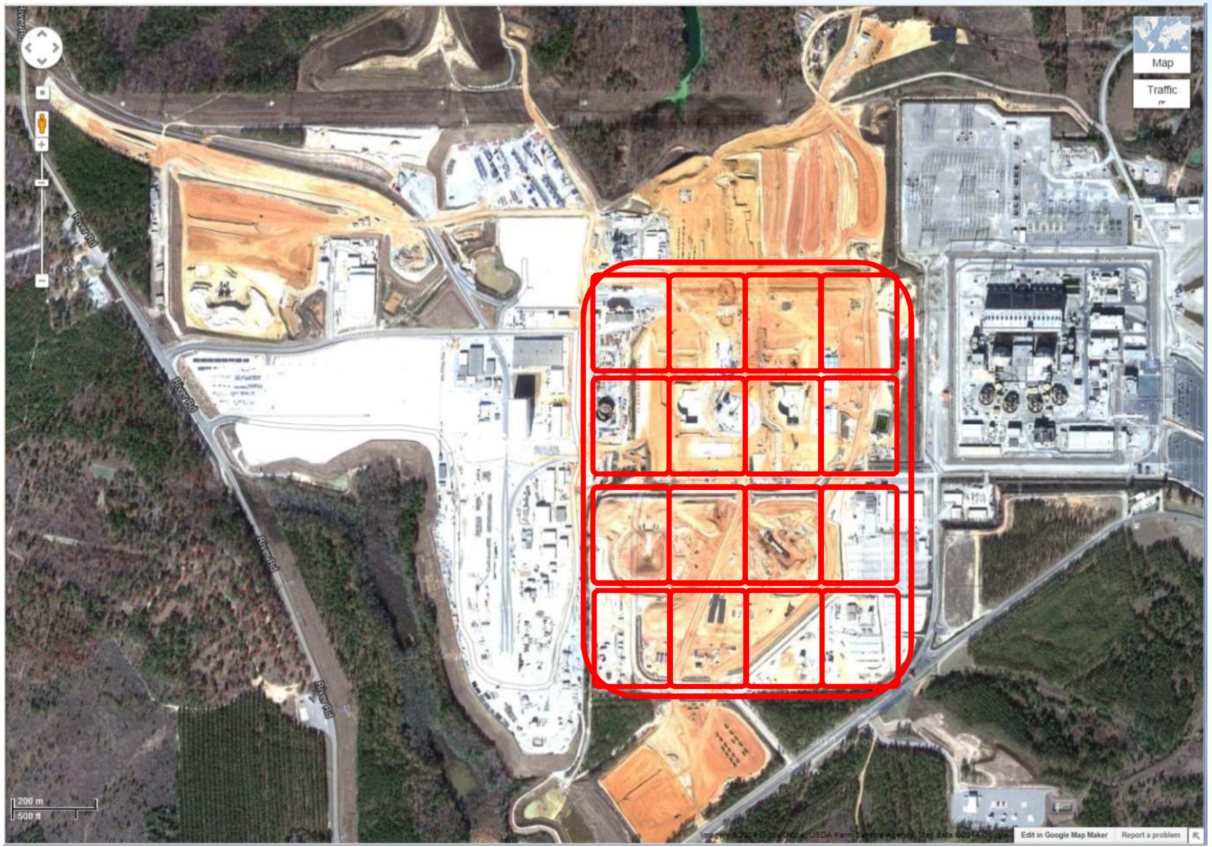


- The Vogtle 3 and 4 Nuclear power plant USA - 2 units = 2220 MWe

HTR-PM footprint …

- The HTR-PM - (Two-reactor unit) = 210MWe

Footprints compared …



- 2 units = 2220 MWe : 16 units = 3360 MWe
- Cost of land and infrastructure …perhaps comparable

Status and major accomplishment in Technology Developer Countries

Countries	Recent Milestone
Argentina	**CAREM25** is in advanced stage of construction. Aiming for fuel loading & start-up commissioning in 2019
Canada	**CNSC** is performing design reviews for several innovative SMR designs, mostly non-water cooled, including molten salt reactors (MSR)
China	• **HTR-PM** is in advanced stage of construction. Commissioning expected in 2018. • **ACP100** completed IAEA generic reactor safety review. CNNC plans to build **ACP100** demo-plant in **Hainan Provence** in the site where NPPs are already in operation. • China has 3 floating SMR designs (**ACP100S**, **ACPR50S** and **CAP-F**)
Republic of Korea	**SMART** (100 MWe) by KAERI certified in 2012. SMART undertakes a pre-project engineering in Saudi Arabia, for near-term construction of 2 units.
Russian Federation	• Akademik Lomonosov floating NPP with 2 modules of **KLT40S** is in advanced stage of construction. Aiming for commissioning in 2019. • AKME Engineering will develop a deployment plan for **SVBR100**, a eutectic lead bismuth cooled, fast reactor.
United Kingdom	• **Rolls-Royce** recently introduced **UK-SMR**, a 450 MW(e) PWR-based design; many organizations in the UK work on SMR design, manufacturing & supply chain preparation • Identifying *potential* sites for future deployment of SMR
United States of America	• The US-NRC has started design review for **NuScale** (600 MW(e) from 12 modules) from April 2017, aiming for FOAK plant deployment in Idaho Falls. • **TVA** submitted early site permit **(ESP)** for Clinch River site, design is still open.

Status and major accomplishment in Embarking Countries

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Countries	Recent Milestone
Saudi Arabia	• **Vision 2030 → National Transformation Program 2020: Saudi National Atomic Energy Project:** • **K.A.CARE** performs a PPE with **KAERI** to prepare a construction of 2 units of **SMART** • An MOU between K.A.CARE and CNNC on **HTGR** development/deployment in KSA
Indonesia	• Through an open-bidding, an experimental 10 MW(th) **HTR-type SMR** was selected in March 2015 for a basic design work aiming for a deployment in mid 2020s • Site: R&D Complex in Serpong where a 30 MW(th) research reactor in operation • BAPETEN, the regulatory body has issued a site license
Jordan	• Jordan, Saudi Arabia and Republic of Korea is to conduct a feasibility study for a deployment of **SMART** in Jordan
Poland	• **HTGR** for process heat application to be implemented in parallel to large LWRs • **10 MW(th) experimental HTGR at NCBJ** proposed possibly with EU cooperation
Tunisia	• STEG, the National Electricity and Gas Company is active in performing technology assessment for near-term deployable **water-cooled SMRs**
Kenya	• Requested support on human capacity building for Reactor Technology Assessment that covers **SMRs** through **IAEA-TC Project**, to be implemented in **Q1-2018**

Summary

- IAEA is engaged to support Member States in SMR Technology Development and has started addressing challenges in applying Design Safety Requirements for NPPs to SMRs
- 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
- Studies needed to evaluate the potential benefits of deploying SMRs in grid systems that contain large percentages of renewable energy.
- Studies needed to assess “design standardization” and “target costs” in cogeneration markets, the benefits from coupling with renewables to stabilize the power grid, and impacts on sustainability measures from deployment.

60 Years

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Thank you!

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