NUCL 402 Engineering of Nuclear Power Systems

Lecture 5: Advanced Reactors
- GEN IV Reactor

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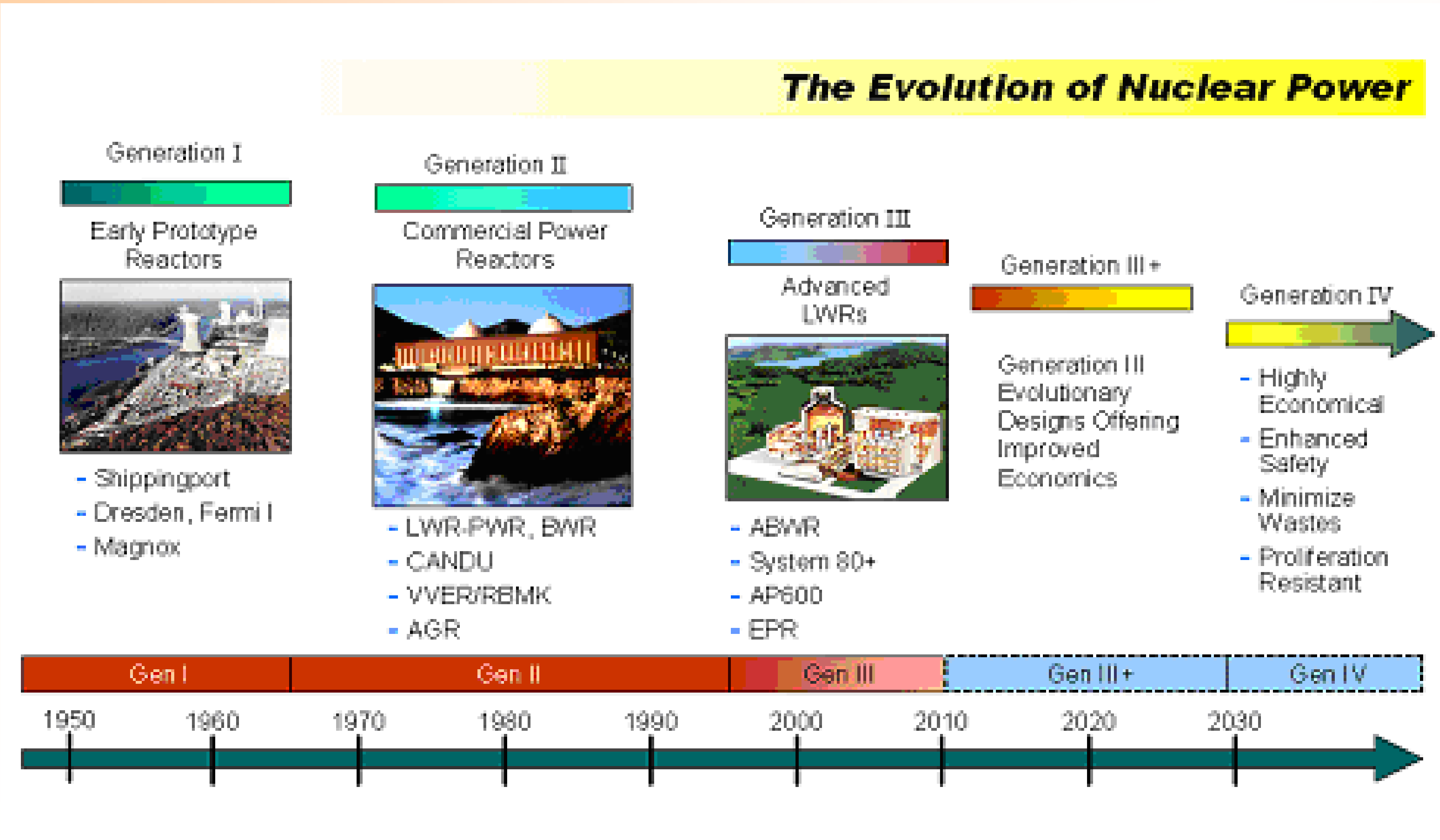
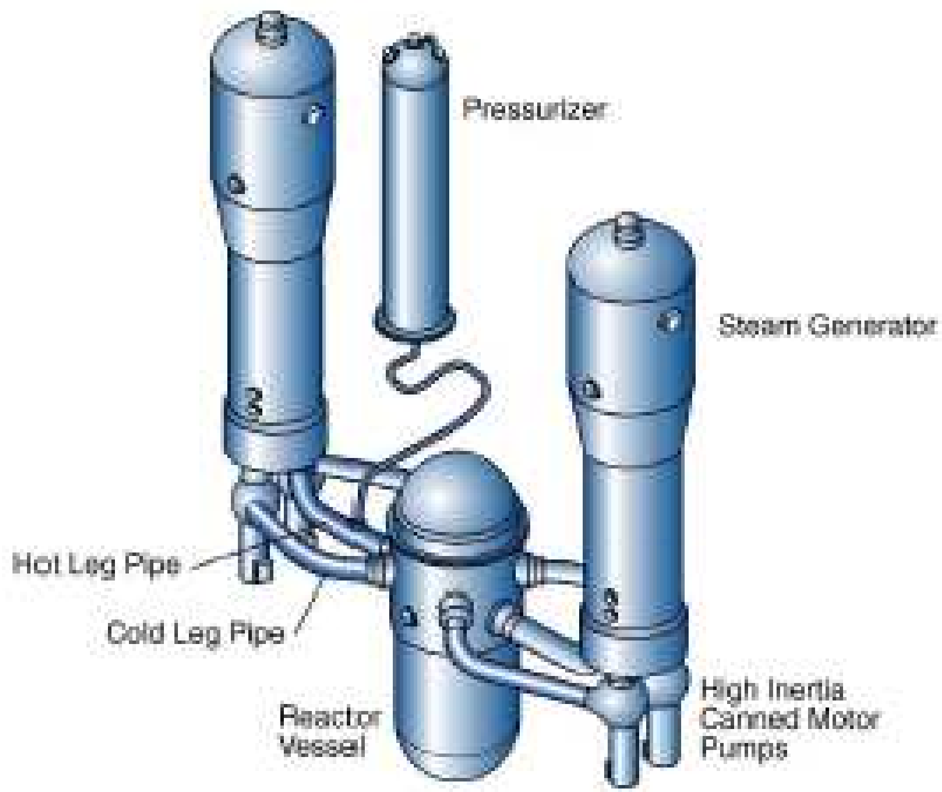

The Evolution of Nuclear Power
Generation I
Early Prototype Reactors
- Shippingport
- Dresden, Fermi I
- Magnox
Generation II
Commercial Power Reactors
- LWR-PWR, BWR
- CANDU
- VVER/RBMK
- AGR
Generation III
Advanced LWRs
- ABWR
- System 80+
- AP600
- EPR
Generation III +
Generation III Evolutionary Designs Offering Improved Economics
Generation IV
- Highly Economical
- Enhanced Safety
- Minimize Wastes
- Proliferation Resistant
Gen I
Gen II
Gen III
Gen III +
Gen IV
1950
1960
1970
1980
1990
2000
2010
2020
2030

AP1000

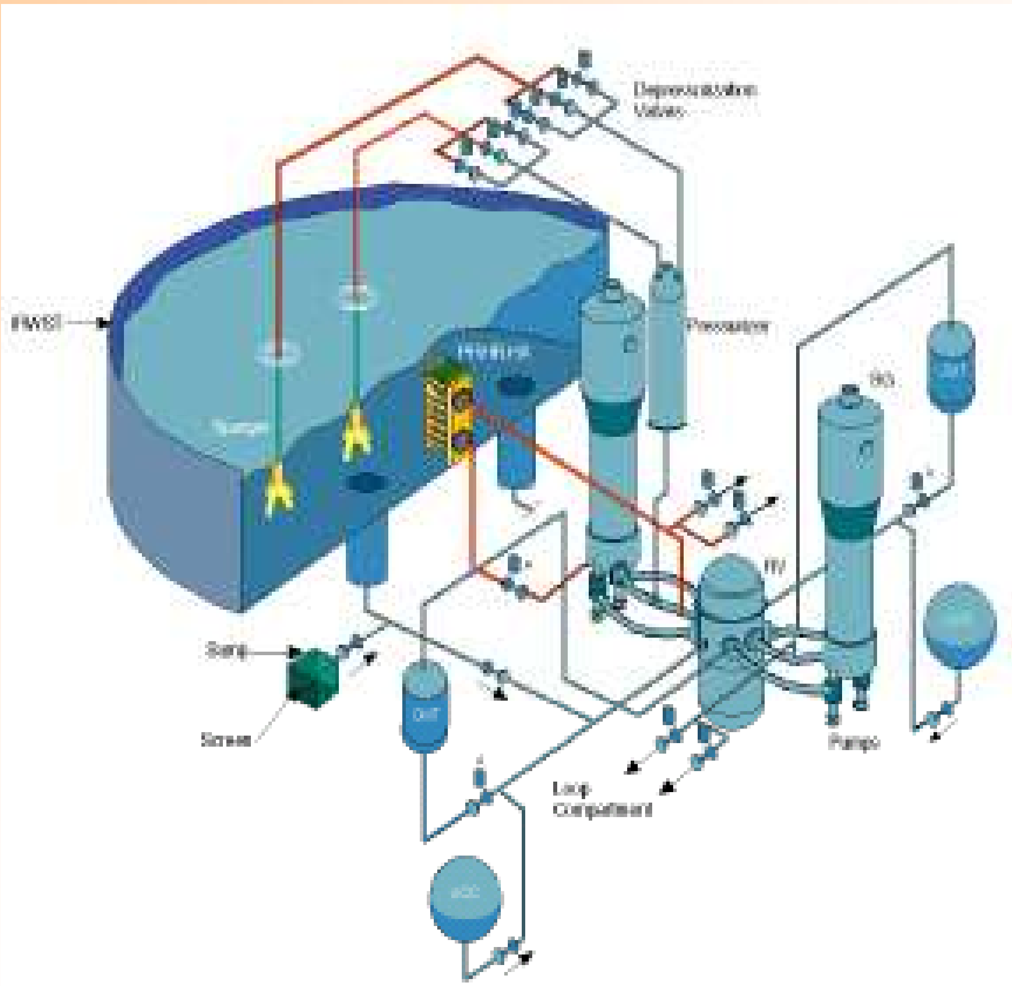
- Advanced 1117 to 1154 MWe nuclear power plant that uses the forces of nature and simplicity of design to enhance plant safety and operations and reduce construction costs
- Passive safety systems are significantly simpler than the traditional PWR safety systems. The AP1000 has 50 percent fewer valves, 83 percent less piping, 87 percent less control cable, 35 percent fewer pumps and 50 percent less seismic building volume than a similarly sized conventional plant. T
- Two steam generators, each connected to the reactor pressure vessel by a single hot leg and two cold legs. There are four reactor coolant pumps
- Fuel design is based on the 17x17 XL (14 foot) design - can operate with a full core loading of MOX fuel.

AP1000 –Reactor coolant system



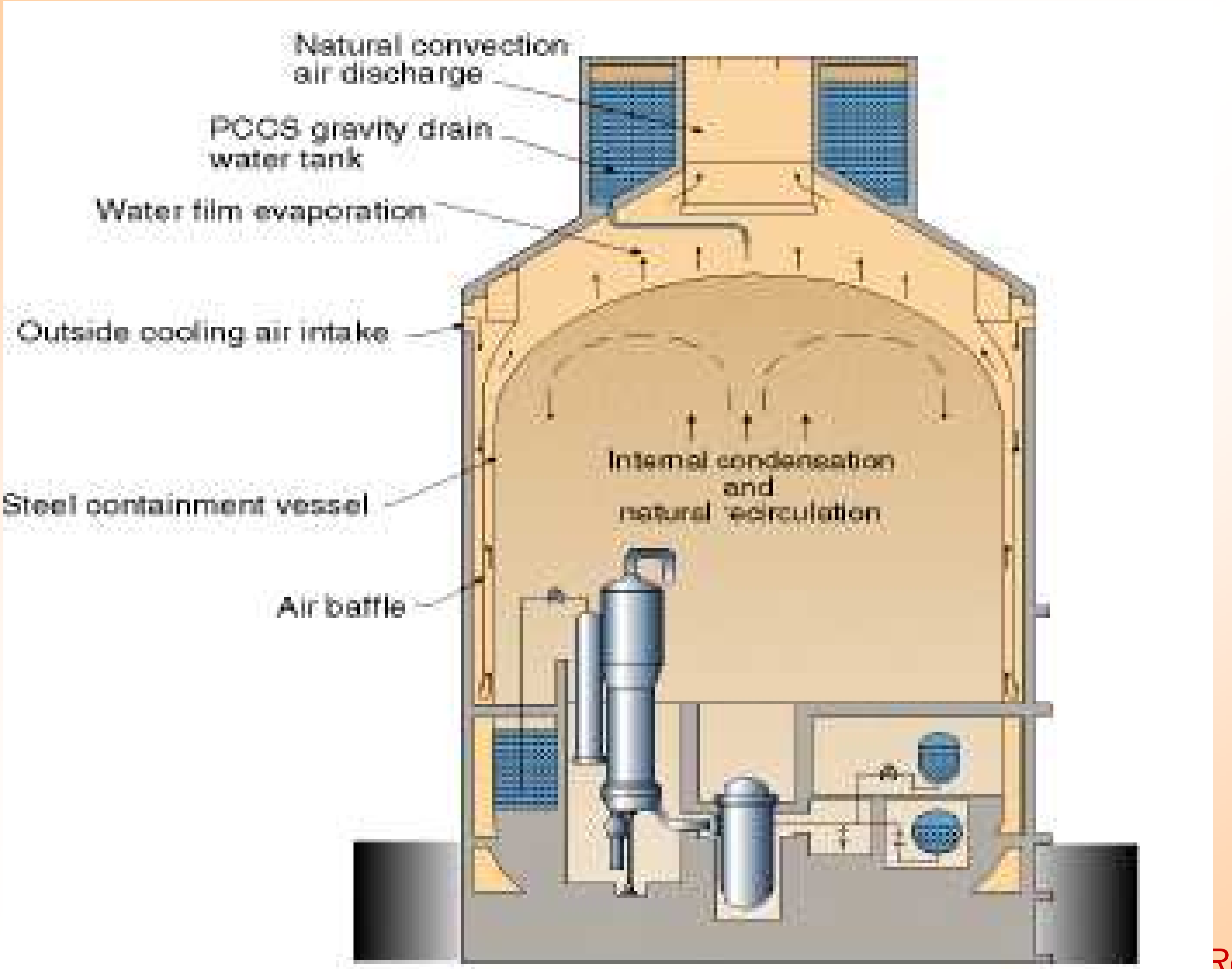
- ✓ Canned motor pumps mounted in steam generator lower vessel head
- ✓ Elimination of RCS loop seal
- ✓ Large pressurizer
- ✓ Top-mounted, fixed in-core detectors
- ✓ All-welded core shroud
- ✓ Ring-forged reactor vessel

AP1000- Passive core cooling system



- ✓ AP1000 has no reliance on AC power
  - –Passive Decay Heat Removal
  - –Passive Safety Injection
  - –Passive Containment Cooling
- ✓ •Long term safe shutdown state > 72 hours without operator action

AP1000- Passive containment cooling



AP1000- Advanced control room

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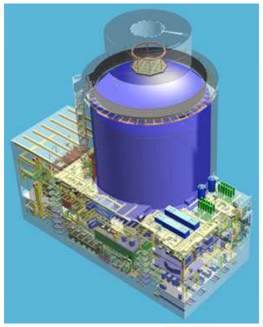
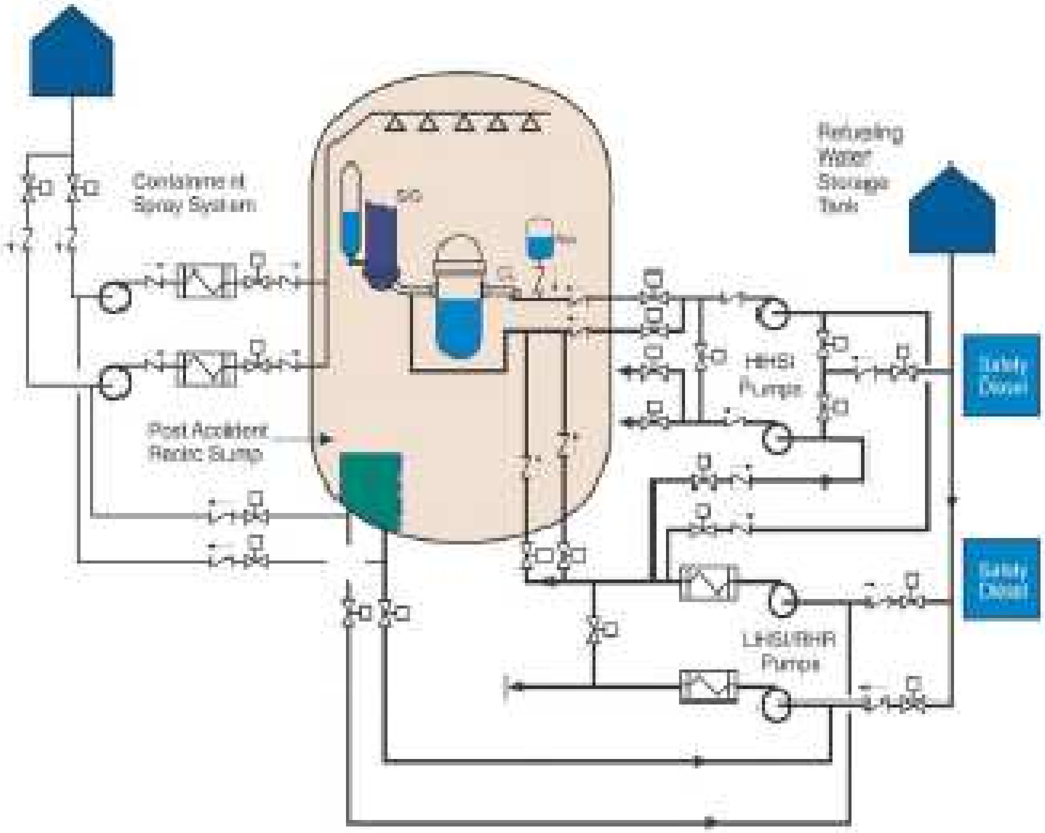
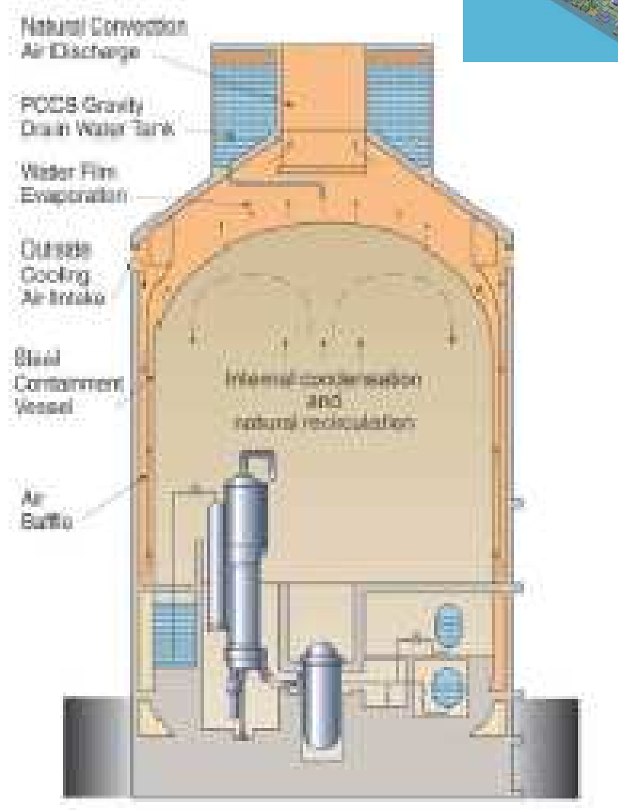
AP1000- Reduced building size



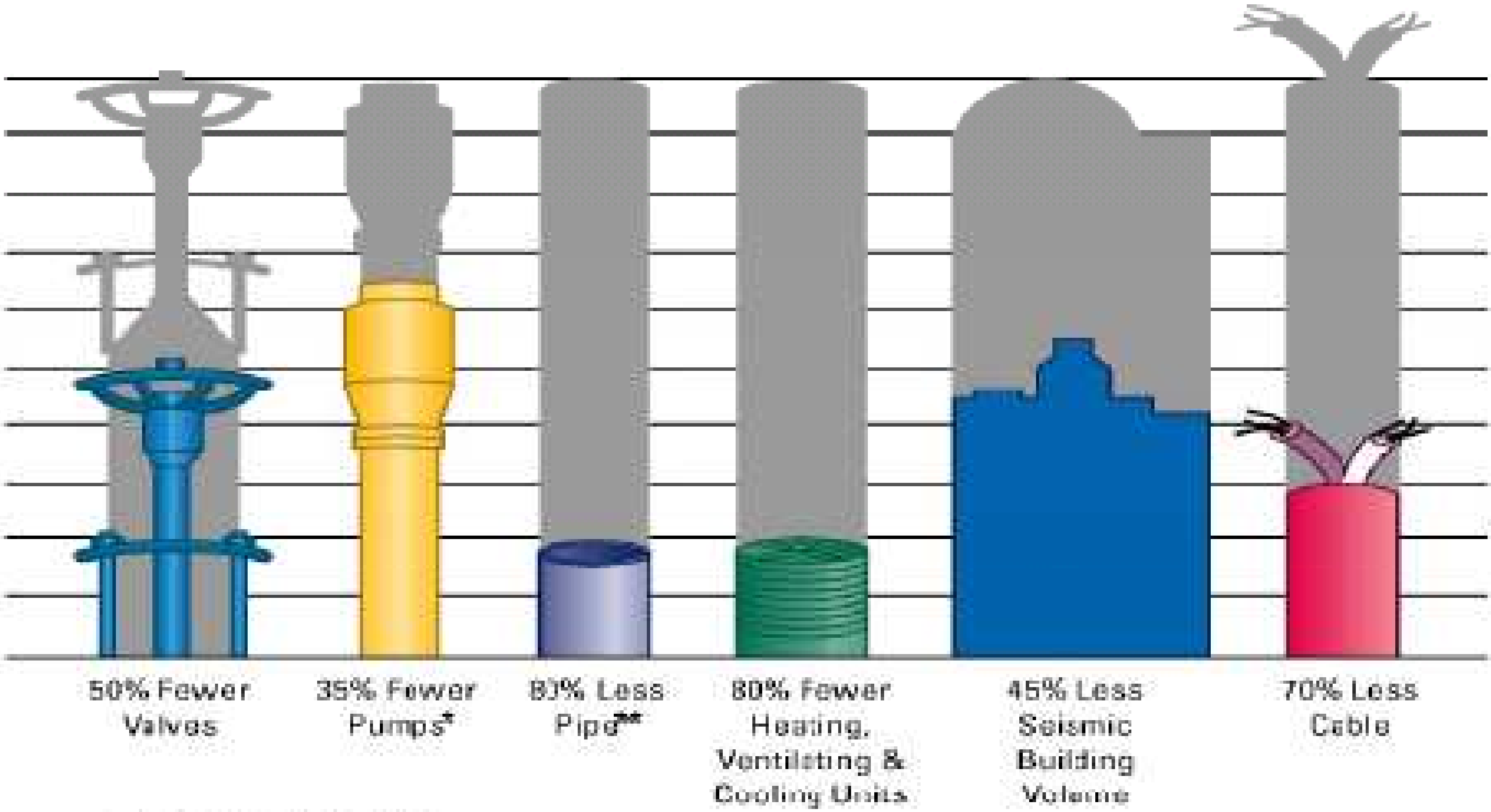
Standard PWR



AP1000



AP1000- Fewer components



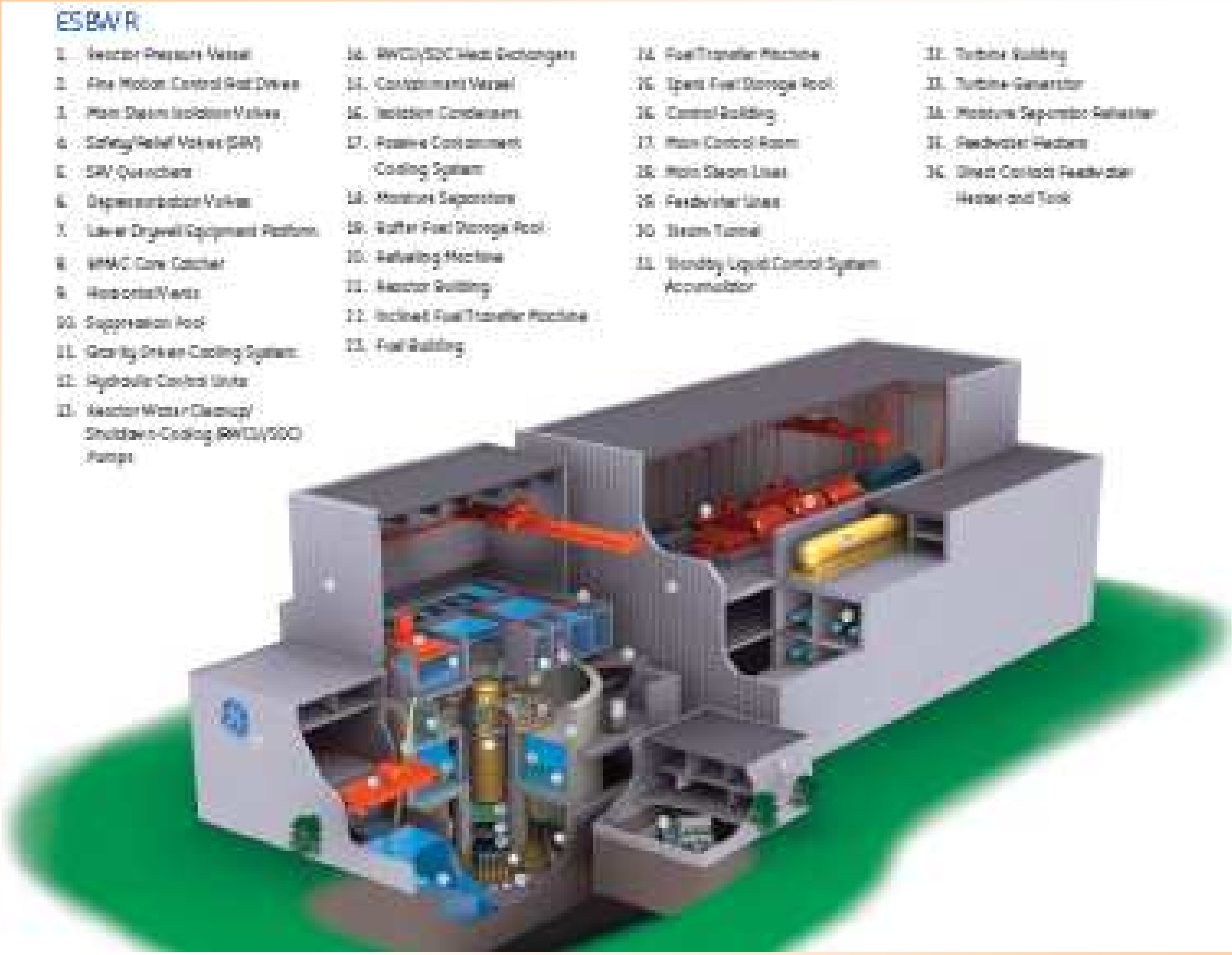
* No safety grade pumps
** Safety Grade

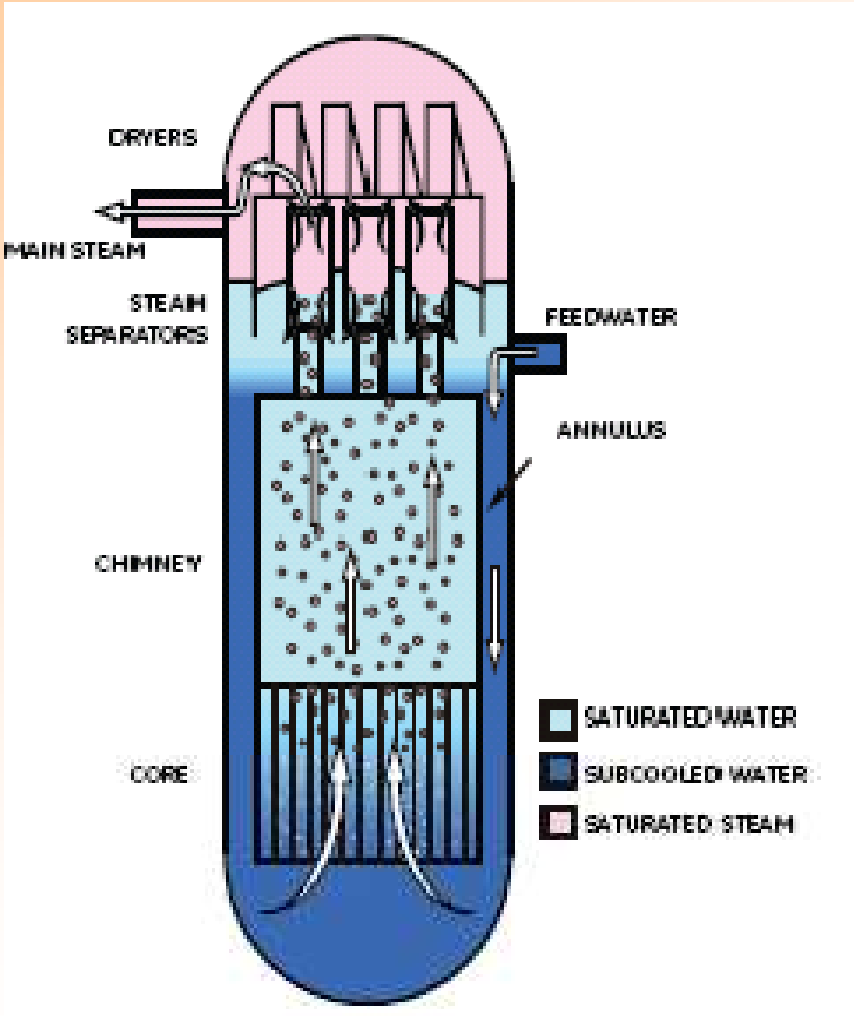
AP1000- Passive Plant economics

Aspect	AP1000
Overnight Capital Cost ($/kWe)	1000 - 1200
Capital Cost Recovery Charge (¢/kWh)	2.1 – 2.5
Fuel & O&M Charge (¢/kWh)	1.0
Decommissioning Charge (¢/kWh)	0.1
Total Generation Costs (¢/kWh)	3.2 – 3.6

ESBWR(Economic simplified BWR)

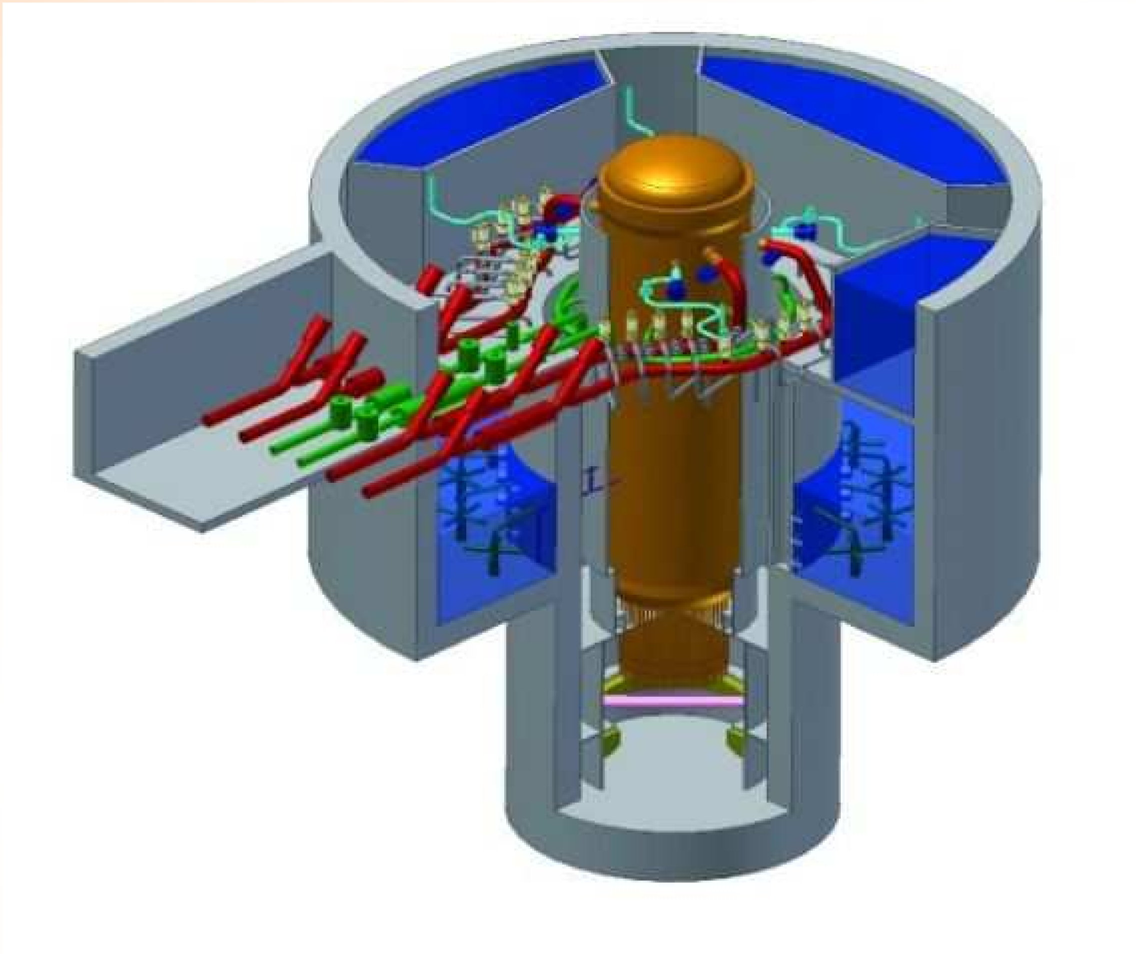
- Simplified design
  - Residual heat transferred to the atmosphere
  - 11 systems eliminated from previous designs
  - 25 percent pumps, valves and motors eliminated from previous designs
- Passive design features reduce the number of active systems, increasing safety
- Incorporation of features used in other operationally-proven BWRs, including passive containment cooling, isolation condensers, natural circulation, and debris-resistant fuel
- Expedited construction schedule due to pre-licensed design and standardized modules


ESBWR
1. Reactor Pressure Vessel
2. Fine Motion Control Rod Drives
3. Main Steam Isolation Valves
4. Safety/Relief Valves (SRV)
5. SRV Quenchers
6. Depressurization Valves
7. Lower Drywell Equipment Platform
8. BiMAC Core Catcher
9. Horizontal Vents
10. Suppression Pool
11. Gravity Driven Cooling System
12. Hydraulic Control Units
13. Reactor Water Cleanup/ Shutdown Cooling (RWCU/SDC) Pumps
14. RWCU/SDC Heat Exchangers
15. Containment Vessel
16. Isolation Condensers
17. Passive Containment Cooling System
18. Moisture Separators
19. Buffer Fuel Storage Pool
20. Refueling Machine
21. Reactor Building
22. Inclined Fuel Transfer Machine
23. Fuel Building
24. Fuel Transfer Machine
25. Spent Fuel Storage Pool
26. Control Building
27. Main Control Room
28. Main Steam Lines
29. Feedwater Lines
30. Steam Tunnel
31. Standby Liquid Control System Accumulator
32. Turbine Building
33. Turbine Generator
34. Moisture Separator Reheater
35. Feedwater Heaters
36. Direct Contact Feedwater Heater and Tank

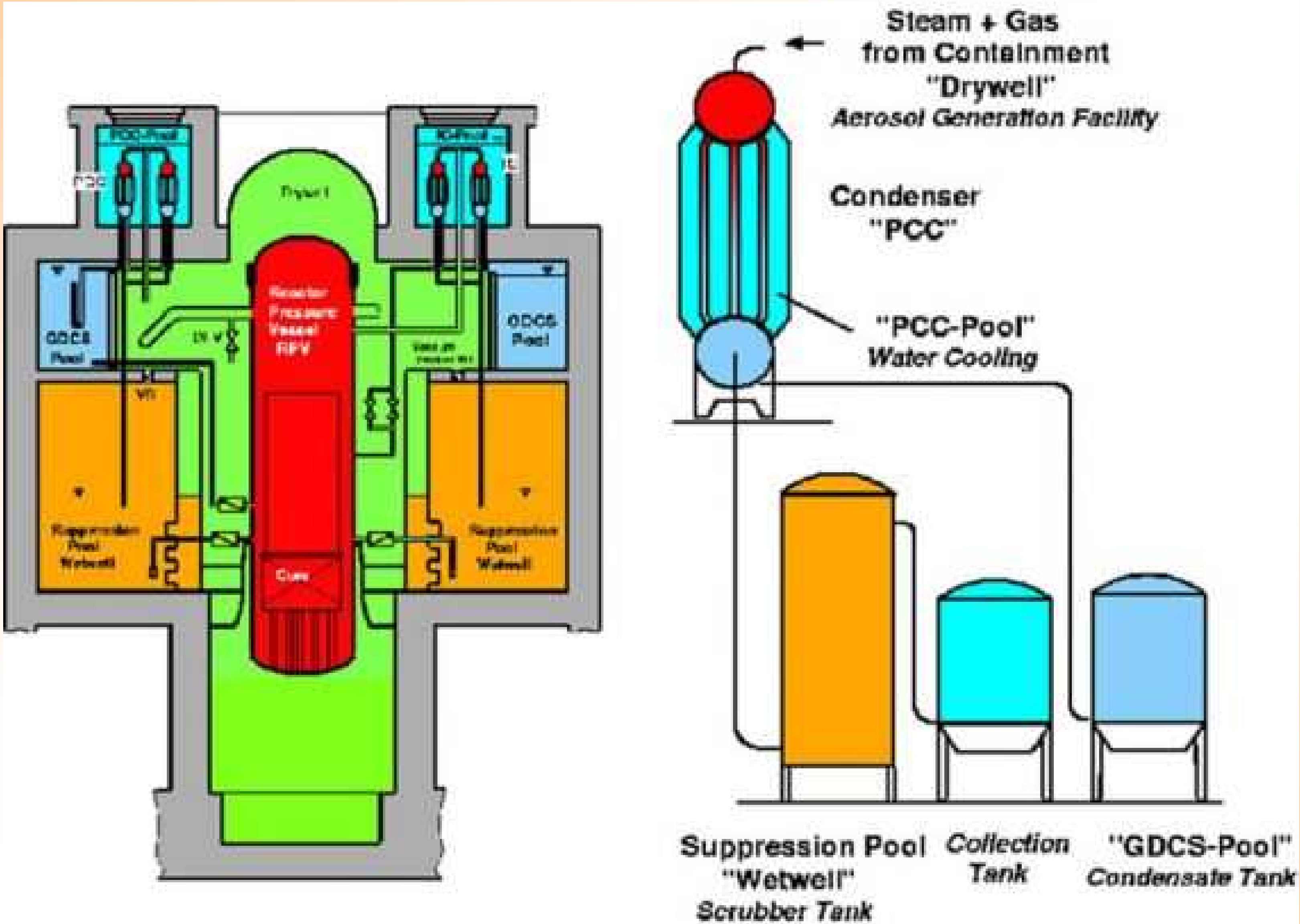


ESBWR

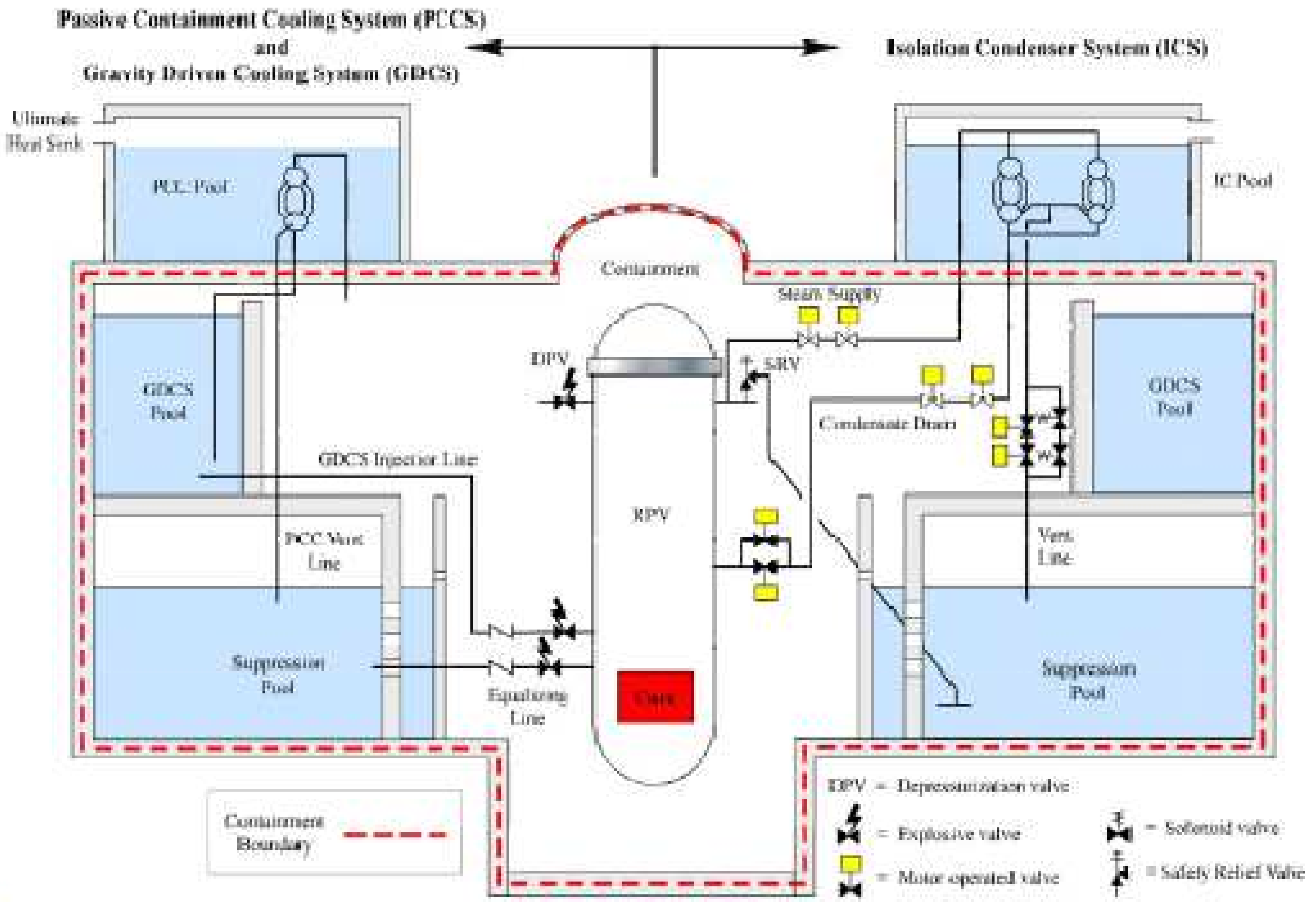
- Design and operation simplification
- Elimination of recirculation pumps decreases maintenance and associated personnel dose
- Very reliable passive Emergency Core Cooling System provides a large margin for loss of cooling accidents (LOCA)
- Passive operation system
- Taller open down-comer and reduced core resistance
- Fine Motion Control Rod Drives instead of pump recirculation flow for core power change
- Taller down-comer provides circulation driving head as well as large water inventory for Loss of Cooling Accident



ESBWR-Passive safety System

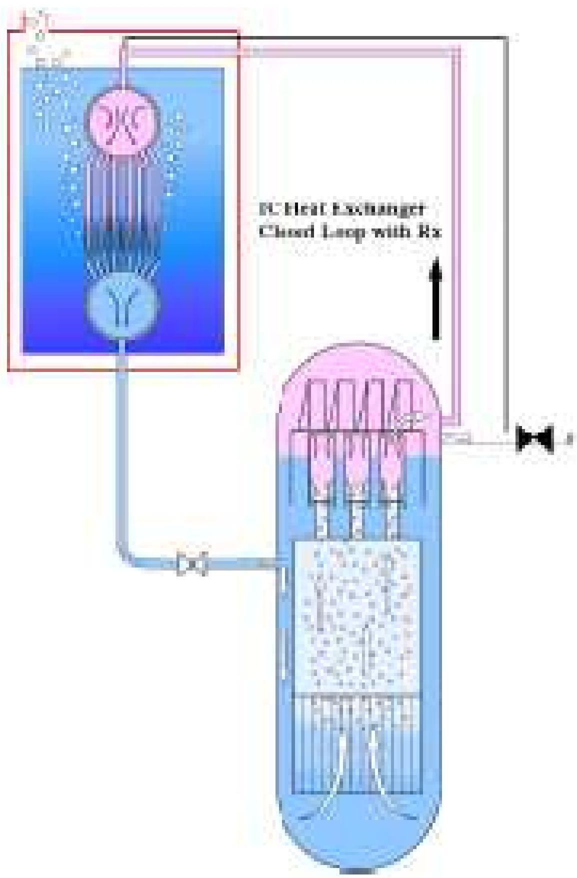


ESBWR-Passive safety System

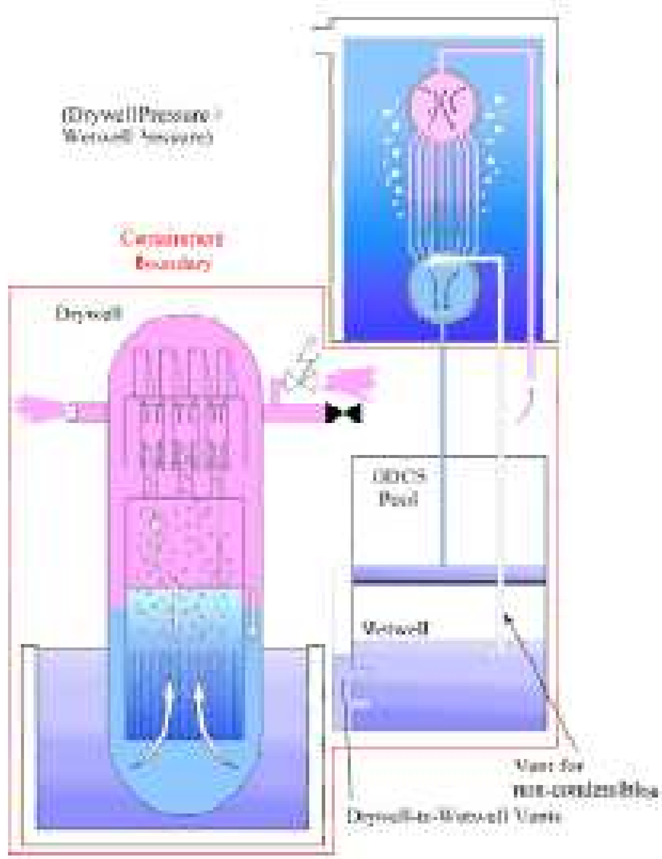


ESBWR-Passive safety System

Isolation Condenser System



Passive Containment Cooling



Optimized Parameters for ESBWR

Parameter	BWR/4-Mk I (Browns Ferry 3)	BWR/6-Mk III (Grand Gulf)	ABWR	ESBWR
Power (MWt/MWe)	3293/1098	3900/1360	3926/1350	4500/1590
Vessel height/dia. (m)	21.9/6.4	21.8/6.4	21.1/7.1	27.7/7.1
Fuel Bundles (number)	764	800	872	1132
Active Fuel Height (m)	3.7	3.7	3.7	3.0
Power density (kw/l)	50	54.2	51	54
Recirculation pumps	2(large)	2(large)	10	zero
Number of CRDs/type	185/LP	193/LP	205/FM	269/FM
Safety system pumps	9	9	18	zero
Safety diesel generator	2	3	3	zero
Core damage freq./yr	1E-5	1E-6	1E-7	3E-8
Safety Bldg Vol (m^3/MWe)	115	150	160	< 130

EPR-General Overview

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EPR-Overview

- Areva design
- Is currently in the pre-certification phase in the US
- Reactor Specifics
  - Advanced PWR design, utilizes light water as moderator
  - Utilizes low and medium enriched uranium as fuel
  - Consists of 241 assemblies
  - Utilizes thermal neutrons
  - 1,600 MW(e) US pre-certified
  - Benefits over previous designs
    - Better efficiency (due to improved uranium use)
    - Improved safety (due to multiple layer safety systems)

EPR-Unique Systems

- ✓ The EPR has four independent emergency cooling loops, each of which can cool reactor independent of the other four.
- ✓ In the event of a core melt, the core will fall through a compartment into what Areva has termed a Corium Spreader.
  - This spreader can then be misted to cool the molten fuel.
- ✓ 2 Currently under construction: 1 in France, 1 in Finland

EPR

GEN IV reactor goals

Sustainability–1. *Generation IV nuclear energy systems will provide sustainable energy generation that meets clean air objectives and promotes long-term availability of systems and effective fuel utilization for worldwide energy production.*

Sustainability–2. *Generation IV nuclear energy systems will minimize and manage their nuclear waste and notably reduce the long-term stewardship burden in the future, thereby improving protection for the public health and the environment.*

Economics–1. *Generation IV nuclear energy systems will have a clear life-cycle cost advantage over other energy sources.*

Economics–2. *Generation IV nuclear energy systems will have a level of financial risk comparable to other energy projects.*

Safety and Reliability –1. *Generation IV nuclear energy systems operations will excel in safety and reliability.*

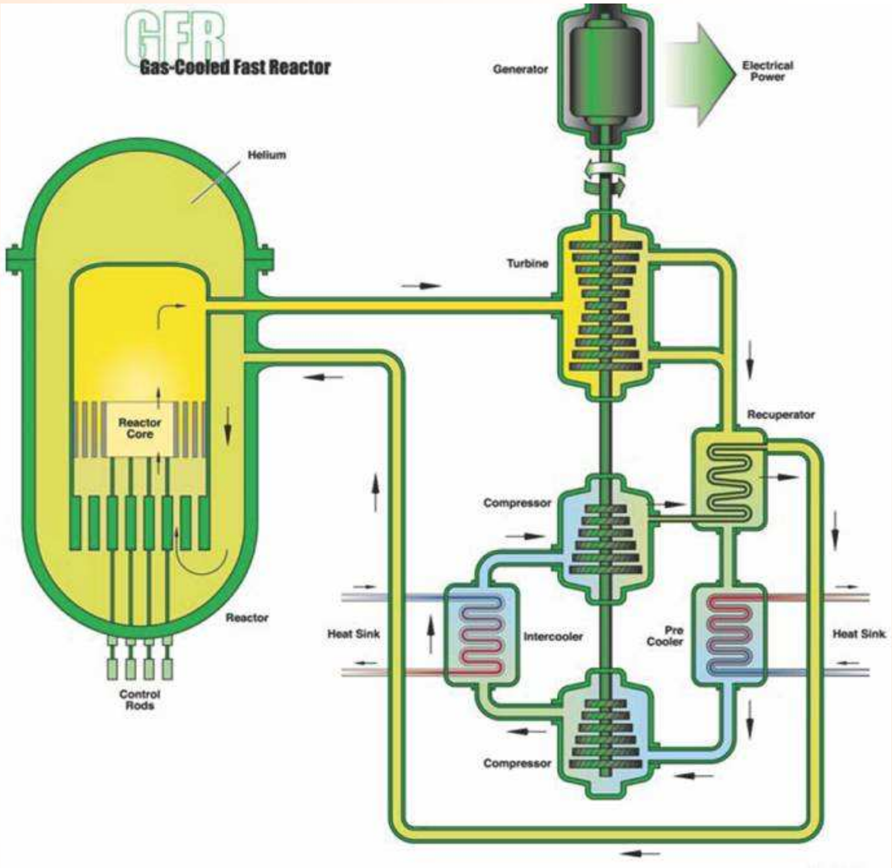
Safety and Reliability–2. *Generation IV nuclear energy systems will have a very low likelihood and degree of reactor core damage.*

Safety and Reliability–3. *Generation IV nuclear energy systems will eliminate the need for offsite emergency response.*

Proliferation Resistance and Physical Protection-1*. Generation IV nuclear energy systems will increase the assurance that they are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.*

Generation IV Reactors

Gas-Cooled Fast Reactor (GFR)



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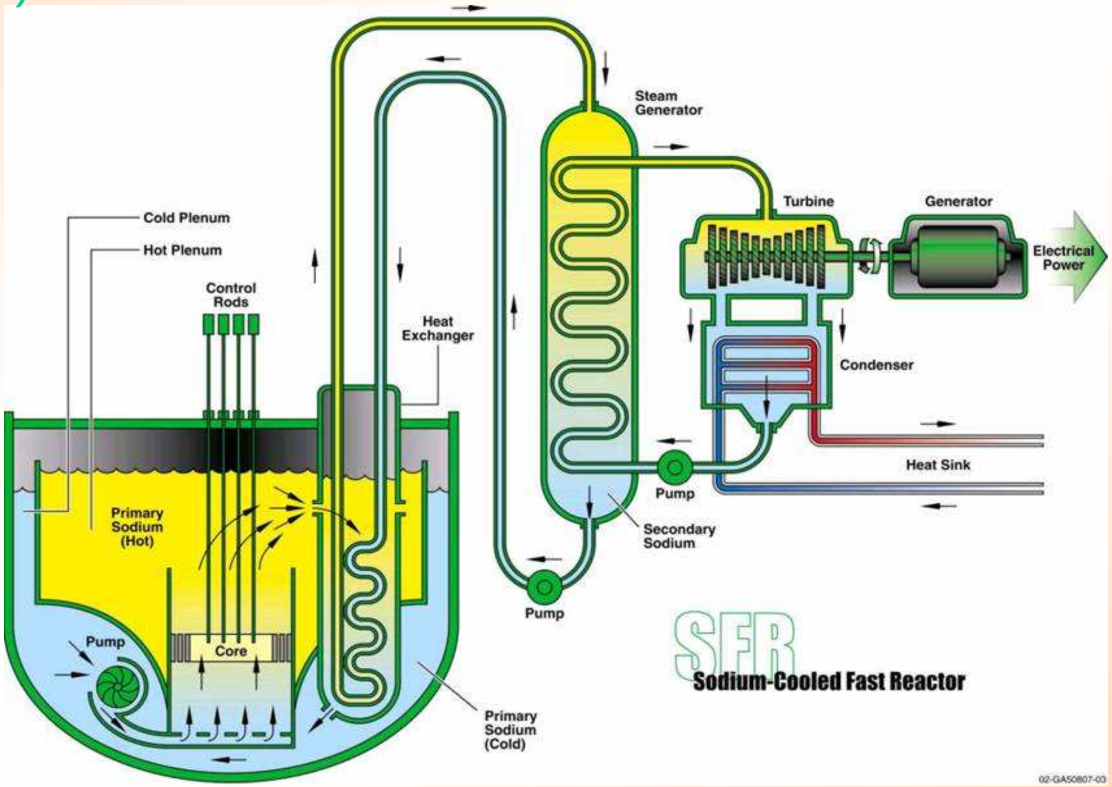
Generation IV Reactors

- ✓ **GFR**
  - **Is currently only a design**
  - **Reactor specifics**
    - **Contains several fuel forms**
      - **Composite ceramic**
      - **Advanced fuel particles**
      - **Ceramic clad elements of actinide compounds**
    - **Helium gas moderated**
    - **Thermal neutron class**
    - **Energy output range of 288 – 1,200 MW(e)**
    - **Benefits over original LWR**
      - **Ability to provide process heat for hydrogen production**
      - **Ability to burn transuranics**
    - **Drawbacks**
      - **High projected capital costs**
      - **Design concept is still at a basic level**

Generation IV Reactors

Sodium-Cooled Fast Reactor (SFR)



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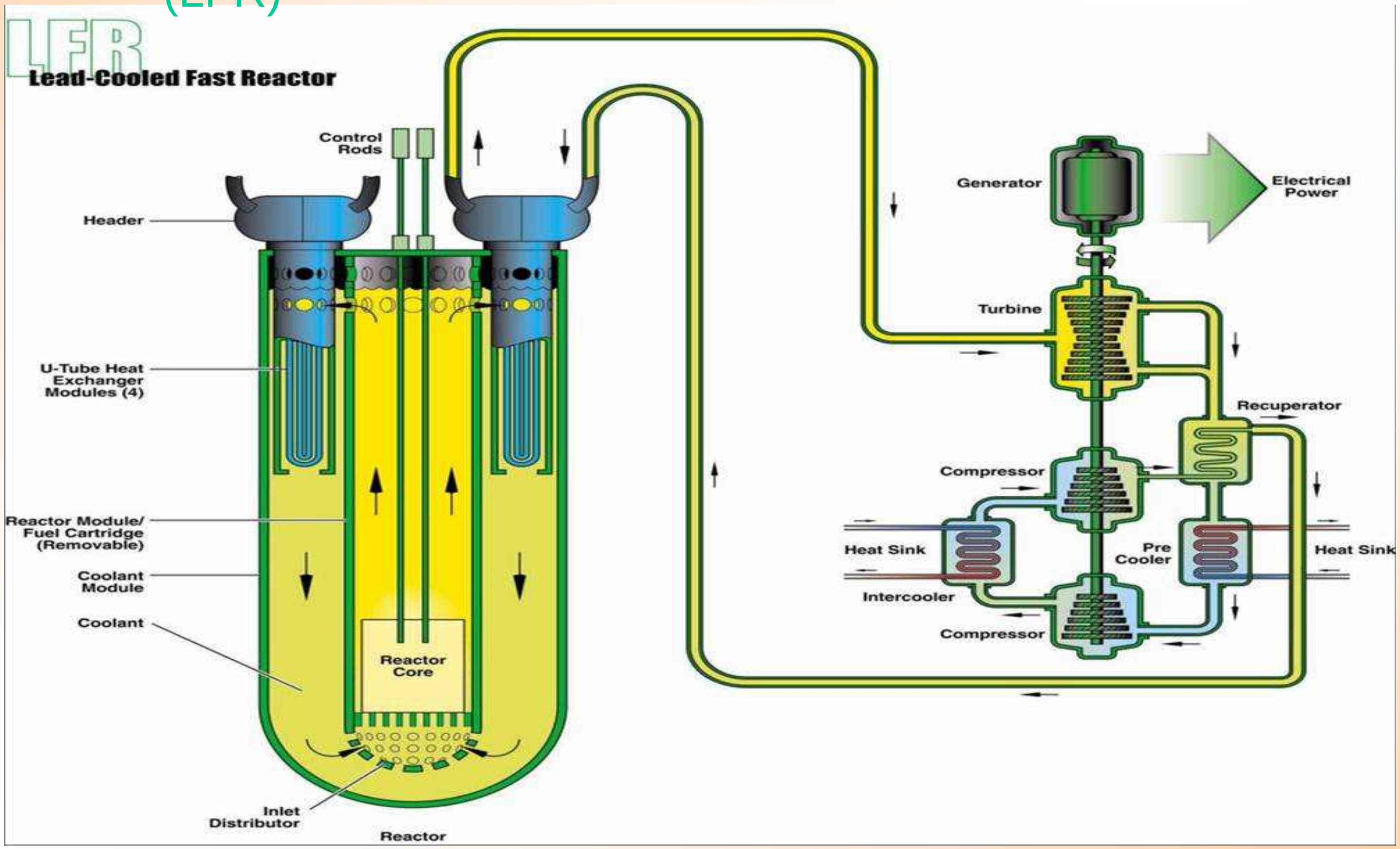
Generation IV Reactors

✓ **SFR**

- **Is currently only a design**
- **Reactor specifics**
  - **Fuel can be a combination of mixed uranium-plutonium-oxide (MOX) or mixed uranium-plutonium-zirconium**
  - **Sodium moderated**
  - **Fast neutron class**
  - **50-1500 MW(e) energy range**
  - **Benefits over prior generation reactors**
    - **Improved heat transfer results in better efficiency**
    - **Increased use of neutron spectrum results in less waste**
    - **Low vessel pressure (~1atm) results in improved safety**

Generation IV Reactors

Lead Cooled Fast Reactor
(LFR)



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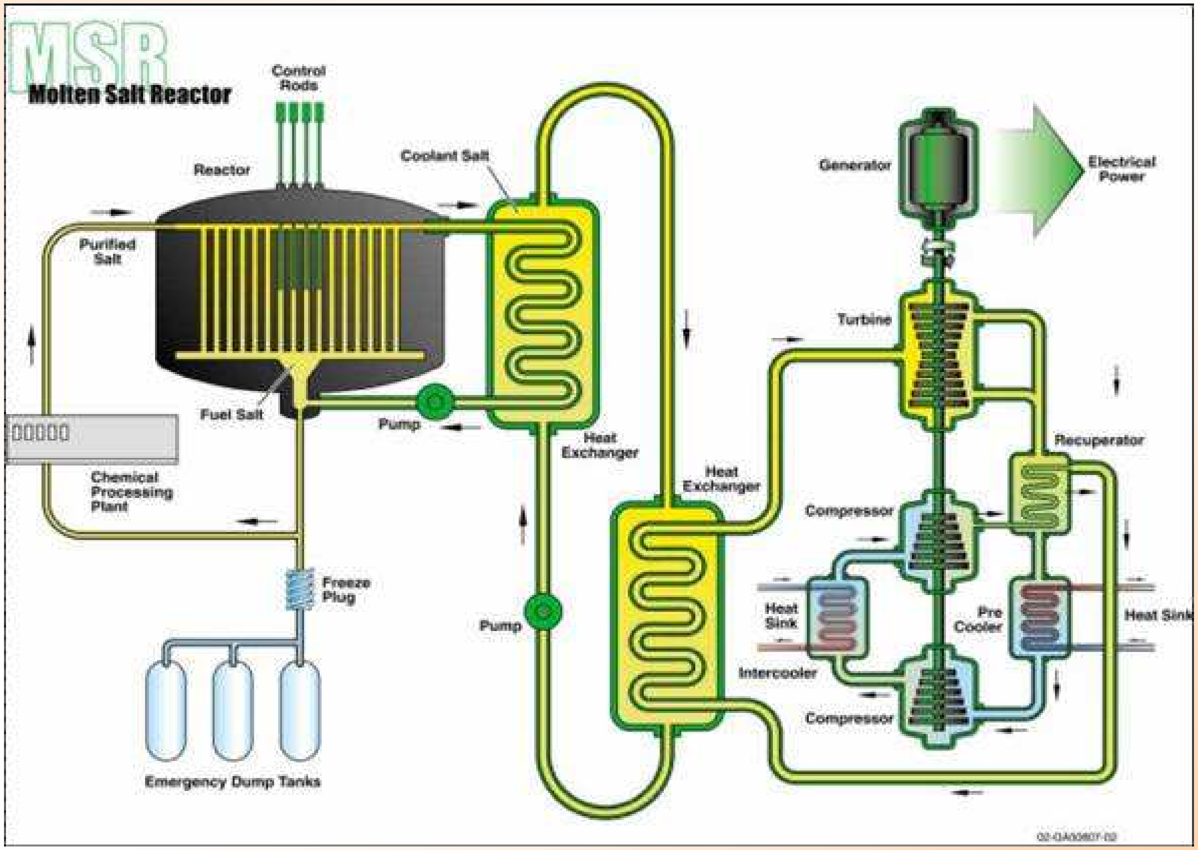
Generation IV Reactors

✓ **LFR**

- **Currently only a design**
- **Reactor specifics**
  - **Utilizes metal uranium or nitride-metal based uranium**
  - **Lead moderated**
  - **Fast neutron spectrum**
  - **50-1200 MW(e) energy range**
  - **Benefits over previous generation reactors**
    - **Better efficiency due to longer intervals between fueling**
    - **Less waste due to increased use of neutron spectrum**
  - **Drawbacks – Lead can harden rendering the reactor inoperable**

Generation IV Reactors

Molten Salt Reactor (MSR)



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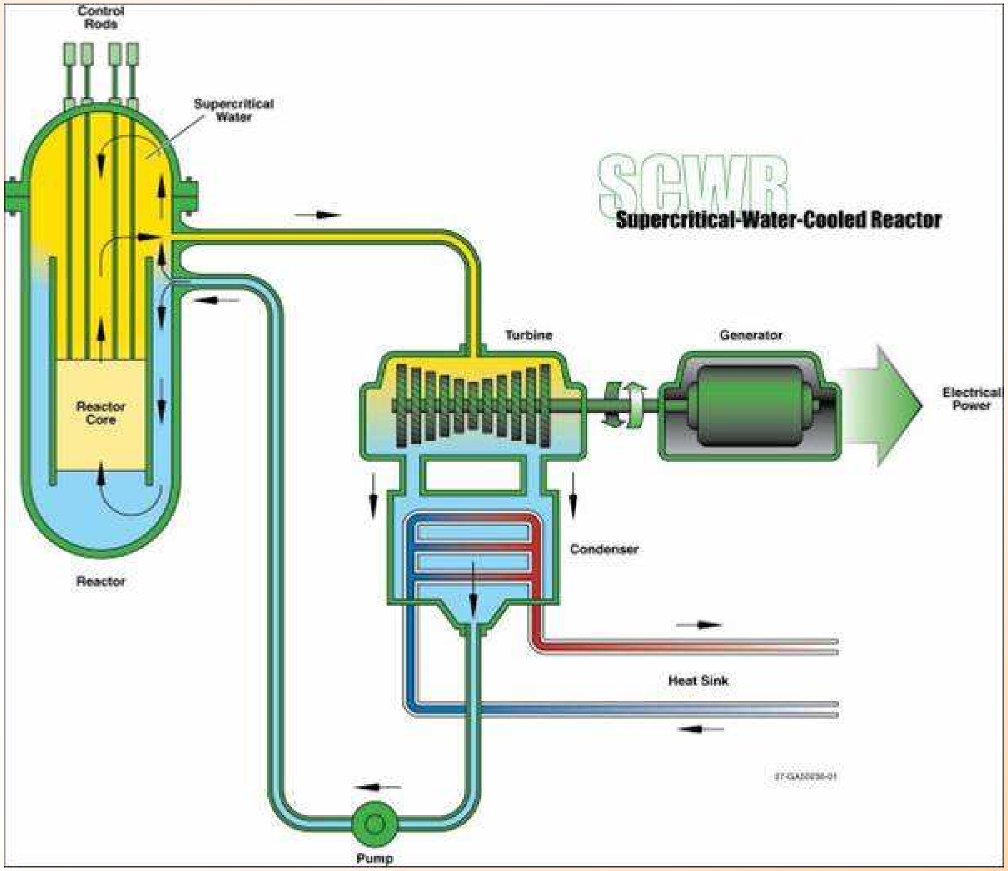
Generation IV Reactors

- **MSR**
  - Initial experiments in 1950s with this technology were to create aircraft reactors.
  - Initial reactor reached 2.5MW(t)
  - Reactor specifics
    - Closed fuel cycle
    - Fuel and fission products dissolved in fluoride salt
    - Graphite moderated
    - Thermal to epithermal neutron class
    - Gen IV projected energy output of 1000 MW(e)
    - Benefits over LWR
      - Can be used to burn waste fuel, thereby reducing total waste
      - Efficiencies are projected to reach upwards of 60%, with a core outlet temperature of 1000 degrees C
      - Reduced pipe pressure due to very low vapor pressure of molten salt
    - Drawbacks
      - Design has not been looked at in detail since 1970s
      - Extremely complex design
      - Molten salt is combustible if exposed to atmosphere

Generation IV Reactors

Supercritical-Water Cooled Reactor (SCWR)



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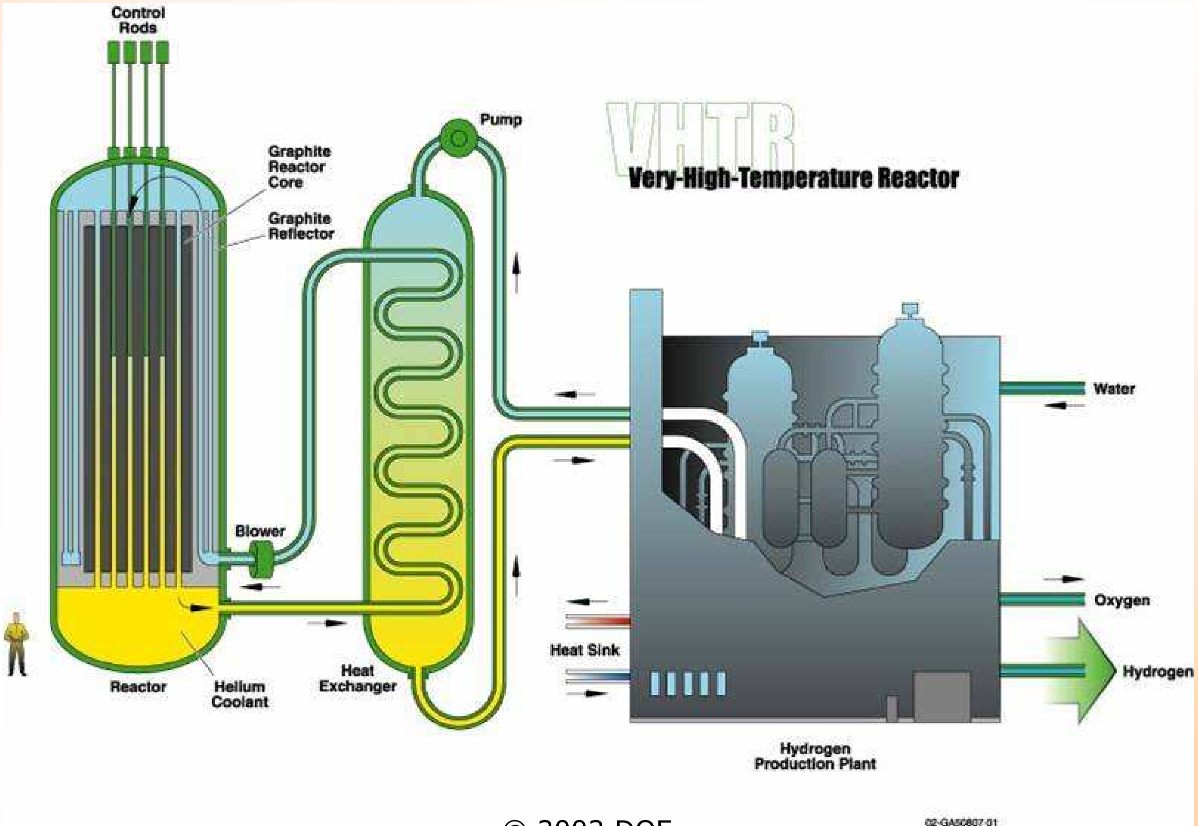
Generation IV Reactors

- SCWR
  - Research is primarily being conducted by Japanese and US
  - Reactor specifics
    - Can theoretically be fueled with U-235, Th, or MOX on a thermal neutron spectrum as a once through cycle
    - Can also be run as a closed cycle, fast neutron reactor with actinide fuel rods
    - Super critical water moderated (25 MPa)
    - Estimated energy output of 1700 MW(e)
    - Benefits over Gen III designs
      - High level of fuel flexibility
      - Higher efficiency (45% vs. 33% due to increased core I/O T)
      - Existence of SCW coal plants proves that SCW integrity can be maintained
      - Elimination of systems means containment size reduction
    - Drawbacks
      - Dramatically reduced coolant inventory
      - Materials research has revealed many problems

Generation IV Reactors

Very High-Temperature Reactor
(VHTR)



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Generation IV Reactors

- VHTR
  - Two experimental reactors have been built in Japan and China with respective outputs of 30 and 10 MW(t)
  - Reactor specifics
    - Utilizes a once through U-235 fuel cycle
    - Core design can be either prismatic block or pebble bed
    - Graphite moderated
    - Utilizes helium as a coolant
    - Neutron class can be either fast or thermal
    - Energy output of 600 MW(e)
    - Benefits over LWRs
      - Can be used to produce hydrogen
      - NGNP plant planned for US
      - Similar design to older US GCR at Ft. Saint Vrain and Peach Bottom
    - Drawbacks
      - New design has not yet been utilized in US
      - Relatively low energy output compared to Gen III LWRs and Gen IV reactors