# Overview of Available NPP Designs


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**IAEA INTERREGIONAL WORKSHOP ON**
**Project Management for New Nuclear Power Projects**
**10-14 May 2010, Rep. of Korea**

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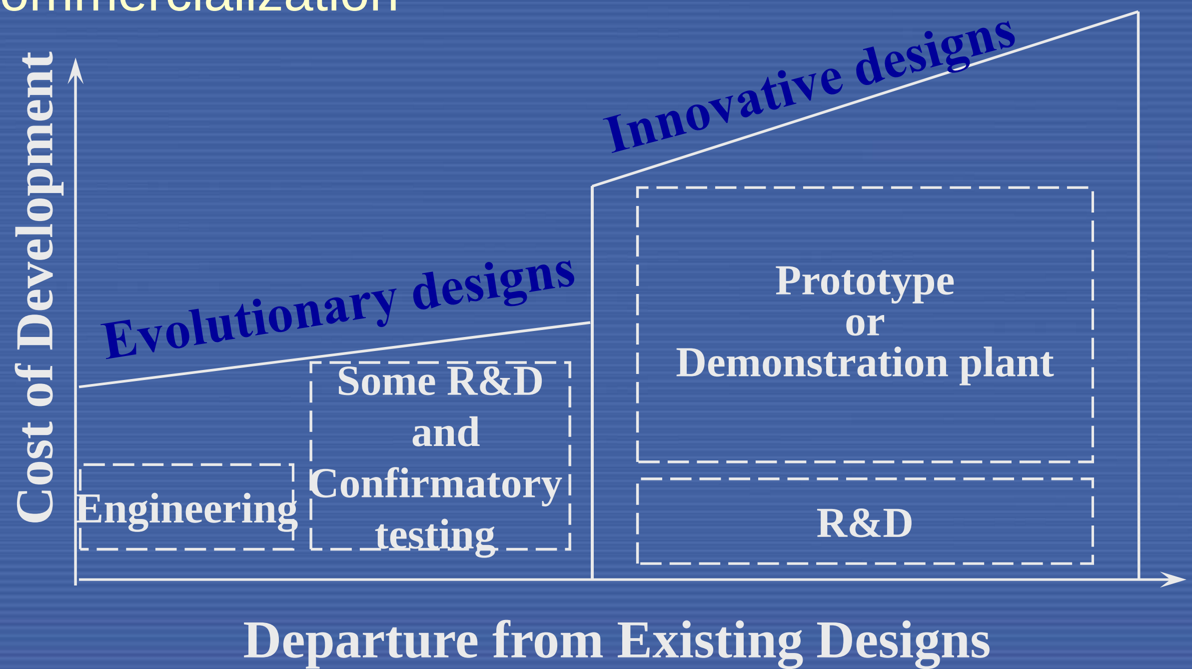
International Atomic Energy Agency

# Advanced Reactor Designs

**(defined in IAEA-TECDOC-936)**

- **Evolutionary Designs** - achieve improvements over existing designs through small to moderate modifications

- **Innovative Designs** - incorporate radical conceptual changes and may require a prototype or demonstration plant before commercialization

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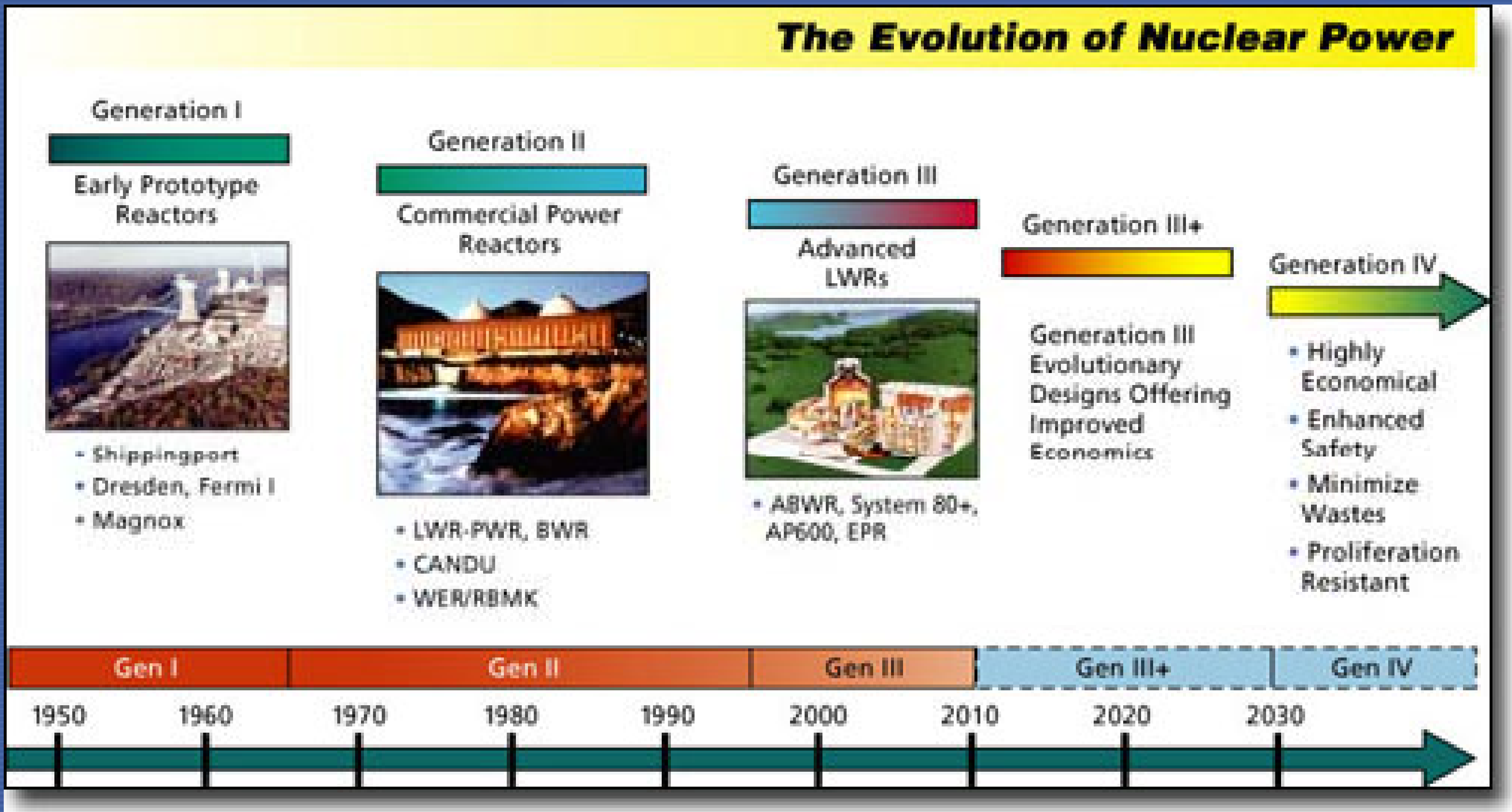
# Another classification…

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# Evolutionary = Generation III & III+

- Current NPP → Generation II
- Advanced NPP
  - Evolutionary NPP → Generation III, Generation III+
  - Innovative NPP → Generation IV

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# Motivation for new designs

- Economics
- Performance
- Safety

# DEVELOPMENT OF ADVANCED DESIGNS

## *Proven means:*

- ***Standardization and series construction***

  Rep. of Korea's Standardized Plants ("OPRs"), Japan's ABWRs, India's HWRs

- ***Multiple unit construction at a site***

  France's 58 PWRs at 19 sites

- ***Improving construction methods to shorten schedule***

  Techniques used at Kashiwazaki-Kariwa 6 &7, Hamaoka 5 & Shika-2; Qinshan III 1&2; Lingau 1&2; Yonggwang 5&6; Tarapur 3&4

- ***In developing countries, furthering self-reliance by increasing portion of construction and component fabrication performed domestically***

  Experience at Qinshan III 1&2; Lingau 1&2; Yonggwang 5&6, Cernavoda 1&2

- ***Economy of scale***

  N4 and Konvoi to EPR; KSNP to APR-1400; ABWR to ABWR-II; AP-600 to AP-1000; 1550 MWe ESBWR; 220 MWe HWR to 540 & 700 MWe HWR; WWER-1000 to WWER-1500

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# DEVELOPMENT OF ADVANCED DESIGNS

## *New Approaches:*

- ***Modularization, factory fabrication, and series production*** (e.g. for SMRs)
- ***Development of highly reliable components and systems, including "smart" (instrumented and monitored) components*** with methods for detecting incipient failures to improve reliability and reduce dependence on costly redundancy and diversity practices
- ***Improving the technology base for reducing over-design*** decreasing the need for large margins simply to allow for limitations of calculational methodology and data uncertainties
- ***Development of passive safety systems***[1] for cases where the safety function can be met more simply than with active systems
- ***Improved corrosion resistant materials***
- ***Design features for longer lifetime***

[1] defined in IAEA-TECDOC-626

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# DEVELOPMENT OF ADVANCED DESIGNS

## *New Approaches:*

- ***Development of computer based techniques*** for co-ordinating design, procurement, manufacture, construction and maintenance
- ***Further development of PSA methods and databases to support***
  - plant simplification, and
  - establishment of risk-informed regulatory requirements
- ***Establishment of user design requirements*** including strong focus on economic competitiveness (EPRI-URD; European Utility Requirements, etc)
- ***Establishment of international consensus regarding commonly acceptable safety requirements*** so that standardized designs could be built in many countries without extensive re-design efforts
- ***Development of systems with higher thermal efficiency; and expanded applications***

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# IAEA Publications

# NPPs Currently in Operation

| TYPE | Number of Units | Total Capacity [MWe] |
|---|---|---|
| **BWR** | 92 | 83,548 |
| **FBR** | 1 | 560 |
| **GCR** | 18 | 8,949 |
| **LWGR** | 15 | 10,219 |
| **PHWR** | 46 | 22,840 |
| **PWR** | 266 | 245,611 |
| **TOTAL** | 438 | 371,727 |

Source: PRIS, IAEA, 2010

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# Water Cooled Reactor Concepts

**Large Size (above 700 MWe)**

- ABWR and ABWR-II (GE,Hitachi, Toshiba)
- APWR and APWR+ (Mitsubishi)
- AP-1000 (Westinghouse)
- ATMEA (AREVA & MHI)
- CNP-1000 (CNNC)
- EC6 and ACR-1000 (AECL)
- EPR (Framatome ANP)
- ESBWR (GE/Hitachi)
- KERENA (Framatome ANP)
- OPR-1000 and APR-1400 (KHNP)
- WWER-1000, WWER-1200, WWER-1500 (Atomenergoproject/Gidropress)
- 700 MWe PHWR (NPCIL)
- 300 MWe AHWR (BARC)

**Medium size (300-700 MWe)**

- WWER-640 (Atomenergoproject /Gidropress)
- 540 MWe PHWR (NPCIL)
- IRIS (Westinghouse)

**Small size (below 300 MWe)**

- CAREM (CNEA/INVAP)
- SMART (KAERI)
- KLT-40 (OKBM)
- NuScale
- mPower

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# Boiling Water Reactors (BWR)

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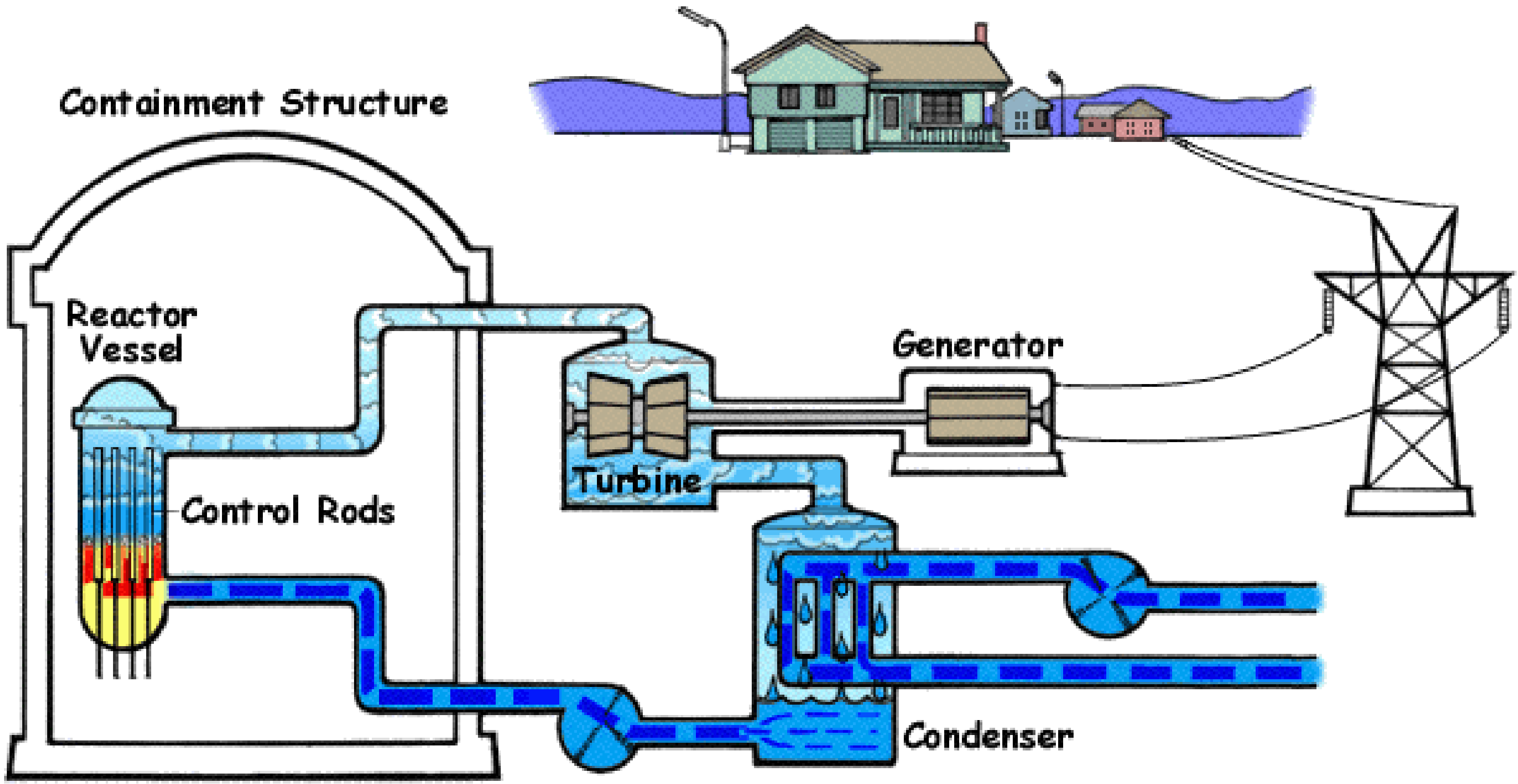
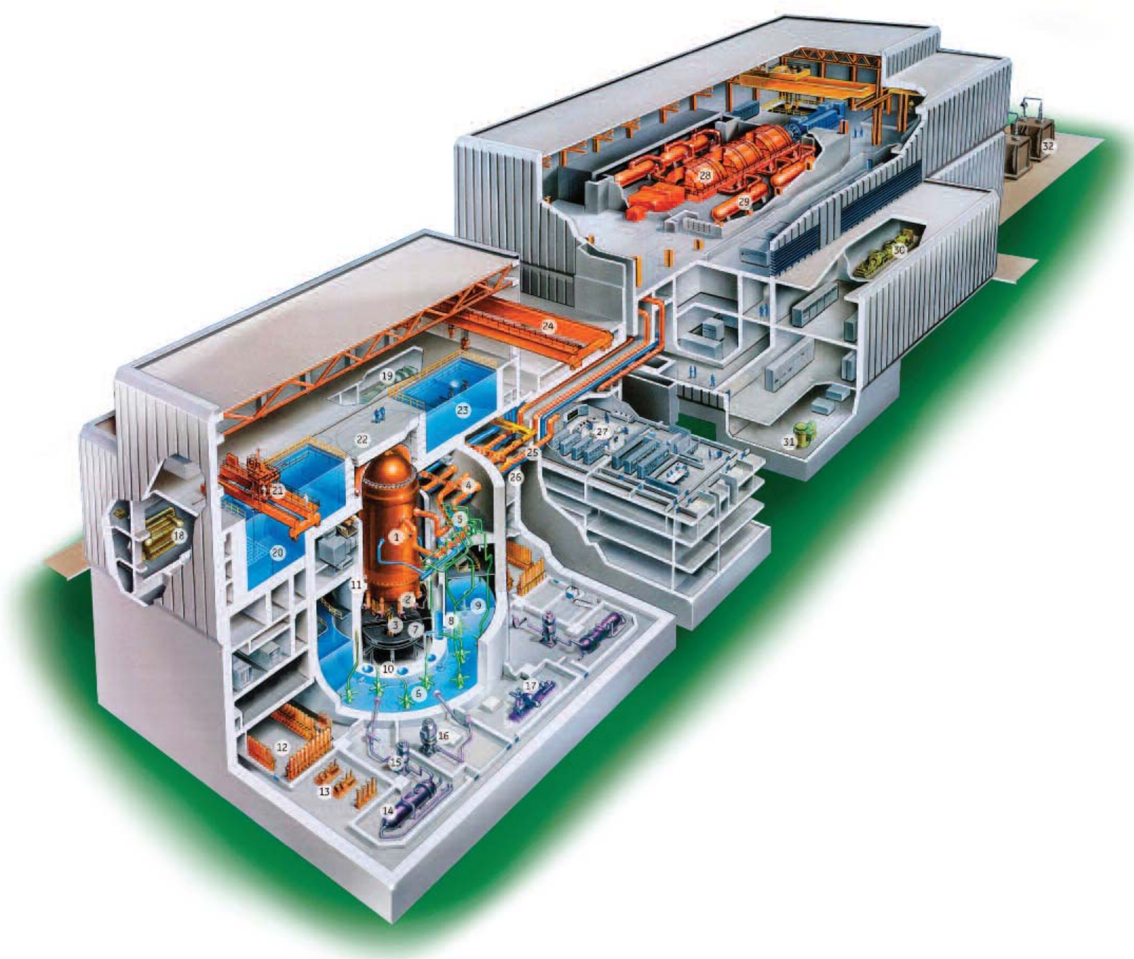
# Boiling Water Reactor (BWR)



# Advanced Boiling Water Reactor (ABWR)

- Originally by GE, then Hitachi & Toshiba
- Developed in response to URD
- First Gen III reactor to operate commercially
- Licensed in USA, Japan & Taiwan, China
- 1380 MWe - 1500 MWe
- Shorter construction time
- Standardized series
  - 4 in operation (Kashiwazaki-Kariwa -6 & 7, Hamaoka-5 and Shika-2)
  - 7 planned in Japan
  - 2 under construction in Taiwan, China
  - Proposed for South Texas Project (USA)



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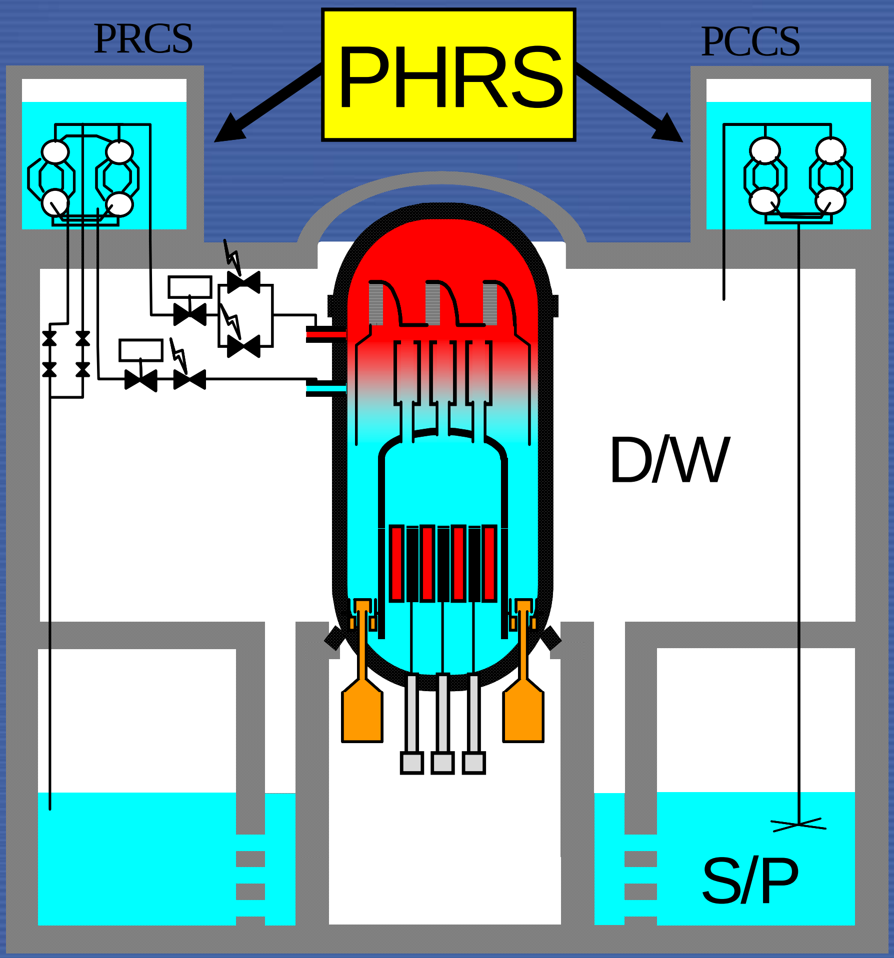
# ABWR-II

- Early 1990s – TEPCO & 5 other utilities, GE, Hitachi and Toshiba began development
- 1700 MWe
- Goals
  - 30% capital cost reduction
  - reduced construction time
  - 20% power generation cost reduction
  - increased safety
  - increased flexibility for future fuel cycles
- Goal to Commercialize – latter 2010s

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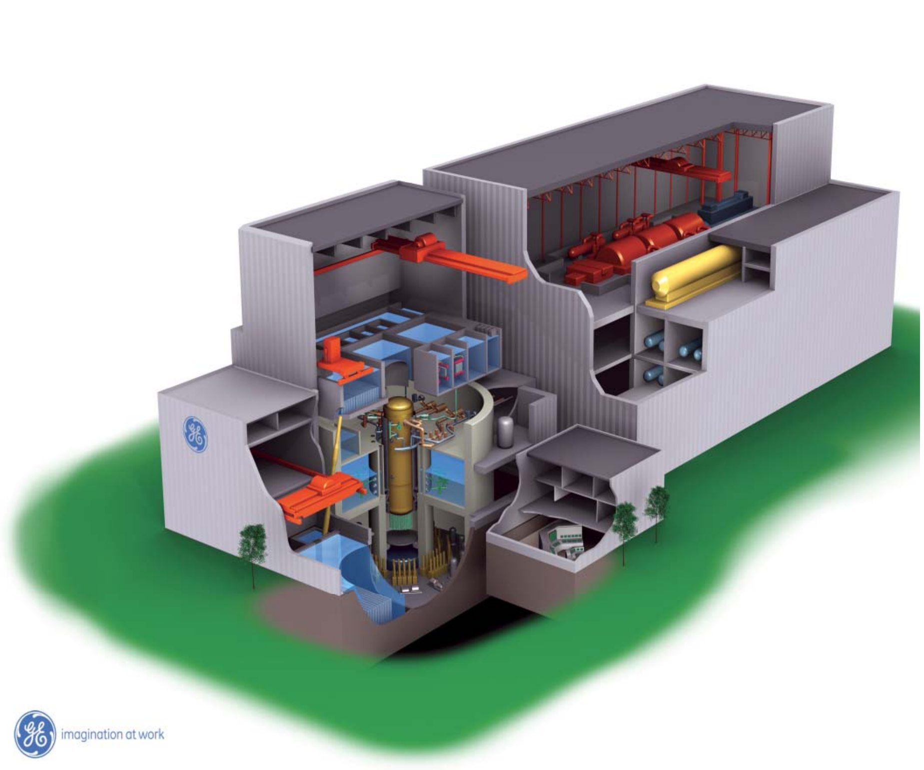
# ESBWR

- Developed by GE
- Development began in 1993 to improve economics of SBWR
- 4500 MWt ( ~ 1550 MWe)
- In Design Certification review by the U.S.NRC
- Meets safety goals 100 times more stringent than current
- 72 hours passive capability
- Key Developments
  - NC for normal operation
  - Passive safety systems
    - Isolation condenser for decay heat removal
    - Gravity driven cooling with automatic depressurization for emergency core cooling
    - Passive containment cooling to limit containment pressure in LOCA
  - New systems verified by tests

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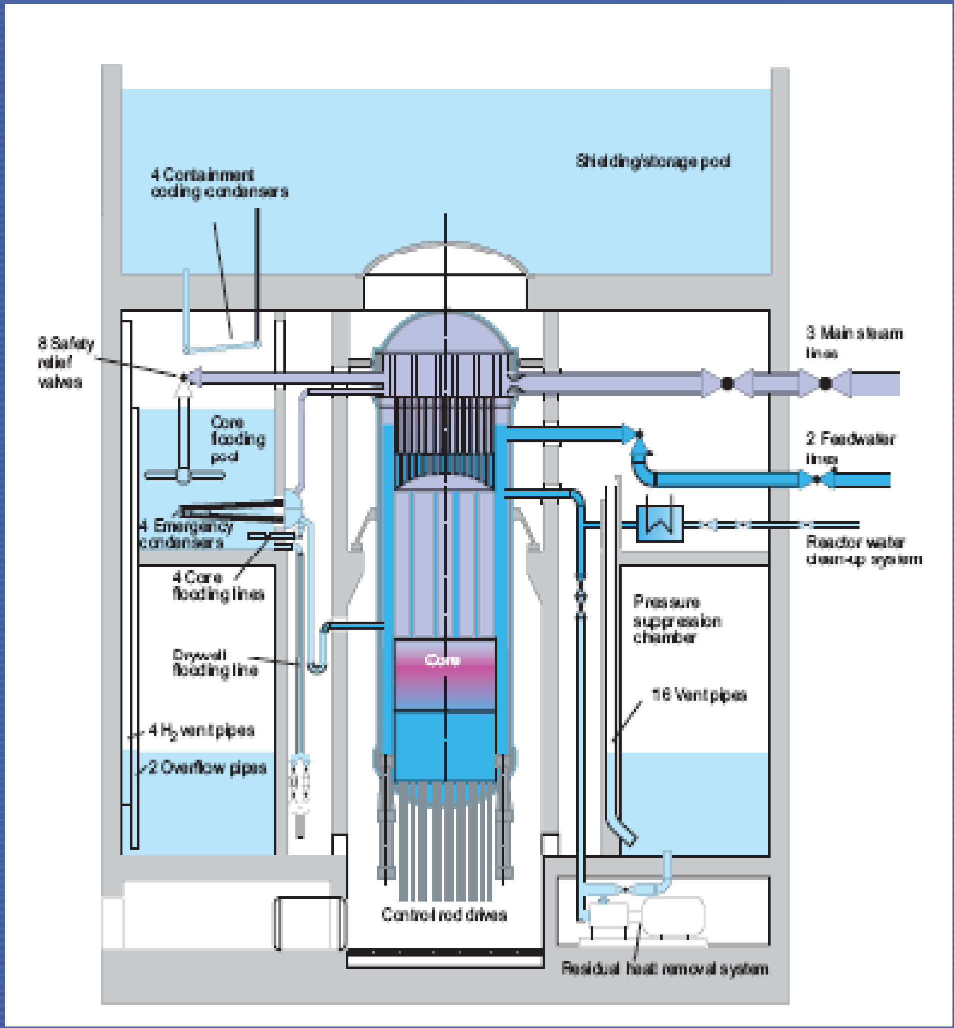
# KERENA = SWR-1000

- AREVA & E.On
- Reviewed by EUR
- 1250+ MWe
- Uses internal re-circulation pumps
- Active & passive safety systems
- Offered for Finland-5
- Gundremingen reference plant
- New systems verified by test (e.g. FZ Jülich test of isolation condenser)

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# Pressurized Water Reactors (PWR)

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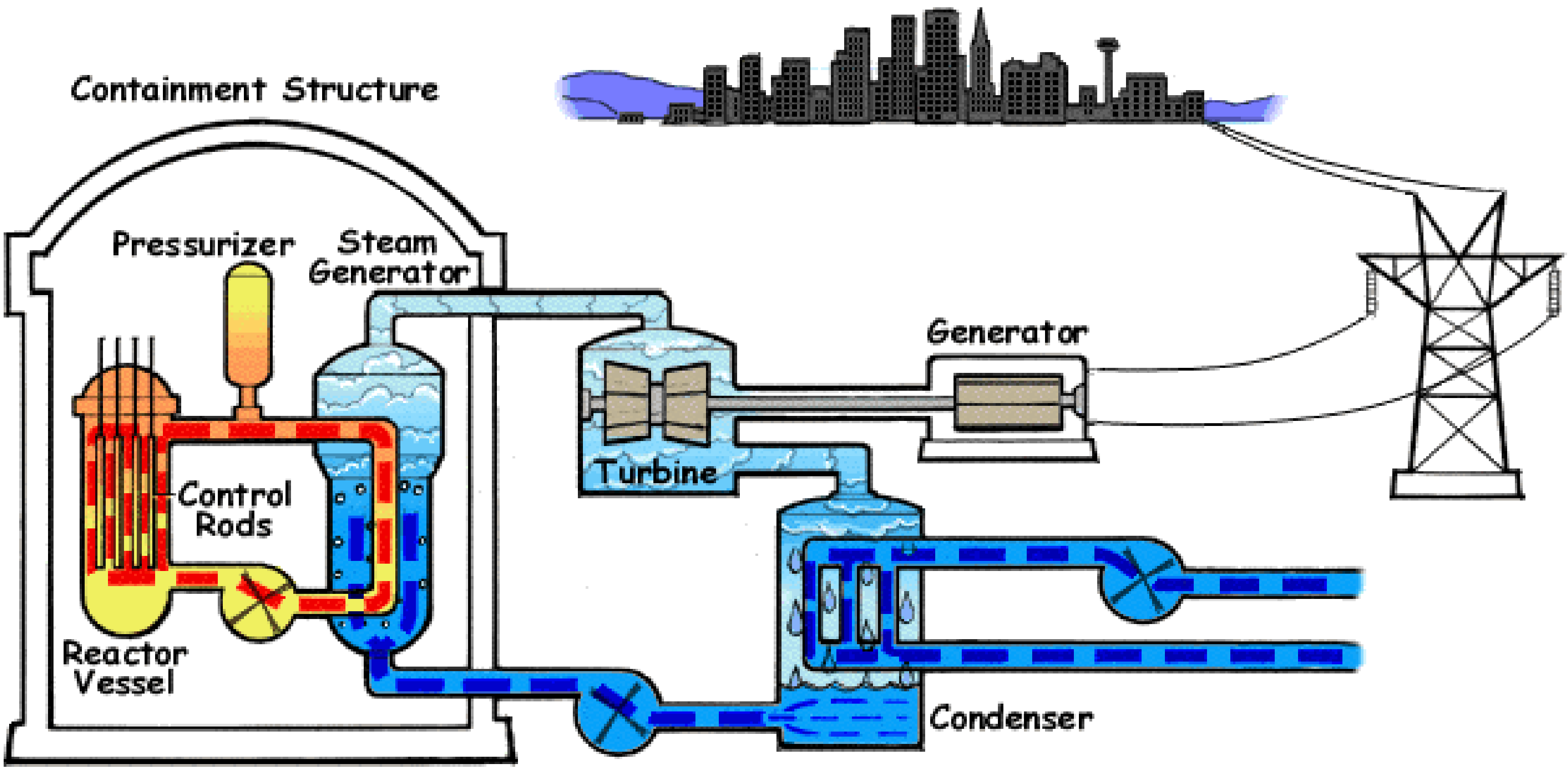
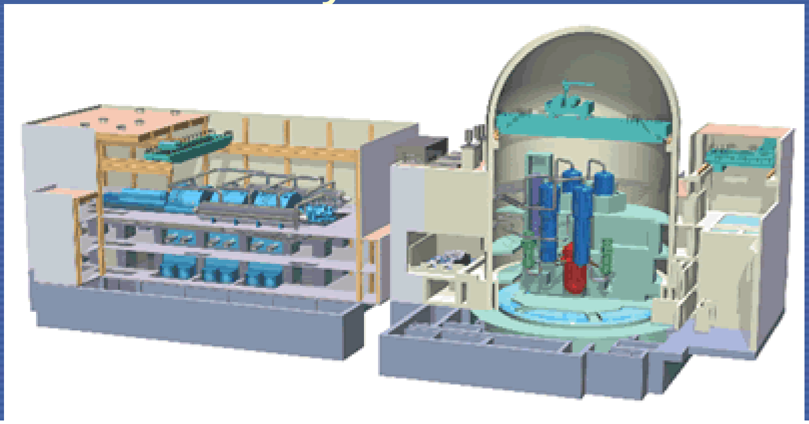
# Pressurized Water Reactor (PWR)



# Advanced Pressurized Water Reactor APWR & APWR+

- Mitsubishi & Japanese utilities
- 2x1540 MWe APWRs planned by JAPC at Tsuruga-3 & -4
  - Advanced neutron reflector (SS rings) improves fuel utilization and reduces vessel fluence
- 1700 MWe "US APWR" in Design Certification by the U.S.NRC
  - Evolutionary, 4-loop, design relying on a combination of active and passive safety systems
  - Full MOX cores
  - 39% thermal efficiency
  - Selected by TXU for Comanche Peak
- 1700 MWe "EU-APWR" to be evaluated by EUR



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# EPR

- AREVA
- 1600+ MWe PWR
- Incorporates experience from France's N4 series and Germany's Konvoi series
- Meets European Utility Requirements
- Incorporates well proven active safety systems
  - 4 independent 100% capacity safety injection trains
- Ex-vessel provision for cooling molten core
- Design approved by French safety authority (10.2004)
- Under construction
  - Olkiluoto-3 (operation by 2012?)
  - Flamanville-3 (operation by 2012)
- Planned in China (2 units at Taishan) and India
- U.S.NRC is reviewing the US EPR Design Certification Application

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# WWER-1000 / 1200 (AEP)

- The state-owned AtomEnergoProm (AEP), and its affiliates (including AtomStroyExport (ASE) et.al) is responsible for nuclear industry activities, including NPP construction
- Advanced designs based on experience of 23 operating WWER-440s & 27 operating WWER-1000 units
- Present WWER-1000 construction projects
  - Kudankulam, India (2 units)
  - Belene, Bulgaria (2 units)
  - Bushehr, Iran (1 unit)
- WWER-1200 design for future bids of large size reactors

- Tianwan
  - first NPP with corium catcher
  - Commercial operation: Unit-1: 5.2007; Unit-2: 8.2007
- Kudankulam-1 & 2
  - Commercial operation expected in 2010
  - Core catcher and passive SG secondary side heat removal to atmosphere

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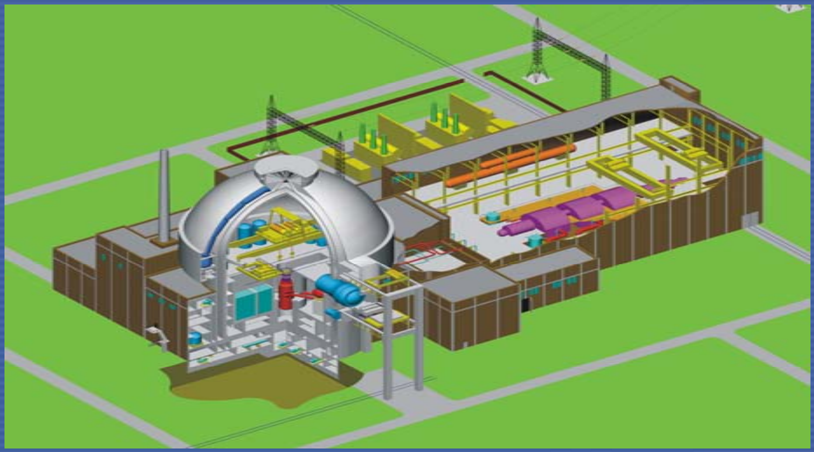
# WWER-1200

Commissioning of 17 new WWER-1200s in Russia expected by 2020

- Novovoronezh – 2 units
- Leningrad – 4 units
- Volgodon – 2 units
- Kursk – 4 units
- Smolensk – 4 units
- Kola – 1 unit



- Uses combination of active and passive safety systems
- One design option includes core catcher; passive containment heat removal & passive SG secondary side heat removal
- 24 month core refuelling cycle
- 60 yr lifetime
- 92% load factor

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# APR-1400

- Developed in Rep. of Korea (KHNP and Korean Industry)
- 1992 - development started
- Based on CE's System 80+ design (NRC certified)
- 1400 MWe - for economies of scale
- Incorporates experience from the 1000 MWe Korean Standard Plants
- Relies primarily on well proven active safety systems
- First units will be Shin-kori 3,4
  - completion 2013-14
- Design Certified by Korean Regulatory Agency in 2002

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# AP-600 and AP-1000

- Westinghouse
- AP-600:
  - Late 80's–developed to meet URD
  - 1999 - Certified by U.S.NRC
  - Key developments:
    - passive systems for coolant injection, RHR, containment cooling
    - in-vessel retention
    - new systems verified by test
- AP-1000:
  - pursues economy-of-scale
  - applies AP-600 passive system technology
  - Certified by U.S.NRC (2006) [1]
  - Contract for 4 units in China
    - Sanmen & Haiyang: 2013 – 2015
  - Contract for 2 units in US
    - Plant Vogtle
    - Proposed in several other sites in US

[1]Amended Application currently under review

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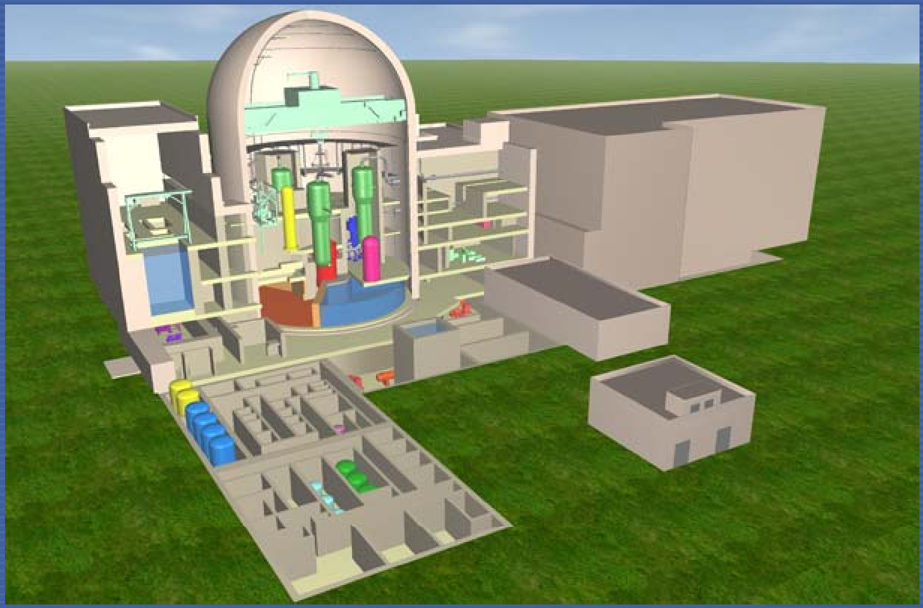
# ATMEA

- 1100 MWe, 3 loop plant
- Combines AREVA & Mitsubishi PWR technology
- Relies on active safety systems & includes core catcher
- Design targets:
  - 60 yr life
  - 92% availability
  - 12 to 24 month cycle; 0-100% MOX



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# Chinese advanced PWRs CPR (CGNPC) and CNP (CNNC)

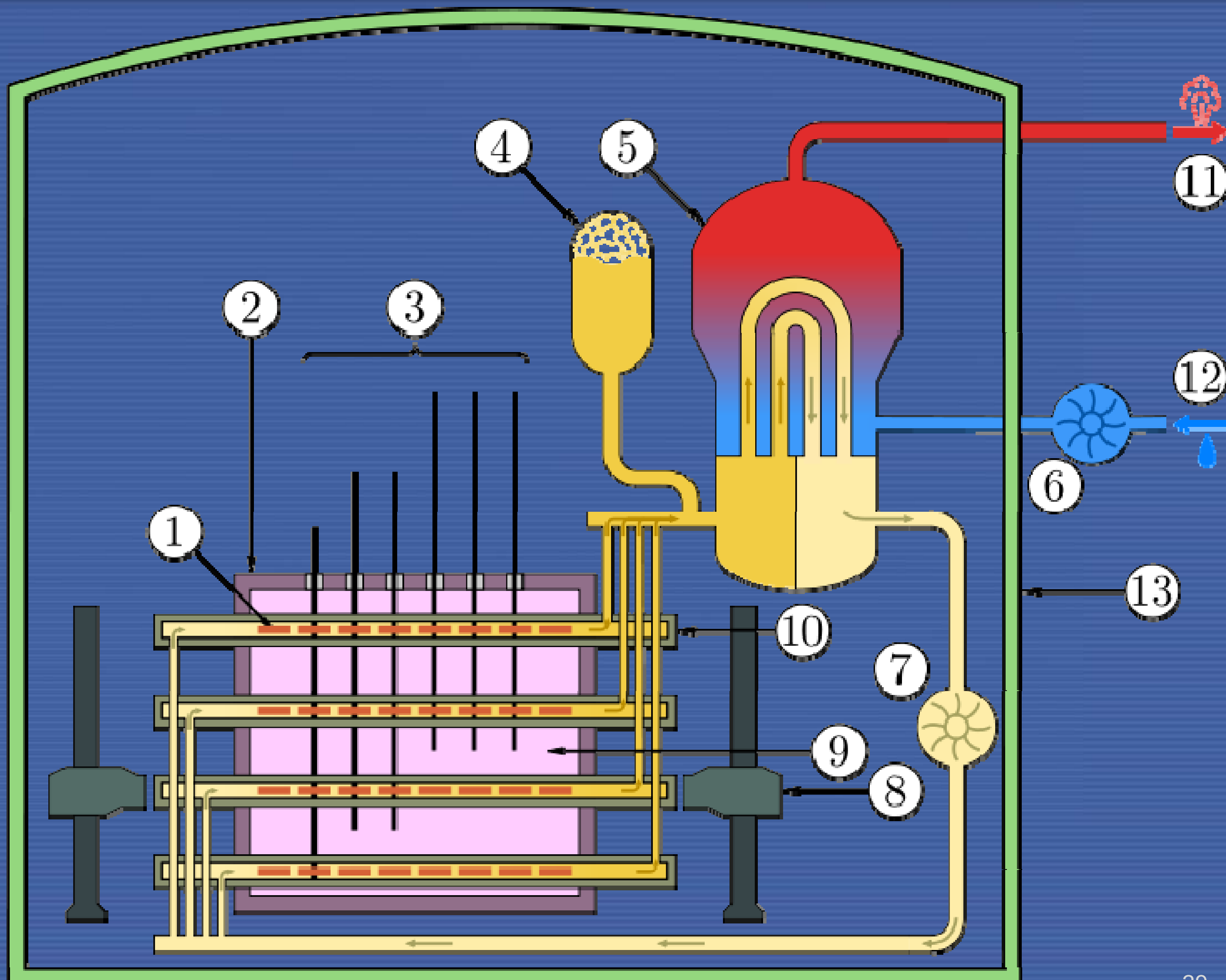
- CPR-1000
  - Evolutionary design based on French 900 MWe PWR technology
  - Reference plant: Lingau-1&2 (NSSS Supplier: Framatome; commercial operation in 2002)
  - Lingau-3&4 are under construction (with > 70% localization of technology; NSSS Supplier: Dongang Electric Corporation);
  - Now a Standardized design
  - Hongyanhe 1,2,3,4; Ningde 1; Yangjiang 1,2; Fuquing 1,2; Fanjiashan 1&2 under construction; more units planned: Ningde 2,3,4 and Yangjiang 3,4,5,6

- CNP-650
  - Upgrade of indigenous 600 MWe PWRs at Qinshan (2 operating & 2 under construction)

# Heavy Water Reactors (HWR)

# Pressurized Heavy Water Reactor (PHWR)

1. Nuclear Fuel Rod
2. Calandria
3. Control Rods
4. Pressurizer
5. Steam Generator
6. Light Water Condensate pump
7. Heavy Water Pump
8. Nuclear Fuel Loading Machine
9. Heavy Water Moderator
10. Pressure Tubes
11. Steam
12. Water Condensate
13. Containment

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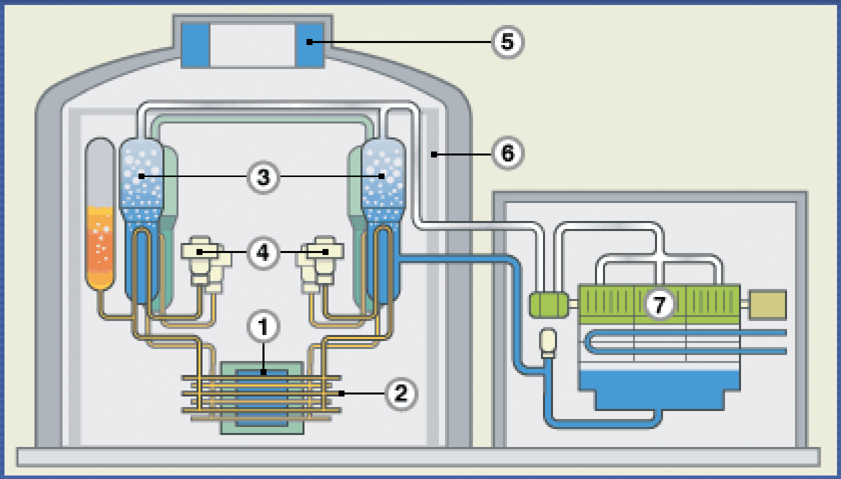
# ACR-700 & ACR-1000




- AECL
- 740 MWe Enhanced CANDU-6
- 1000 MWe Advanced CANDU reactor
- 284 / 520 horizontal channels
- Low enriched uranium– 2.1%,
- 60 yr design life
- Continuous refueling
- Combination of active and passive safety systems
- CNSC has started "pre-project" design review
- Energy Alberta has filed *an Application for a License to Prepare Site* with the CNSC -- for siting up to two twin-unit ACR-1000s --- commissioning by ~2017
- 30 CANDU operating in the world
  - 18 Canada (+2 refurbishing, +5 decommissioned)
  - 4 South Korea
  - 2 China
  - 2 India (+13 Indian-HWR in use, +3 Indian-HWR under construction)
  - 1 Argentina
  - 2 Romania (+3 under construction)
  - 1 Pakistan

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# India’s HWR

- 540 MWe PHWR [evolution from current 220 MWe HWRs]
  - » Nuclear Power Corporation of India, Ltd.
  - » First units: Tarapur-3 & -4 connected to grid (2005 & 6)

- 700 MWe PHWR [further evolution – economy of scale]
  - » NPCIL
  - » Regulatory review in progress
  - » Use of Passive Decay Heat Removal System; reduced CDF from PSA insights
  - » Better hydrogen management during postulated core damage scenario
  - » First units planned at Kakrapar & Rawatbhata

- 700 MWe Advanced HWR
  - » BARC
  - » for conversion of Th232  or U238 (addressing sustainability goals)
  - » vertical pressure tube design with natural circulation

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# Small and Medium Size Reactors (SMR)

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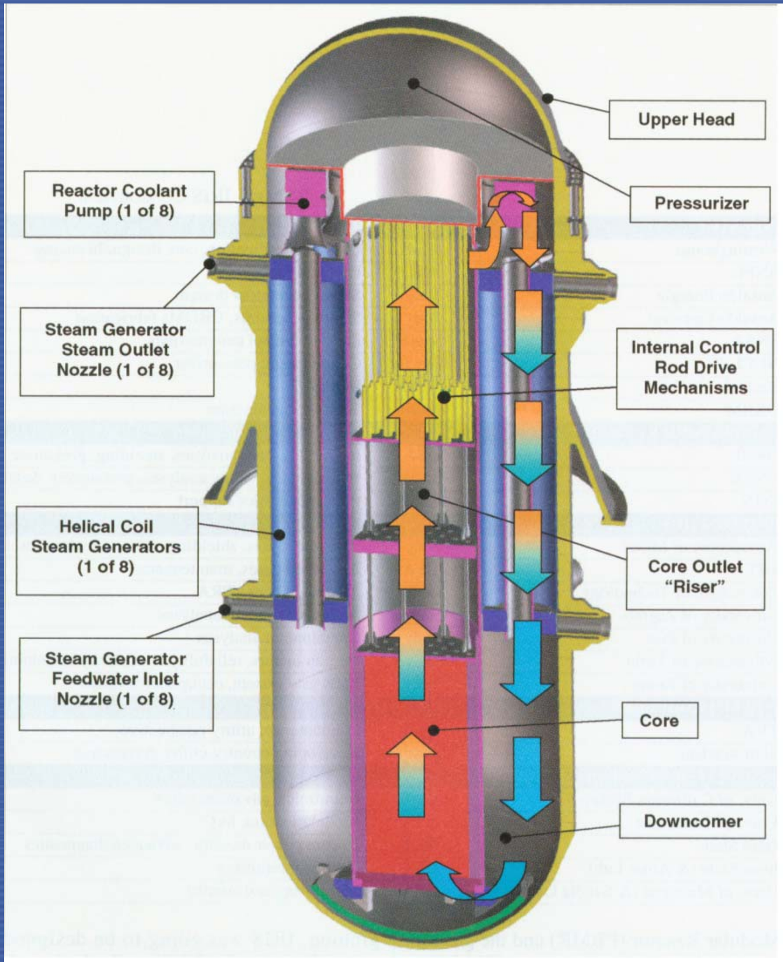
# IRIS (International Reactor Innovative and Secure)

- Westinghouse
- 100-335 MWe
- Integral design
- Design and testing Involves 19 organizations (10 countries)
- Pre-application review submitted to the USNRC in 2002
- To support Design Certification, large scale (~6 MW) integral tests are planned at SPES-3 (Piacenza, IT)
  - Construction start – late 2009
- Westinghouse anticipates Final Design Approval (~2013)

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# SMART

- Korea Atomic Energy Research Institute
- 330 MWe
- Used for electric and non-electric applications
- Integral reactor
- Passive Safety

# CAREM (Central Argentina de Elementos Modulares)

- Developed by INVAP and Argentine CNEA
- Prototype: 25 MWe
- Expandable to 300 MWe
- Integral reactor
- Passive safety
- Used for electric and non-electric applications
- Nuclear Safety Assessment under development
- Prototype planned for 2012 in Argentina's Formosa province

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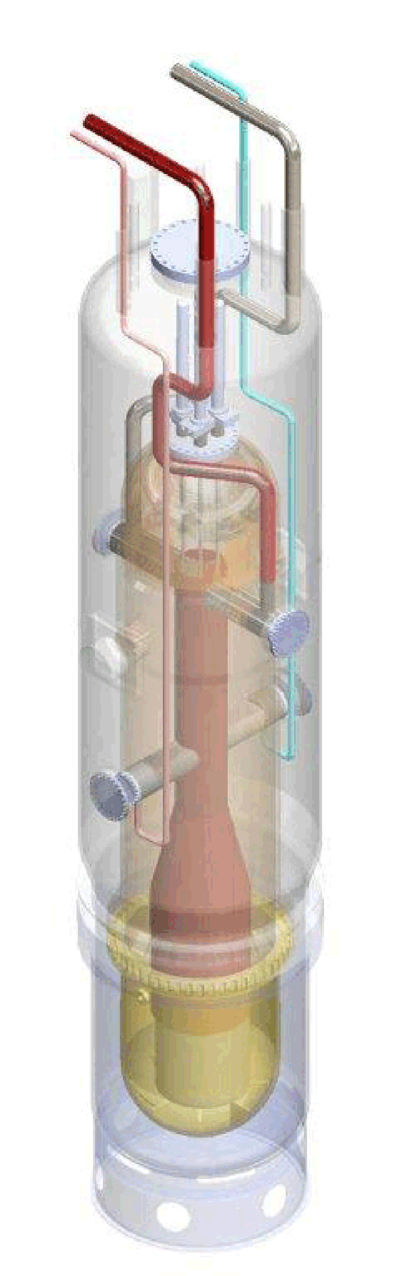
# NuScale

- Oregon State University (USA)
- 45 MWe
- 90% Capacity Factor
- Integral reactor
- Modular, scalable
- Passive safety
- Online refueling
- To file for Design Certification with US NRC in 2010.



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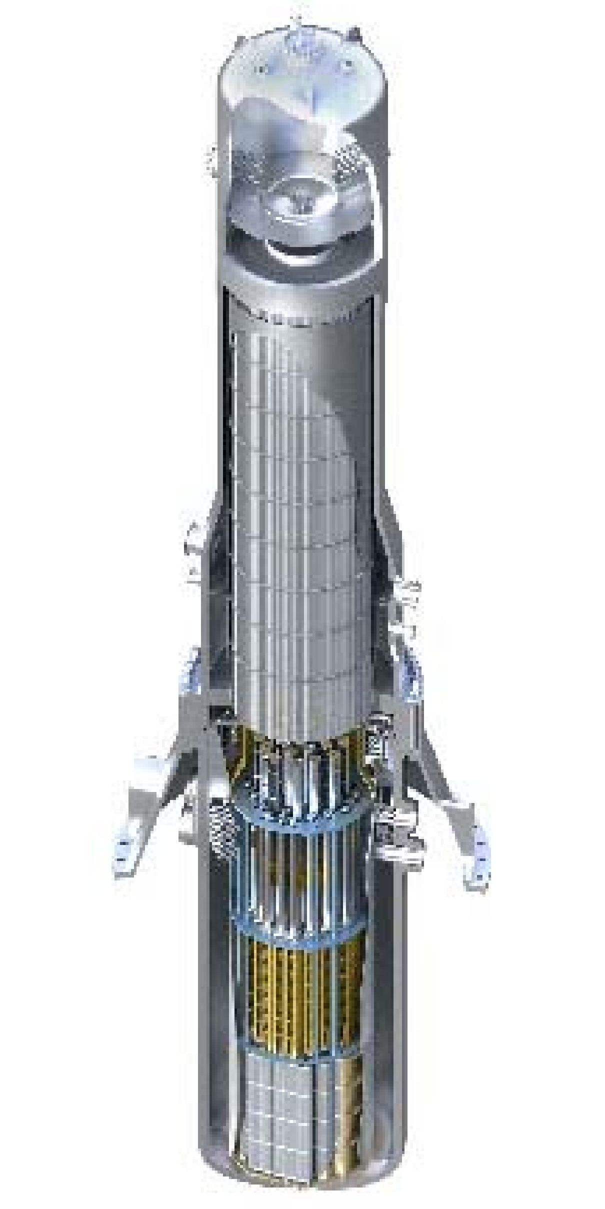
# B&W mPower

- Integral reactor
- Scalable, modular
- 125 – 750 MWe
- 5% enriched fuel
- 5 year refueling cycle
- Passive safety
- Lifetime capacity of spent fuel pool



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# Floating Reactors

- Provide electricity, process heat and desalination in remote locations
- KLT-40S (150 MWt → 35 MWe)
- VBER-150 (350 MWt → 110 MWe)
- VBER-300 (325 MWe)

Construction of pilot plant (2 units) started April 2007

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# GAS-COOLED REACTOR DEVELOPMENT

- More than 1400 reactor-years experience
- $CO_2$ cooled
  - 22 reactors generate most of the UK's nuclear electricity
  - also operated in France, Japan, Italy and Spain
- Helium cooled
  - operated in UK (1), Germany (2) and the USA (2)
  - current test reactors:
    - 30 MW(th) HTTR (JAERI, Japan)
    - 10 MW(th) HTR-10 (Tsinghua University, China)
- In South Africa a small 165 MWe prototype plant is planned
- Russia, in cooperation with the U.S., is designing a plant for weapons Pu consumption and electricity production
- France, Japan, China, South Africa, Russia and the U.S. have technology development programmes

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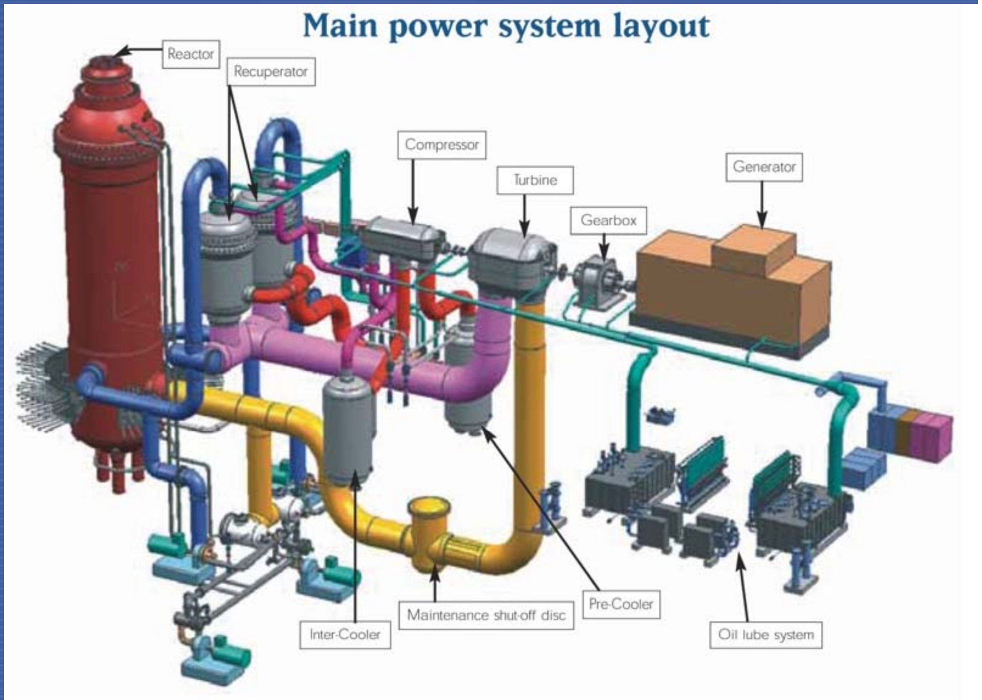
# PBMR (Pebble Bed Modular Reactor)

- Eskom, South Africa Government, Westinghouse
- Gas Cooled (Helium)
- 165 MWe
- Electrical and non-electrical applications
- Prototype to be built by 2014

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# Fast Reactor Development

- **France:**
  - Conducting tests of transmutation of long lived waste & use of Pu fuels at Phénix (shutdown planned for 2009)
  - Designing 300-600 MWe Advanced LMR Prototype “ASTRID” for commissioning in 2020
  - Performing R&D on GCFR
- **Japan:**
  - MONJU restart planned for 2009
  - Operating JOYO experimental LMR (Shutdown for repair)
  - Conducting development studies for future commercial FR Systems
- **India:**
  - Operating FBTR
  - Constructing 500 MWe Prototype Fast Breeder Reactor (commissioning 2010)
- **Russia:**
  - Operating BN-600
  - Constructing BN-800
  - Developing other Na, Pb, and Pb-Bi cooled systems
- **China:**
  - Constructing 25 MWe CEFR – criticality planned in 2009
- **Rep. of Korea:**
  - Conceptual design of 600 MWe Kalimer is complete
- **United States**
  - Under GNEP, planning development of industry-led prototype facilities:
    - Advanced Burner Reactor
    - LWR spent fuel processing

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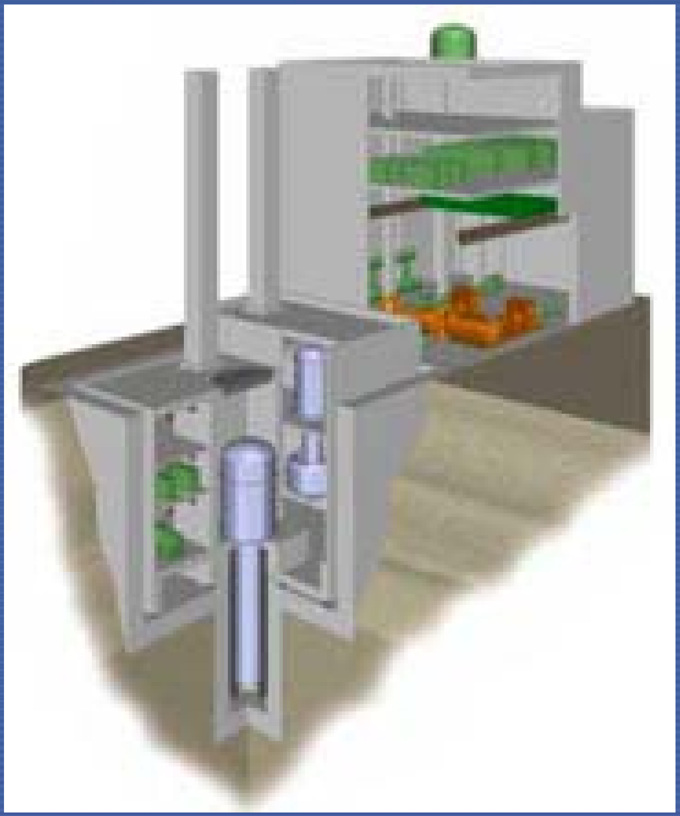
# 4S (Super Safe, Small and Simple)

- Toshiba & CRIEPI of Japan
- 50 MWe
- Sodium Cooled
- 10 – 30 year refueling period
- Submitted for US NRC Design Certification
- Proposed for Galena, Alaska



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# Generation IV Reactor Designs

- Several design concepts are under development to meet goals of
  - Economics
  - Sustainability
  - Safety and reliability
  - Proliferation resistance and physical protection
- All concepts (except VHTR) are based on closed fuel cycle
- Concepts include small, modular approaches
- Most concepts include electrical and non-electrical applications
- Significant R&D efforts are still required
- International cooperation needed for pooling of resources

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# Generation IV Reactor Designs

- Gas Cooled Fast Reactors (GFR)
- Very High Temperature Reactor (VHTR)
- Super-Critical Water Cooled Reactor (SCWR)
- Sodium Cooled Fast Reactor (SFR)
- Lead-Cooled Fast Reactor (LFR)
- Molten Salt Reactor (MSR)

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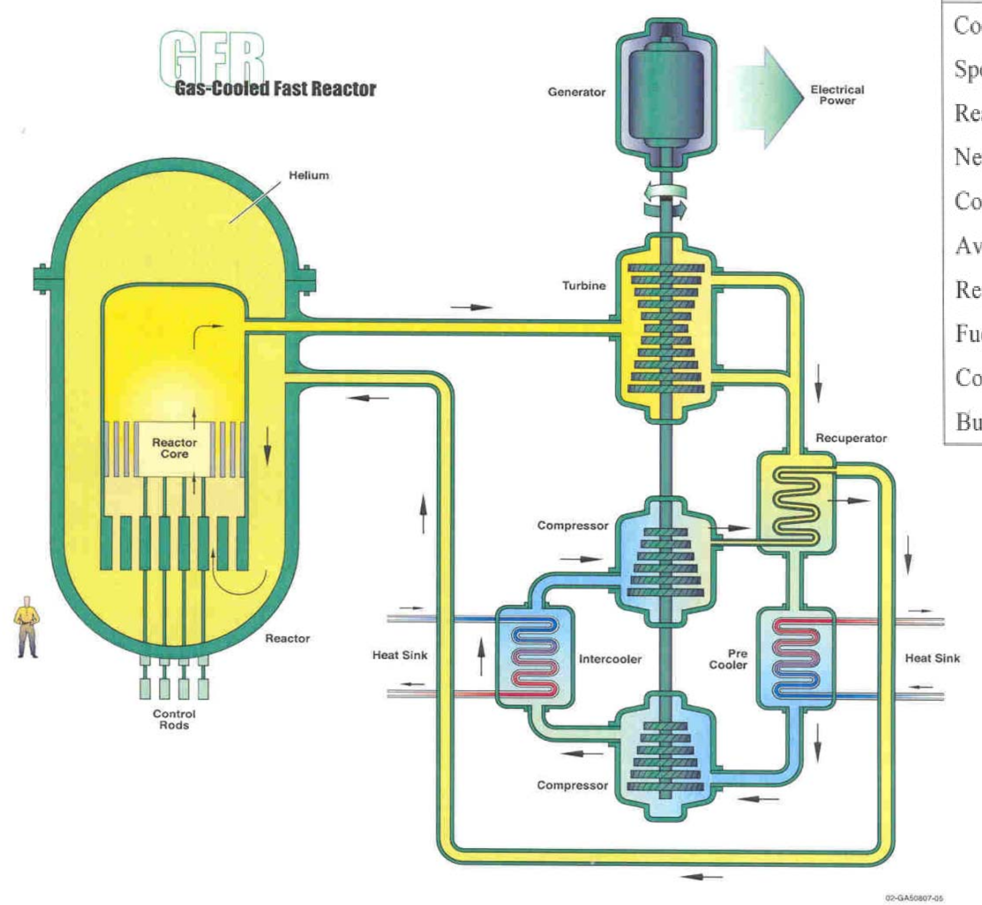
# Gas Cooled Fast Reactor




| Reactor parameter | Reference Value |
|---|---|
| Coolant | Helium |
| Spectrum | Fast |
| Reactor power | 600 MWth |
| Net plant efficiency (Brayton cycle) | 48% |
| Coolant inlet/outlet temperature and pressure | 490°C/850°C at 90 bar |
| Average power density | 100 MWth/m$^3$ |
| Reference fuel compound | UPuC/SiC with about 20% Pu content |
| Fuel cycle | Closed |
| Conversion ratio | Self-sufficient |
| Burn up | 5% FIMA |

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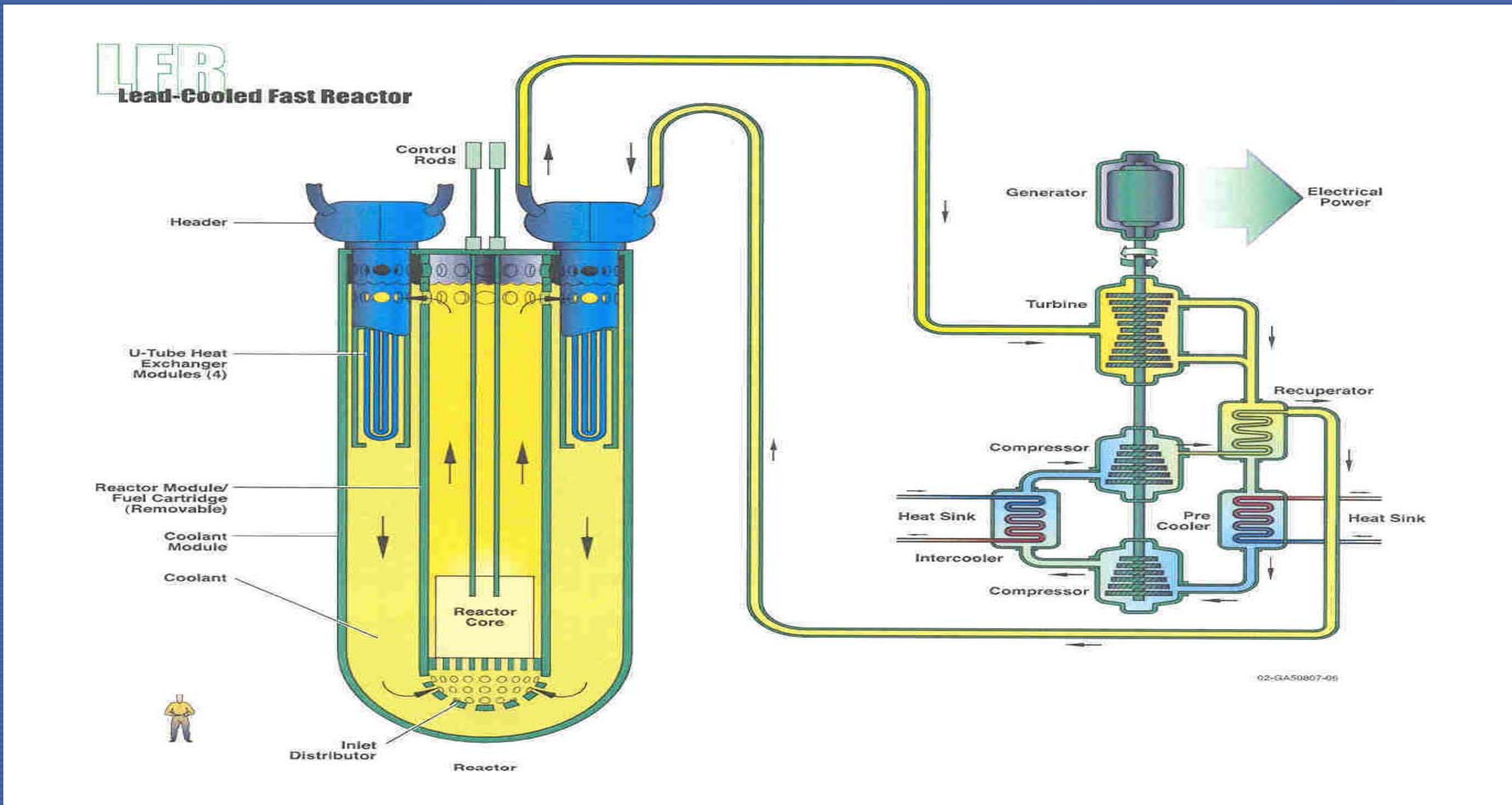
# Lead Cooled Fast Reactor

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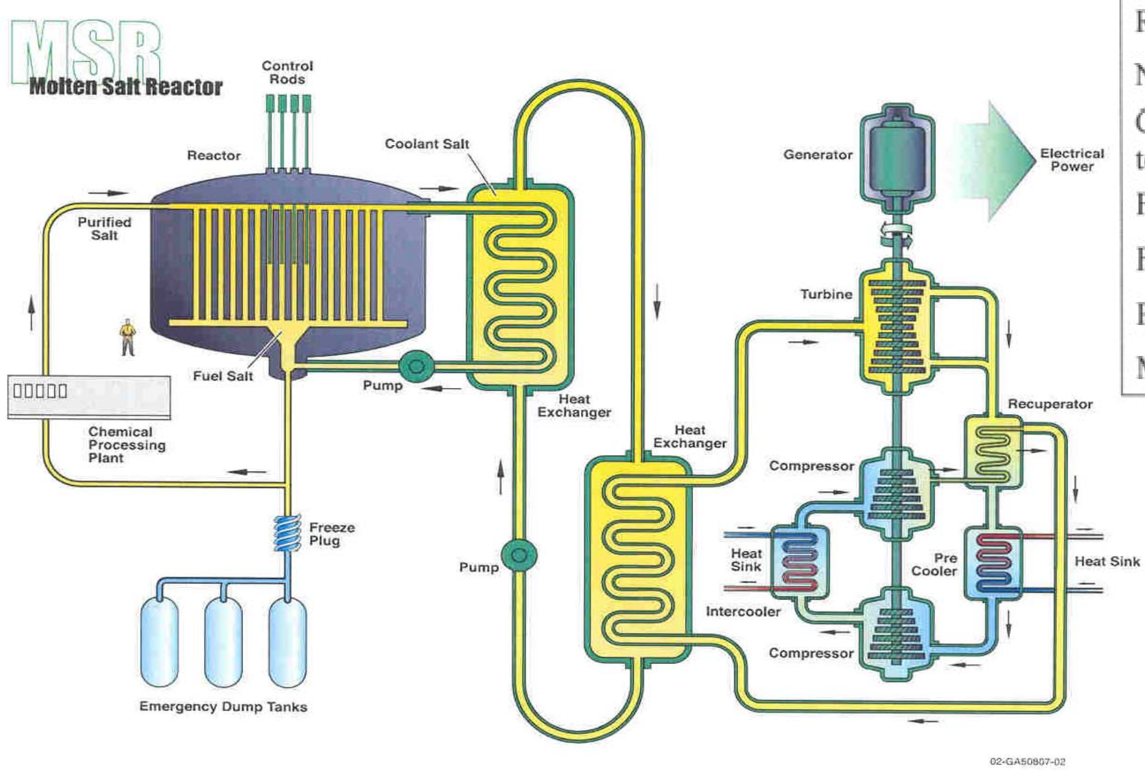
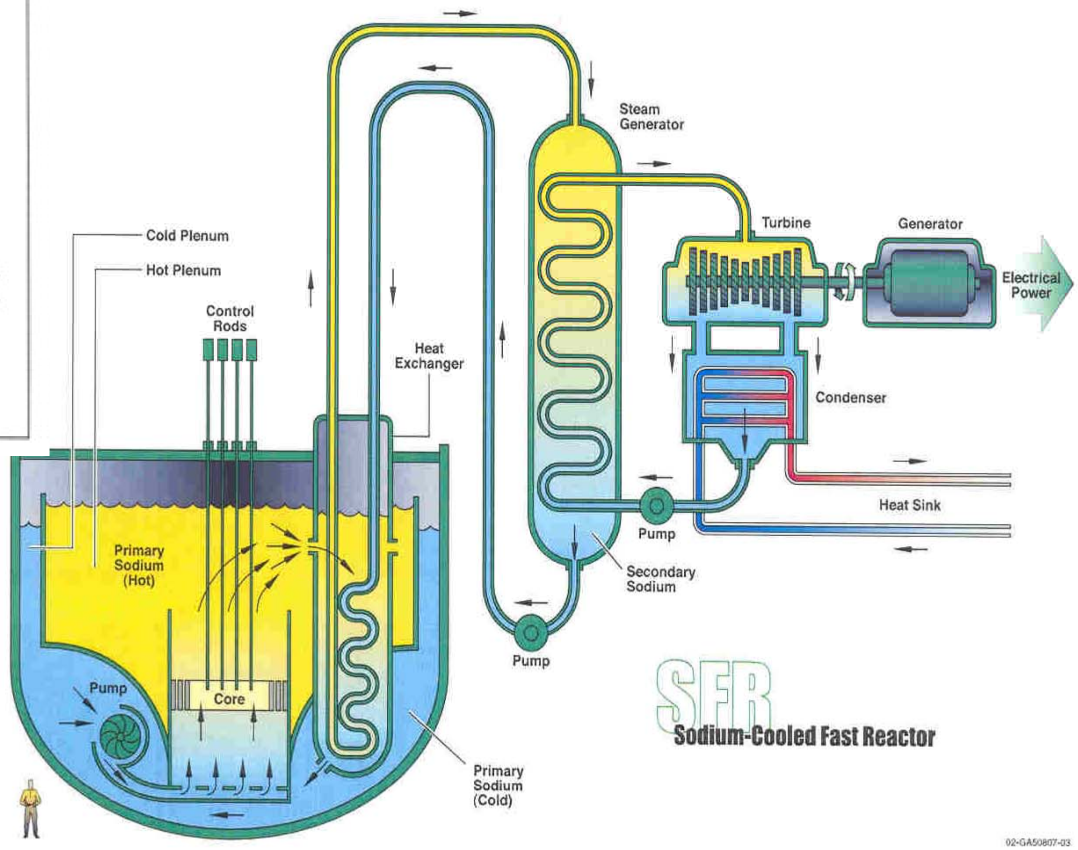
# Molten Salt Reactor




| Reactor parameter | Reference Value |
|---|---|
| Coolant | Molten Salt |
| Spectrum | Thermal |
| Reactor power | 1000 MWe |
| Net plant efficiency | 44 to 50 % |
| Coolant inlet/outlet temperature and pressure | 565 - 750°C (850°C for hydrogen production) |
| Fuel | Uranium/Plutonium Fluoride |
| Fuel cycle | Closed |
| Power Density | 22MWth/$m^3$ |
| Moderator | Graphite |

# Sodium cooled Fast Reactor

| Reactor parameter | Reference Value |
|---|---|
| Coolant | Sodium |
| Spectrum | Fast |
| Reactor power | 1000-5000 MWth |
| Design | Pool type |
| Coolant outlet temperature and pressure | 530-550°C, 1 bar |
| Fuel | Oxide or metal alloy |
| Fuel cycle | Closed |
| Average Burn-up | About 150-200 GWD/MTHM |
| Conversion ratio | 0.5-1.30 |
| Average Power Density | 350 MWth/$m^3$ |

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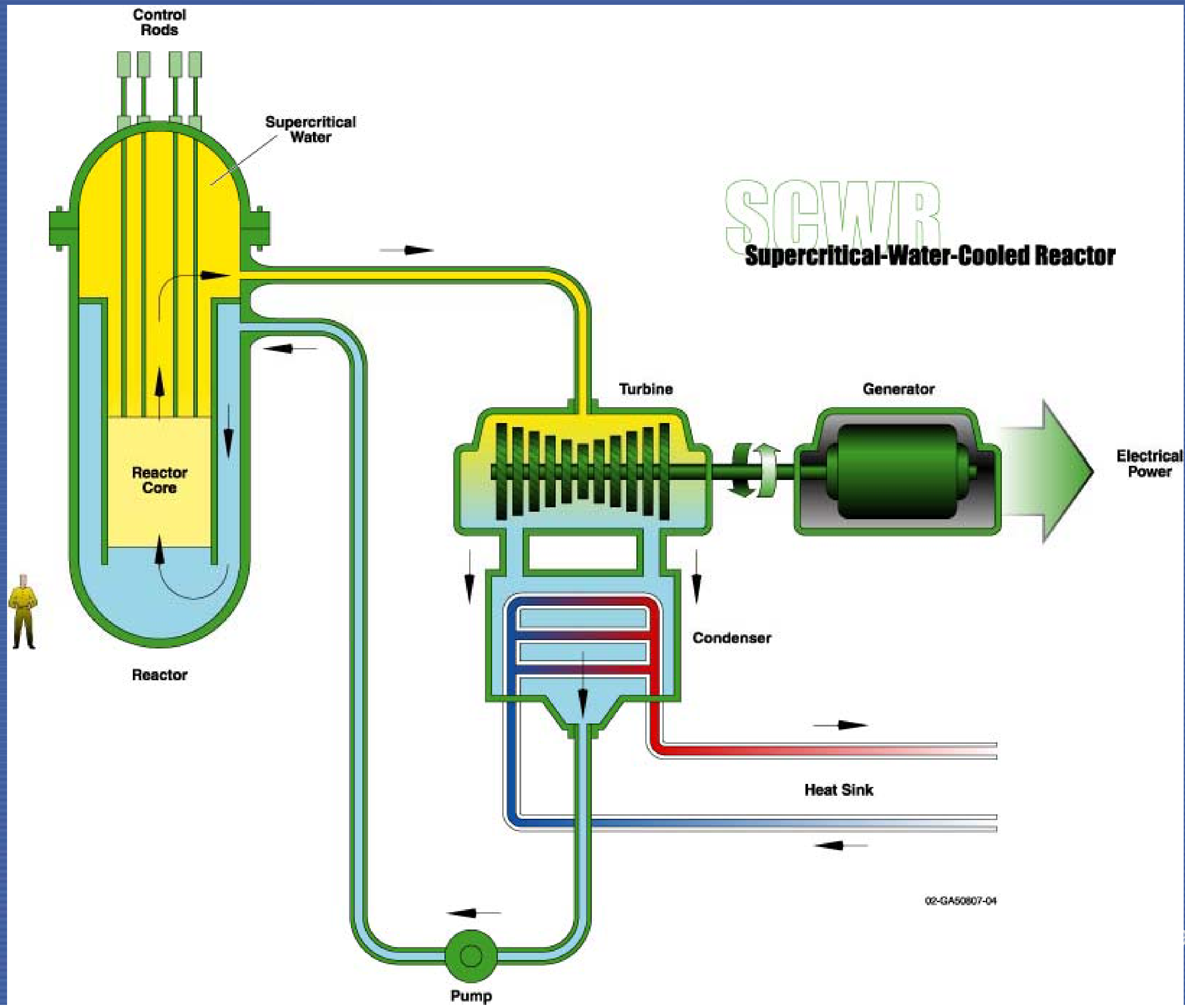
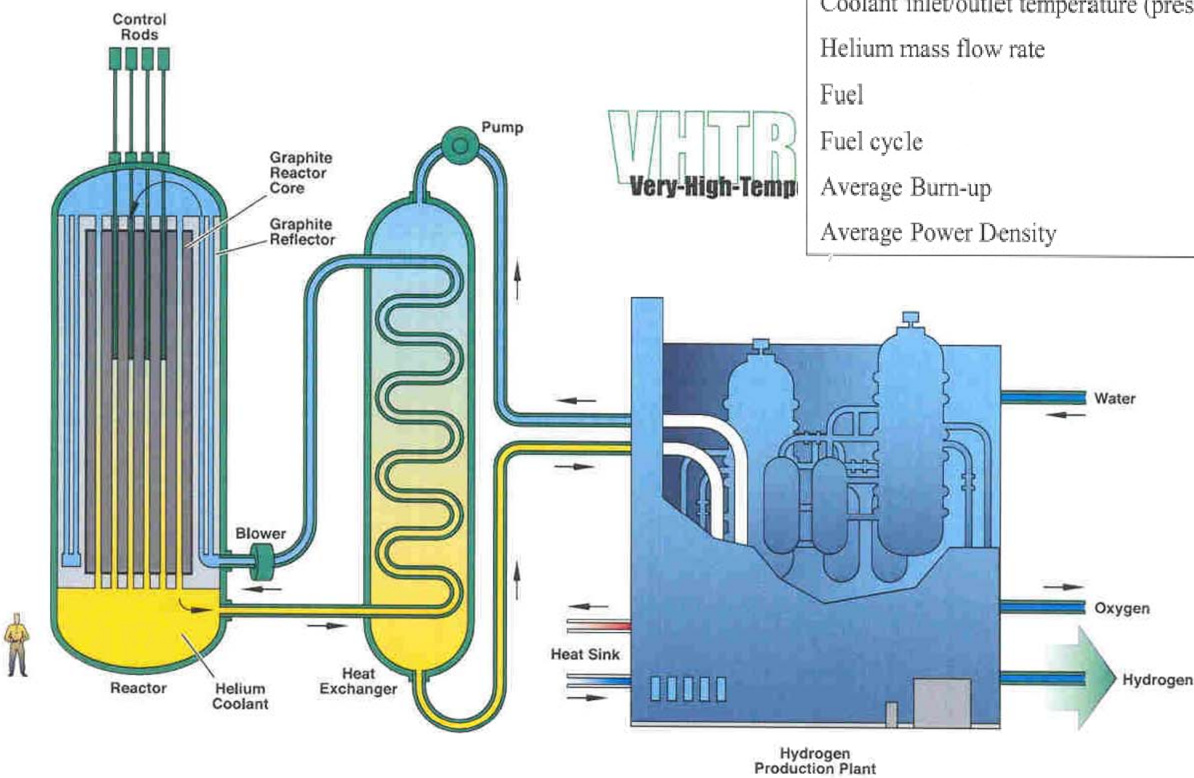
# Super-Critical Water Cooled Reactor

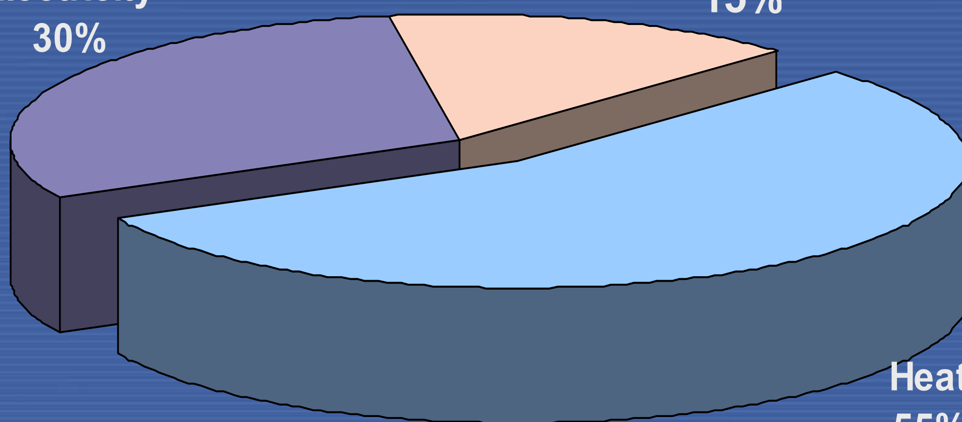


# Very High Temperature Reactor

| Reactor parameter | Reference Value |
|---|---|
| Coolant | Helium |
| Spectrum | Thermal |
| Reactor power | 600 MWth |
| Coolant inlet/outlet temperature (pressure) | 640/1000°C (depending on process) |
| Helium mass flow rate | 320 Kg/s |
| Fuel | $UO_2$ in ZrC-coated particles in blocks, pins or pebbles |
| Fuel cycle | Open |
| Average Burn-up | 150-200GWD/MTHM |
| Average Power Density | 6-10 MWth/$m^3$ |



# The potential for non-electric applications of nuclear energy is large




Energy consumption by application

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# Advanced Applications of Nuclear Energy

- Sea-water desalination
- District heating
- Heat for industrial processes
- Hydrogen production
  - At “fuelling stations” by water electrolysis
  - At central nuclear stations by
    - high temperature electrolysis
    - thermo-chemical processes
    - hybrid processes
- Coal gasification
- Enhanced oil recovery (e.g. from oil shale and tar sands)
- Electricity for Plug-in Hybrid Vehicles

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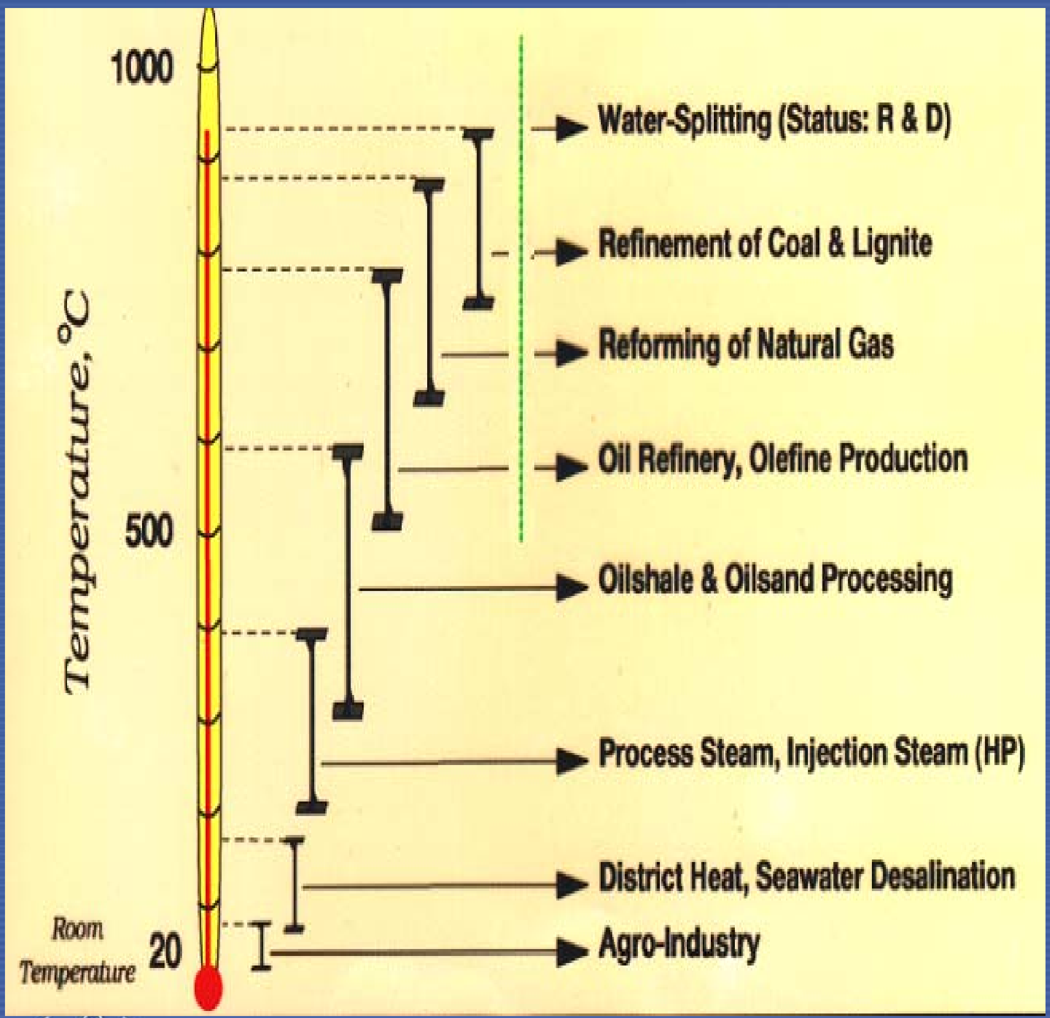
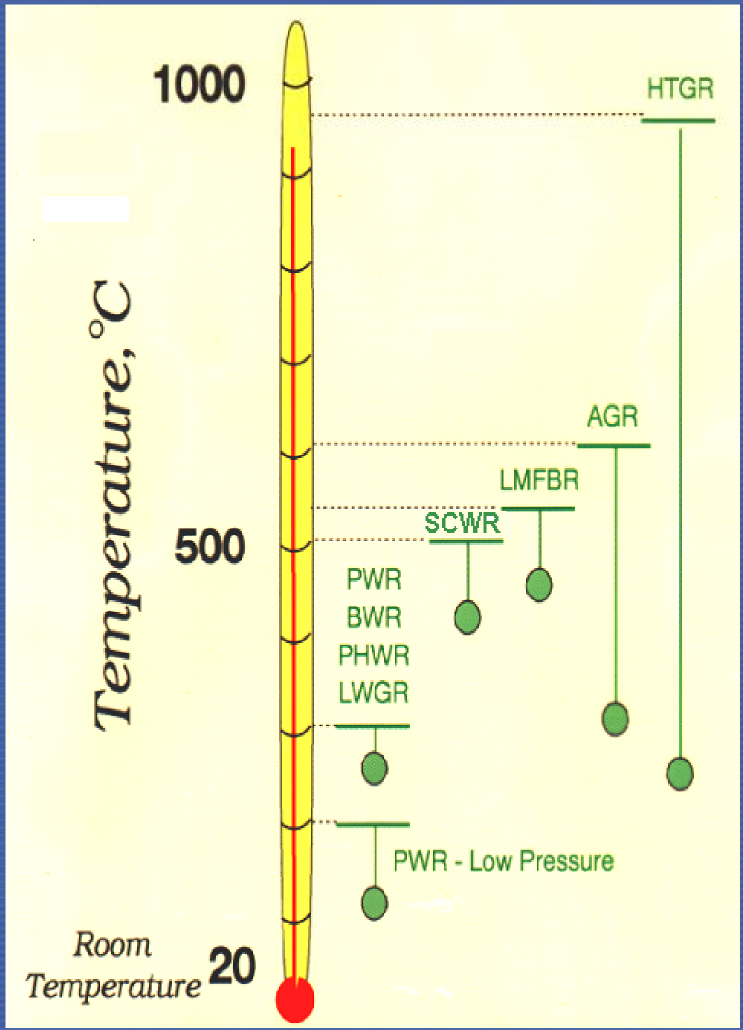
# Nuclear Plants Can Provide the Heat Required for Many Processes

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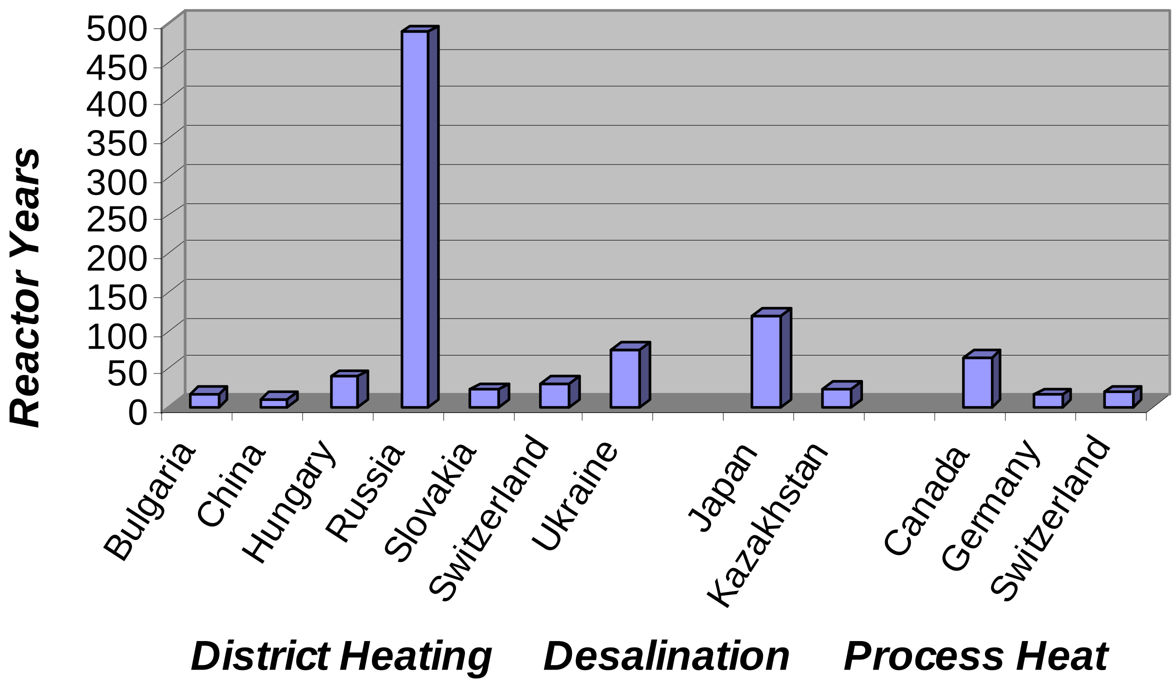
# Non-Electrical Applications

- Today 439 NPPs in operation worldwide
- 30 are being used for cogeneration (about 5 GW(th))
- About 700 reactor-years of experience

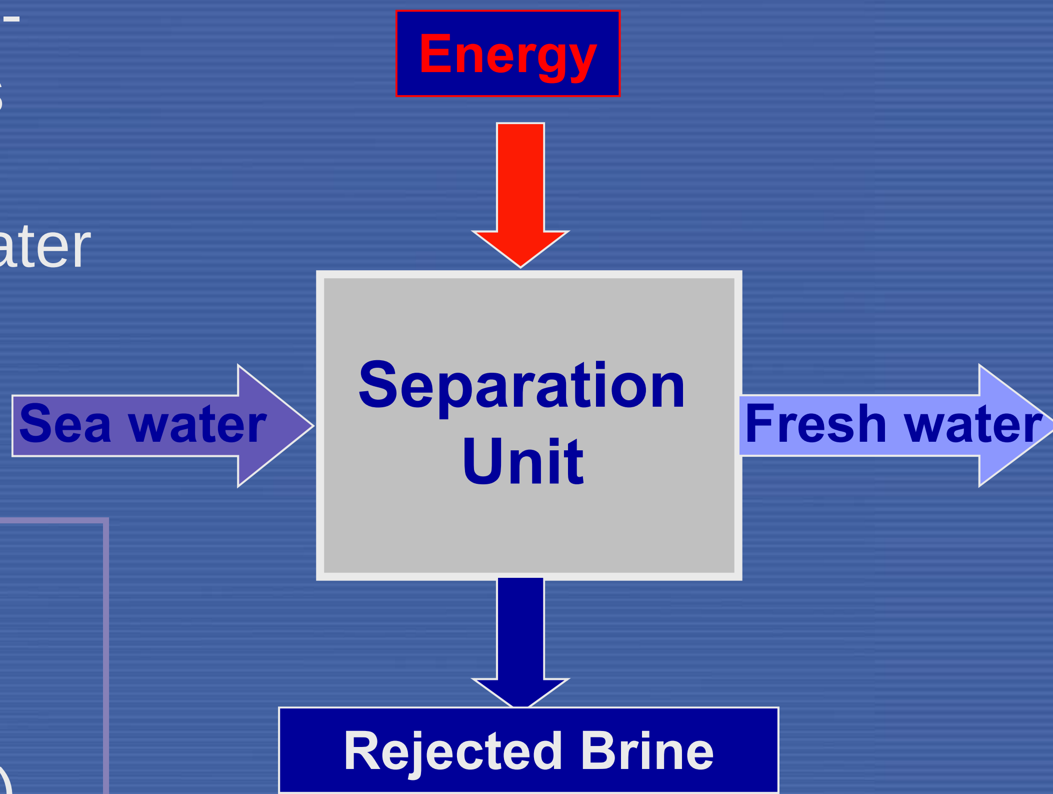


# Characteristics of the heat market

- **District heating**
  - seasonal fluctuation in demand
  - unlikely to be in base-load operation
  - limited distribution line, typically about 20-30 km
  - low grade steam/hot water
- **Industrial process heat**
  - high, medium and low temperature
  - likely to be base-load, little seasonal change
  - high reliability as a source
  - could be away from population center
  - short distribution line

# Desalination

Fully developed to a large-scale commercial process providing
38 Million m$^3$/d of fresh water in 120 countries




**Distillation**
- Multi-stage flash (MSF)
- Multi effect (MED)
- Vapor compression (TVC)

**Membrane separation**
- Reverse osmosis (RO)

# Reactor Types and Desalination Processes

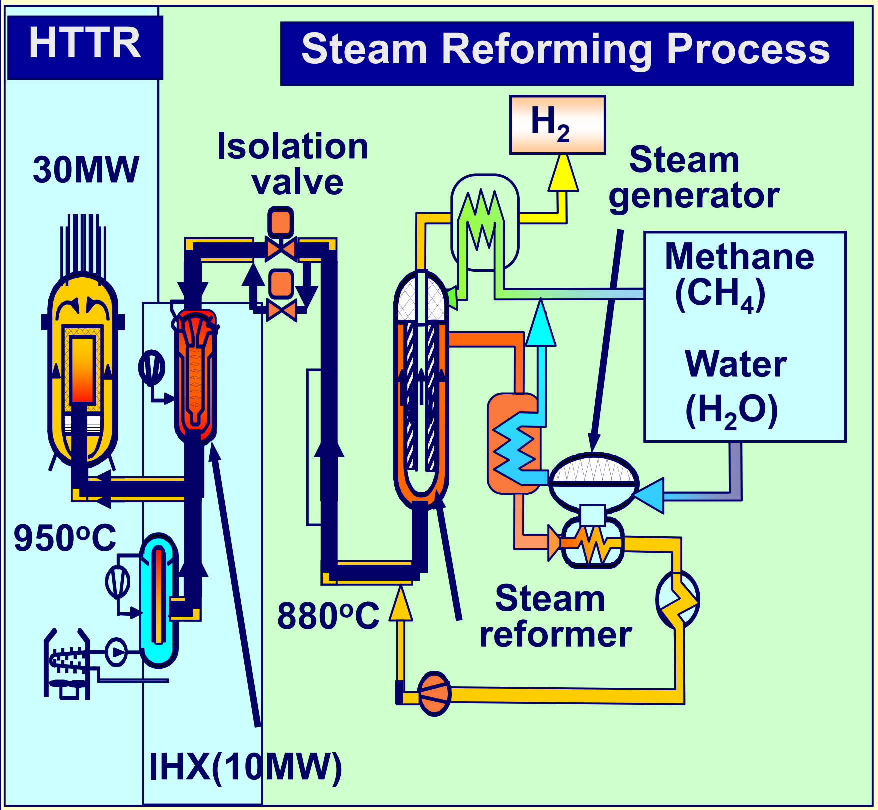
| Reactor type | Location | Capacities (cu.m./d) | Status |
|---|---|---|---|
| LMFR | Kazakhstan (Aktau) | 80,000 | in service till 1999 |
| PWRs | Japan (Ohi, Takahama, Ikata, Genkai)<br>Rep. of Korea<br>Argentina<br>Russia | 1,000 – 2,000<br>40,000<br>12,000 | in service with operating experience of over 125 reactor-years<br>under design<br>under design (floating unit) |
| BWR | Japan (Kashiwazaki) | | never in service following testing in 1980s, due to alternative freshwater sources; dismantled in 1999 |
| PHWR | India (Kalpakkam)<br>Canada<br>Pakistan (KANUPP) | 6,300<br><br>4,800 | under commissioning<br>under design<br>under design |
| NHR | China | | under design |
| HTGR | South Africa, France, The Netherlands | | under consideration |

# Hydrogen production using nuclear power

- High Temperature Electrolysis (up to ~ 1000 C).
- Sulfur-based thermo-chemical cycles for water splitting:
  - Using Sulfur- Iodine cycle (needs about 900C)
  - Hybrid Sulfur cycle (i.e. Electrolysis and Thermo-Ch)
  - Lower temperature processes are under consideration
- Steam reforming of methane (600-800 C)

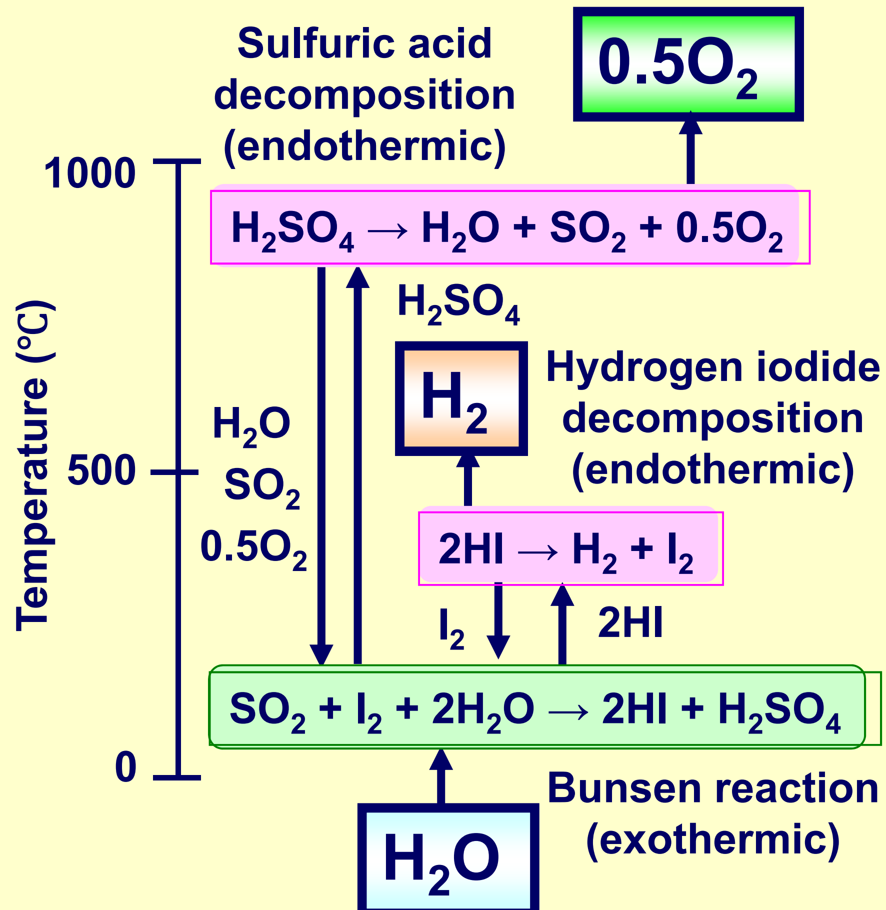
# Hydrogen Production Systems

## Steam Reforming Process




$CH_4 + H_2O \rightarrow 3H_2 + CO$

## IS Process



# ENERGY FOR TRANSPORTATION

- **Transportation**
  - **15 - 20% of the world's energy consumption**
  - **fastest growing energy sector**

- **If nuclear would power part of this sector, it could significantly impact global environmental sustainability**

- **Two examples:**
  - **Electricity**
    - **for plug-in hybrid electric vehicles (very near term)**
    - **For electric transportation systems (Trains; subways,…)**
  - **Hydrogen fuelled vehicles**

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# Conclusions

- There are many designs to choose from
  - Not all are commercially available today
  - All have advantages and disadvantages
- Many of them have been:
  - Endorsed by User Requirements (EUR, URD, etc)
  - Certified by licensing authorities in several countries
  - Built and operated for many years in various countries… or
  - … In the process of being built

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# Conclusions

- Considerations when choosing a design
  - Balance between technology maturity and innovation
  - Balance between constructability and operability
  - Advantages of “Owner Groups”
    - Operating Experience
    - Market for spare parts
    - Assurance of supplier support
  - Development of national capabilities
  - Electrical and non-electrical applications

# Thank you!

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