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Atoms for Peace and Development

Small Modular Reactors and Generation-IV
A Short Overview

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Joint IAEA-ICTP Workshop on the Physics and Technology of Innovative High Temperature Nuclear Energy Systems

Presentation Aim

Introduce you to the recent state of SMRs

To provide an overview of the reasons, status of development and characteristics of Innovative / Advanced reactors

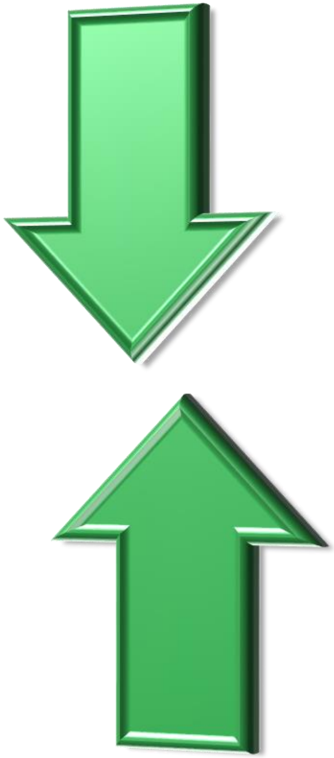
Presentation Objectives

By the end of this session, participants should be able to:

- Define what is a small modular reactor (SMR)
- Summarize the key design and safety features of SMRs
- Explain advantages and challenges of SMRs
- Explain the different Generations –IV reactors systems and their main differentiating factors
- Define what is an advanced reactor and outline their advantages / challenges

Advanced Reactor Design Goals

- **Advanced** reactor designs include both evolutionary and innovative reactor technologies.
- **Evolutionary** designs (Generation III/III+) improve on existing designs through small or moderate modifications with a strong emphasis on maintaining proven design features to minimize technological risk.
- **Innovative** designs (Generation IV) incorporate radical changes in the use of materials and/or fuels, operating environment and conditions, and system configurations.

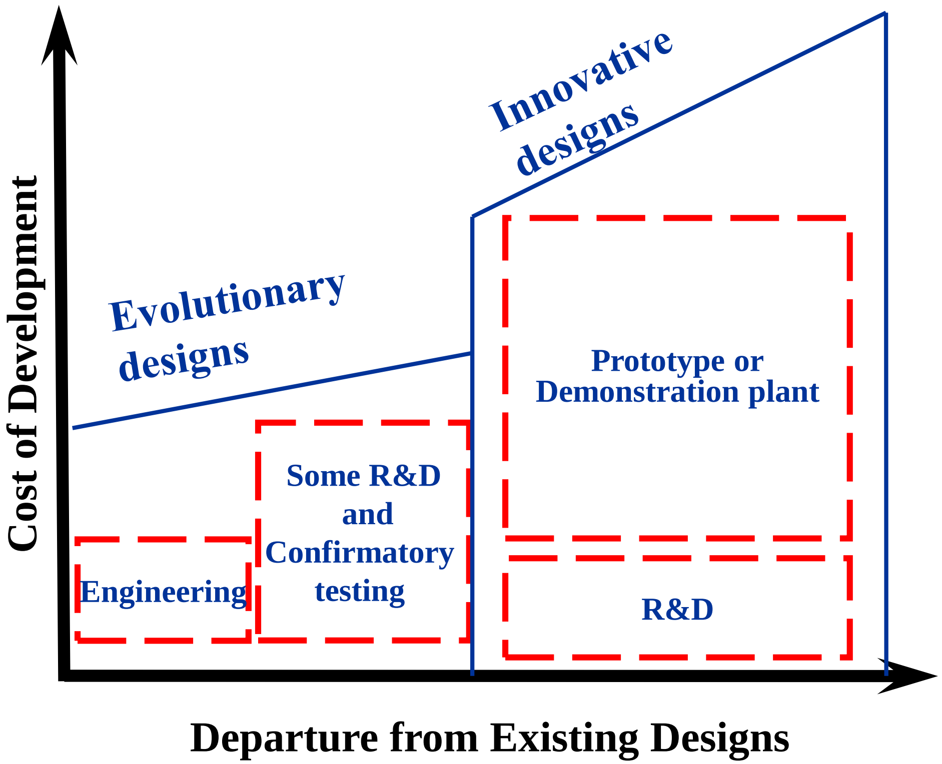


Economic Aspect:
Reduce Cost

Safety Aspect:
Improve Safety

Advanced Reactor Design Goals
Economic Aspect

- The capital cost of existing nuclear power plants account for a large portion of the generating cost as compared to fossil generation methods, which have high fuel costs.
- Reduction in capital cost (and to a lesser degree operating, maintenance and fuel costs) is an important goal for many new reactor designs.
- Development costs of new reactors increase as more changes are made from current designs.



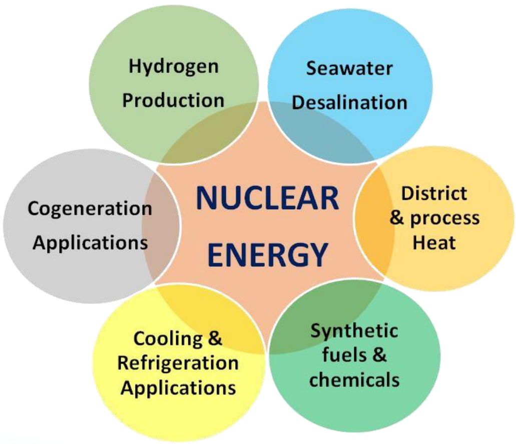
Advanced Reactors and their Applications

SMRs

CAREM-25, HTR-PM, KLT-405, RITM-200, AHWR, NuScale, SMART, 4S, PRISM…

EVOLUTIONARY

ABWR, ACR 1000, AP1000, APWR, Atmea-1, CANDU 6, EPR, ESBWR, VVER 1200, CAP1400, APR1400, HPR1000…



INNOVATIVE

LFR, GFR, SFR, SCWR, VHTR, MSR, ADS

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Advanced Reactor Development

Small Modular Reactors (SMRs)

Exploring Innovative Reactor Technologies / GEN-IV

SMR, definition & target Applications

Advanced Reactors that produce electric power up to 300 MW, built in factories and transported as modules to utilities and sites for installation as demand arises.

A nuclear option to meet the need for flexible power generation for wider range of users and applications

Replacement of aging fossil-fired units

Cogeneration needs in remote and off-grid areas

Potential for enhanced safety margin through inherent and/or passive safety features

Economic consideration – better affordability

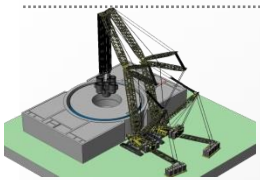
Potential for innovative energy systems:

- Cogeneration & non-electric applications
- Hybrid energy systems of nuclear with renewables

SMR Development Objectives

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

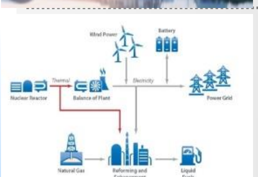
Wider Range of Users

Smaller Footprint
- Reduced emergency planning zone

Site Flexibility

Replacement for Aging Fossil-fired Plants
- Reduced greenhouse gas

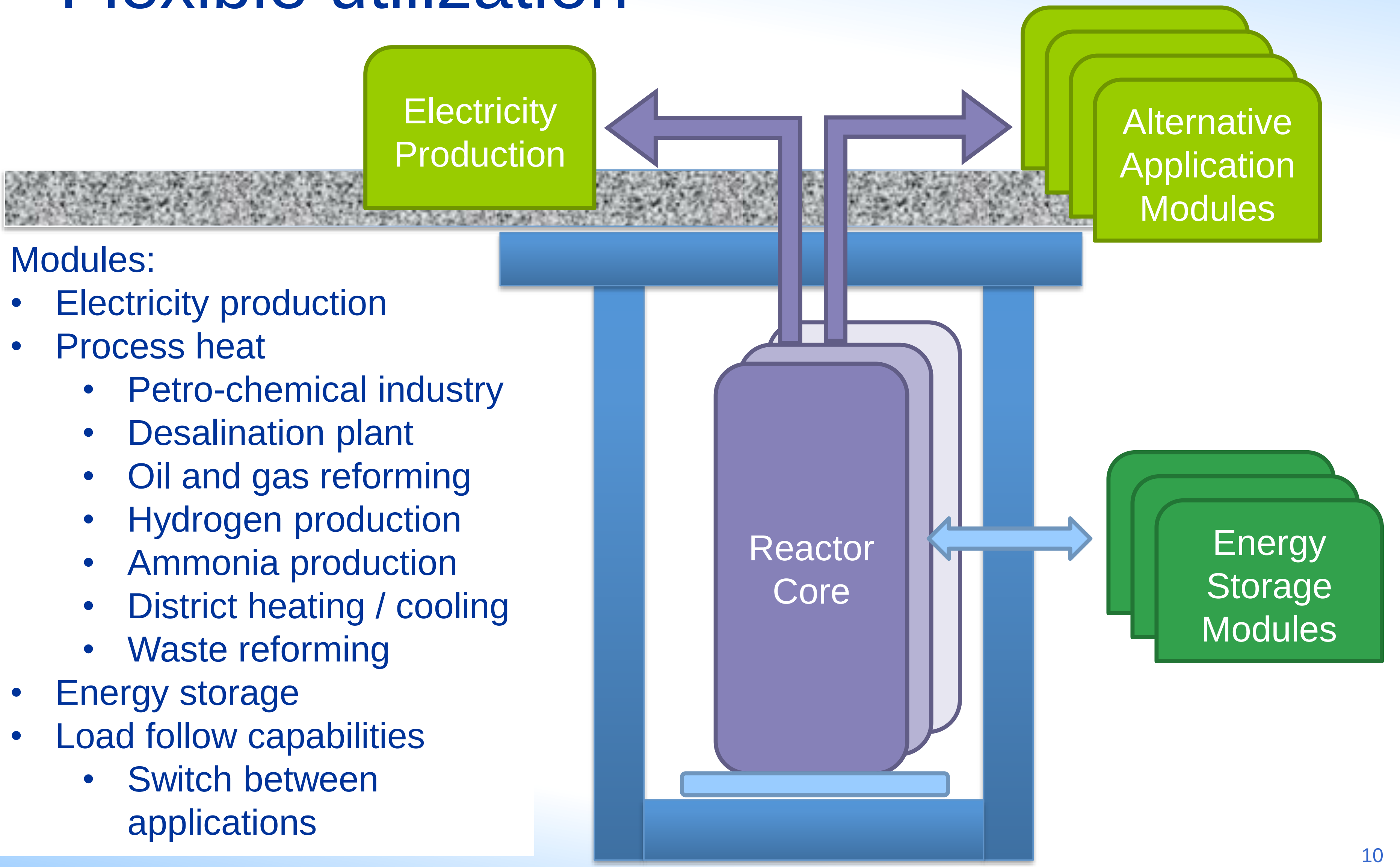
Reduced CO_2 Production



Potential Hybrid Energy System
- Optimized use of renewables

Integration with Renewables

What's new that SMRs can offer? Flexible utilization



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

Role of SMRs in Climate Change

SMR Renewables Hybrid Energy System to Reduce GHG Emission

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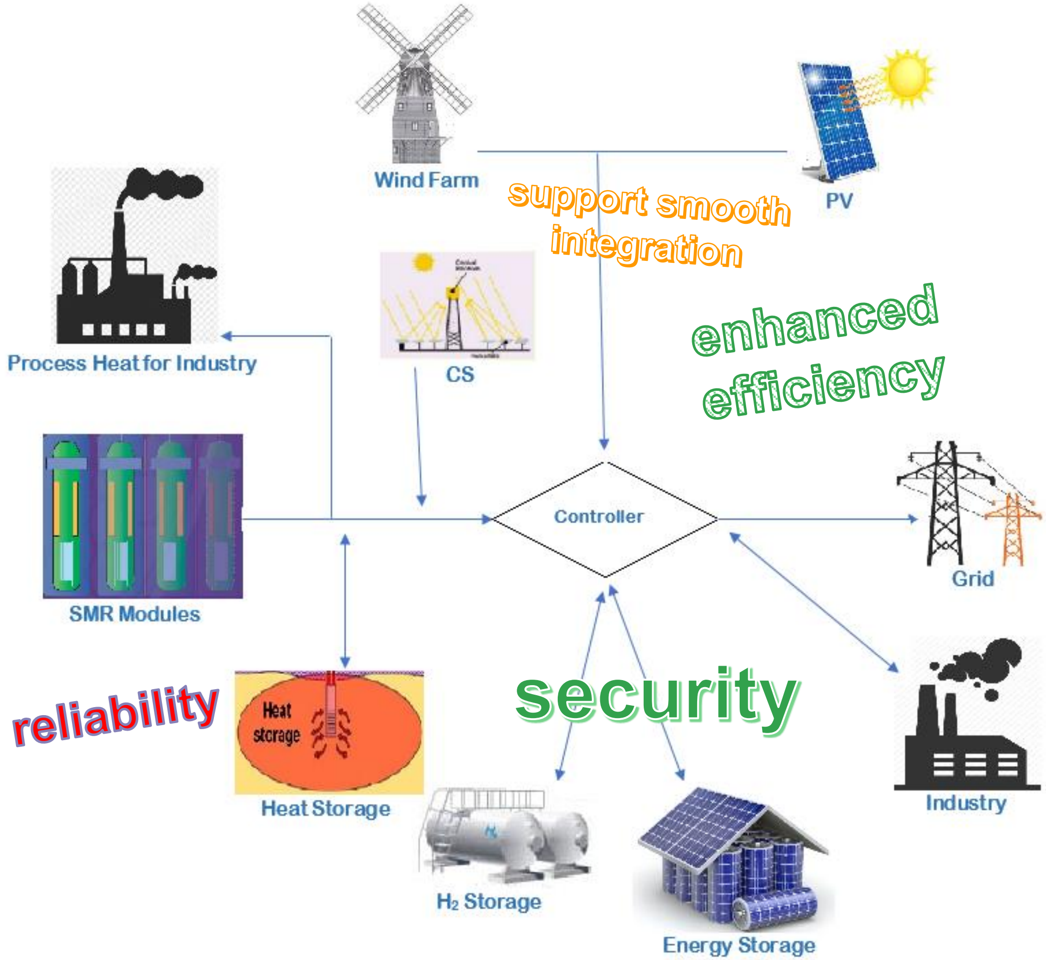
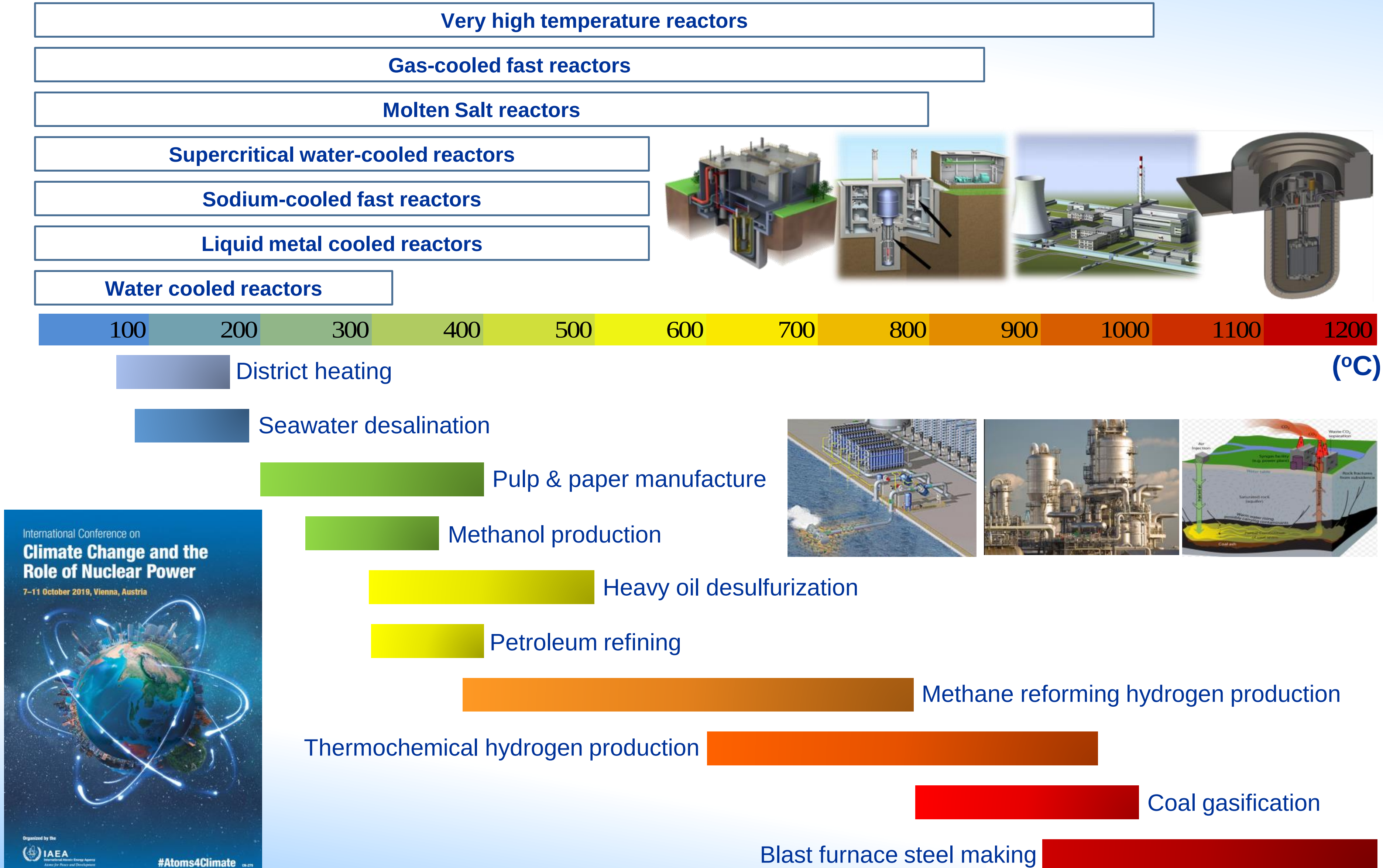
- Hybrid Energy System (HES) utilizes two or more energy resources as inputs to two or more physically coupled subsystems to produce one or more energy commodities as outputs
- HES integrate energy conversion processes to optimize energy management, reliability, security, and sustainability.
- The *"SMR RES HES"* facilitate effective integration of renewable energy, overcoming the challenges of intermittency and transmission constraints.

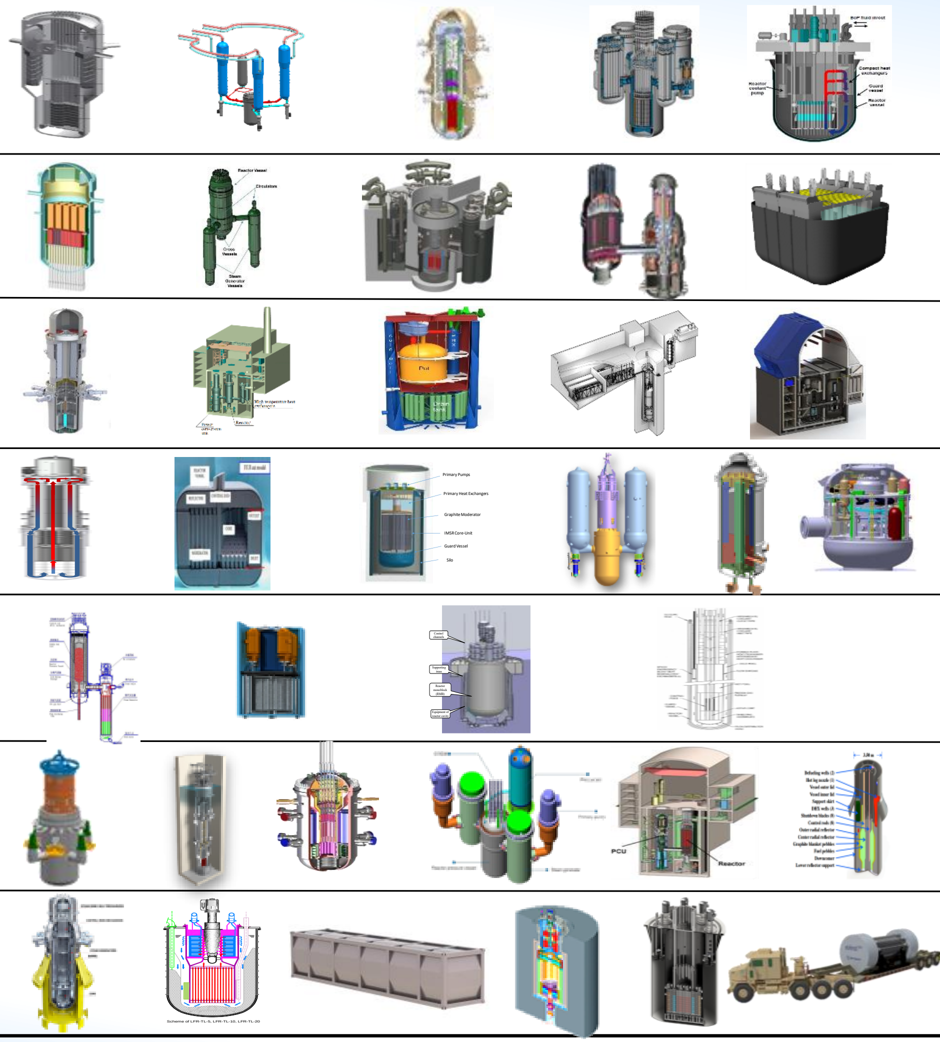


TECDOC on Options to Enhance Energy Supply Security using Hybrid Energy Systems based on SMR – Synergizing Nuclear and Renewables.
Expected publication in 2020

Non-electric Applications of SMRs at Different Coolant Output Temperature

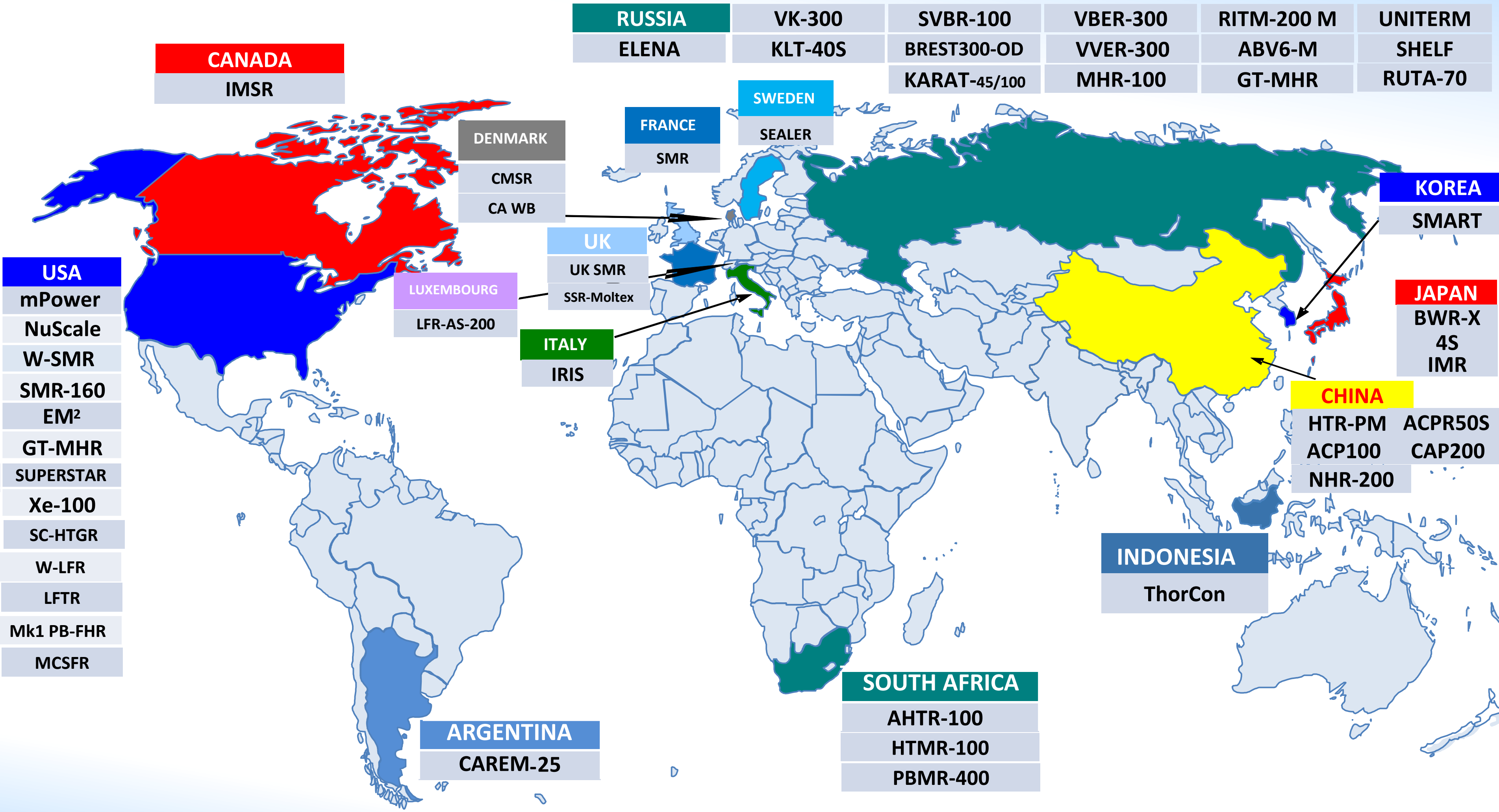


SMR Designs Based on Power Range



Power Range MW(e)	Reactor Designs
> 301	IMR UKSMR IRIS VBER-300 Westinghouse LFR
251-300	DMS SC-HTGR BREST-OD-300 GT-MHR Stable Salt Reactor
201-250	Westinghouse SMR MHR-T ThorCorn LFTR Em²
151-200	mPower FUJI IMSR CAP200 PBMR-400 France SMR
101-150	HTR-PM CMSR SVBR100 SUPERSTAR
51-100	ACP100 nuScale SMART ACPR50S MHR100 MK1-PBFHR
0-50	CAREM25 LFR-TL-X CA Waste Burner A-HTR-100 SEALER eVinci

SMR Technology Development



SMRs: Immediate Deployment

CAREM

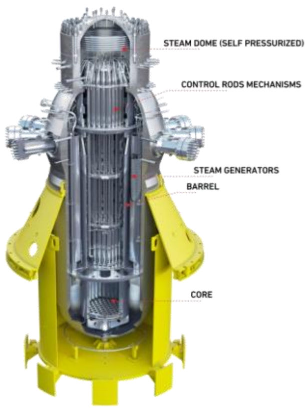


Image Courtesy of CNEA, Argentina

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
- **Advanced stage of construction**
- **First Criticality: September 2021**

KLT-40S

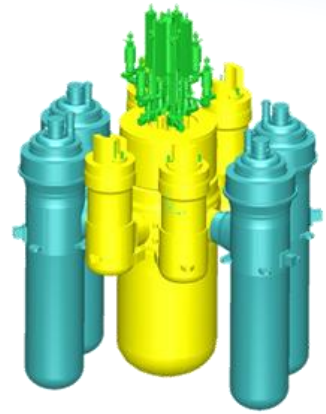


Image Courtesy of Afrikantov, Russia

Prepared for Commercial Operation

Floating PWR type SMR

Forced circulation

- 35 MW(e) / 150 MW(th)
- Core Outlet Temp: 316°C
- Fuel Enrichment: 18.6% UO_2
- Floating power unit for cogeneration; onsite refuelling not required; spent fuel take back to the supplier
- **Construction Completed**
- **Start-up Commissioning Completed**
- **Commercial Operation from December 2019 in Pevek**

HTR-PM

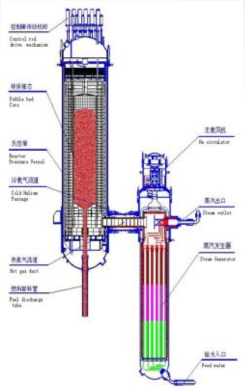


Image Courtesy of Tsinghua University, China

Under Commissioning

HTGR type SMR

Forced circulation

- 210 MW(e) / 2x250 MW(th)
- Core Outlet Temp: 750°C
- Fuel Enrichment: 8.5% TRISO coated particle fuel
- Inherent safety, no need for offsite safety measures
- Multi reactor modules coupled with single steam turbine
- **Construction Completed**
- **Now in the Start-up Commissioning: 2019-2020**
- The HTR-PM 600 (6 modules) under design, potential sites identified

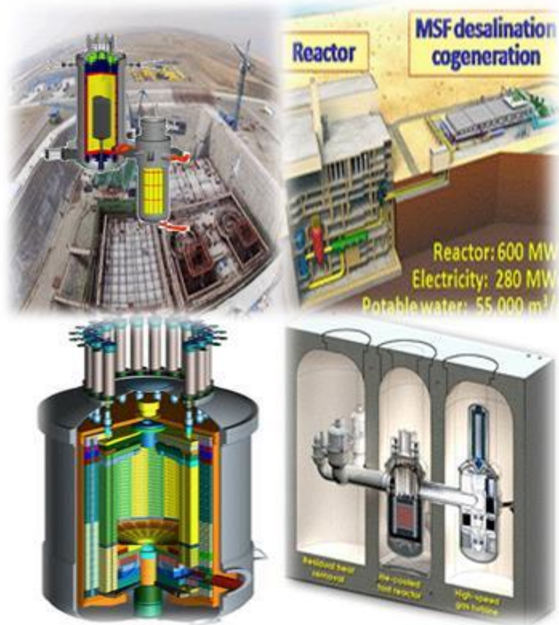
… Akademik Lomonosov with KLT-40S in deployment

SMR for Near-, Medium- and Long-Term Deployment

Water cooled SMRs

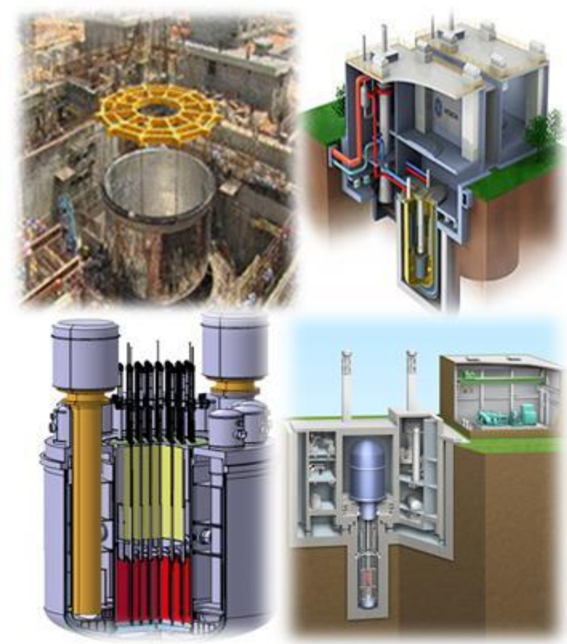
CAREM
SMART
ACP100
NuScale

Gas cooled SMRs



HTR-PM
GTHTR300
HTMR100
EM²

Liquid metal cooled SMRs



PFBR
PRISM
SVBR
4S

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

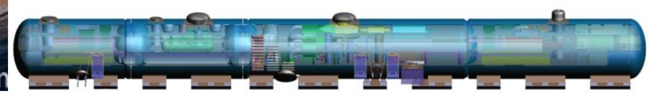
ACPR50S

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

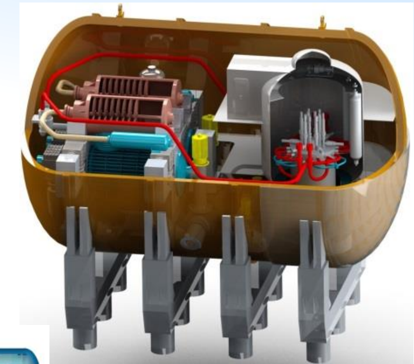


Transportable, immersed nuclear power plant

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

High Temperature Gas Cooled SMRs (Examples)

HTR-PM

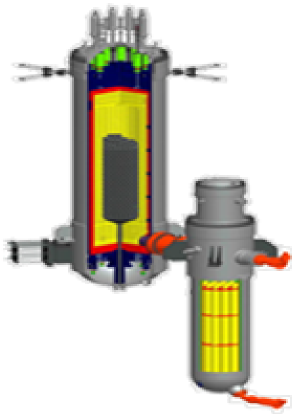


Image Courtesy of INET, China

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 Commercial Operation in 2019

GTHTR300

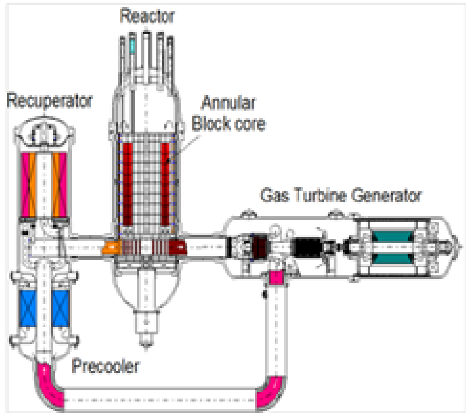


Image Courtesy of JAEA, Japan

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

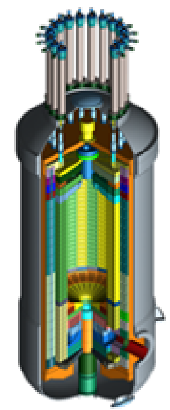


Image Courtesy of STL, South Africa

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

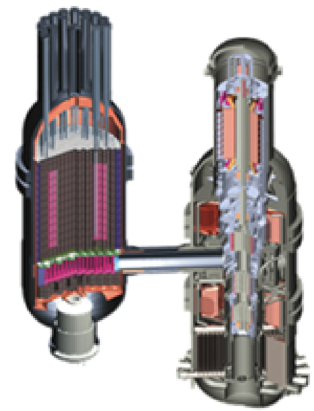


Image Courtesy of General Atomics, USA

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

Water Cooled SMR Designs for district heating

DHR-400

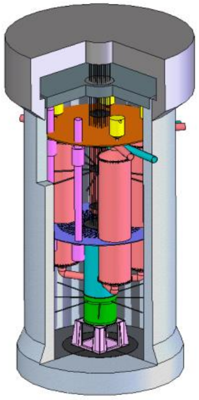


Image Courtesy of CNNC, China

Basic Design

Pool Type SMR

Forced circulation

- 0 MW(e) /400 MW(th)
- Core Outlet Temp: 98°C
- Fuel Enrichment: <5% UO_2
- Designed to replace traditional coal plants for district heating
- Multi-purpose applications including district heating, sea water desalination & radioisotope production
- Seeking a construction license in 2019
- First plant that is expected to be built in Xudapu, Liaoning, China.

RUTA-70

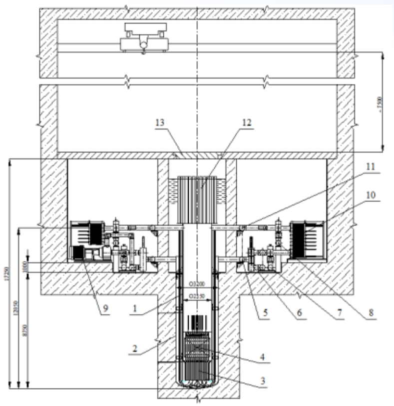


Image Courtesy of , NIKIET, Russian Federation

Conceptual Design

Pool type SMR

Natural / Forced circulation

- 0 MW(e) / 70 MW(th)
- Core Outlet Temp: 102°C
- Fuel Enrichment: 3% UO_2
- Designed for low temperature process heat, coupling with desalination system, radioisotope production or other applications

Generation IV SMRs (Examples)

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PRISM

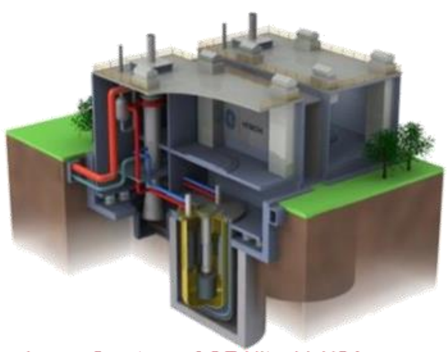


Image Courtesy of GE Hitachi, USA

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

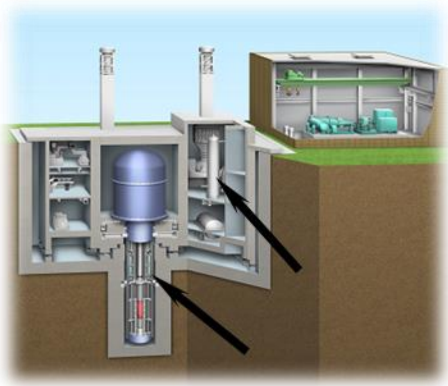


Image Courtesy of TOSHIBA, Japan

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

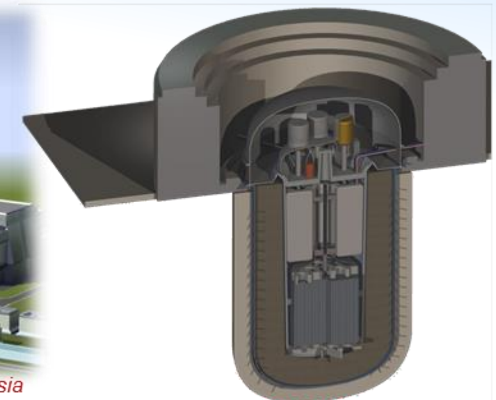


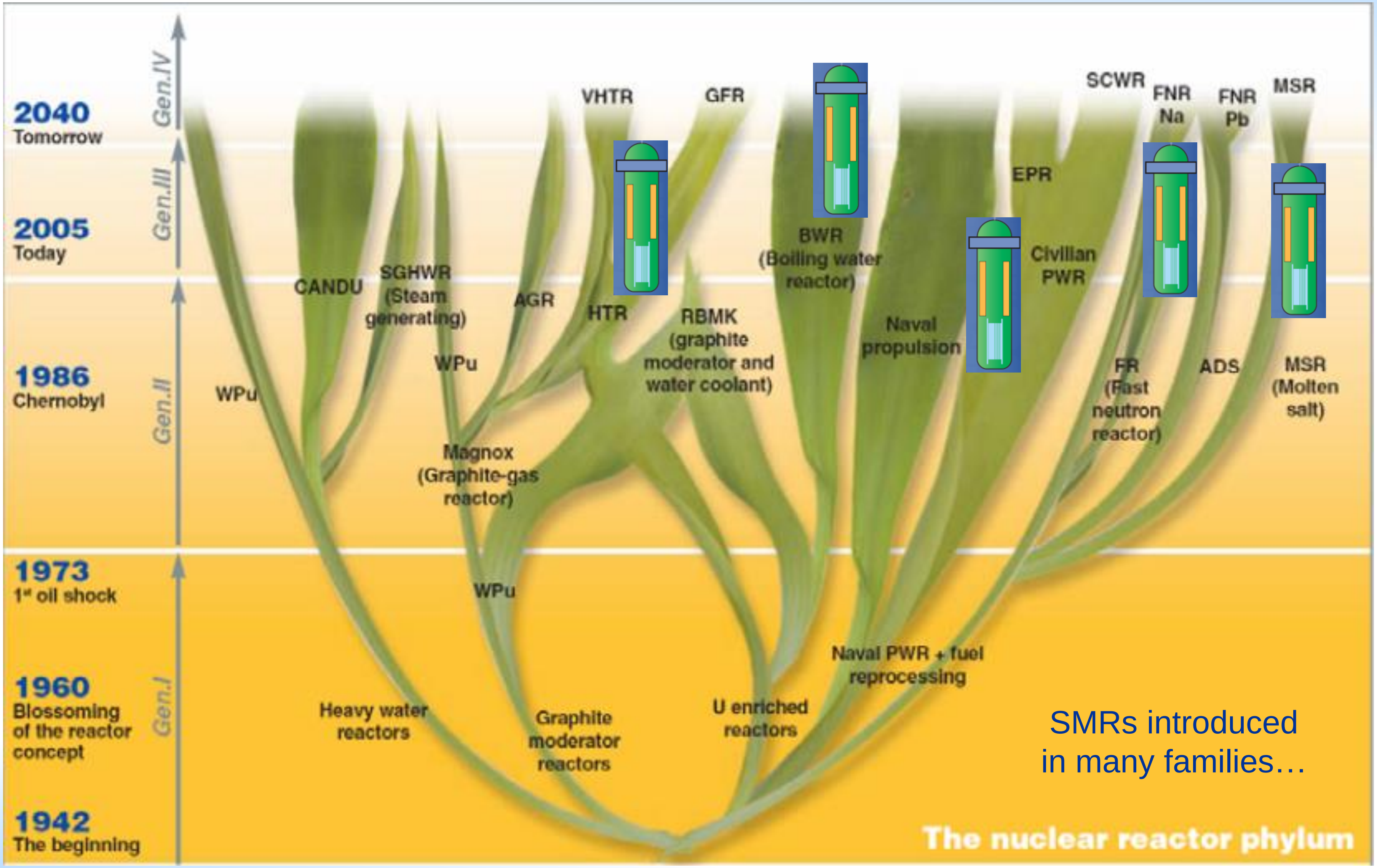
Image Courtesy of Terrestrial Energy, Canada

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

Reactor Classification through Decades of Development: *Nuclear Tree*



SMRs introduced in many families…

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

SMR Key Design Features

Simplification by Modularization and System Integration

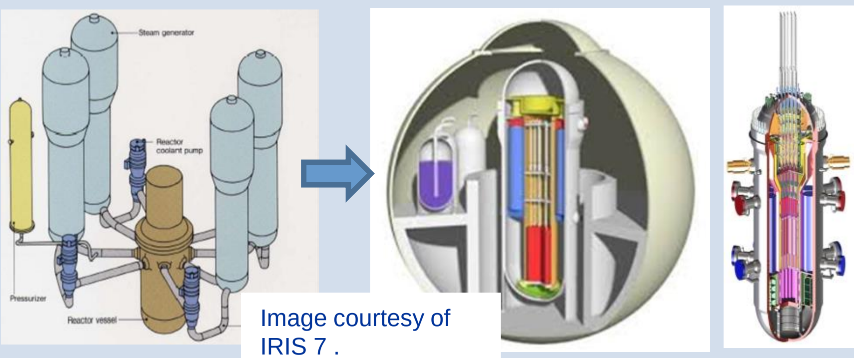


Image courtesy of IRIS 7 .

Multi-module Plant Layout Configuration

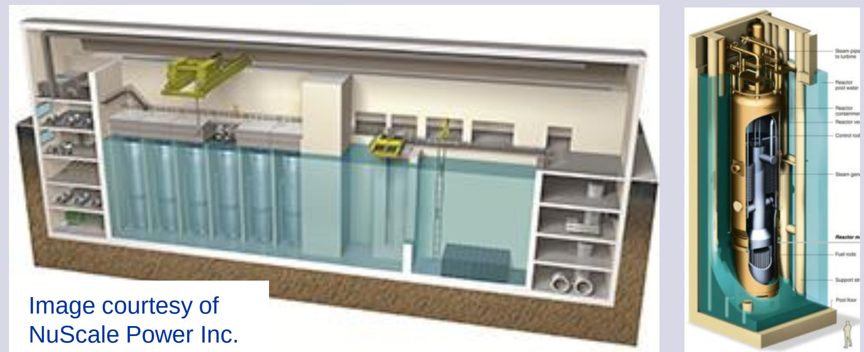


Image courtesy of NuScale Power Inc.

Underground construction for enhanced security and seismic

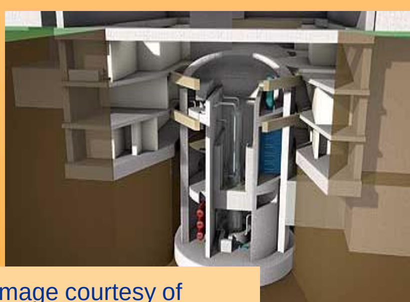


Image courtesy of BWX Technology, Inc.

Enhanced Safety Performance through Passive System

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

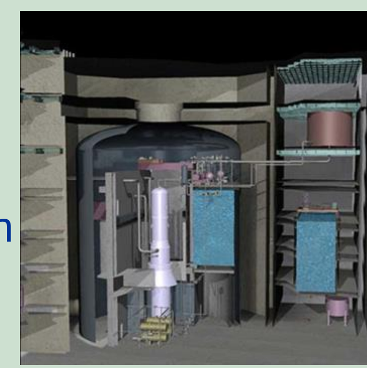
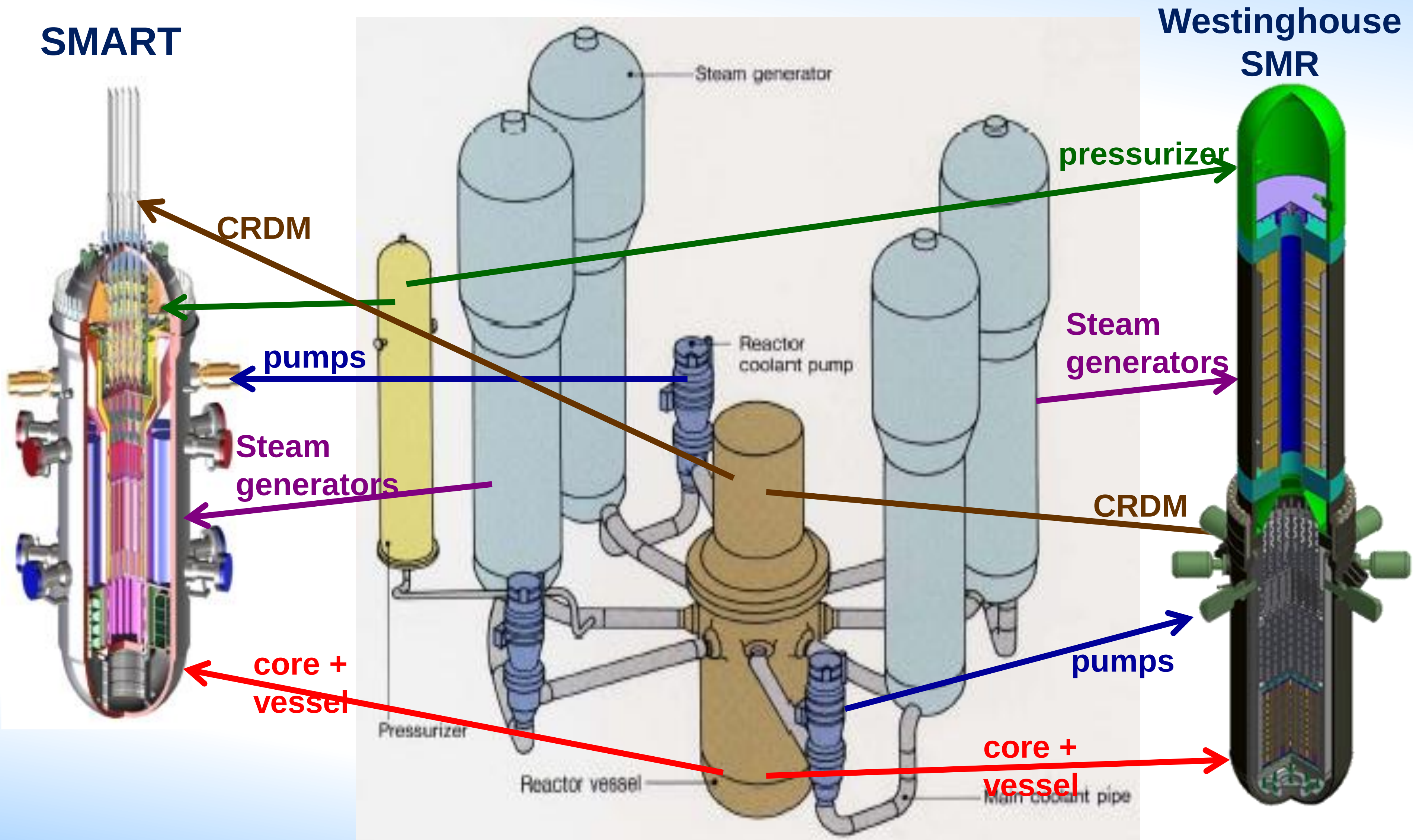
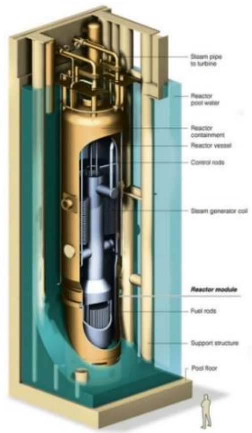


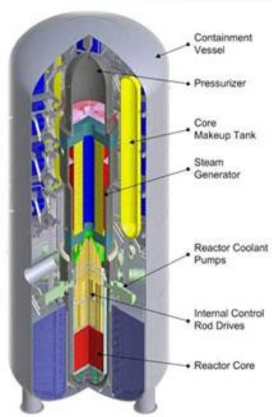
Image courtesy of BWX Technology, Inc.

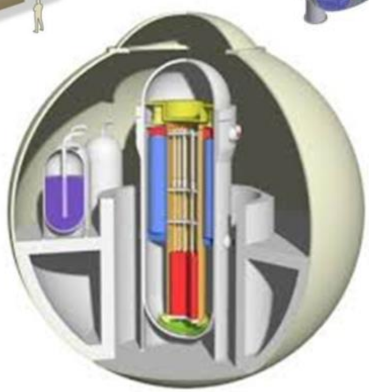
Concept of Integral PWR based SMR

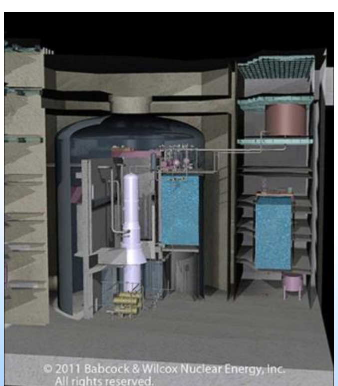


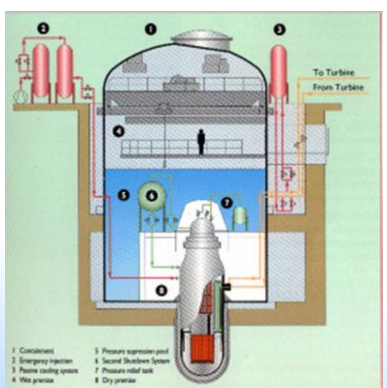
Design Features Offered by iPWRs





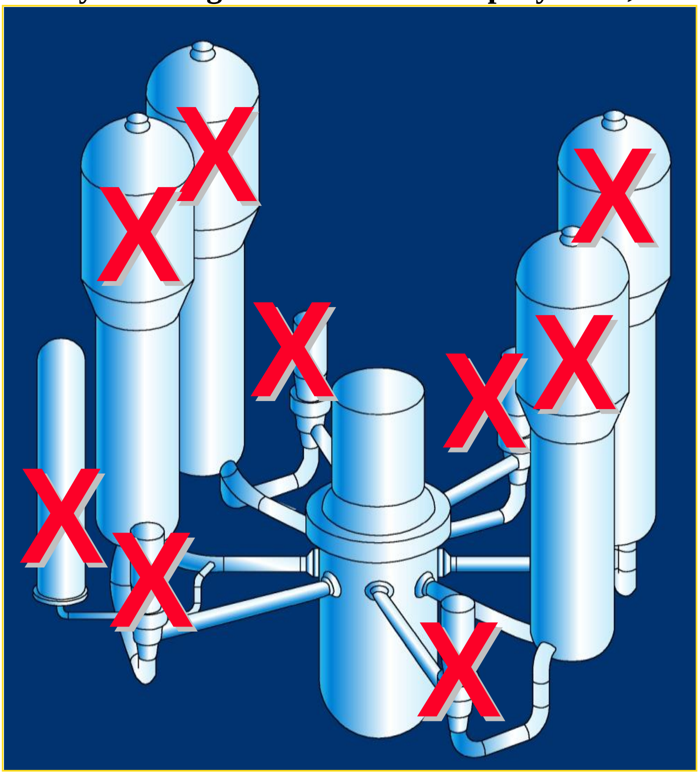


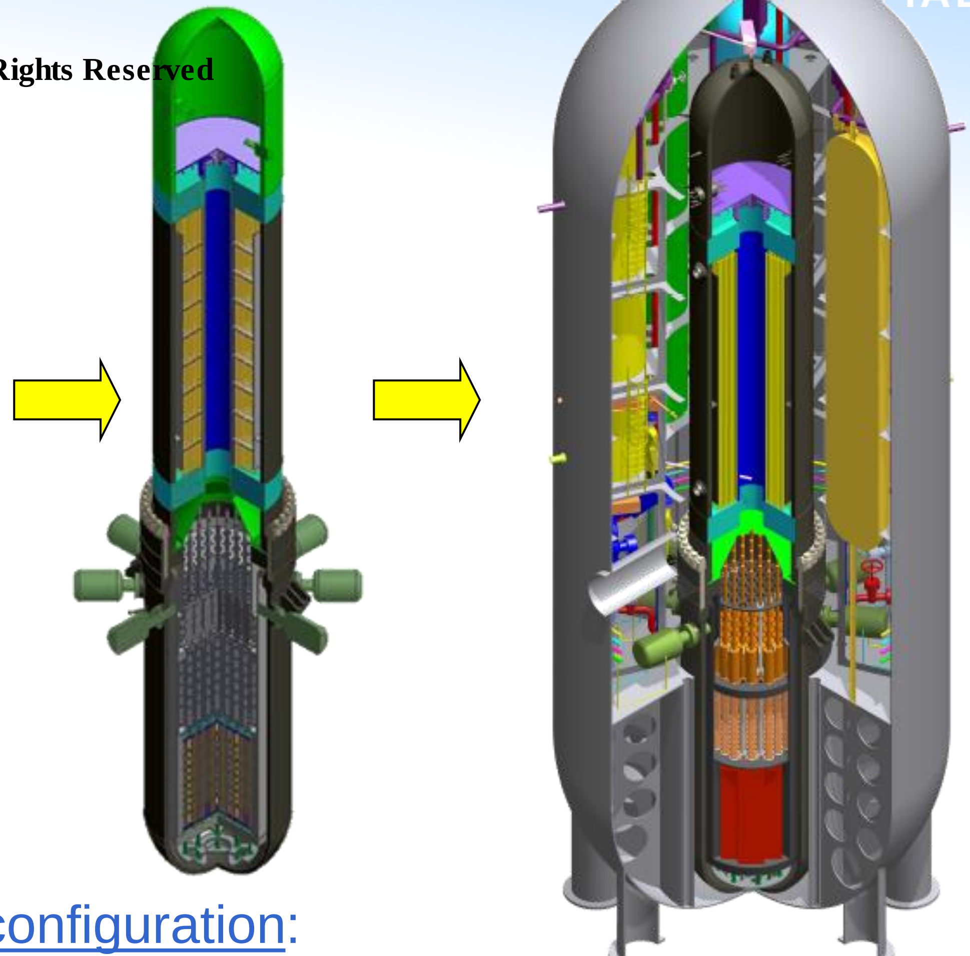




- *Enhanced performance engineered safety features*
  - Natural circulation primary flow
  - Reactivity control (internal CRDM, gravity driven secondary shutdown)
  - Residual heat removal system (passive heat removal systems)
  - Safety injection System (active and/or passive injection)
- *Improved containment options*
  - Passively cooled Containment
  - Concrete containment with spray system
  - Pressure suppression containment
- *Severe accident mitigation features*
  - In-vessel Corium retention
  - Hydrogen passive autocatalytic recombiner
  - Inerted containment

Integral Primary System Configuration





Benefits of integral vessel configuration:

- eliminates loop piping and external components, thus enabling compact containment and plant size → reduced cost
- Eliminates large break loss of coolant accident (improved safety)

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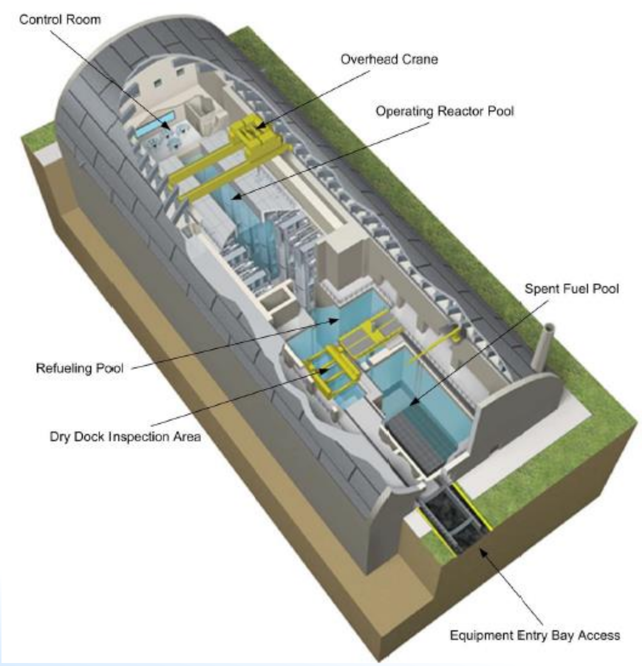
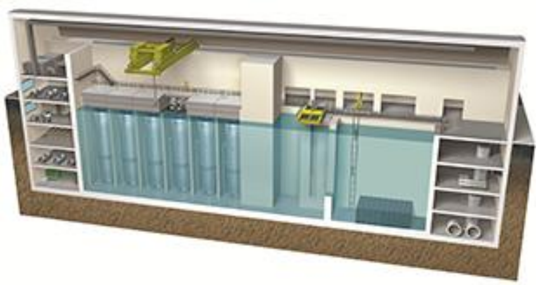
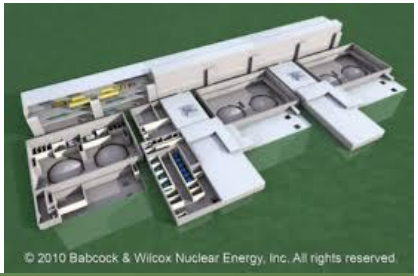
SMR Key Design Features

- 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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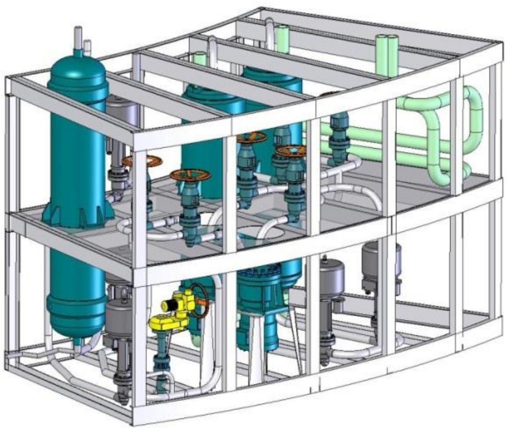
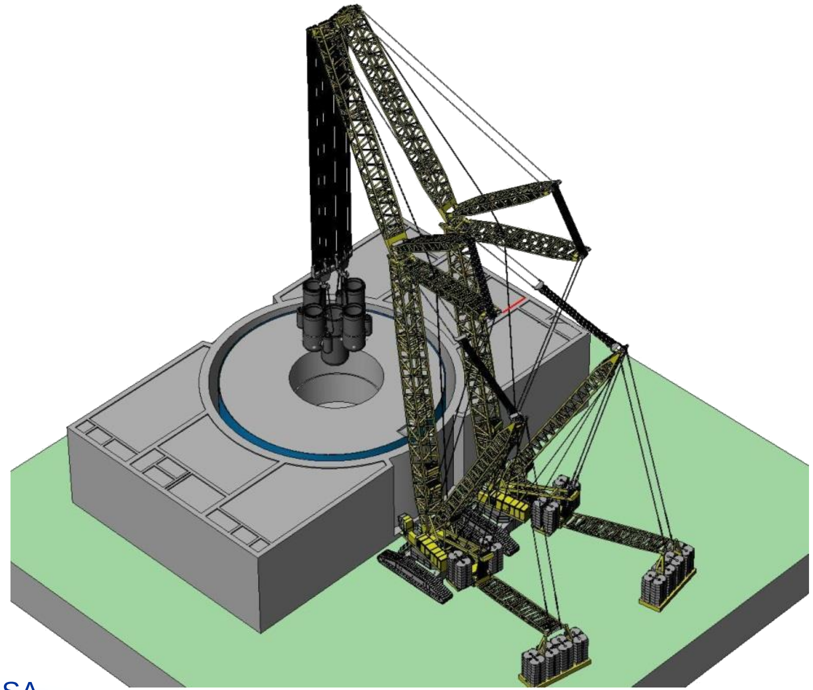
SMR Key Design Features

- Modularization (construction technology)
  - Factory manufactured, tested and Q.A.
  - Heavy truck, rail, and barge shipping
  - Faster construction
  - Incremental increase of capacity addition as needed





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SMR Issues & Challenges

Due to the large number of deviations from existing designs and new applications, SMR development faces several challenges which require R&D and confirmatory testing.

These issues are further enhanced for innovative SMR designs.

	Issues and Challenges
Technology	▪ Licensability (first-of-a-kind structure, systems and components) ▪ Non-LWR technologies ▪ Operability and maintainability ▪ Staffing for multi-module plant ▪ Human factor engineering ▪ Supply chain for multi-modules ▪ Advanced R&D needs
Non-Technology	▪ Economic competitiveness ▪ Plant cost estimate uncertainty ▪ Regulatory infrastructure ▪ Availability of designs for newcomers ▪ Physical security ▪ Post Fukushima action items on institutional issues and public acceptance

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Advanced Reactor Development

Small Modular Reactors (SMRs)

Exploring Innovative Reactor Technologies / GEN-IV

Generations of Nuclear Energy

Generation I

Early Prototypes

- Shippingport
- Dresden
- Magnox

Generation II

Commercial Power

- PWRs
- BWRs
- CANDU

Generation III

Advanced LWRs

- CANDU 6
- System 80+
- AP600

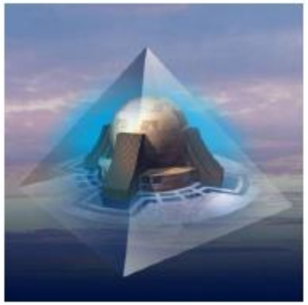
Generation III+

Evolutionary Designs

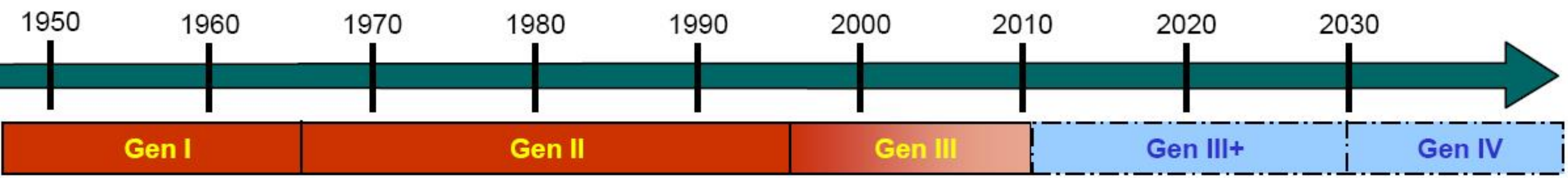
- ABWR
- ACR1000
- AP1000
- APWR
- EPR
- ESBWR

Generation IV

Revolutionary Designs



- Safe
- Sustainable
- Economical
- Proliferation Resistant and Physically Secure



Generation IV Goals

- Sustainability

1. Generate energy sustainably, and promote long-term availability of nuclear fuel
2. Minimize nuclear waste and reduce the long term stewardship burden

- Safety & Reliability

3. Excel in safety and reliability
4. Have a very low likelihood and degree of reactor core damage
5. Eliminate the need for offsite emergency response

- Economics

6. Have a life cycle cost advantage over other energy sources
7. Have a level of financial risk comparable to other energy projects

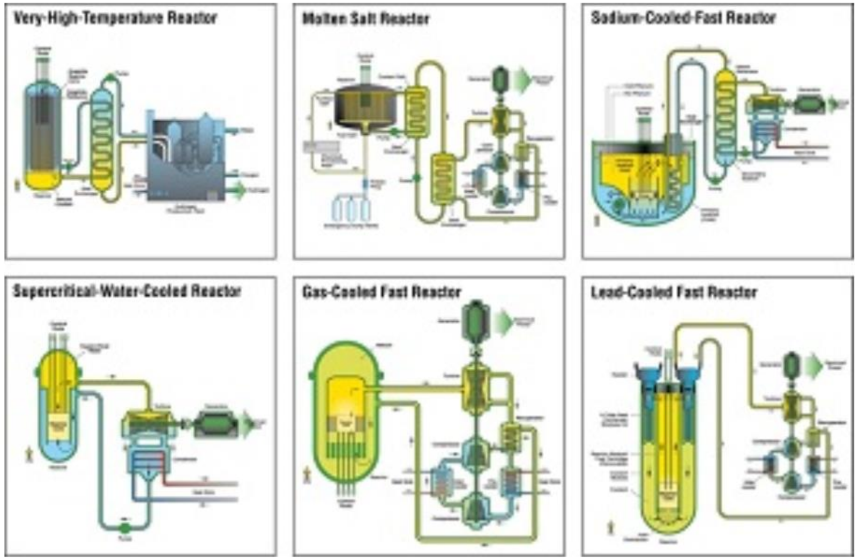
- Proliferation Resistance & Physical Protection

8. Be a very unattractive route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism

GIF

Generation-IV Forum

- Since 2000
- co-operative international endeavour to carry out the R&D needed to establish the feasibility and performance capabilities of the next generation nuclear energy systems
- Selected 6 reactor systems
- Cross cutting working groups:
  - Economics
  - Proliferation Resistance & Physical Protection
  - Risk & Safety
- Task forces:
  - Education and Training
  - Safety Design Criteria
  - R&D Infrastructure



- **GFR** Gas-cooled Fast reactor
- **LFR** Lead-cooled fast reactor
- **MSR** Molten salt reactor
- **SFR** Sodium-cooled fast reactor
- **SCWR** Supercritical water cooled reactor
- **VHTR** Very high temperature reactor

Innovative Reactors: Main Feature → Sustainability

- High operating temperatures → high efficiency + non-electric applications
- Closing the fuel cycle → natural U resources + waste management
- Advanced fuels with high burn-up: mixed U-Pu, MA-based, Th
- Economic competitiveness with respect to other energy sources
- Excel in proliferation resistance and physical protection
- *Safety performances should be at least equivalent to the ones of the most advanced evolutionary reactors*

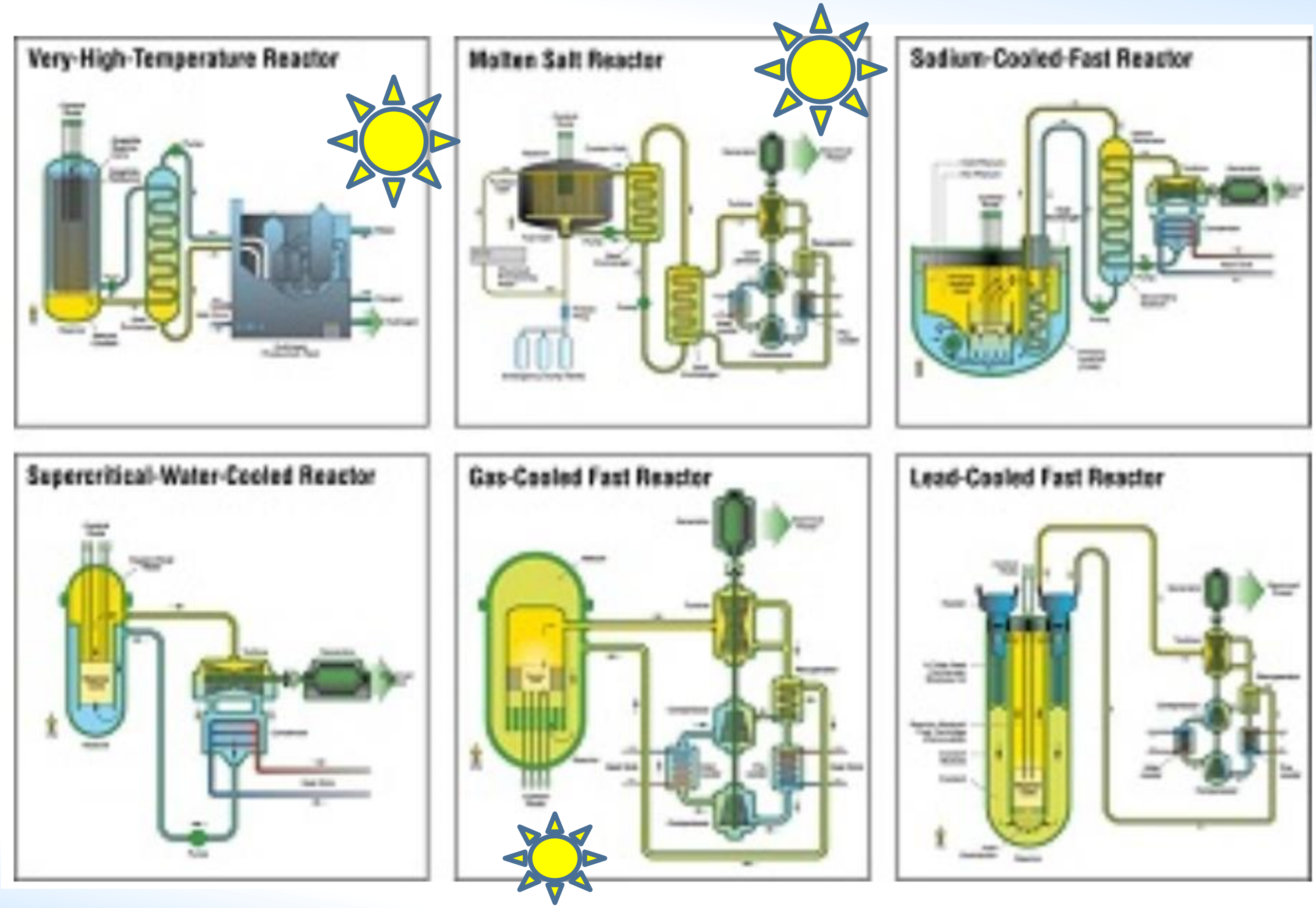
Innovative Reactors: Main Trade-offs

- Advanced materials and fuels have to be first developed, then tested and qualified → it may require decades !
- Technical and licensing uncertainties: limited (or no…) operational experience
- All concepts still require substantial R&D, are currently at a pre-conceptual design phase and need industrial demonstration:
  - GFR: experimental plant
  - LFR: demonstration plant
  - SFR: prototype plant
- Full closed fuel cycle (multi-recycling & MA transmut.) still to be demonstrated

Comparison of Gen IV systems

System	Neutron Spectrum	Coolant	Outlet temp. (℃)	Fuel cycle	Power (MWe)
Sodium-cooled Fast Reactor (SFR)	Fast	Sodium	500-550	Closed	50-1500
Very-High-Temperature Reactor (VHTR)	Thermal	Helium	900-1000	Open	250-300
Lead-cooled Fast Reactor (LFR)	Fast	Lead	480-570	Closed	20-1200
Supercritical-Water-cooled Reactor (SCWR)	Thermal/ Fast	Water	510-625	Open/ Closed	300-1500
Gas-cooled Fast Reactor (GFR)	Fast	Helium	850	Closed	1200
Molten Salt Reactor (MSR)	Thermal/ Fast	Fluoride salts	700-800	Closed	1000

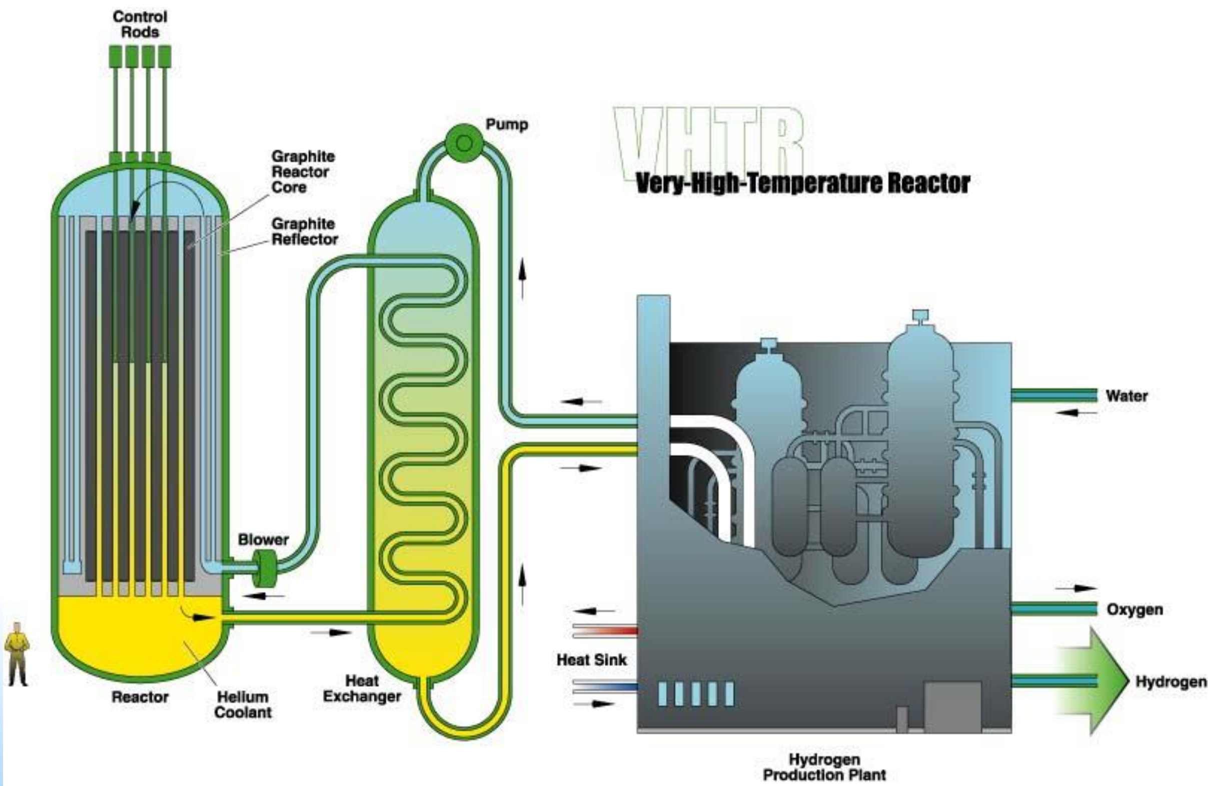
This workshop focus on "Innovative High Temperature Nuclear Energy Systems"

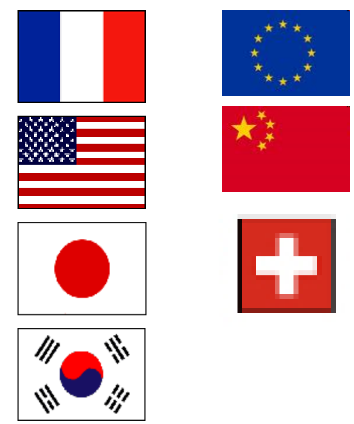


Focus on VHTR and MSRs, and high temperature applications… so only the other systems are briefly explained

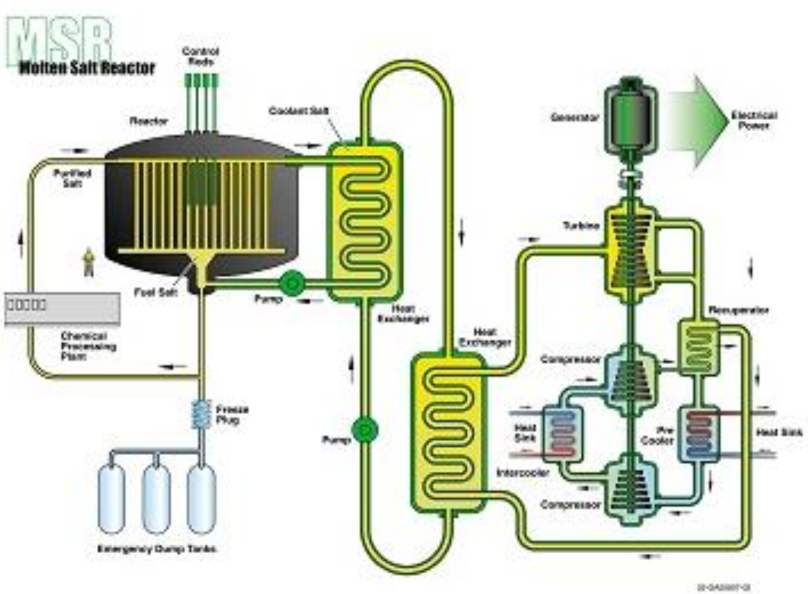
Very High Temperature Reactors (VHTRs)

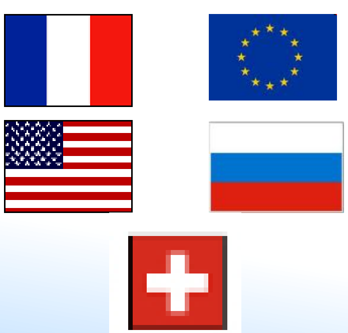
- The Very High Temperature Reactor (VHTR) is a Generation IV reactor concept that uses a graphite-moderated nuclear reactor with a once-through uranium fuel cycle.
- The VHTR is a type of High Temperature Reactor (HTR) that can conceptually have an outlet temperature of 1000°C.
- The reactor core can be either a “prismatic block” or a “pebble-bed” core.
- The high temperatures enable applications such as process heat or hydrogen production via the thermochemical sulfur-iodine cycle.





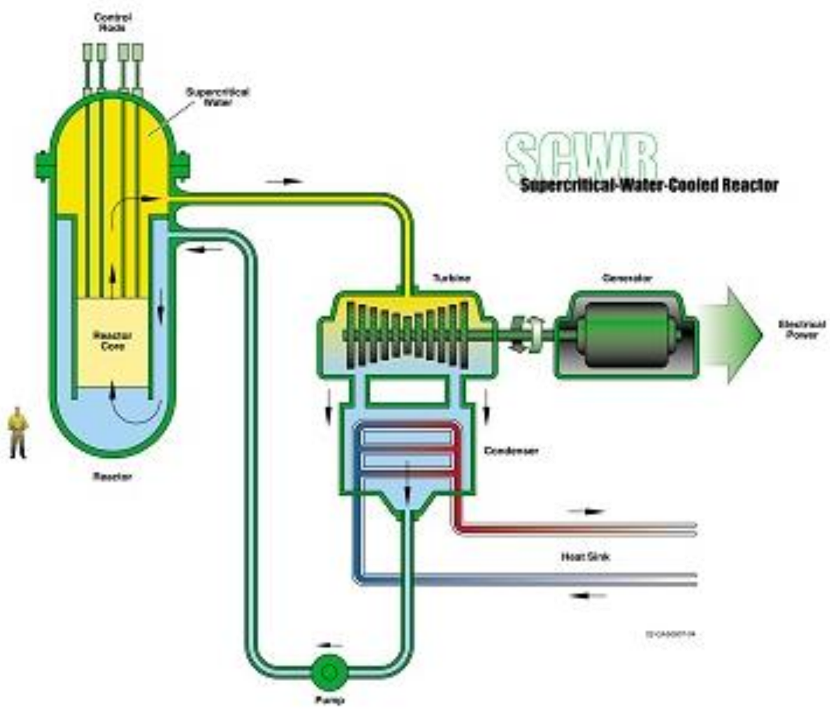
Molten Salt Reactors (MSR)

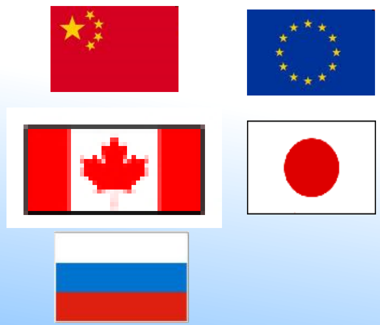




- salt-fueled and salt-cooled as main subclasses
- higher temperatures (400-800ºC)
- atmospheric or low pressure
- fast and thermal spectrum:
  - typically graphite moderated or fast spectrum designs
- other variations includes:
  - fuel-salt within fuel rods cooled by another molten salt;
  - or coated particle graphite pebbles (similar to that used in HTGRs)
- chloride and fluoride coolant and fuel-salts

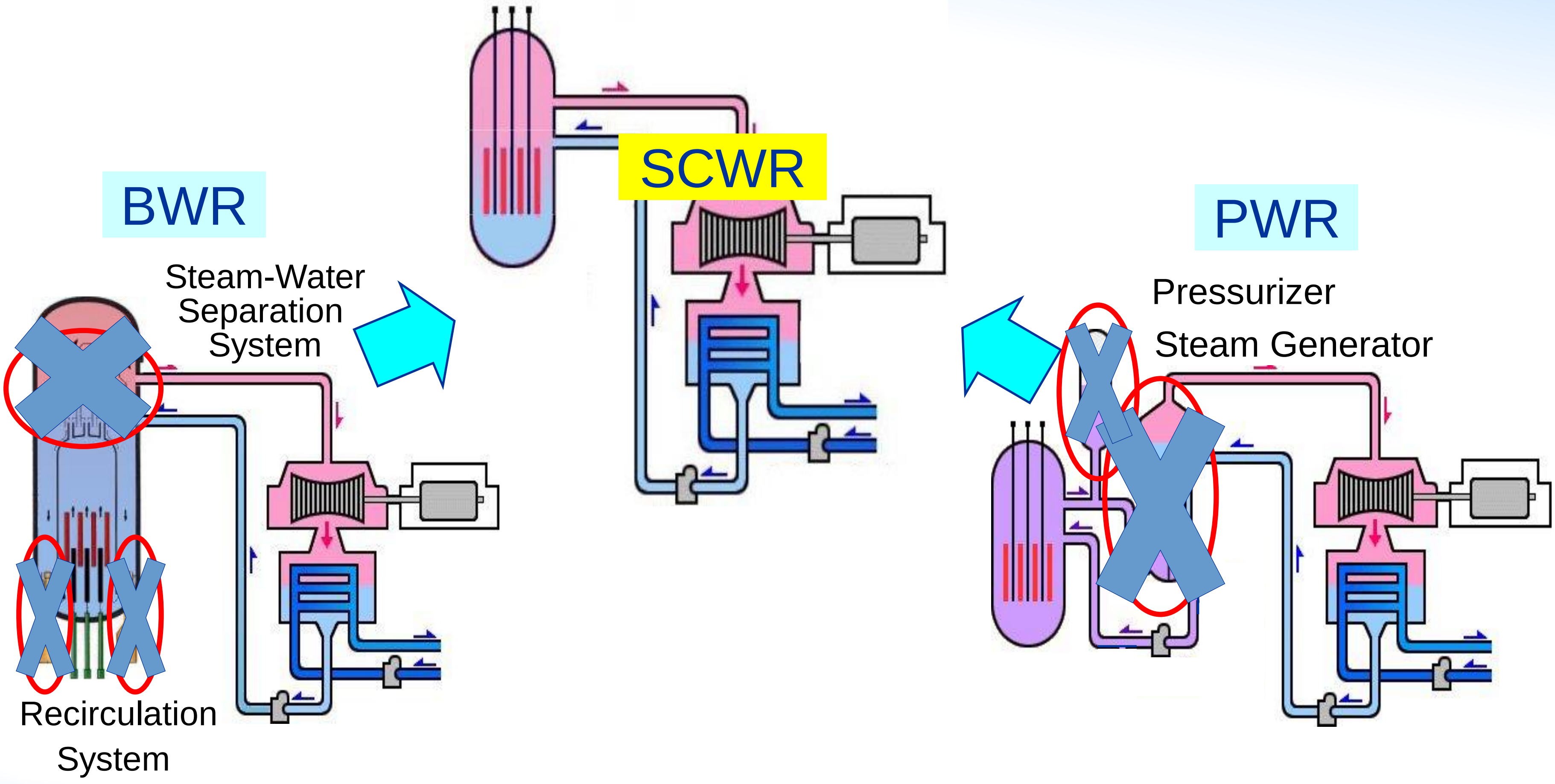
Supercritical Water Reactors (SCWR)





- The SCWR is a water-cooled reactor (WCR) concept that uses water pressurized above its critical pressure (i.e. 22.1 MPa) as reactor coolant.
- The core outlet coolant temperature is expected to exceed 500 deg-C.
- The thermal efficiency is much higher than conventional WCRs (around 1.3 times higher).
- The primary system can be simplified compared with conventional WCRs.
- Flexible design options:
  – Pressure-vessel / Pressure-tube type reactor
  – Thermal-spectrum / Fast-spectrum / Mixed-spectrum core

SCWR: Primary System



SCWR: R&D Needs

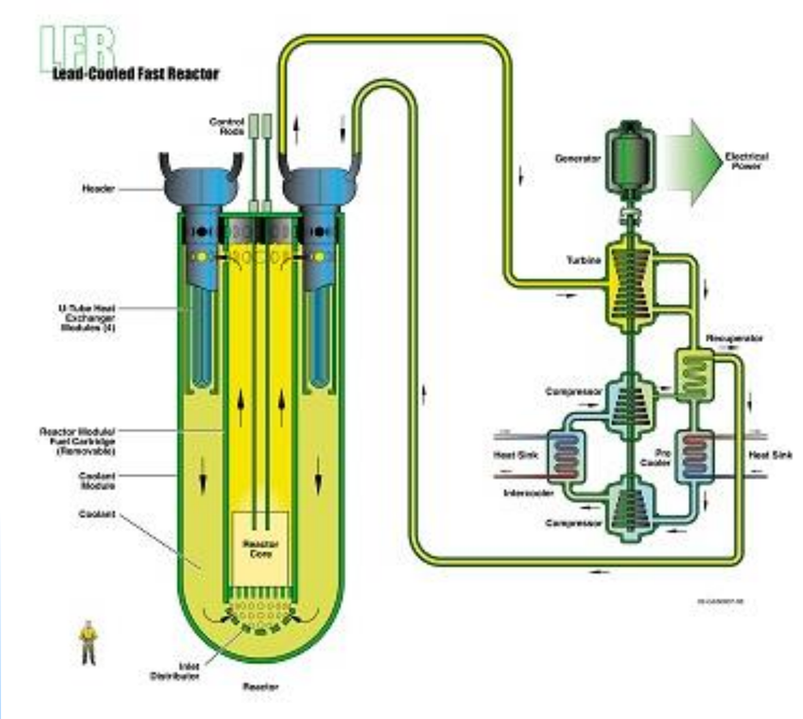
- The R&D needs arise mainly from, but are limited to, the issues associated with the high operation pressure and temperature:
  - Thermal-hydraulics
    - Supercritical pressure (SCP) water in bundle
  - Materials and Chemistry
    - Cladding materials
    - Water chemistry under irradiated SCP conditions
  - Development of computational tools for new systems
    - System integration and safety assessment

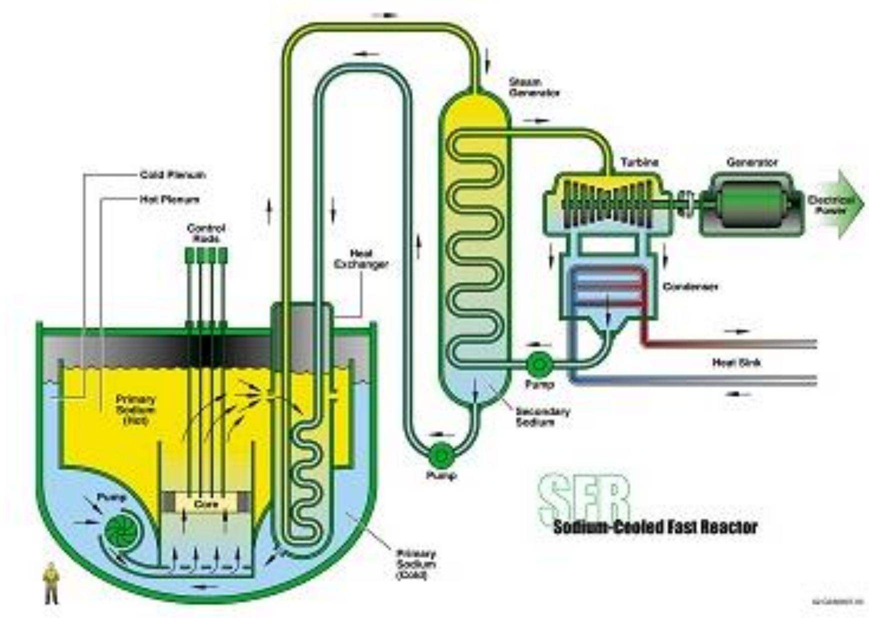
Common needs for all SCWR concepts

Fast Reactors

Existing Fleet and Under Construction

Future Innovative Designs / GEN-IV





Fast Reactor technology as future solution …

- Extend the current nuclear resources from about 120 years to a thousand years
  - ….. But many discussions that U resources are plentiful… a question of economy
- Generate more energy from fuel (and even breed more fuel)
- Significantly reduce radioactive waste in quantity and in radio-toxicity
  - Burn light water reactor waste while producing energy and more fuel

Why Fast Reactors ?

If ONLY WCRs:

- Uranium resources are under potential stress if only U-WCRs with open fuel cycle are deployed
- Stress on resources will appear some decades prior to the predicted exhaustion date if the committed uranium issue is addressed
- The potential future scarcity of uranium resources can be a serious issue for regions of the world where the energy demand growth is and will continue to be high, and where nuclear energy is widely expected to at least partially meet that demand
- A large number of new U mines should be opened and operated → environmental issues
- As a consequence of a U-WCRs / once-through fuel cycle, a large amount of spent fuel – and in particular of TRUs (Pu + MA) which are the most hazardous nuclear wastes - will build-up worldwide

- Low efficiency in fuel usage, only 1-3% of uranium
- Low thermal efficiency (30-34 %) by using water as coolant in the primary circuit
- The presence of a moderator medium leads to large cores with rather low power density

Why and How Fast Reactors Can Overcome These Issues, Making Nuclear Power More Sustainable

IAEA

Comparison of Characteristics of Typical Thermal and Fast Reactors

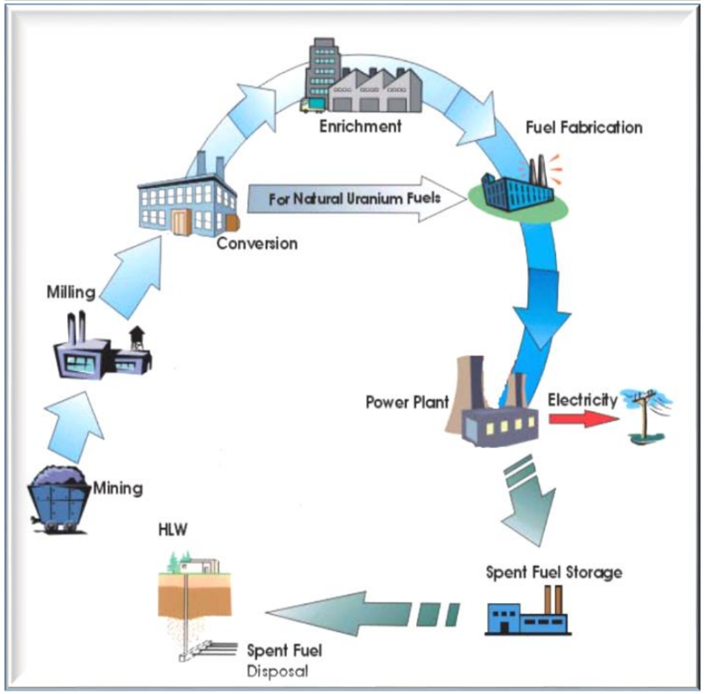
- No moderator to keep neutron energy high and enable breeding
- High fuel enrichment due to low cross-sections in fast spectrum
- As a consequence smaller cores and higher power density
- Need of coolants with higher heat transfer properties: liquid metals
- High power density and proper coolant: steam at 487 C and 17.7 MPa, efficiency of 40%

Feature	Reactor Type	
	Thermal	Fast
Average neutron energy	Low (0.0253 eV)	High (100-200 keV)
Fuel	Uranium-oxide UO_2	Mixed-oxide (PuO_2-UO_2)
Fuel concentration (%)	Low (0.7-5 U-235)	High (15-20 Pu-239)
Fertile conversion	Low	High
Core volume (liter)	Large	Small
Power density (kW/liter)	10	400
Coolant	Light or Heavy water	Liquid metal
Thermal efficiency (%)	28-34	40
Fuel burn-up (GWd/t)	7-40	> 100
High level waste	Produced	Partially incinerated
Neutron flux ($n/cm^2/s$)	10^{14}	$5 \cdot 10^{15}$
Maximum neutron fluence (n/cm^2)	10^{22}	$2 \cdot 10^{23}$

Extending Fuel Supply for Next Centuries

Non effective use

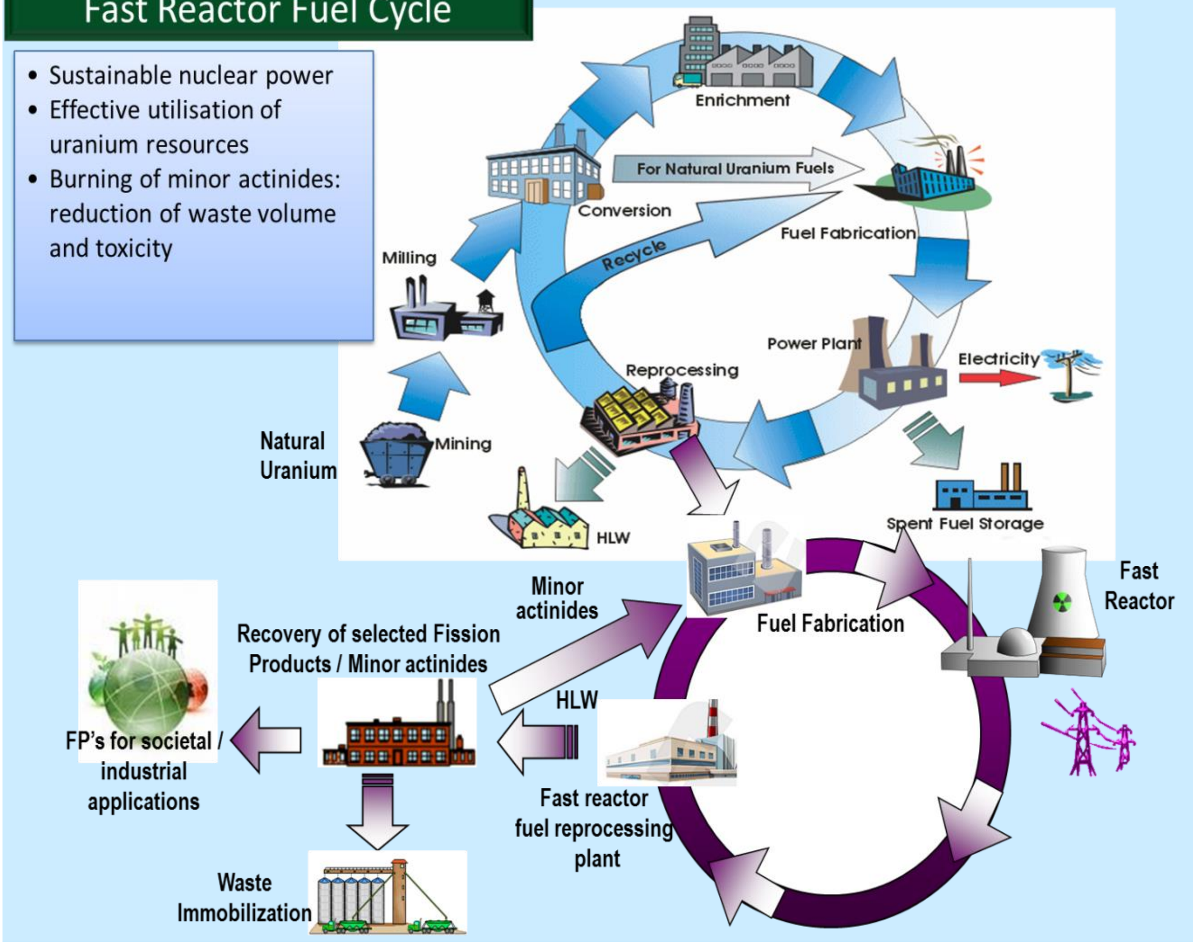
LWR Open Fuel Cycle



Only a small fraction (a few %) of the energy potential of natural uranium is exploited… 300+ NPP operating today

Fast Reactor Fuel Cycle

- Sustainable nuclear power
- Effective utilisation of uranium resources
- Burning of minor actinides: reduction of waste volume and toxicity



Fuel Sustaining Cycle

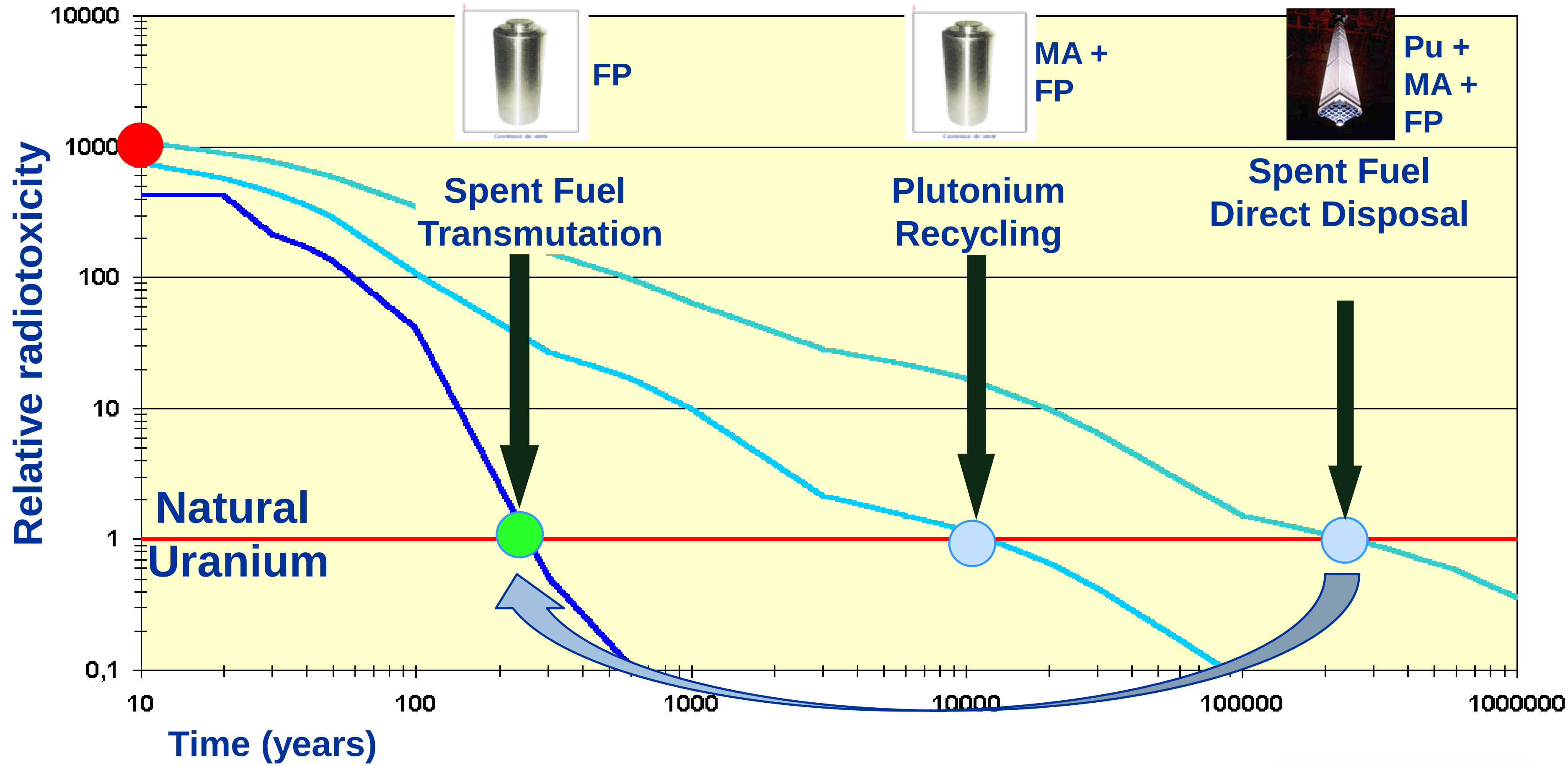
FRs: Great flexibility thanks to excess of neutrons and transmutation performances

As first discovered by Enrico Fermi in 1944, the nuclear characteristics of transuranics (TRU) cross sections in a fast neutron spectrum allow a great FR flexibility:

- Breed (i.e. Conversion Ratio CR>1) ➡ Sustainability
- Burn (TRU or MA), i.e. CR<1 ➡ Transmutation to facilitate waste management
- Breed (e.g. Pu) and burn (MA)
- CR~1: Self-sustaining cycles (isogenerator systems)

Extremely important for the sustainability is also the concept of Doubling Time (CDT) – associated with breeding - i.e. the time required for a breeder reactor to produce enough material to fuel a second reactor

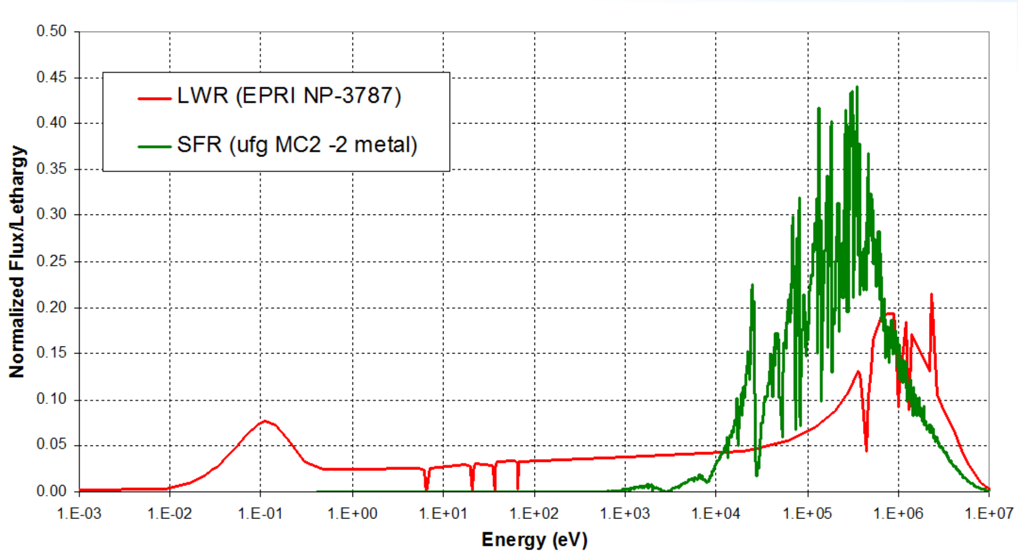
Fast Reactors Technology can reduce the time waste remain radiotoxic from 250,000 years to about 400 years.



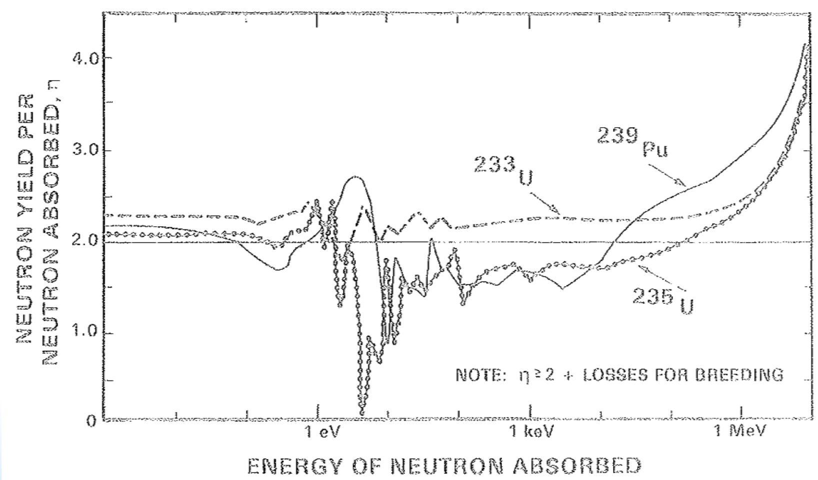
Duration Reduction 1,000x

Volume Reduction 100x

Reviewing the Physics:



- In LWR, most fissions occur in the 0.1 eV thermal "peak"
- In SFR, moderation is avoided – no thermal neutrons



Neutron yields for various fissile atoms (Source: A. Waltar, A. Reynolds)

Neutron yields 'η' in thermal and fast spectrum reactors

Reactor types	Natural Uranium	Uranium 235	Uranium 233	Plutonium 239
Thermal	1.34	2.04	2.26	2.06
Fast	< 1	2.20	2.35	2.75

Breeding possible with ^{239}Pu in fast energy range

Fast Reactors in Operation and Under Construction

Japan

Joyo, experimental reactor (140 MWt): suspended, closed

Monju, prototype (280 MWe): (shutdown since 1995, closed)

France

Phenix, prototype (250 MWe): shut down in Sep.2009

No new plans

Russia

BOR-60, experimental (12 MWe): in operation

MBIR, experimental (55 Mwe): under construction

BN-600, prototype (600 MWe): in operation

BN-800, demonstration (800 MWe): in operation

China

CEFR, experimental (20 MWe): in operation

India

FBTR, experimental (13 MWe): in operation

PFBR, prototype (500 MWe): under commissioning

MONJU

BN-800

CEFR

Fast Reactor Technology Advantages

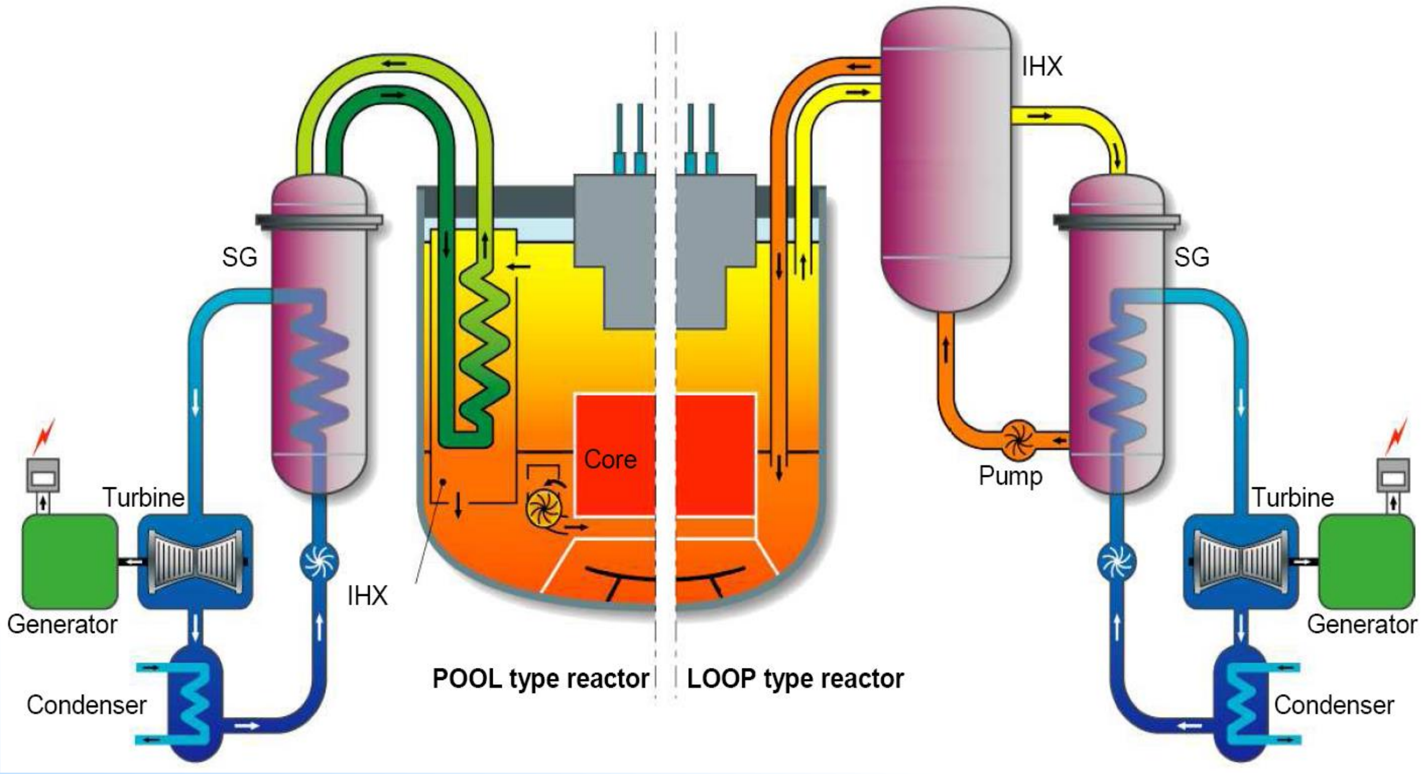
- Enhanced safety characteristics
  - Atmospheric pressure in the primary circuit
  - High thermal inertia
  - Large coolant boiling margin
  - Natural convection
  - But, core is not in its most reactivity configuration
- Higher thermal efficiencies (higher temperatures)
- More efficient use of U resources
- Reduction of waste

Why FRs are not Largely Deployed?

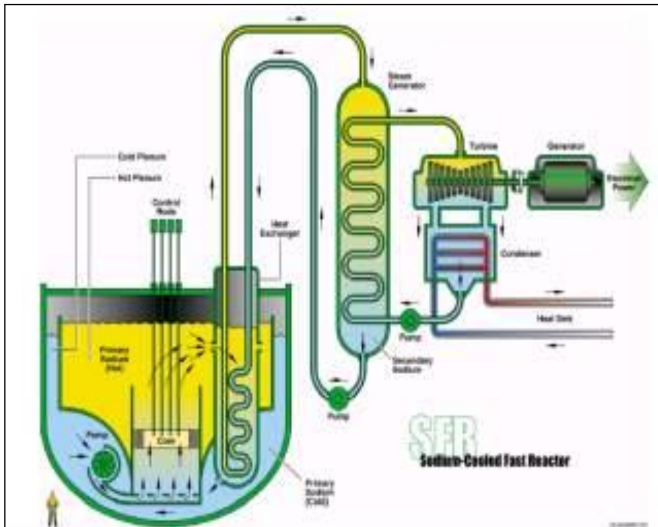
- Proliferation concern and restrictions in sharing of reprocessing technology (possible dual purpose).
- Uranium proved to be much more abundant than originally imagined.
- Demand for nuclear energy declined after the Three Mile Island and Chernobyl accidents, as well as from the belief that fossil energy was plentiful and would remain cheap.
- Higher (investment and O&M) costs with respect to LWR: potentiality of fast reactors has been recognized since the beginning of nuclear power era.
- The intrinsic characteristics of fast spectrum require more complex and expensive technologies (both for the reactor and the associated fuel cycle)

What Types of FRs: System Designs

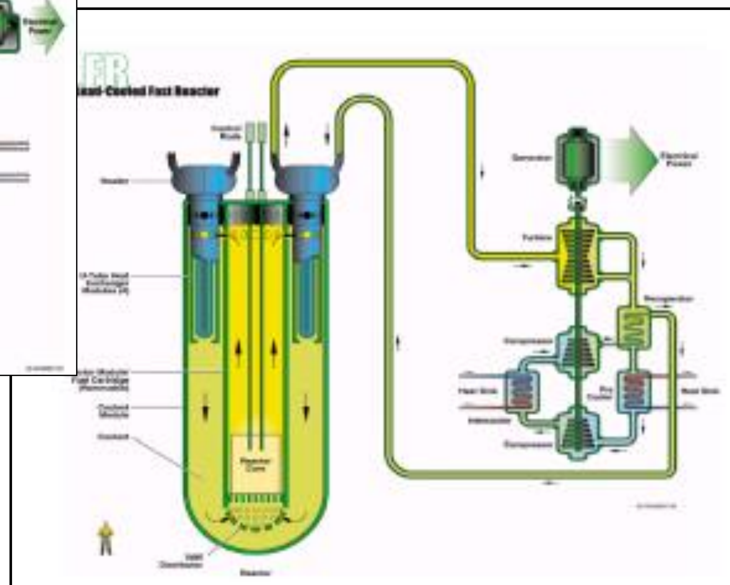
- System Configuration / lay-out: loop, pool, semi-integral
- Primary coolant: Na, Heavy Liquid Metals (Pb, Pb-Bi), Gas, Molten Salts
- Energy Conversion System / Power Cycle: direct / indirect, Rankine (steam) / Brayton (gas)



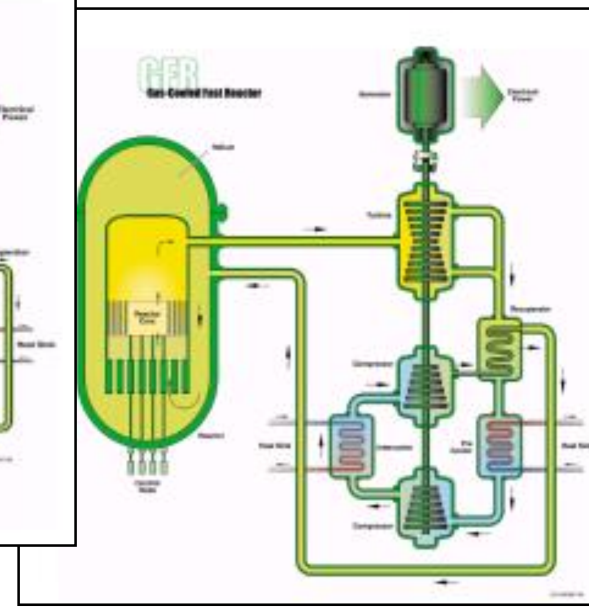
What Types of FRs?



Sodium Fast Reactor



Lead Fast Reactor



Gas Fast Reactor

Sodium Cooled Fast Reactors (SFR)

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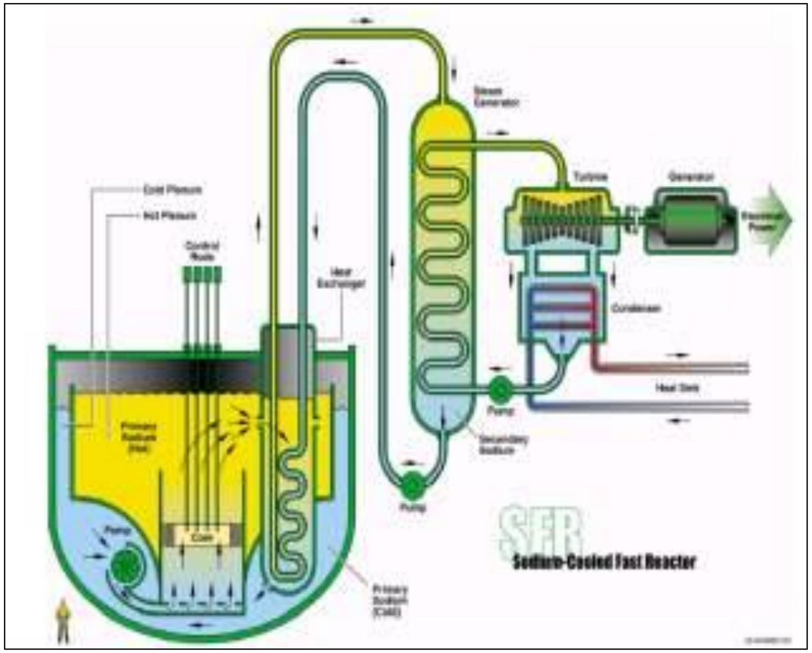

- Safety and Operations
  - Review and assessment of passive/active safety and severe accident issues
  - Development of SFR Safety Design Criteria (GIF and IAEA)
- Advanced Fuel
  - Selection of high burn-up MA bearing fuel(s), cladding and wrapper withstanding high neutron doses and temperatures.
- Global Actinide Cycle International Demonstration (GACID) - But plans based on Joyo and Monju …
- Most mature technology (but also many problems in past operating plants)

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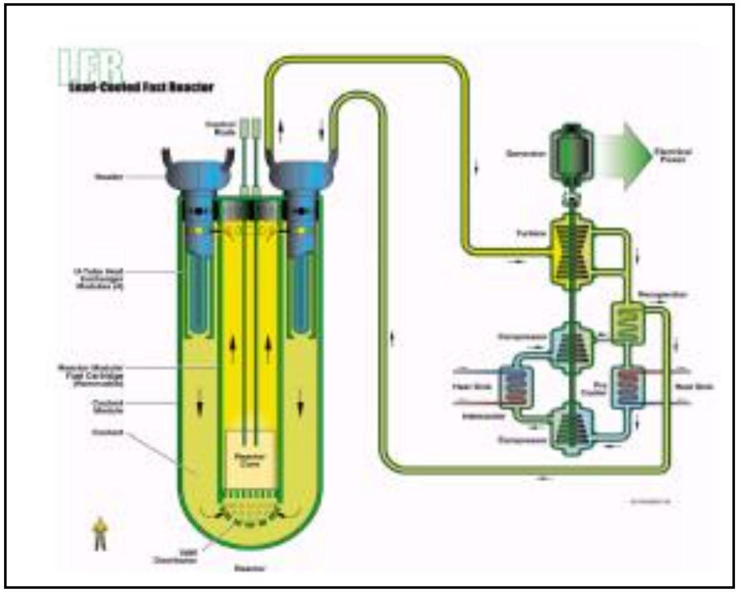
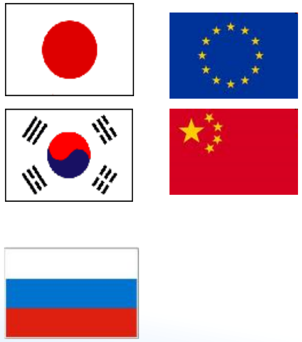
Lead Cooled Fast Reactors (LFR)





- Developed white paper on safety including developing SDC
- Performed a LFR system safety assessment
- Several reference designs being presented

MYRRHA
Multipurpose hYbrid Research Reactor for High-tech Applications

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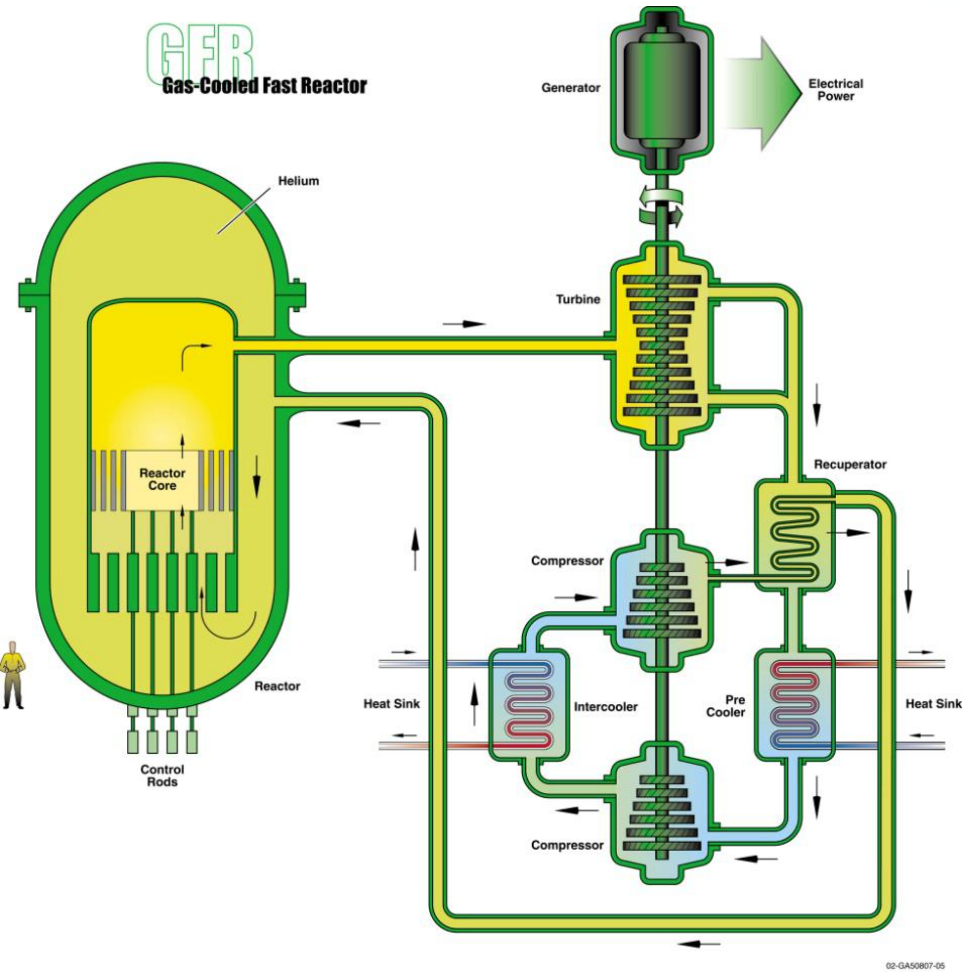
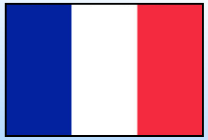
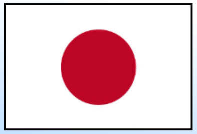
GFR



- Temperature (~ 850 °C), He cooled, and fast spectrum to achieve a closed fuel cycle
- Biggest challenge is the loss of coolant accident, and decay heat removal without external power supply
- Fuel technology development still need substantial R&D (out-of-pile and irradiation tests)
- Major components and systems qualification
- Small experimental reactor design studies underway to perform technology demonstration
- Possibly the least developed of all the systems

Challenges for Innovative FRs

- At present, there is a wide convergence on the choice of sodium as coolant, with oxide, metal (e.g. for high conversion ratio) or nitride fuel.
- However, it seems important to explore/develop a viable backup option, such as lead (or lead-bismuth) coolant with oxide or nitride fuel, or gas coolant with carbide fuel.
- In this context, an innovative sodium-cooled prototype and a demo/experimental plant for exploring a backup option should/could be the focus of international initiatives.
- Other internationally recognized major challenges are:
  - ✓ The very limited availability of fast spectrum irradiation facilities, in particular to test and qualify advanced materials, fuels and targets (currently only BOR-60 in Russian Federation and FBTR in India);
  - ✓ The industrial demonstration of a fully closed fuel cycle with fast reactors, including the multi-recycling of the fuel as well as the (homogenous or heterogeneous) partitioning and transmutation of minor actinides (Am, Cm and Np).

Presentation Objectives

By the end of this session, participants should be able to:

- Define what is a small modular reactor (SMR)
- Summarize the key design and safety features of SMRs
- Explain advantages and challenges of SMRs
- Explain the different Generations –IV reactors systems and their main differentiating factors
- Define what is an advanced reactor and outline their advantages / challenges

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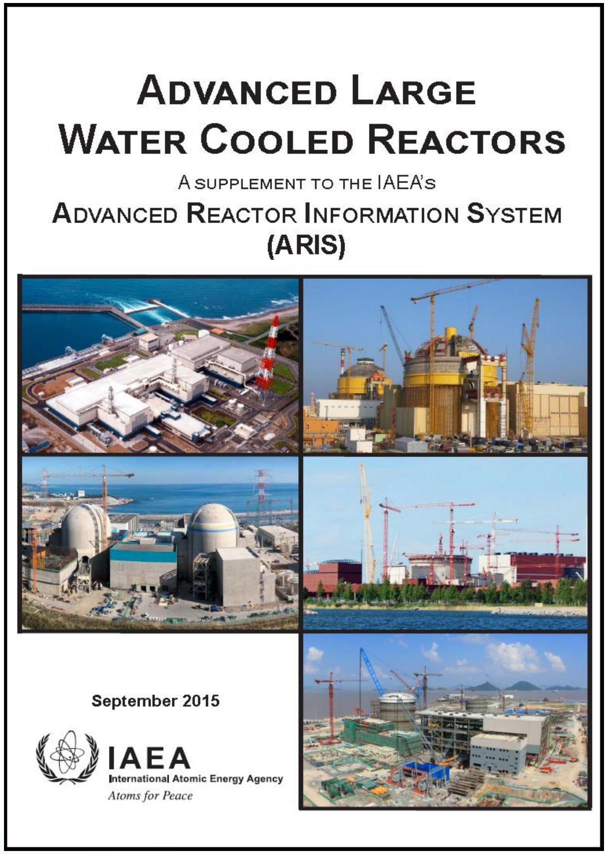
Thank you!

IAEA Booklets on Advanced Reactors



Large WCR and FR are published as-needed

SMR Booklet is published every 2 years