Japan's SMR (Small Modular Reactor) Designs

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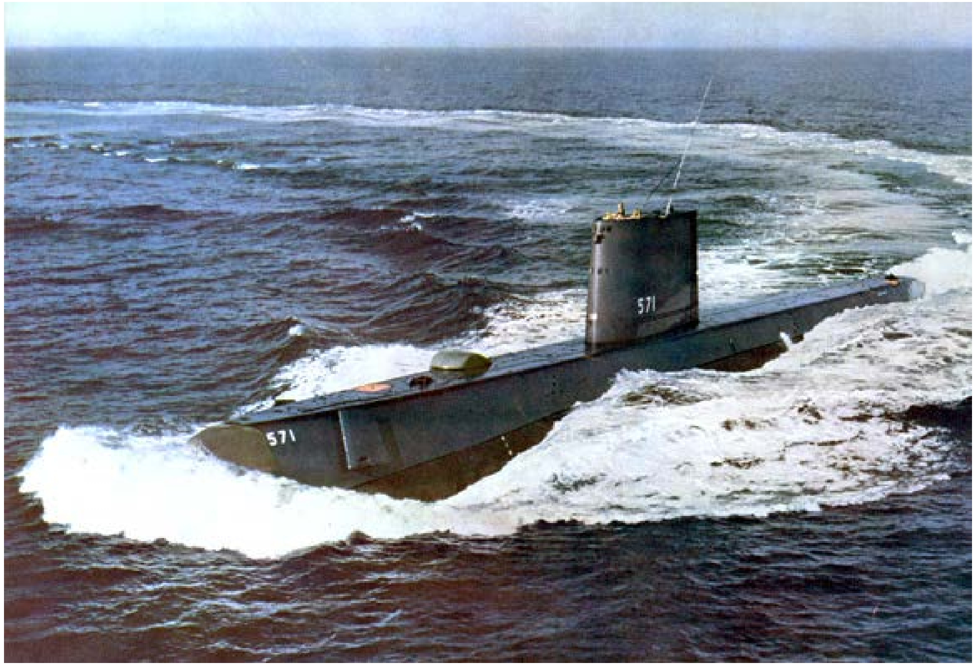
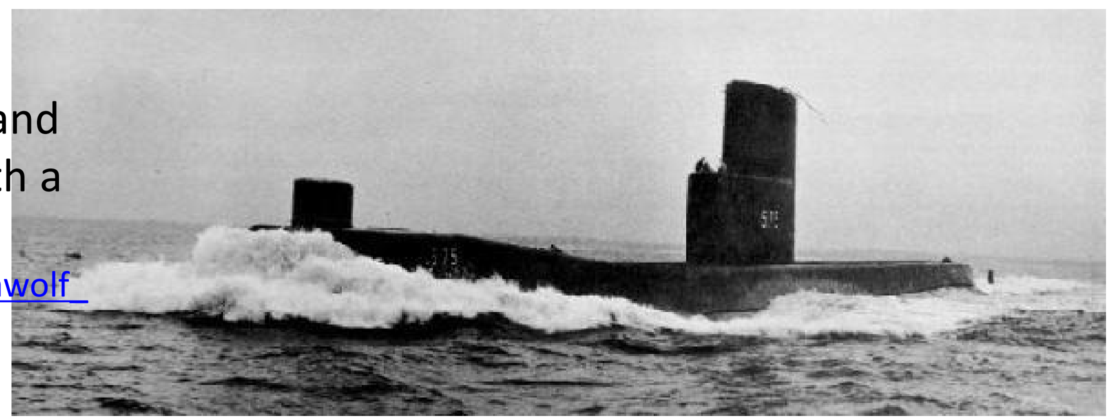
Nautilus and Seawolf



USS *NAUTILUS* (SSN-571)
The world's first nuclear-powered submarine which sailed beneath the Arctic icepack to the North Pole and broadcast the famous message "*Nautilus* 90 North."
http://www.hnsa.org/ships/nautilus.htm

USS *Seawolf* (SSN-575)
The second nuclear submarine, and the only U.S. submarine built with a sodium cooled nuclear reactor.
http://en.wikipedia.org/wiki/File:USS_Seawolf_(SSN-575)_underway.JPG



Possible motivation or driving forces of SMR

- The need for flexible power generation for wider range of users and applications;
- Replacement of aging fossil-fired units;
- Potential for enhanced safety margin through inherent and/or passive safety features;
- Economic consideration – better affordability;
- Potential for innovative energy systems:
  - Cogeneration & non-electric applications
  - Hybrid energy systems of nuclear with renewables

according to the presentation of Dr. Subki of IAEA, 2013

Economics of Small Nuclear Reactors by OECD/NEA Studies

(1991) **Small and Medium Reactors**

http://www.oecd-nea.org/brief/brief-07.html

- Volume I. Status and Prospects
- Volume II. Technical Supplement

(2011) **Current Status, Technical Feasibility and Economics Of Small Nuclear Reactors**

http://www.oecd-nea.org/ndd/reports/2011/current-status-small-reactors.pdf

- Brief characterization of SMR available for commercial deployment
- Characterization of advanced SMR designs
- Small and modular reactors (“mini” reactors) and their attributes
- Factors affecting the competitiveness of the SMR
- Assessment of the deployment potential of the various proposed SMR designs
- Safety designs of advanced SMR
- Licensing issues

(2013) ***Economics and Market of Small Reactors***

According to the presentation of Alexey Lokhov, OECD/NEA-NDD, 2013

What is different in SMR compared with large reactors?

- **Economy of scale** ***vs.*** **Economy of serial production**
- The absolute cost of one reactor is smaller than for large reactors i.e. expected to be easier to finance
- "Modular construction" -> Tasks that used to be performed in sequence are done in parallel with factory-built modules
  - Already implemented in some large reactors (e.g. ABWR, AP1000)
  - But in case of SMR the module could be the *entire* reactor system
- Redundancy of production unit:
  - Better flexibility (outages)
- Potential co-generation (water desalination, heat production)
  - The power output of SMRs suits well existing heat and water distribution network
  - Multiple modules -> redundancy -> guarantee of continued supply
- Decommissioning: Potentially smaller costs if modules are replaceable and factory disassembled/decommissioned

According to the presentation of Alexey Lokhov, OECD/NEA-NDD, 2013

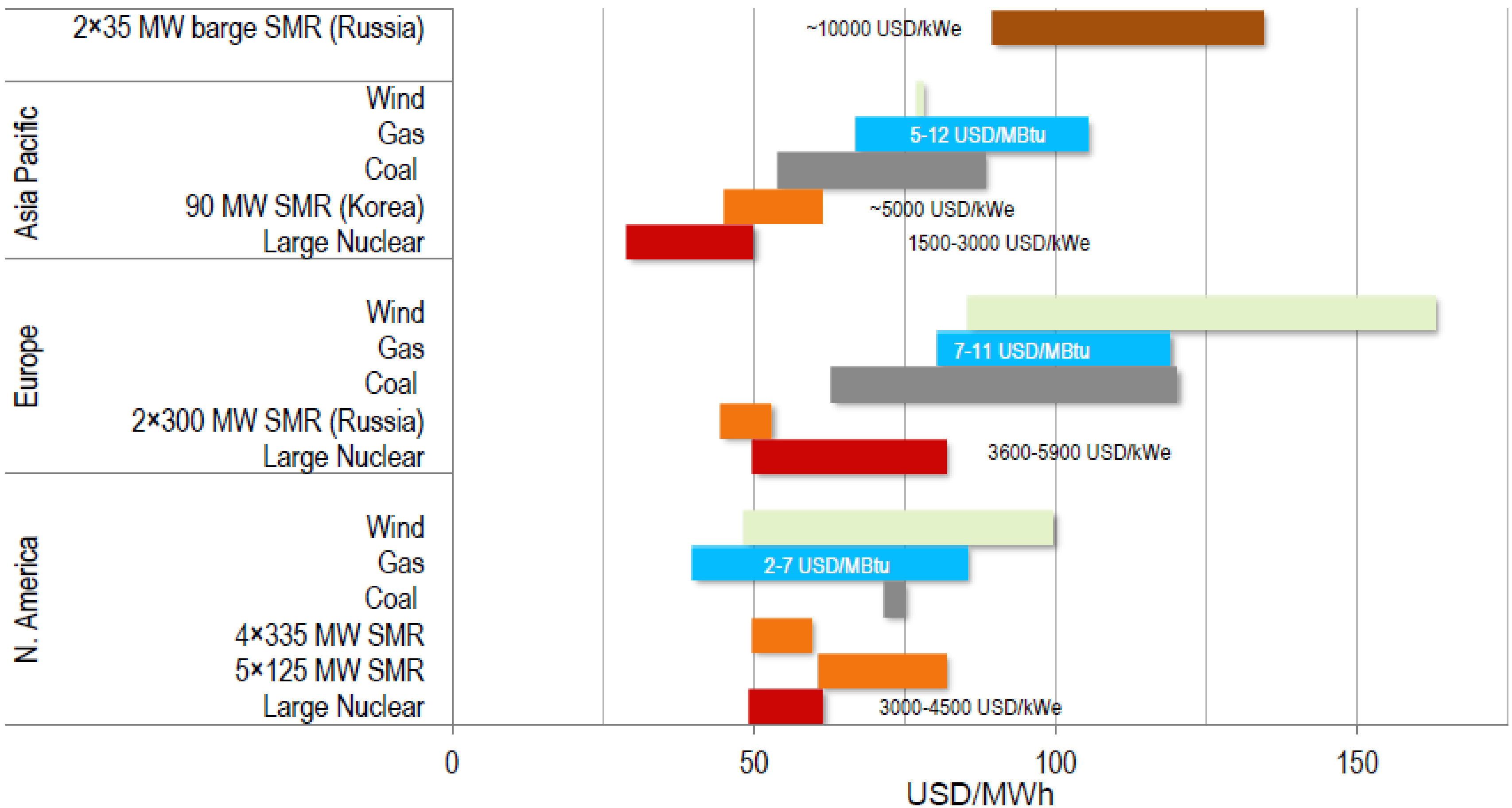
SMRs target two general classes of applications

- **Traditional deployment** and direct competition for electricity production with large NPP and other sources of power, and heat or steam supply with co-generation. Relatively ***small upfront capital investment for one unit*** of a SMR provides more flexibility in staging capacity increases, resulting in smaller financial risks.
- **Niche applications in remote or isolated areas** where large generating capacities are not needed, the electrical grids are poorly developed or absent, and where the non-electrical products (heat or desalinated water) are as important as the electricity.

Modified the presentation of Alexey Lokhov, OECD/NEA-NDD, 2013

LCOE estimates for SMRs and alternative sources, at 5% real discount rate)

The band represents the uncertainty on data and calculations



Estimates suggest that SMRs may be economically competitive

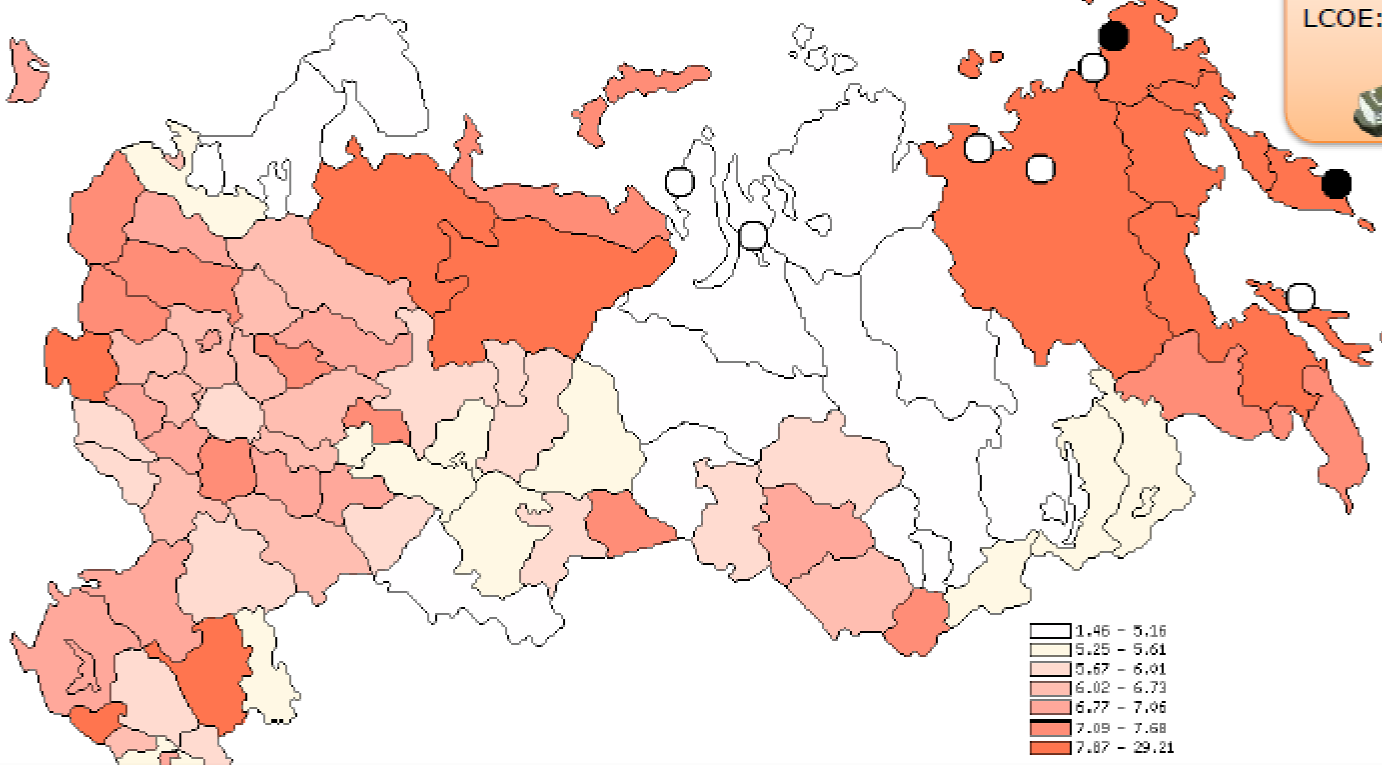
According to the presentation of Alexey Lokhov, OECD/NEA-NDD, 2013

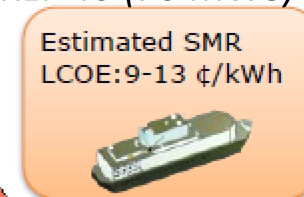
Development of small nuclear reactors (SMRs)

Example of niche application in remote areas in Russia

Map of electricity tariffs (in USD cents per kWh) in Russia in 2010

Based on Order #216-e/2 of the Russian Federal Tariff Service (22 September 2009): http://www.fstrf.ru/tariffs/info_tarif/electro/0





Land-based and barge-mounted SMR plants with LCOE substantially higher compared to alternative sources could still be competitive in these niche markets if they meet certain technical and infrastructure requirements, defined by the specific climate, siting and transportation conditions.

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Features of SMR designs

High Temperature Gas Cooled Reactor

- Inherent Robust Safety
  - Solid confinement of fuel and radioactivity
  - Strong resistance to loss of coolant flow, SBO
  - Possible elimination of core melt accident
- Utilization of high temperature to industrial application; hydrogen, etc.
- Possible utilization of Thorium

LWR

- Based on proven LWR technologies
- Common fuel and fuel cladding
- Simplification by application of passive safety system
- Possible utilization of large water pool for long term cooling

Fast Reactor

- Long life core without refueling
- Possible application for proliferation resistant system with closed fuel cycle (IFR)
- Possible elimination of core destructive accident
- Possible utilization of natural convection cooling

Thermal neutron, graphite-moderated and helium gas-cooled HTGR

☐ Features of HTGR

- High temperature heat of 950 °C
  High thermal efficiency of 50%
- High level inherent safety
- Small-sized reactor
- No water for cooling

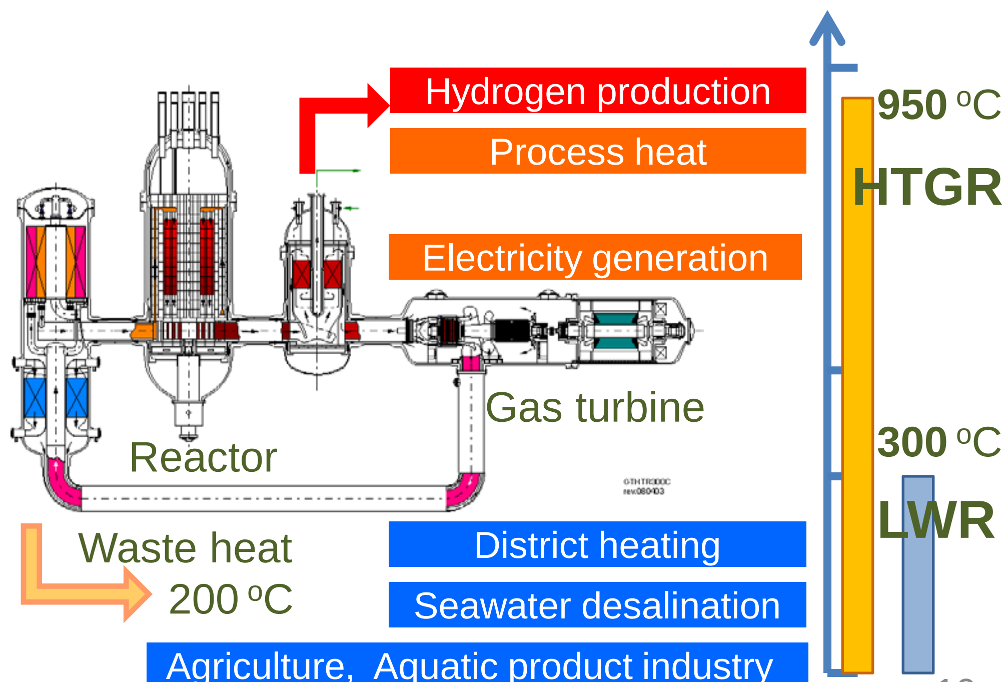
☐ Multi-purpose use

as

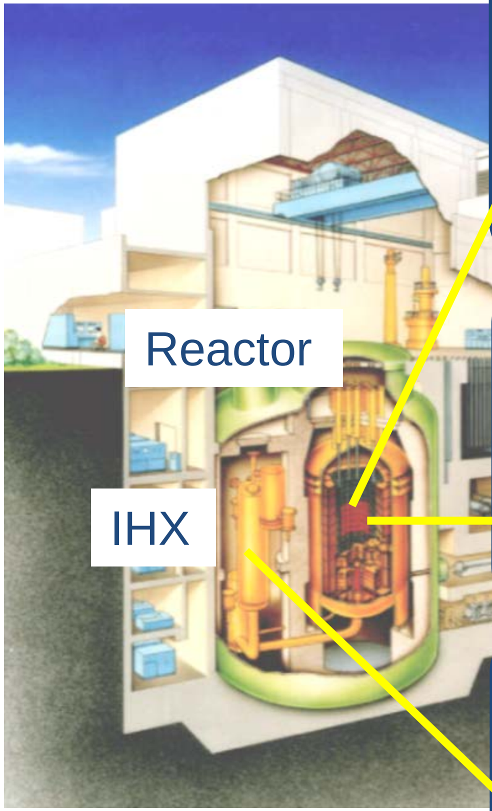
- Decentralized energy plant
- *Gen-IV reactor*

Typical specification

- Coolant temperature : 950 °C
- Thermal Output : Max. 600MW
- Heat utilization ratio : 70-80%
  - with waste heat recovery



Japan’s leading edge technologies in HTGR

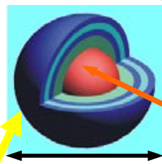


HTTR

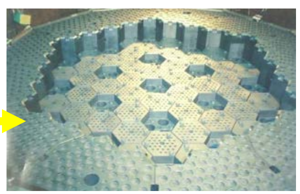
(30MW, 950 ºC)

HTGR Test Reactor of JAEA at Oarai Japan

Ceramic cladding of fuel



Isotropic Graphite



Heat-resistant Superalloy

- Quartet coating technology

  for cladding to have heat resistance

  Confinement of radioactive materials for about three times longer than of LWR

  Temperatures up to 1600 ºC

- Hot-pressurizing technology

  for graphite to have isotropy

  High strength, thermal conductivity, and radioactive-resistance

  Temperatures up to 2400 ºC

- Fortifying technology

  for metal to have heat resistance

- High-temp. structural technology

  for components

- Helium-handling technology

  for coolant to reduce leakage

  (Chemical, mechanical and nuclear-physical stability)

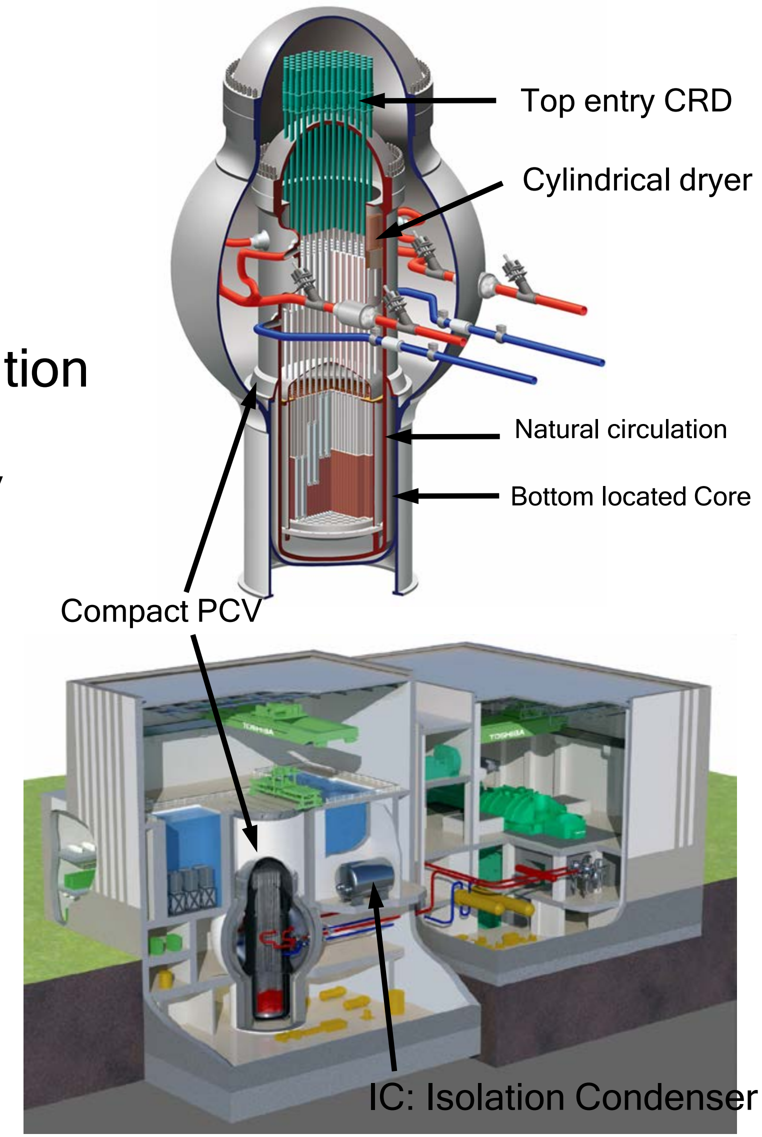
Utilization of heat at high temperature of 950 ºC

CCR : Compact Containment Boiling Water Reactor

■Economical and Safety SMR
- ➢300～600MWe

■Economic competitiveness
- ➢Simplified direct cycle & natural circulation
- ➢Passive safety systems
- ➢High pressure resistible Compact PCV
  - ✓*design pressure : 4MPa*
- ➢Short construction period : 24months

■Comprehensive safety
- ➢Large reactor coolant inventory
- ➢Bottom-located core
- ➢Passive Reactor cooling
- ➢Simplified RPV bottom
  - ✓*with no pipings or nozzles*

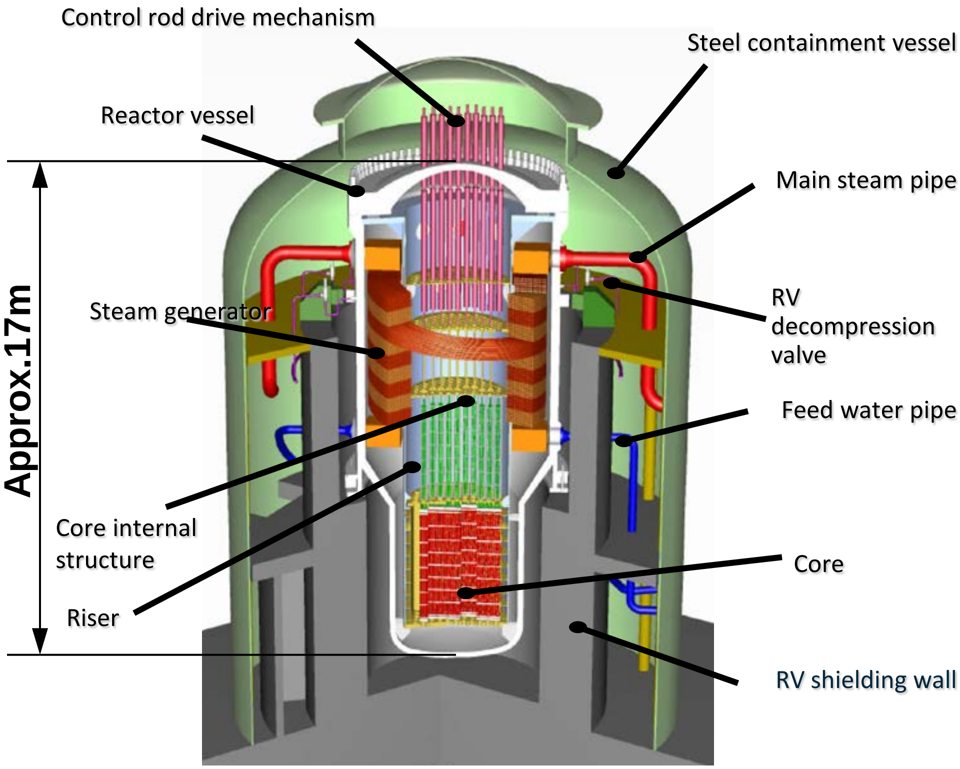


CCR-400 (423MWe)

IMR : Integrated Modular Reactor

- **Integrate the primary system into the reactor Vessel**
- **Safety: LOCA avoidance**
- **Economic: Small and simple**
  - **The volume of containment is 1/10 of the this classes PWR**

Electric output	350MWe
Coolant	light water
Fuel type	PWR fuel assembly
Modular unit	Power uprate by multiple modules

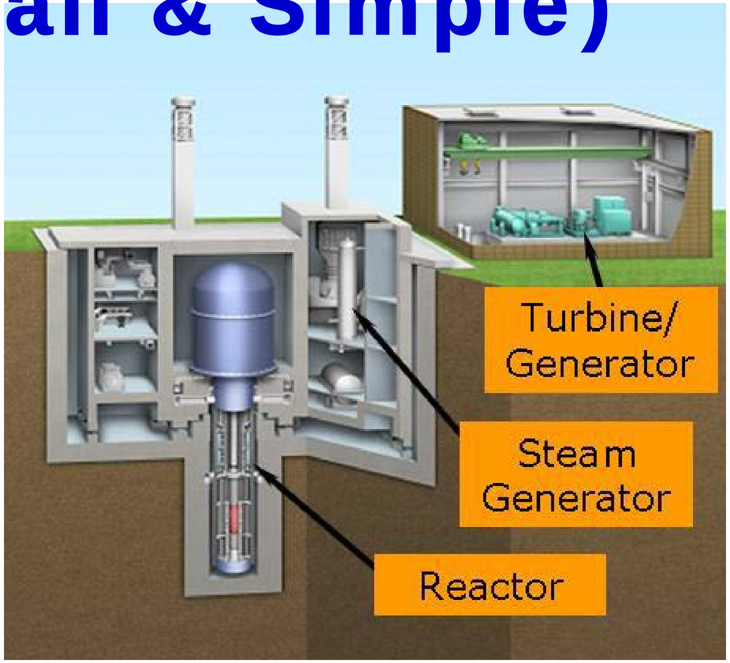


[Note] The conceptual design was performed by MHI and JAPC.

JAPC: The Japan Atomic Power Company (Electric utility)
LOCA: Loss of coolant accident

4S

4S (Super-Safe, Small & Simple)



- Distributed Power Supply
- Sodium-Cooled Fast Reactor

  (10MWe／50MWe)
- No Refueling for 30 Years

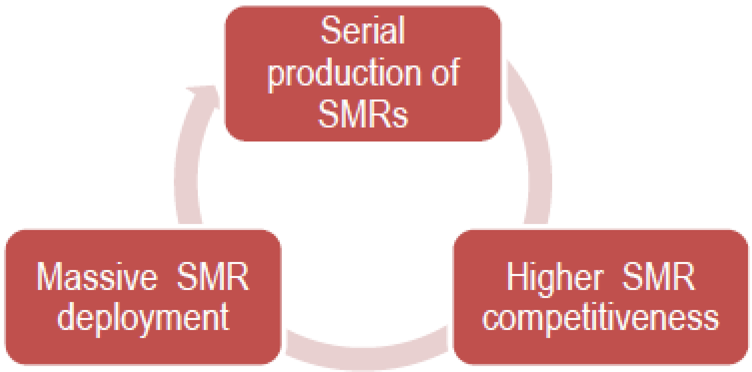
  Metallic Fuel & Long Cylindrical core with small diameter
- Passive Safety

  Negative reactivity feedback of metallic core & Decay Heat Removal System Utilizing Natural Air Draught
- Law Maintenance Requirement by Passive Components and Minimal Moving Parts by EMP
- High Security & Safeguards

  Reactor building is below grade

Development of small nuclear reactors (SMRs)

- SMRs, including multi-module plants, generally have higher generation costs than NPP with large reactors.
- The generation costs for SMR might decrease in case of **large scale serial production** which is very important for proving competitiveness of SMR
  - Large initial order is needed to launch the process. Who can be the first customer?
  - How many SMR designs will be really deployed?



Need to fortify specific features of each concept and designs for segregation and competition

- In summary, **SMR could be competitive with many non-nuclear technologies for generating electricity in the cases when NPP with large reactors are, for whatever reason, unable to compete**
- *The challenges facing SMRs are: Licensing, siting, multiple units/modules on the same site, the number of reactors required to meet energy needs (and to be competitive), and the general public acceptability of new nuclear development.*

Modified the presentation of Alexey Lokhov, OECD/NEA-NDD, 2013