Types and Development of SMR and HTGR

Follow-up Training Course (FTC) Indonesia

On Reactor Engineering (RE)

19 May 2026

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Integrated Support Center for Nuclear Nonproliferation, Security and Human Resources Development (ISCN)
Japan Atomic Energy Agency (JAEA)

A lot of countries are planning to build new NPPs.

Main Reason:

- Recent strange weather due to Greenhouse Gas
- Increase of Oil price due to unstable world situation
- Increase of electricity demand
  Especially, stable electricity for **AI Data Center**

Nuclear Energy is "Environmentally Friendly", "Stable" and "Cheaper(?)".

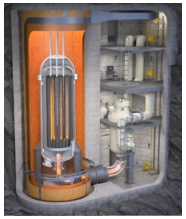
Classification of Innovative Reactors

Large Scale NPP:
1,000 ~ 1,600 MWe

PWR

BWR

SMR :
~ 300 MWe



Microreactors :
~ 20MWe

(Efficiency: ~35%)
Electric Power

+

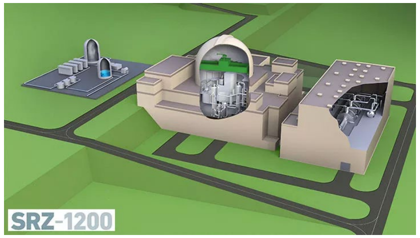
(More than 50%)
Thermal Power

- Local Heating
- Seawater Desalination
- Hydrogen Production
- Industrial Process Heating

Large Scale NPPs (Generation III+)

■Power: 1,000 ~ 1,600 MWe

- AP1000 (U.S.A.)
- EPR, EPR-2 (France)
- VVER1200, VVER-TOI (Russia)
- HPR1000, CAP1400
- (China)
- APR1400 (Korea)
- SRZ-1200 (Japan:MHI)
- ABWR, HI-ABWR (Japan:Hitachi-GE)

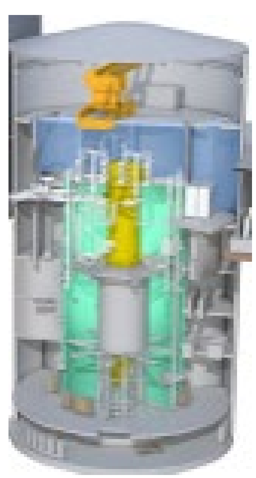


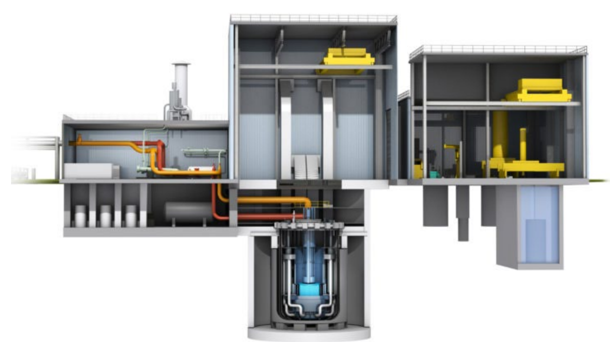
Black: Operating   Blue: Design stage

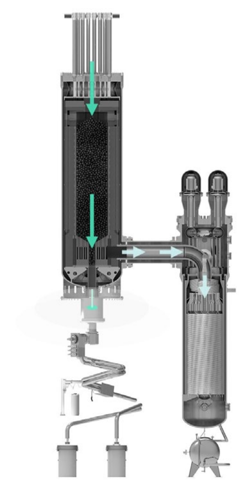
SMRs (Generation IV)

■Up to 300 MWe (per module)

- Carbon-free base-load power sources mainly in small grids such as off-grid areas
- A long-term stable mobile power supply for remote communities, island areas
- **AI Data Center electricity consumption (Google, Amazon, Microsoft, etc.)**

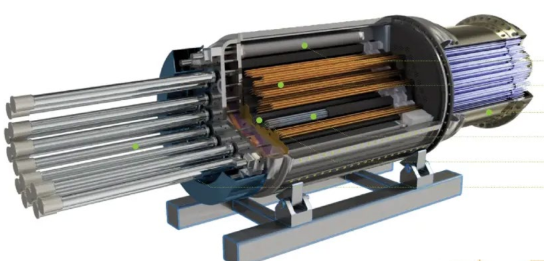


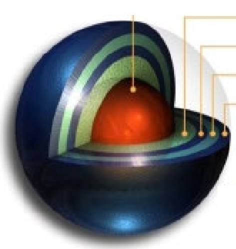


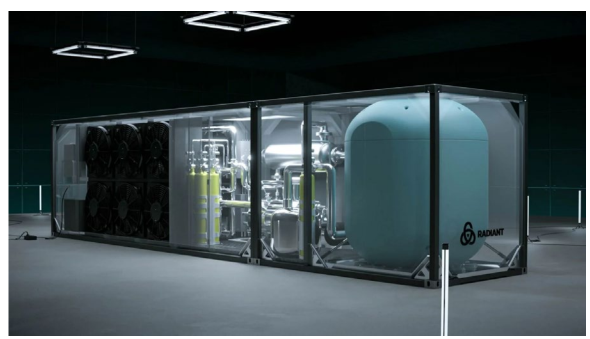


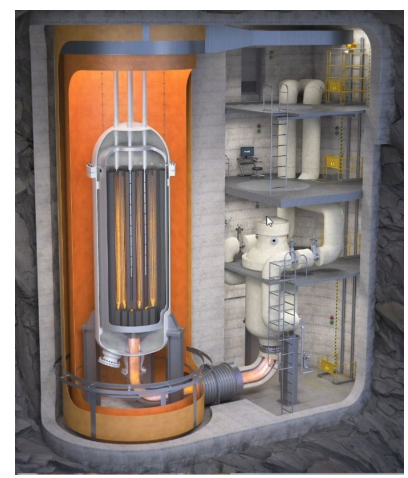
Microreactors (Generation IV)

- **Up to 20 MWe**
  - emergency power supply for disaster areas, army bases and space rockets
  - easily transported by track or train
  - No LWR type
  - HALEU TRISO fuel

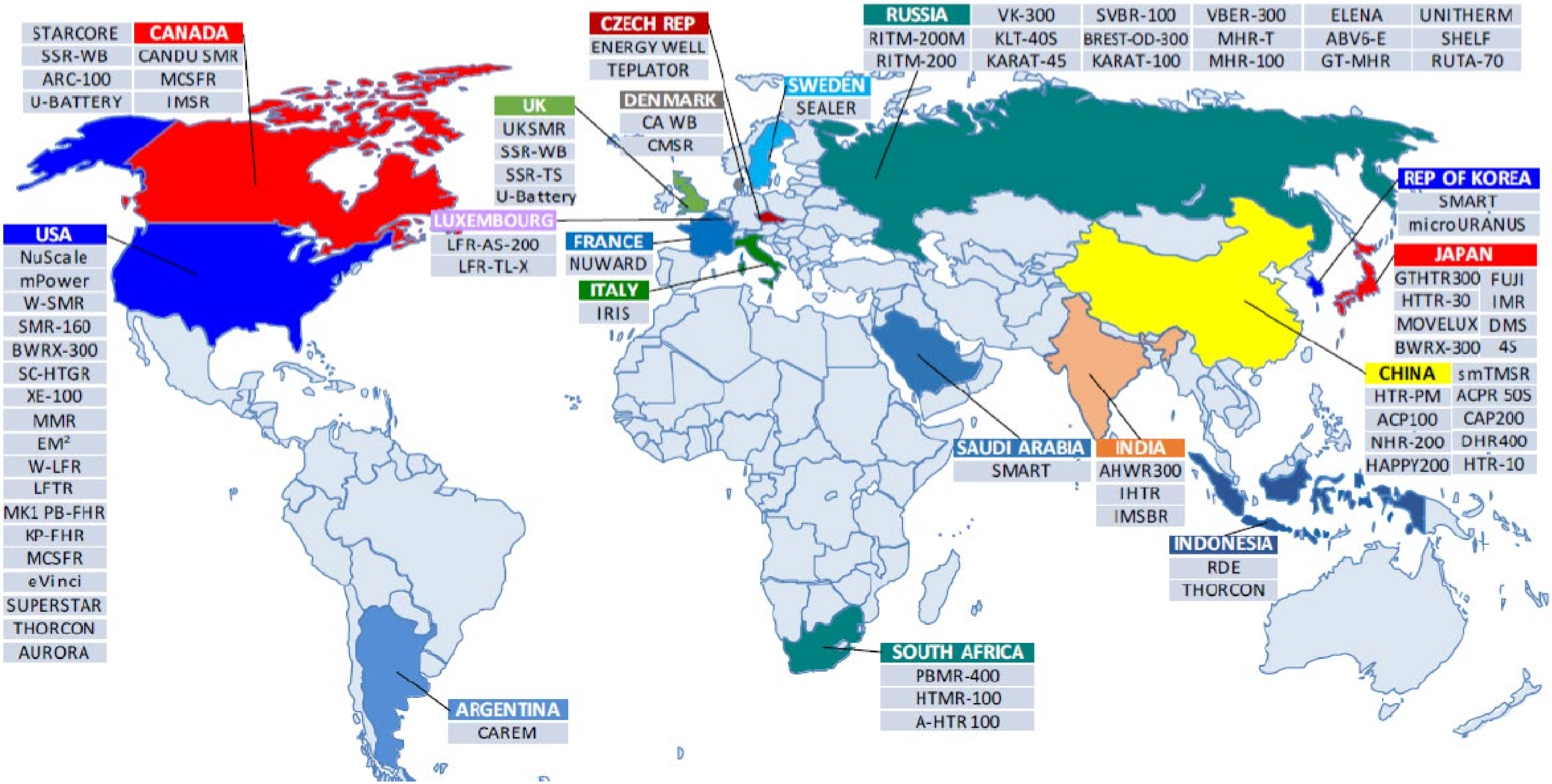








Global map of SMR technology development



IAEA Nuclear Energy Series: Technology Roadmap for Small Modular Reactor Development (2021)

Main Features of SMR

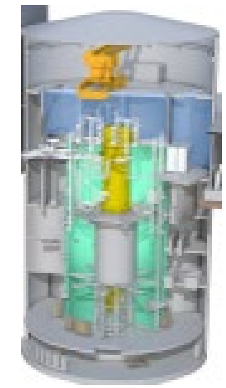
- **Passive safety**
  - inherent safety based on small scale
  - simplification of reactor safety system
- **Modular design**
  - Integrated design
  - Most modules produced in factories
  - reduction in on-site construction work
  - short construction period
  - number of modules according to energy demand
- **High energy conversion efficiency**
  - suitable for cogeneration and non-electric applications
    (For example, district heating and hydrogen production)
- **Low initial capital cost? (≠ generation cost per unit power)**

  Ex. BWRX-300: ~0.6 Billion $, Rolls-Royce SMR: 2.3 Billion $
  AP1000 (Vogtle in U.S.A.): 17 Billion $ in 2023

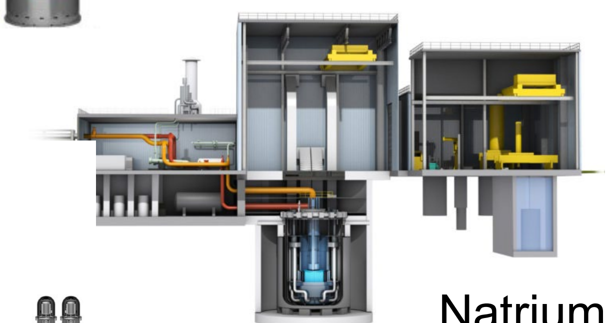
Design Type of SMR

- **PWR**
  VOYGR (Nuscale Power)
  SMR-160, 300 (Holtec)
  Rolls-Royce SMR (RR)
  AP300 SMR (Westinghouse)
- **BWR**
  BWRX-300 (GE-Hitachi)
- **Fast Reactor**
  Natrium (TerraPower)
- **MSR**
  Hermes (Kairos Power)
  TMSR-500 (ThorCon, Indonesia)
- **HTGR**
  Xe-100 (X-energy)
  HTTR (JAEA)
  HTR-PM (China)
- **Marine-Based Reactor**
  KLT-40S (Russia)

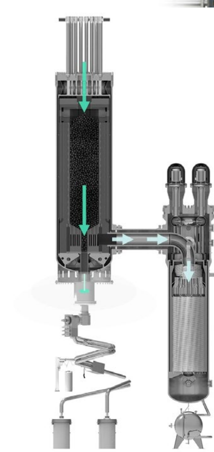
VOYGR



BWRX-300



Natrium

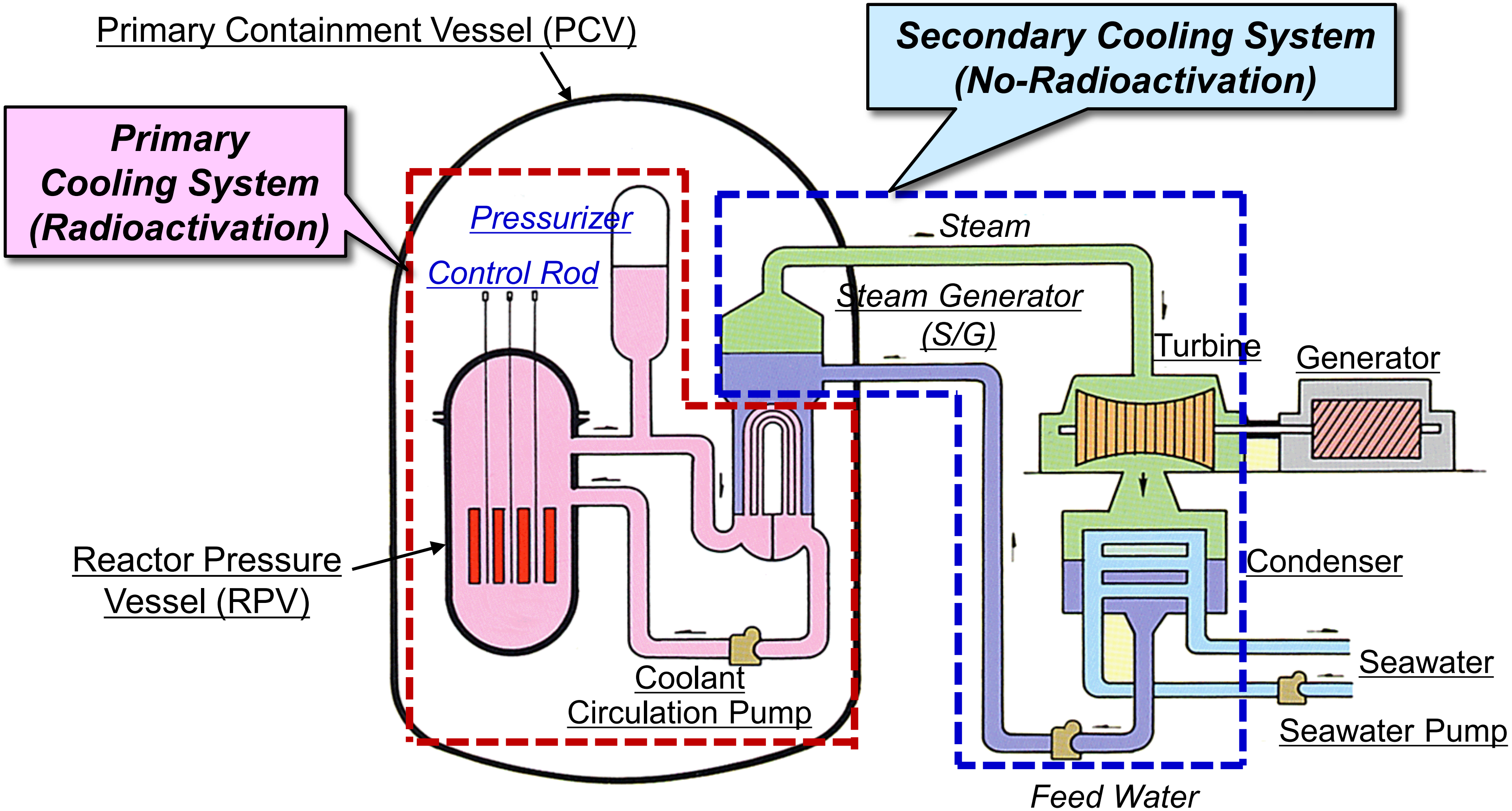


Xe-100

KLT-40S

OECD/NEA Small Modular Reactors: Challenges and Opportunities(2021)

PWR Main Plant System Configuration



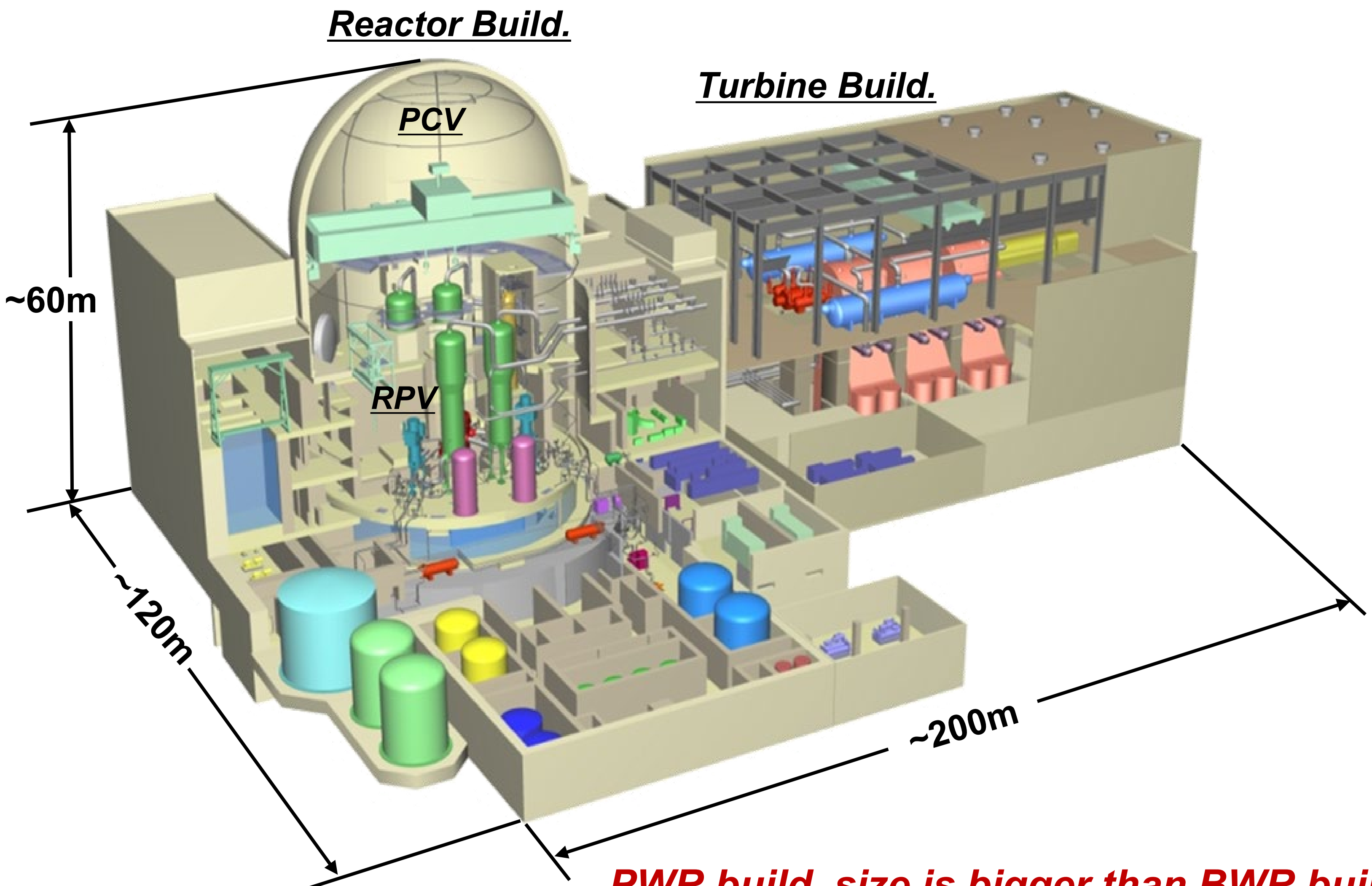
Main Plant Specifications of PWR (1,100MWe class)

RPV Pressure	Core Flow rate	Core Outlet Temp.	Core Inlet Temp.	Steam Flow Rate	Feed Water Temp.
15.4MPa	*60,100t/h*	*325°C*	*289°C*	*6,760t/h*	*223°C*

Source: http://www.fepc.or.jp/library/pamphlet/zumenshu, p5-2, pdf, 2008年度版、日本原子力文化振興財団.

Bird's Eye View of PWR NPP (Facility Size Image)

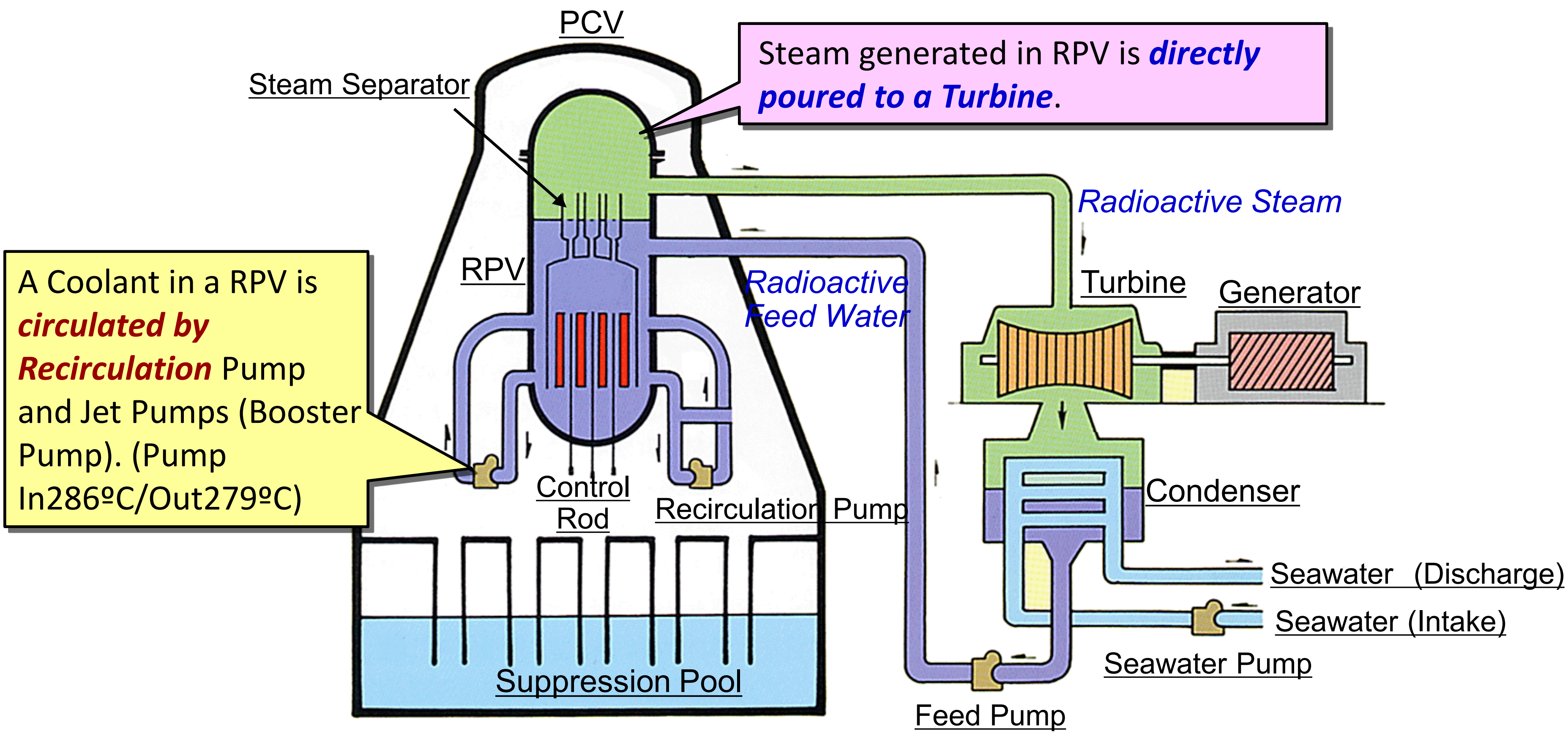
<4 Loops PWR Plant, 1,200MW Class>



PWR build. size is bigger than BWR build.

Source: "Nuclear Power 2010 " by Resources and Energy Agency

BWR Main Plant System Configuration

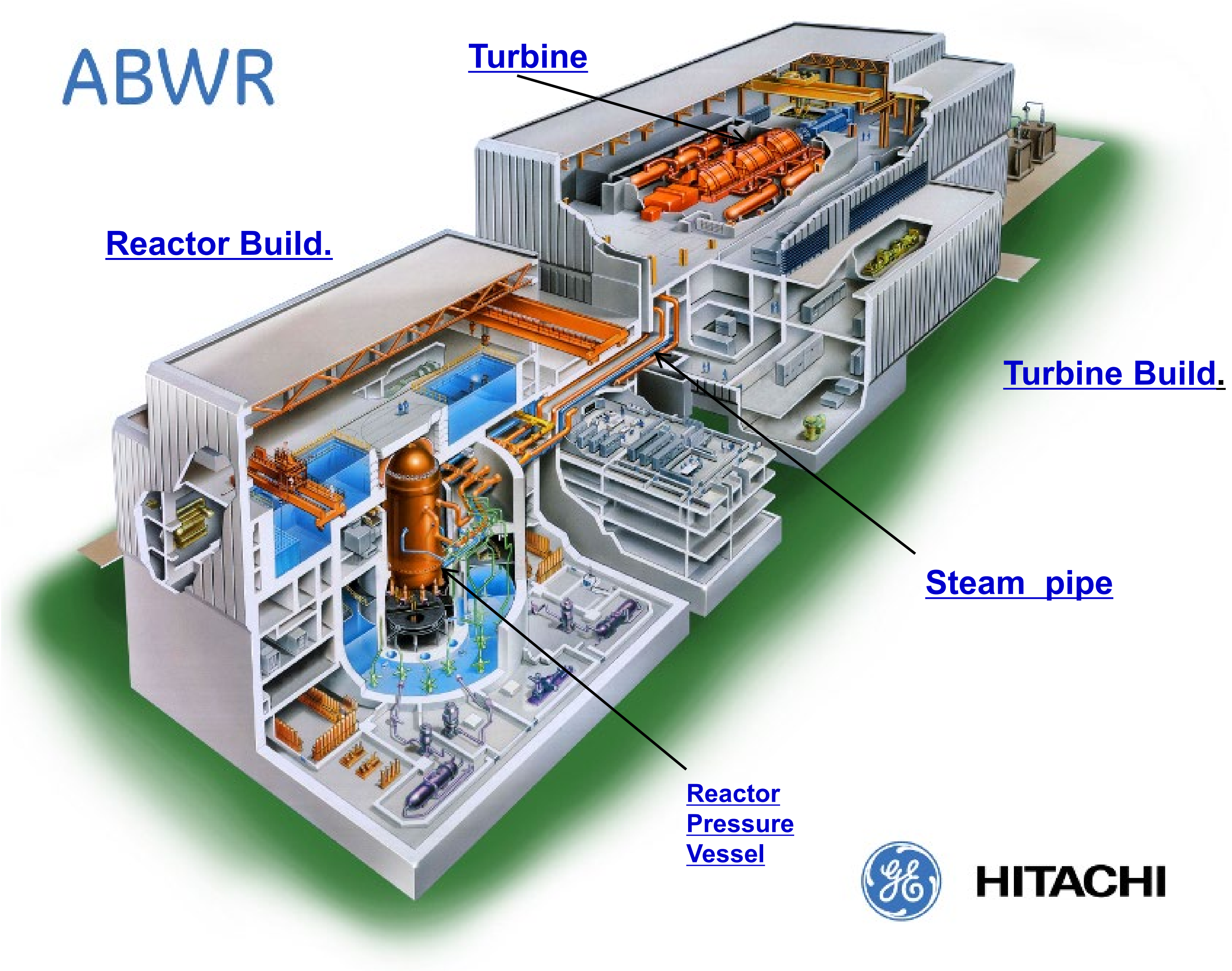


Main Plant Specifications of BWR (1,100MWe class)

RPV Pressure	Core Flow rate	Core Outlet Temp. (Pump Inlet)	Core Inlet Temp. (Pump. Outlet)	Steam Flow Rate	Feed Water Temp.
6.9MPa	*48,300t/h*	***286ºC***	***279ºC***	*6,410t/h*	***216ºC***

Source: http://www.fepc.or.jp/library/pamphlet/zumenshu, p5-2, pdf, 2008年度版、日本原子力文化振興財団.

Bird’s Eye View of ABWR NPP



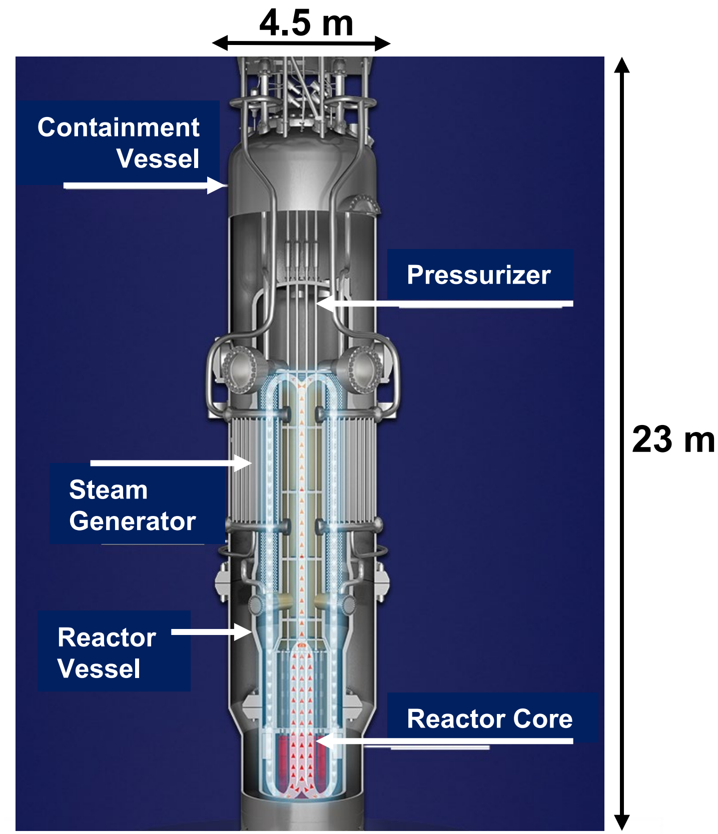
Feature of PWR and BWR type SMRs

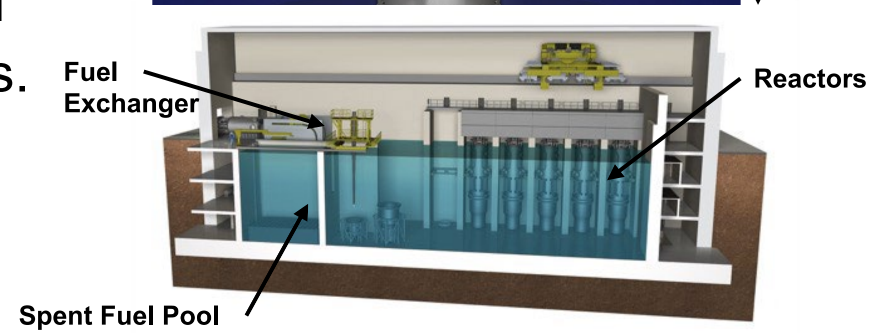
- Fuel: UO_2 (~ 5% Enrichment)
  (same as conventional large scale LWRs)
- Coolant: Light Water (H_2O)
- Reactor Outlet Temperature: around 300 ^oC
- Reactor Pressure: 16 MPa (PWR), 7 MPa (BWR)
- Passive Safety
  - Cooling water circulates through the nuclear core by natural convection
  - Elimination of piping and external components

A lot of experiences of large-scale power plants and nuclear ships

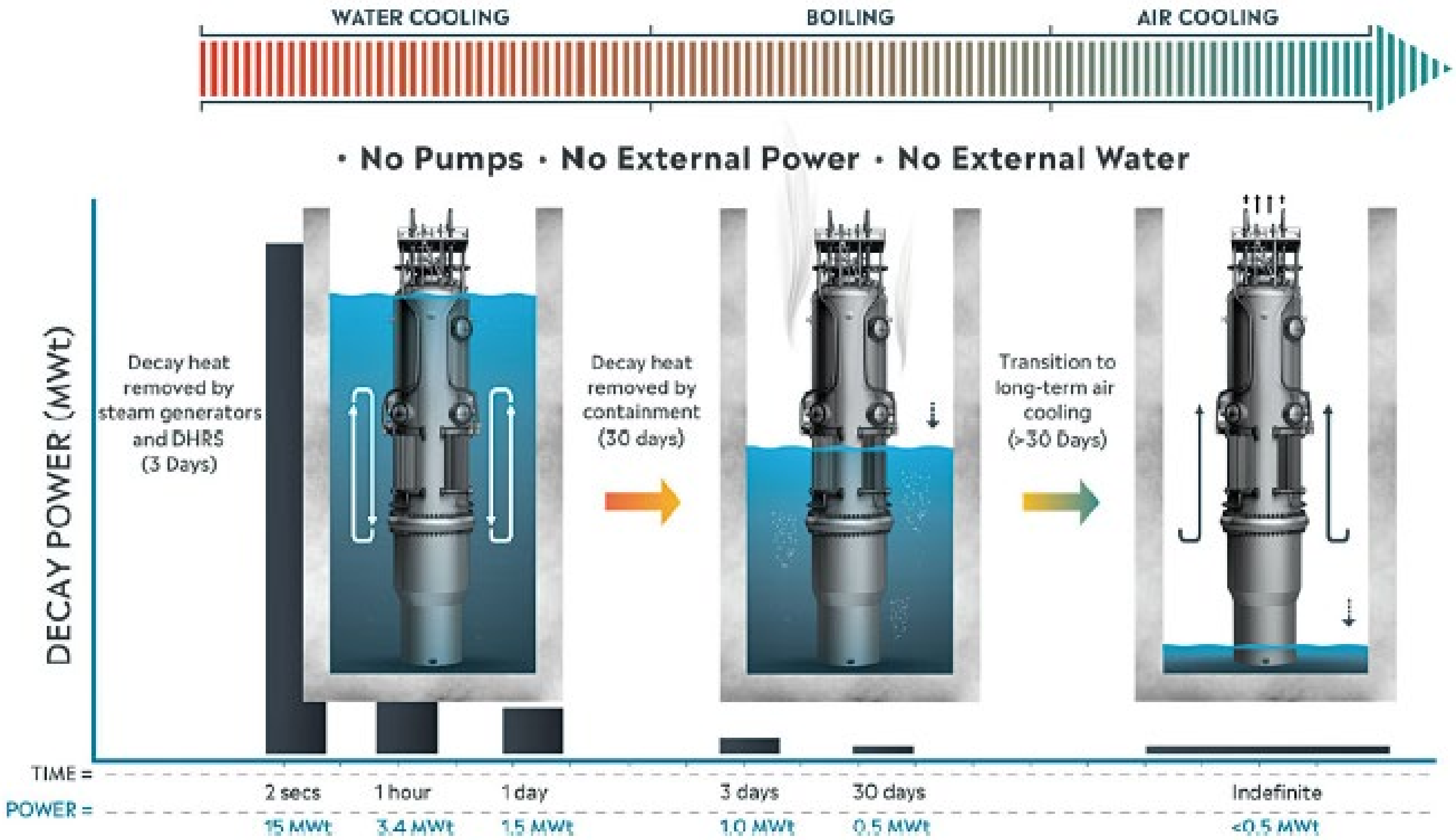
PWR Type: NuScale Power Module (NuScale Power)

- Power: 77 MWe per module
  (4, 8,12 module)
- Design life: 60 years
- Fuel cycle: 18-22 months
- SG: 2 integrated tube bundles
- Integrated reactor design eliminates large bore piping: no large-break loss-of-coolant accidents
- Passively safe: cooling water circulates through the core by natural convection eliminating coolant pumps.
- System submerged in a below-grade pool of water in an earthquake and aircraft impact resistant building



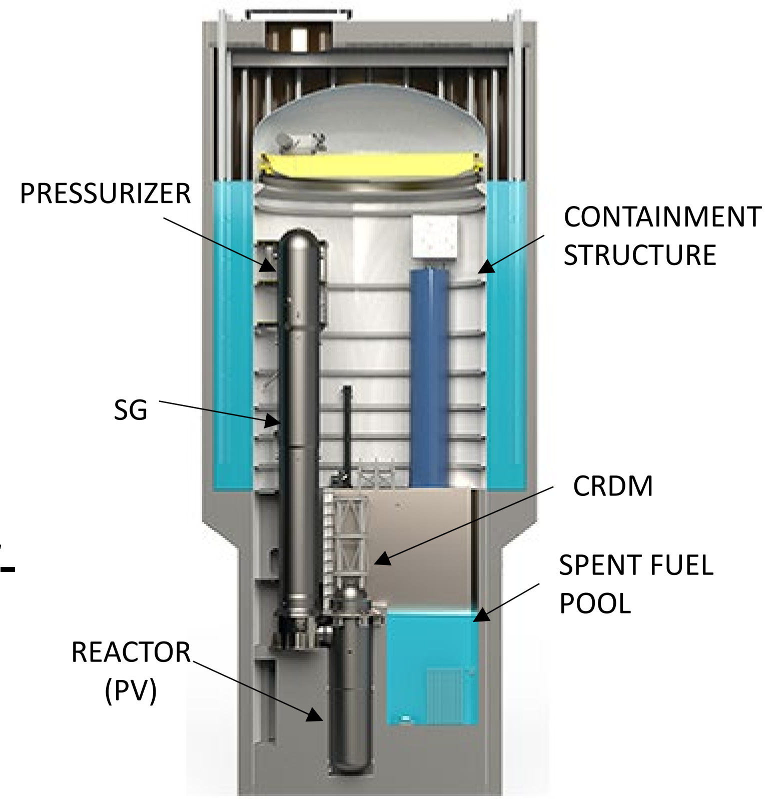


Passive Safety System by not using dynamic equipment such as pumps to cool the core



PWR Type: SMR-300 (Holtec)

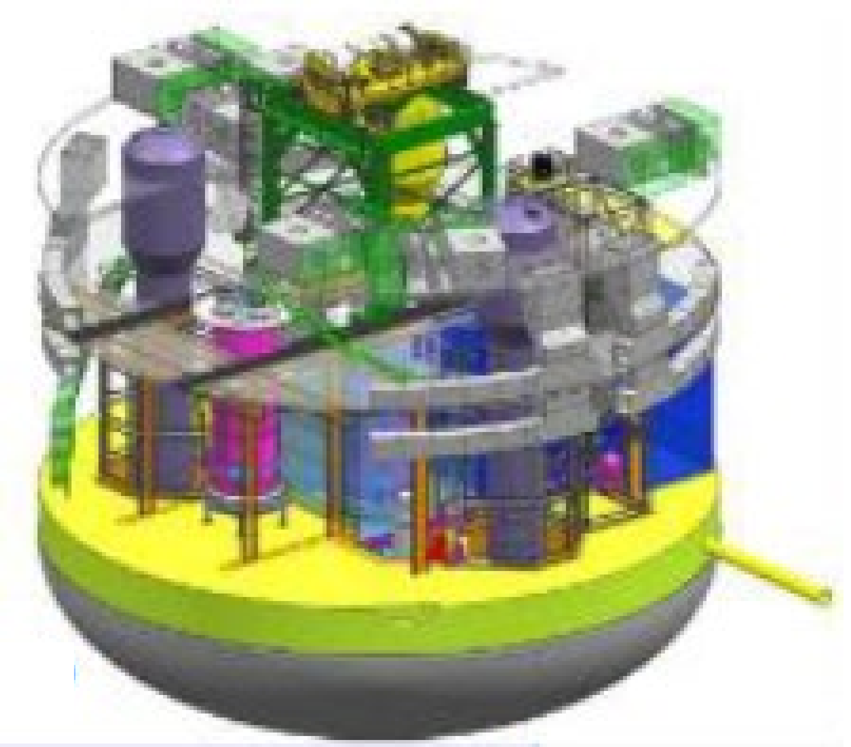
- Power: 320 MWe
- Fuel cycle: 24 months
- Service life: 80 years
- On-site underground storage of used fuel
- Short construction cycle: 30~36 months
- Coolant loop: 2
- The primary system is based on incorporation of forced flow capability overlayed on gravity-driven flow.
- A Passive Containment Cooling System integrates decay heat removal from the spent fuel pool and reactor core under off-normal conditions, including station blackout.
- The Containment is protected by a Containment Enclosure Structure engineered to withstand a crashing aircraft.

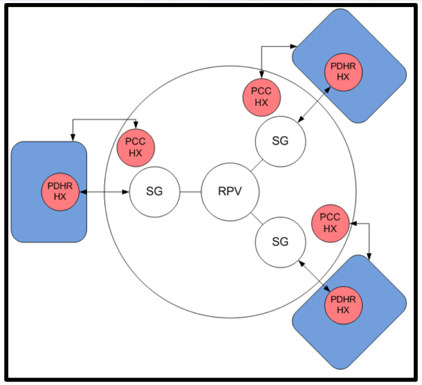


https://holtecinternational.com/products-and-services/smr/

PWR Type: SMR plant (Rolls-Royce)

- Power: 470 MWe
- Coolant loop: 3
- 3 vertical U-tube Steam Generators
- Core inlet temp.: 295°C
- Core outlet temp.: 322°C
- Fuel: Industry standard 17x17 UO_2 assembly
- Fuel enrichment: <4.95%
- Fuel cycle: 18 months
- Design life: 60 years
- Both active and passive decay heat removal (PDHR) systems





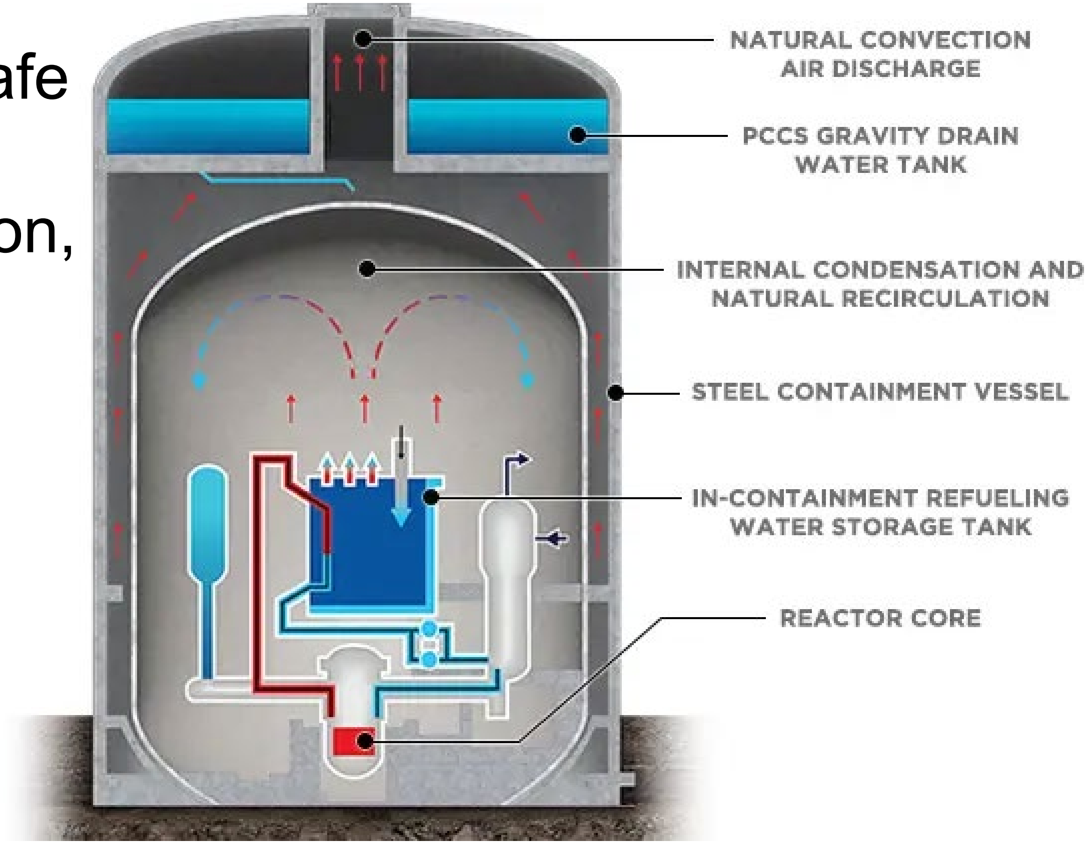
PDHR System

https://www.nuclearuniversities.ac.uk/wp-content/uploads/2021/09/Sophie-Macfarlane-Smith.pdf

PWR Type: AP300 SMR (Westinghouse)

[Design based on proven AP1000 (2 loop) technology]

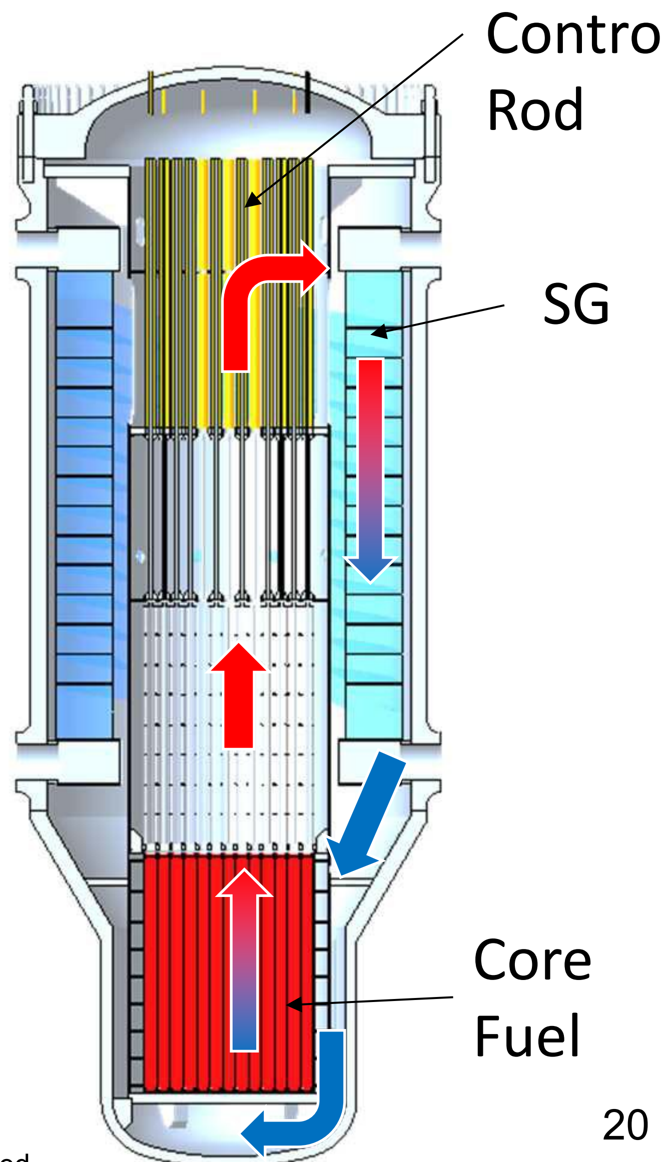
- Power: 300 MWe
- Coolant loop: 1
- Design life: 80 years
- Fail safe: maintain safe shutdown condition without operator action, back-up power or pumps



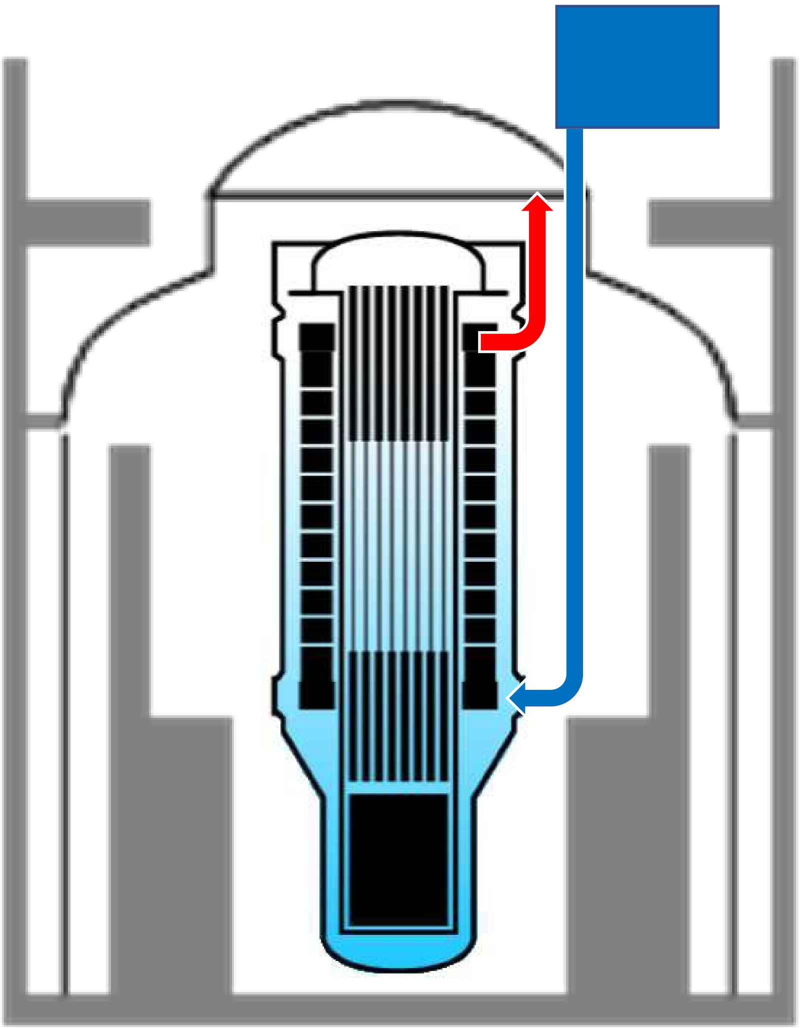
https://westinghousenuclear.com/energy-systems/ap300-smr/

PWR Type: Mitsubishi Integrated SMR (MHI)

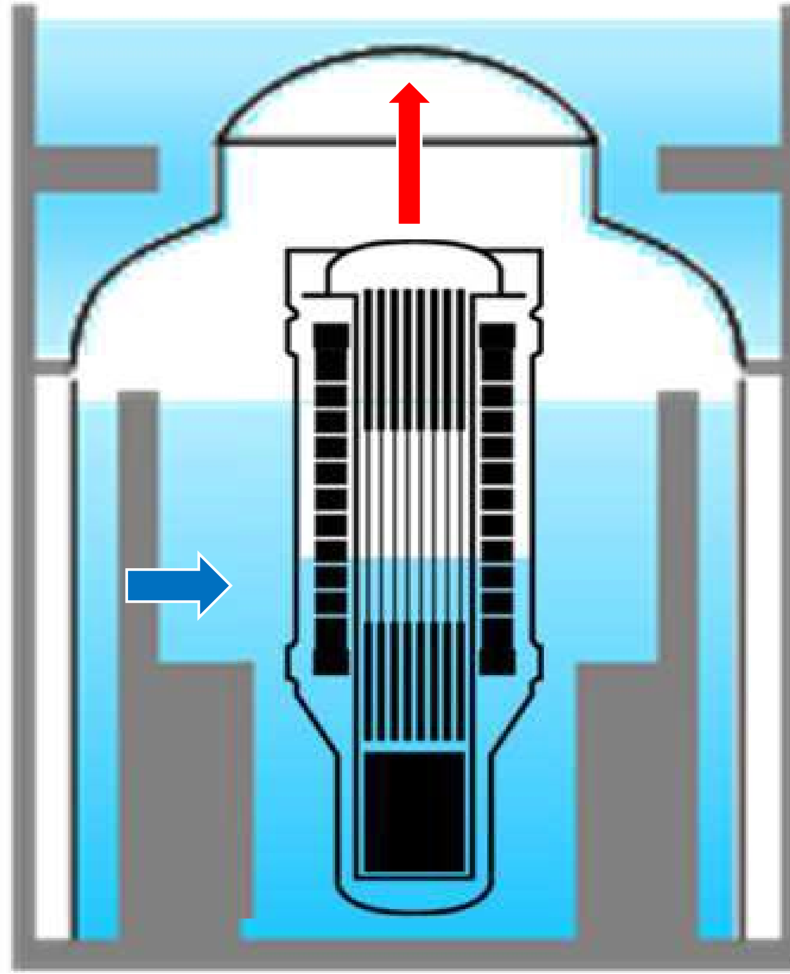
- Power: 300 MWe
- Steam generator in the reactor vessel against the elimination of loss-of-coolant
- Natural circulation
- Underground and Double containment vessel



Passive Safety System by not using dynamic equipment such as pumps to cool the core



SG Cooling



CV Cooling

BWR Type: BWRX-300 (Hitachi-GE)

- Power: 300 MWe
- Fuel: UO_2 (~4.95% enrichment)
- Refueling Cycle: 12 – 24 months
- Design life: 60 years
- Reactor Isolation valve integrated with the pressure vessel (reduce LOCA risk)
- Eliminate dynamic equipment by adopting natural circulation
- Significant reduction in construction costs by adopting advanced construction methods
- Underground containment vessel

BWRX-300 (GE-Hitachi)

GE Hitachi Nuclear Energy,「GE Hitachi Nuclear Energy Selected by Ontario Power Generation as Technology Partner for Darlington New Nuclear Project」, December 2021.
https://www.ge.com/news/press-releases/ge-hitachi-nuclear-energy-selected-by-ontario-power-generation-as-technology-partner

Feature of Sodium cooled Fast Reactor (SFR) Type

- Fuel:HALEU (High-Assay, Low Enriched Uranium） fuel
  (~20% enrichment)
- Coolant: Liquid Sodium
- Reactor Outlet Temperature: 500 ~ 550 ^{o}C
- Primary Pressure: Low
  (almost same as atmosphere pressure)
- Safety
  - Low pressure
  - Passive decay heat removal by natural circulation
  - Passive reactor shutdown system: Control rods lose their holding power and fall spontaneously at high temperatures.

Feature of SFR Type (continued)

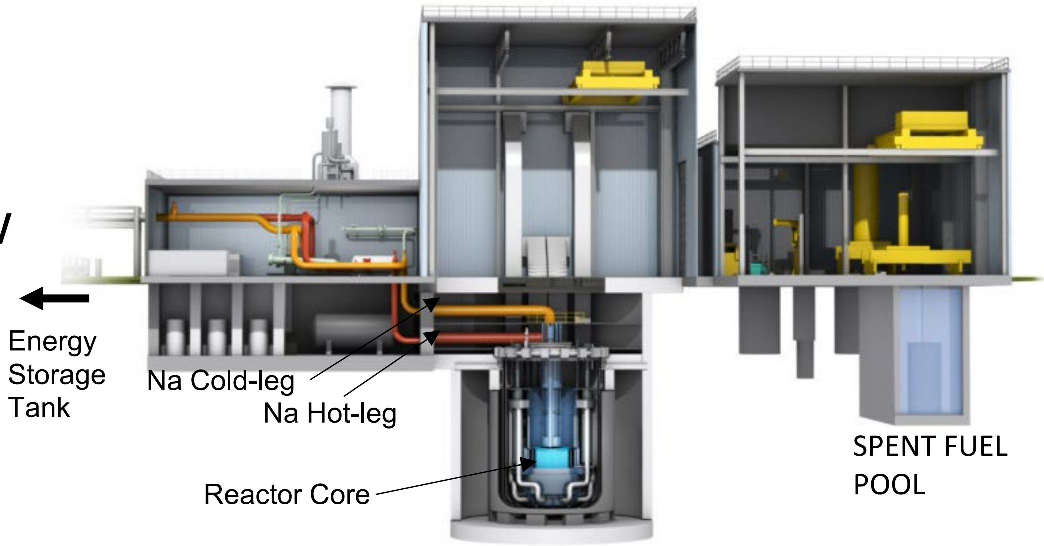
- Improve effectiveness of nuclear fuel cycle
  - Volume reduction of high-level radioactive waste
  - Reduction of hazardous level of radioactive waste
  - Effective use of Uranium resources

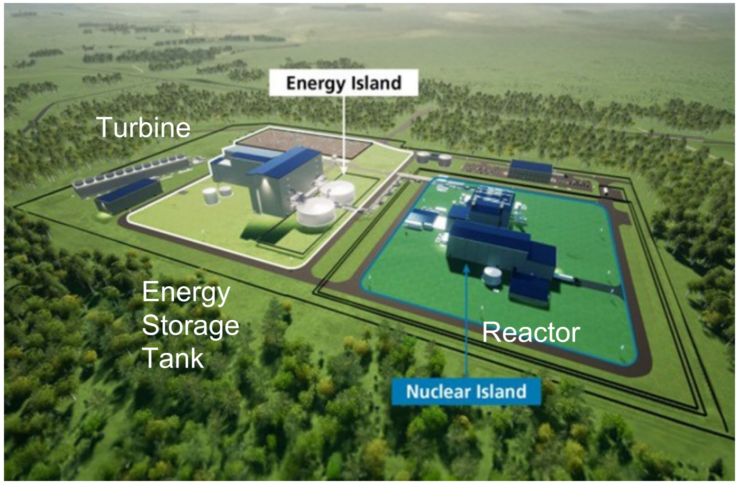
■Sodium-Water reaction at coolant leakage

■Keep high temperature
(200 ^{o}C during shutdown)

FR Type : Natrium (TerraPower by Bill Gates and GE-Hitachi)

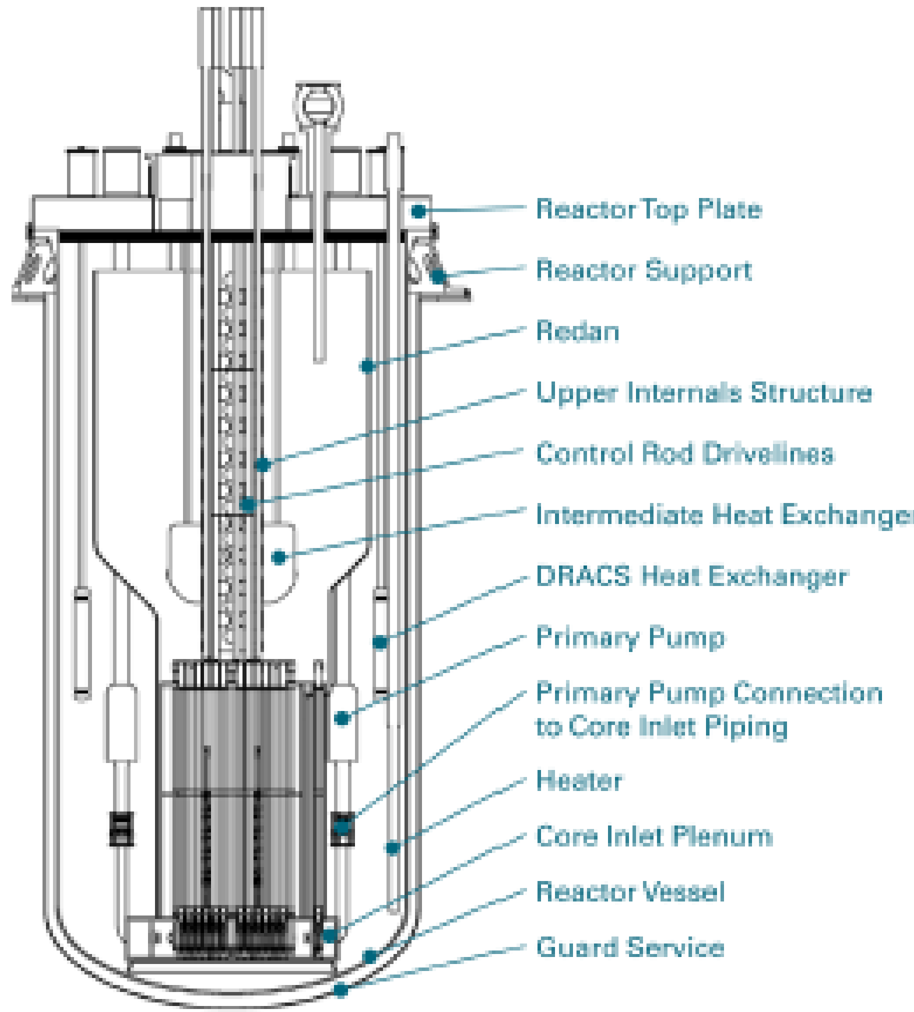
- Power: 345 MWe
- Tank type module reactor (Based on PRISM)
- HALEU （High-Assay, Low Enriched Uranium） fuel (~20% enrichment)
- Coolant: Sodium (Na)
- Combination with a molten salt energy storage system (capacity of 500 MWe output for 5.5+ hours)
- <u>flexible power production</u>
- Operation at Kemmerer: after 2030





FR Type : ARC-100 (ARC Clean Technology)

- Power: 100 MWe (286 MWt)
- Reactor Type: Low pressure pool-type reactor
- Outlet temperature: 510ºC
- Fuel Type: Metal fuel(U-Zr alloy)
- Fuel Enrichment: Avg. 13.1%
- Fuel cycle: 20 years
- Design Life: 60 years
- Superheated steam cycle
- Experience in EBR-II (20MWe, Operation: 1964-1994 ANL)



https://www.arc-cleantech.com/technology

Feature of Molten Salt Reactor (MSR) Type

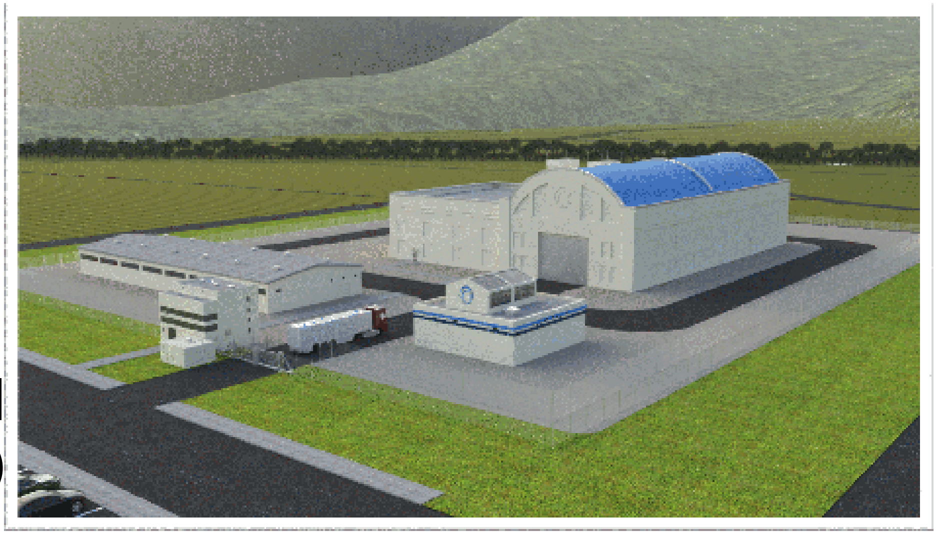
- Fuel:HALEU (High-Assay, Low Enriched Uranium）fuel
  (~20% enrichment)
- Coolant: Molten Salt
- Reactor Outlet Temperature: 600 ~ 700 ^{o}C
- Primary Pressure: Low
- High energy efficiency (high temperature)
- High passive safety (fuel and coolant are a single fluid)
- Thorium fuel utilization
  - ✓Reduction of radioactive waste (Long-lived actinides can be turned into reactor fuel by chemical separation)
  - ✓lower risk of weaponization

■Corrosion of pipes by molten salt

MSR Type : KP-FHR (Kairos Power)

(Investment from Google)

- Power: 140 MWe (350 MWt)
- Main/ Reheat Temp.: 585 °C
- Outlet Temp.: 650 °C
- Fuel Enrichment: 19.75%
- Fuel: TRISO coated particle fuel (Tri-structural Isotropic Particle)
- Coolant: 'Flibe' molten fluoride salt

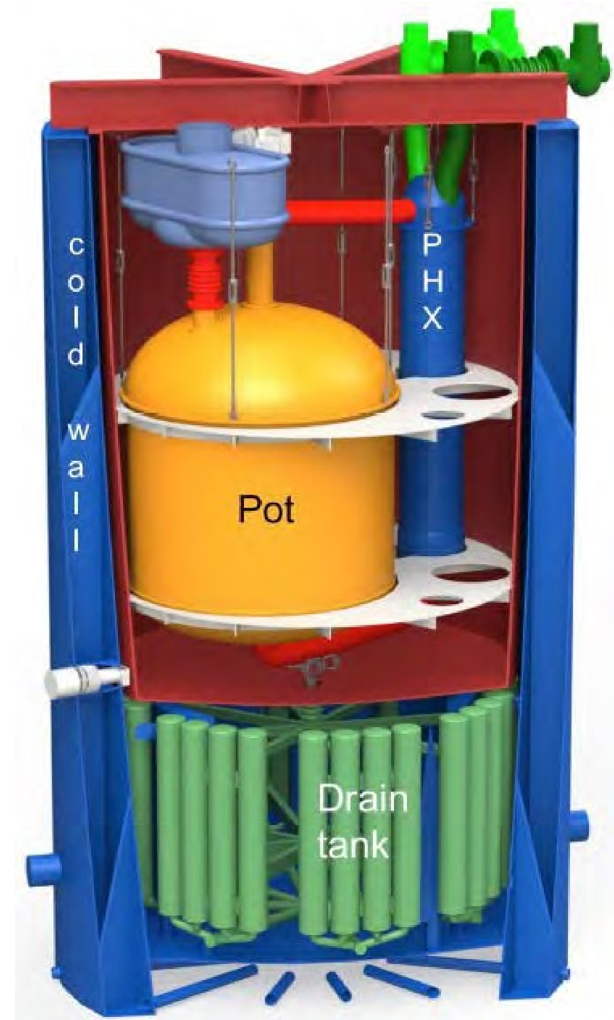


Demonstration reactor: Hermes-1

- Power: 35 MWt (1/10 KP-FHR)
- No electric power
- Operation in ~~2027~~ in ORNL, Tennessee, USA (--> 2029: 28 months extended)

MSR Type : TMSR-500 (ThorCon, Indonesia)

- Power: 500 MWe (250 x 2 module)
- Fuelsalt: NaF-BeF2-ThF4-UF4
- Fuelsalt flow: 2,934 kg/s
- Pot inlet Temp.: 565 °C
- Pot outlet Temp.: 704 °C
- Moderator: Graphite
- Maintenance: 4 years interval
- Floating Canship at Kelasa Island
- Commercial Operation in 2031?



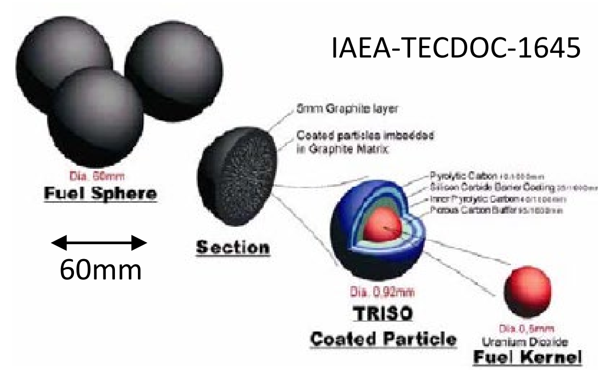
IAEA Aris Data 2020 – ThorCon Power TMSR

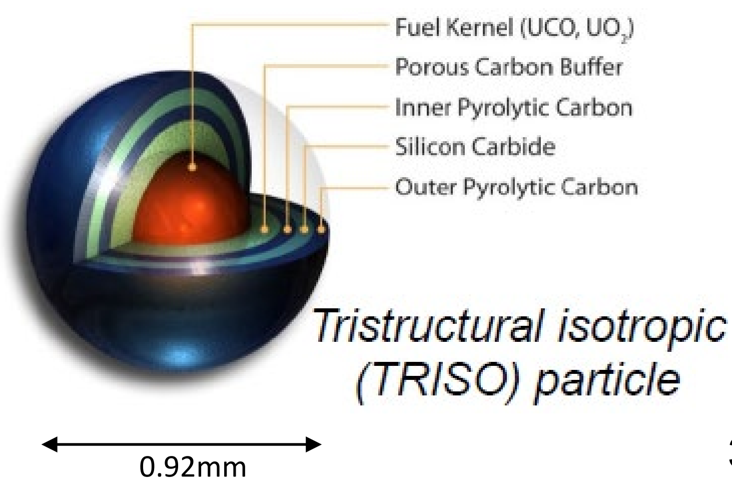
Feature of High Temperature Gas cooled Reactor HTGR (Pebble Bed and Prismatic type)

- Superior safety
  - No hydrogen explosion occurs because it is cooled by chemically stable helium gas instead of water.
  - Temperature does not rise too high during loss of coolant accident or SBO because the graphite structures absorb and dissipate heat.
  - Multiple layers of fuel coatings make the reactor fuel extremely difficult to melt.
- Diverse and efficient use of heat
  - industrial applications such as hydrogen production using high-temperature heat (750~950 ^{o}C)
  - District heating and seawater desalination using low-temperature heat

Feature of HTGR: Pebble Bed type

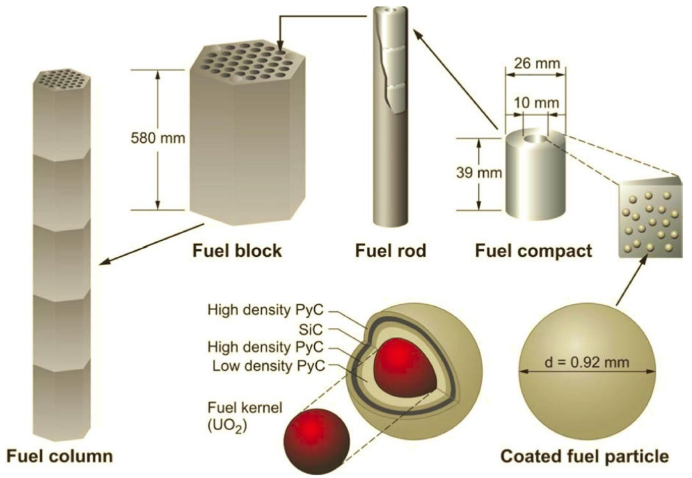
- Fuel Type: TRISO (TRI-Structural ISOtropic) Fuel
- Fuel:HALEU (High-Assay, Low Enriched Uranium） fuel
  (~20% enrichment)
- Coolant: Helium Gas
- Reactor Outlet Temperature: ~750 °C
- Primary Pressure: 4~6 MPa
- Continuous Operation
  by On-line Fuel Loading
- Reactivity Change during
  earthquake





Feature of HTGR: Prismatic type

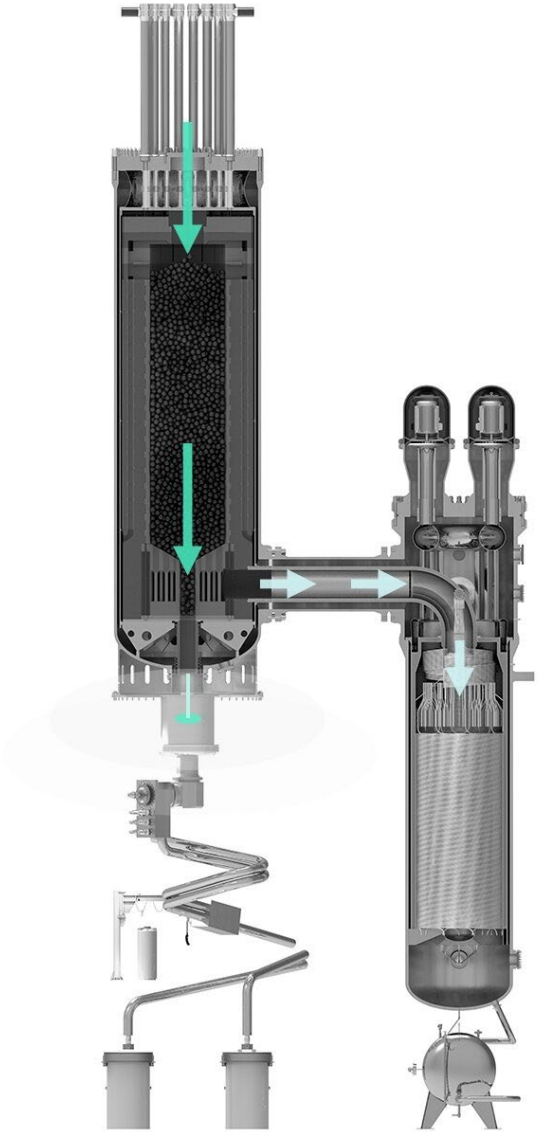
- Fuel Type: Block
- Fuel:HALEU (High-Assay, Low Enriched Uranium） fuel (~20% enrichment)
- Coolant: Helium Gas
- Reactor Outlet Temperature: ~950 ^{o}C
- Primary Pressure: 4~6 MPa
- No additional safety measures (No fuel or reactor vessel meltdown even if no electricity and no scrum)
- Low energy density and Large size structure (RV size: 10 times of PWR)



HTGR Type: Xe-100 (X-energy)

(Investment from Amazon)

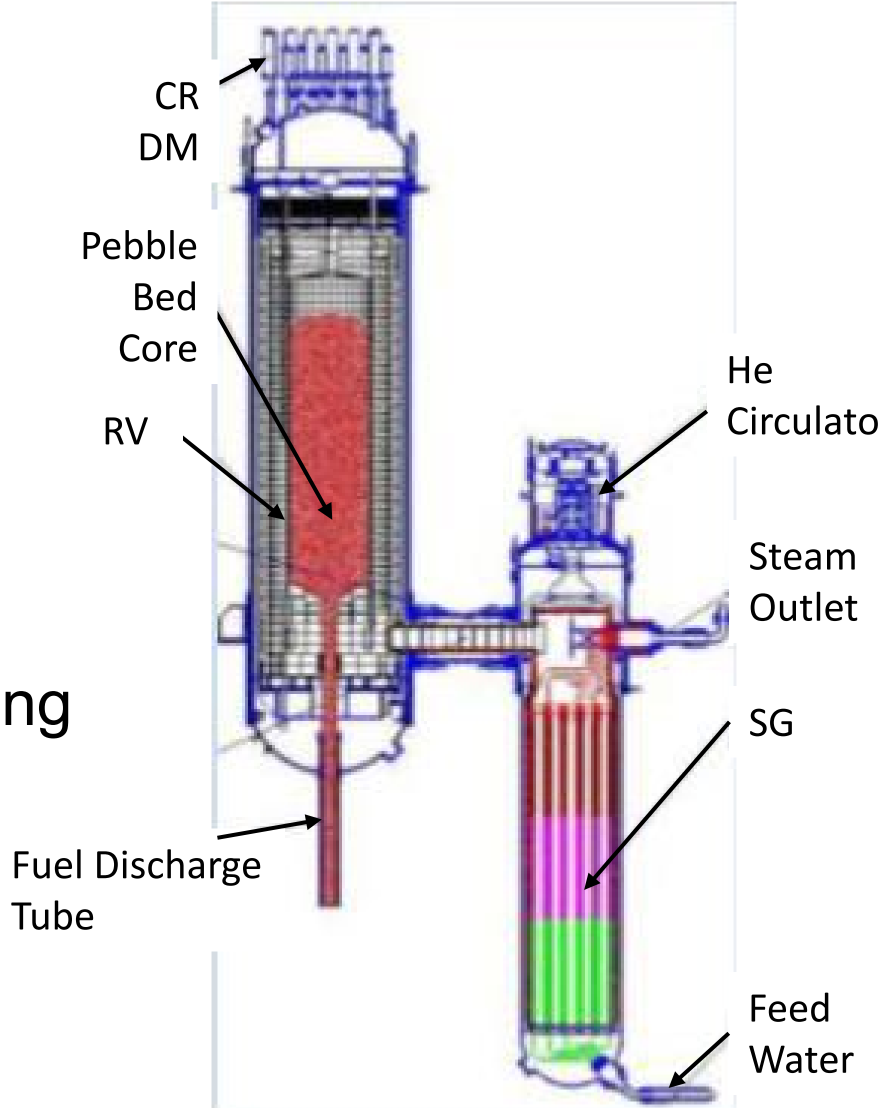
- Power: 80 MWe
- Coolant: Helium
- High temperature tolerant graphite core structure
- 220,000 Graphite Pebbles with TRISO Particle fuel
- Helium temp.: 750 ^{o}C
- Helium pressure: 6 MPa
- Steam temp.: 565 ^{o}C
- Steam pressure: 16.5 MPa
- Refuel interval: Online refueling (95% plant availability)
- Operational life: 60 years



https://x-energy.com/reactors/xe-100

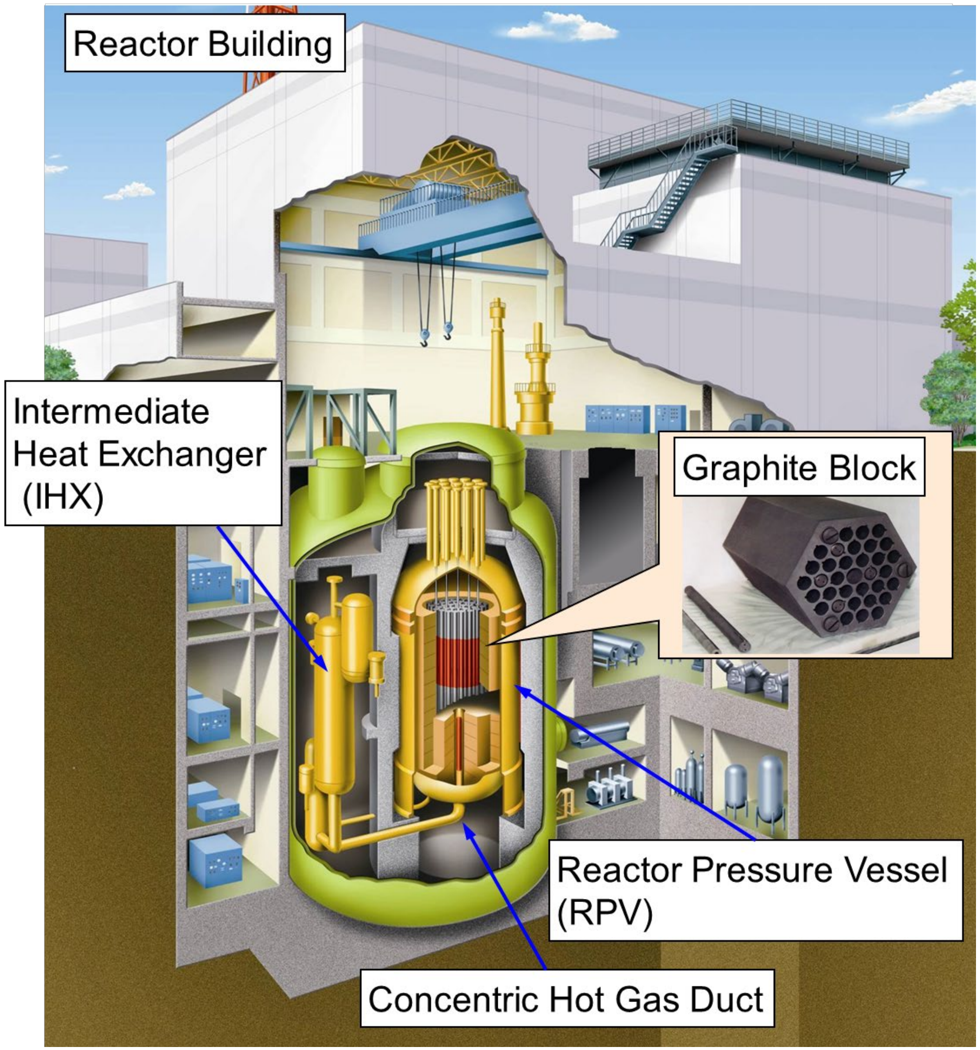
HTGR Type: HTR-PM (INET Tsinghua University, China)

- Power: 210 MWe (x 2 unit)
- Pebble-Bed Module HTGR
- Enrichment: 8.5% (7g)
- Diameter: 60 mm
  (more than 245,000 pebbles)
- Forced Circulation
- Core Outlet Temp: 750^{o}C
- Refuel interval: Online Refueling
- Commercial Operation:
  December 2023
- Local Heating Project in 2024



M. Hadid Subki IAEA, July 2022

HTGR Type: HTTR (High Temperature Engineering Test Reactor) (JAEA)



Thermal power	**30 MW**
Fuel	**Coated fuel particle / Prismatic block type**
Core material	**Graphite**
Coolant	**Helium**
Inlet temp.	**395°C**
Outlet temp.	**950°C**
Pressure	**4 MPa**

1998 : First criticality
2001 : Full power operation
2010 : 50 days continuous 950°C Operation
2010 : Loss of core flow test at 9MW

(Great East Japan Earthquake : 2011)

2021 : Restart
2022 : Loss of core cooling test at 9MW
2024 : Loss of core cooling test at 30MW

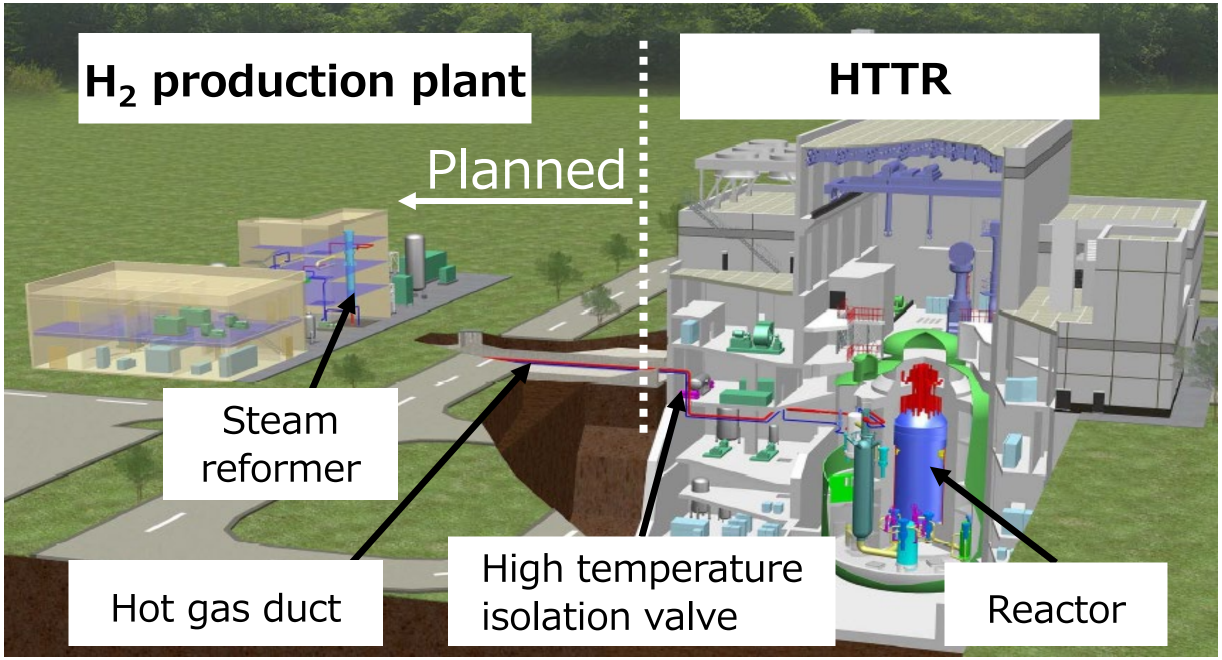
R&D activities using HTTR in JAEA

Objectives

- Safety design for coupling reactor and H_2 production plant
- Demonstration between reactor and H_2 production plant (high temperature isolation valves, hot gas duct, etc.)

Tasks

- Continuous H_2 production by **steam reforming method** (need natural gas) test and plant dynamic tests (~ 2030)



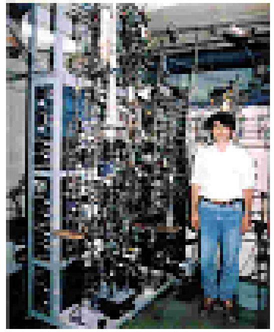
HTTR heat application test

Ref.) H. Sato, "Perspectives on the Role of JAEA towards Industrial Application of HTGR," OECD/NEA WS High temperature reactor and industrial heat application, October 7, 2021.

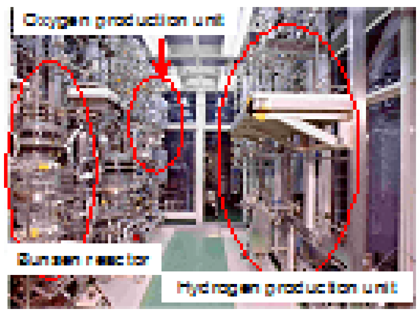
R&D on IS process for H_2 production at JAEA

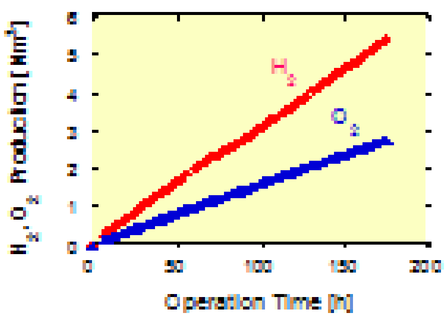
(1) Laboratory-scale test

- ✓ *Verification of closed-cycle continuous hydrogen production condition by IS Process (1997)*



(2) Bench-scale test

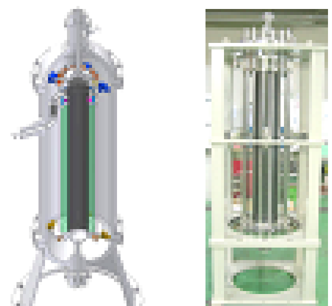




- ✓ *Demonstration of one-week continuous H_2 production (30 NL/h, 2004)*

(3) Process engineering

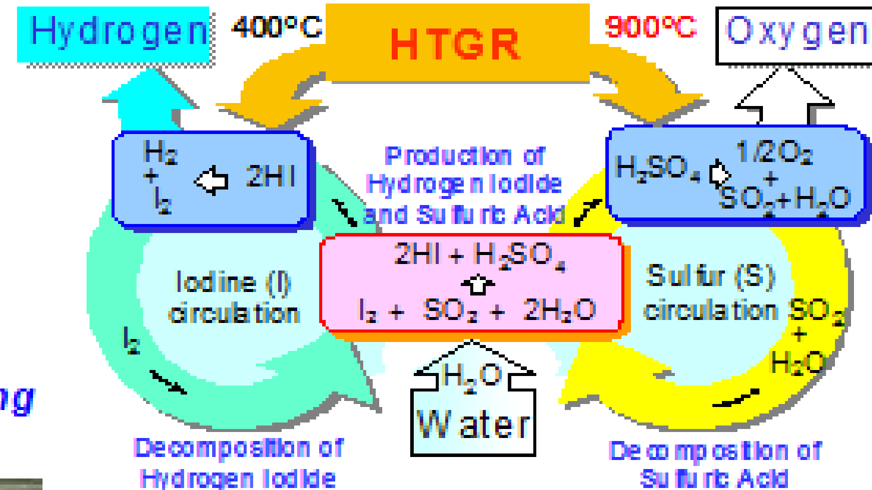
➤ *Materials, components*



- ✓ *Ceramic heat exchanger for sulfuric acid decomposer (2006)*
- ✓ *Development of chemical reactors (ongoing activity)*

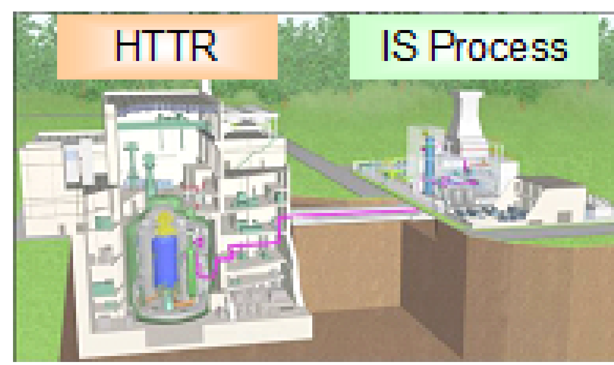
➤ *Process improvement*

- ✓ *Efficiency enhancement (ongoing activity)*
- ✓ *System simplification*



Scheme of IS process

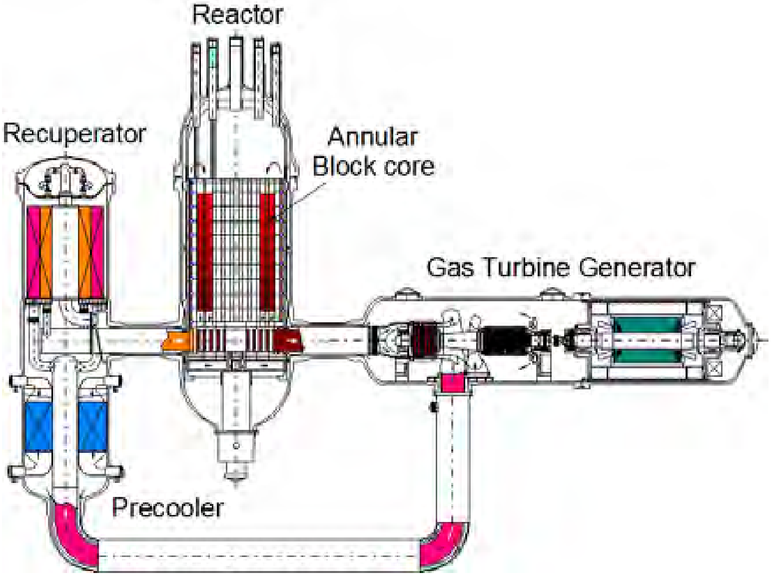
(4) HTTR-IS test - future plan -



HTGR Type: GTHTR300 (JAEA Consortium)

- Power: 300 MWe
- Tank type module reactor
- Coolant: Helium
- Moderator: Graphite
- Coated fuel particle
  (Diameter <1mm)
- Core Inlet temp.: 587-633 ^{o}C
- Core Outlet temp.: 850-950 ^{o}C
- Helium gas turbines for electricity production
- IS process for hydrogen production
- Desalination and other products

Kernel（UO_2）
Buffer Layer
iPyC Layer
SiC Layer
oPyC Layer



IAEA: Advances in Small Modular Reactor Technology Developments (2020)

Feature of Marine-Based Reactor Type

- **Basic Design is PWR.**
- Mobile power for island areas and disaster areas
- A lot of experiences from nuclear ships
- Decay heat removal using seawater without power source
- Low impact from tsunamis and earthquakes
- Reduce evacuation of residents at severe accident

Marine-Based Reactor:
KLT-40S (Afrikantov OKBM, Russia)

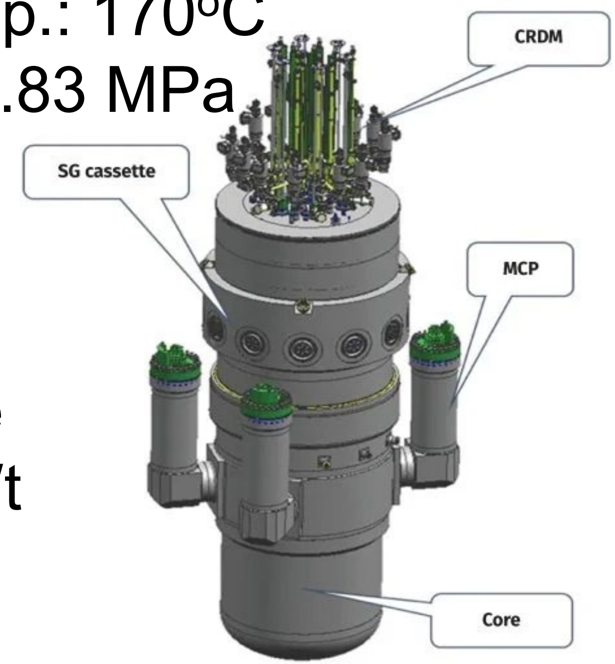
- Compact Loop PWR
- 35 MWe per module (x 2)
- Core Outlet Temp. 316^{o}C
- Refuel interval: 36 months
- Fuel Enrichment: 18.6%
- Commercial Operation: May 2020
- Location: Pevek, Russia

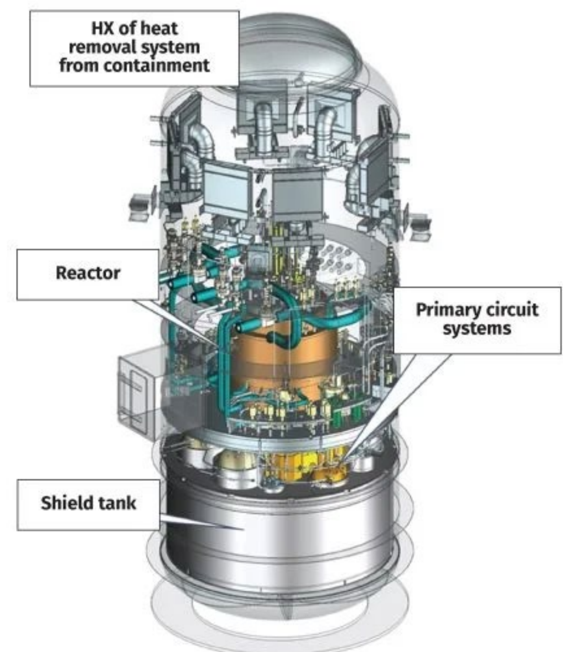
Alexander Ryumin | TASS | Getty Images

Marine-Based Reactor:RITM-200N (Rosatom)

(for icebreakers ‘Arktika’, ‘Sibir’, ‘Ural’ and ‘Yakutia’)

- Power: 55 MWe (x 2)
- Design Life: 60 years
- Fuel Enrichment: below 20% UO_2
- Primary Loop: 4
- Steam Temp. 295^{o}C
- Feed water Temp.: 170^{o}C
- Steam Press.: 3.83 MPa





RITM-400

- Power: 80MWe
  315MWt

https://www.neimagazine.com/analysis/the-ritm-200n-as-a-terrestrial-unit/?cf-view

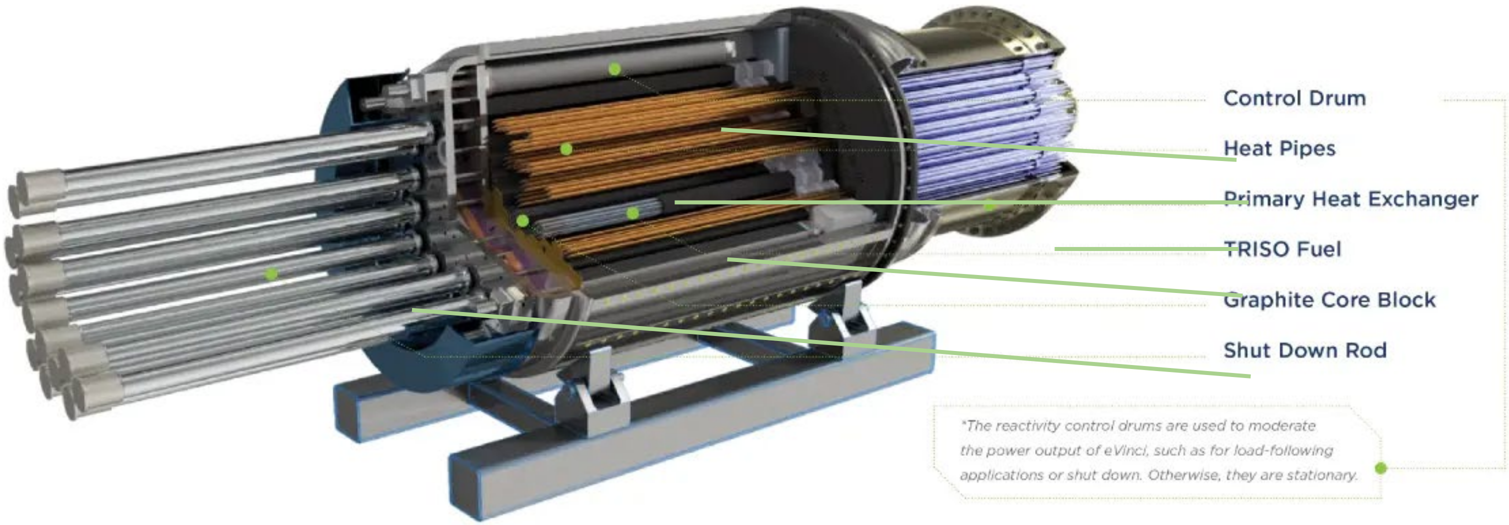
Offshore Floating Nuclear Plant (OFNP) in Japan

- Usual Large Scale PWR (600~1000 Mwe)
- Use of technology for construction of offshore oil field facilities
- Eliminates evacuation of residents in the event of accidents because of far distance from land

Ref. Nuc. Tec., 194, 1(2016)

Micro-Reactor: eVinci (Westinghouse)

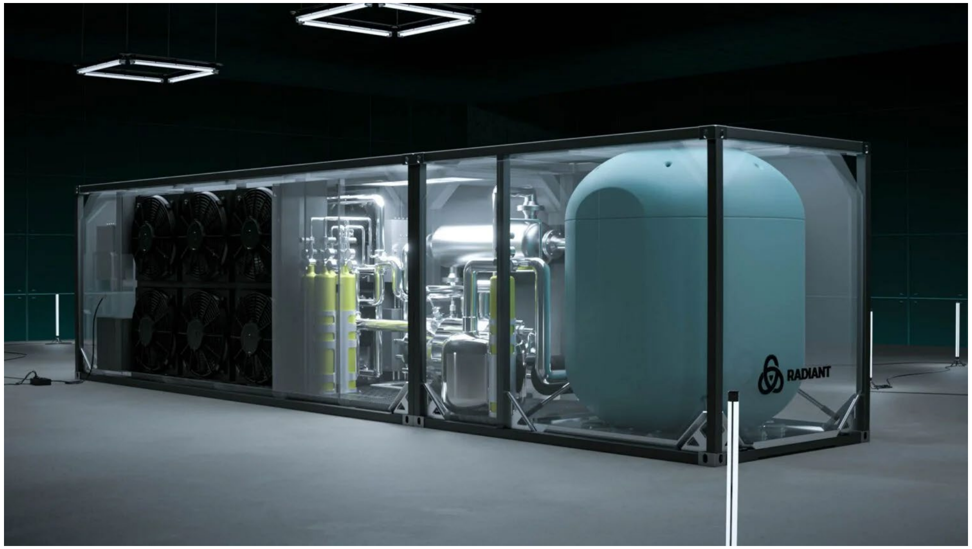
- Power:5MWe (15MWth)
- Refueling Cycle: 8 year or more
- Heat pipe: passive heat transport devices
- TRISO fuel:19.75% enriched fuel
- Control drums: Adjust reactivity
- Shut Down Rods: Inserted during transport



https://westinghousenuclear.com/energy-systems/evinci-microreactor/

Micro-Reactor: Kaleidos (Radiant, Idaho NL)

- Reactor Type: High temperature gas cooling reactor
- Power: 1.2 MWe (1.9 MWt)
- Fuel: HALEU TRISO fuel (3 layer)
- Fuel Cycle: 5 years
- Radiant will deploy Kaleidos reactors to Buckley Space Force Base by 2028 — delivering resilient, cyber-secure power within 48 hours of arrival. (all components are in one container)
- 50 units per year in 2030s



https://www.radiantnuclear.com

Micro-Reactor: Aurora (Oklo)

- Reactor Type: liquid metal-cooled fast reactor
- Power: 15 MWe x 2 + 50 MWt
- Fuel: HALEU metallic uranium-zirconium
  (~19% Uranium Enrichment)
- Clean energy for Air Force Base
- Experience in EBR-II (20MWe at INL (Idaho National Lab.))

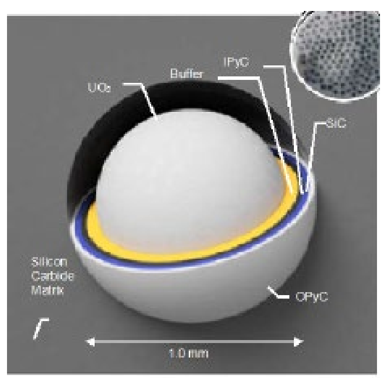
Oklo's Aurora powerhouse

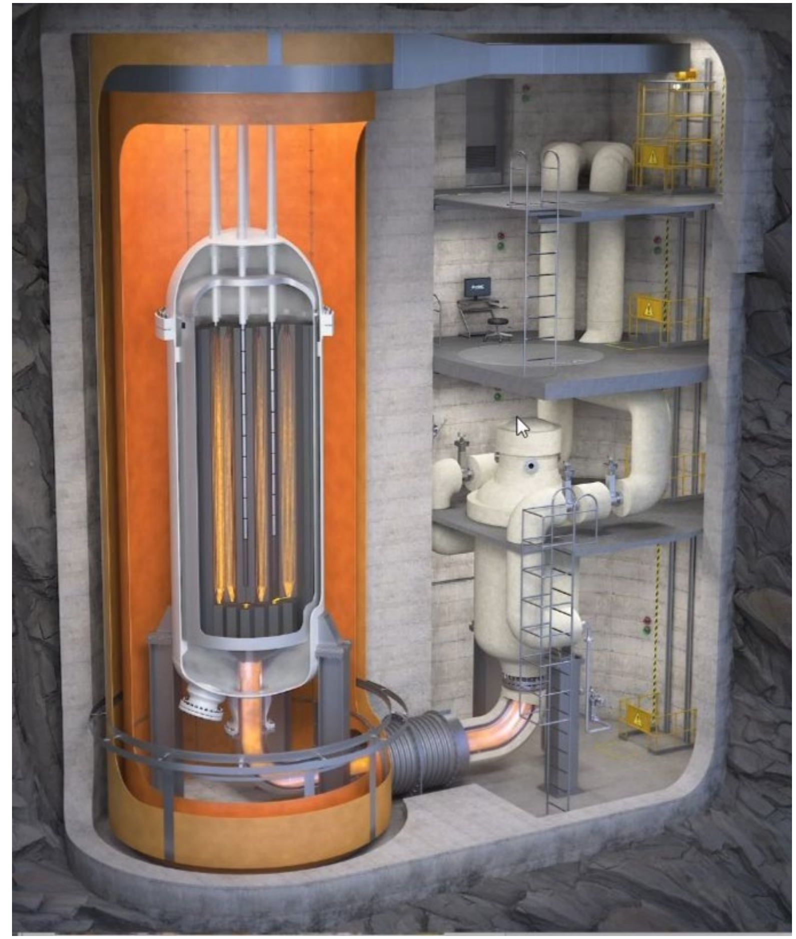
EBR-II

https://www.oklo.com/technology/default.aspx

Micro-Reactor: KRONOS MMR (NANO Nuclear Energy Inc. and University of Illinois)

- Reactor Type: High temperature gas cooling reactor
- Power: 3.5~15 MWe (10~45MWth)
- Coolant : Helium gas
- Lifetime: 20 years without refueling
- Steam Temp: 660 ^{o}C
- Fuel: Ceramic Micro-encapsulated (FCM) fuel [HALEU: 9.9-20% Enrichment]





https://nanonuclearenergy.com/kronos-mmr/

https://nanonuclearenergy.com/wp-content/uploads/2025/01/KRONOS-MMR-Lifecycle.mp4

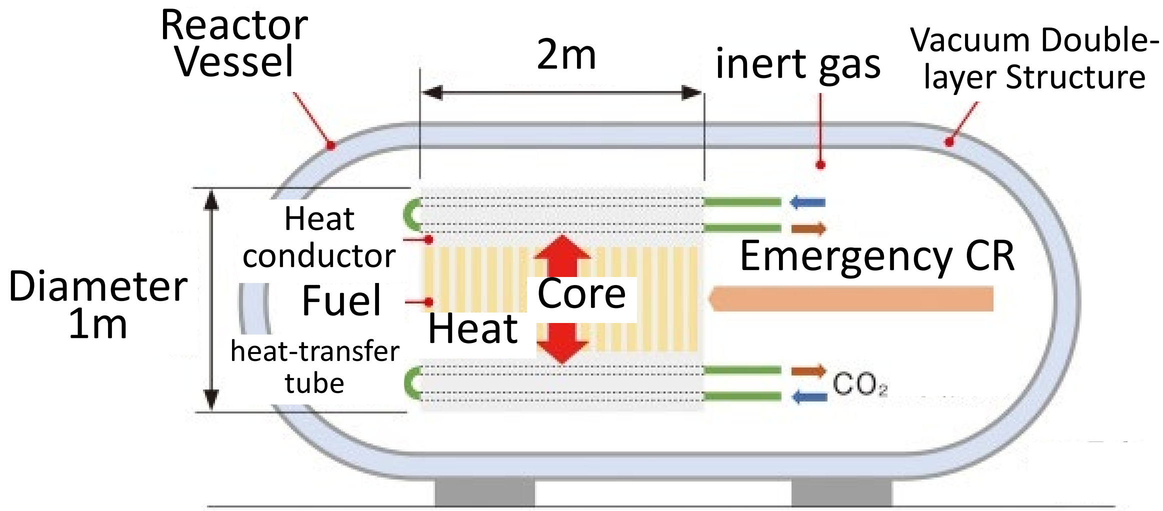
Micro-Reactor: Project Pele (BWXT)

- Reactor Type: High temperature gas cooling reactor
- Power: 1 ~ 5 MWe (Demonstration 1.5MWe for DOD)
- Fuel: HALEU TRISO fuel (3 layer)
- Reactor system moves in 6m long shipping containers
- Reactor system can be operational within 72 hours, including on-site assembly. (7 days for disassembly)
- 2028 Electricity Produce (2025 July fabricate reactor core)

https://www.bwxt.com/what-we-do/advanced-technologies/terrestrial-micro-rx

Micro-Reactor (MHI)

- Reactor Type: All-solid-state reactor
- Power: ~0.5 MWe (~1.0MWt)
- Core Outlet Temperature: ~ 850 ^{o}C
- Design Life: 25 years
- Fuel: HALEU (~20% Uranium Enrichment) No Fuel Exchange
- Emergency power supply for disaster area



Schedule of SMRs in the world

- The first NuScale Power Module will be built in 2029.
  → Canceled due to increased construction costs
- The first BWRX-300 in Ontario, Canada could be operational by 2029.
- 3 Rolls-Royce SMRs will be built in North Wales, UK. (Operation: mid-2030s)
- The first Xe-100 will be build for electricity and heat for Dow Chemical Company plant in Texas in five years(?).
- The construction of Natrium (non-nuclear part) has begun in Wyoming.
- The construction plans for most SMRs will be delayed because they use HALEU fuel (~20% enrichment).
- U.S.A. and UK will build uranium enrichment facilities.

Question: Which SMR is best for your country?

- PWR type
- BWR type
- Sodium cooled Fast Reactor
- Morten Salt Reactor
- High Temperature Gas cooled Reactor
- Marine-Based Reactor (PWR type)

OR

- Large Scale PWR (more than 1,000 MWe)

Thank you for your attention!