Some Nuclear History and Small Modular Reactors

AFRY, Varberg

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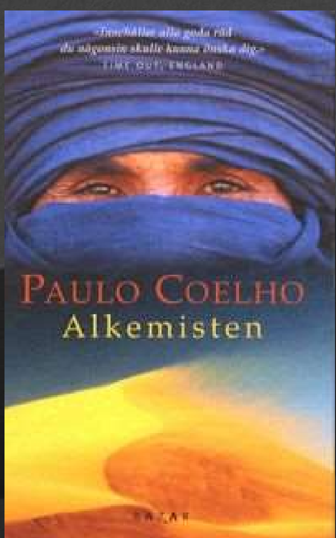

Traditional nuclear site

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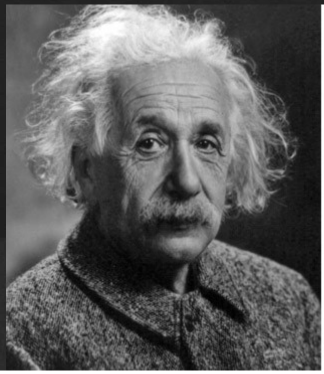
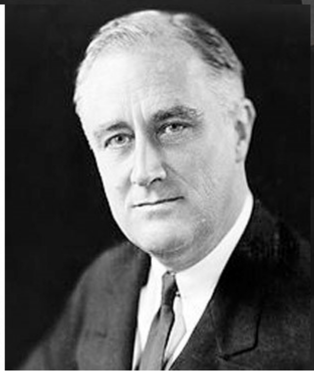
Nuclear power gains momentum

- In 1938, the first nuclear fission was carried out by Otto Hahn's team at the University of Berlin.
  - Uranium was bombarded with neutrons.
- In 1939, Albert Einstein wrote a letter to United States President Roosevelt warning him that the newly discovered nuclear fission could be used to create an explosive release of energy (research was underway in several countries). Einstein also advised the establishment of a US nuclear research program.
- In response to Einstein's letter, the United States started the Manhattan Project in 1942.





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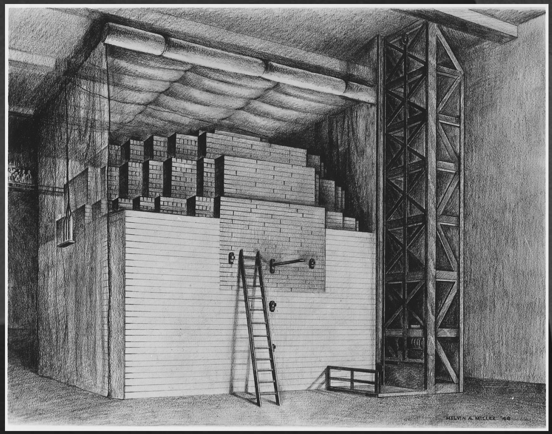
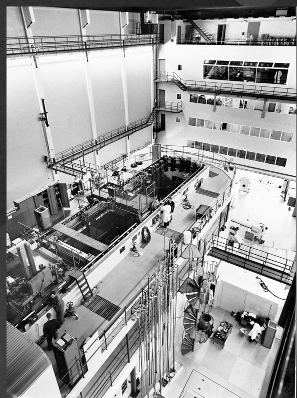
The reactor and the atomic bomb

- Within the Manhattan Project, in 1942 Enrico Fermi's team at the University of Chicago carried out the first controlled and self-sustaining chain reaction -> the world's first reactor

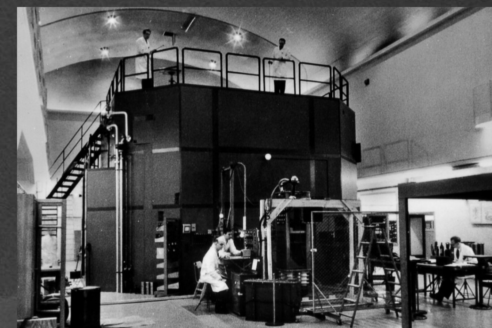


- In July 1945, the first atomic bomb test was carried out in the New Mexico desert in the United States.
- In August 1945, the United States dropped atomic bombs on Hiroshima and Nagasaki in Japan.

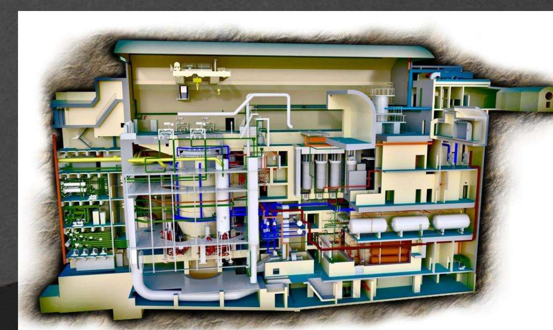
The first Swedish reactors



Sweden's first reactor, named R1, went critical (1 MW) in Stockholm in 1954.

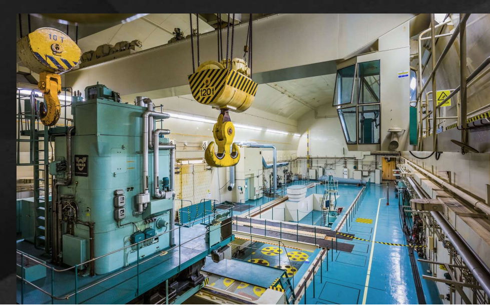


R2 went critical (50 MW) in Studsvik outside Nyköping in 1960.



Ågesta (Stockholm) went critical in 1963. 55 MW district heating and 10 MW electricity.

Marviken (Norrköping) was commissioned in 1969 but was never started (100 MW electricity was planned).



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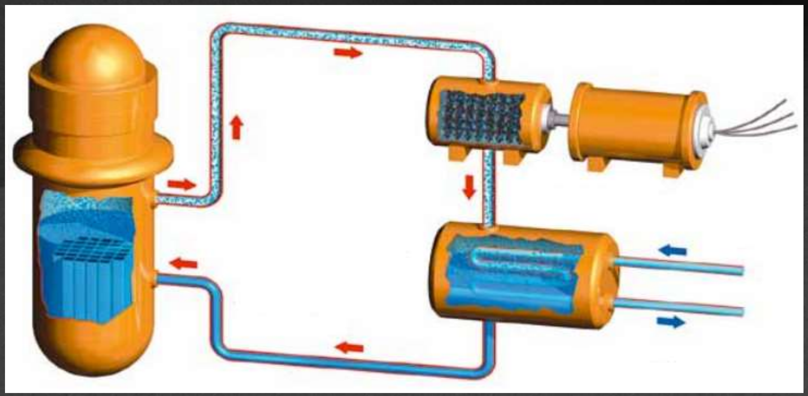
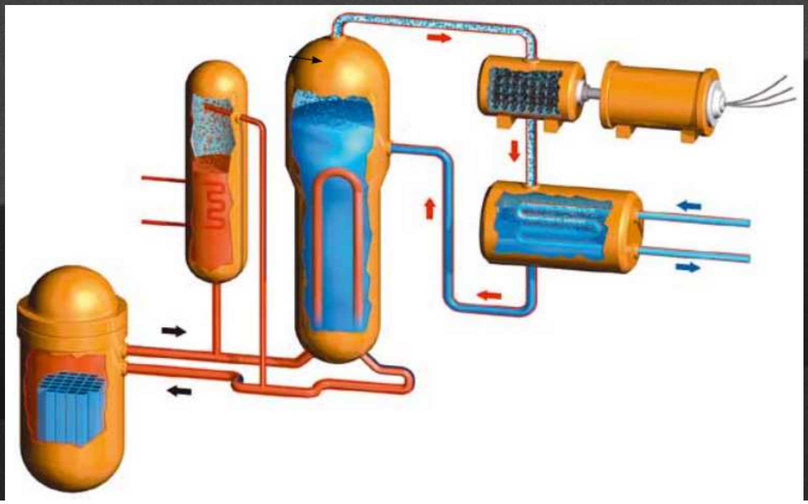
Traditional reactor types



Boiling water reactor (BWR)



Pressurized water reactor (PWR)

Nuclear sites of Sweden

Electrical output (Sweden)

Reactor	Type	Commercial production	Electric power
Oskarshamn 1 (O1)	BWR	1972	Shut down 2017
Ringhals 1 (R1)	BWR	1976	Shut down 2020
Ringhals 2 (R2)	PWR	1975	Shut down 2019
Oskarshamn 2 (O2)	BWR	1975	Shut down 2013
Barsebäck 1 (B1)	BWR	1975	Shut down 1999
Barsebäck 2 (B2)	BWR	1977	Shut down 2005
Forsmark 1 (F1)	BWR	1980	1014 MW
Forsmark 2 (F2)	BWR	1981	1121 MW
Ringhals 3 (R3)	PWR	1981	1074 MW
Ringhals 4 (R4)	PWR	1983	1130 MW
Forsmark 3 (F3)	BWR	1985	1172 MW
Oskarshamn 3 (O3)	BWR	1985	1400 MW

These are not original numbers. Several power uprates have taken place during the time of operation.

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New build cost

After significant delays and cost increases:

- Olkiluoto 3 (PWR, 1600 MWe) online 2023: 12 billion USD (120 billion SEK)
- Flamanville 3 (PWR, 1650 MWe) online 2024: 14 billion USD (140 billion SEK)
- Hinkley Point C (PWR, 2*1630 MWe), under construction: 30 billion USD per unit (300 billion SEK per unit)

Sanmen, China:

- Westinghouse AP1000 (PWR, 2*1157 Mwe): < 5 billion USD (50 billion SEK) per unit (in today’s value)
- Contract agreed 2007, site work started 2008 and plant construction started 2009.
- Both units online 2018 as the first AP1000 reactors achieving criticality.

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Costs of nuclear power plants during lifetime

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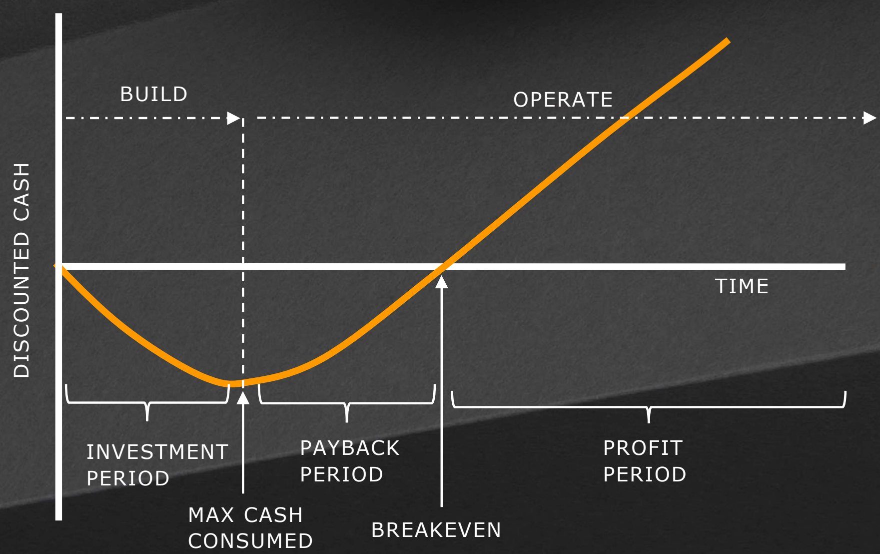
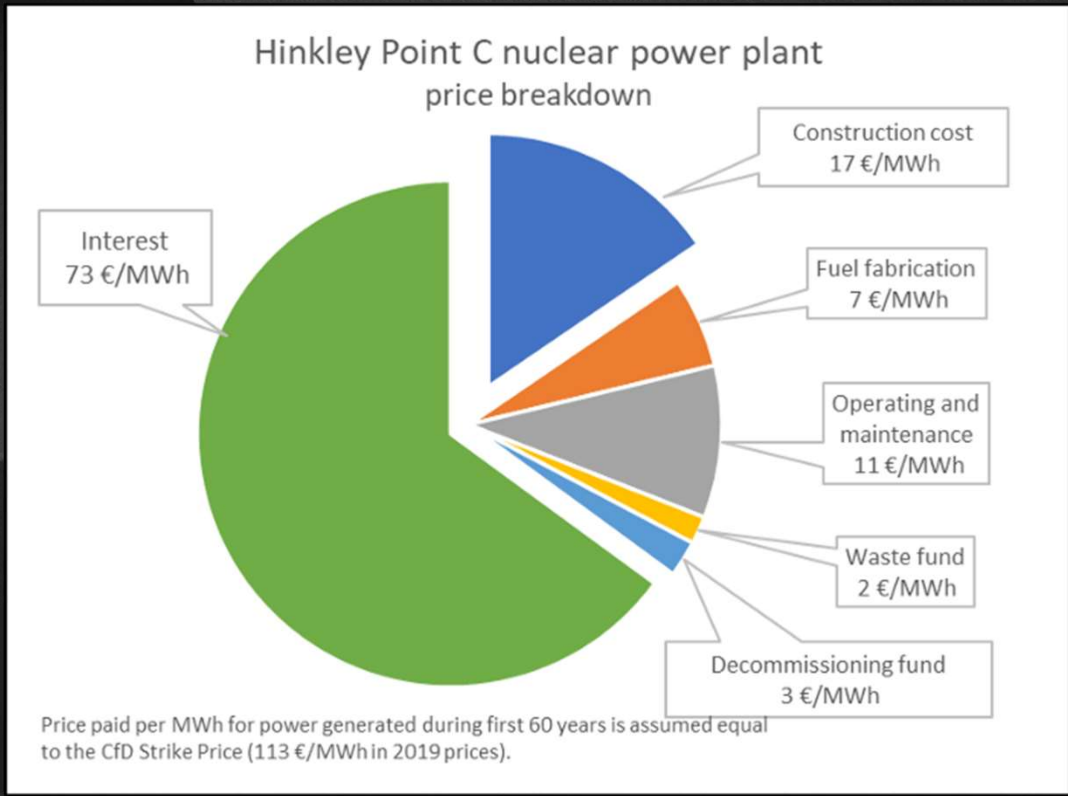
Capital cost dominates





Why choose SMR

What is an SMR and why choose this over a traditional nuclear reactor?

Defining SMR

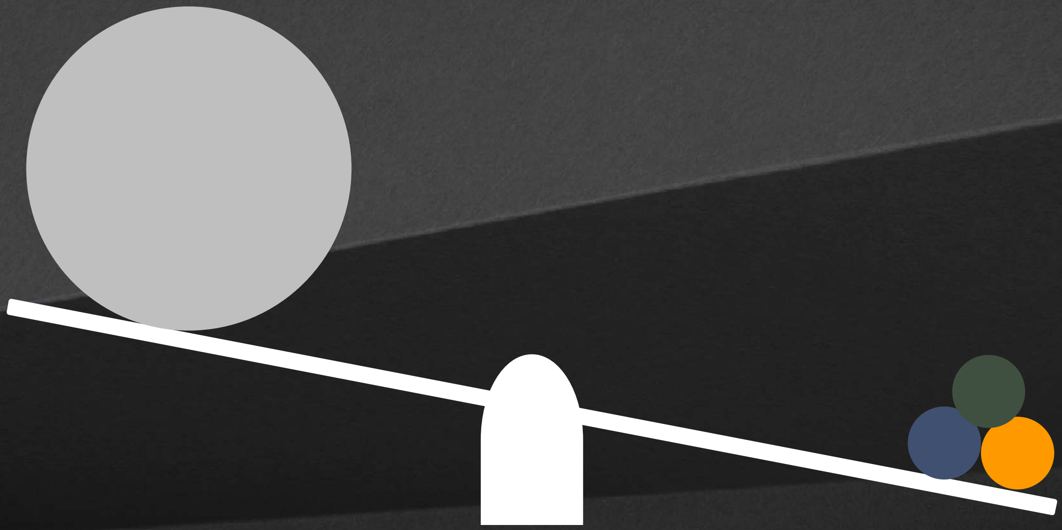
- Small
- Modular
- Reactor

Small modular reactors (SMR) is not limited to a certain technical design.

There are a number of SMR concepts.

"Small"

The International Atomic Energy Agency (IAEA) defines "small" as under 300 MW electric power output per unit.



1st

- Lower upfront capital
- Shorter construction lead-times

2nd

- Use of standard components
- Facilitates series production

3rd

- Flexible location
- Improved logistics

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"Small"

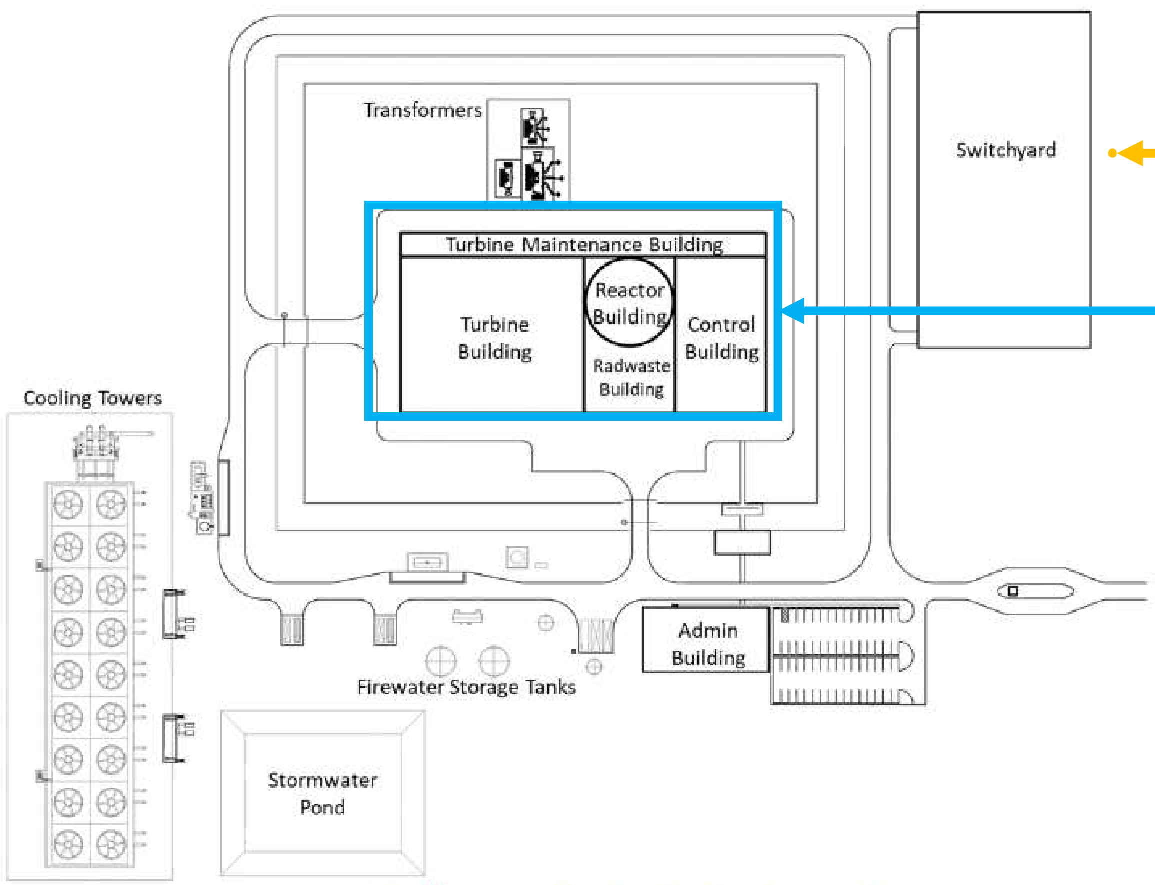

Figure 9-1: BWRX-300 Plant Layout, Site Plot Plan

The reference site for BWRX-300 is entirely confined in a 260 m by 332 m footprint, which includes the plant buildings, switchyard, cooling tower (if needed), site office, parking lot, warehouse, and other supporting facilities, see Figure 9-1. Figure 9-2 is an 3D rendering of the reference site. The reference site uses mechanical draft cooling towers, but other options are available including hybrid or dry cooling towers or once through cooling to a lake, river or ocean.

The power block is comprised of to the Reactor Building, Turbine Building, Control Building, Rad Waste Building and the Turbine Maintenance Building. The footprint of the power block is approximately 140 m x 70 m.

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“Modular”

1st

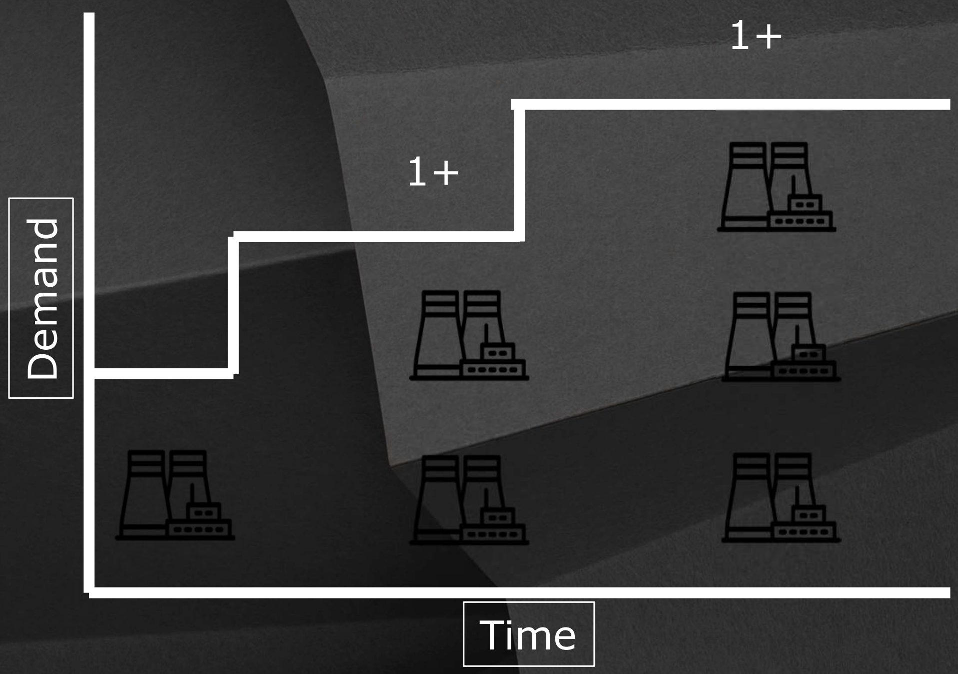
- Pre-fabricated modules
- Transported to and assembled on site

2nd

- Built over time
- Better matching actual demand

3rd

- First-of-a-kind, uncertain
- Nth-of-a-kind, predictable



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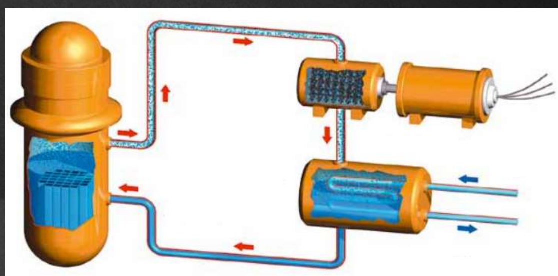
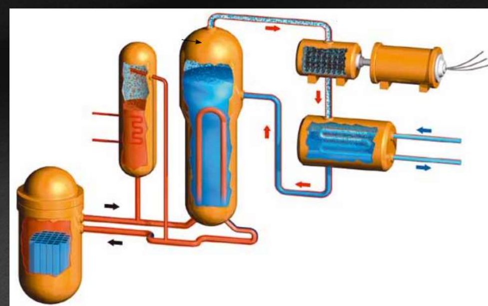
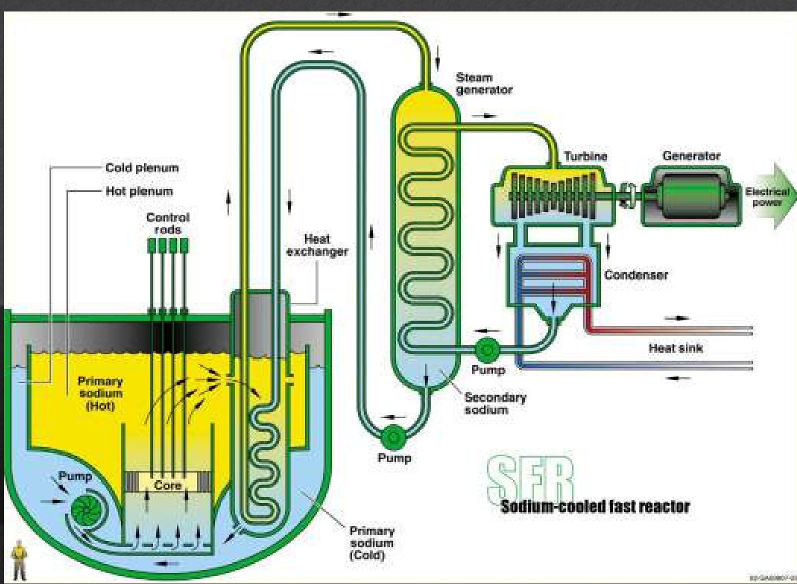
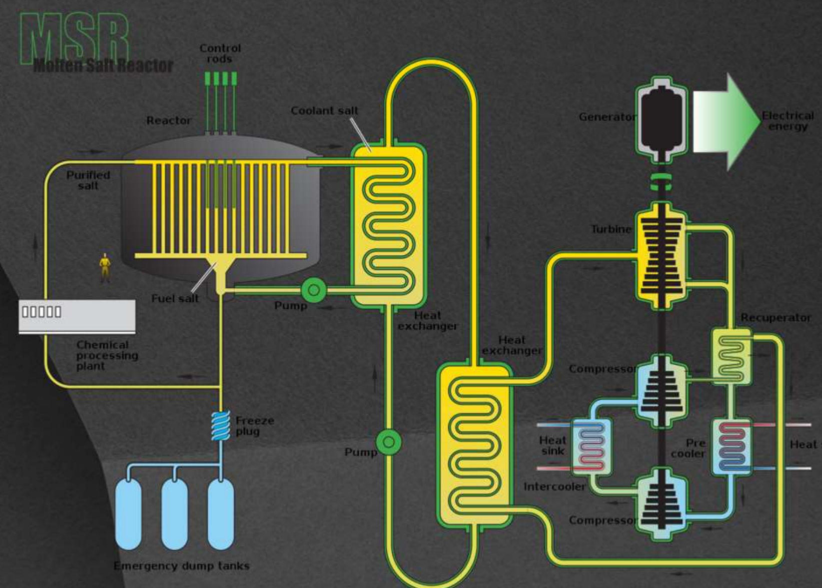
“Reactor”



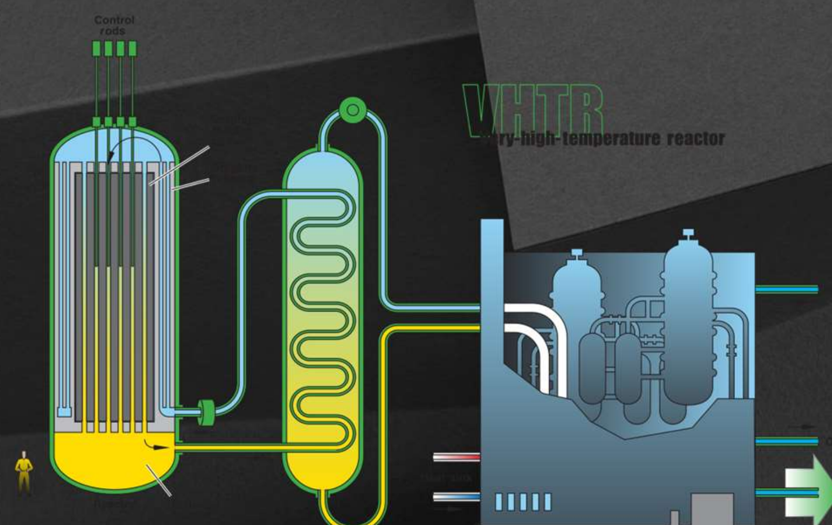




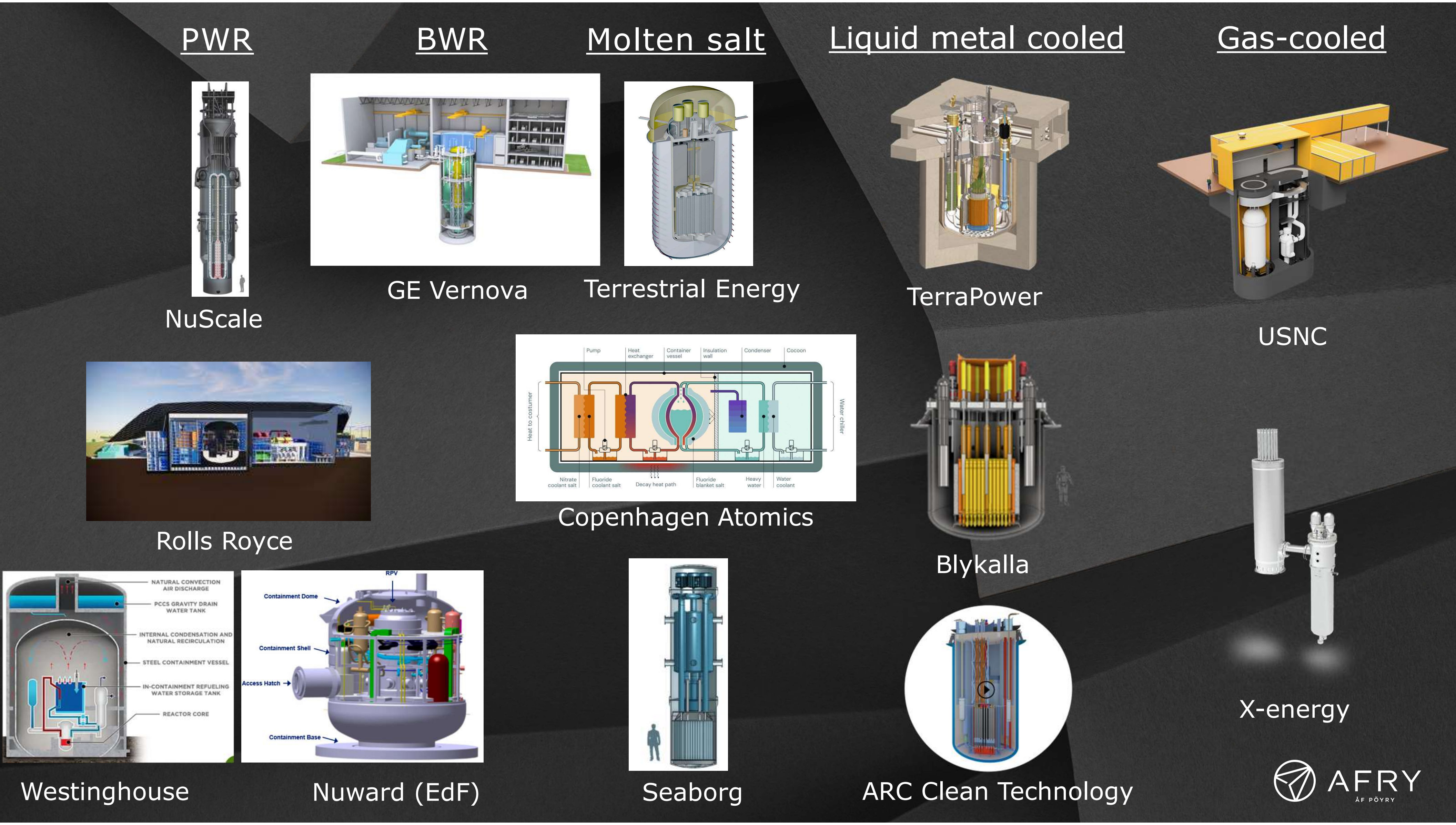
Steam generator
Turbine
Generator
Electrical power
Cold plenum
Hot plenum
Control rods
Heat exchanger
Condenser
Heat sink
Pump
Secondary sodium
Primary sodium (Hot)
Pump
Core
Pump
Primary sodium (Cold)
SFR
Sodium-cooled fast reactor



MSR
Molten Salt Reactor
Control rods
Reactor
Coolant salt
Purified salt
Fuel salt
Pump
Heat exchanger
Chemical processing plant
Freeze plug
Emergency dump tanks
Heat exchanger
Pump
Generator
Electrical energy
Turbine
Recuperator
Compressor
Heat sink
Pre cooler
Heat sink
Intercooler
Compressor



Control rods
VHTR
ry-high-temperature reactor
Oxygen
Hydrogen


PWR
BWR
Molten salt
Liquid metal cooled
Gas-cooled
NuScale
GE Vernova
Terrestrial Energy
TerraPower
USNC
Rolls Royce
Pump
Heat exchanger
Container vessel
Insulation wall
Condenser
Cocoon
Heat to costumer
Water chiller
Nitrate coolant salt
Fluoride coolant salt
Decay heat path
Fluoride blanket salt
Heavy water
Water coolant
Copenhagen Atomics
Blykalla
NATURAL CONVECTION AIR DISCHARGE
PCCS GRAVITY DRAIN WATER TANK
INTERNAL CONDENSATION AND NATURAL RECIRCULATION
STEEL CONTAINMENT VESSEL
IN-CONTAINMENT REFUELING WATER STORAGE TANK
REACTOR CORE
RPV
Containment Dome
Containment Shell
Access Hatch
Containment Base
X-energy
Westinghouse
Nuward (EdF)
Seaborg
ARC Clean Technology
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Conventional vs advanced

Reactor Technology

Conventional

- Pressurized water reactor
- Boiling water reactor

- Highly experienced and recognized
- Strong supply chains exists (components, fuel)

- Relatively low temperatures (limited field of use besides electricity production)
- Low potential to create industry renaissance

Advanced

- Molten salt reactor
- Liquid metal cooled
- Gas-cooled reactor

- Enhanced / less complex safety concepts
- Potential to use spent fuel and long fuel cycles
- Simple and cost-effective designs
- High-temp -> multiple field of use

- Little or no experience in licensing, operation and maintenance
- Novel / lack of supply chains (components, fuel)

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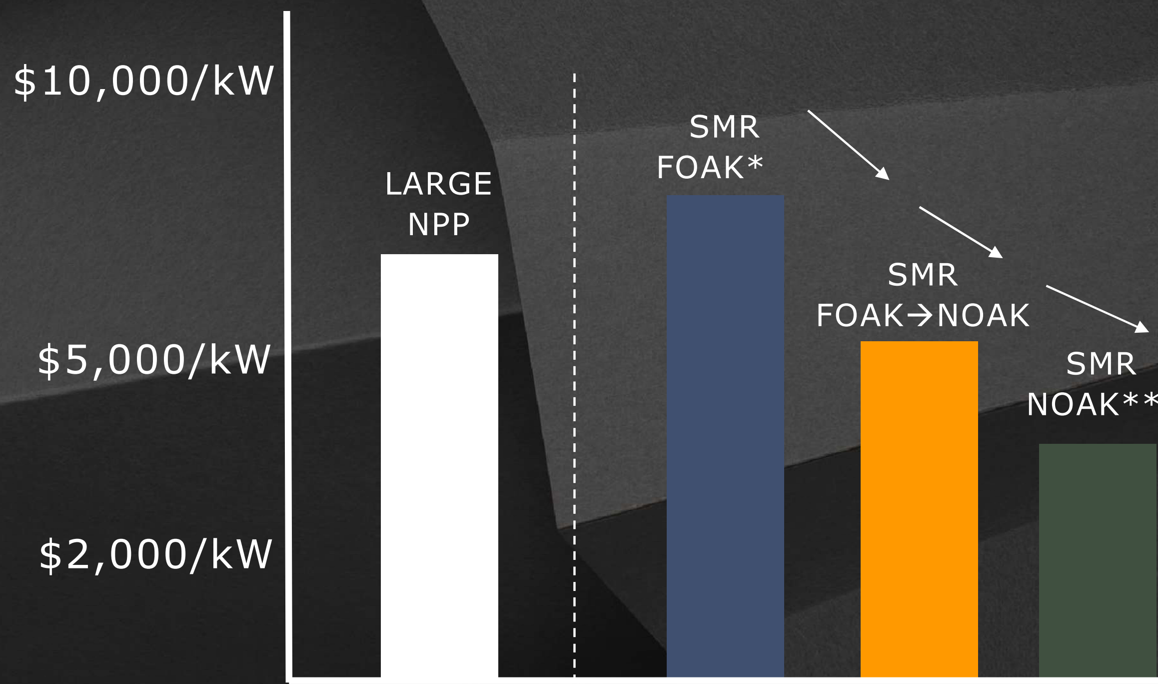
Idea of dealing with cost

- Smaller reactor
- Reduced complexity
- Standardization

- Shorter build time
- Higher learning rate (repeating project)

- Reduced project risk
- Reduced financial risk

- Reduced capital cost
- Reduced overall cost



***FOAK** (FIRST-OF-A-KIND UNIT) – DEMONSTRATION REACTOR UNITS TO SHOW CASE VIABILITY OF DESIGN
****NOAK** (NTH-OF-A-KIND UNIT) – COMMERCIALLY DEPLOYED UNITS PRODUCED IN A FACTORY SETTING

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Flexible location

Besides from the nuclear electricity production advantages

- plannable
- low-carbon
- concentrated area-wise
- heavy generator input to electric grid stability

and the SMR-specific already mentioned

- ❑ cost, including capital cost
- ❑ modularity, standardization and series production
- ❑ variety of industrial application and efficiency

there is a siting flexibility in favor of the SMR

- ➢ isolated geographical locations
- ➢ electrical grid limitations (preventing a large unit)

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Risks

What are the risks if choosing to go for a nuclear new build (e.g. SMR)?

Risks

Competence:
Long time has passed since major nuclear new builds and currently limited amount of skilled people.

Construction:
Complex project with recent difficulties delivering on time and budget.

Market:
Deregulated market with uncertain price of electricity (revenue) vs cost of capital.

Program:
Changed conditions for the final repository of radioactive waste and spent nuclear fuel.

Regulatory:
(safety concept and environmental impact)
Politics and regulatory turns on nuclear power as well as absence of global standard.

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No international/global licensing

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Licensing new build in Sweden

Three parts of licensing where an application needs to be submitted and approved:

- Nuclear (Kärntekniklagen – Strålsäkerhetsmyndigheten (SSM))
- Environmental impact (Miljöbalken – Mark- och miljödomstolen)
- Building permit (Plan- och bygglagen – Kommunen)

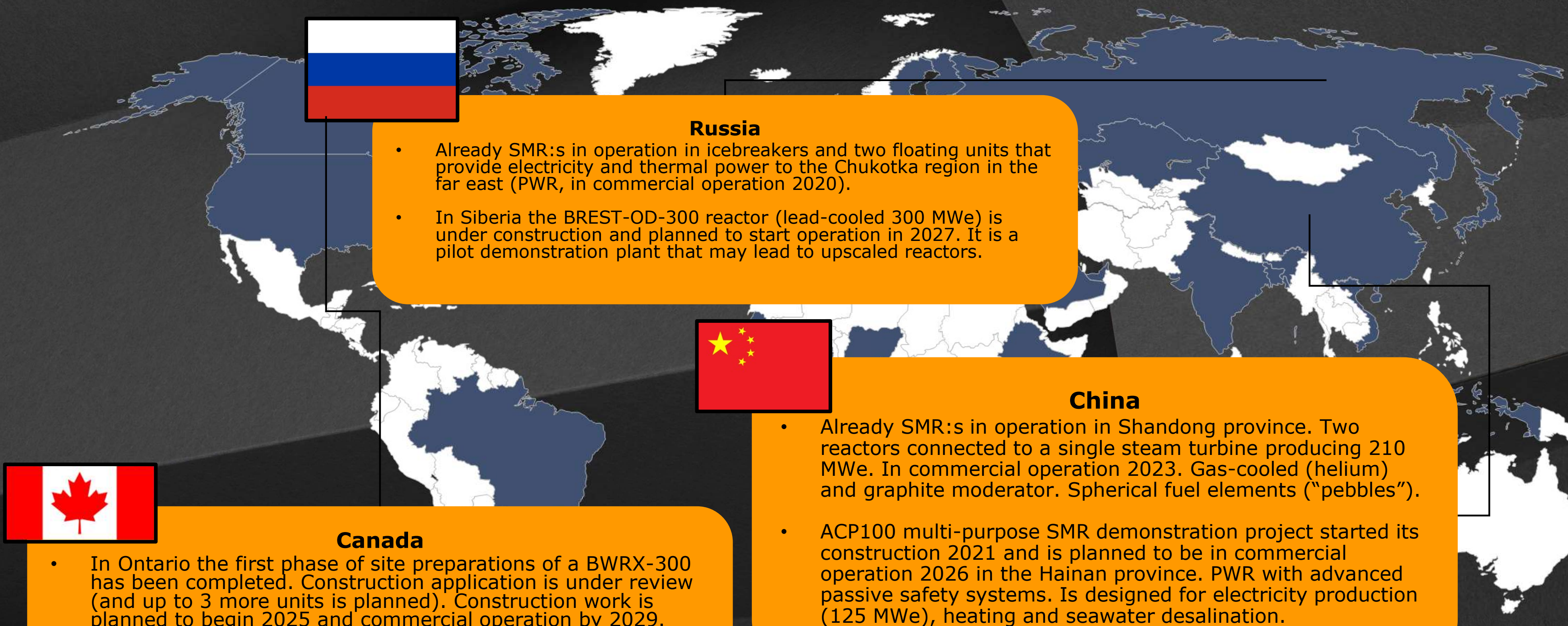
SMR as a viable alternative

A recent feasibility study by Vattenfall concludes the following necessary items for SMR to be a viable alternative:

- Acceptance by society
- High degree of standardization
- Fulfilment of requirements given by authorities
- Predictable and efficient permitting process
  (Nothing in the current legislation is preventing SMRs, however Vattenfall believes a simplification is needed.)
- Economically competitive
- Risk-sharing with the government is needed, no matter size of nuclear power.

Russia and China – In the SMR lead

A lot of international SMR activities are taking place – however the amount of actual construction work is limited.



Russia

- Already SMR:s in operation in icebreakers and two floating units that provide electricity and thermal power to the Chukotka region in the far east (PWR, in commercial operation 2020).
- In Siberia the BREST-OD-300 reactor (lead-cooled 300 MWe) is under construction and planned to start operation in 2027. It is a pilot demonstration plant that may lead to upscaled reactors.

China

- Already SMR:s in operation in Shandong province. Two reactors connected to a single steam turbine producing 210 MWe. In commercial operation 2023. Gas-cooled (helium) and graphite moderator. Spherical fuel elements ("pebbles").
- ACP100 multi-purpose SMR demonstration project started its construction 2021 and is planned to be in commercial operation 2026 in the Hainan province. PWR with advanced passive safety systems. Is designed for electricity production (125 MWe), heating and seawater desalination.

Canada

- In Ontario the first phase of site preparations of a BWRX-300 has been completed. Construction application is under review (and up to 3 more units is planned). Construction work is planned to begin 2025 and commercial operation by 2029.
- Site preparation application is under review regarding an ARC-100 (sodium-cooled) in New Brunswick.

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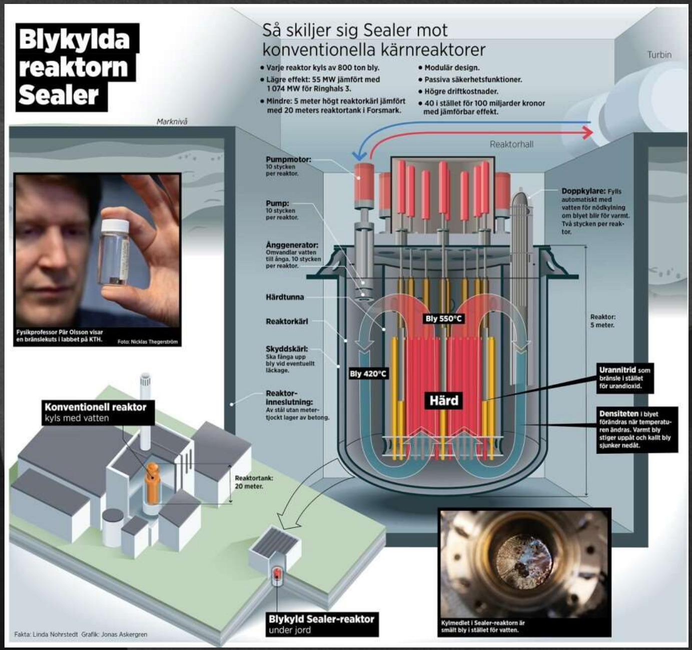
Blykalla

- Lead-cold with highly enriched uranium nitride fuel.
- Sealer-E, electrical test reactor of 2,5 MW in order to test processes, cooling, pumps etc. Construction started in February, 2025, at Oskarshamn nuclear power plant site. Financed by the Swedish State and privately.
- First nuclear permit application planned to be submitted 2026. Vision to have SEALER-One built by 2030. Then plan to mass-produce SEALER-55 (55 MWe).
- Produces 530 degree Celsius steam that opens up for other industrial applications than electricity production, such as hydrogen production.



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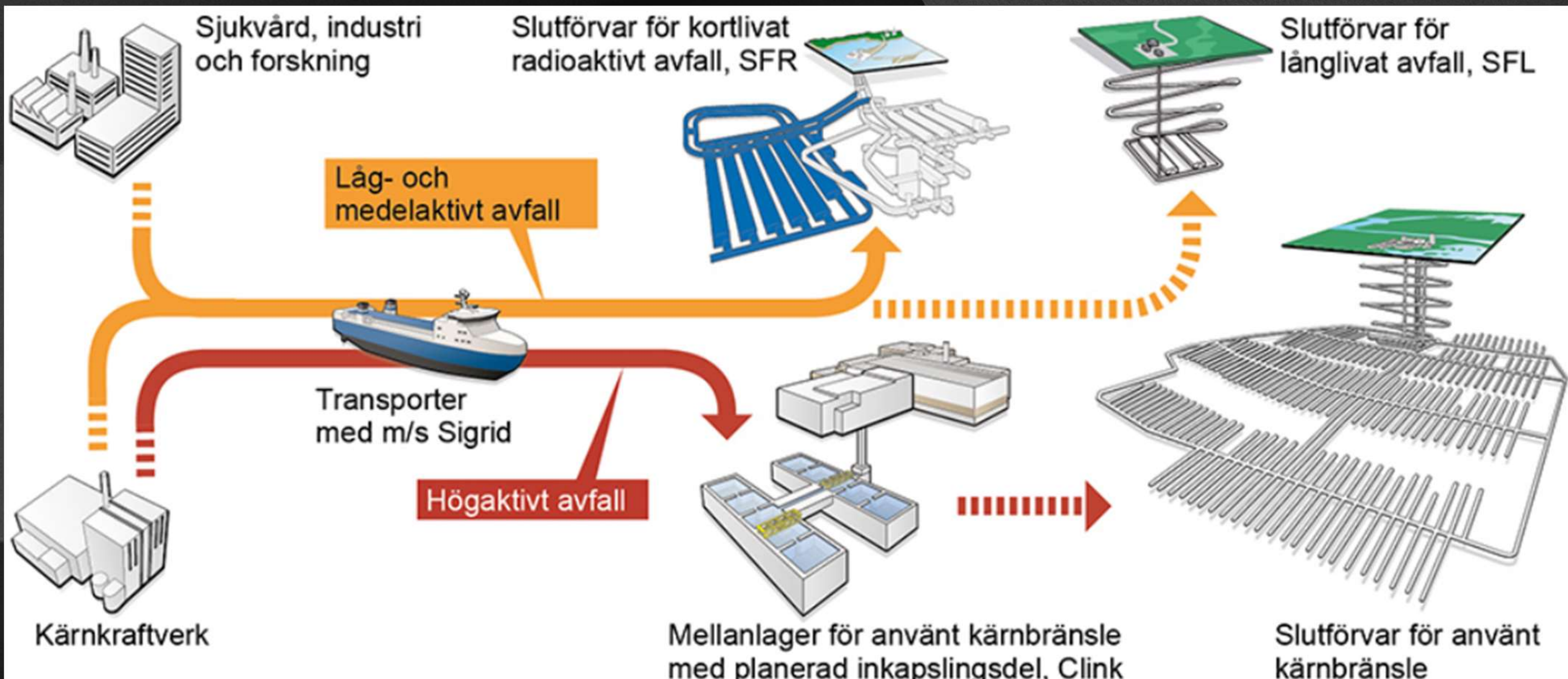
Vattenfall - Ringhals

Vattenfall is looking into possibilities of nuclear new build at Ringhals (including SMRs).

Nuclear waste handling system



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