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# INTRODUCTION TO SMR'S

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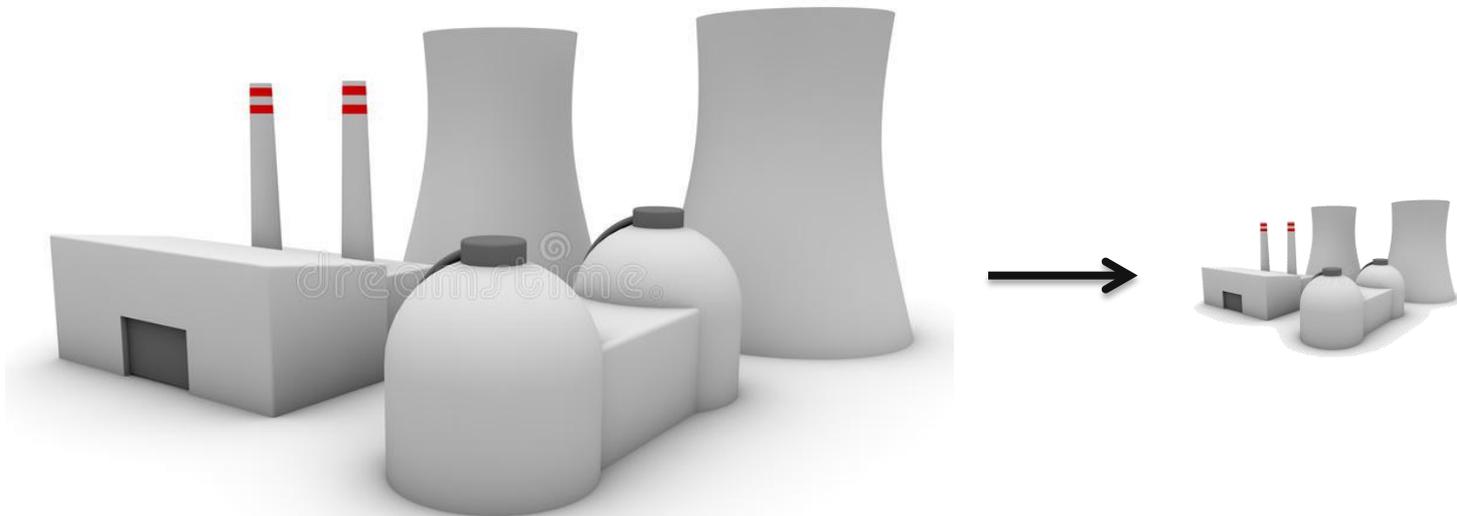
Ferry Roelofs  
20 April 2018



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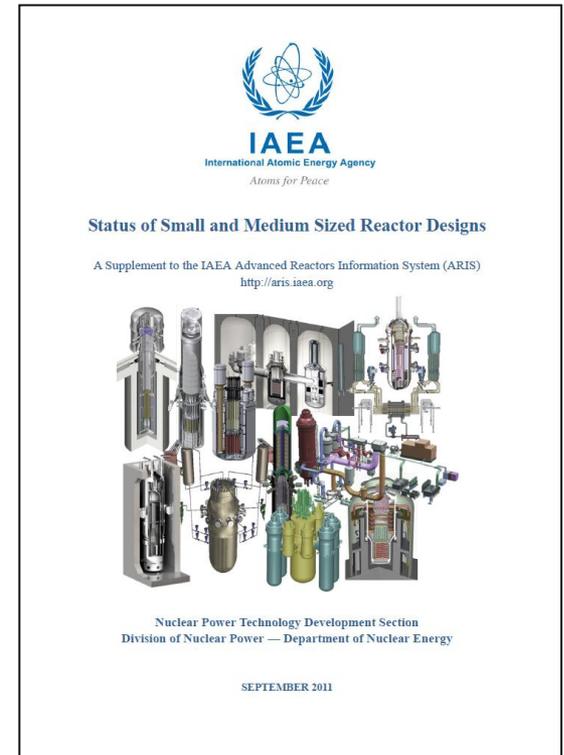
# WHAT IS AN SMR?

# WHAT IS AN SMR?

## DEFINITION: IAEA

### IAEA

- Small to Medium sized Reactors
- < 700 MWe or even < 300 MWe
- Small grids
- Low rates of increase in demand
- (Developing countries with developing grids)
- Multi-module offers operation flexibility
- Cogeneration
- Alternative fuel management



IAEA, 2011

# WHAT IS AN SMR?

## DEFINITION: US DOE

### – US DOE

- **S**mall **M**odular **R**eactor
- < 300 MWe
- ‘Plug and play’
- Flexibility (financing, siting, sizing, end use)
- Phased investment when modular constructed
- Isolated areas
- Proliferation resistant by cassette fuelling

**SMALL MODULAR REACTORS**

*The U.S. Department of Energy's Office of Nuclear Energy*

**Small Modular Reactors (SMRs) are nuclear power plants that are smaller in size (300 MWe or less) than current generation base load plants (1,000 MWe or higher). These smaller, compact designs are factory-fabricated reactors that can be transported by truck or rail to a nuclear power site.**

**The** Department of Energy (DOE) believes that there is a need and a market in the United States for SMRs. The DOE Office of Nuclear Energy's Small Modular Reactor program will advance the licensing and commercialization of SMR designs.

**BENEFITS OF SMRS**

The term "modular" in the context of SMRs refers to a single reactor that can be grouped with other modules to form a larger nuclear power plant. Even though current large nuclear power plants incorporate factory-fabricated components (or modules) into their designs, a substantial amount of field work is required to assemble components into an operational power plant. SMRs are envisioned to require limited on-site preparation as they are expected to essentially be ready to "plug and play" when they arrive from the factory. SMRs provide simplicity of design, economies and quality of factory production, and offer more flexibility (financing, siting, sizing, and end-use applications) compared to larger nuclear power plants.

SMRs can reduce a nuclear plant owner's capital outlay or investment due to the lower plant capital cost. Modular components and factory fabrication can reduce construction costs and duration. Additional modules can be added incrementally as demand for energy increases. SMRs can provide power for applications where large plants are not needed or sites lack the infrastructure to support a large unit. This would include smaller electrical markets, isolated areas, smaller grids, limited water and acreage sites, or unique industrial applications. SMRs can replace aging fossil plants or complement existing industrial processes or power plants with an energy source that does not emit greenhouse gases. Some reactor designs will produce a higher temperature process heat for either electricity generation or industrial applications.

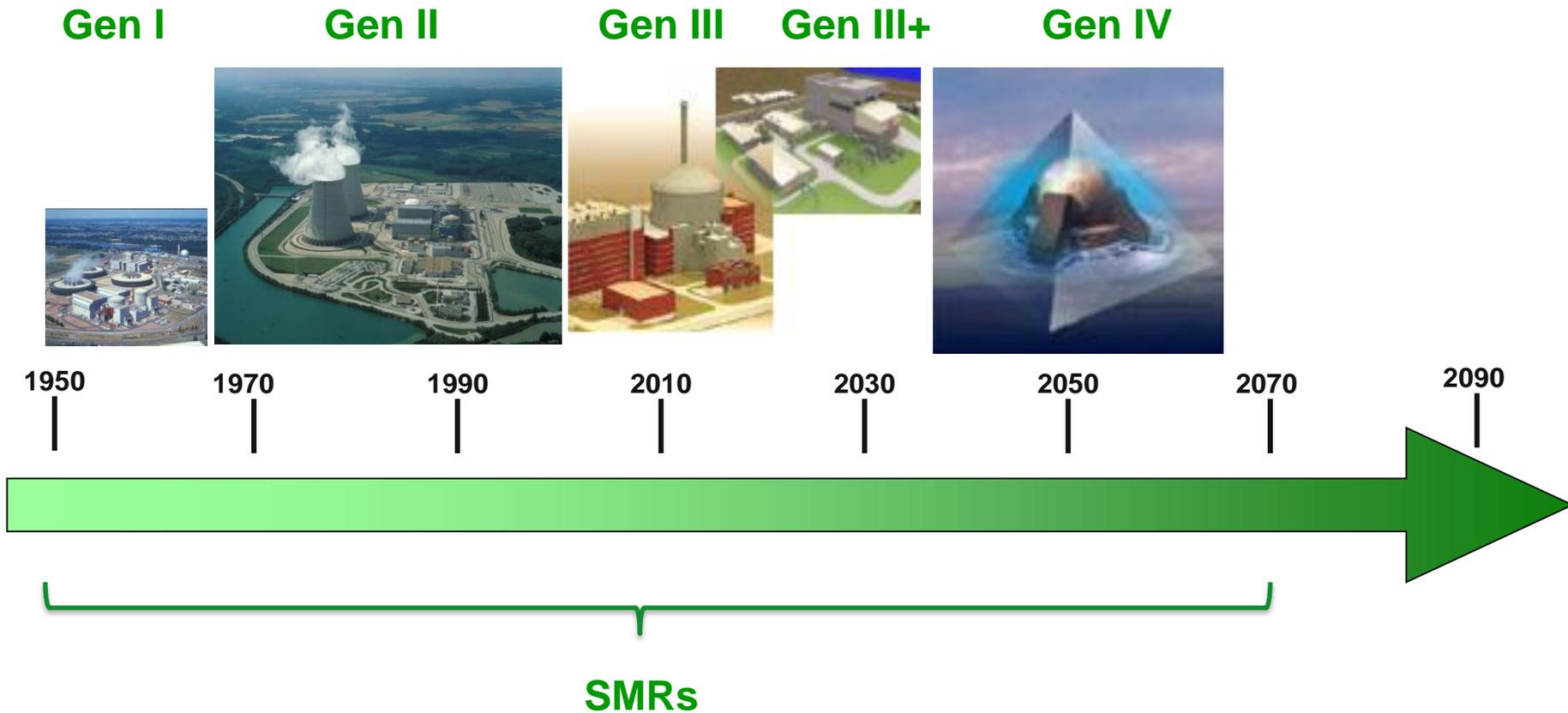
SMRs also provide potential nonproliferation benefits to the United States and the wider international community. Some SMRs will be designed to operate for decades without refueling. These SMRs would be fabricated and fueled in a factory, sealed and transported to sites for power generation or process heat, and then returned to the factory for defueling at the end of the life cycle. This approach could help to minimize the transportation and handling of nuclear material. There is both a domestic and international market for SMRs and U.S. industry is well positioned to compete for these markets.

[www.nuclear.energy.gov](http://www.nuclear.energy.gov)  
February 2010

US DOE, 2010

# WHAT IS AN SMR?

## REACTOR GENERATIONS



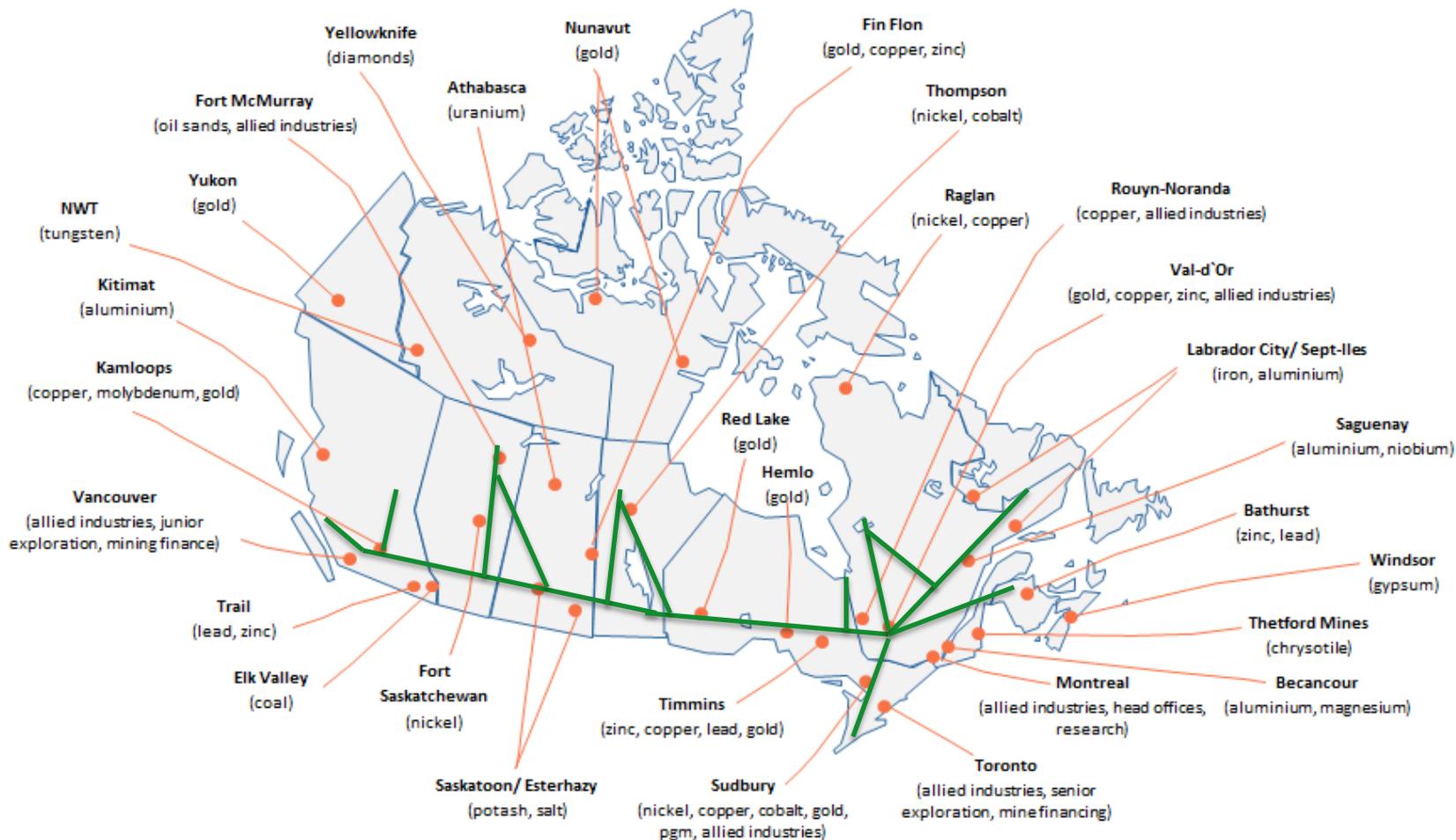
# WHY SMR'S?

# WHY SMR?

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- Small grids / off-grid locations
  - Developing countries
  - Islands
  - Arctic/desolate regions
- Low rates of increase in demand
- Reduction of investment risk
  - Small size
  - Phased investment (per unit)
- Combined heat and power (cogeneration)
  - Linked to industry end-user

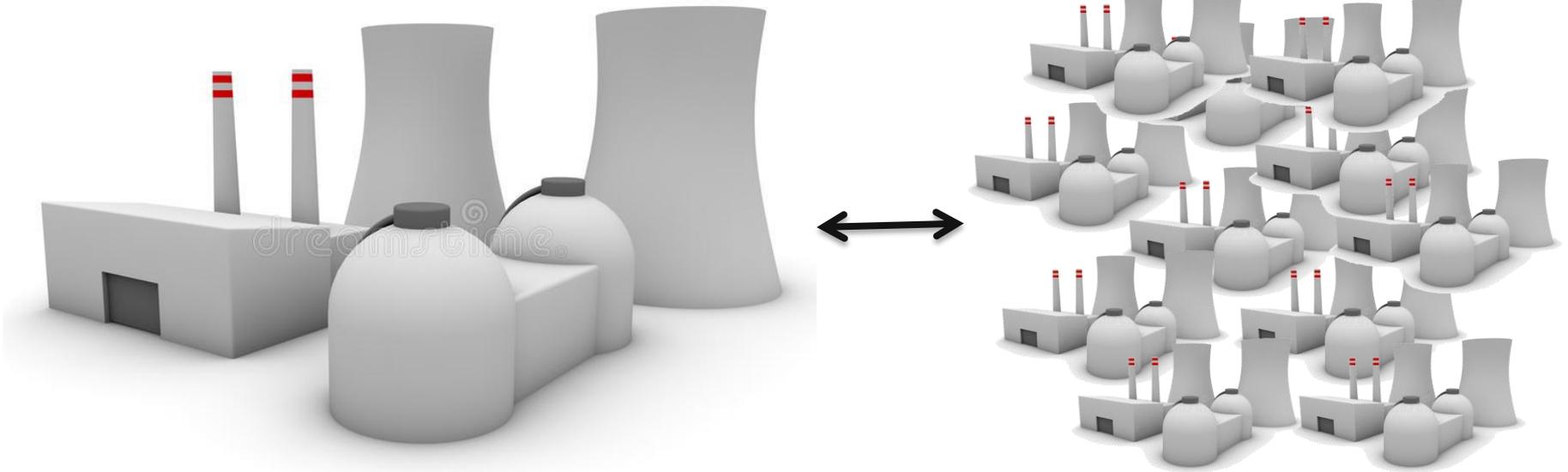
# WHY SMR? MINING VS POWER GRID (CANADA)



# WHY SMR?

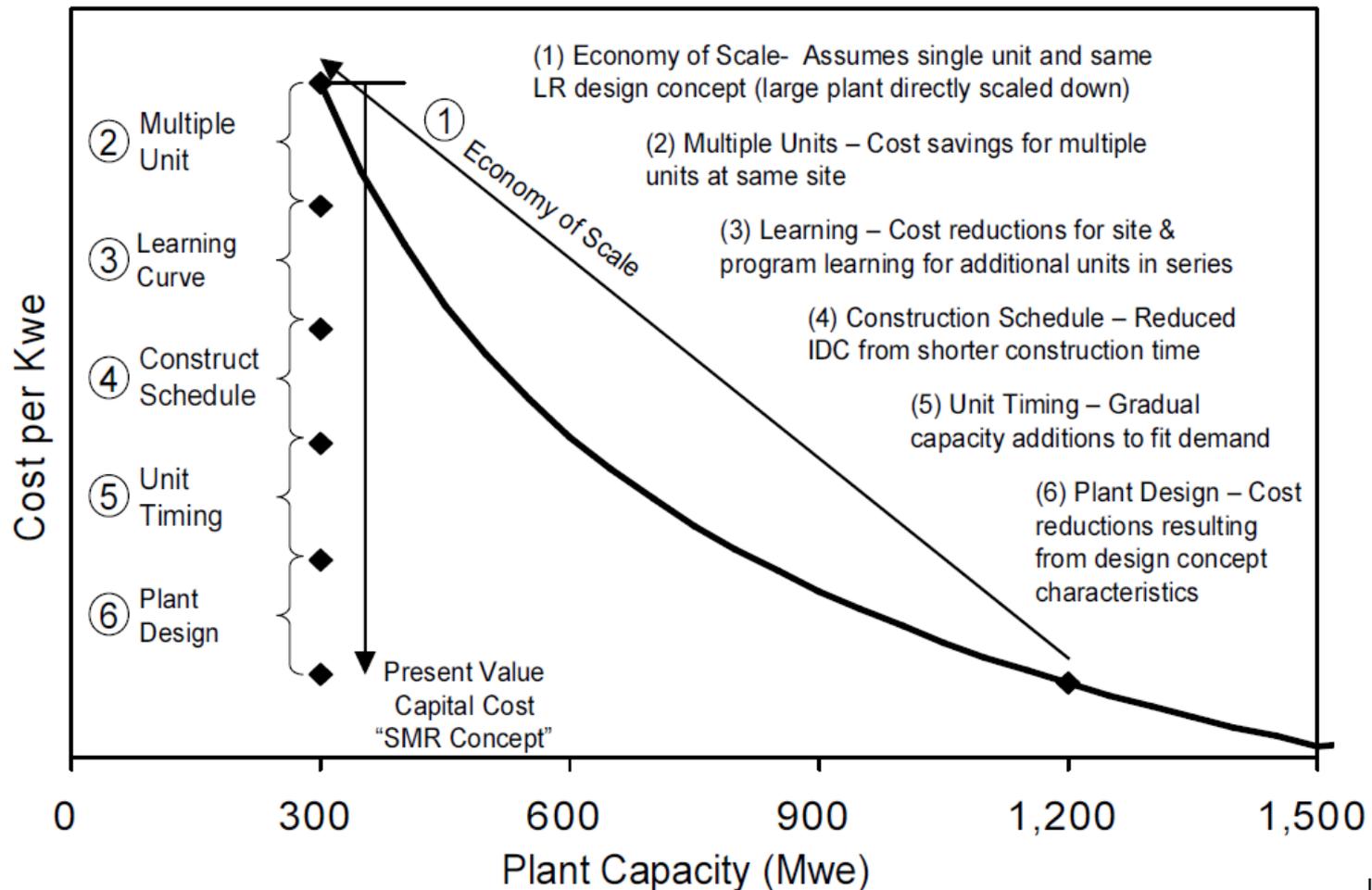
## ECONOMICS OF NUMBERS VS SCALE

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# WHY SMR?

## ECONOMICS OF NUMBERS VS SCALE

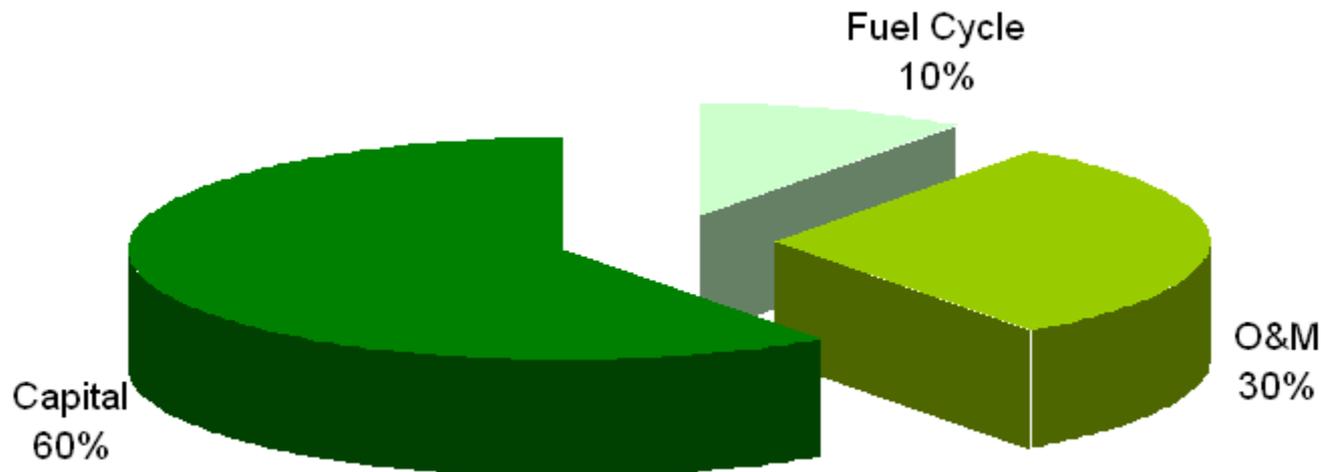


# WHY SMR?

## COST DISTRIBUTION IN NUCLEAR

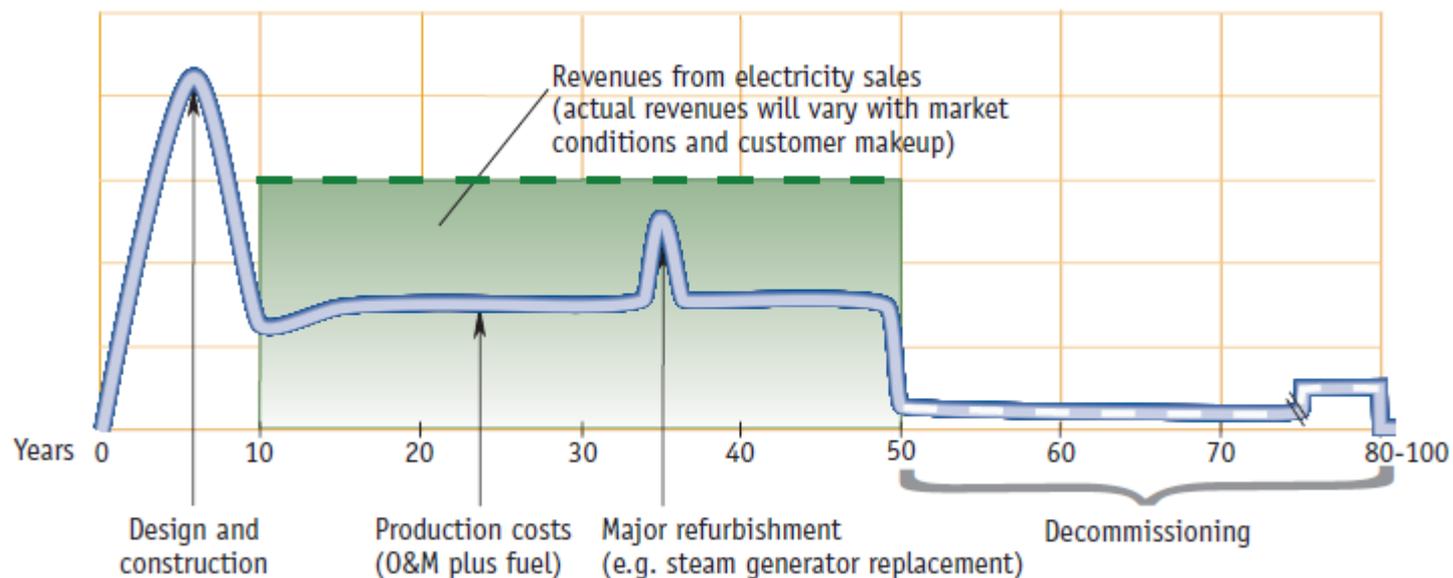
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- Nuclear: Capital costs by far most important
  - Reduction in capital cost = reduction in electricity generation cost



# WHY SMR?

## CASH FLOW

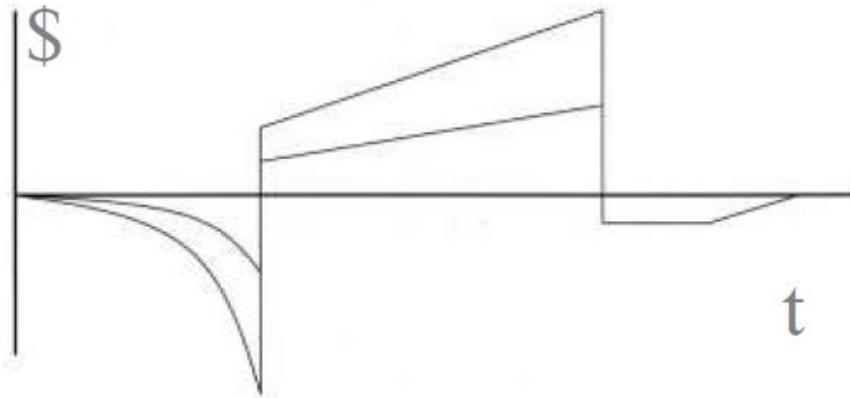


# WHY SMR?

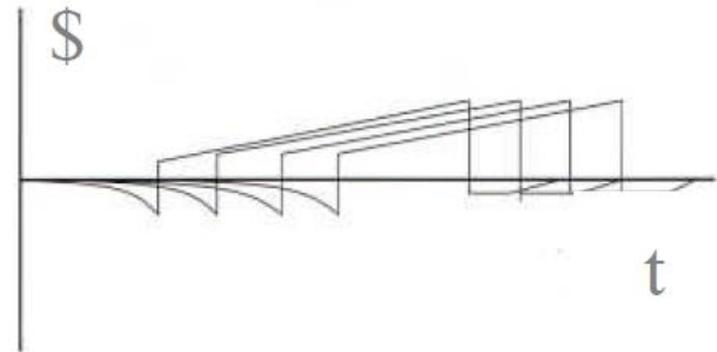
## INVESTMENT RISK REDUCTION

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Cash flow large reactor



Cash flow multiple SMR's



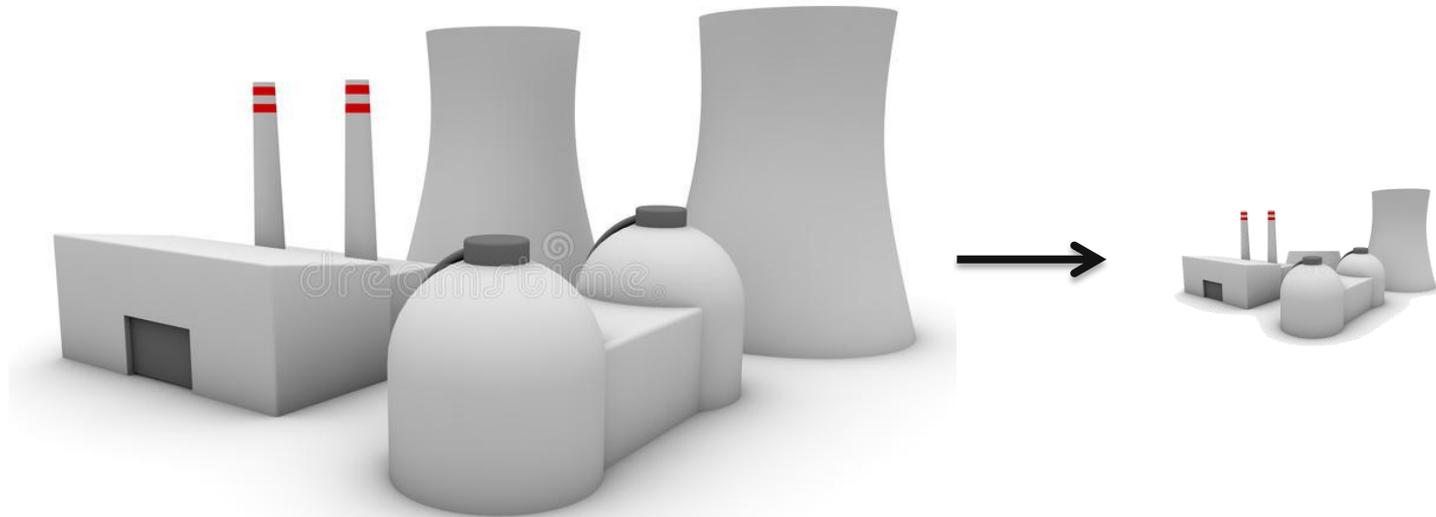
# WHY SMR?

## DESIGN SIMPLIFICATION

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1000 MWe / 3000 MWth

200 MWe / 600 MWth



- Thermal power is an important factor in design of safety systems
- Decay heat 10% ↓ of nominal thermal power

# WHY SMR?

## BENEFITS & DRAWBACKS



### Technology Issues

- Shorter construction period (modularization)
- Potential for enhanced safety and reliability
- Design simplicity
- Suitability for non-electric application (desalination, etc.).
- Replacement for aging fossil plants, reducing GHG emissions

### Non-Techno Issues

- Fitness for smaller electricity grids
- Options to match demand growth by incremental capacity increase
- Site flexibility
- Reduced emergency planning zone
- Lower upfront capital cost (better affordability)
- Easier financing scheme



### Technology Issues

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

### Non-Techno Issues

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

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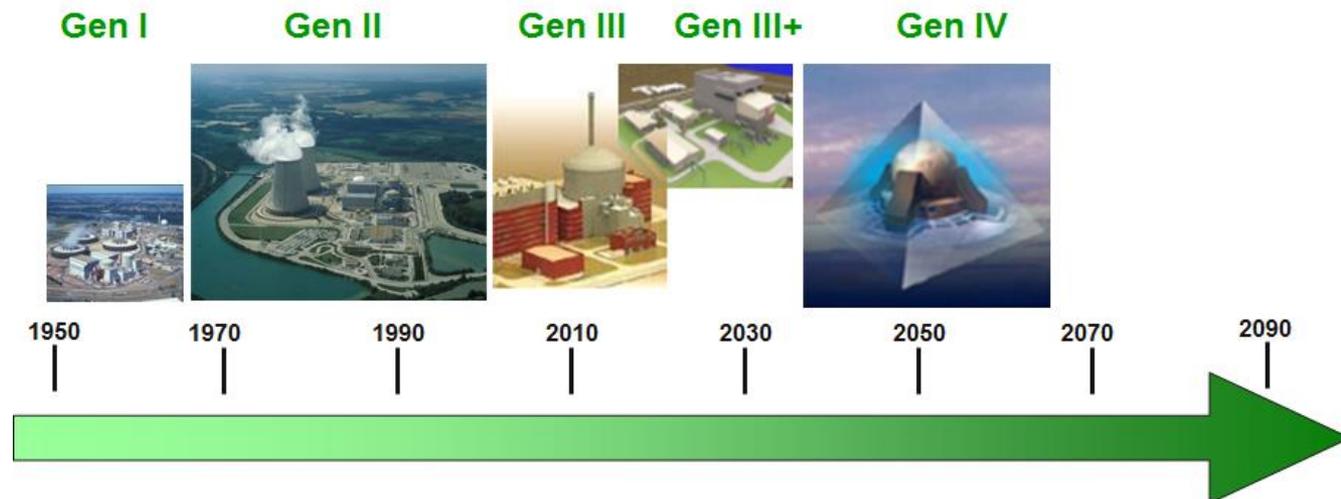
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**WHICH SMR'S**

# WHICH SMR'S?

## DIFFERENT TYPES

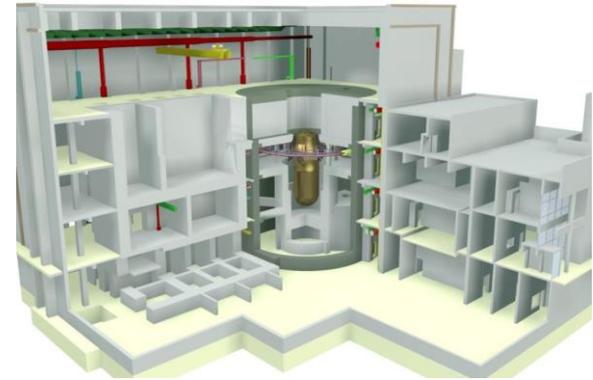
- SMR's are technology independent:
  - Light Water Reactor
    - Mostly PWR, often integral
  - High Temperature Reactor
    - Very suitable for cogeneration
  - Molten Salt Reactor
    - Many start-ups
  - Sodium Fast Reactor
    - Scaled down versions of large SFR
  - Lead Fast Reactor
    - Some dedicated designs
  - Gas Fast Reactor
    - One special design



# WHICH SMR'S?

## LWR: CAREM

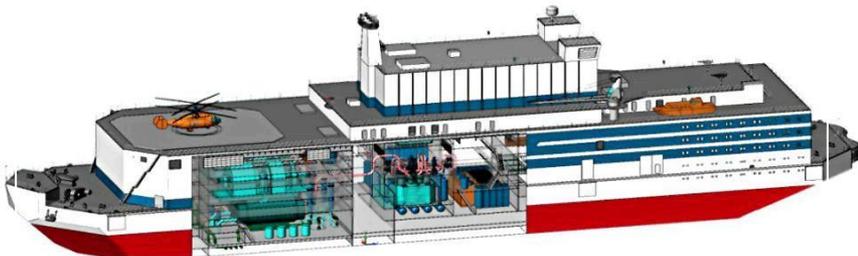
- **Central Argentina de Elementos Modulares**
- Vendor: CNEA / INVAP
- 27 MWe
- Integral primary system (steam generators in vessel)
- Electricity & desalination
- Construction of prototype in Formosa started in 2014. Operation start planned in 2019.
- Prototype to be followed by larger versions (100-200 MWe)
- Under consideration for desalination in Saudi Arabia



# WHICH SMR'S?

## LWR: KLT-40S

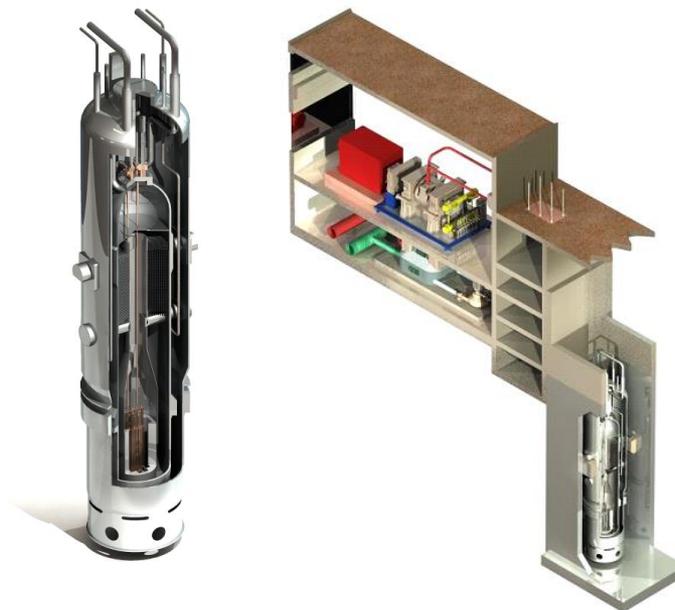
- Vendor: OKBM
- 35-70 Mwe
- Refuelling 3-4 yr
- Floating nuclear plant
- Twin reactor plant proven for ice-breaker propulsion
- First plant 'Akademik Lomonosov' under construction for Pevek in the Chukota region (electricity & heat supply for naval base) as replacement of 35 MWe thermal plant by 2020. Start planned 2019.



# WHICH SMR'S?

## LWR: NUSCALE

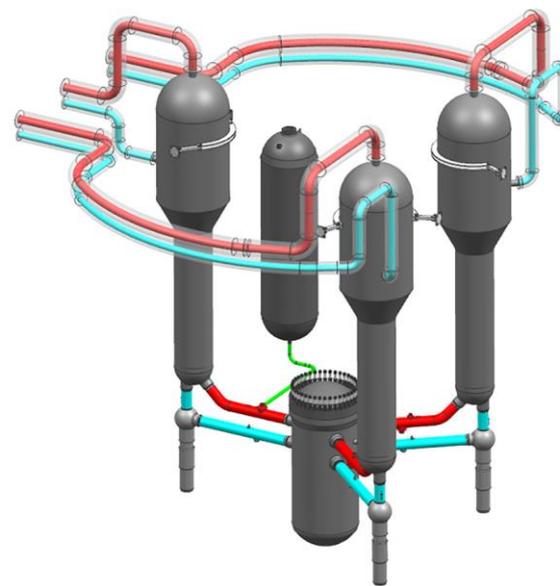
- Vendor: NuScale Power
- 160 MWth / 50 MWe
- Integral primary system
- <12 reactors in shared pool
- Refuelling 2 yr
- Natural circulation
- Electrically heated prototype



# WHICH SMR'S?

## LWR: UK SMR

- **UK SMR**
  - Vendor: Rolls-Royce
  - 400-450 Mwe
  - 3-loop PWR
  - Optimise LCOE vs capital costs
  - Operation start 2030

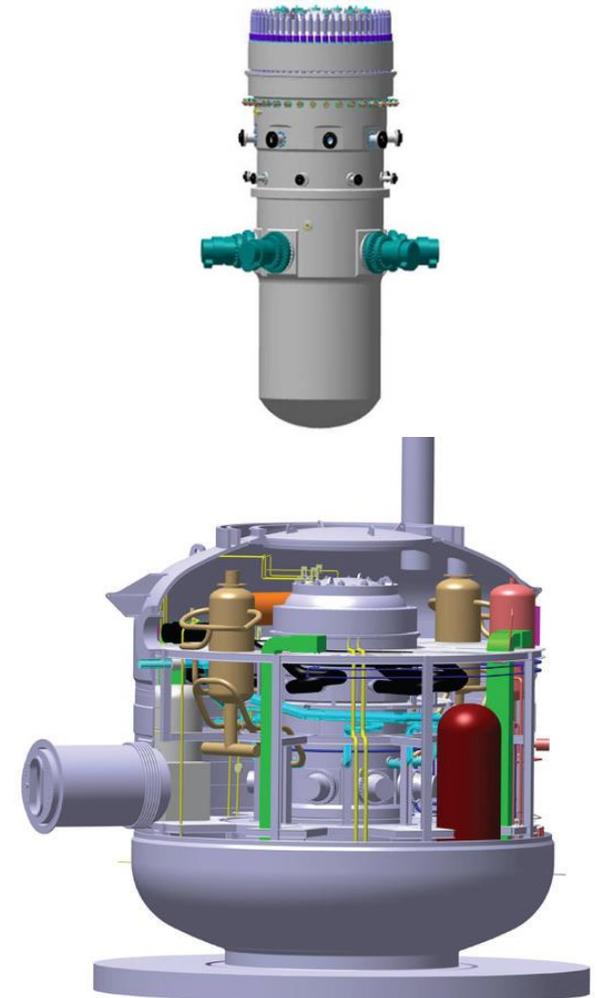
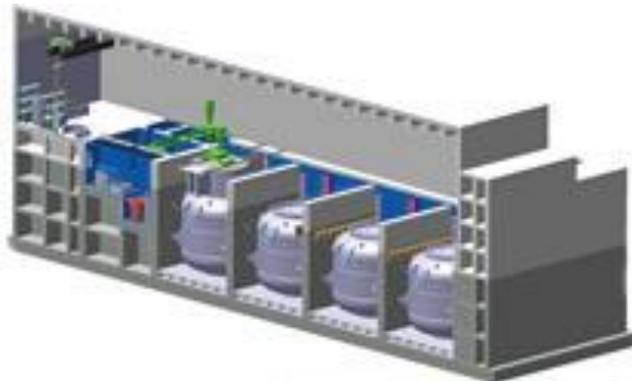


# WHICH SMR'S?

## LWR: FRANCE

- **French SMR**

- Vendor: Technicatom / Naval Group / CEA / EDF
- 170 MWe
- Integral PWR
- Metallic containment shell submerged in water pool
- 2-4 units per site
- Grace time: 1 week

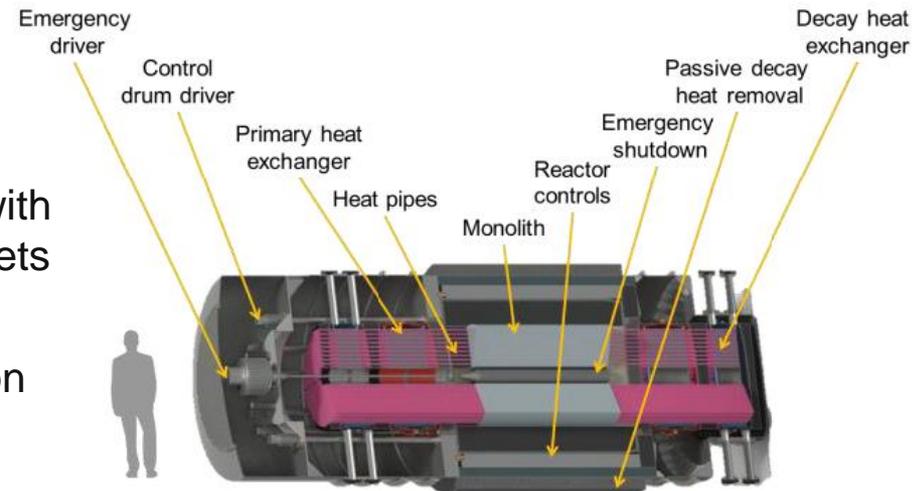


# WHICH SMR'S?

## LWR: EVINCI

- **eVinci microreactor**

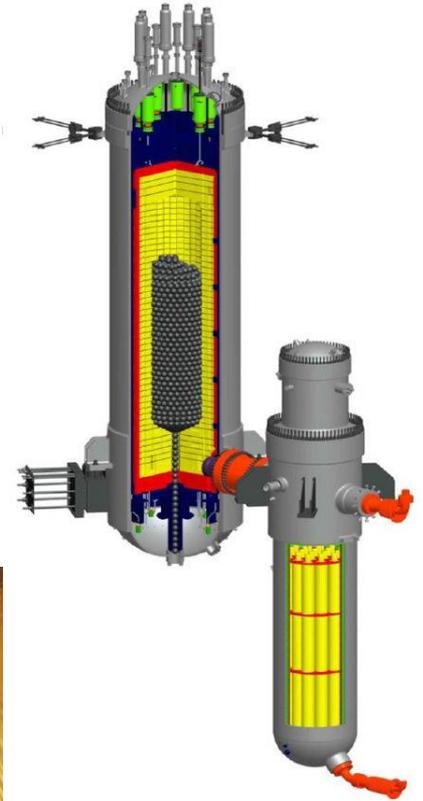
- Vendor: Westinghouse
- 0.2 - 25 MWe electricity and heat
- Unique core design, steel monolith with channels for heat pipes and fuel pellets
- Refuelling 10 yr
- Qualification for commercial operation planned by 2024
- Market: Off-grid customers



# WHICH SMR'S?

## HTR: HTR-PM

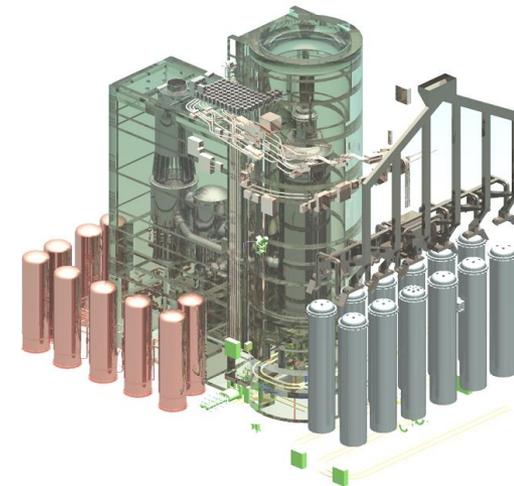
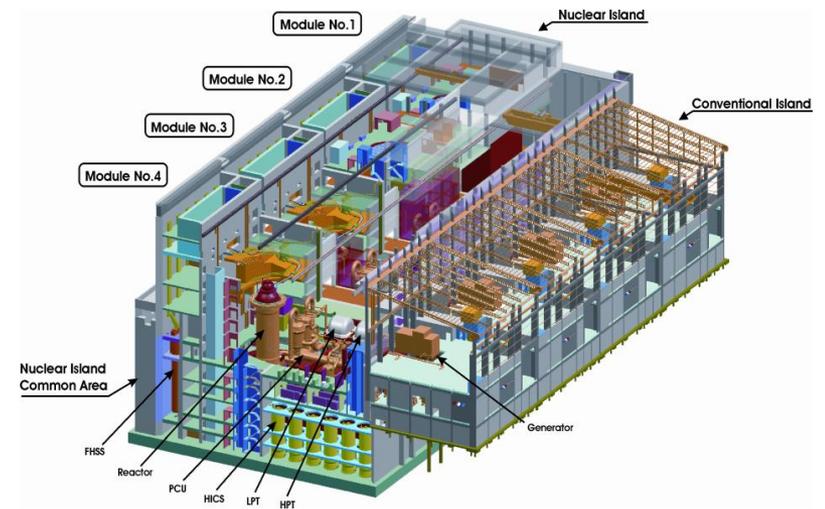
- **HTR-Pebble Modular**
  - Vendor: CNECC, China
  - 500 MWth / 200 MWe
  - Based on German HTR-Modul Design
  - Steam cycle (indirect)
  - ~500 000 Pebbles
  - Modular
  - Start operation planned 2018



# WHICH SMR'S?

## HTR: PBMR

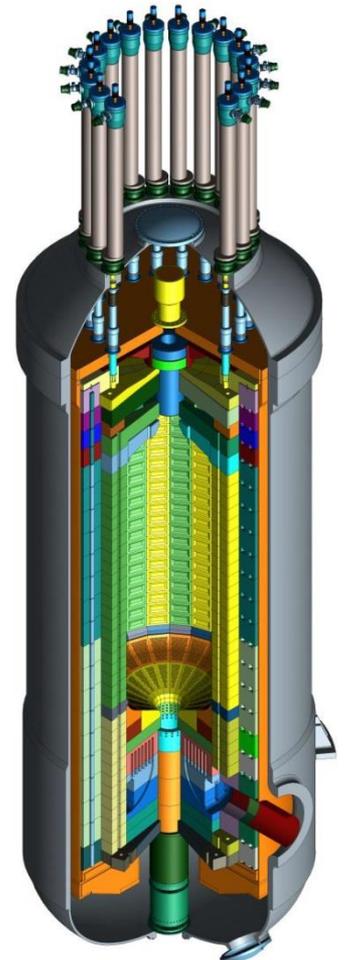
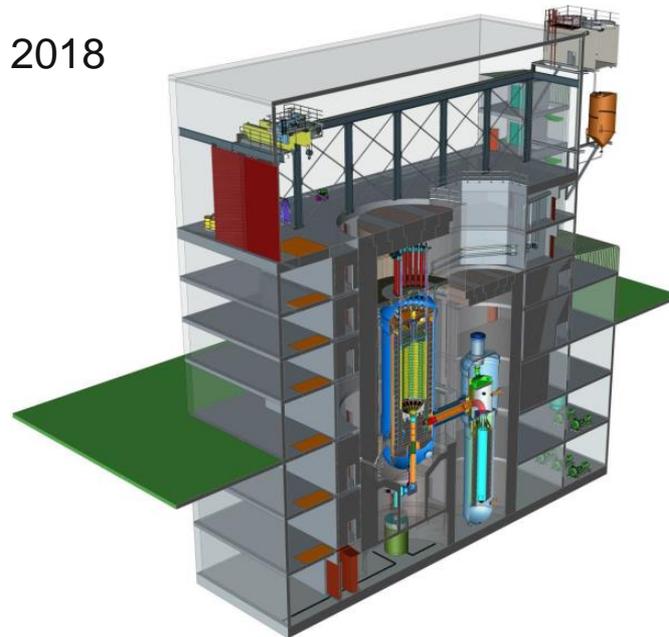
- **Pebble Bed Modular Reactor**
  - Vendor: PBMR, South-Africa
  - 165 MWe
  - Pebbles
  - Based on German HTR-Modul Design
  - Brayton cycle (direct)
  - Project abandoned in 2010



# WHICH SMR'S?

## HTR: HTMR

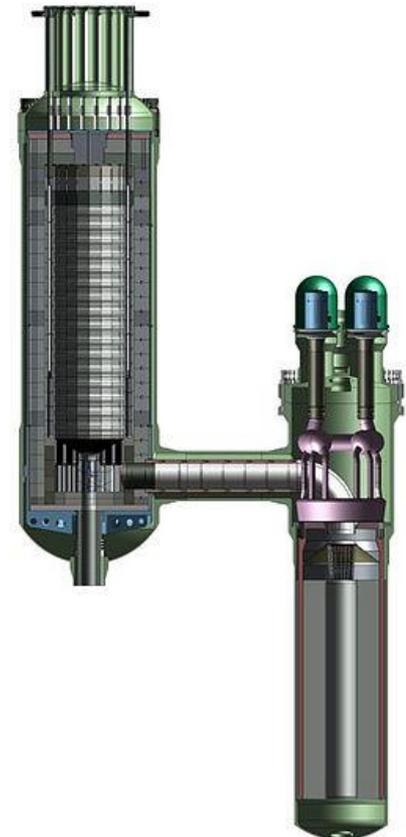
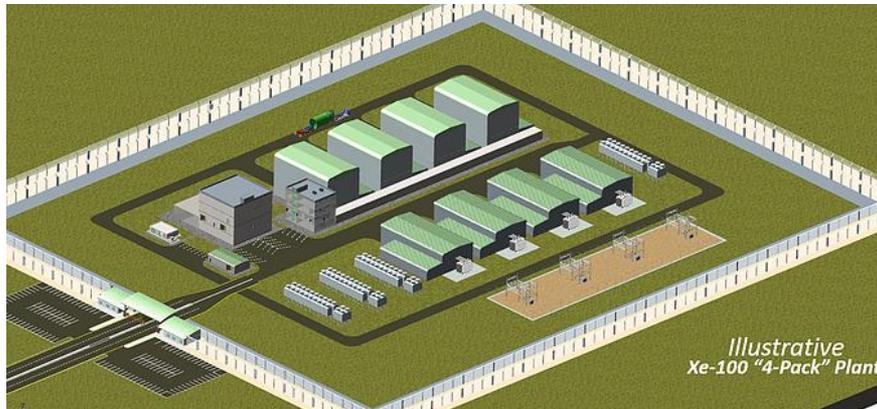
- **H**igh **T**emperature **M**odular **R**eactor
  - HTMR Ltd
  - 35 MWe / 100 MWth
  - 750°C
  - Steam cycle
  - Flexible fuel (U, Pu, Th)
  - Conceptual design planned for 2018



# WHICH SMR'S?

## HTR: XE-100

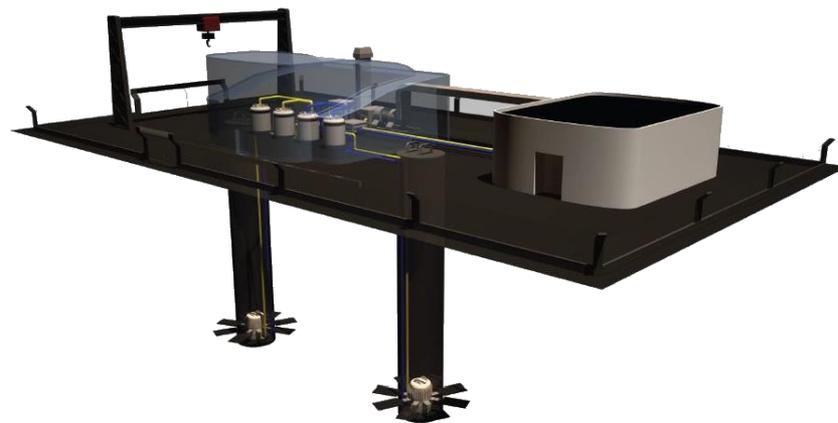
- **X-energy 100**
  - X-Energy, USA
  - 200 MWth / 76 MWe
  - ~220 000 Pebbles
  - Steam production at 540°C
  - Underground building
  - Conceptual design started in 2017
  - MoU on potential in Jordan



# WHICH SMR'S?

## HTR: STARCORE

- **StarCore**
  - StarCore Power LLC
  - 36 MWth / 20 MWe
  - 5 yr refuelling
  - Underground building
  - Fully automated



# WHICH SMR'S?

## HTR: U-BATTERY

- **U-Battery**
  - U-Battery
  - 10 MWth / <4 MWe
  - 750°C process heat
  - Industrial power units
  - Off-grid locations
  - Back-up for large plant emergency diesels
  - Demonstration by 2026



# WHICH SMR'S?

## MSR: IMSR

- **Integral Molten Salt Reactor**
  - Terrestrial Energy
  - 400 MWth / 192 MWe
  - Sealed and replaceable core
  - Refueling 7 yr
  - Successfully concluded first phase of Canadian regulatory program

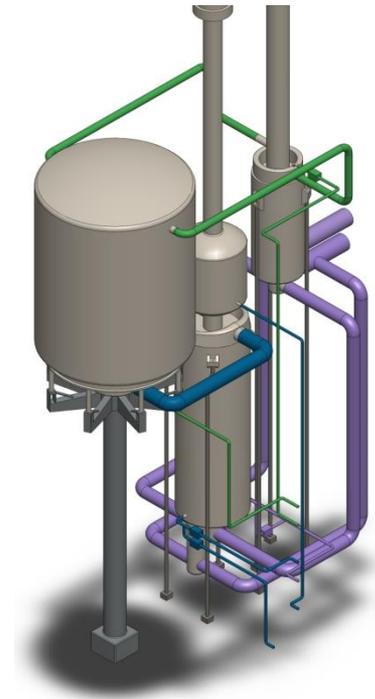
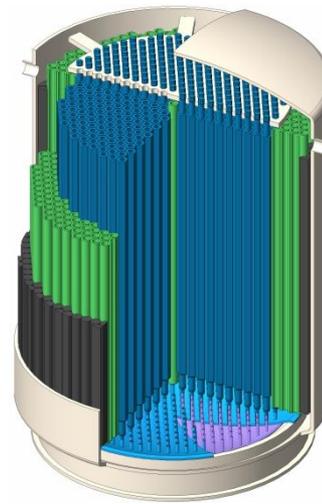
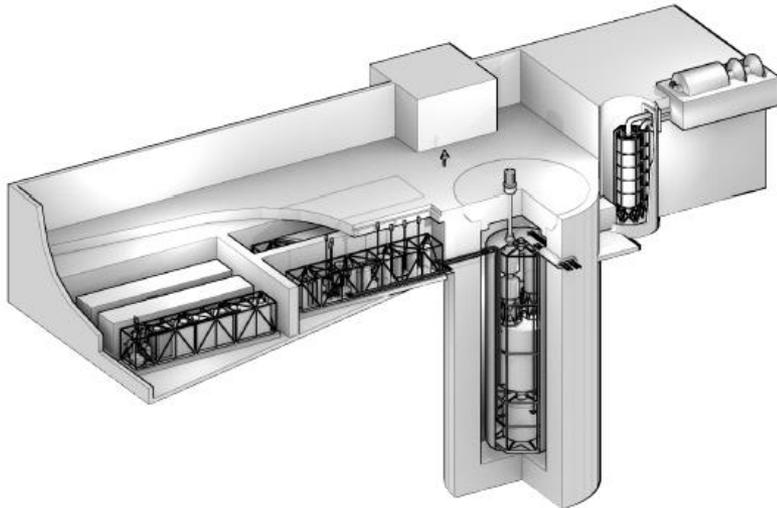


# WHICH SMR'S?

## MSR: LFTR

- **Liquid-Fluoride Thorium Reactor**

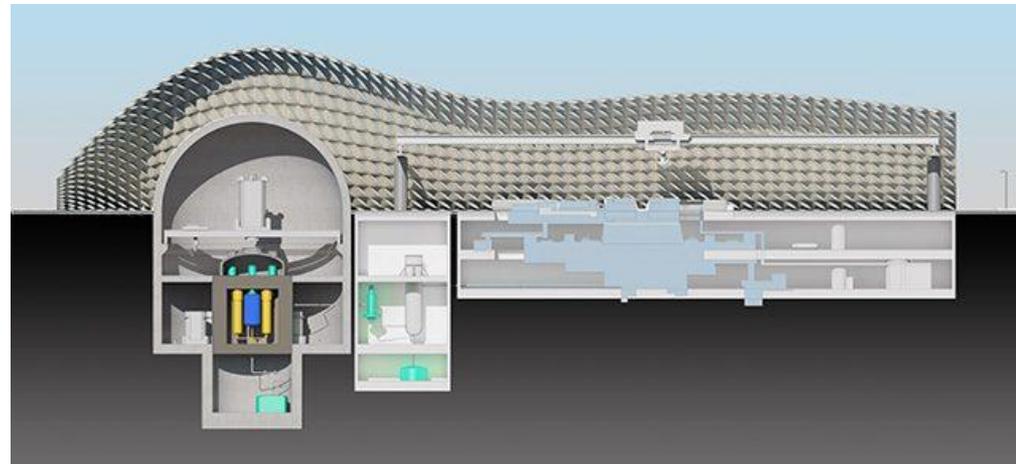
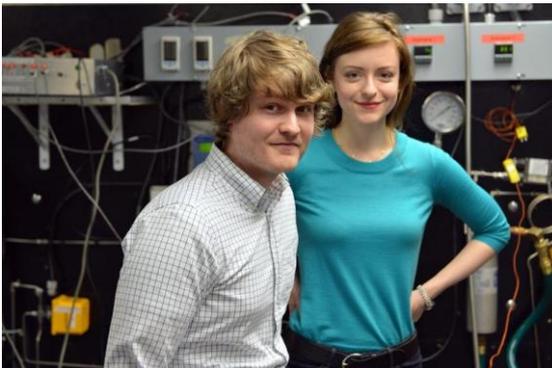
- Design: Flibe Energy
- FLiBe salts
- Graphite Moderator
- 600 MWth / 250 MWe
- Fuel: Th
- Breeder



# WHICH SMR'S?

## MSR: TAP

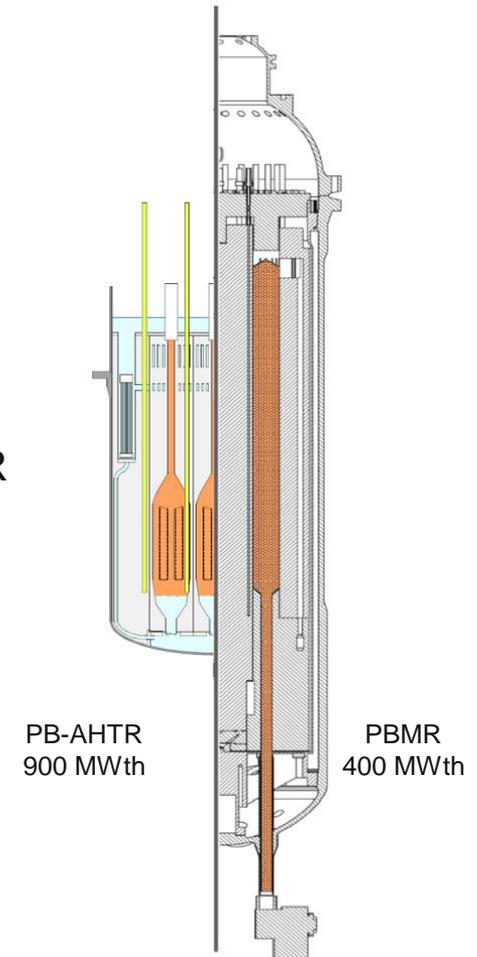
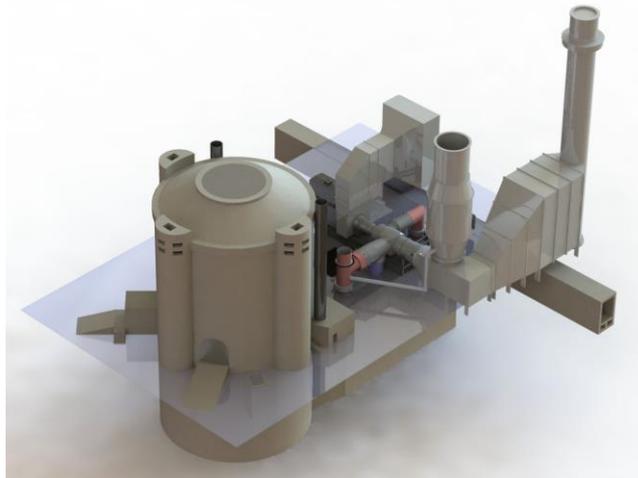
- **TransAtomic Power**
  - Design: Transatomic Power
  - Li-F based salt
  - Moderator: Zirconium Hydride
  - 1250 MWth / 520 MWe
  - Core outlet: 650°C
  - Efficiency: 44%
  - Fuel: Uranium
  - 'Walkaway safe'



# WHICH SMR'S?

## MSR: MK1-PB FHR

- **Mark-1 Pebble Bed Fluoride salt-cooled High temperature Reactor**
  - Designs: ORNL / MIT / University of California
  - 236 MWth / 100 MWe PB-FHR
  - Molten salt coolant
  - Core outlet: 700°C
  - Fuel similar to HTR
  - Increased heat capacity compared to gas cooled HTR
  - Smaller more economic system compared to gas cooled HTR



# WHICH SMR'S?

## LFR: SEALER



- **Swedish Advanced Lead Reactor**

- Design: LeadCold
- Lead coolant
- 8-20 MWth / 3-7 MWe

### Potential Demo Site

- Cambridge Bay (Canada)

### Purpose

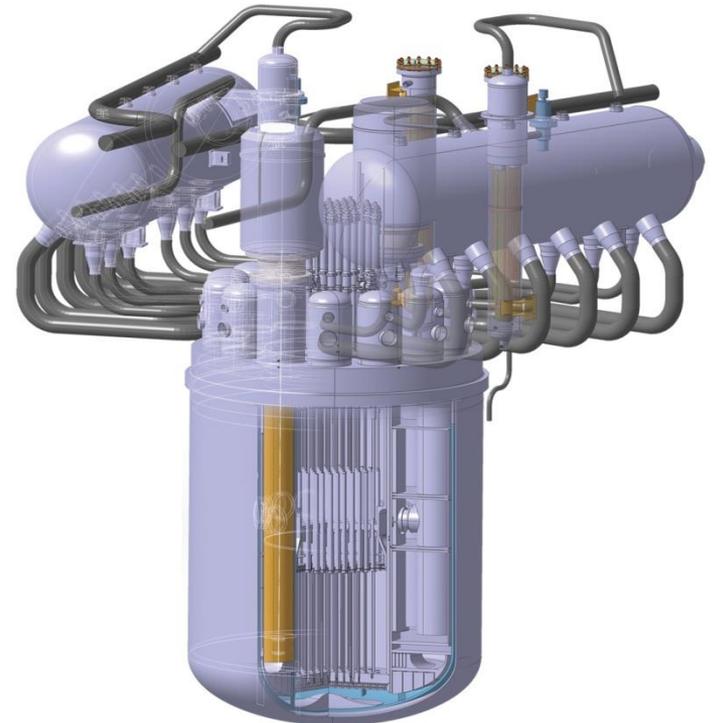
- Electricity production for isolated (arctic) communities or mines



# WHICH SMR'S?

## LFR: SVBR

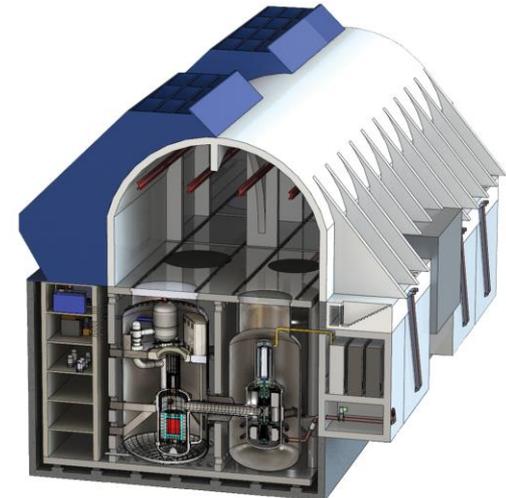
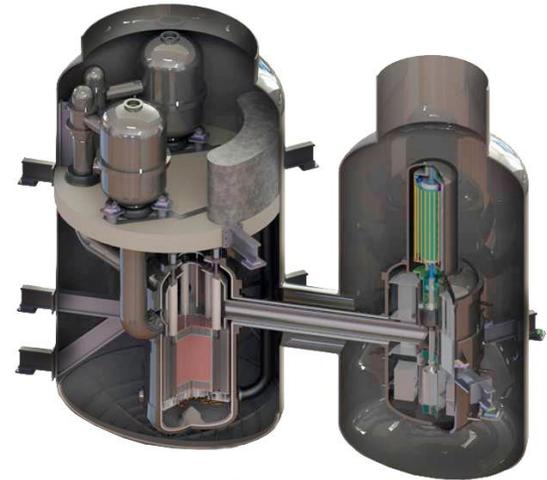
- **Svintsovo-Vismutovyi Bystryi Reaktor**
  - Design: AKME
  - 280 MWth / 100 MWe
  - Core temperature 345 – 495°C
  - Lead-bismuth coolant
  - Integral primary system
  - Forced cooling
  - Refuelling 8 yr
  - License obtained in 2015 for Dimitrovgrad.  
Need for private investors.
  - Electricity, district heat & desalination



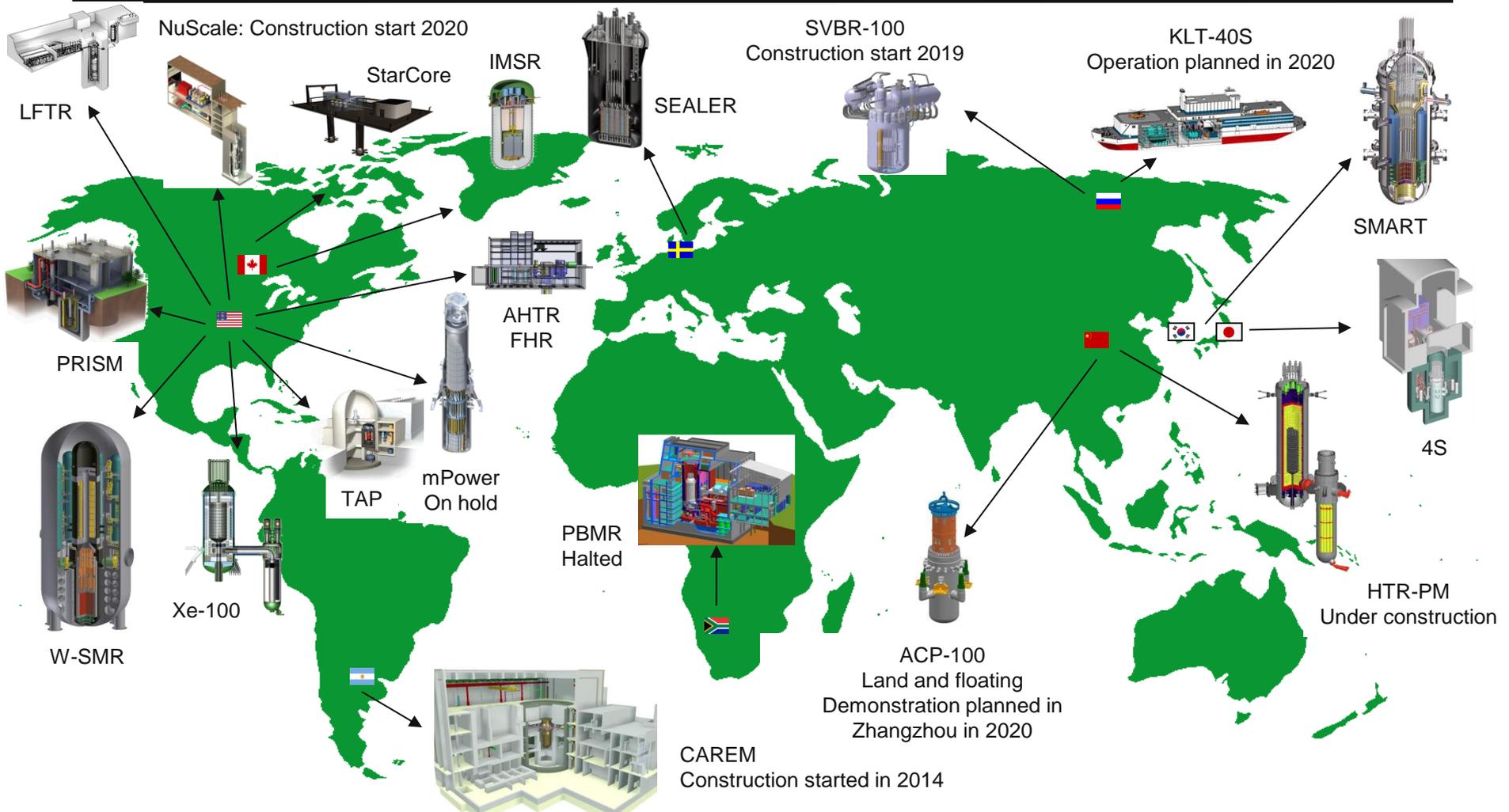
# WHICH SMR'S?

## GFR: EM<sup>2</sup>

- **Energy Multiplier Module**
  - Design: General Atomics
  - 500 MWth / 240 MWe
  - Core temperature up to 850°C
  - Refuelling 30 yr

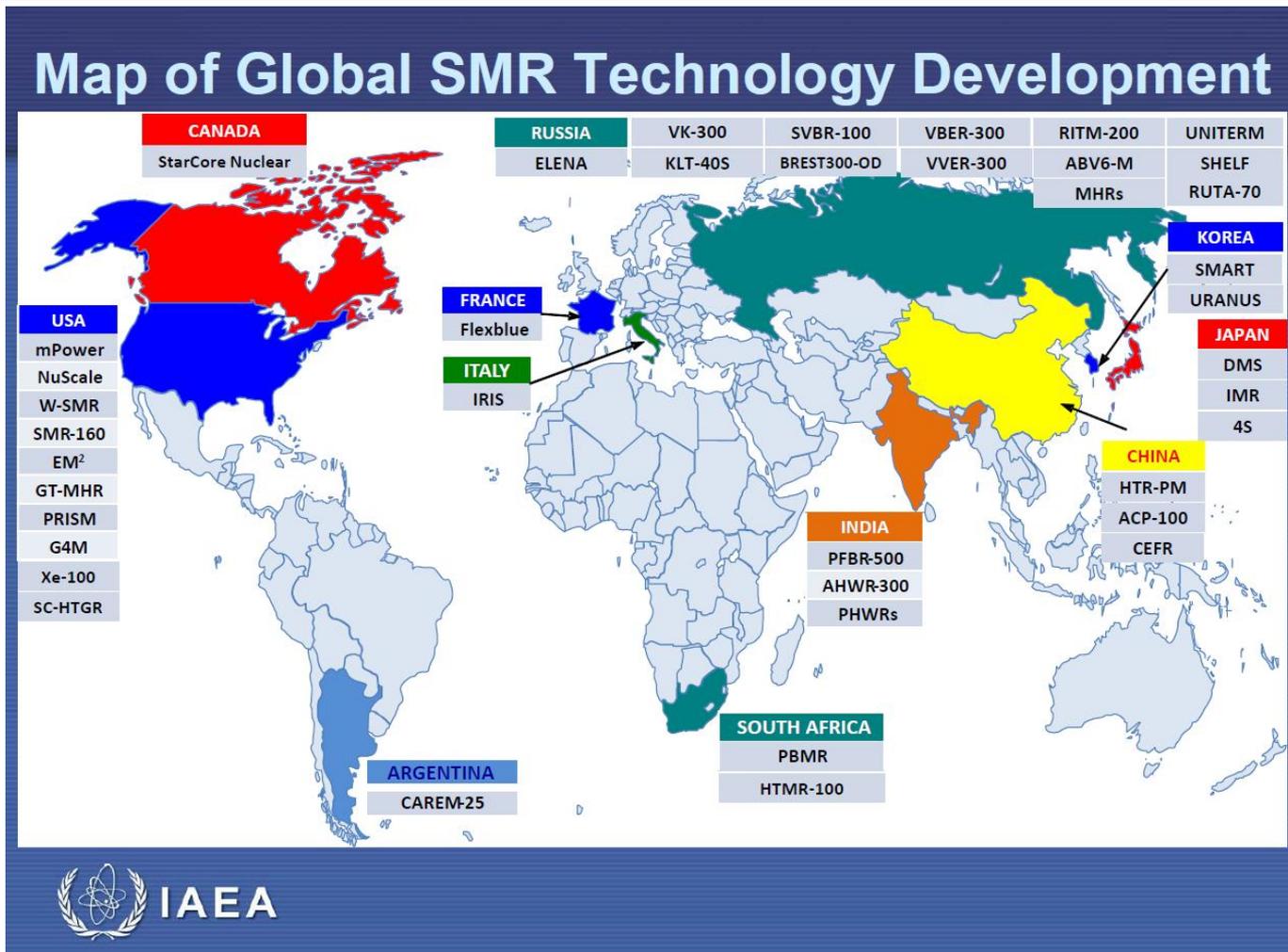


# WHICH SMR'S? INTERNATIONAL PLAYING FIELD



# WHICH SMR'S?

## INTERNATIONAL PLAYING FIELD



# DUTCH SMR!

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- **GKN**  
'**G**emeenschappelijke **K**erncentrale **N**ederland'
  - 1968 - 1997
  - Dodewaard
  - 55 MWe
  - Gen I BWR



# QUESTIONS?

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