Joint ICTP-IAEA Workshop on
Physics and Technology of Innovative Nuclear Energy Systems
12-16 December 2022

OVERVIEW OF SMALL MODULAR REACTORS – DESIGN AND TECHNOLOGY

Chirayu Batra

Chief Technology Officer

TerraPraxis

https://www.terrapraxis.org/

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TERRA PRAXIS

Outline

- SMRs
  - Broad Definition
  - Benefits: What do they offer?
  - Technology: How the technology is different/same?
  - Different Designs: brief description and how they are bringing innovation
  - Diversified applications: Beyond electricity production
  - Challenges: path to deployment
  - What's next?: Global Development and deployment Scenario

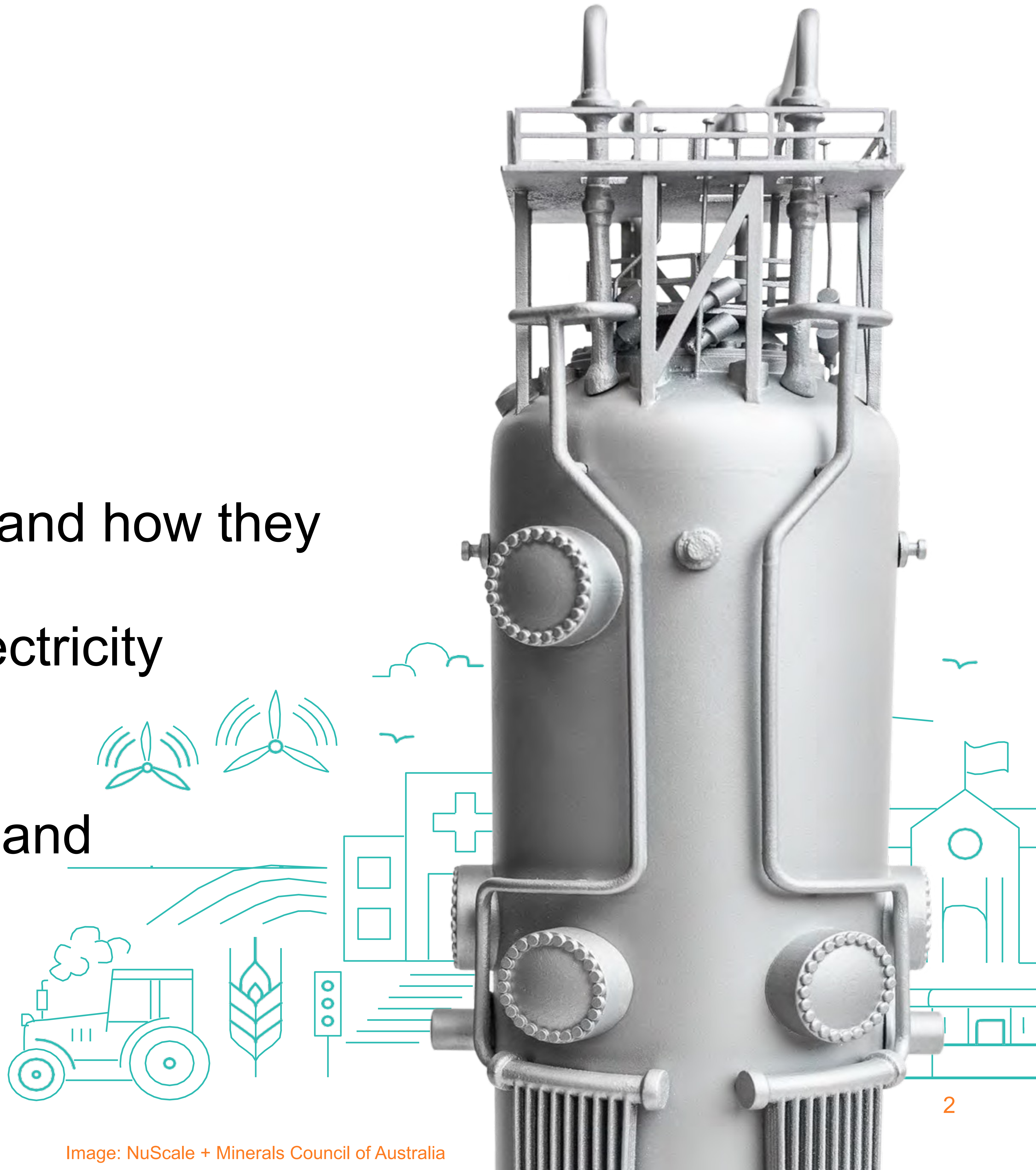
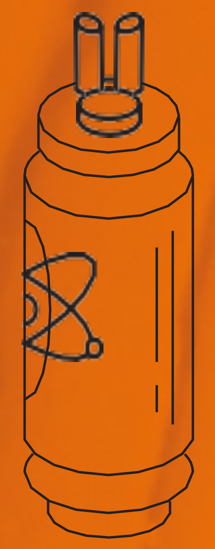


Image: NuScale + Minerals Council of Australia



WHAT ARE SMRS, BENEFITS, KEY FEATURES AND TECHNOLOGY...

SMR: Size

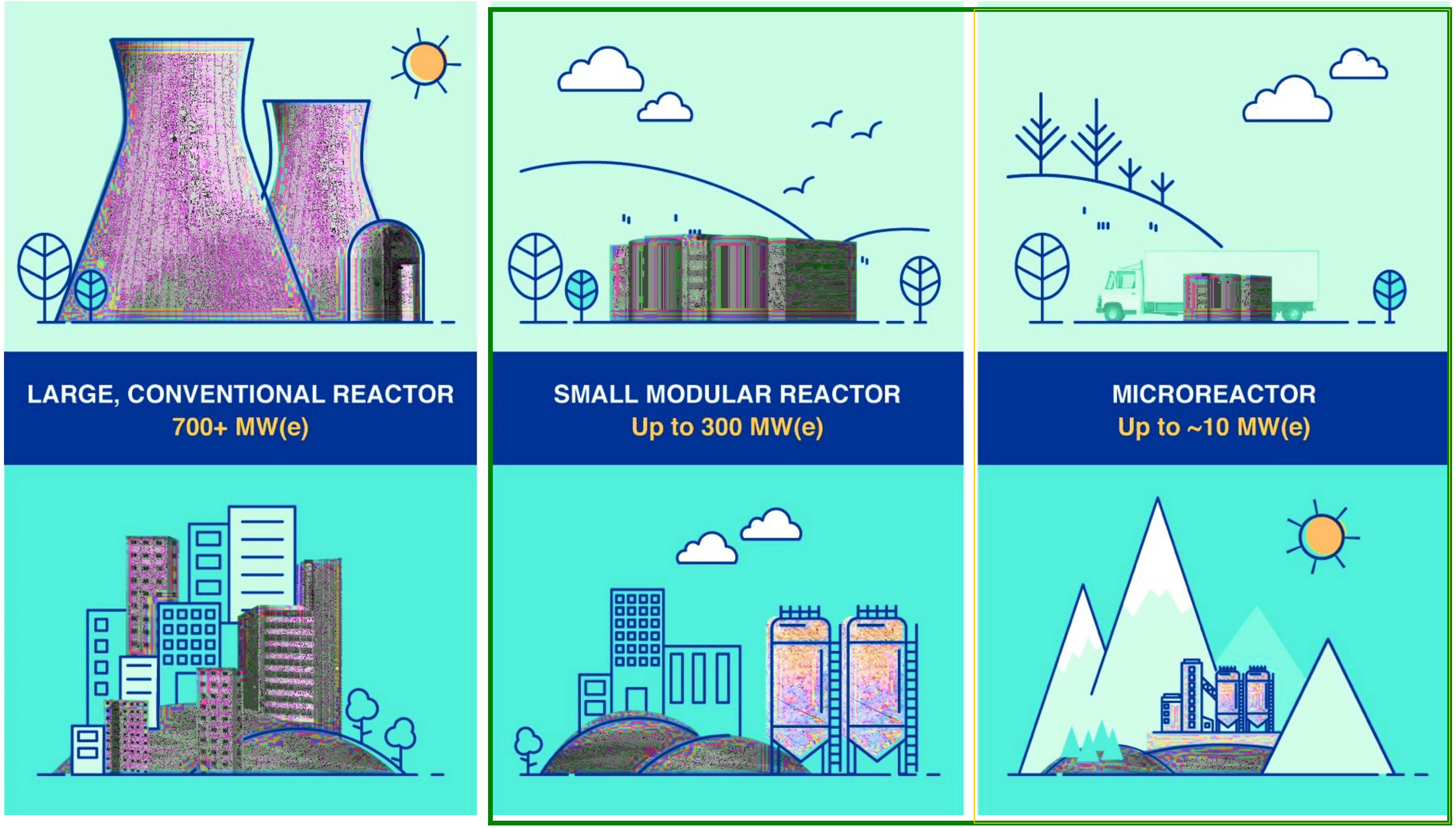


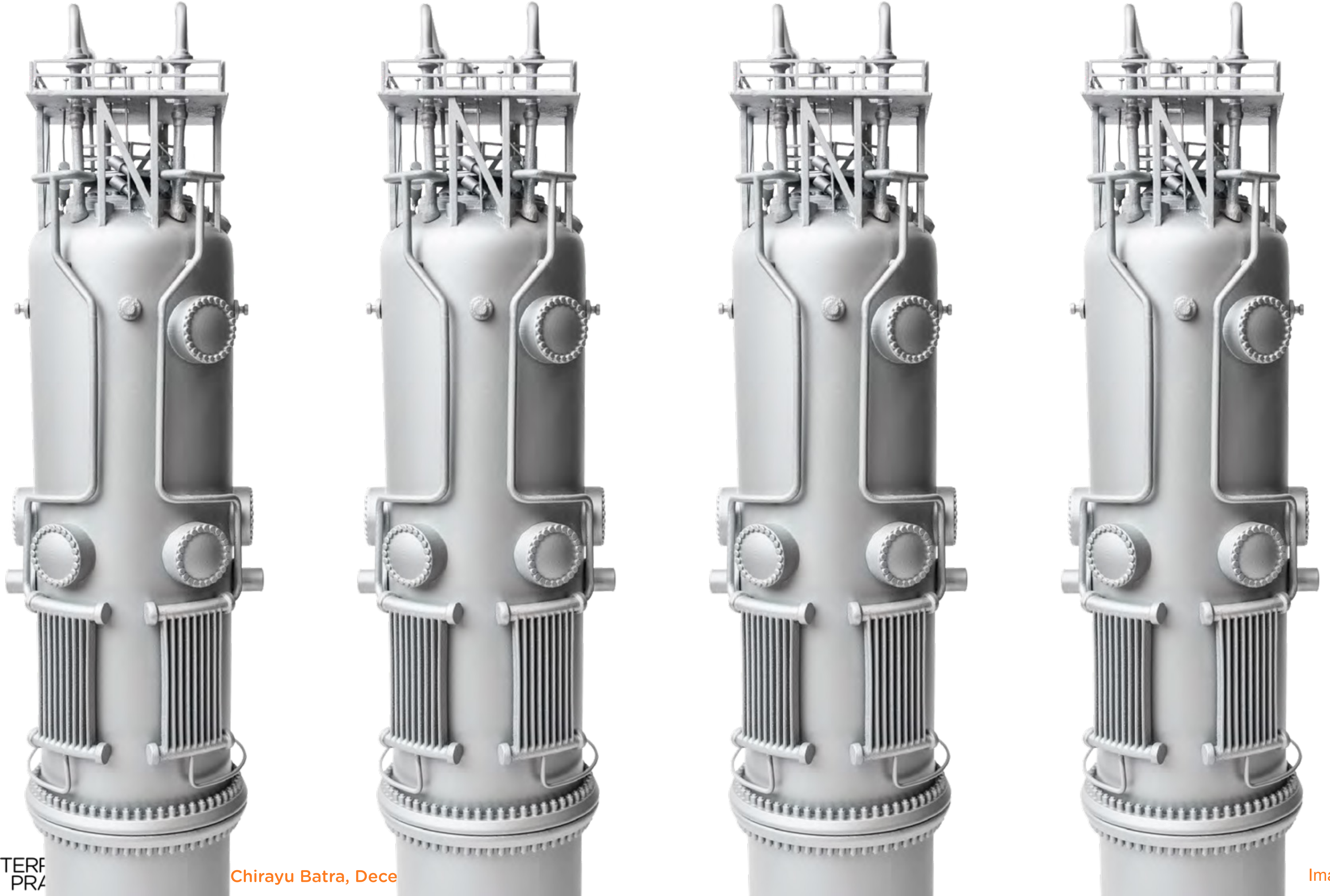
Image: IAEA

- **Small**: Smaller land footprint, typically have less than 300 MW(e) power output and have a compact design
- *Microreactors* are sub-category of SMRs, most designs have less than 10 MW(e) power output and have a niche market

Nuclear power plants provide flexibility in terms of power and energy market

SMR: Modular

Modularization is considered a key part of the concept of an SMR

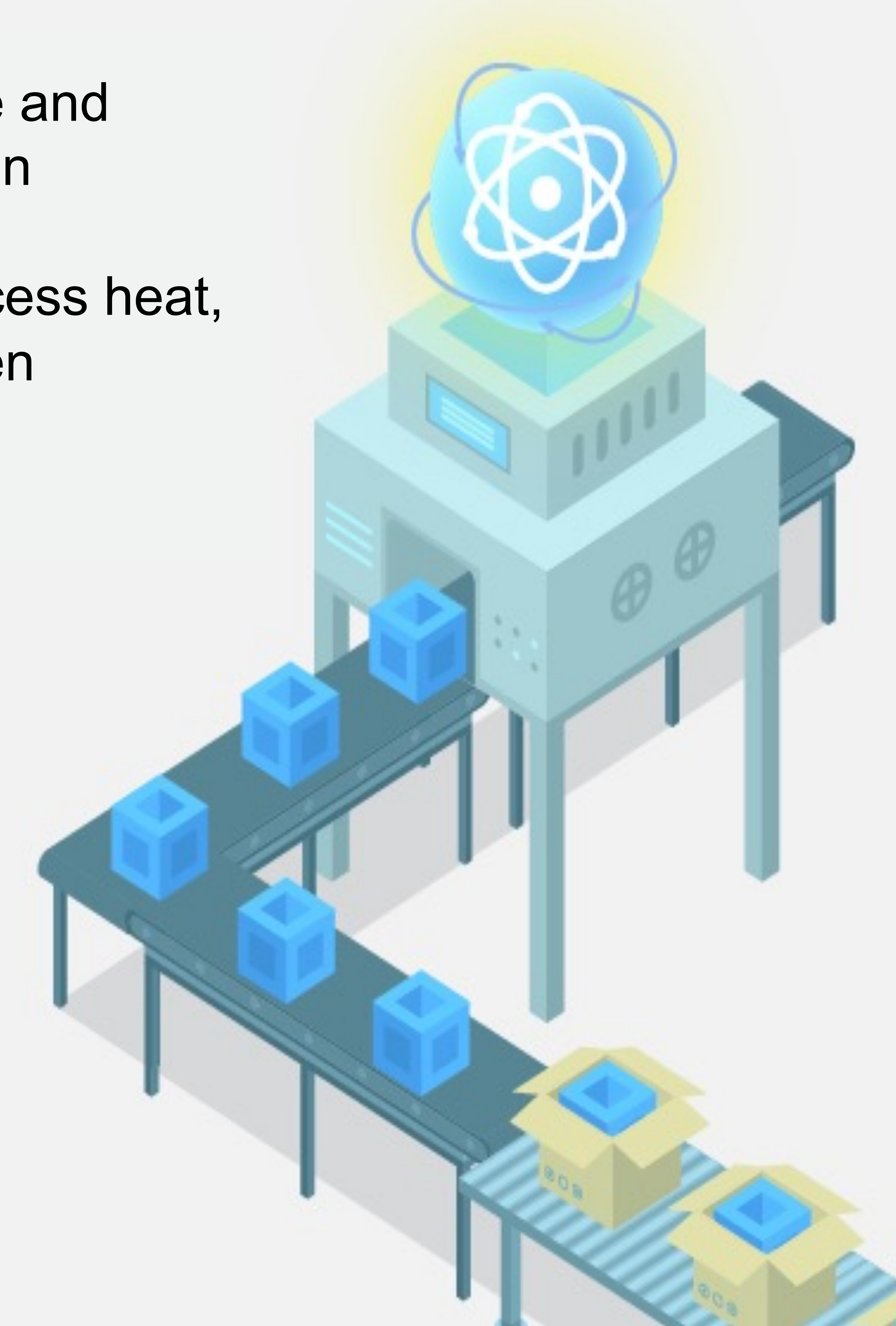


- **Modular**: Modular in *design*, *construction* and *arrangement of power modules* inside a power plant
- Ability to fabricate major components of the nuclear steam supply system in a factory environment and ship to the point of use
- Reduced on-site preparation
- Substantially reduce the lengthy construction times and risks
- Multi- module as per energy demand

Image: NuScale

SMR: Multi-purpose Applications

- SMRs provide options for wide and versatile applications other than electricity production
- District Heating, industrial process heat, Nuclear Desalination, Hydrogen production, and so forth.

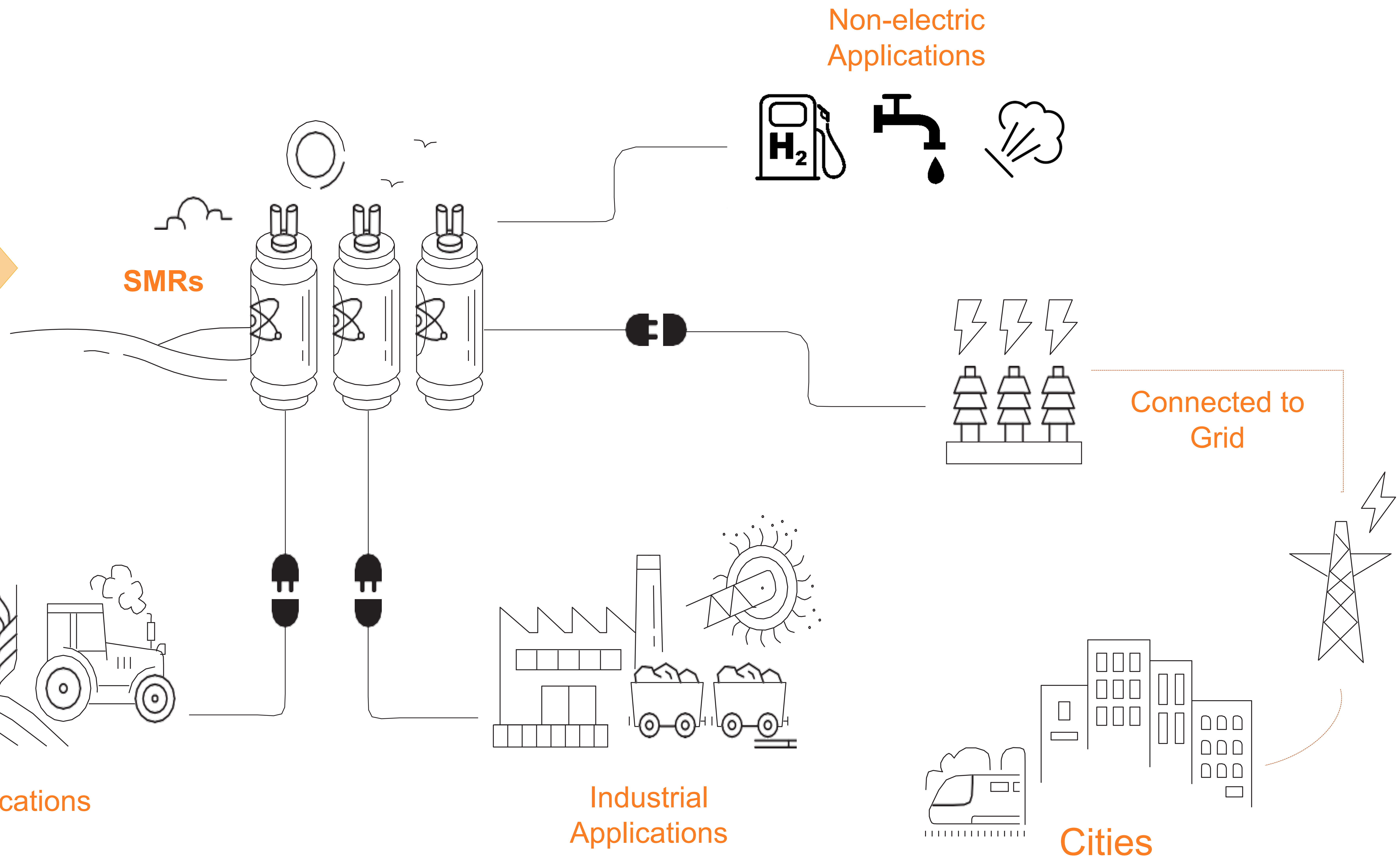


electricity
clean water
hydrogen
heating
grid storage
vehicles
synthetic fuels
ammonia
metals refining
and more

Co-generation

SMRs: Nuclear Power System

SMRs can either be connected to **grid** or create their own **ecosystem** or live in a **hybrid** energy system



A Categorization of SMR Technology

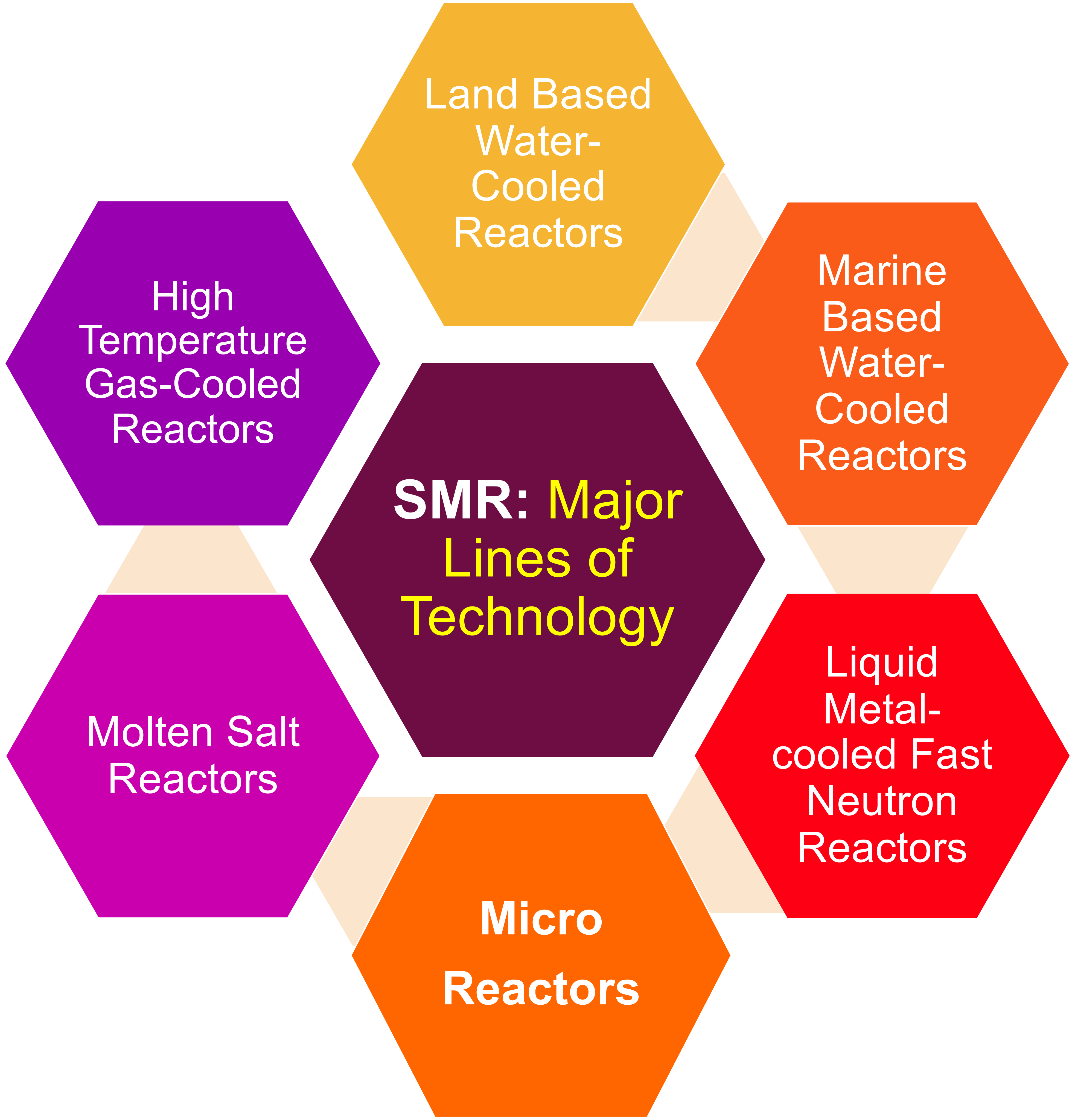


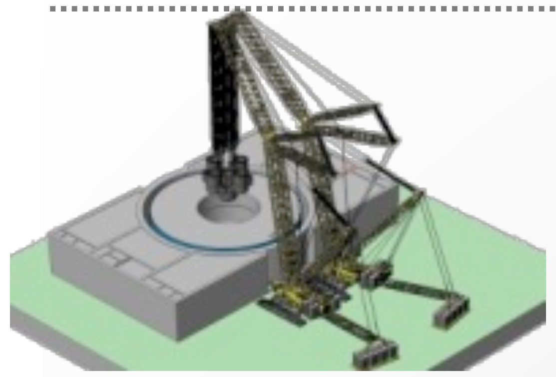
Image: IAEA SMR Booklet

Key Attributes of SMRs

- Enhanced Safety
- Versatile
- Modular
- Reduced Waste
- Affordable
- Non-electric applications

Economic
- Lower Upfront capital cost
- Economy of serial production

Better Affordability

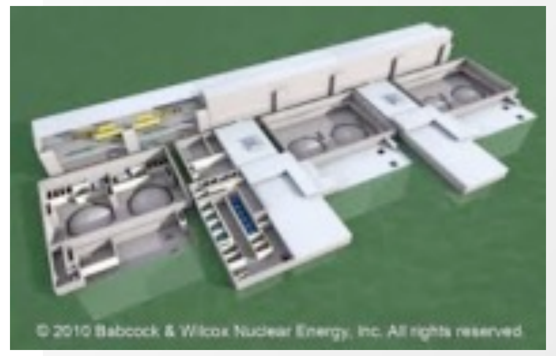


Modularization
- Multi-module
- Modular Construction

Shorter construction time

Flexible Application
- Remote regions
- Small grids

Wider range of Users

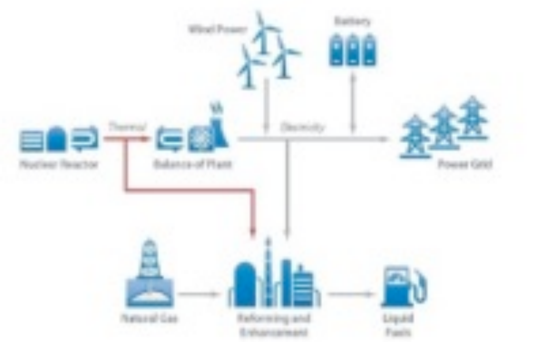


Smaller footprint
- Reduced Emergency planning zone

Site flexibility

Replacement for aging fossil-fired plants

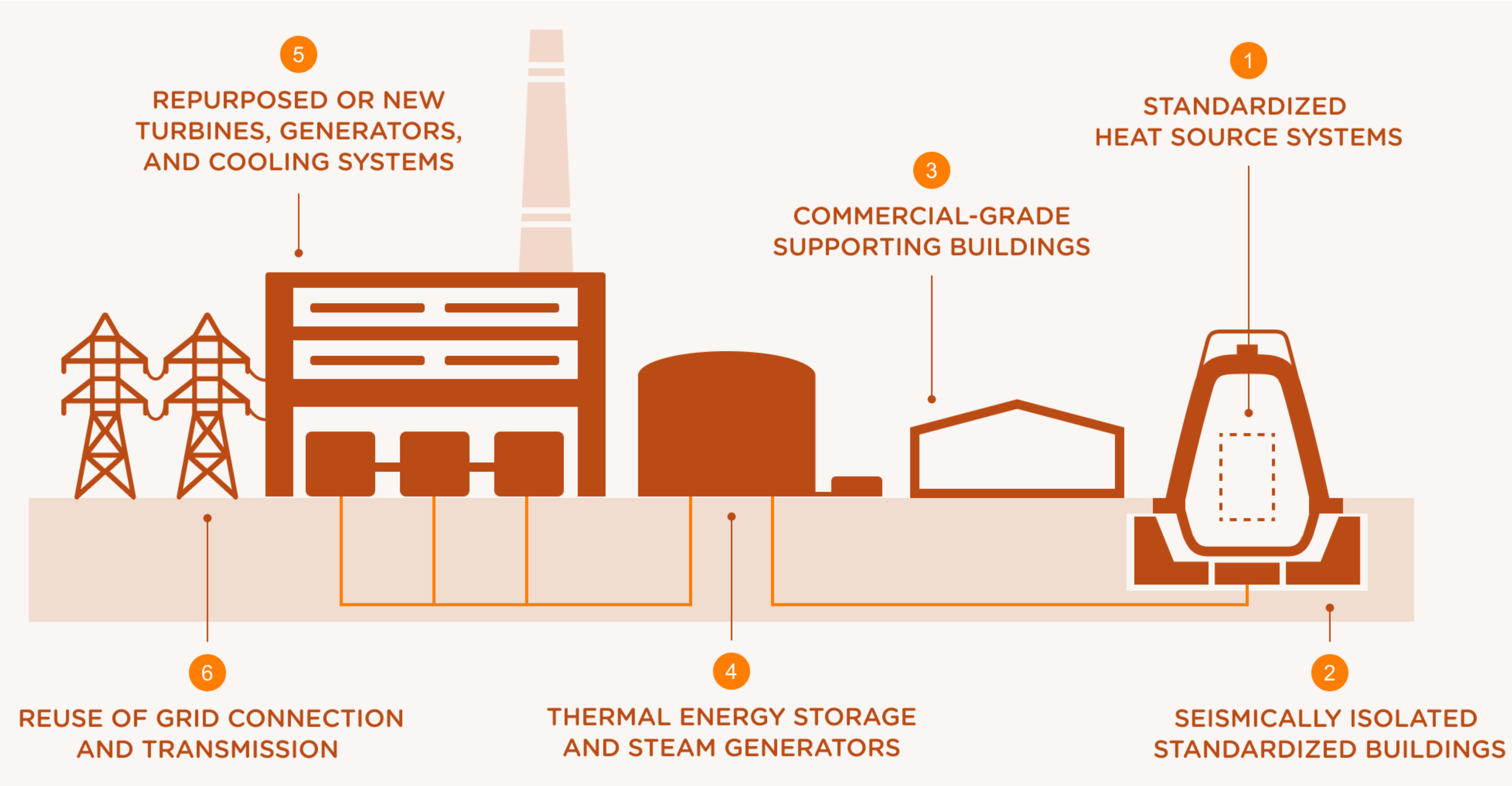
Reduced CO_2 production



Potential Hybrid Energy System

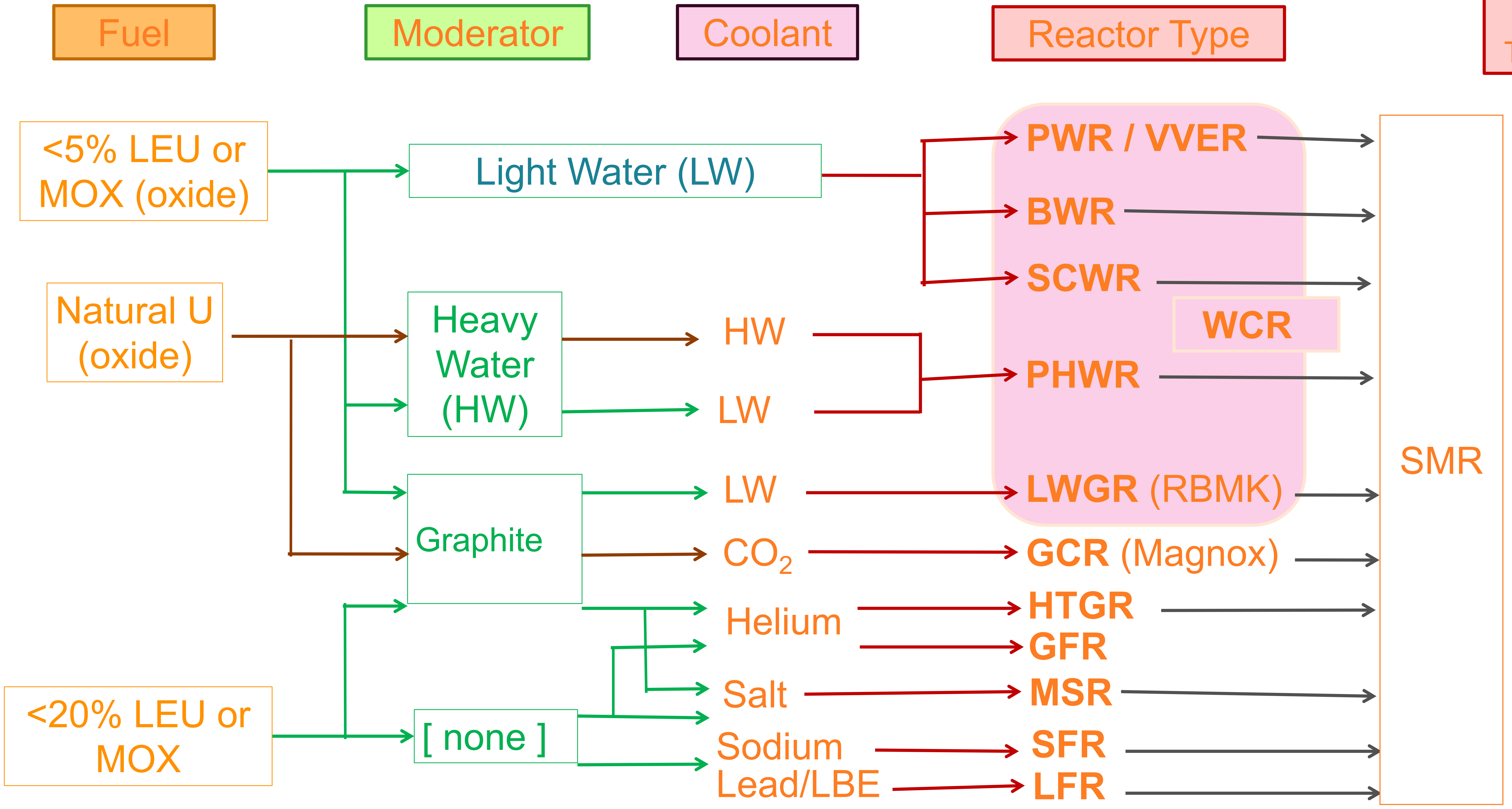
Integration with Renewables

SMR Application: Repowering Coal



https://www.terrapraxisrepower.com/

SMR: Reactor Technology/Types

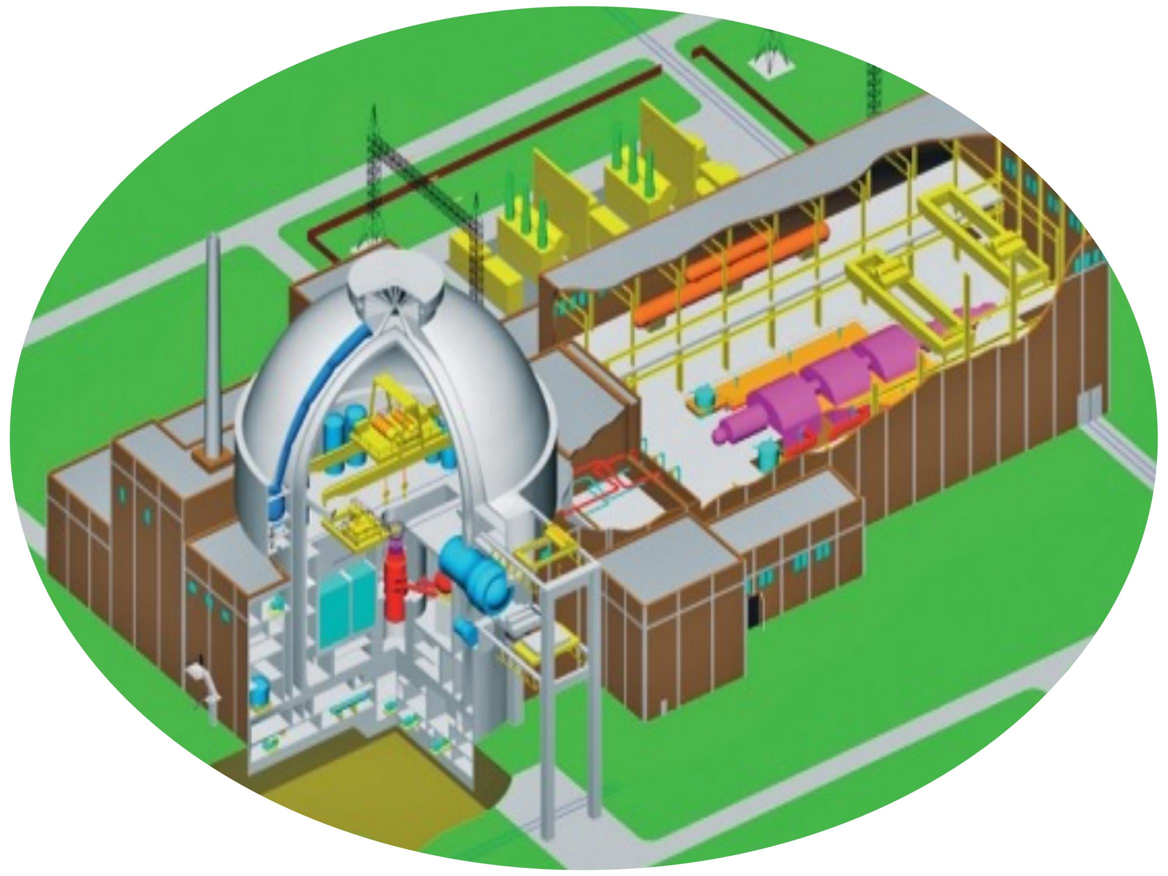


Reactor Type	Outlet Temperature	Steam Cycle Efficiency
PWR / VVER	317 °C	~33%
BWR	286 °C	~35%
SCWR	520 °C	~43%
PHWR	305 °C	~32%
LWGR (RBMK)	284 °C	~31%
GCR (Magnox)	360 °C	~31%
HTGR	650 °C	~43%
MSR	697 °C	~45%
SFR	522 °C	~39%
LFR	495 °C	~43%

MOX: mixed-oxide containing any combination of U, Pu and Th oxides

SMRs are of major technology-lines, many designs incorporate advanced features

SMR: Advanced Reactors



SMRs

CAREM, HTR-PM, KLT-40S, ACP100, AHWR, NuScale, SMART, NUWARD, 4S, EM^2…

EVOLUTIONARY

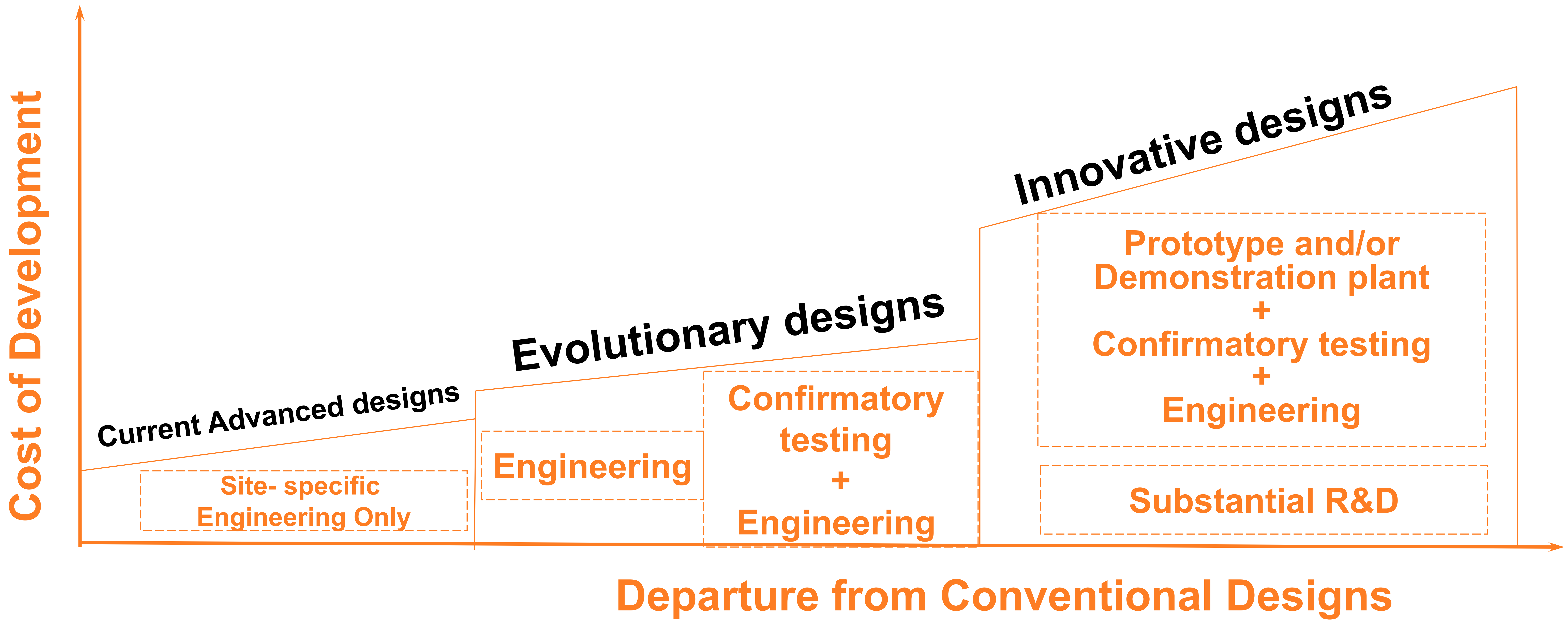
ABWR, ACR-1000, AP1000, APWR, ATMEA1, EPR, ESBWR, WWER 1200, CAP1400, APR1400, HPR1000…

INNOVATIVE

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

Advanced Designs

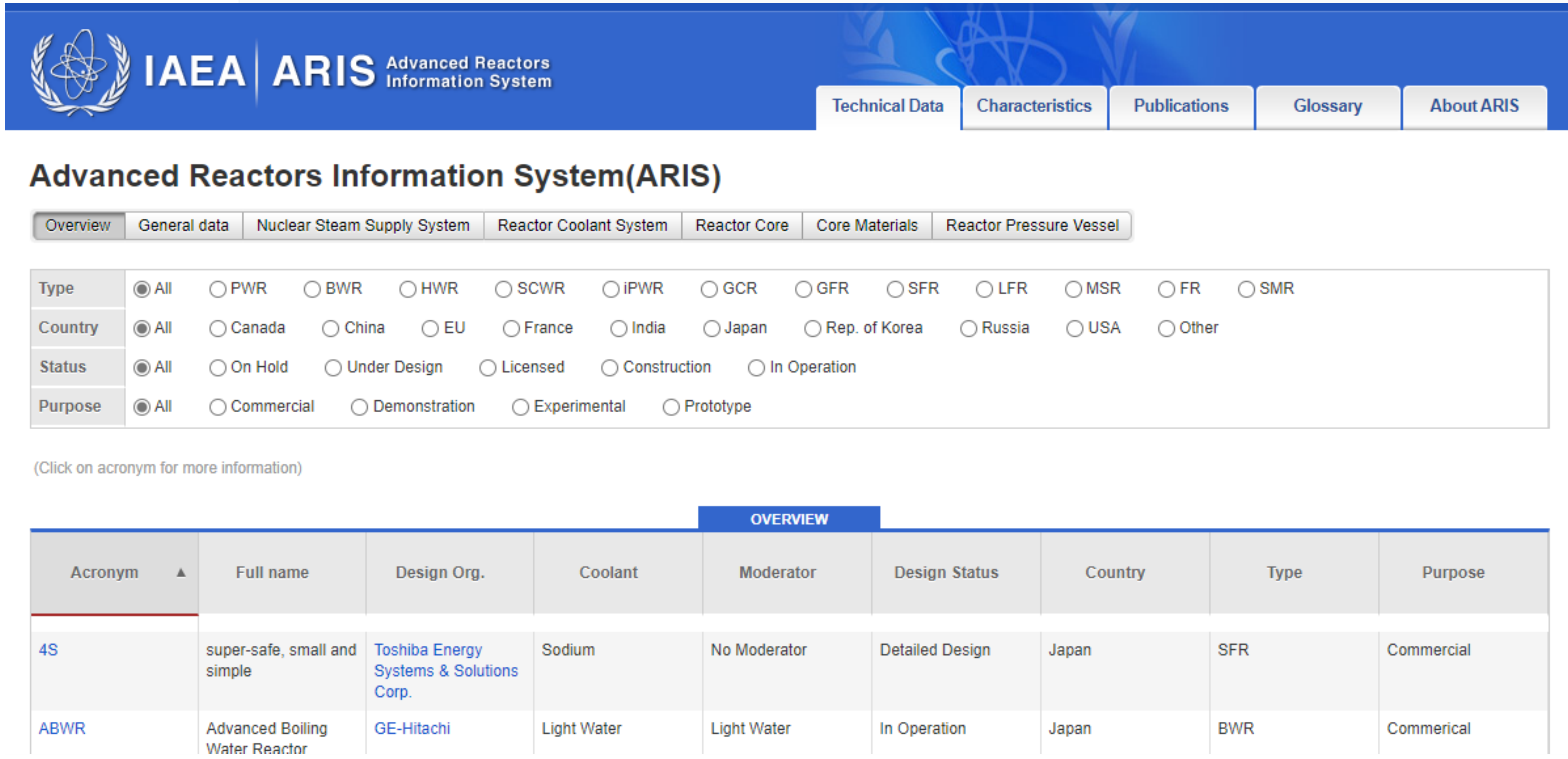
- IAEA defines two kinds of advanced designs:
  - ✓ **Evolutionary designs** to achieve improvements over existing designs through small to moderate modifications;
  - ✓ **Innovative designs** to incorporate radical conceptual changes in design approaches or system configuration.



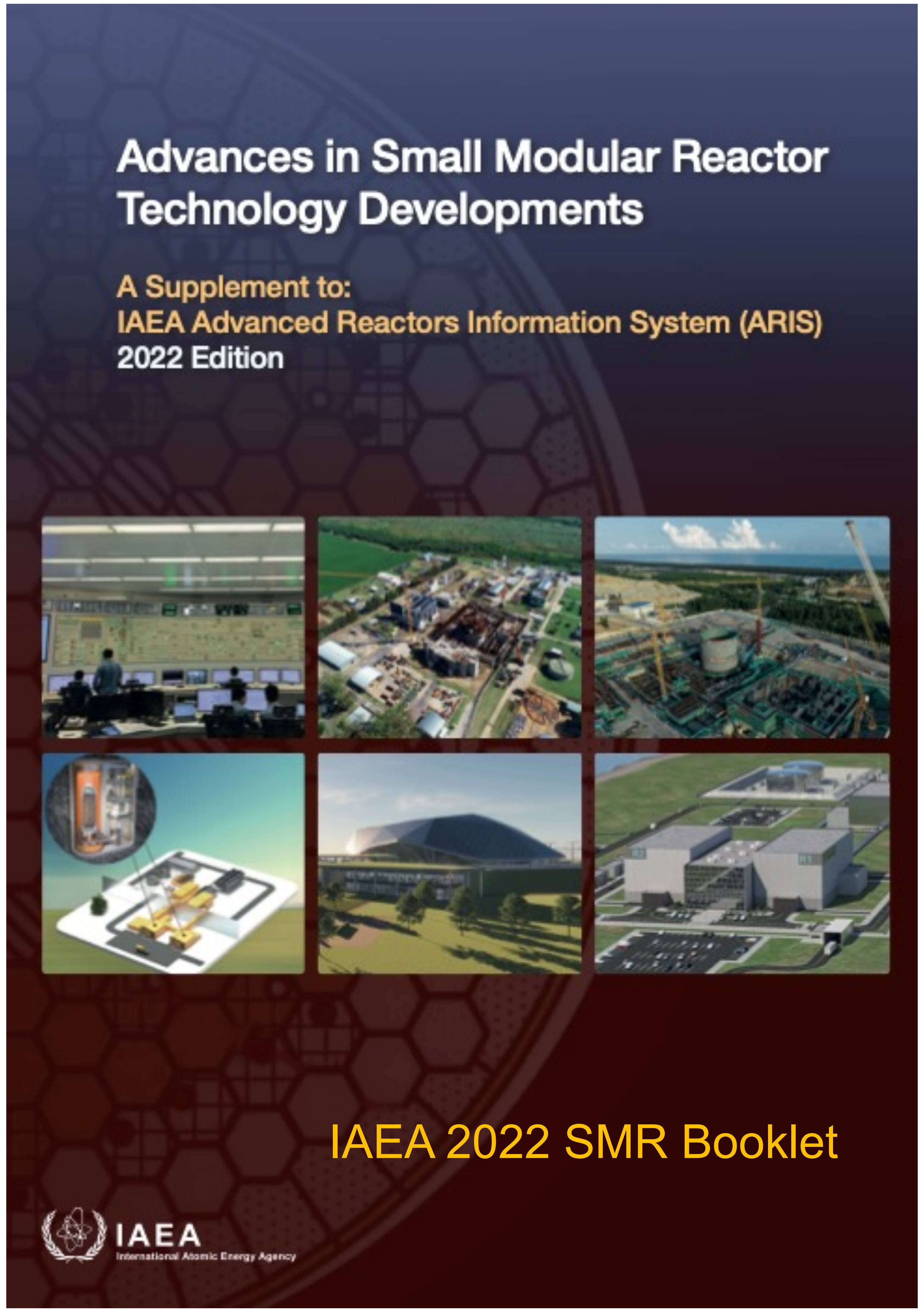
DIFFERENT SMR DESIGNS, DESCRIPTION AND INNOVATIVE FEATURES

ARIS: Advanced Reactor Information System

- Most up-to-date information about all available nuclear power plant designs, as well as important development trends
- Design description from evolutionary nuclear plant designs for near term deployment, to innovative reactor concepts still under development
- Information is provided directly by design organizations
- *New upgraded and modernized ARIS will be available soon*

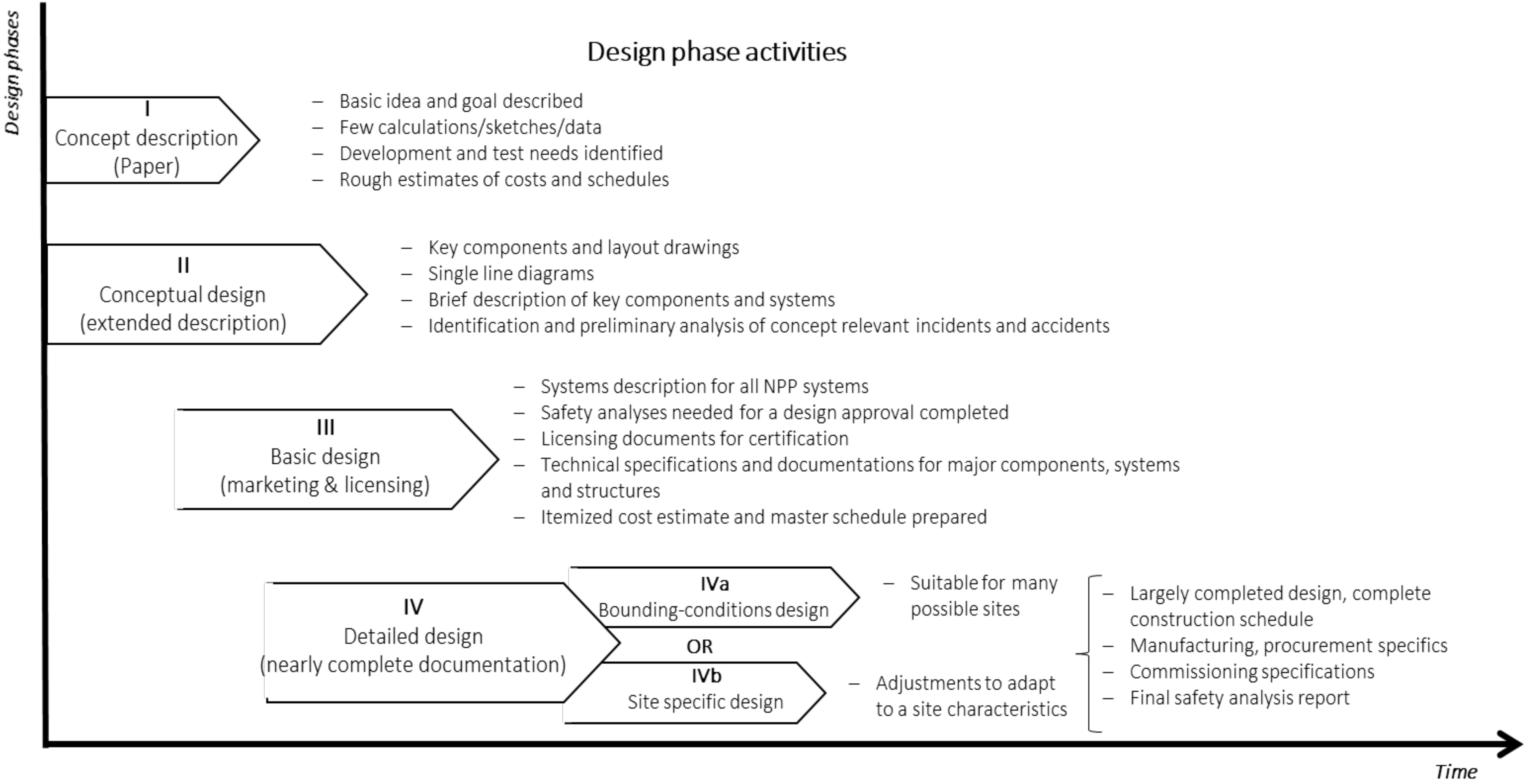


IAEA-ARIS SMR Booklet 2022



IAEA SMR Booklet, 2022 Edition	
Number of reactor designs:	83 *(16 more than 2018-edition, 11 more than 2020-edition)*
Member states involved:	**18** countries
Reactor types included:	• Water-cooled Land Based – **25** • Water-cooled Marine Based – **8** • High temperature Gas cooled – **14** • Liquid Metal cooled (fast) – **8** • Molten Salt – **13** • Microreactors - **12** • Test Reactors (HTGR only) – **3**
Distinguishing features	• New annexes on economic challenges, decommissioning, and experimental testing for design verification and validation • Insightful annexes with various charts and tables
Status	Published, hardcopies available
Downloadable version	https://nucleus.iaea.org/sites/smr/Shared%20Documents/2022%20IAEA%20SMR%20ARIS%20Booklet_rev11_with%20cover.pdf

Design Development Phases



Review: Salient Design Characteristics

Simplification by Modularization and System Integration

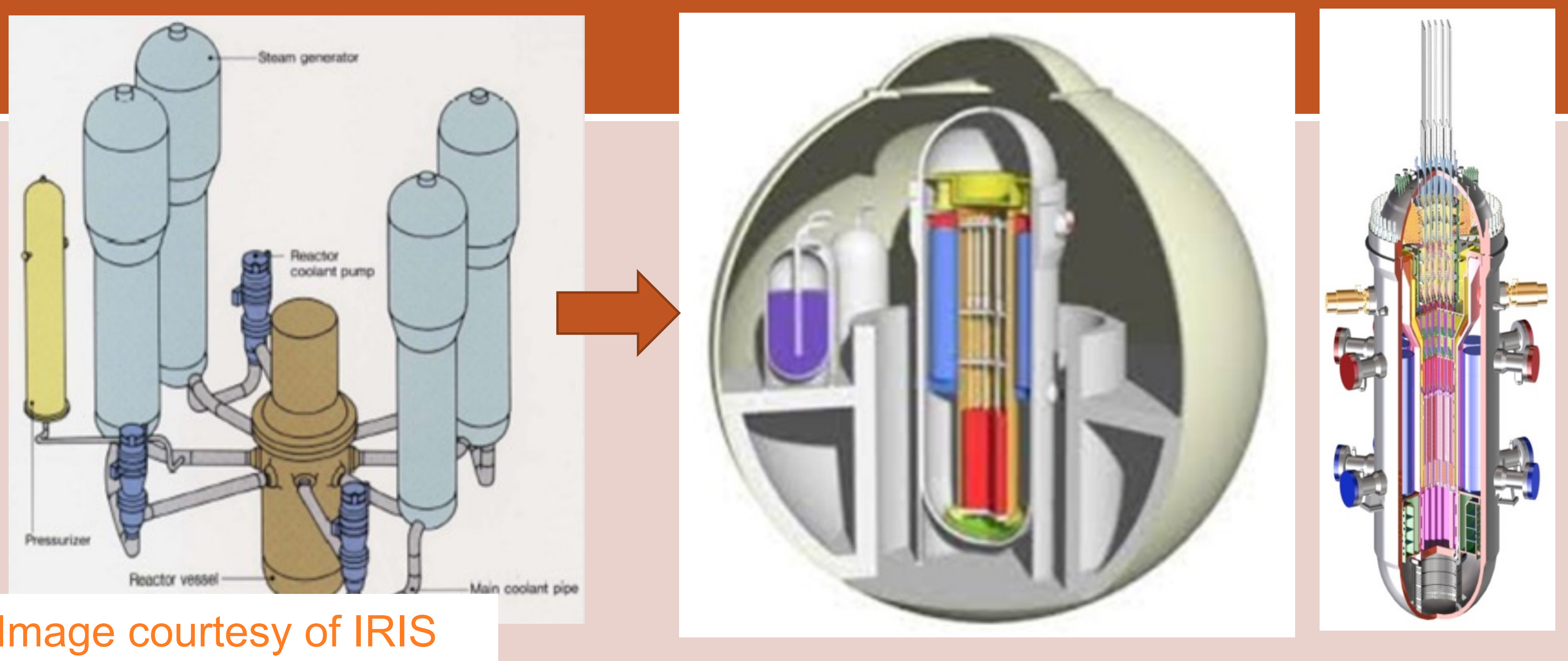


Image courtesy of IRIS

Multi-module Plant Layout Configuration

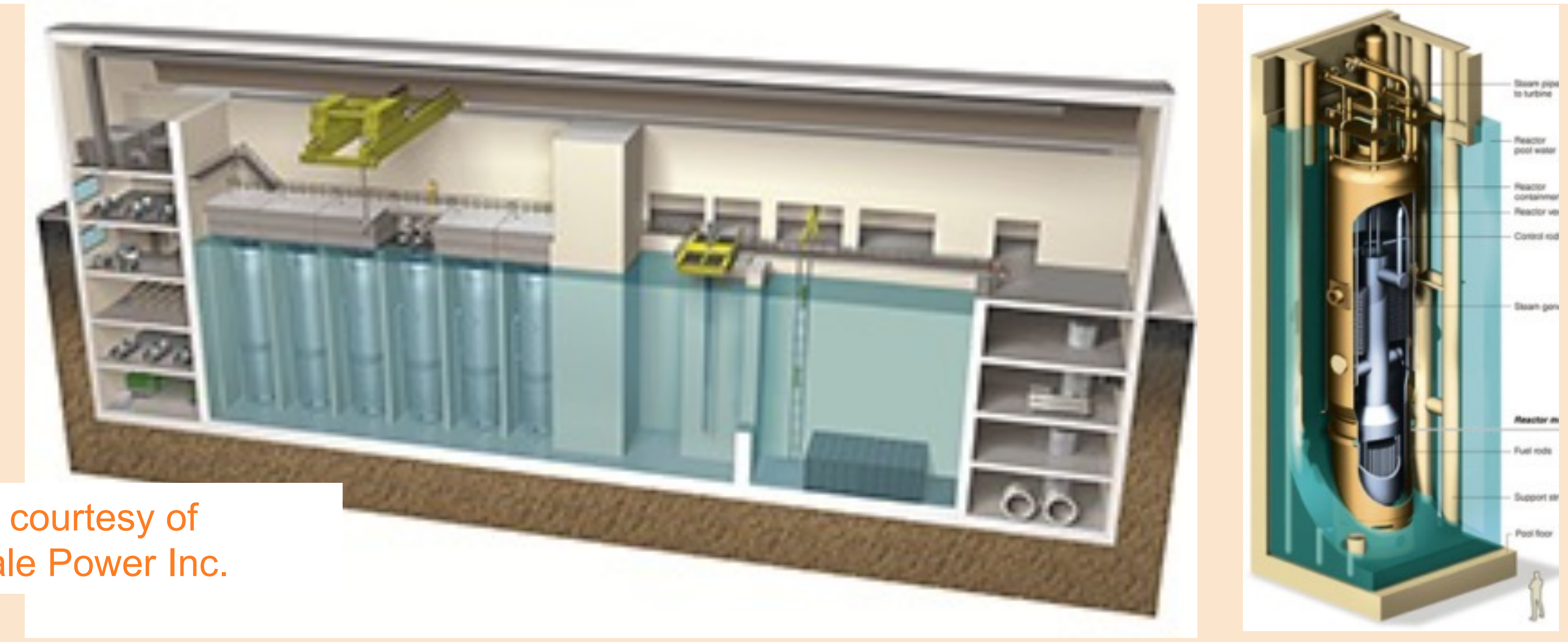


Image courtesy of NuScale Power Inc.

Underground construction for enhanced security and seismic

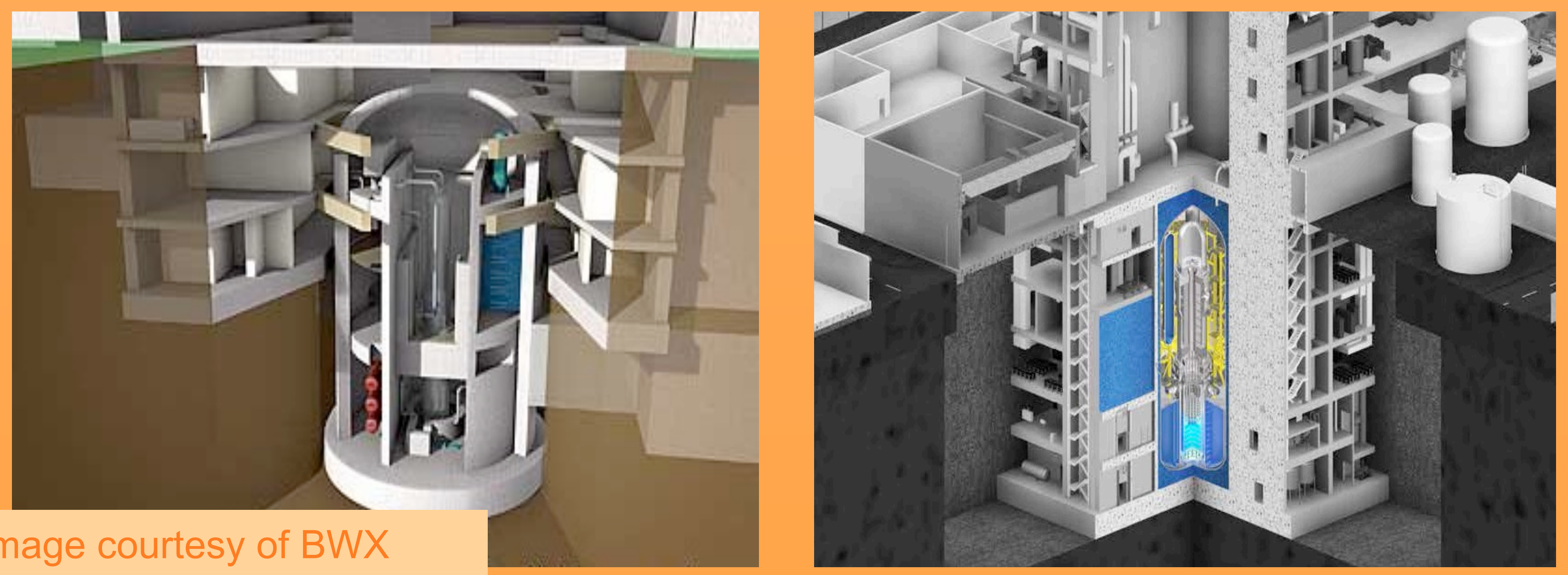


Image courtesy of BWX Technology, Inc.

Enhanced Safety Performance through Passive System

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

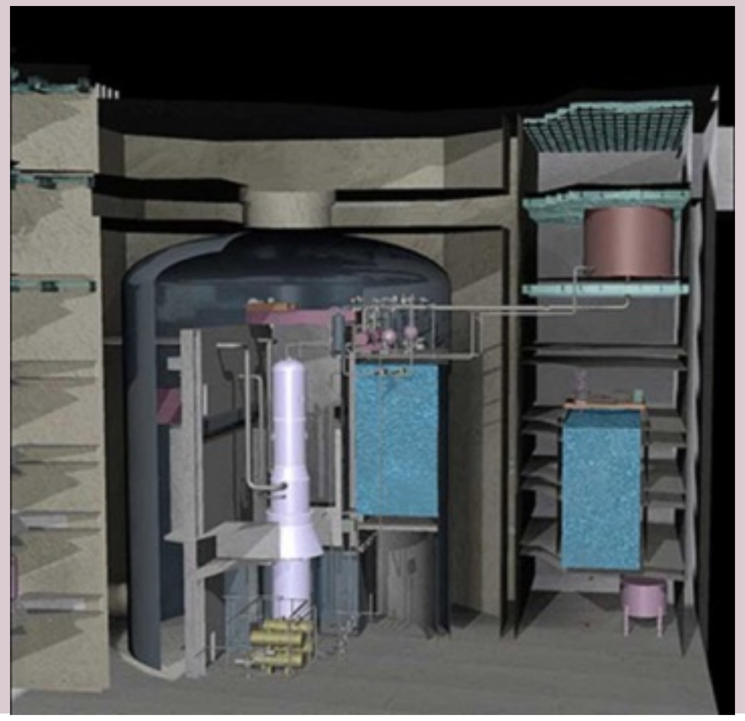
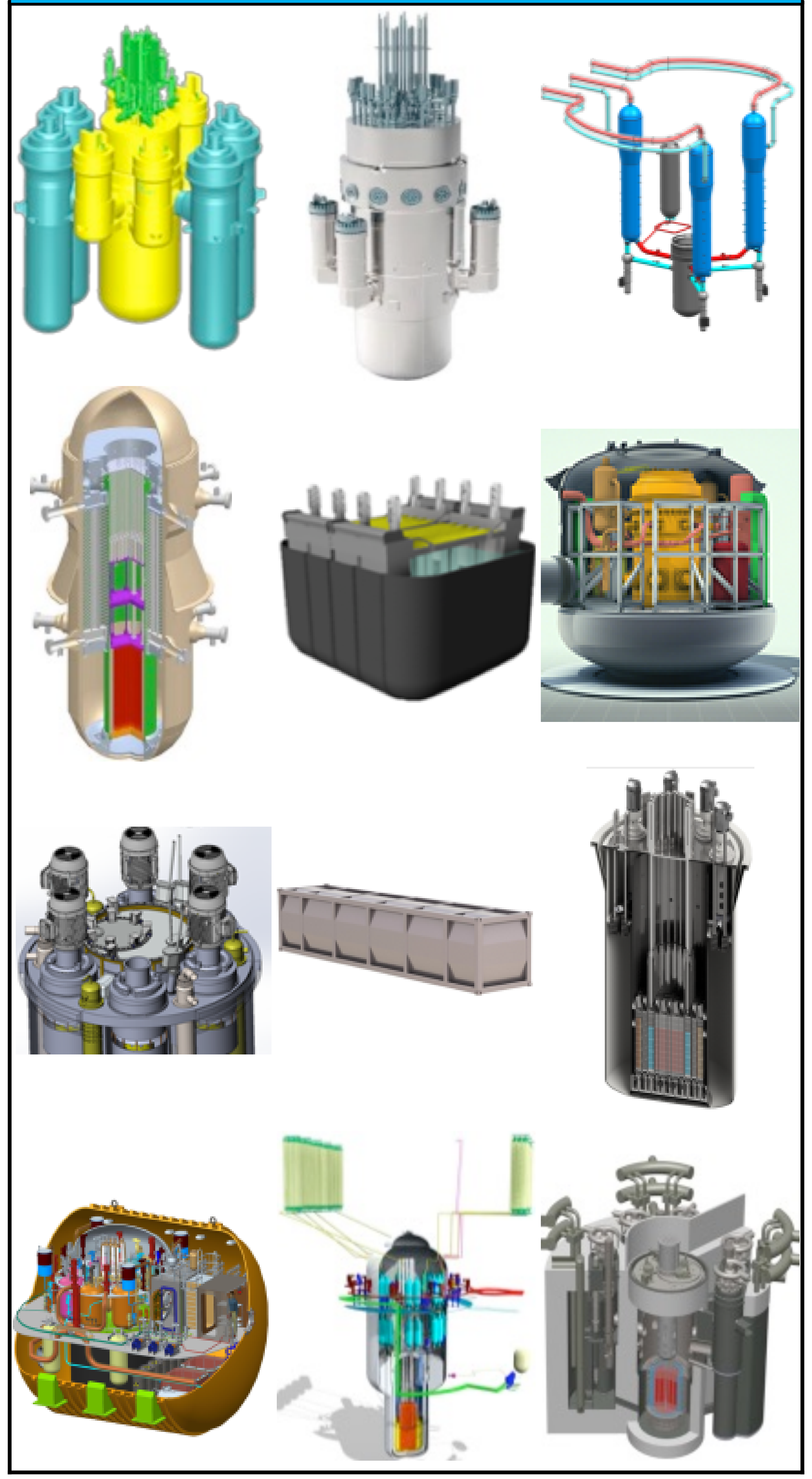


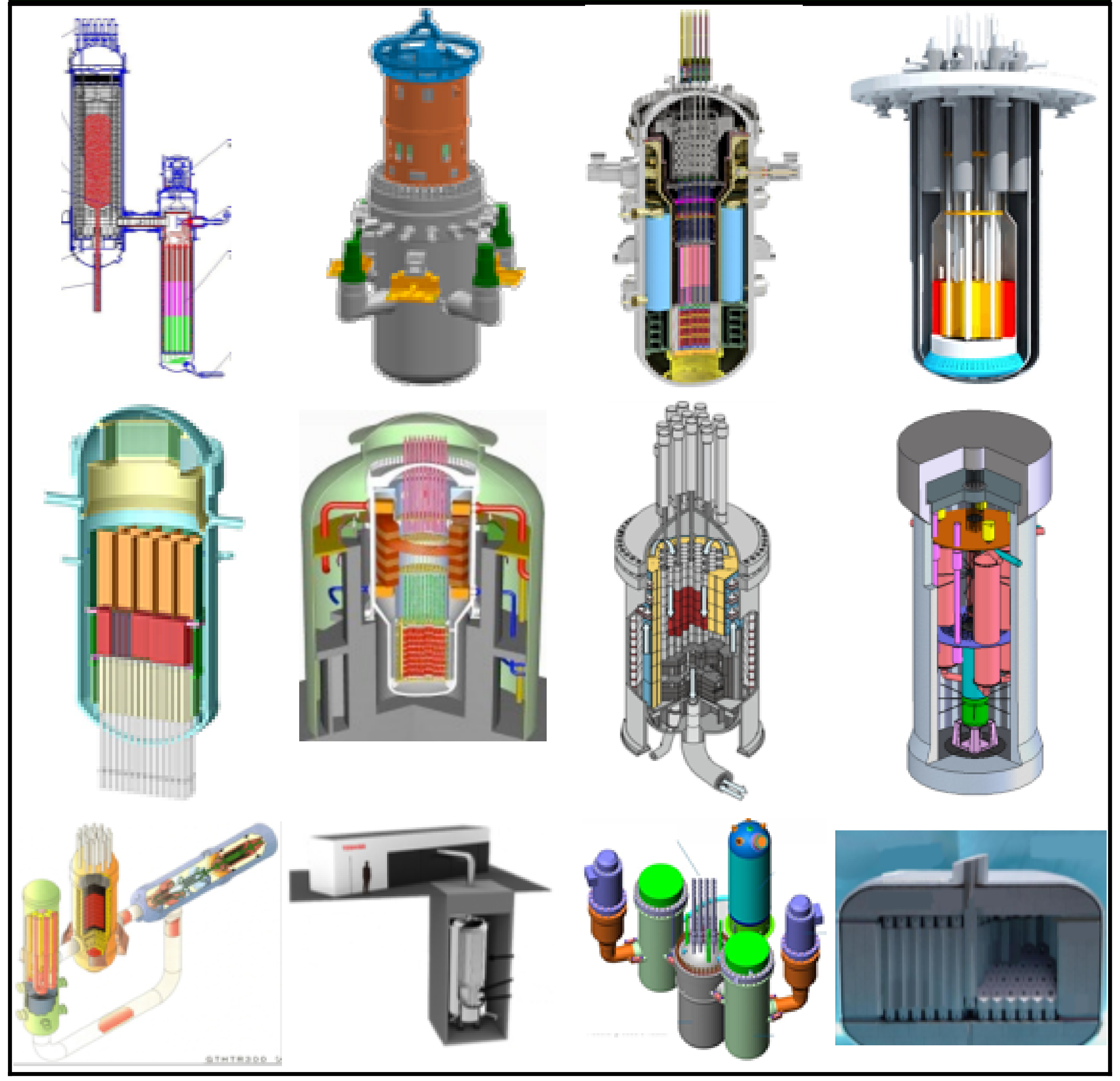
Image courtesy of BWX Technology, Inc.

SMR designs across the World's Regions

Europe, United Kingdom and Russian Federation



Asia



Africa

North America and South America

More than 80 designs of all major types in different stage of design development

Players in SMR Technology Development

Europe, United Kingdom, Russian Federation

- Rolls Royce
- EDF
- CEA
- TechnicAtome
- Moltex Energy – safer, cheaper, nuclear
- Naval Group
- Seaborg
- Politecnico Milano
- Rosatom
- OKBM Afrikantov – A SC "Rosatom" company
- Copenhagen Atomics
- National Research Center "Kurchatov Institute"
- НИКИЭТ им. Н.А. Доллежаля
- LeadCold
- OKB «Gidropress»
- Urenco – The Energy to Succeed
- Hydromine

Asia

- 海核工程研究设计院
- 国家核电 SNPTC
- SINAP
- 서울대학교 Seoul National University
- 清華大學 Tsinghua University
- ThorCon
- 中國科學院 Chinese Academy of Sciences
- CGN
- مدينة الملك عبد الله للطاقة الذرية والمتجددة KA-CARE
- ITMSF
- 한국전력공사 Korea Electric Power Corporation
- KHNP
- KAERI Korea Atomic Energy Research Institute
- Hitachi GE
- JAEA
- 国家电投 SPIC
- Toshiba
- Mitsubishi Heavy Industries
- Kawasaki Heavy Industries, Ltd.
- भा प अ कें BARC – Atoms in the service of the nation
- NFI Nuclear Fuel Industries, Ltd.
- 中核集团 CNNC
- batan

Africa

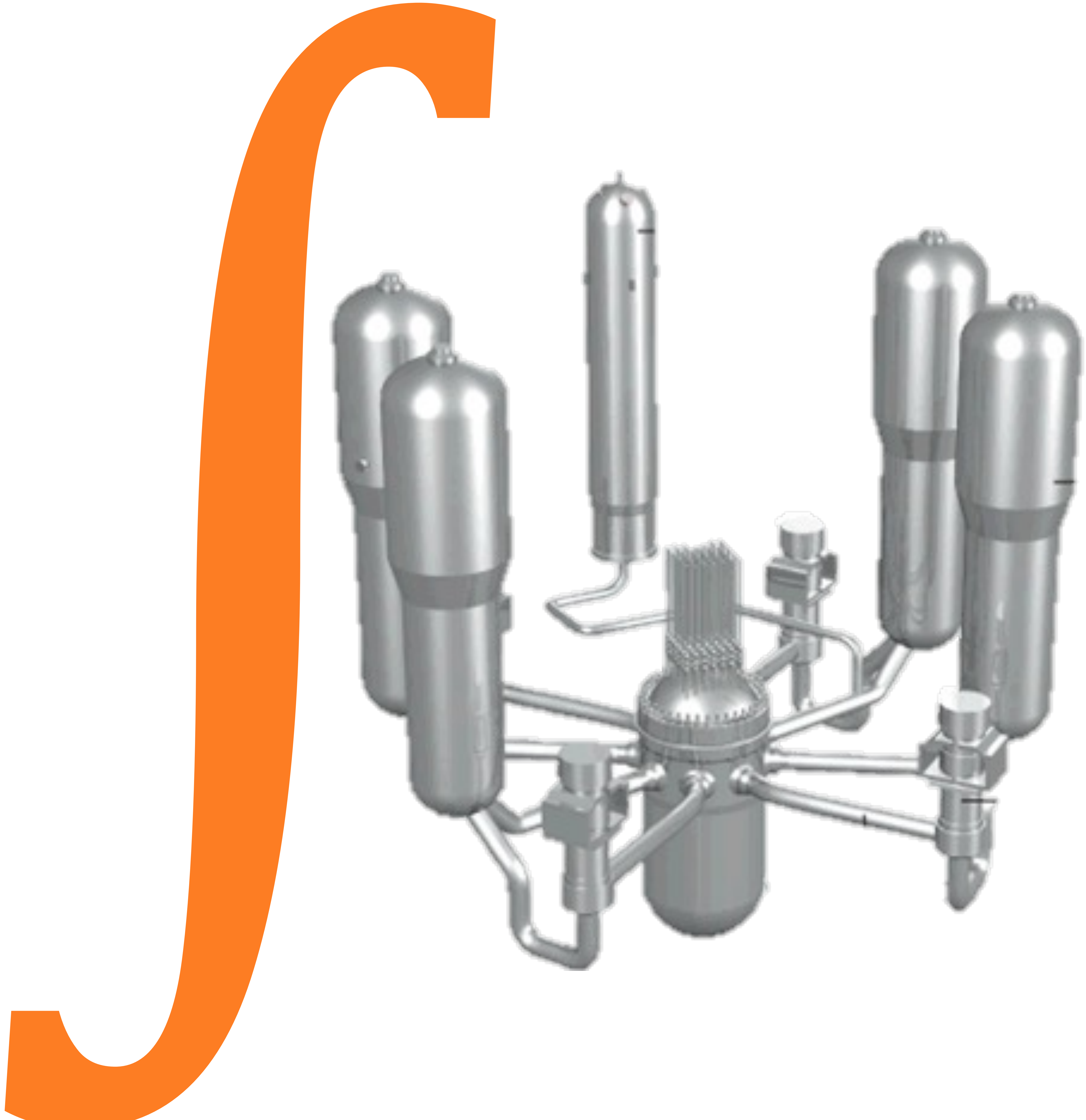
- PBMR
- Eskom
- Steenkampskraal Thorium – STL Nuclear (Pty) Ltd

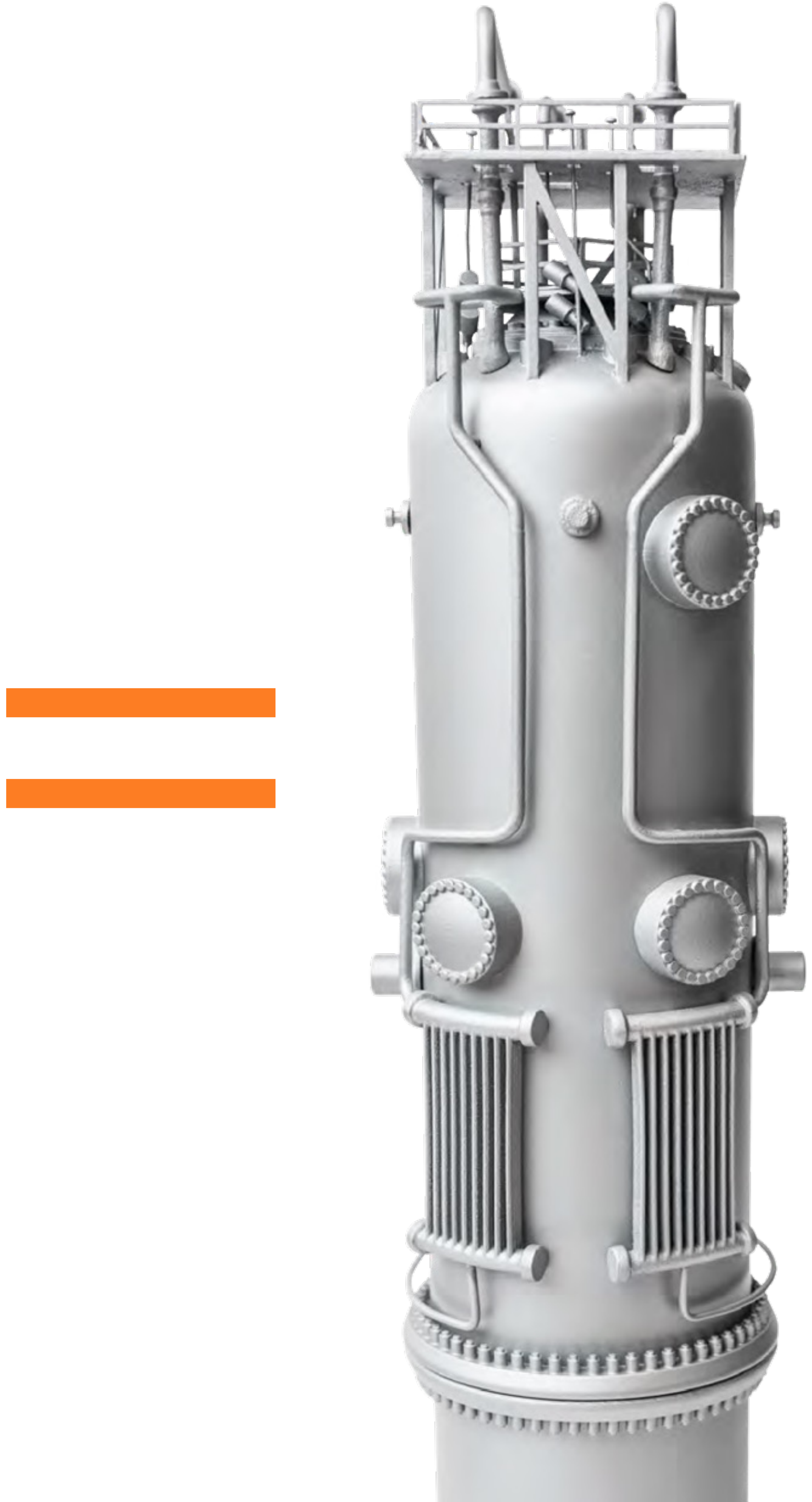
North America, Latin America

- CNEA
- INVAP
- NuScale
- Candu – An SNC-Lavalin Technology
- Terrestrial Energy
- Bechtel
- Holtec International
- E I
- Ultra Safe Nuclear
- Framatome
- GE Hitachi
- Flibe Energy
- Westinghouse
- Kairos Power
- Canadian Nuclear Laboratories
- Berkeley University of California
- X-energy
- ThorCon
- Generation mPower
- Oklo

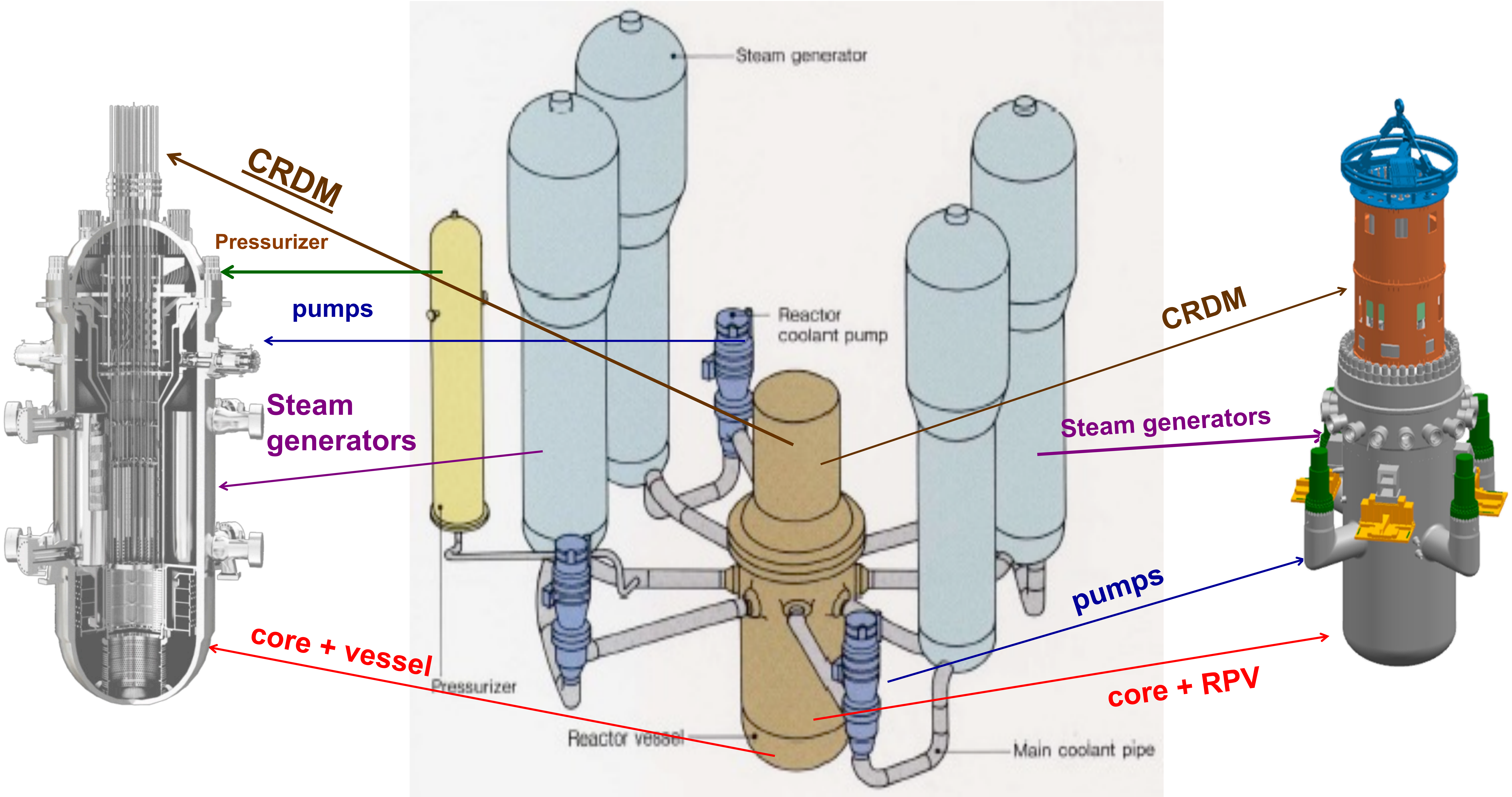
More than 60 design organizations in 18 countries

Design Example 1: Integral-PWR type SMR





Design Example: 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 iPWR-SMRs

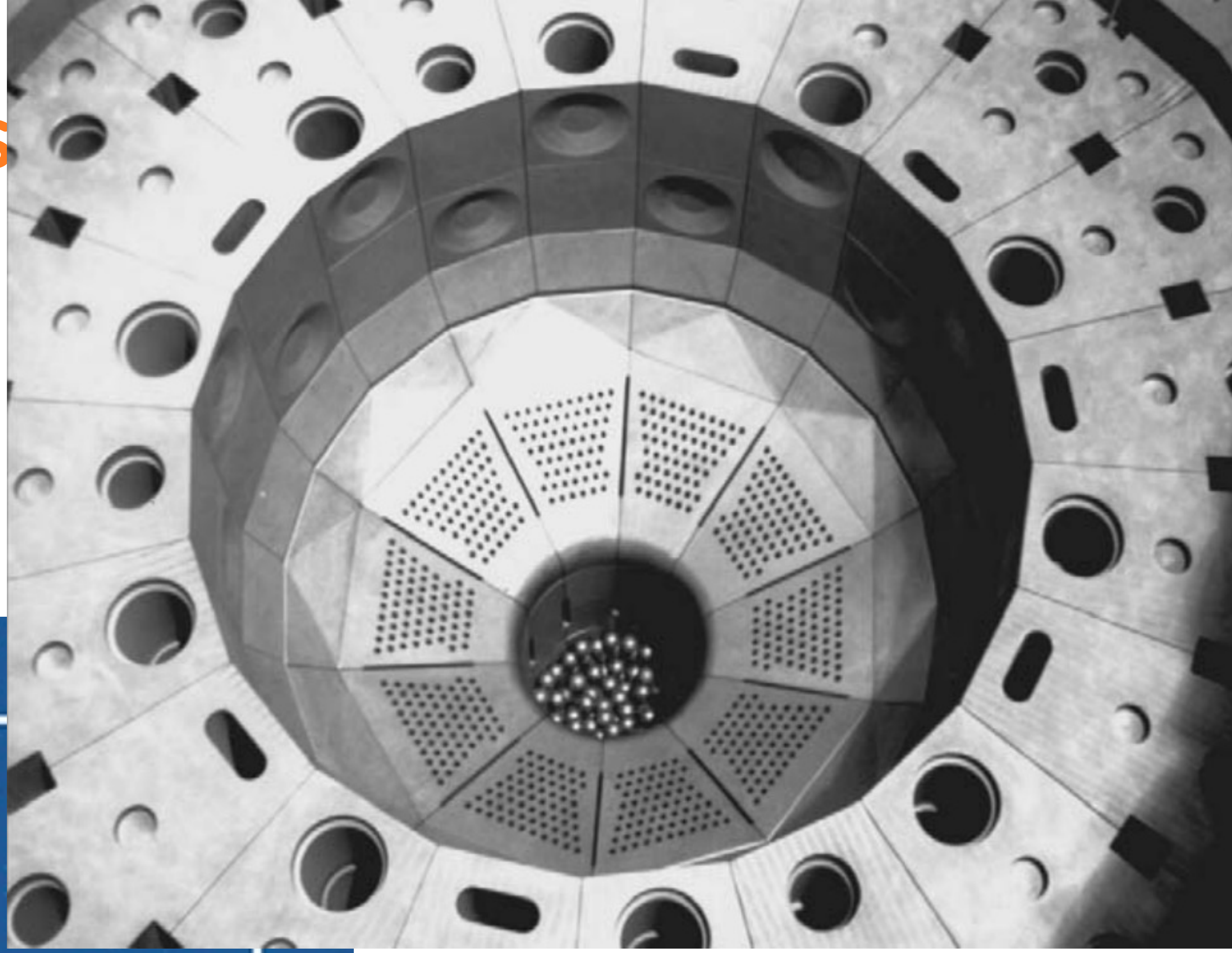
- Enhanced performance engineered safety features:
  Natural circulation primary flow (adopted by e.g., CAREM, NuScale, SMR-160, and ABV6M designs) → No LOFA
- Reactivity control
  - Internal CRDM (adopted by e.g., IRIS, mPower, Westinghouse SMR, and CAREM designs)
    - No rod ejection accident
  - Gravity driven secondary shutdown system (adopted by e.g., CAREM, IRIS, Westinghouse SMR designs)
- Residual heat removal system
  - Passive Residual Heat Removal System (adopted by e.g., CAREM, mPower, Westinghouse SMR)
  - Passive Residual heat removal through SG and HX submerged in water pool (adopted by e.g., IRIS, SMART, NuScale)
- Safety injection System
  - Passive Injection System (adopted by e.g., CAREM, mPower)
  - Active injection System (adopted by e.g., ACP100, SMART)
  - Flooded containment with recirculation valve

iPWRs: Safety Advantages & Challenges

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

Design Example 2: Pebble-bed type HTGRs

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



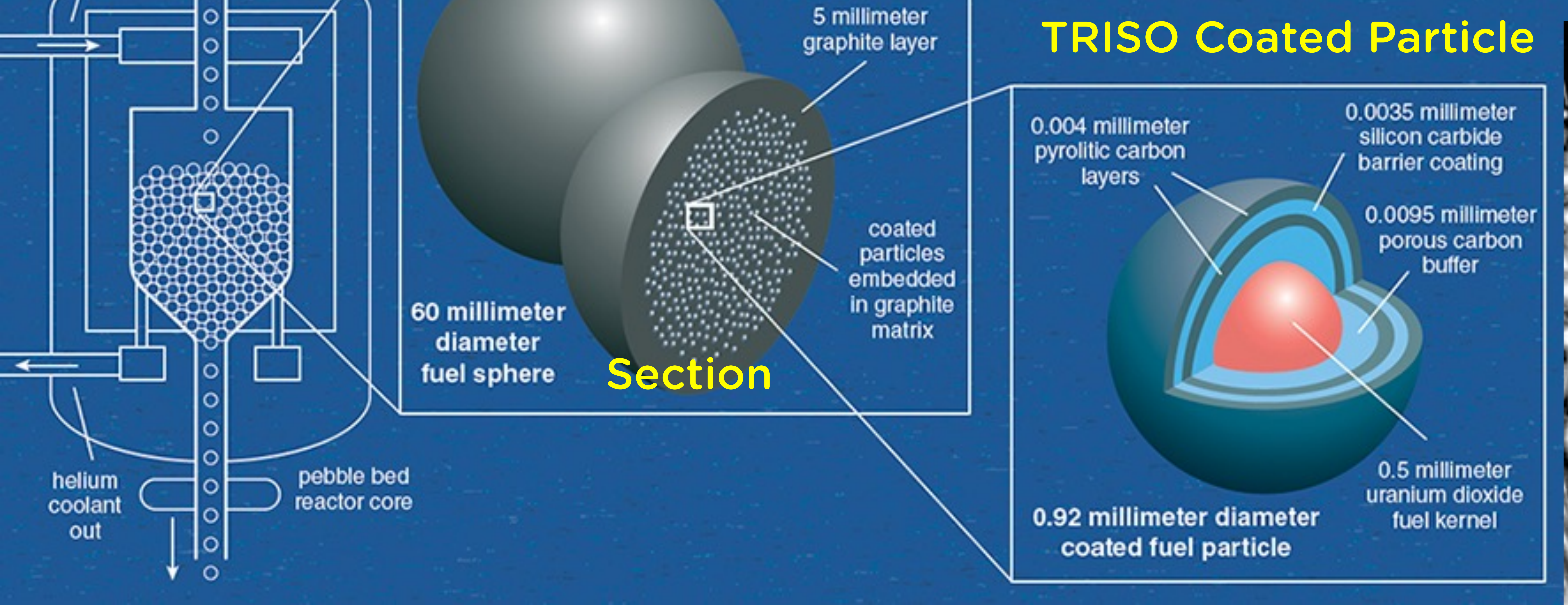
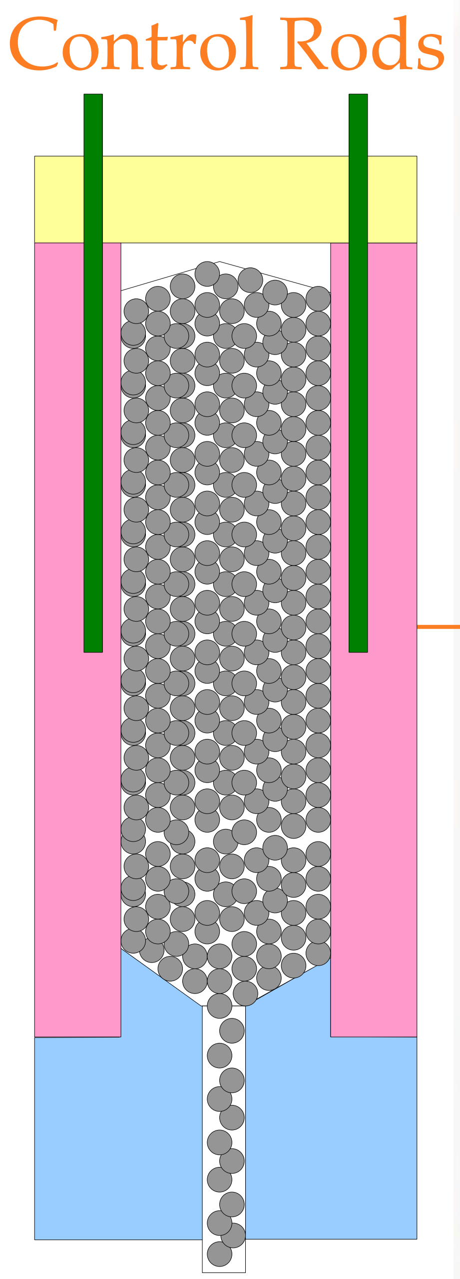


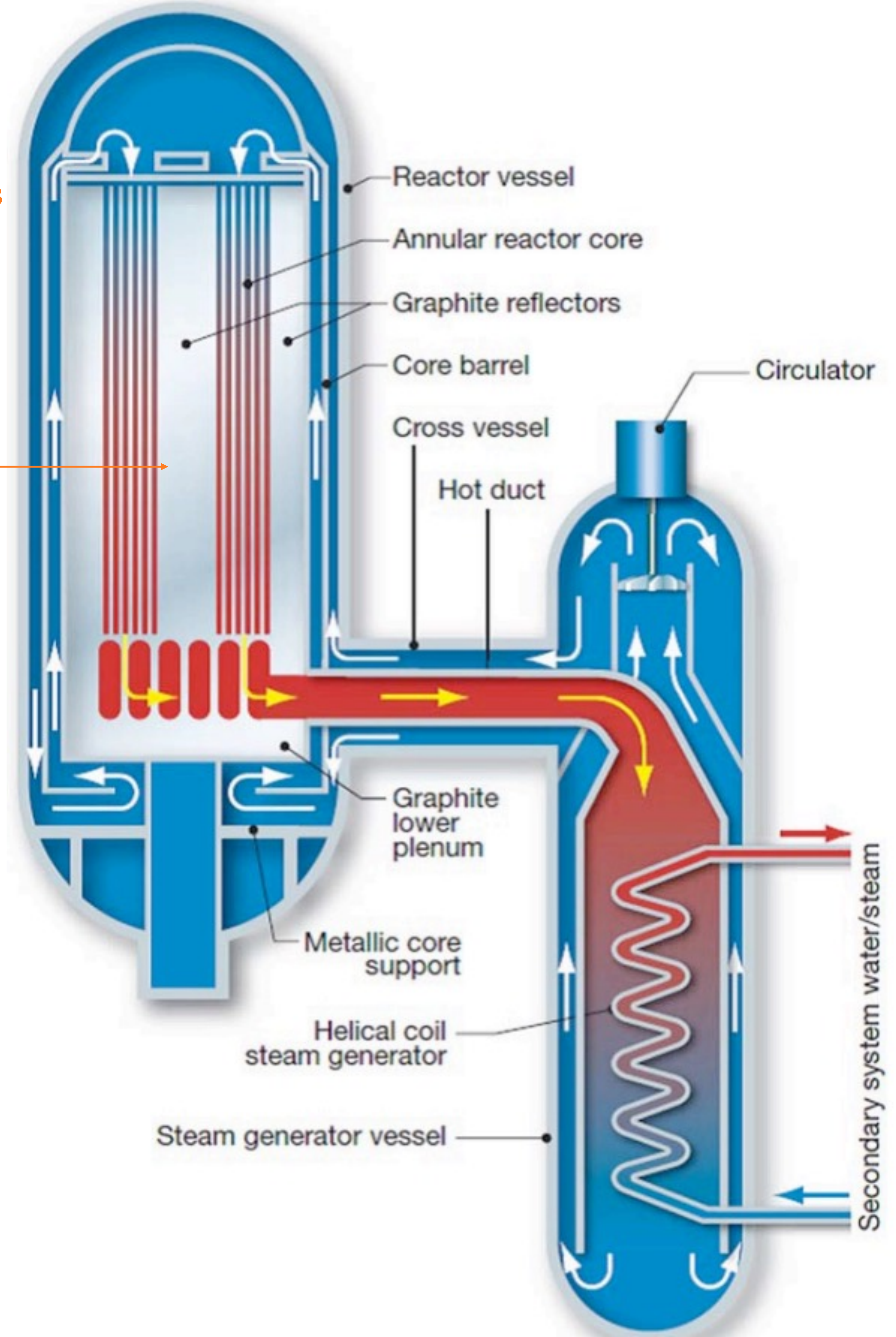
Image: American Scientist, HTR-10, THTR

Pebble-bed Reactor design parameters

Example: HTR-PM Parameters

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





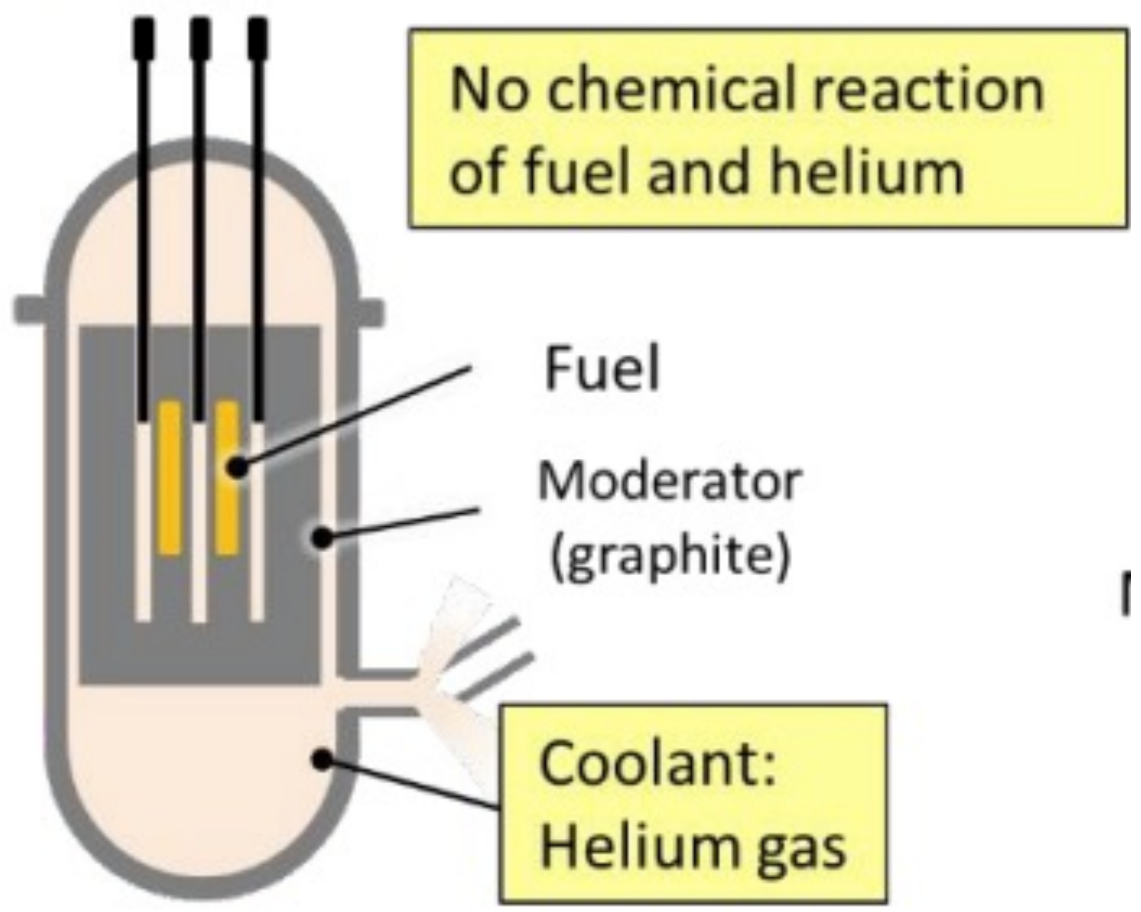
HTGR – Benefits

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

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

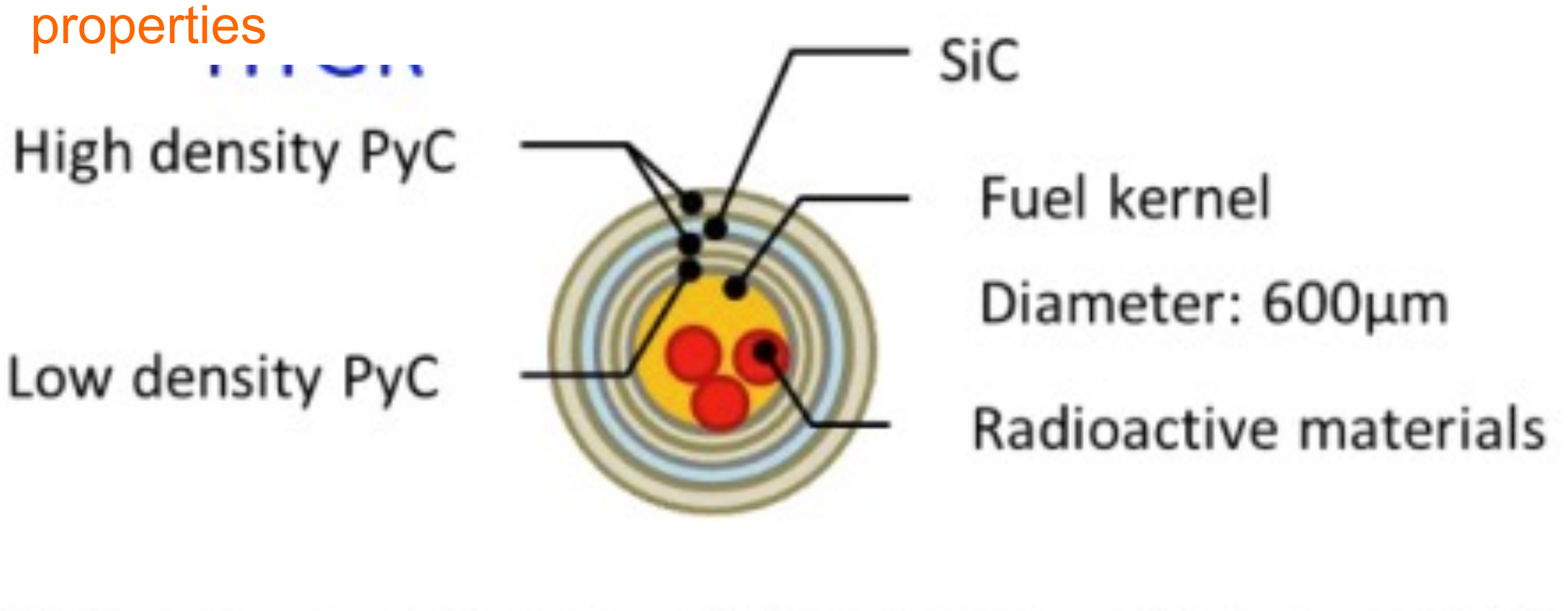
Image: X-energy, JAEA, Wikipedia

Chemically inert



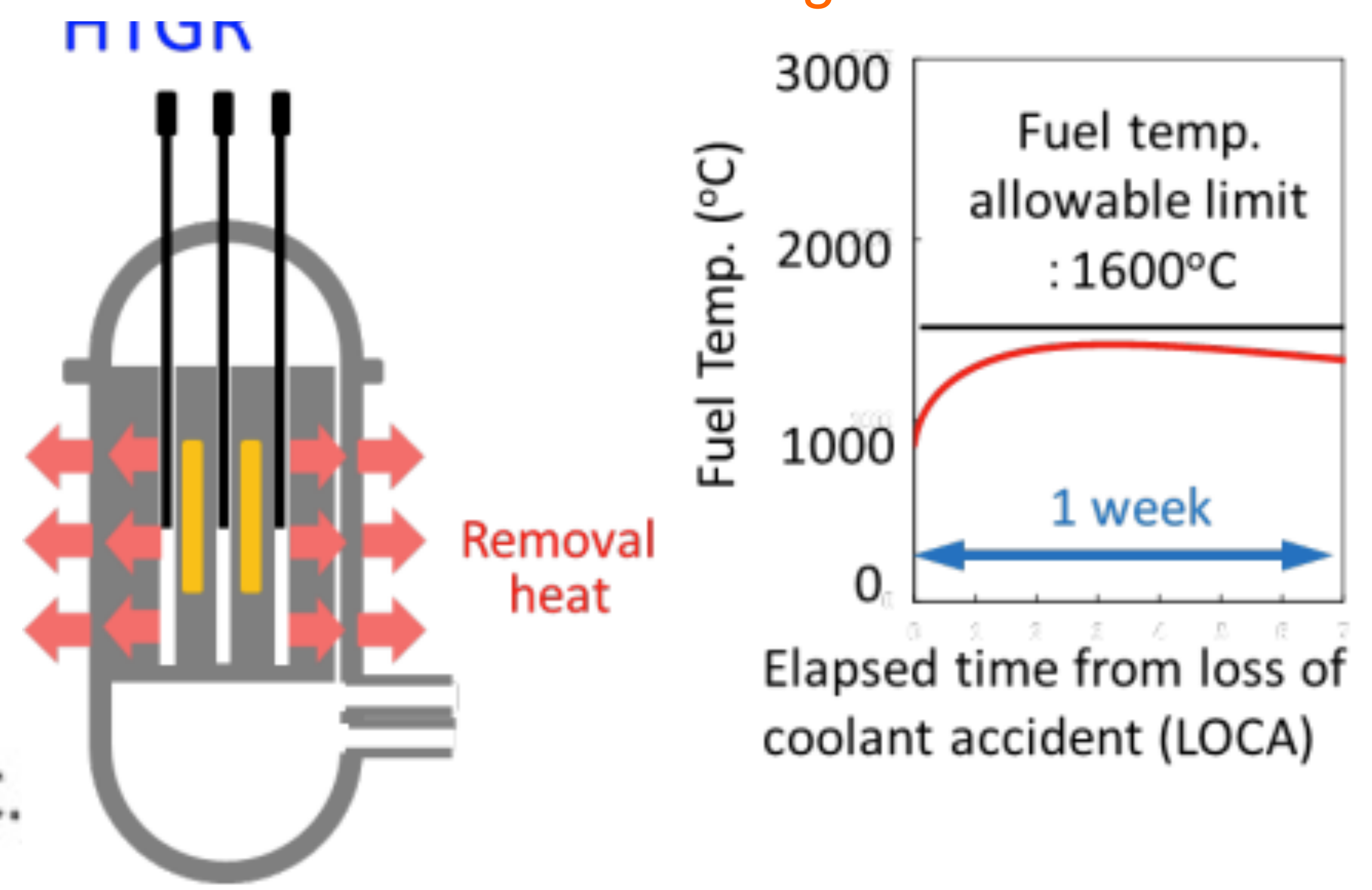
In case of vapor or air ingress accident, the surface of graphite oxidizes but safety of the core never be lost

Excellent heat resistant properties



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

No immediate accident management



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

HTGRs – Challenges

- The low power density leads to large reactor pressure vessels (but site requirements not larger)

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

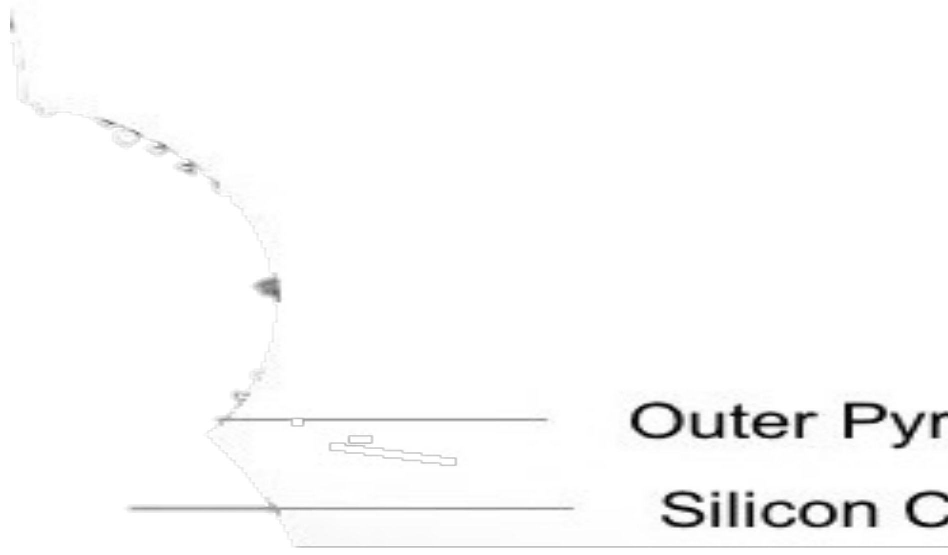


Image: HTR=PM, X-energy

Future development areas

- Very High Temperature Materials
  Metals: For increased temperatures, need for vessel, pipes and IHX
  Carbon composite materials for control rods, in-core applications, turbine blades
- Cogeneration and Hydrogen production commercial demonstration
- Direct cycle helium turbine (Brayton cycle)
- Graphite - Knowledge preservation
  New graphite grades development and testing
  More corrosion resistant graphite
- Recuperator / compact heat exchangers (printed circuit type for compact design)
- Economic demonstration for electricity, cogeneration, and high temperature heat production

Areas of ongoing progress in the field

(1) Performance of HTGR fuel

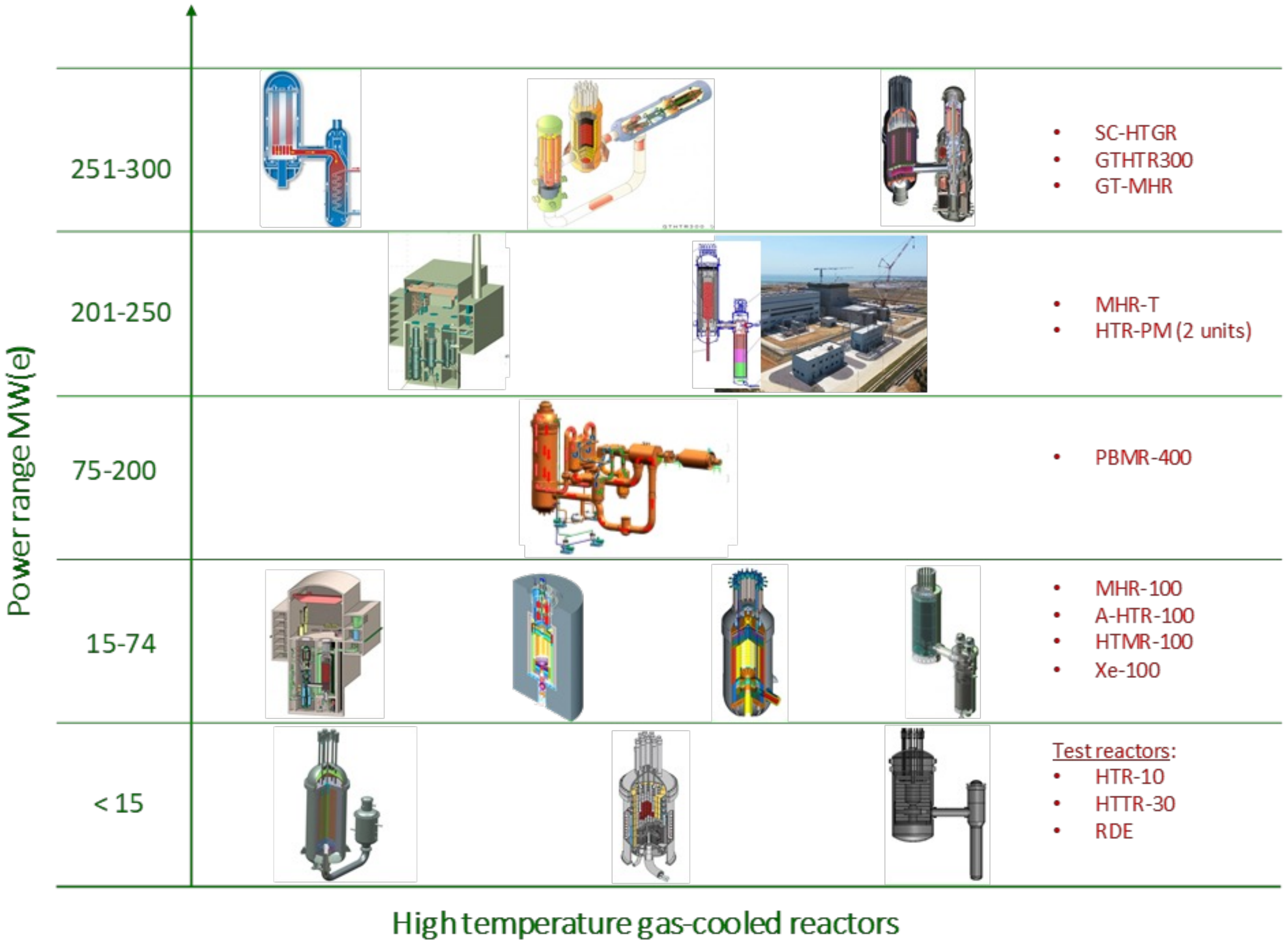
(2) Safety and accident analysis of HTGR (including reactor physics analysis, thermal-hydraulics analysis)

(3) Source term analysis of HTGR

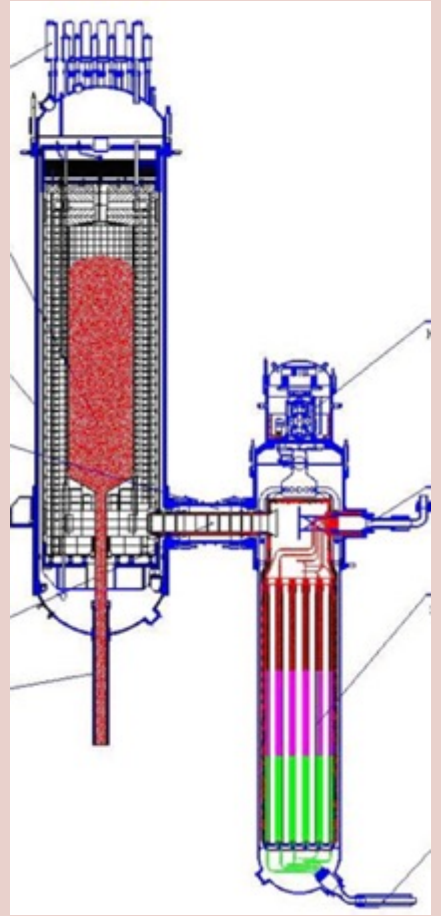
(4) Control of multimodular HTGRs and related human factor analysis

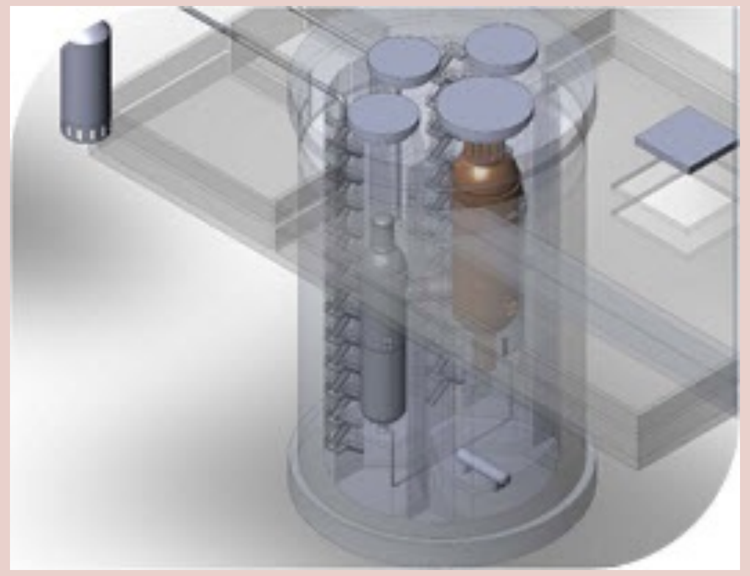
(5) Optimizing radiation protection of HTGR

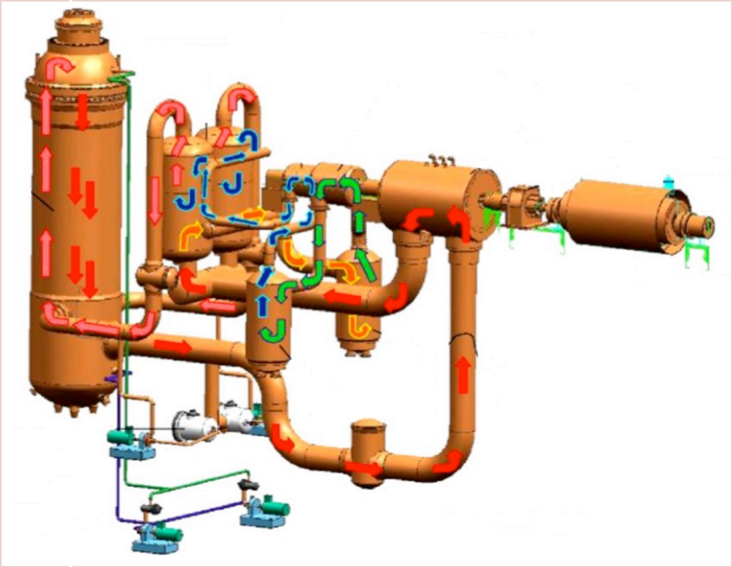
Power Range of HTGR-type SMRs

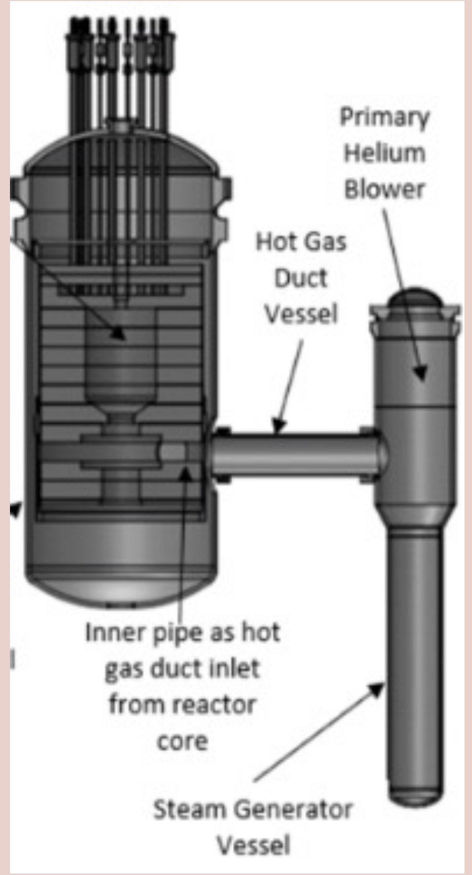


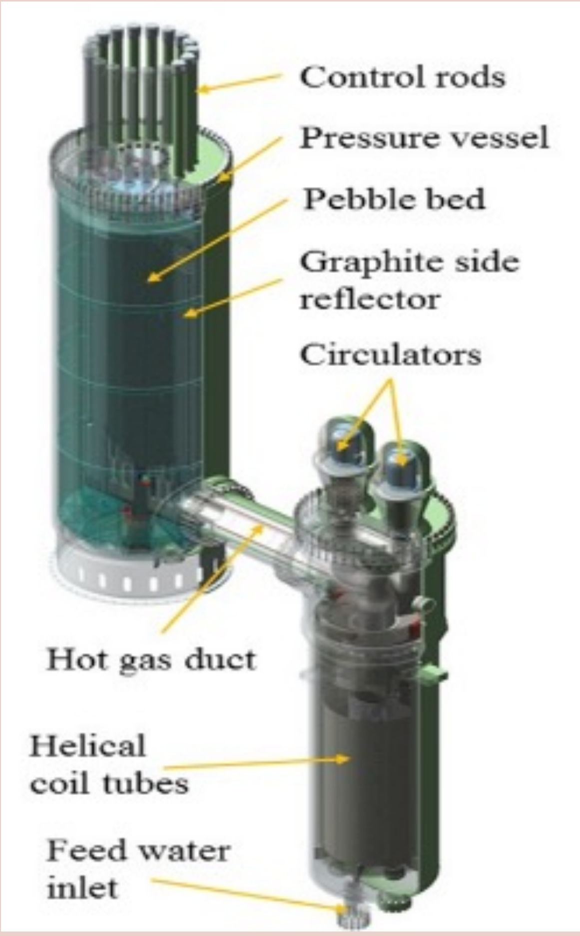
HTGR-type SMRs (Examples)









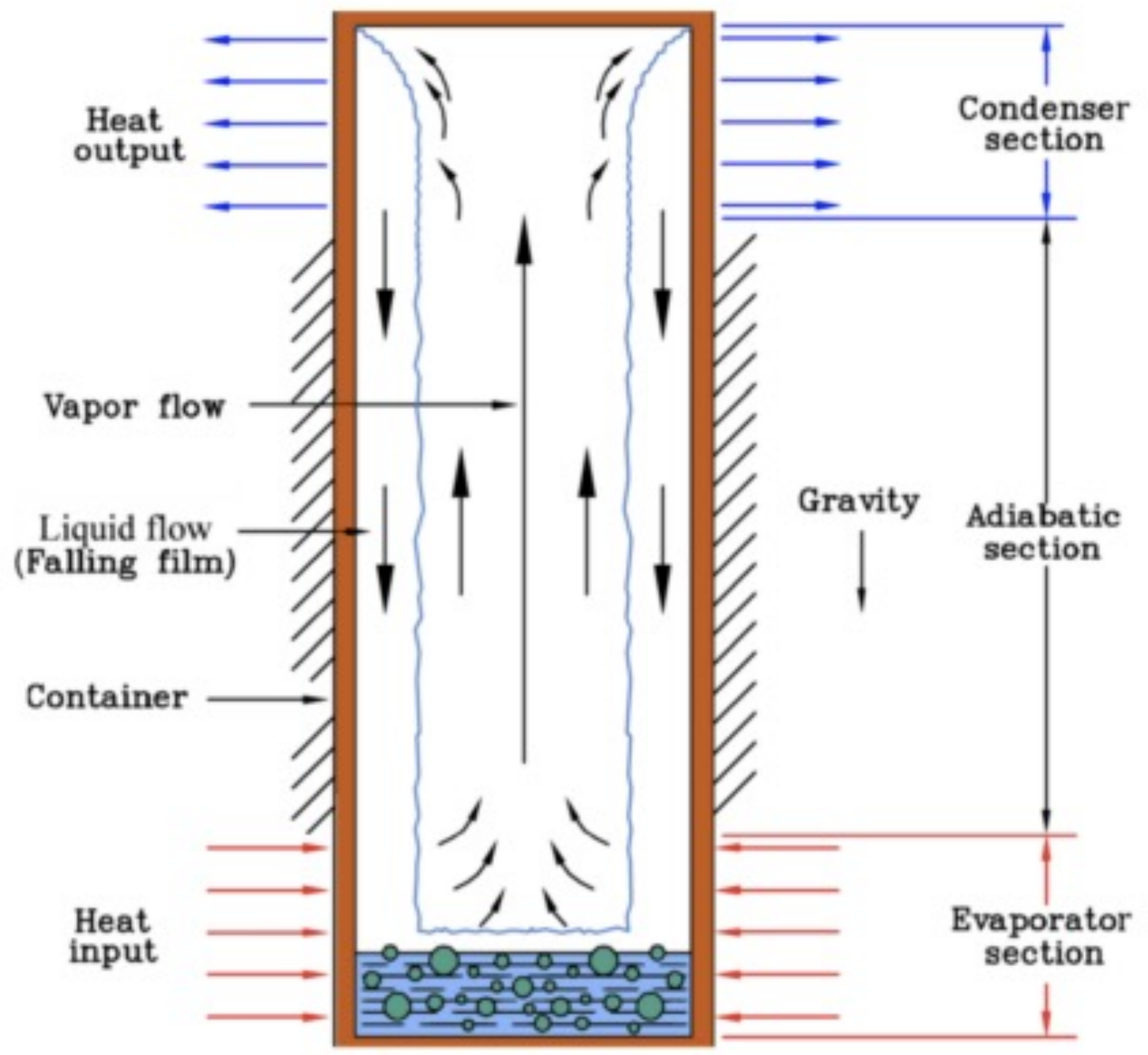


HTR-PM (China)	SC-HTGR (France)	GTHTR300 (Japan)	PBMR-400 (South Africa)	Xe-100 (X Energy, United States)
Design Status: Achieved first criticality on 13 Sept 2021 in Shidao Bay, planned grid connection by end of 2021	Design Status: Conceptual Design	Design Status: Pre-Licensing; Basic Design Completed	Design Status: Preliminary Design Completed, Test Facilities Demonstration	Design Status: Basic design development . Applied for VDR in July 2020. To submit design certification to the U.S. NRC in 2021 for construction in 2025 - -2026
• INET Tsinghua University, China • Modular **pebble-Bed** HTGR • 250 MWt / 210 MWe x 2 modules • Forced Circulation • Core Outlet Temp: 750°C • 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: 750°C • 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: 850-950°C • 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: 900°C • Enrichment: 9.5% • Refuel interval: Online refuelling	• X Energy, LLC, United States of America • **Pebble-Bed** Modular HTGR • Forced Helium Circulation • 200 MWt / 82.5 MWe • Core Outlet Temp: 750°C • Enrichment: 15.5% • Refuel interval: Online refuelling

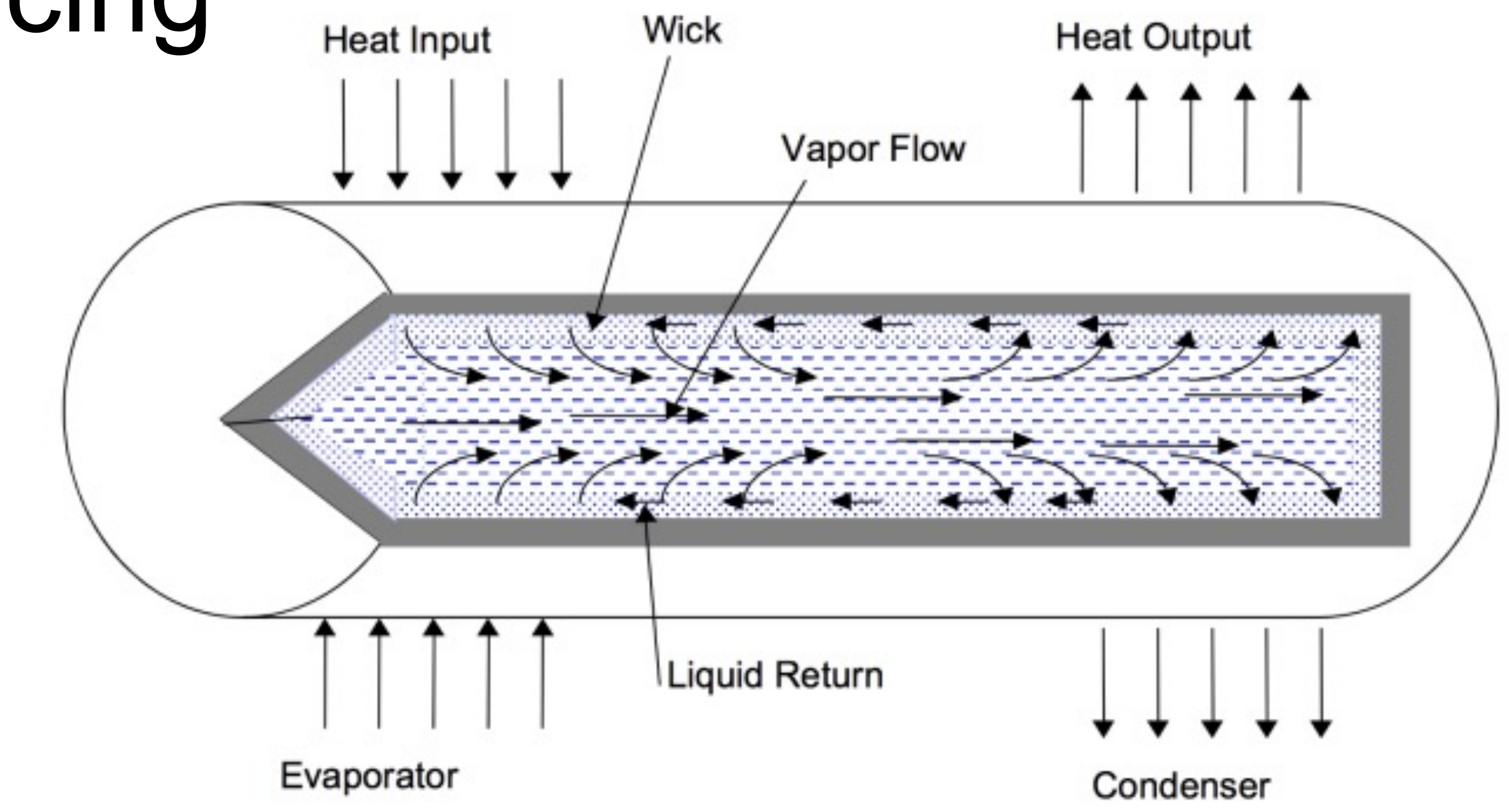
Design Example 3: Heat Pipe Reactors (Micro Reactors)

- Principle
  - Heat pipes are heat transfer devices
  - Utilize thermal conduction and phase transition of a working
  - Two-phase (boiling and condensation) allow large heat trans with minimal △T between heat source and sink
- Benefits
  - Excellent heat transfer rates
  - Completely passive, no moving parts (other than fluid)
  - Completely sealed system, no exchange of fluid or interfacing system

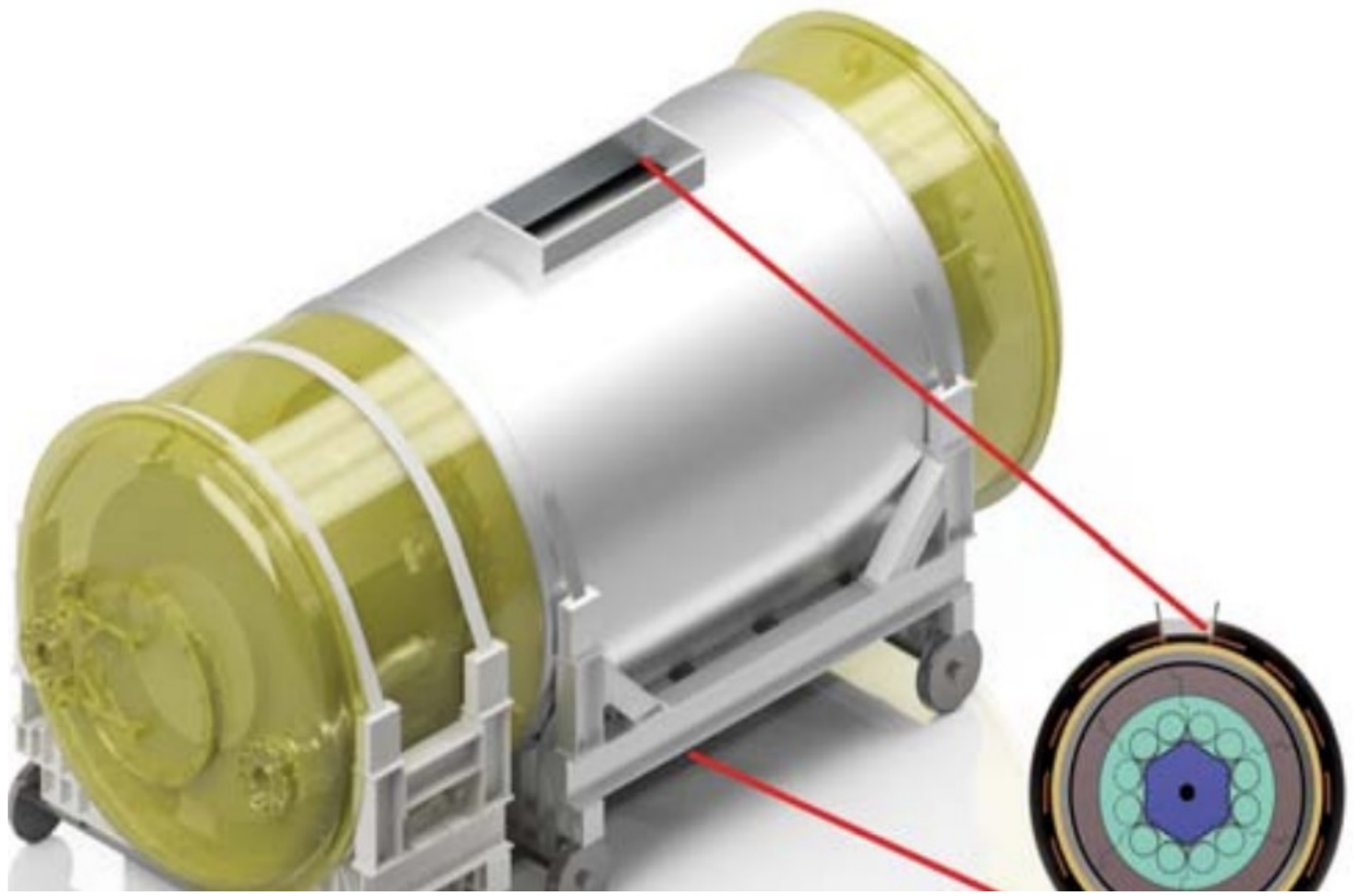
Gravitational
(thermosyphon or Perkins tube)

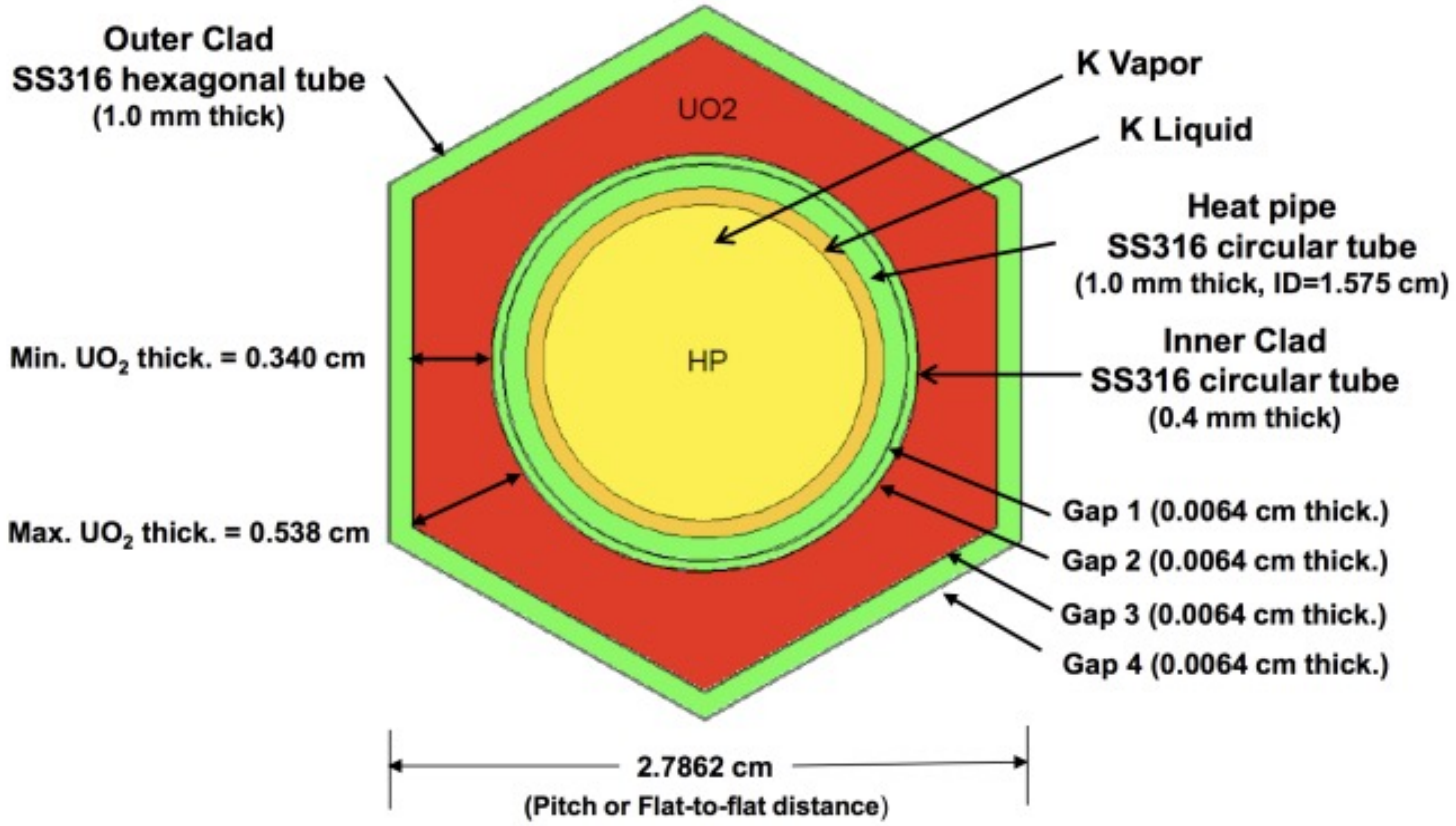


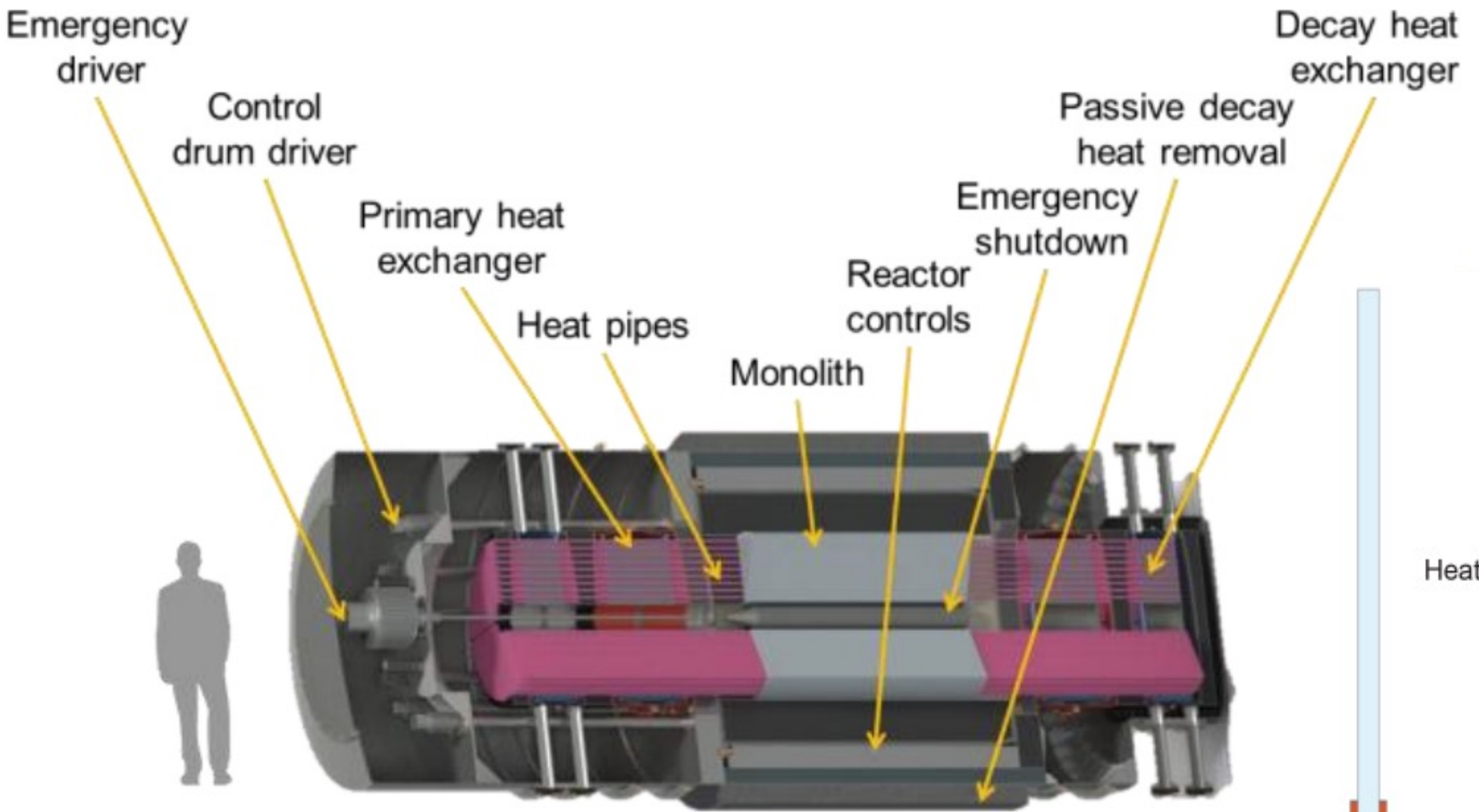
Capillary
(wicking)

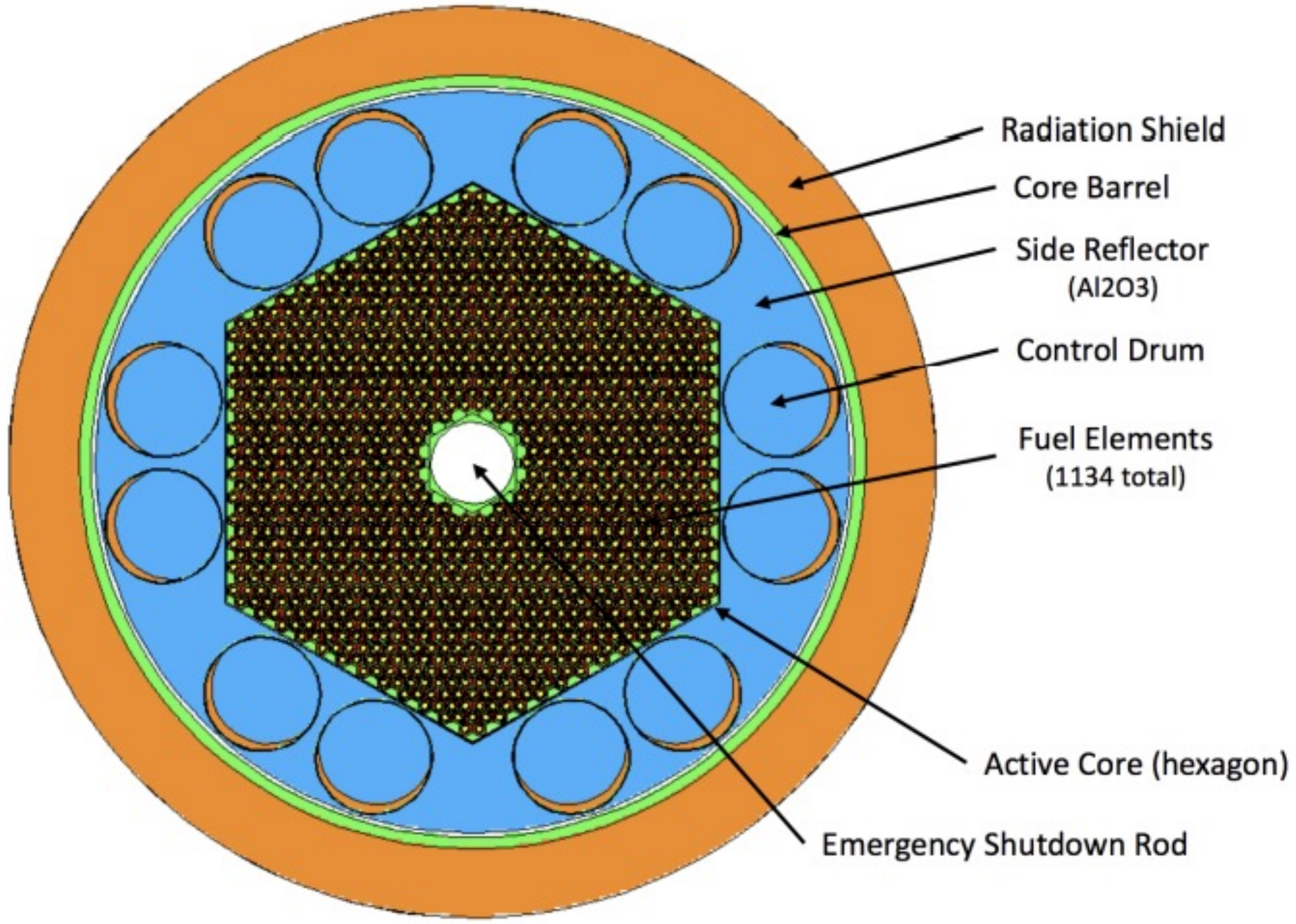


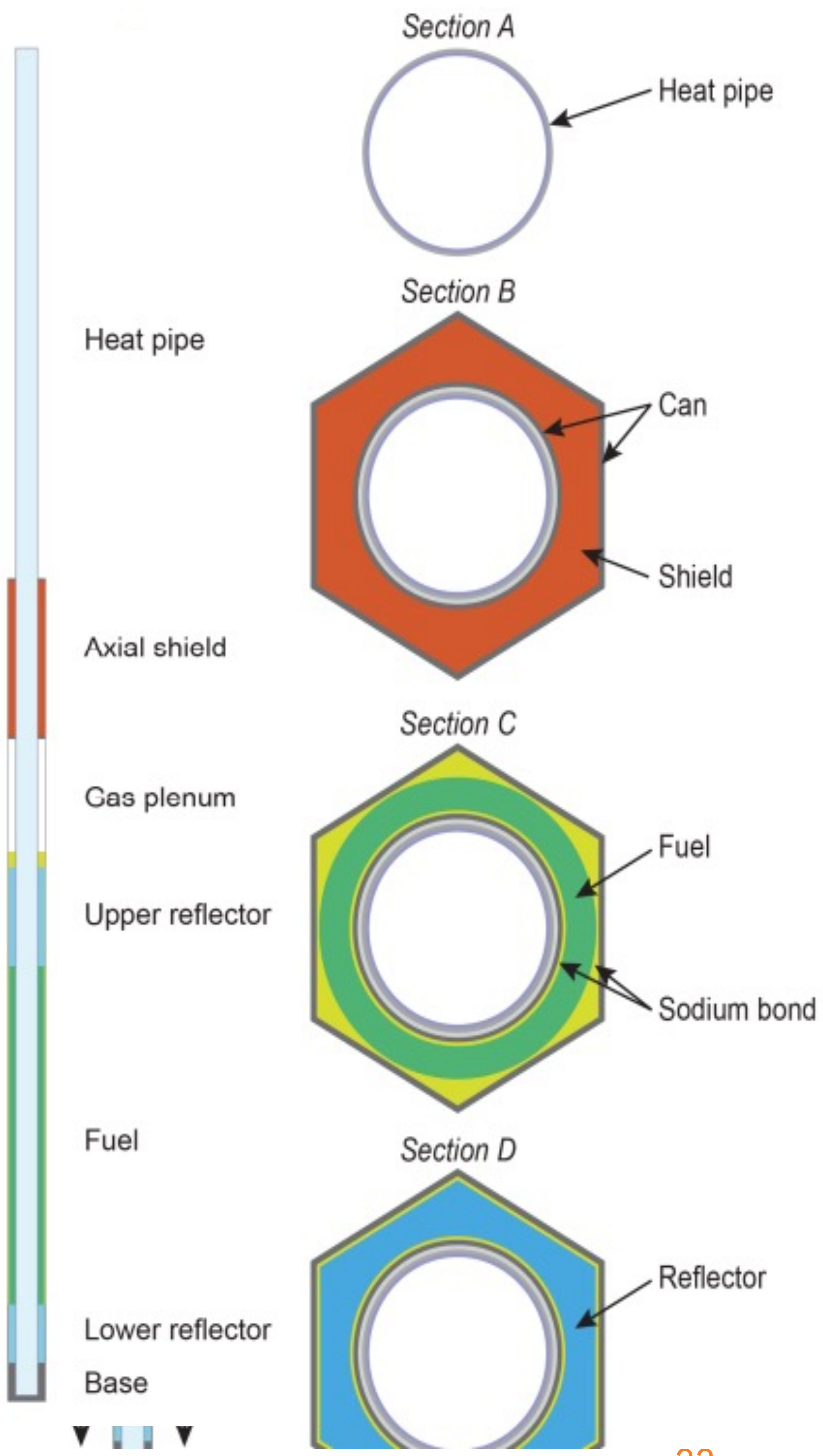
Heat Pipe Reactor











Hexagonal fuel elements with centre heat pipes

Heat Pipe Reactor: Advantages and Challenges

- Design Advantages
  - Very compact
  - Can operate at high temperatures
  - No positive void coefficient
  - Strong negative temperature feedbacks
  - Reduced corrosion issues
  - Passive heat removal pathways
  - Orientation independent (capillary)
- Design Challenges
  - Working fluids usually have high thermal neutron absorption (which is why they are typically fast reactors)

- Operation Advantages
  - Load following
  - Multiple coolants loops, which eliminates major LOCAs
  - Small coolant inventory
  - Fewer components (no pumps, valves, etc.)
  - Fewer moving parts
- Operation Disadvantages
  - Heat pipe degradation and lifetime
  - Lack of long-term operation data (exposure to
  - radiation, formation of decay products, etc.)
  - Creation of non-condensable gases from activation product decay or chemical processes, which may reduce the effective length of the condenser

Microreactors – rationales

Development objective: micro nuclear system to produce reliable, safe, clean, and cost-effective electricity and heat to small islands, communities in remote regions, mining industries, and as alternative to diesel generators.

- Potential to meet the needs in energy portfolios where fossil dominates
- Support national lower carbon policies as well as resilience aims
- Power needs in regions inaccessible by known power generators / plants
- Promote applications of new technologies
- **Salient features comparing to Large NPPs**
- Multiple applications (electric and non-electric)

Technology lines
HTGR
LMFR
Heat Pipe Reactor
MSR
PWR

Microreactors – specific characteristics

- Inherent and passive safety features
- Substantially lower upfront capital costs
- Much smaller footprints, reduced-sized or even eliminated EPZ
- Rapid deployability from modularity (even an entire reactor)
- High transportability from mobility
- Scalability, Resiliency, Self-regulating
- Long refueling interval
- Much smaller radionuclide inventories
- Potential to operate in island-mode & to black-start

- Salient design characteristics of SMRs:
  - Simplification by modularization and system integration;
  - Multi-module plant layout configuration;
  - Underground construction for enhanced security and seismic;
  - Enhanced Safety
  - Easier to implement passive system.

Land footprint

Two orders of magnitude lower than large NPP

Nuclear Power Plants

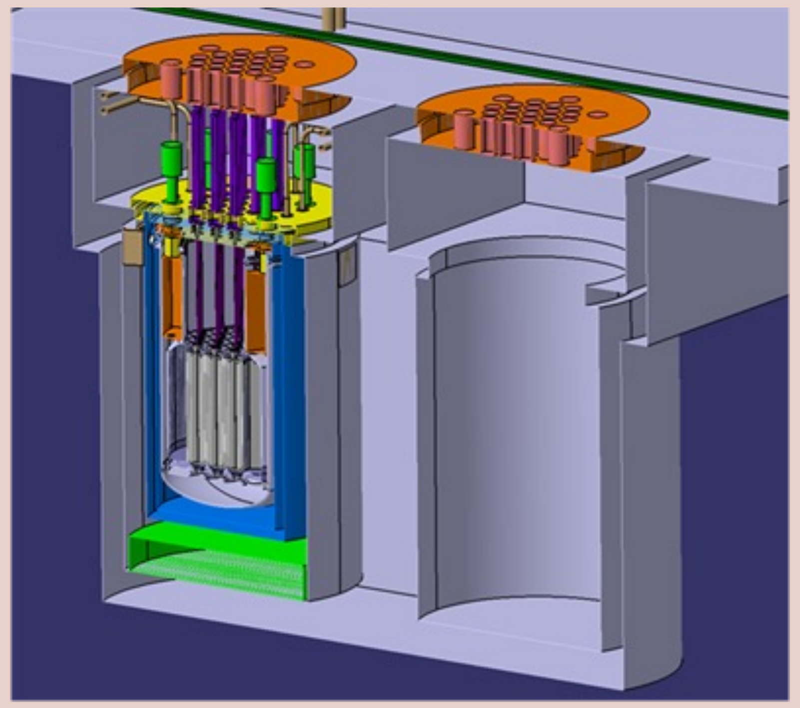
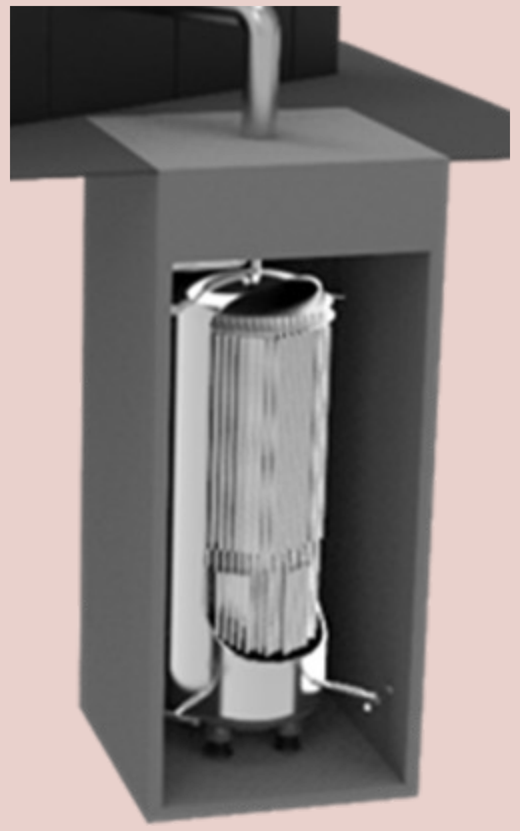
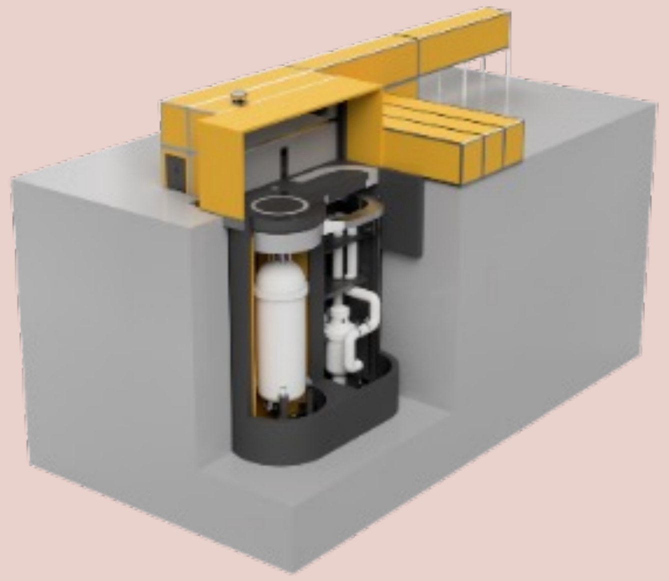
- One of the lowest power generation technologies, only higher than Combined Cycle Gas Turbines (CCGTs) and offshore wind, in terms of life cycle land occupation (m^2-year/MW·h).
- Large water-cooled NPPs require approximately 2.5km^2 (varying considerably from site to site)

Microreactors

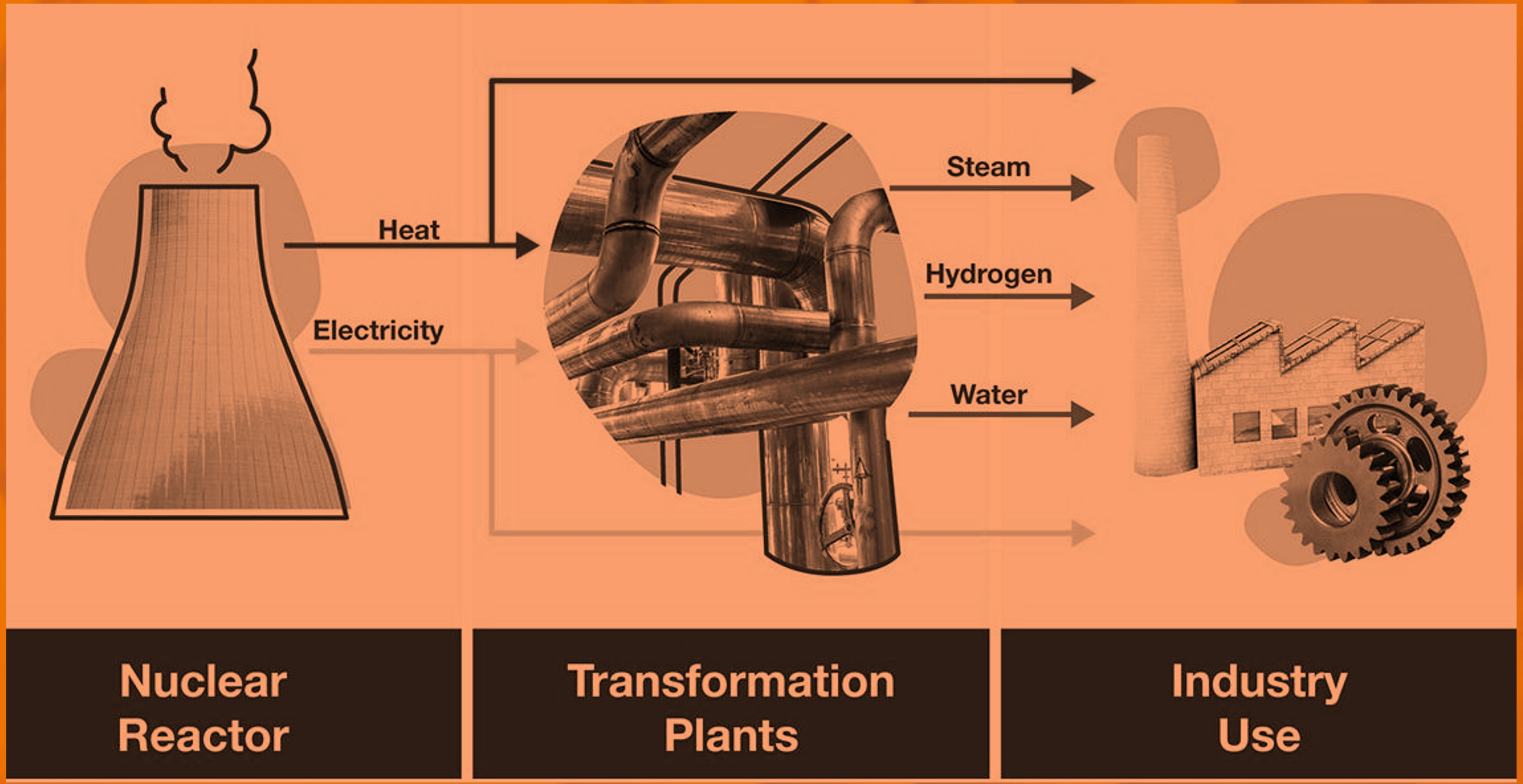
- Possibility of furtherly reduced EPZ in comparison to SMRs, for which reduced EPZ is already under consideration
- Most of the components can be factory-assembled
- Reduction of plant size in turn lowers the capital cost

Microreactor Designs	Power Level	Footprint (m^2)
Energy Well	20 MWt 8 MWe	<4000 (Plant)
MoveluX	10 MWt 3-4 MWe	100 (Plant)
U-Battery	10 MWt 4 MWe	TBC
AURORA	4 MWt 1.5 MWe	4180 (Plant)
eVinci	7-12 MWt 2-3.5 MWe	<4000 (Plant)
MMR	15 MWt >5 MWe	12480 (Site)

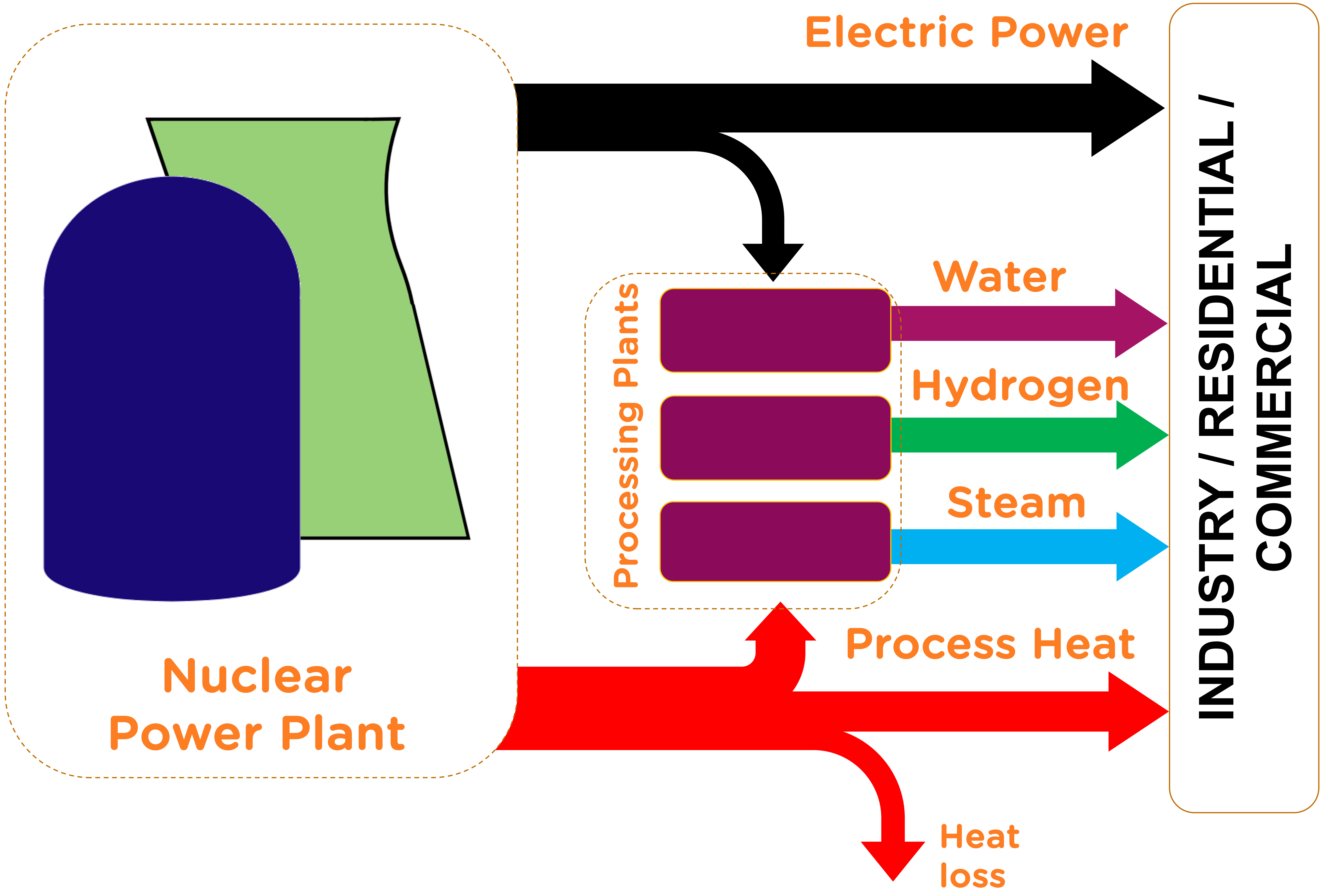
Microreactor Designs

Energy Well	MoveluX	U-Battery	AURORA	eVinci	MMR
					
Design Status: Pre-conceptual design, neutronics, thermohydraulic and materials studies done	Design Status: Conceptual design, complete test without fuel, FOAK demo after 2030	Design Status: Conceptual design, VDR with CNSC	Design Status: Accepted combined license application by the US NRC – returned for reapplication	Design Status: Conceptual Design, vendor design review with CNSC	Design Status: Preliminary Design, vendor design review with CNSC
• Centrum výzkumu Řež, Czech Republic • Fluoride HTR, Pool type • Molten Salt FLiBe coolant • 20 MWt / 8 MWe • Forced circulation • TRISO fuel • Enrichment: ~ 15% • No onsite refueling • Refueling cycle: 84 months	• Toshiba, Japan • Heat-Pipe cooled • Calcium-hydride moderated reactor • 10 MWt / 4 MWe • Natural circulation • Silicide fuel, Hexagonal • Enrichment: < 5% • Continuous operation • 100 m^2 plant footprint	• URENCO, UK • HTGR • 10 MWt / 4 MWe • Forced helium circulation • TRISO fuel • Hexagonal FAs • Enrichment: < 20% • 5 EPFYs core life • 30 year design life	• OKLO Inc., USA • Liquid Metal Fast Reactor • Liquid metal coolant, no moderator • 4 MWt / 1.5 MWe • Metal fuel • Refueling cycle: up to 20 years • Design life: 20 years per deployment	• Westinghouse, USA • Heat Pipe cooled • Metal hydride moderator • TRISO or another encapsulation • 7-12 MWt / 2-3.5 MWe per module • Enrichment: 5-19.75% • Refuel interval: 36+ months • No onsite refuelling, Replace reactor approach • Design life: 40 years	• USNC, USA, Canada • HTGR / micro-reactor / nuclear battery • 15 MWt / 5 MWe • Core Outlet Temp: 630^{o}C • FCM TRISO graphite, Hexagonal fuel block • Enrichment: HALEU 19.75% • Refuel interval: fueled once during lifetime

BEYOND ELECTRICITY PRODUCTION

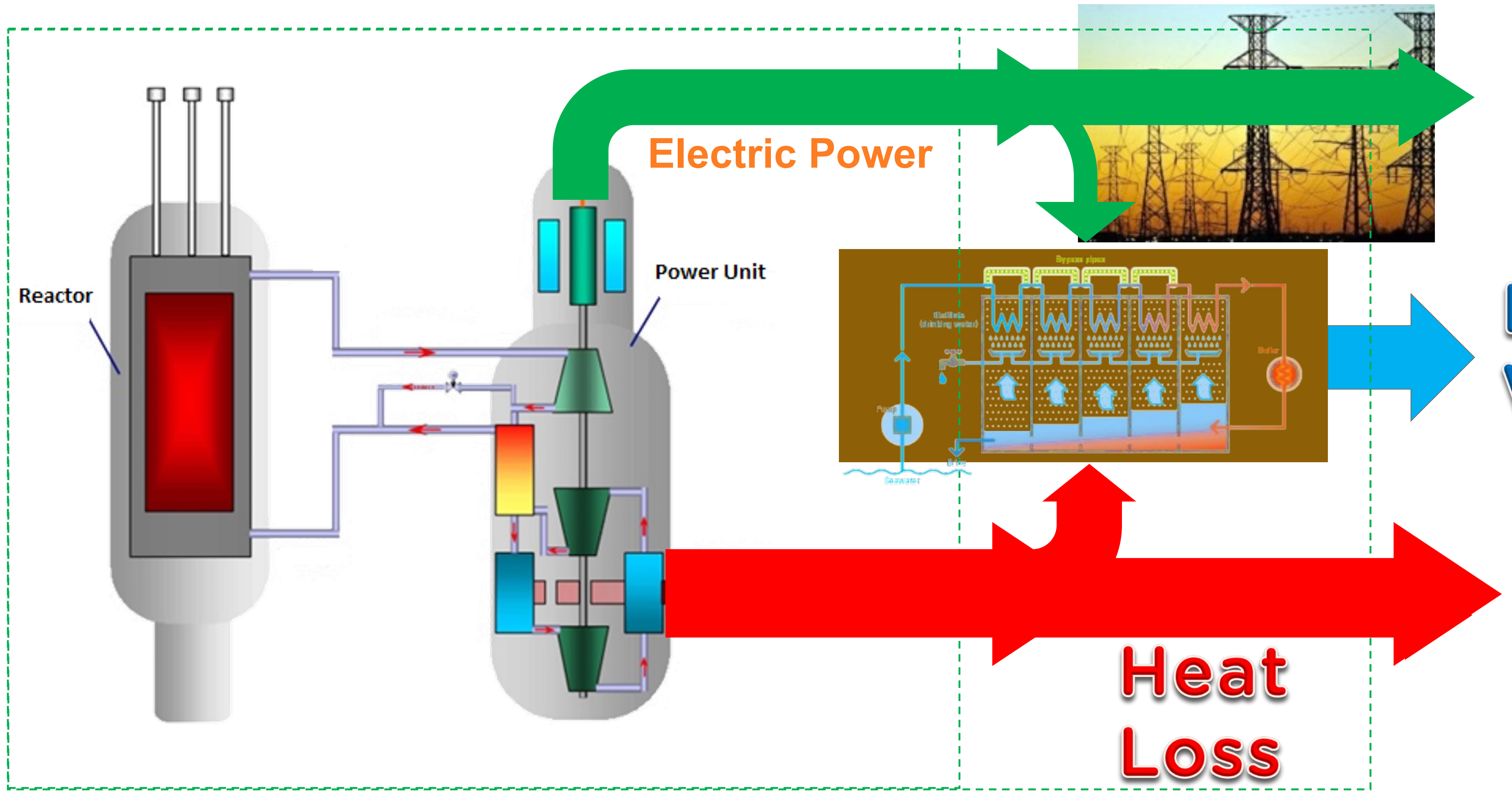


Nuclear Cogeneration



Potential of Using Recovered Waste Heat

Waste heat: Heat extracted from NPP with no penalty to the power production



- *Improves overall efficiency*
- *Added revenues*
- *Can be used as Off-Peak Power (substantially improves economics)*

Advanced Reactors for Non-Electric Applications

Very high temperature reactors

Gas-cooled fast reactors

Molten Salt reactors

Supercritical water-cooled reactors

Sodium-cooled fast reactors

Liquid metal cooled reactors

Water cooled reactors

100 200 300 400 500 600 700 800 900 1000 1100 1200

(°C)

District heating

Seawater desalination

Pulp & paper manufacture

Methanol production

Heavy oil desulfurization

Petroleum refining

Methane reforming hydrogen production

Thermochemical hydrogen production

Coal gasification

Blast furnace steel making

NPPs for district heating and water desalination

- **71 NPPs** – including a fast reactor - in the world already operated for non-electric applications
- **District Heating**: decades of experience, in Russia, Hungary, Switzerland, etc
- In May 2020, the new **Floating Nuclear Power Plant** Akademic Lomonosov, powered by two SMR units, provided 1st heat to Pevek district
- In November 2020, **Haiyang NPP** (AP1000) started delivering commercial district heating

Source: http://fnpp.info/

Source: IAEA PRIS (2020)

	Number of Reactors with NEA
TOTALS:	71
⊞Desalination	10
⊞District Heating	56
⊞Process Heating	32

Haiyang begins commercial-scale district heat supply

20 November 2020

Share

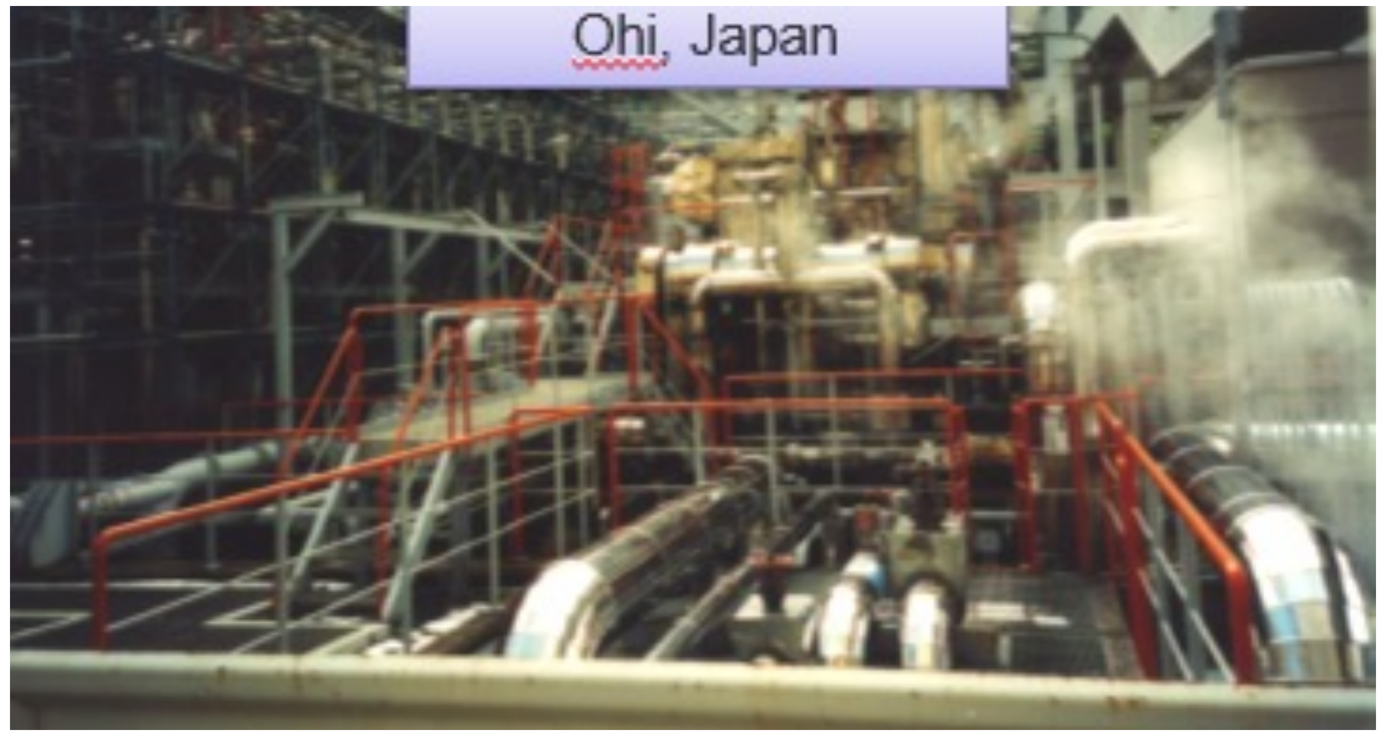
China's Haiyang nuclear power plant in Shandong province has officially started providing district heat to the surrounding area. A trial of the project - the country's first commercial nuclear heating project - was carried out last winter, providing heat to 700,000 square metres of housing, including the plant's dormitory and some local residents.

A pipeline carrying heated water from the Haiyang plant (Image: SPIC)

Source: WNN

Nuclear desalination

Ohi, Japan



Reactors: 10
Total reactor-years: >240
Desalination projects:

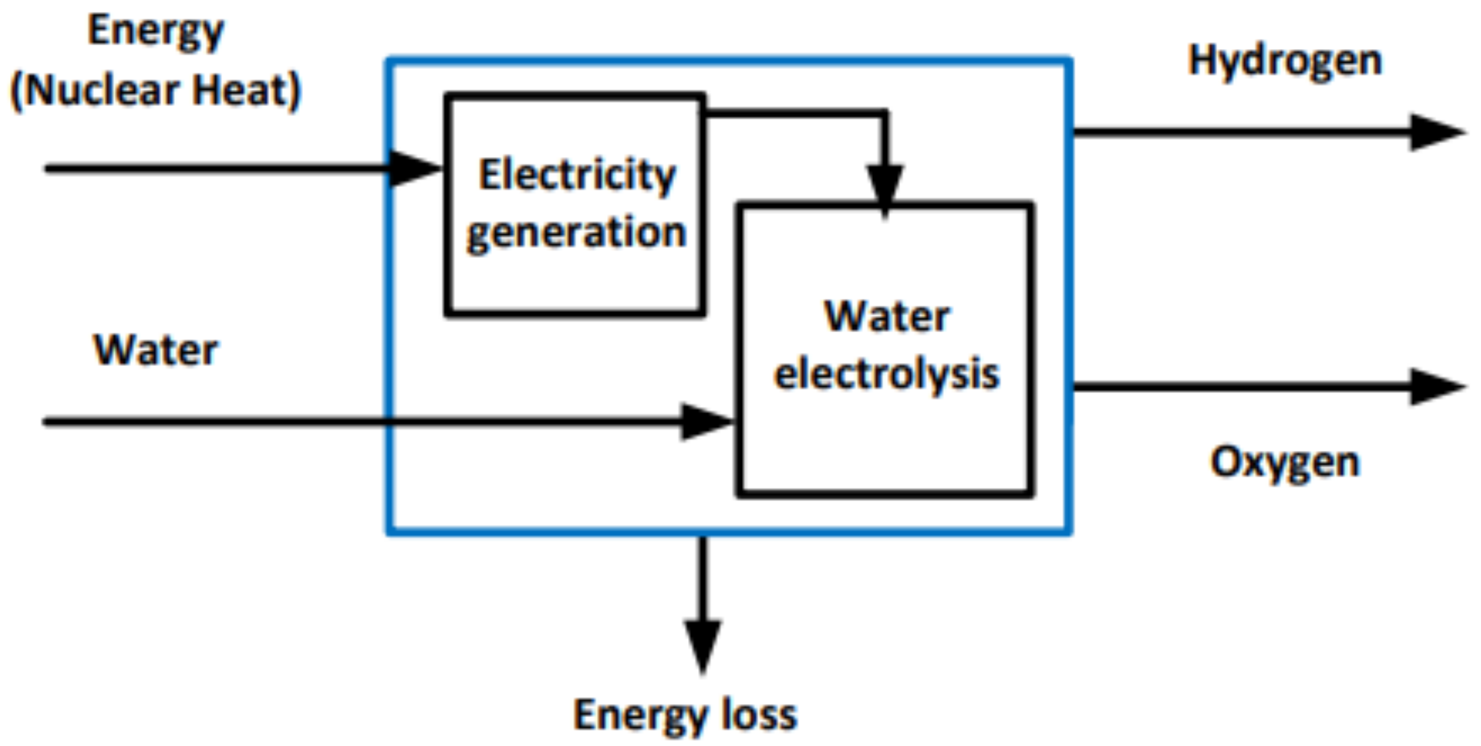
- **Japan:** desalination facilities coupled to PWRs (Genkai, Ohi, Takahama)
- **India:** hybrid demonstration plant at Madras PHWR
- **Pakistan:** thermal demonstration plant at KANUPP PHWR (CANDU)
- **Kazakhstan:** BN-350 fast reactor at Aktau (decomm) used for desalination

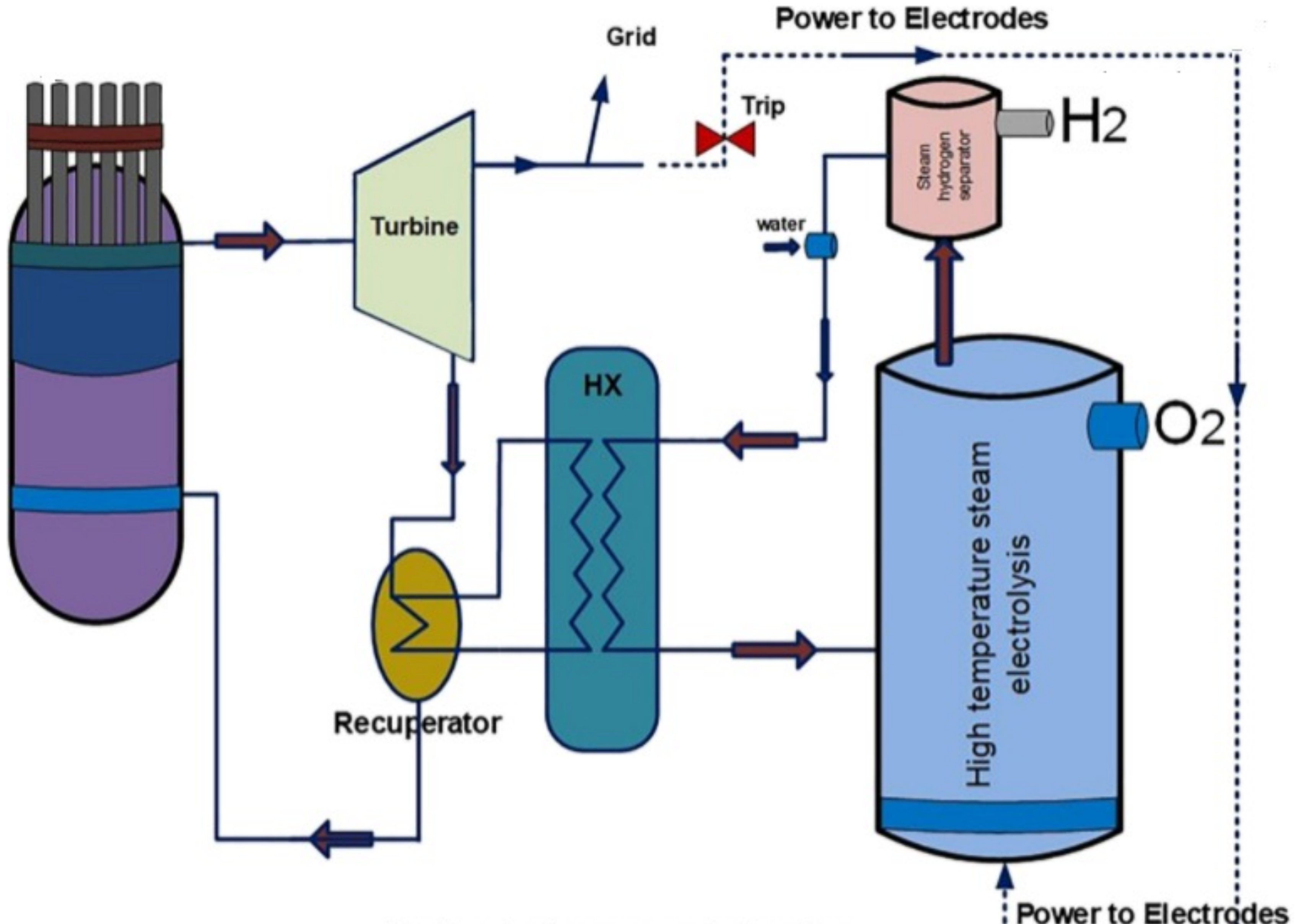
Using existing NPPs with electrolysers to produce hydrogen:

4 major projects funded by US DOE to advance flexible operation of LWRs with integrated H production systems (H2@Scale Initiative)	
FirstEnergy Solutions (FES)	demonstration project using a 2MW PEM electrolyser to be coupled with Davis Besse NPP, Ohio
Xcel Energy	1 MW HTSE coupled with the Prairie Island NPP
Arizona Public Service	study to evaluate the business potential of installing a reversible PEM electrolyser in Palo Verde NPP
Exelon	1 MW PEM electrolyser coupled with one of Exelon's BWR

"These first-of-a-kind projects represent significant advances for improving the long-term economic competitiveness of the LWR industry. They will enable the production of commodities such as hydrogen in addition to electricity from commercial NPPs. These projects also accelerate the transition to a national hydrogen economy by contributing to the use of hydrogen as a storage medium for production of electricity, as a zero-emitting transportation fuel, or as a replacement for industrial processes that currently use carbon-emitting sources in hydrogen production."

Bruce Hallbert, director of DOE's LWR Sustainability Program





Nuclear hydrogen coupled system

Process heat can be delivered by High Temperature Gas Reactors for which an extensive operating experience exists

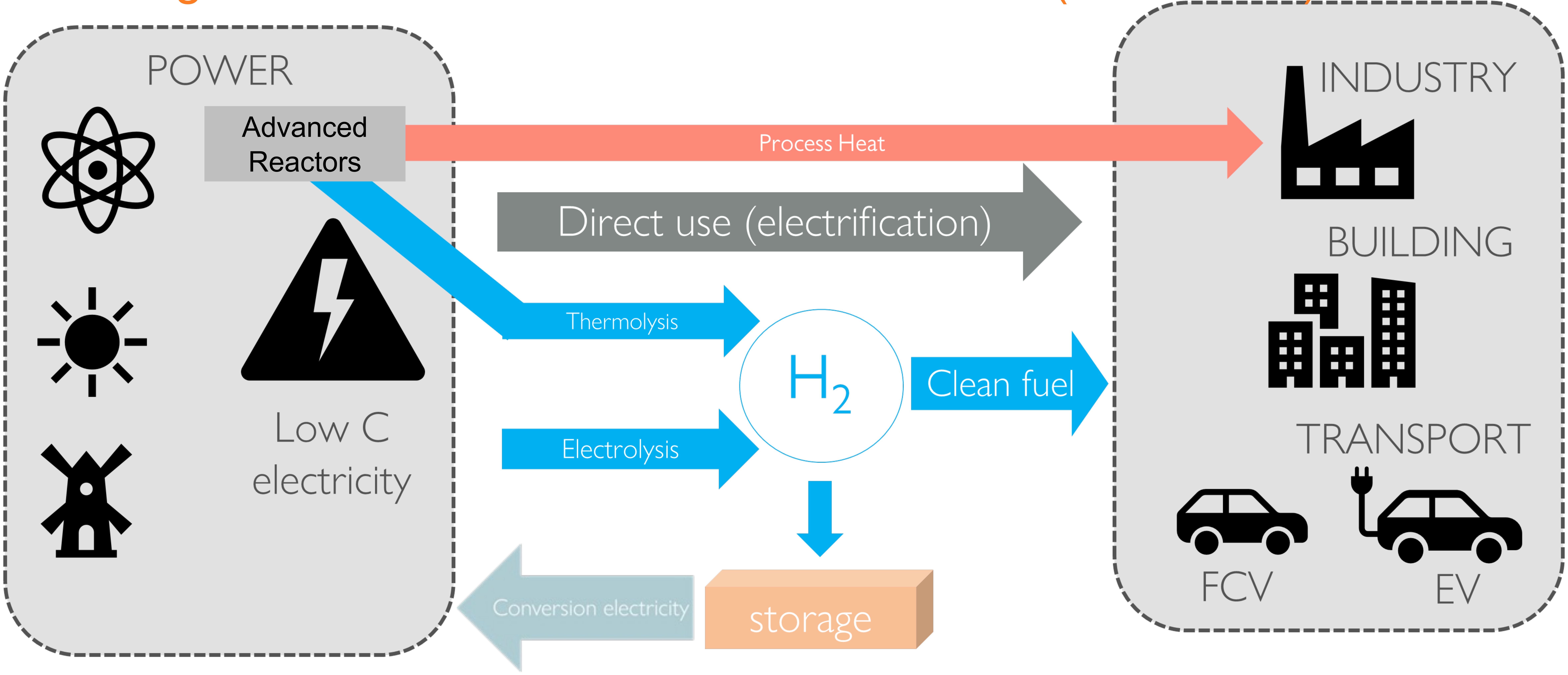
Past Experience | Current test reactors

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

- Wealth of technical know-how available
- Mature technology ready for commercial deployment (in next decade) for temperatures up to ~850 ^{o}C

Coupling via Electricity, Heat and Hydrogen

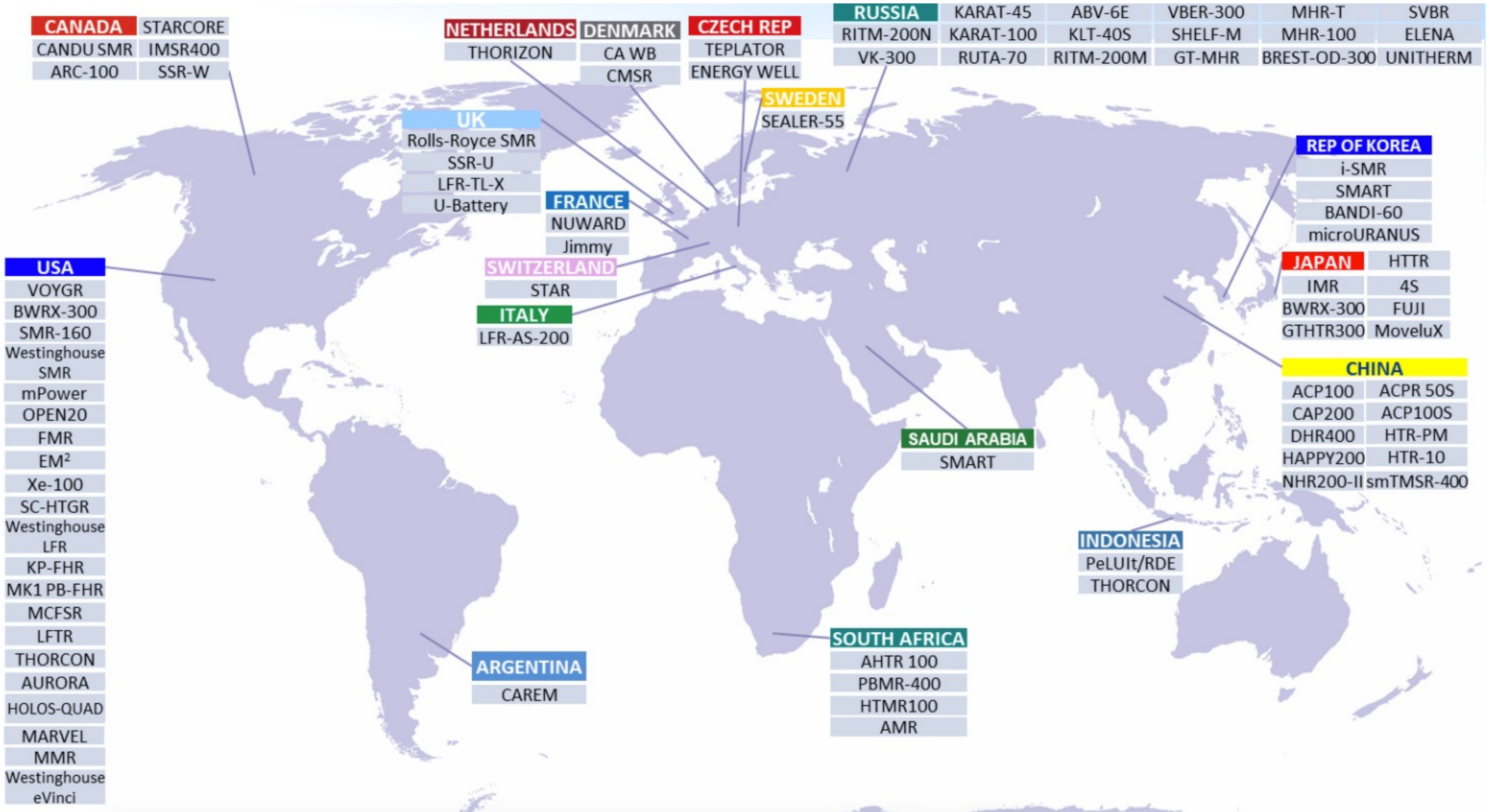
NPPs: large Gen III reactors + Advanced reactors (incl. SMRs)



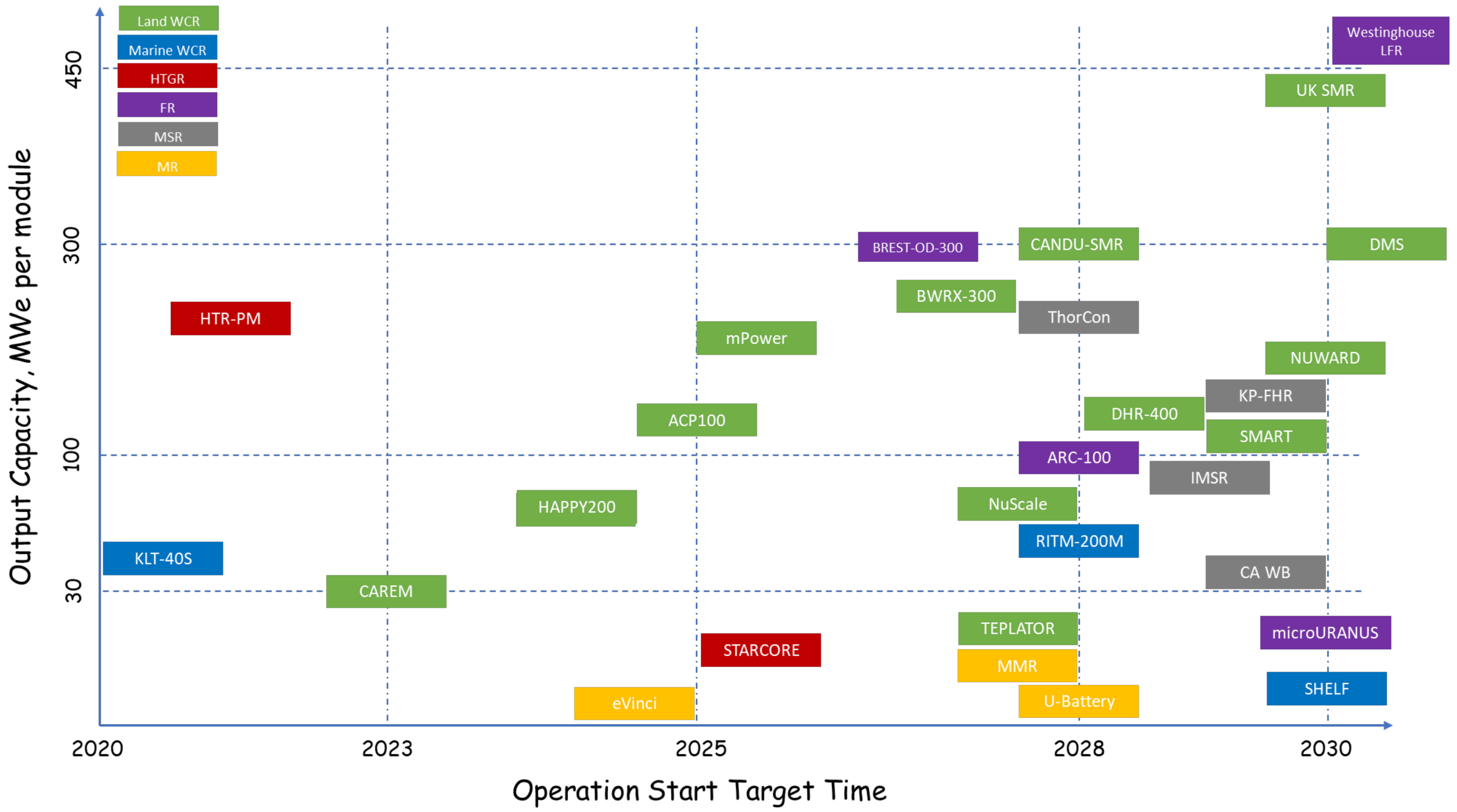
3 low-carbon energy vectors: electricity, heat, hydrogen

GLOBAL SCENARIO, KEY ASPECTS AND CHALLENGES

Global SMR Technology Development



SMR 10-year Deployment Horizon



First 10-year Deployment Horizon

HTR-PM criticality were achieved at the two reactors on 12 Sept. and 10 Nov. 2021, connected to the grid **Dec 2021**

KLT-40S connected to the grid in Dec. 2019, started **commercial operation** at the end of May 2020

SMRs at a very advanced stage:

2 in operation,
1 in advanced stage of construction,
1 received formal construction approval,
1 received SDA from U.S.NRC

CAREM under construction, to start **operation in 2023**

ACP100 has started construction in July 2021 at Changjiang NPP in Hainan province; taking 60 months

NuScale received Standard Design Approval issued by U.S.NRC in Sept. 2020, "will be ready to deliver the first NuScale Power Modules to a client in 2027"

SMRs: key elements for development & deployment

Understanding Technology

Regulatory Framework

Industrial Codes and Standards

Utility Requirements

Supply Chain

Operation preparation

Business Case

Public Acceptance

Legal infrastructure

Human Resource

Safeguard

Security

Issues and Actions for Deployments

Demonstration of Safety and Operational Performance
FOAK, Novel Designs & Technologies

Continuity of Orders, cost competitiveness against alternatives, robust supply chain, and viable financing option

SMR Deployment Competitiveness

Regulatory framework, licensing pathways: global deployment, need for harmonization?

Development of Nuclear Infrastructure for near-term deployment
particularly in Embarking countries

Summary

- Most of the current fleet under construction is large PWRs
- SMRs provide a potentially attractive option to enhance energy supply and security

- In embarking countries with smaller grids, remote areas and the need of non-electric applications
- In expanding nuclear countries for facilitating transition to low carbon energy systems

- The first SMR designs has started operation in a Floating Nuclear Power Plant
- Dozen of SMR designs aim deployment by 2030 to contribute more than 1600 MWe

- Land based SMRs for on grid applications; Floating NPP for small islands and/or remote regions
- Microreactors of up to 10 MWe for small islands, remote regions & alternative to diesel generators

- Embarking countries need to understand their User Requirements & Criteria on Reactor Technology, including that for SMRs, conduct Technology Readiness assessment, address manufacturing aspects, and establish a robust supply chain;

THANK YOU🙏

Chirayu Batra

Email:
Chirayu.Batra@TerraPraxis.org

LinkedIn
www.linkedin.com/in/chirayubatra

Twitter:
@chirayubatra

"I have been driven by the conviction that much more than 1 percent of the energy contained in uranium must be utilized if nuclear power is to achieve its real long-term potential."

\- Enrico Fermi

TERRA PRAXIS