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2022 nuclear summit
Trends in Brazilian Nuclear Market

Overview of Small Modular Reactors – Design and Technology

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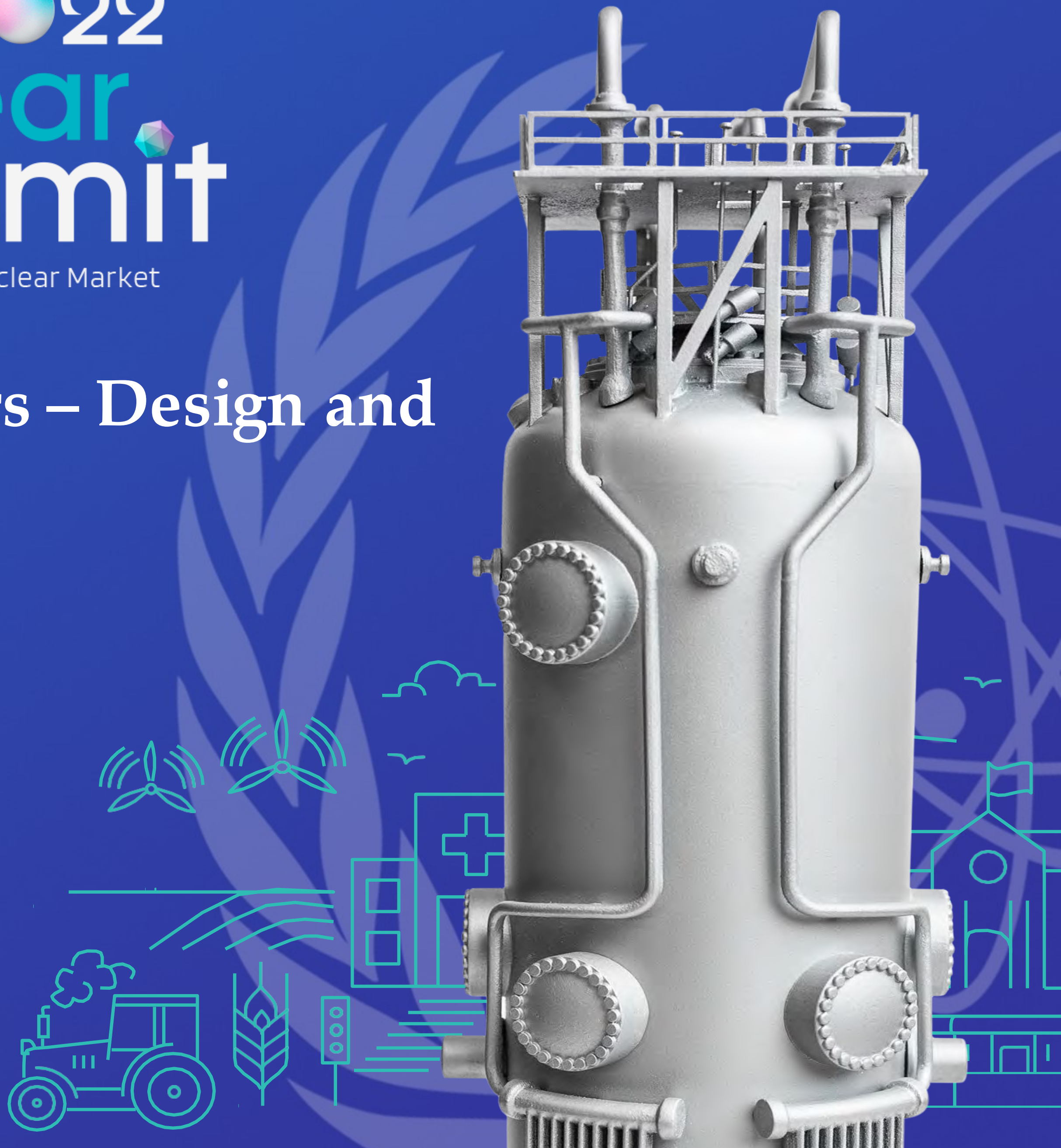

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Outline

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

Image: NuScale + Minerals Council of Australia

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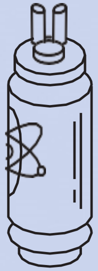
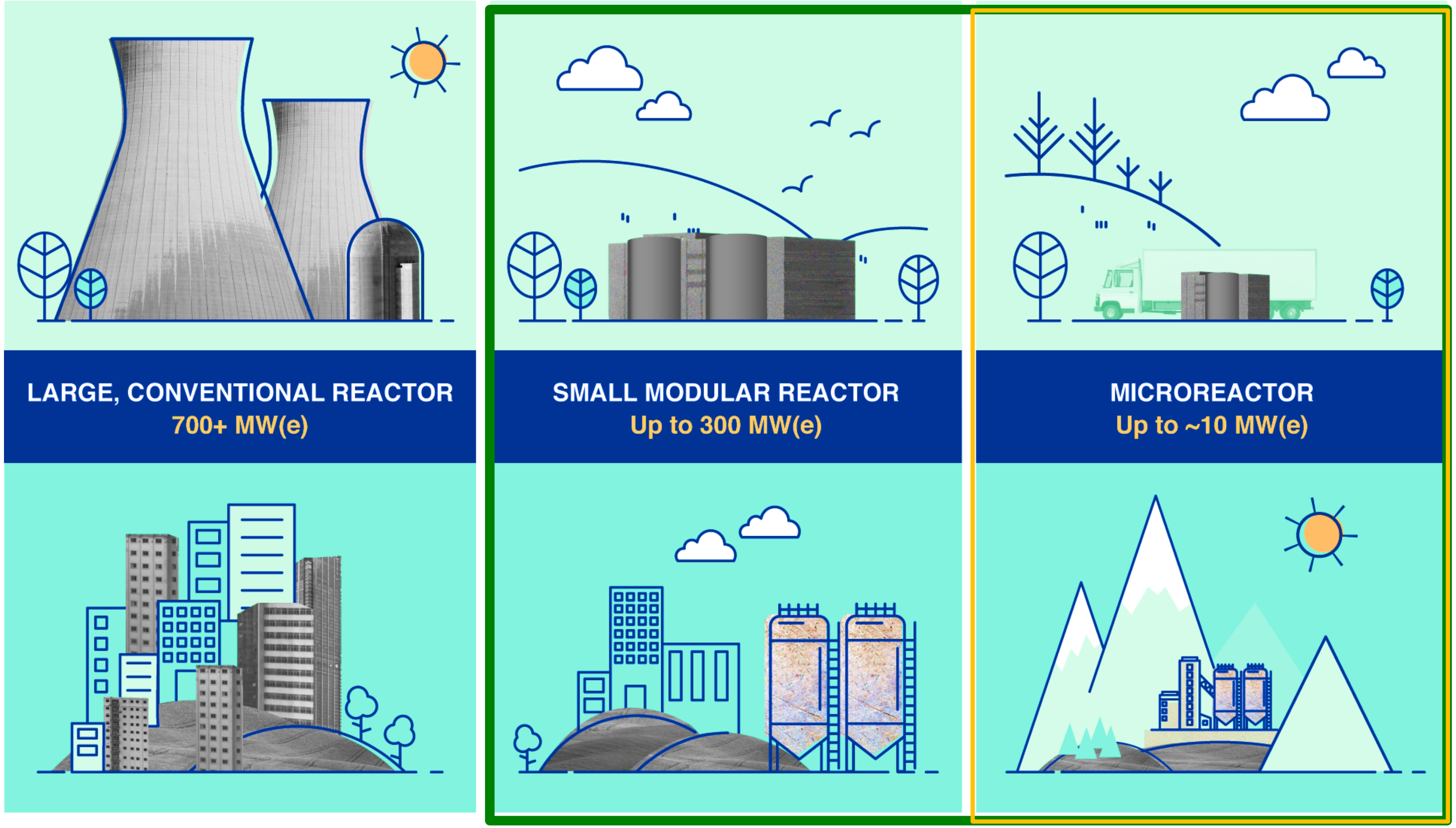


What are SMRs, Benefits, Key Features and Technology…

SMR: Size



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

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

SMR: Modular

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

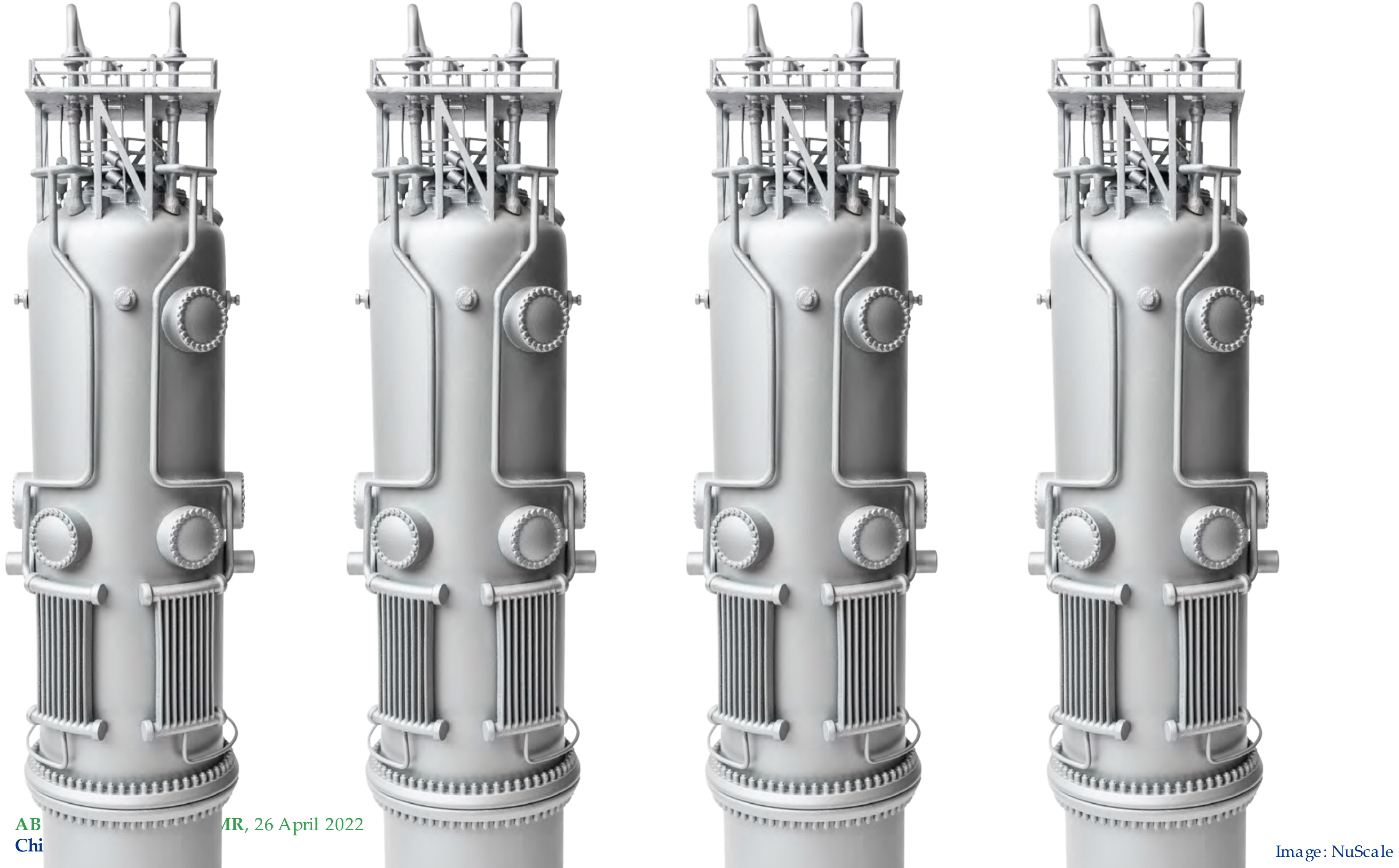
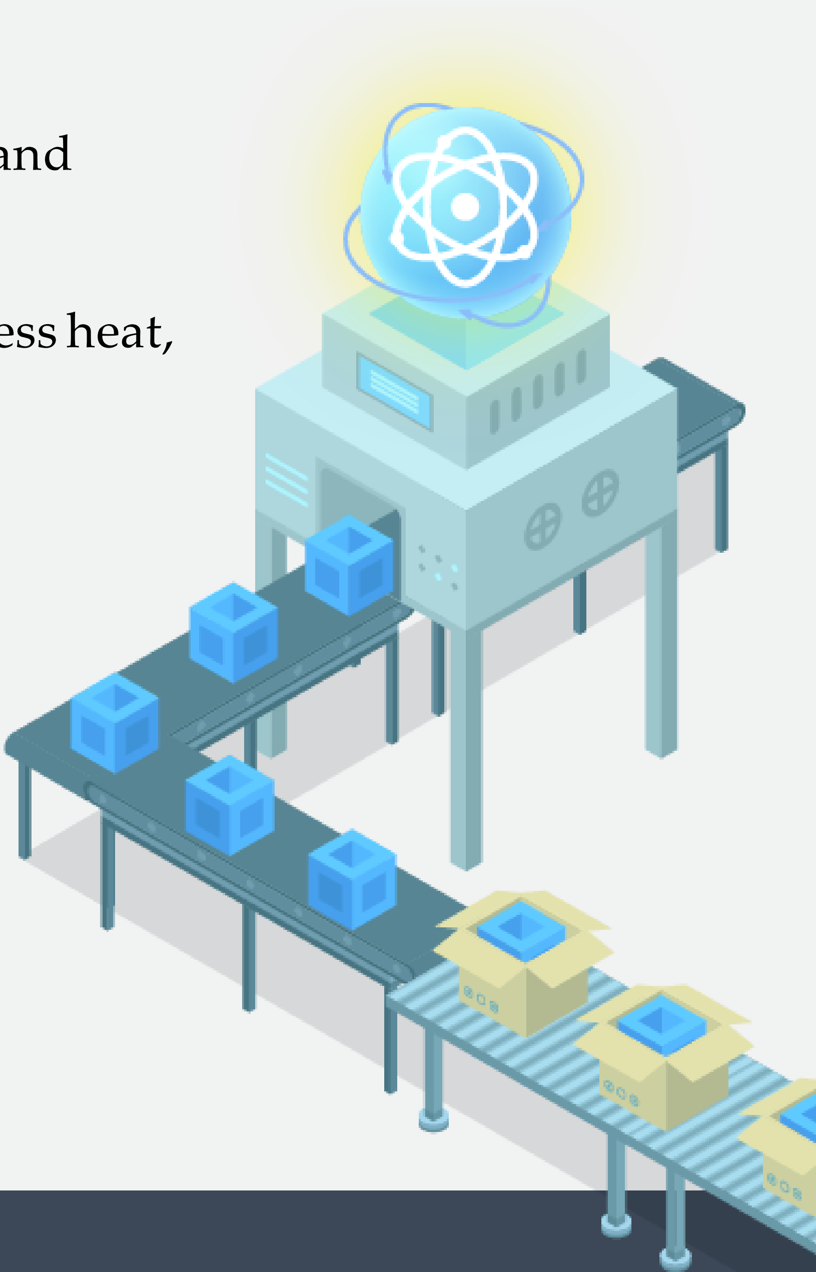


Image: NuScale

- **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

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.

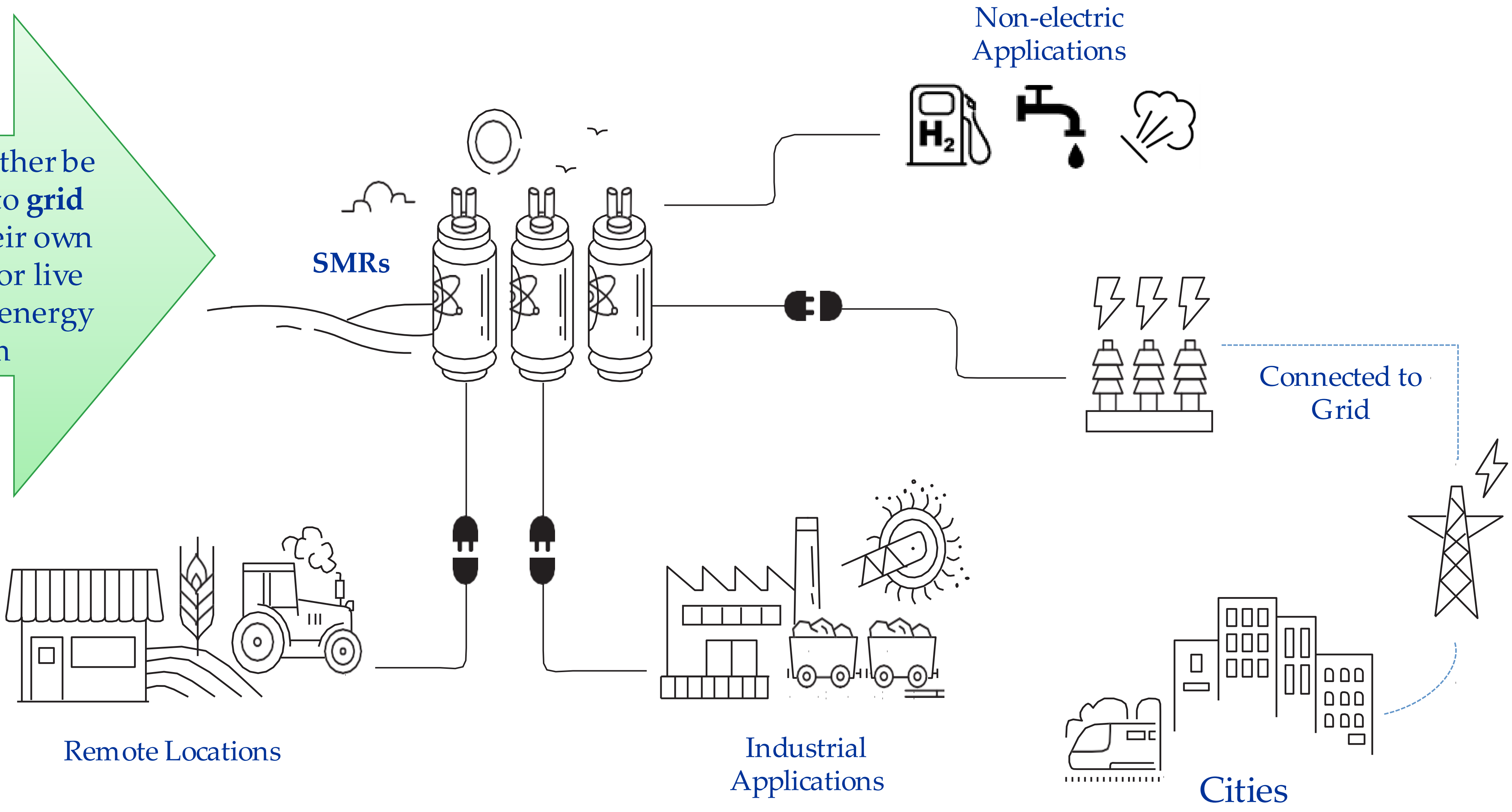


electricity
clean water
hydrogen
heating
grid storage
vehicles
synthetic fuels
ammonia
metals refining
and more

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

SMR: Major Lines of Technology

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

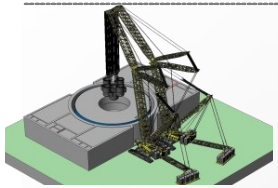
Image: IAEA SMR Booklet

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

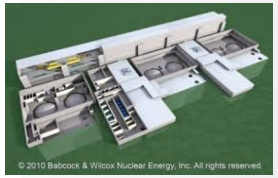


Modularization
- Multi-module
- Modular Construction

→ Shorter construction time

Flexible Application
- Remote regions
- Small grids

→ Wider range of Users

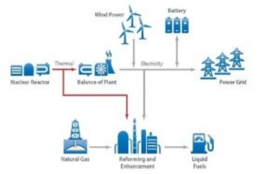


Smaller footprint
- Reduced Emergency planning zone

→ Site flexibility

Replacement for aging fossil-fired plants

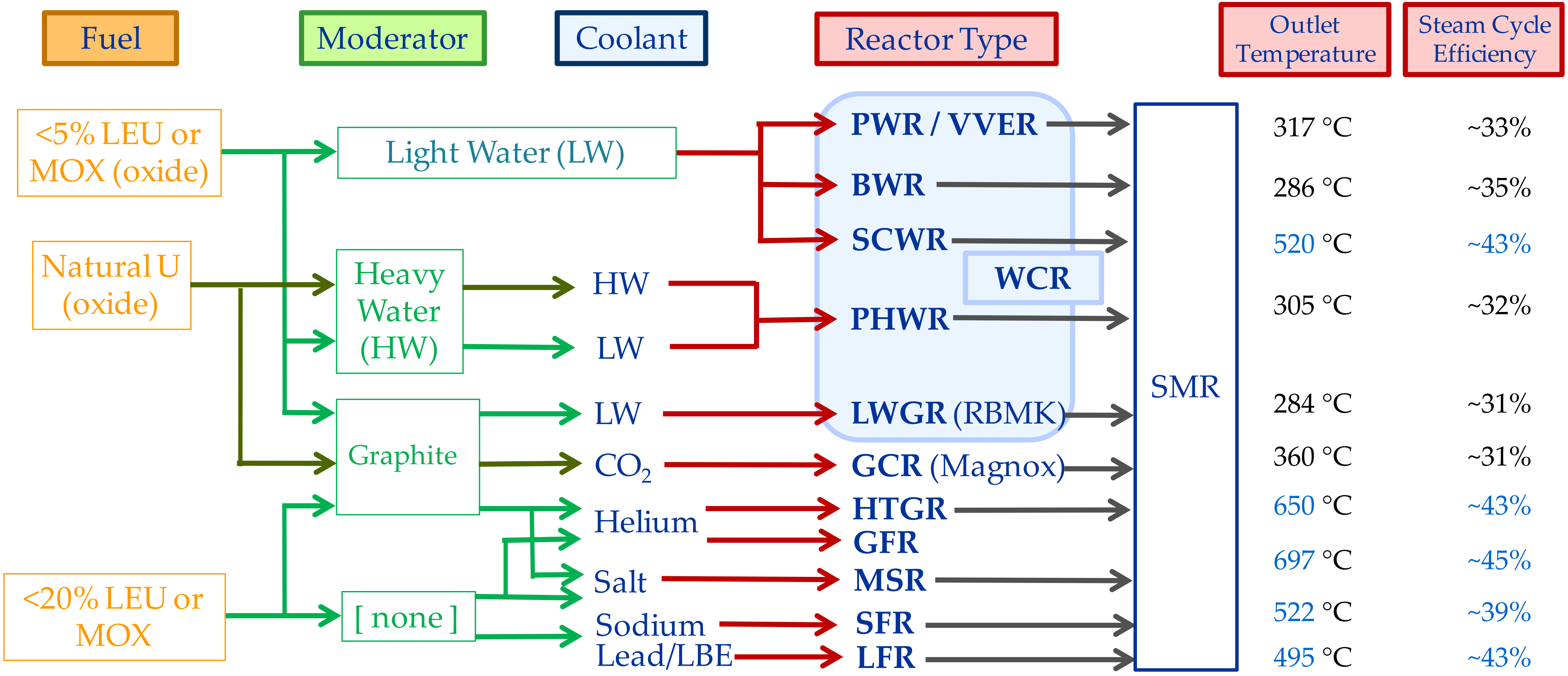
→ Reduced CO_2 production



Potential Hybrid Energy System

→ Integration with Renewables

SMR: Reactor Technology/Types



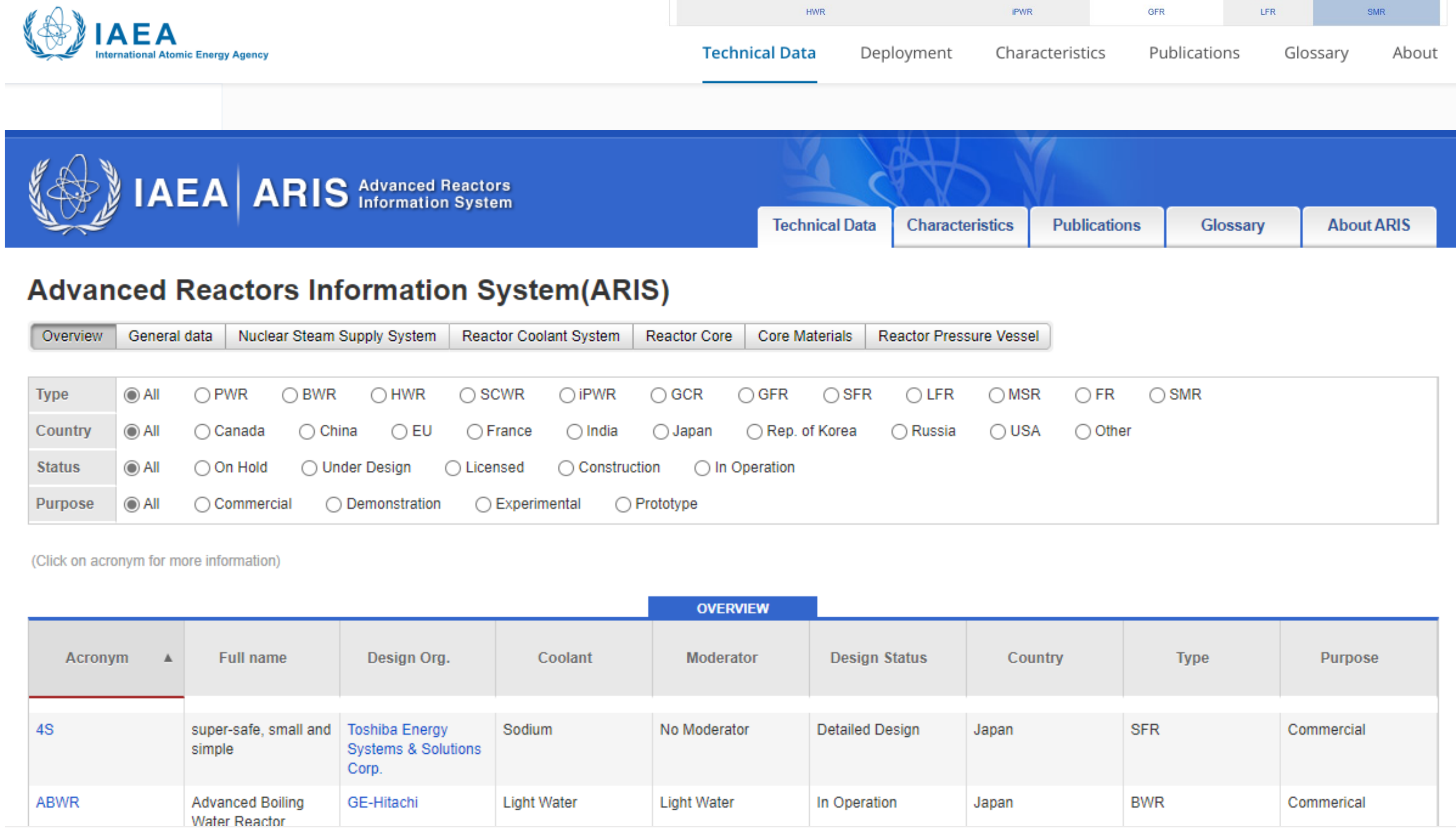
MOX: mixed-oxide containing any combination of U, Pu and Th oxides

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

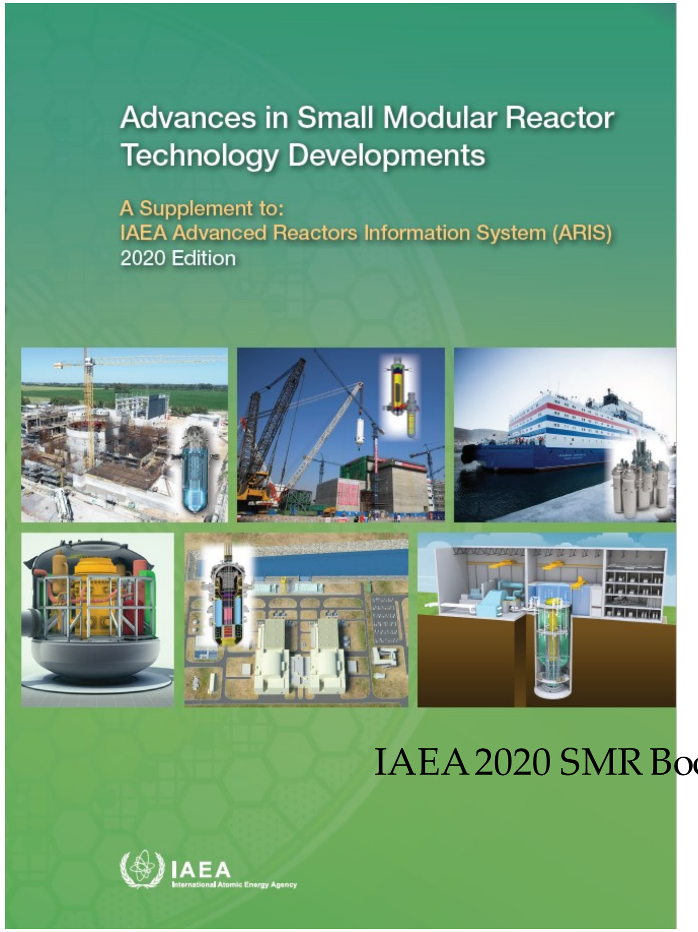
Different SMR Designs, description and innovative features

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 by the end of this year*



IAEA-ARIS SMR Booklet 2020



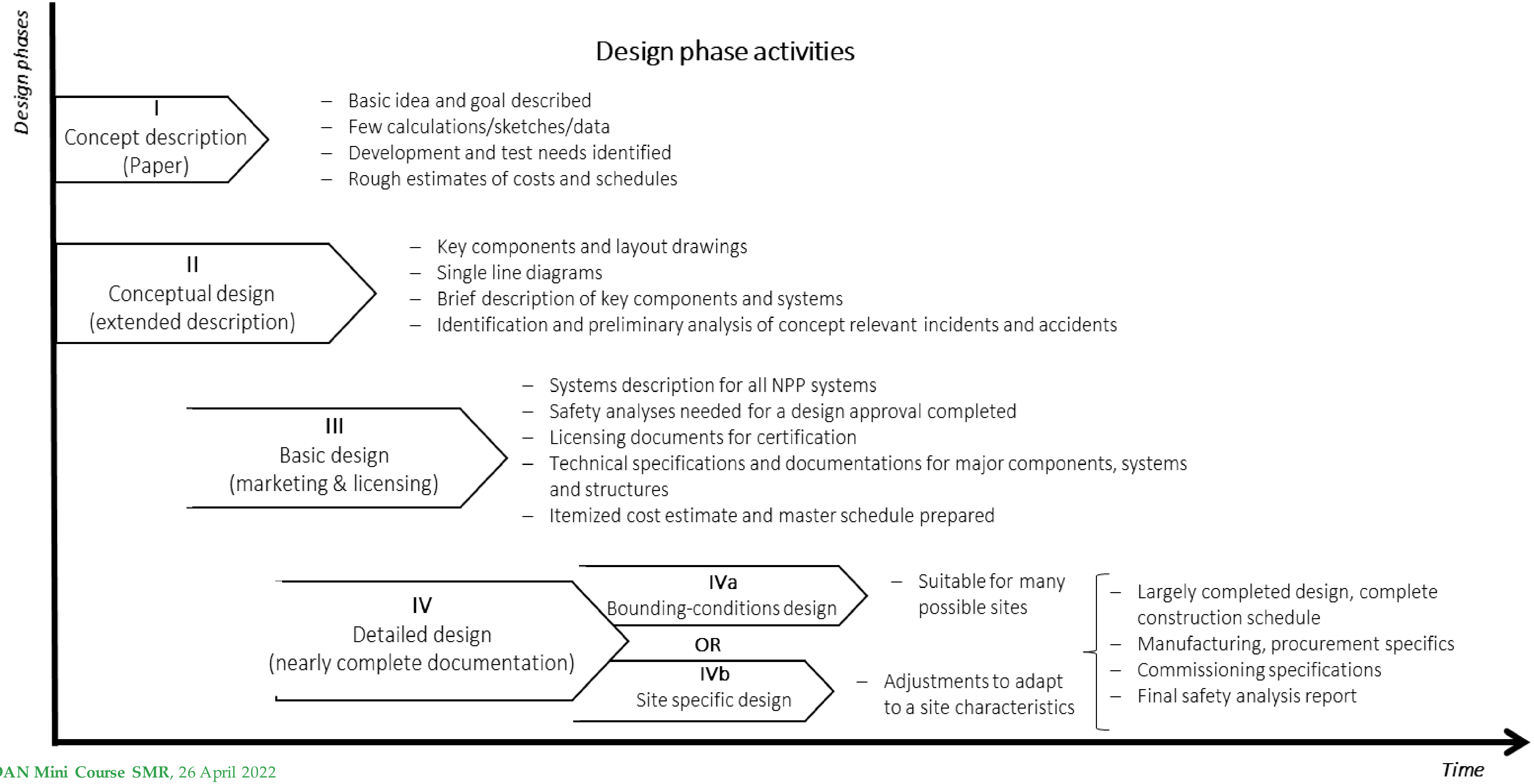
IAEA 2020 SMR Booklet

IAEA SMR Booklet, 2020 Edition	
Number of reactor designs:	72 *(16 more than 2018-edition)*
Member states involved:	18 countries
Reactor types included:	• Water-cooled Land Based – **25** • Water-cooled Marine Based – **6** • High temperature Gas cooled – **14** • Fast Neutron Spectrum – **11** • Molten Salt – **10** • Microreactors - **6** • Test Reactors (HTGR only)
Distinguishing features	• Special coverage on **fuel cycle** approach, **waste management/technology** • Insightful annexes with various charts and tables
Status	Published, hardcopies available
Downloadable version	https://aris.iaea.org/Publications/SMR_Book_2020.pdf

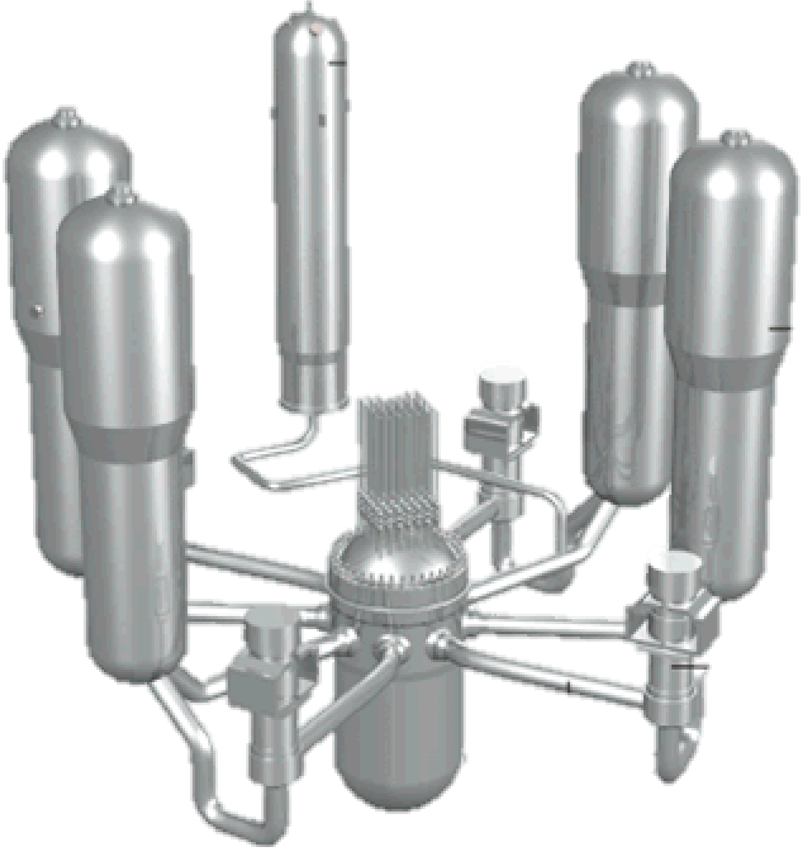
1. Introduction

The IAEA 2020 SMR Booklet is a bi-annual publication supplement to the IAEA Advanced Reactor Information System (ARIS) Database. It provides a brief yet comprehensive design description of 72 different reactor designs. The 2020 version is an updated version of the 2018 booklet. It includes 16 more designs and a more comprehensive set of annexes.

Design Development Phases



Design Example 1: Integral-PWR type SMR



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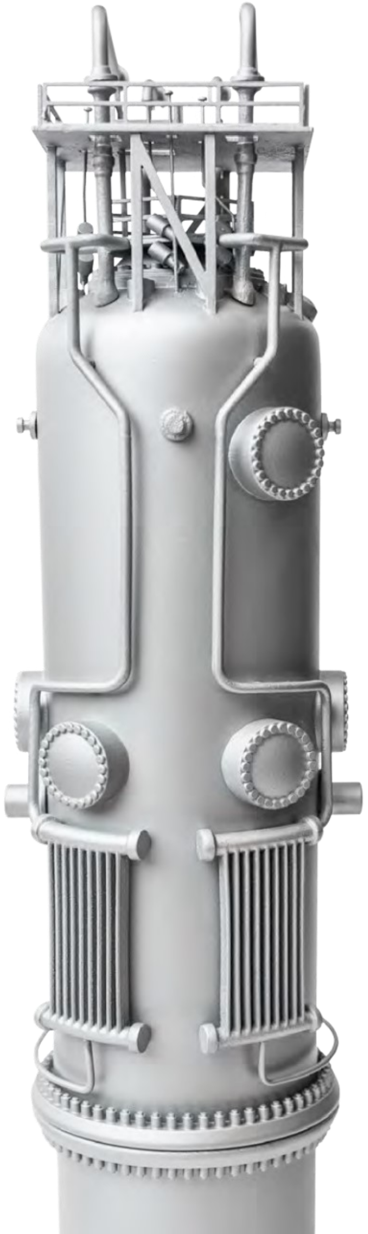
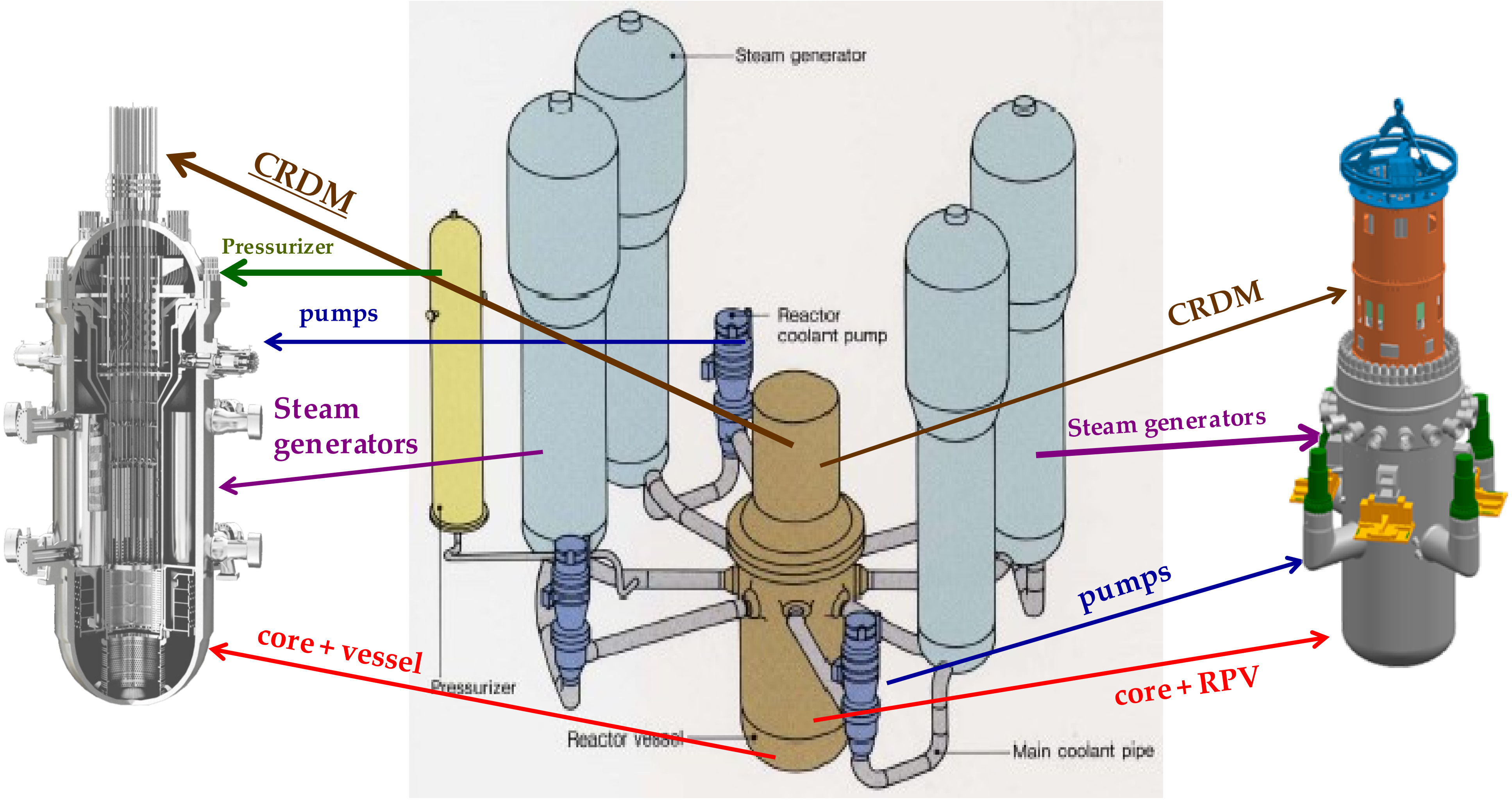


Design Example: Integral-PWR type SMR



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

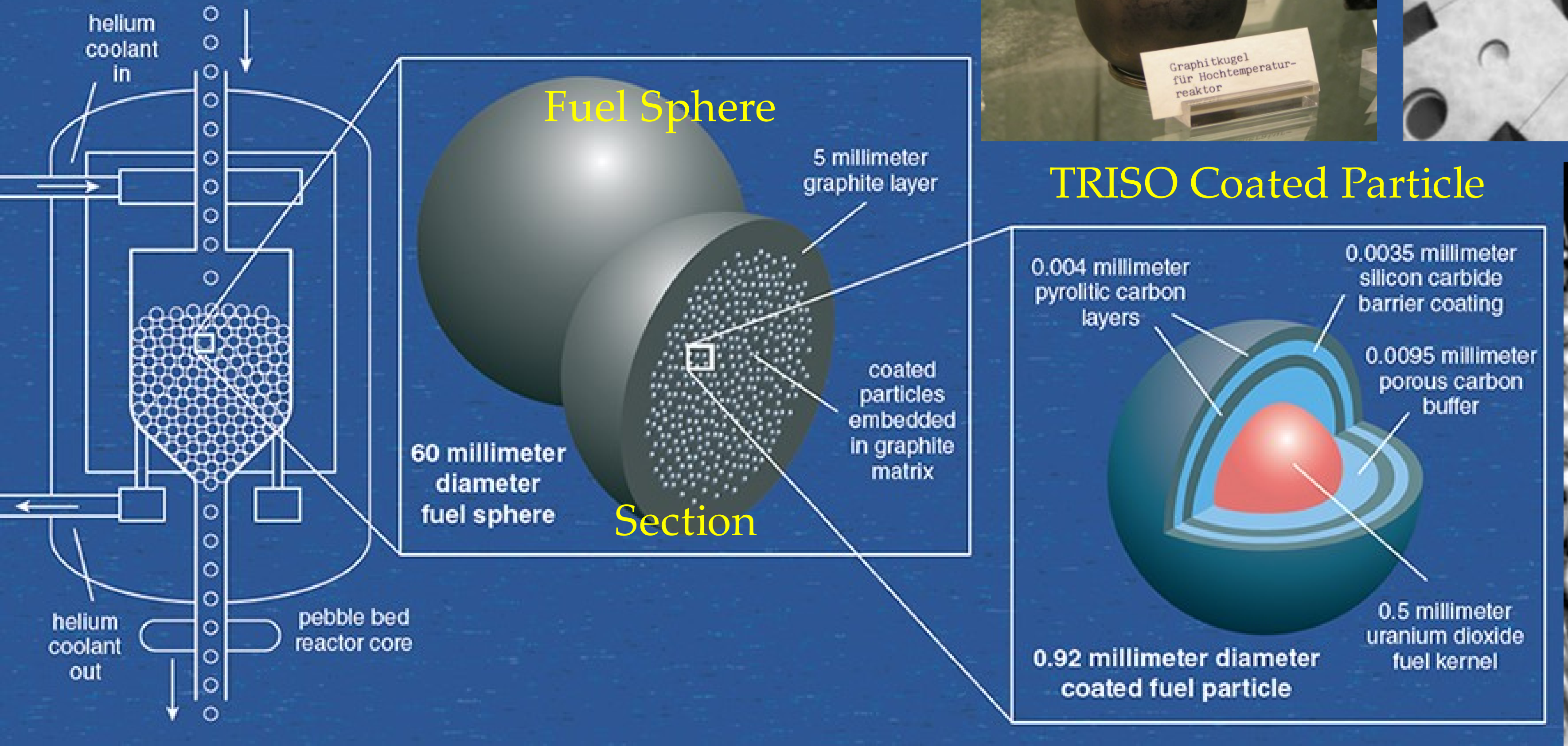
- Enhanced performance engineered safety features:
  Natural circulation primary flow (adopted by e.g., CAREM, NuScale, SMR-160, and ABV6M designs) → No LOFA
  - Reactivity control
    - Internal CRDM (adopted by e.g., IRIS, mPower, Westinghouse SMR, and CAREM designs)
      - No rod ejection accident
    - 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



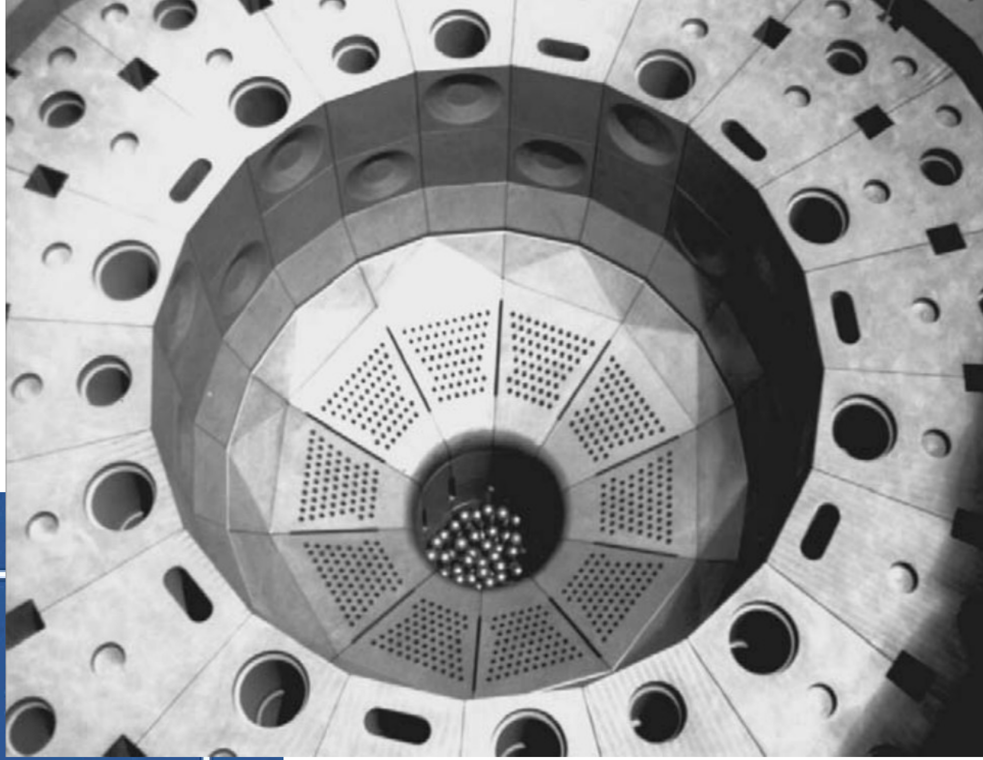
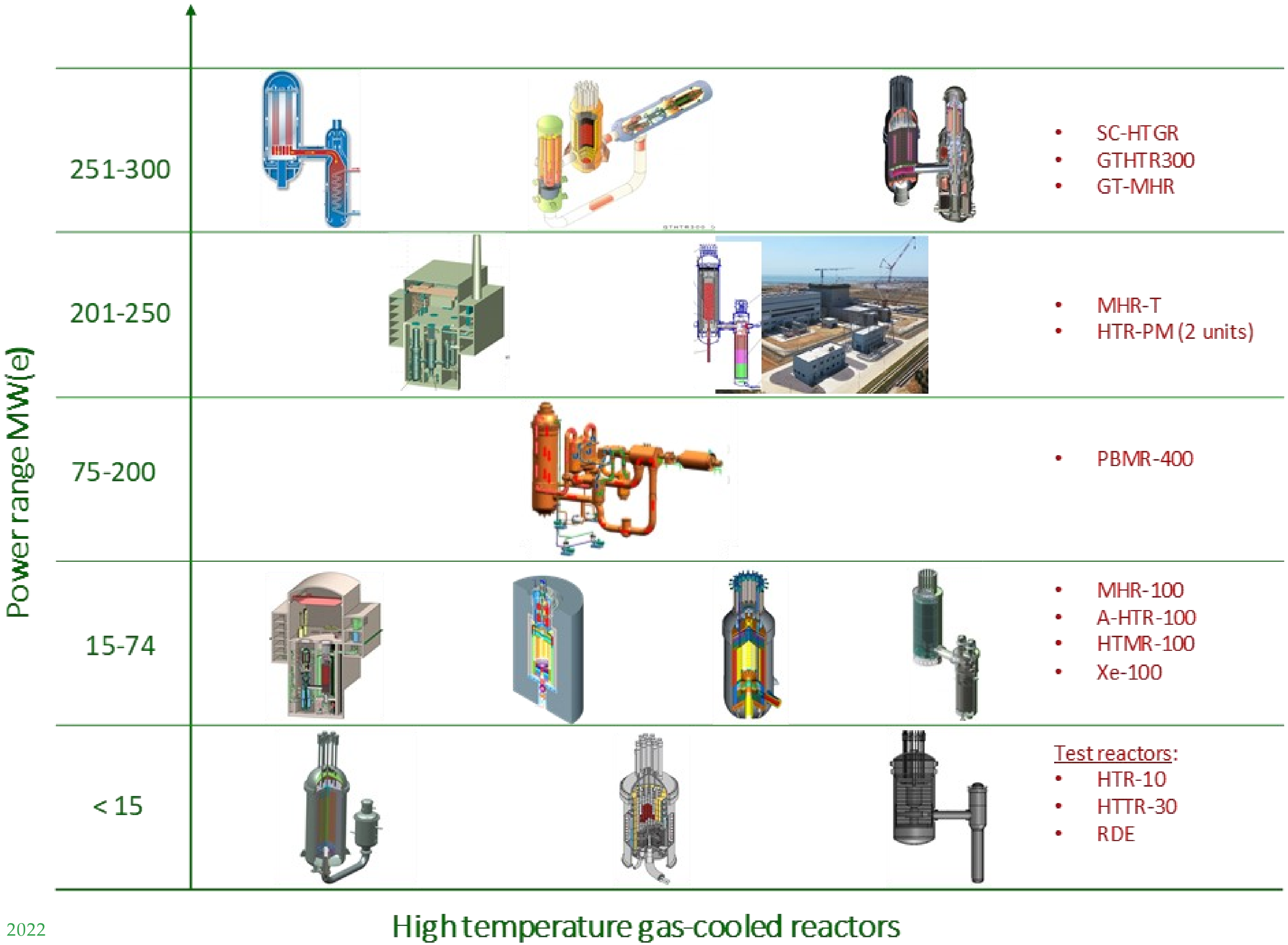
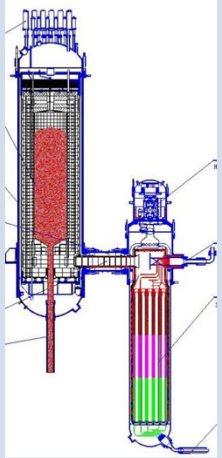
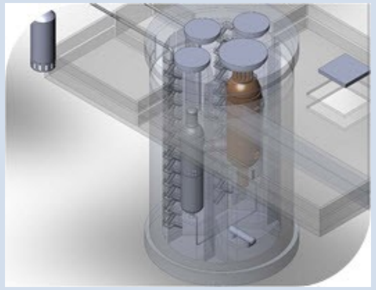
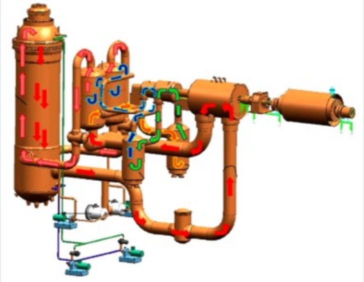
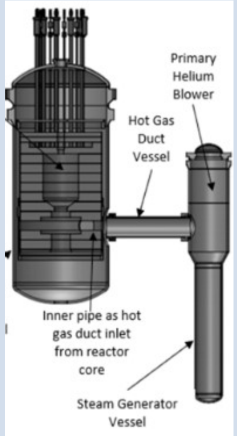
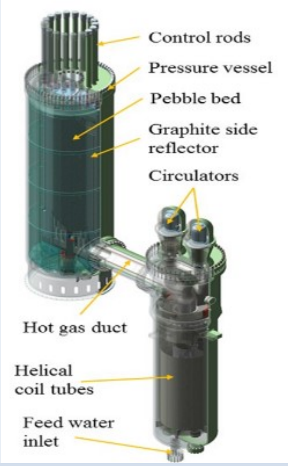


Image: American Scientist, HTR-10, THTR

Power Range of HTGR-type SMRs



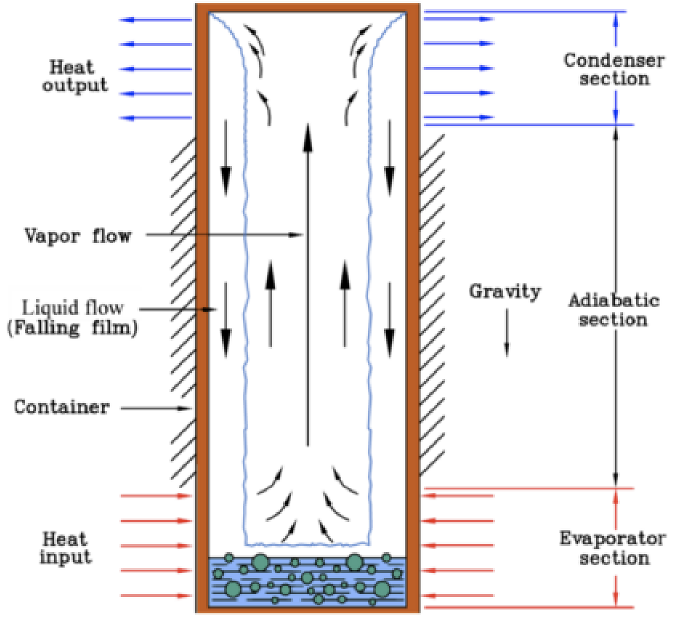
HTGR-type SMRs (Examples)

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

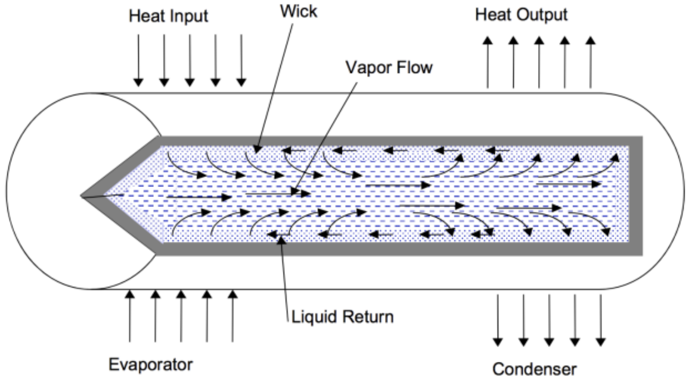
Design Example 3: Heat Pipe Reactors (Micro Reactors)

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

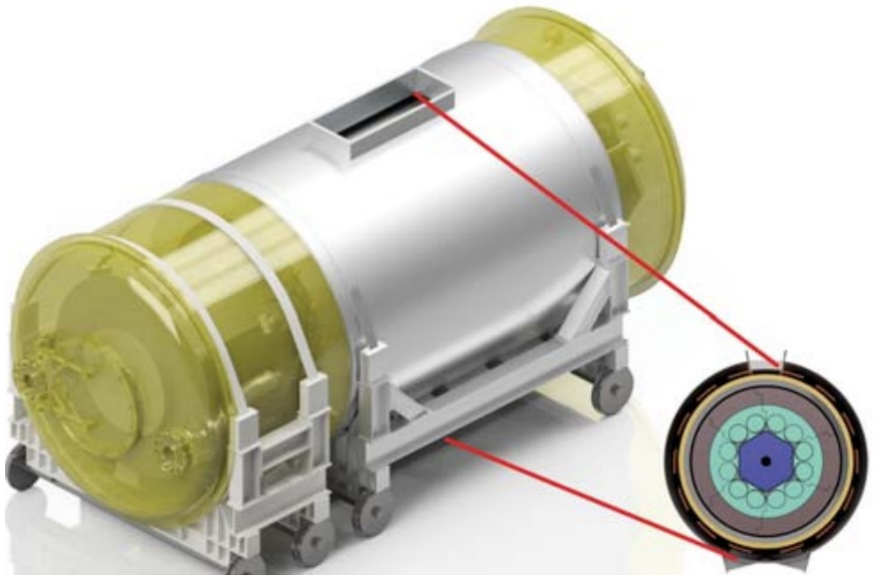
Gravitational
(thermosyphon or Perkins tube)

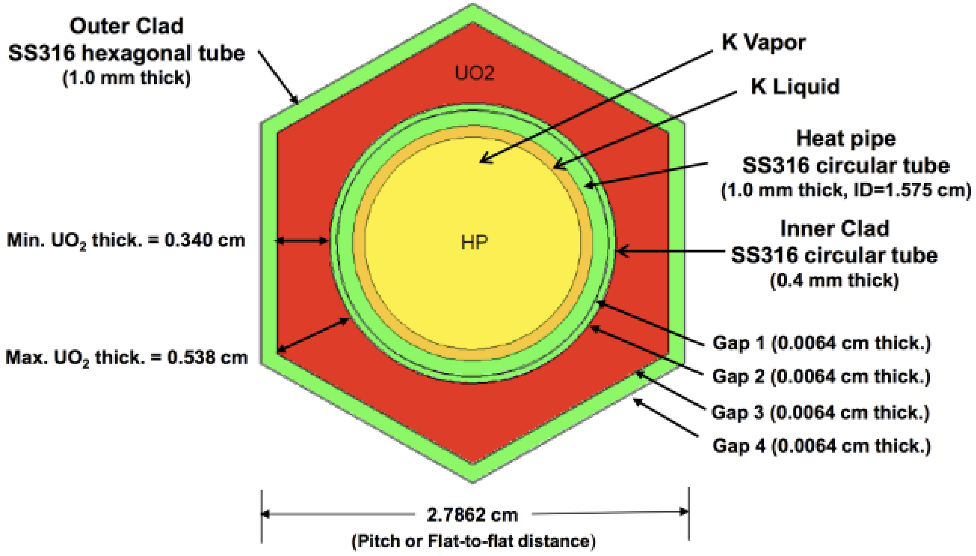


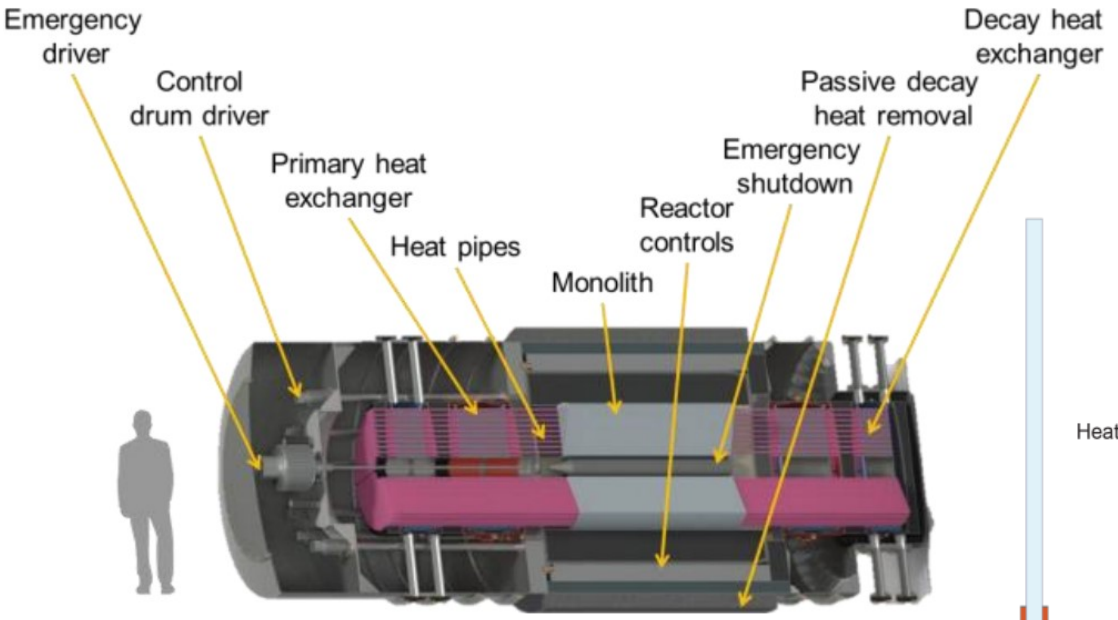
Capillary
(wicking)

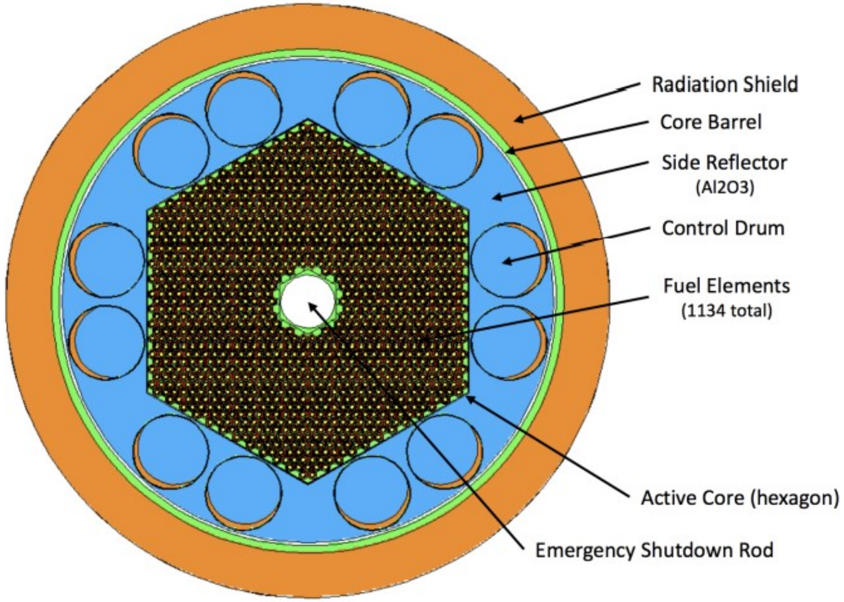


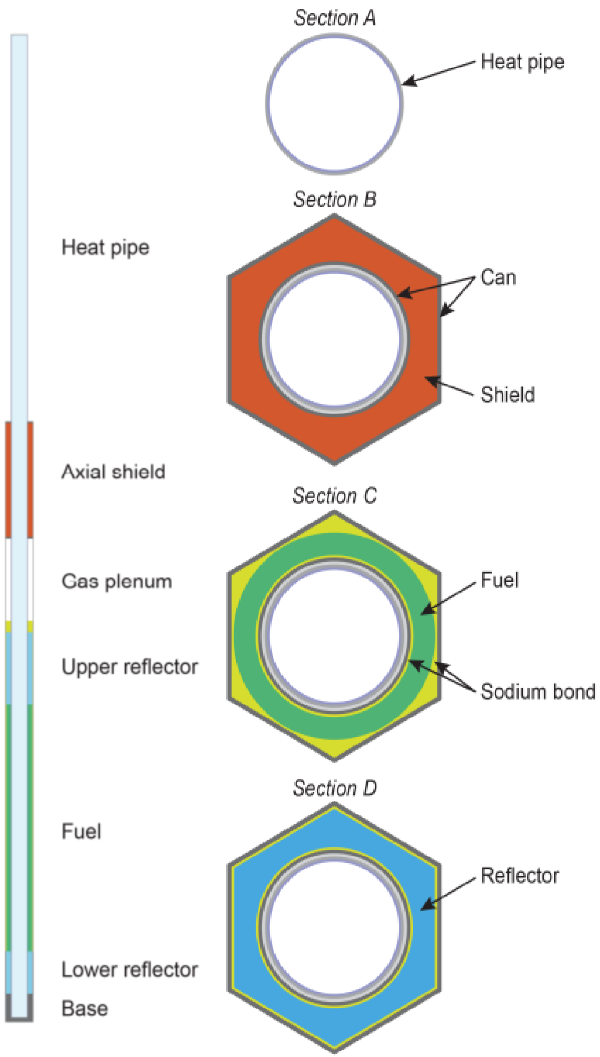
Heat Pipe Reactor











Hexagonal fuel elements with centre heat pipes

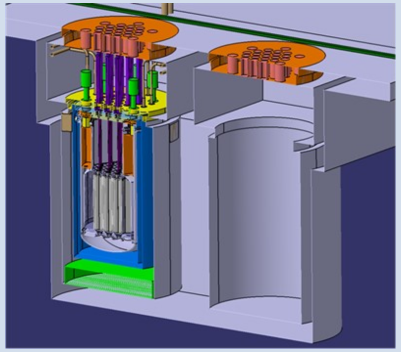
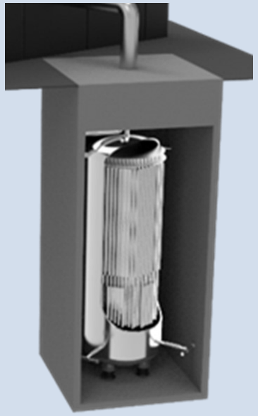
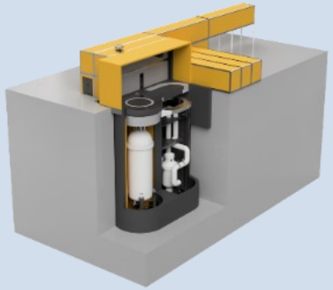
Heat Pipe Reactor: Advantages and Challenges

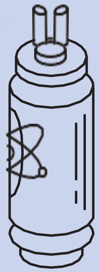
- Design Advantages
  - Very compact
  - Can operate at high temperatures
  - No positive void coefficient
  - Strong negative temperature feedbacks
  - Reduced corrosion issues
  - Passive heat removal pathways
  - Orientation independent (capillary)
- Design Challenges
  - Working fluids usually have 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

Microreactor Designs

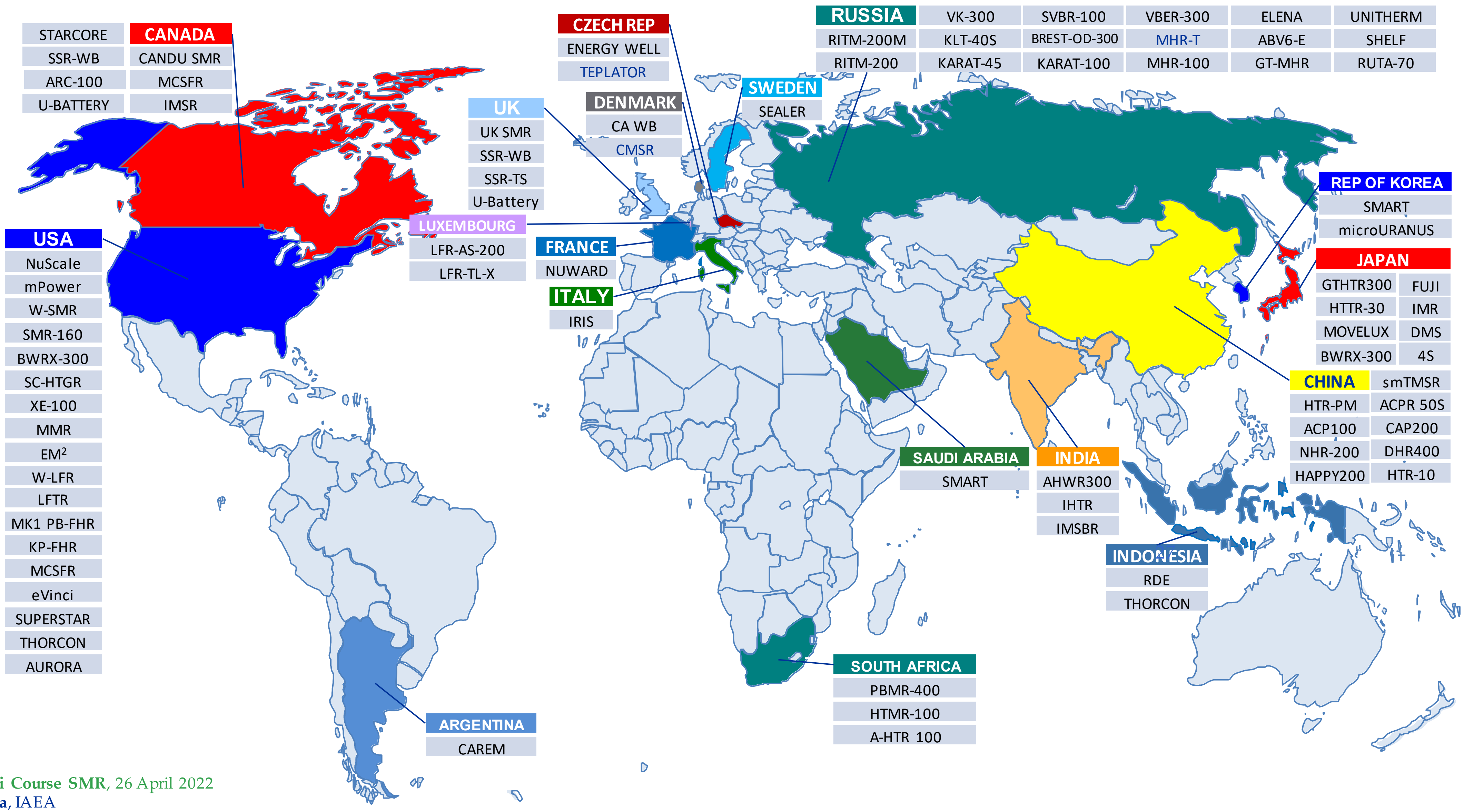
Six designs included in IAEA SMR Booklet (2020 Edition)

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	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 m² 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°C • FCM TRISO graphite, Hexagonal fuel block • Enrichment: HALEU 19.75% • Refuel interval: fueled once during lifetime



Global Scenario, key aspects and challenges

Global SMR Technology Development



SMR 10-year Deployment Horizon

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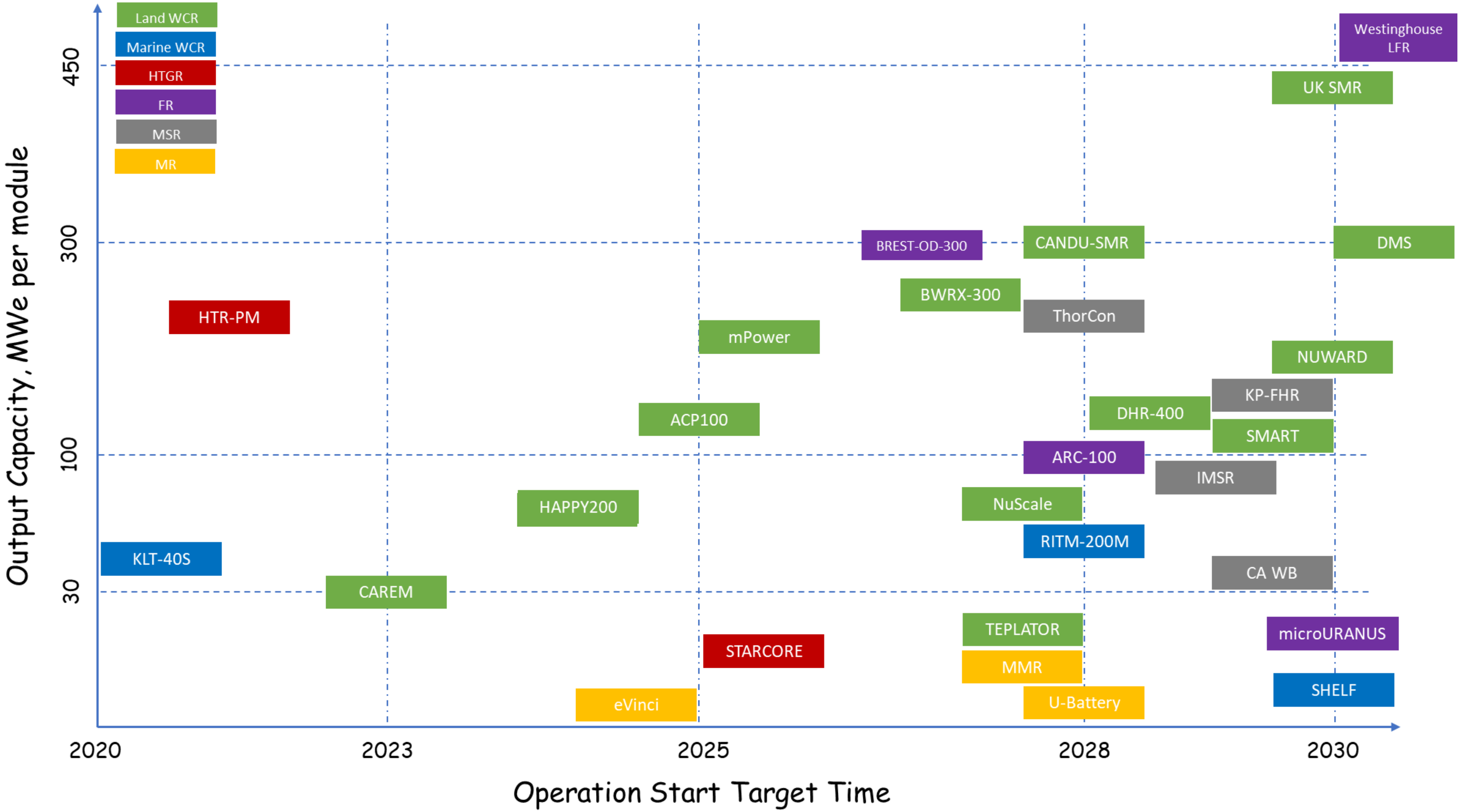


First 10-year Deployment Horizon

SMRs at a very advanced stage: 1 in operation, 1 in commissioning, 1 in advanced stage of construction, 1 received formal construction approval, 1 received SDA from U.S.NRC

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

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

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

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
- Safeguard
- Human Resource
- Operation preparation
- Business Case
- Public Acceptance
- Legal infrastructure
- Security

Issues and Actions for Deployments

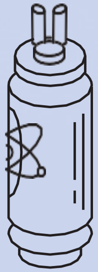
Demonstration of Safety and Operational Performance
FOAK, Novel Designs & Technologies

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



IAEA Activities

IAEA Activities on SMRs

IAEA

Agency-wide Platform on SMRs and their Applications

Development and Deployment Status
- ARIS Database
- SMR Booklet

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

Economics
- Economic Appraisal of SMR Projects: Methodologies and Applications

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

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

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

Generic User Requirements and Criteria
- Key policy of Member State on the expectations of its users on SMR technology

Reactor Technology Assessment
- Updated Method incorporates SMR

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Thank you

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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