A Survey of Power Plant Designs

Elizabeth K. Ervin

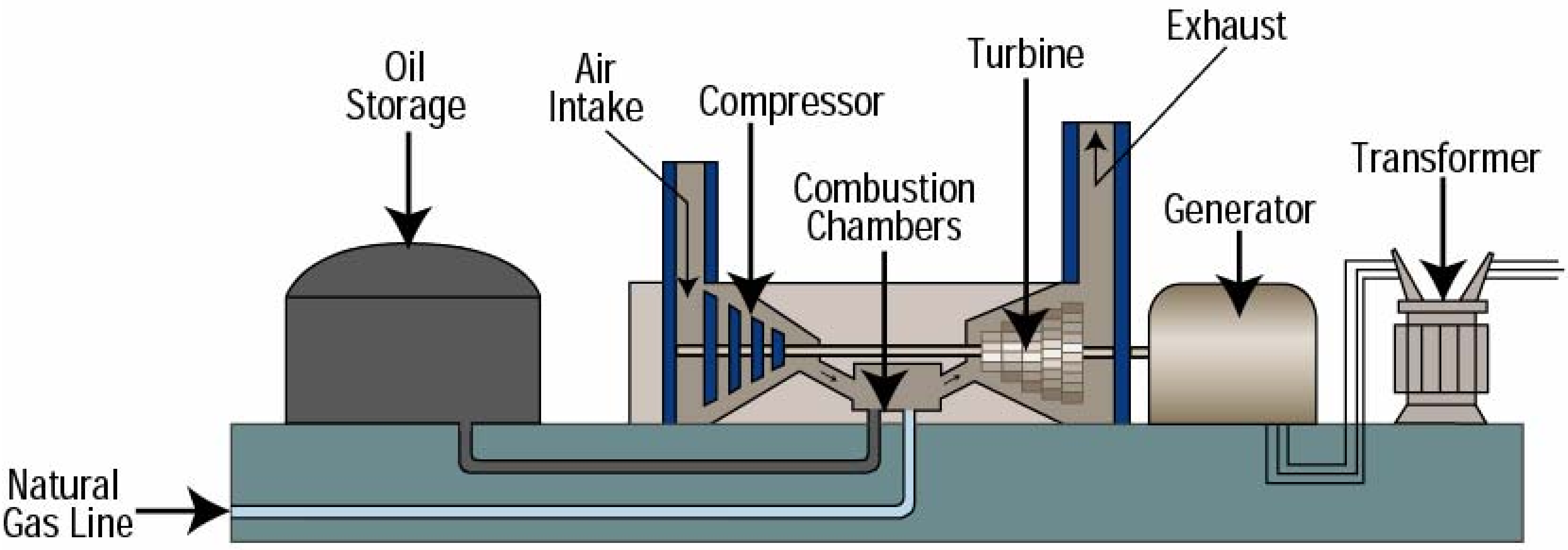
(with many thanks to internet and text sources)

www.ent.ohiou.edu/~thermo/index.html

The General James M Gavin Steam Power Plant near Cheshire, Ohio
full capacity: 2,600,000kW

Israel Urieli (Dr. Iz), Associate Professor, Mechanical Engineering, Ohio University

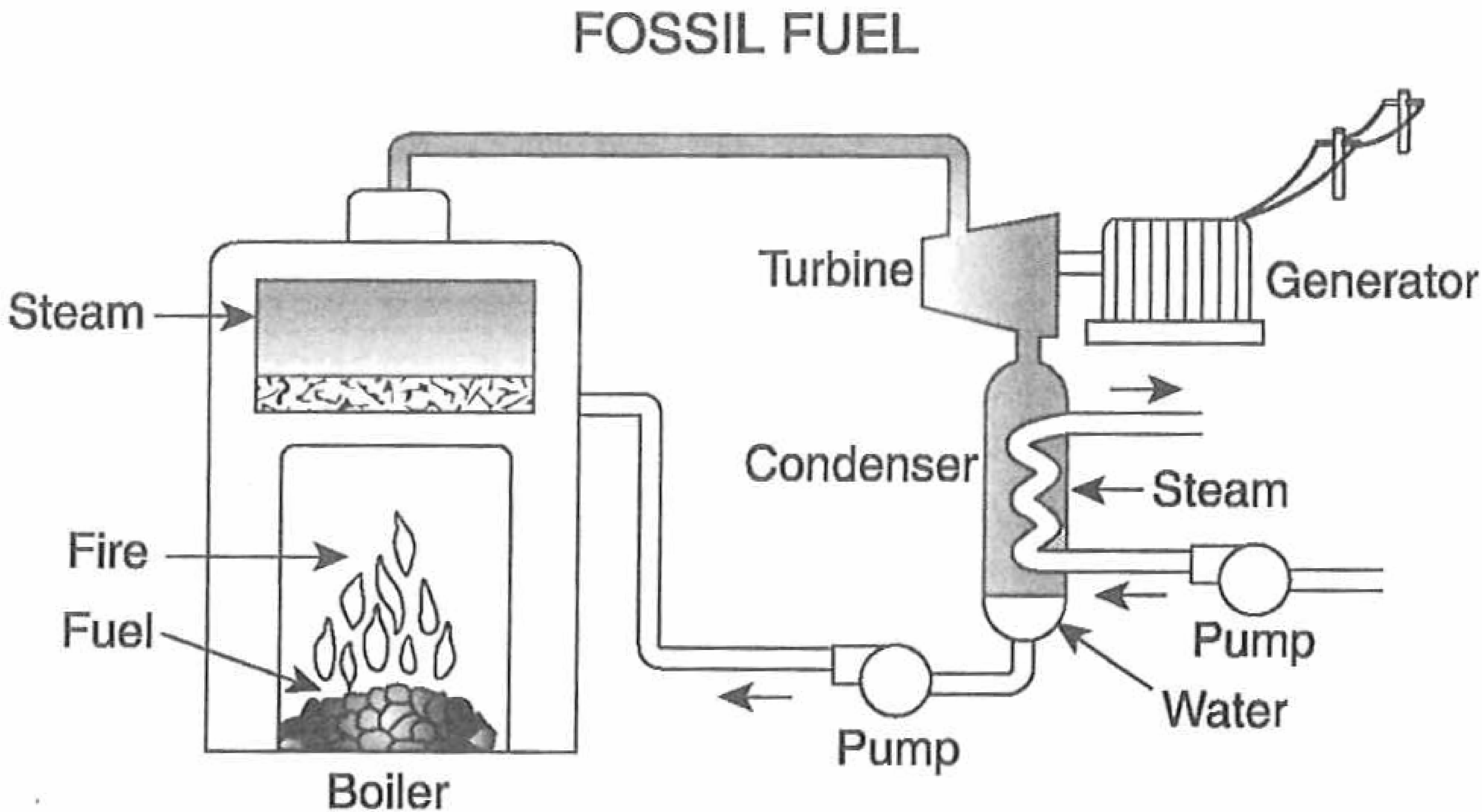
Combustion Turbine Power Plant



Open System

The turbine burns either natural gas or oil. Fuel is mixed with compressed air in the combustion chamber and burned. High-pressure combustion gases spin the turbine, which drives the generator.

Source: Tennessee Valley Authority (TVA), http://www.tva.gov



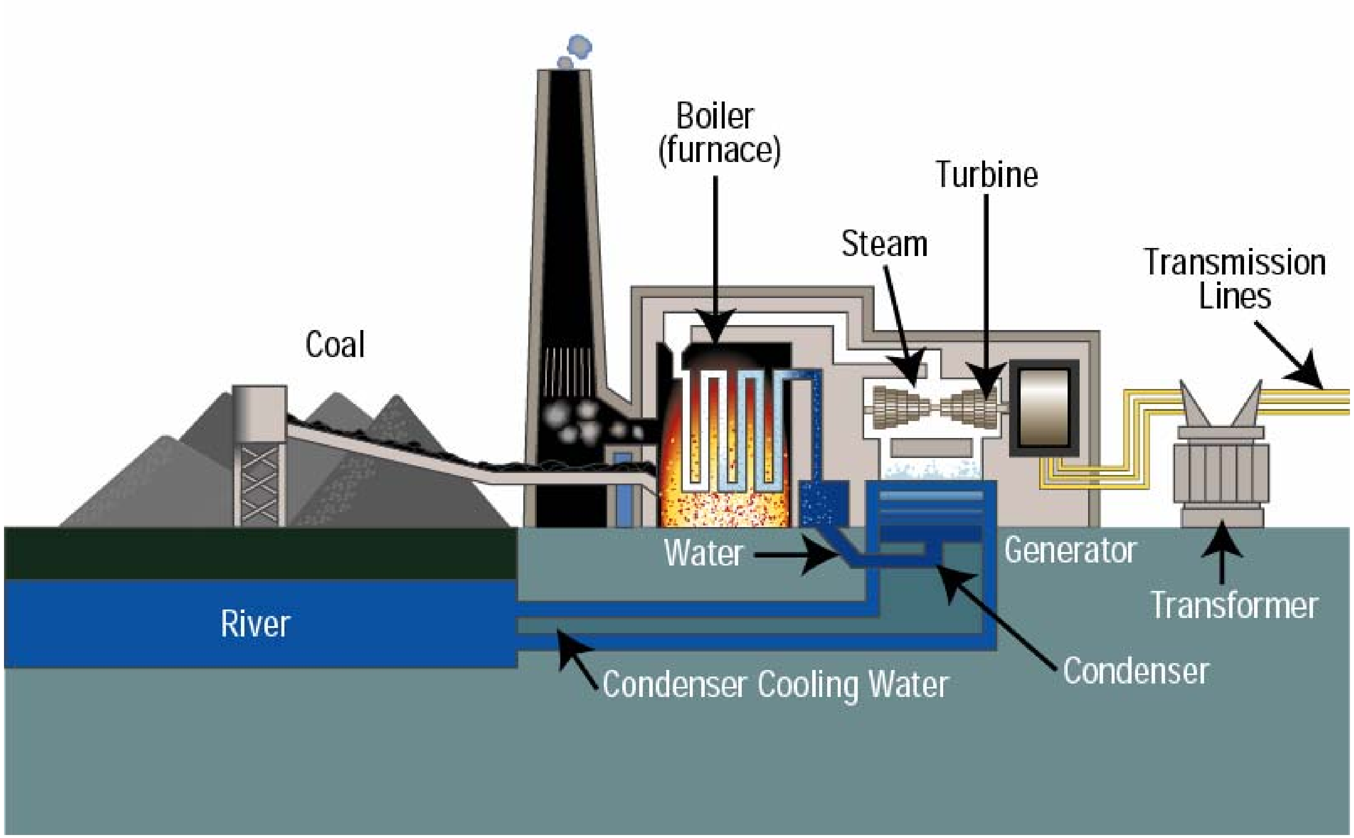
Sustainable Energy, MIT 2005.

Allen Fossil Plant is on the Mississippi River five miles southwest of downtown Memphis.

Paradise Fossil Plant is located in western Kentucky on the Green River near the village of Paradise. The plant has three units, completed between 1963 and 1970, and three large natural-draft cooling towers to provide cooling water. Producing 2,273 MW, the plant consumes some 20,000 tons of coal a day.

The Southaven Combined-Cycle Combustion Turbine Plant is located near Desoto County, Mississippi.
Running on natural gas, plant capacity is 810 MW.

Coal-fired Power Plant

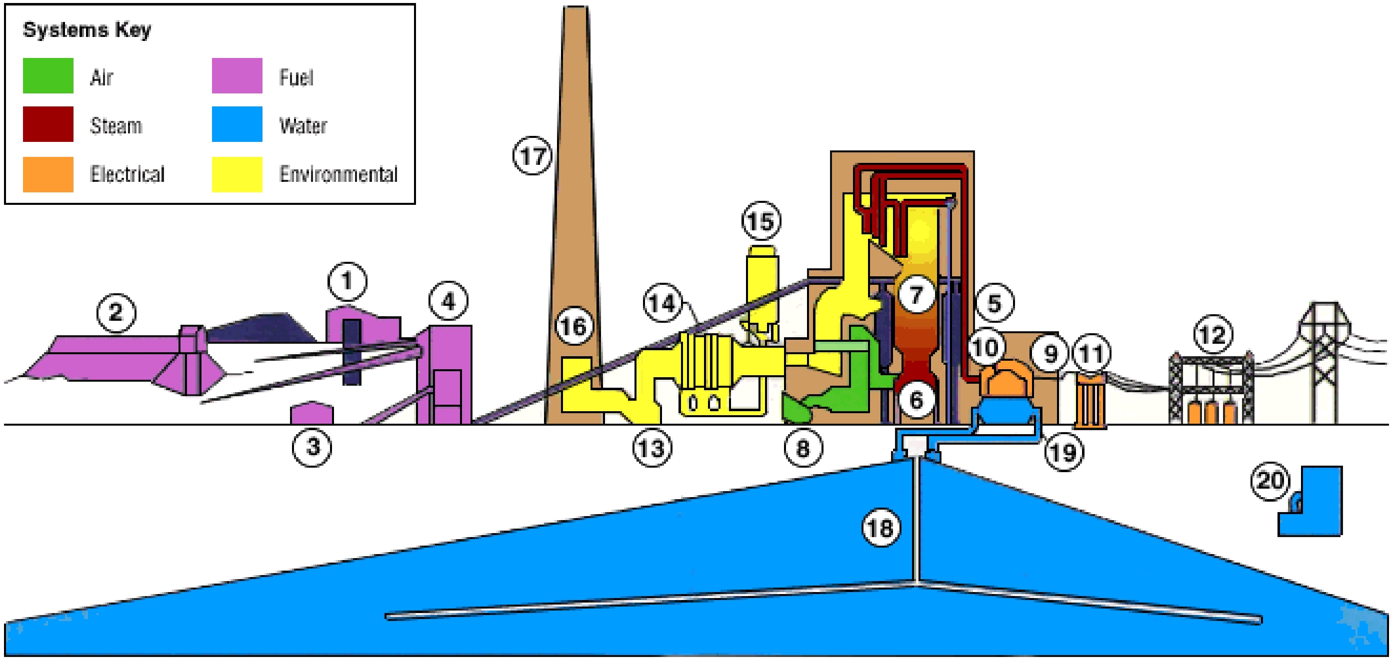


Coal burned in the boiler heats water to produce steam. The steam spins the turbine, which drives the generator.

Source: Tennessee Valley Authority (TVA), http://www.tva.gov

Coal fired Plant

Otpco.com



Fuel handling
(1) Rotary dumper
(2) Storage building
(3) Alternate fuel-handling facility
(4) Transfer house

Furnace
(5) Silos
(6) Cyclone furnaces
(7) Boiler furnace
(8) Forced-draft fans

Electric generation
(9) Turbine
(10) Generator

Electric transmission
(11) Transformer
(12) Substation

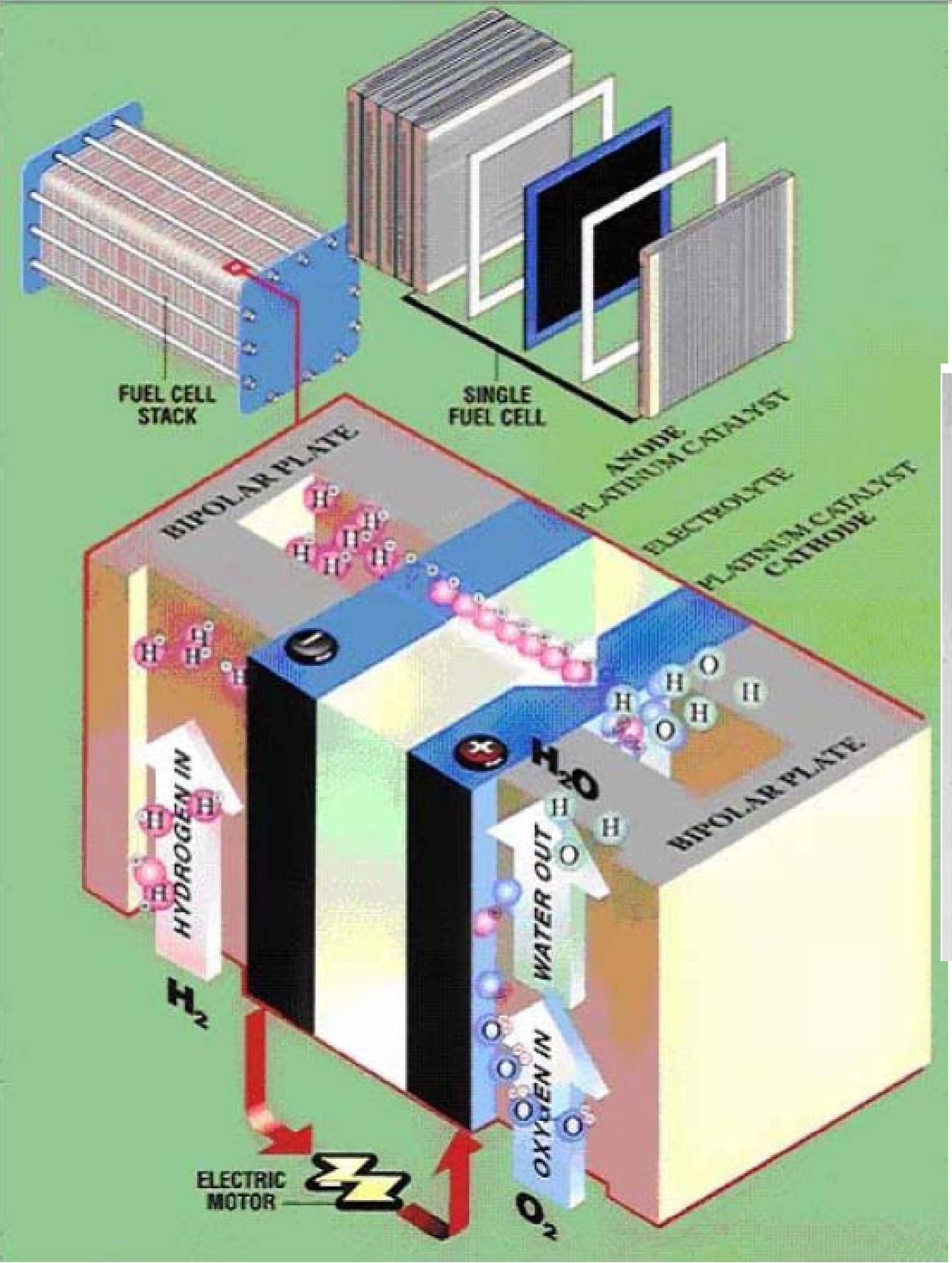
Environmental equipment
(13) Fans
(14) Precipitator
(15) Ash silo
(16) Stack
(17) Emission monitors

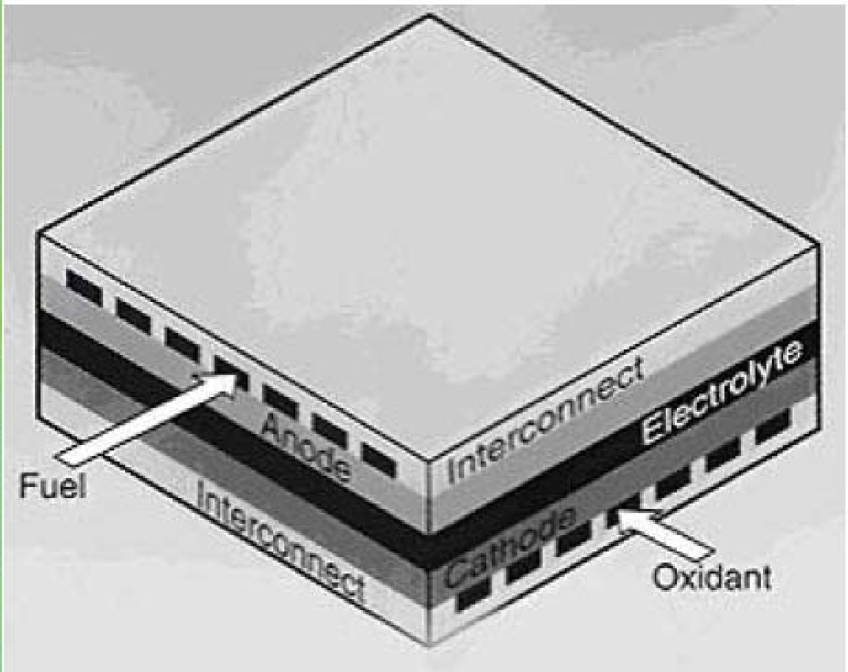
Water handling
(18) Cooling pond
(19) Condenser
(20) Brine concentrator

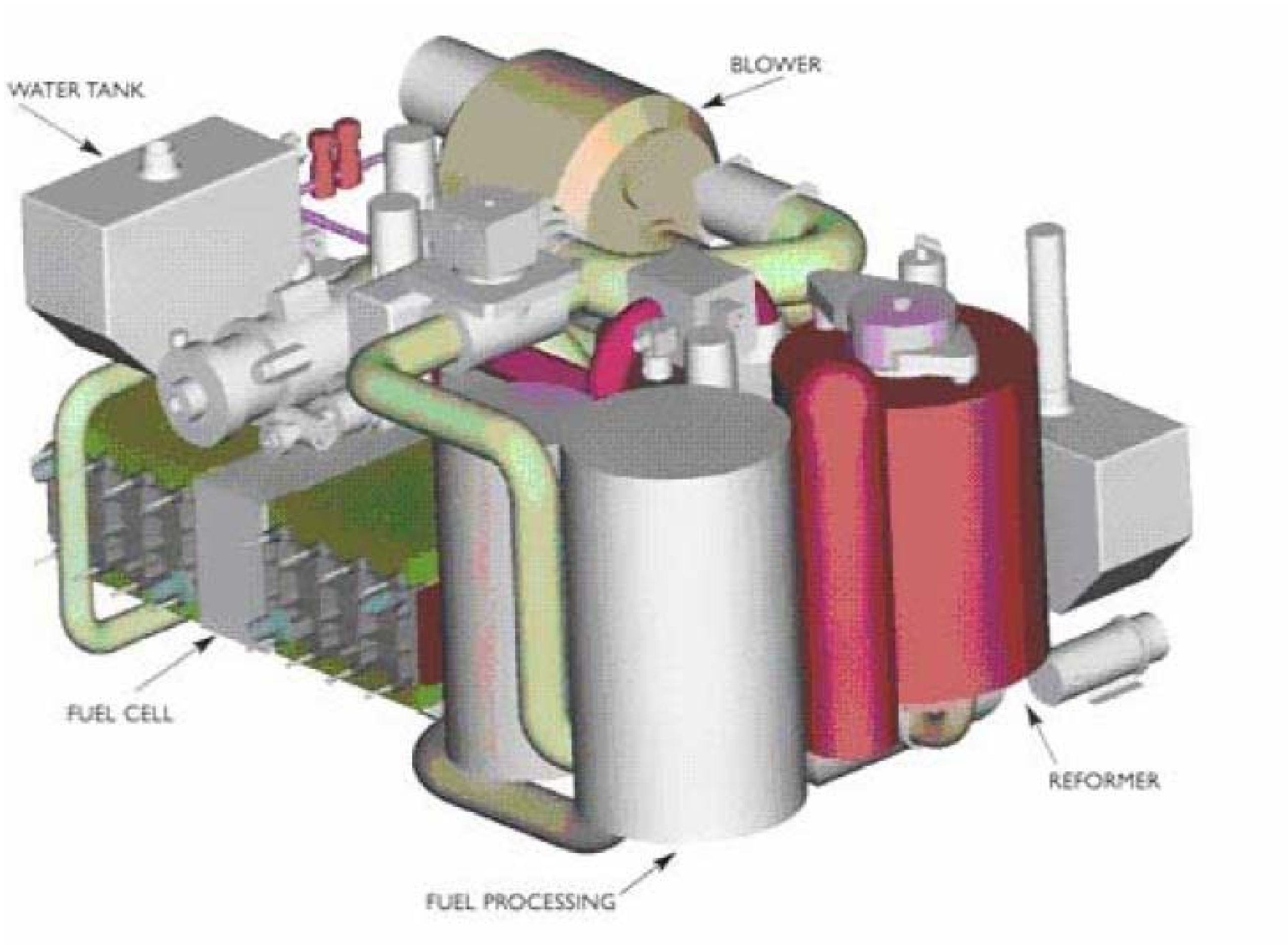
Kemper Combustion Turbine Plant is located in Kemper County, Mississippi, near the city of DeKalb. With four combustion turbine generating units, plant capacity is 340 MW. Note the cooling towers. ---TVA

Fuel Cells

Input: H and O
Output: Water

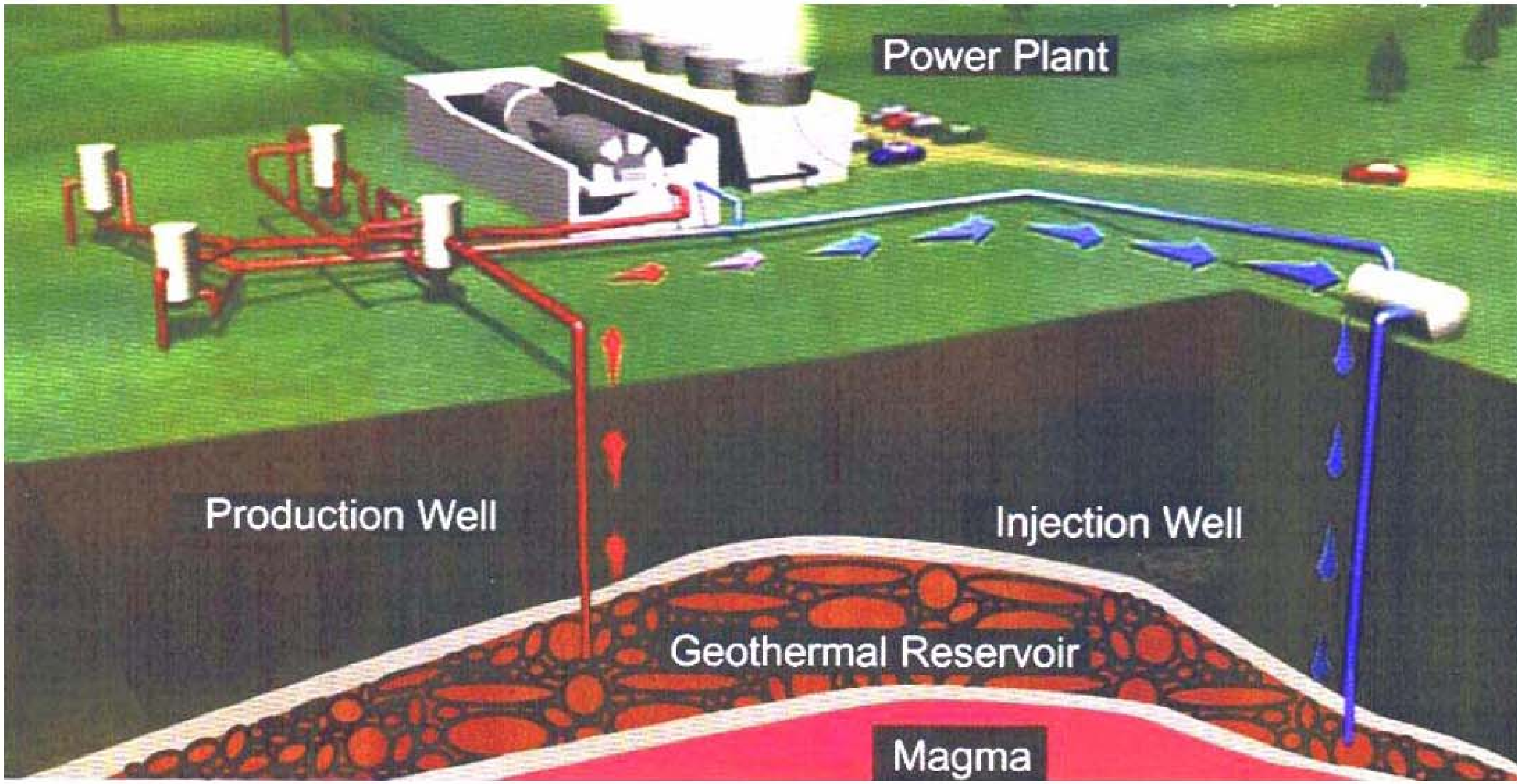






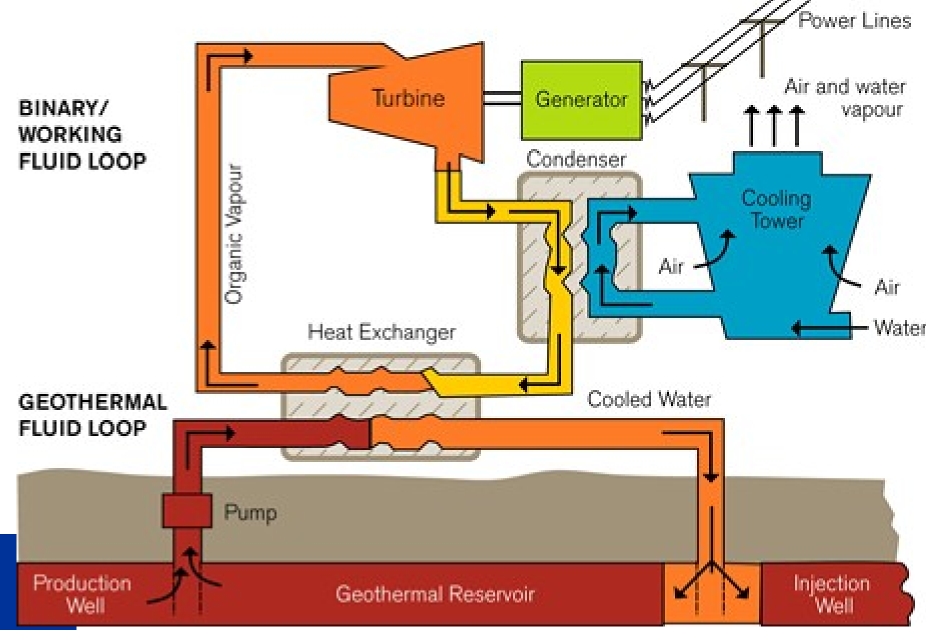
Configuration of a 50 kW Fuel cell Power Plant with a methanol reformer.

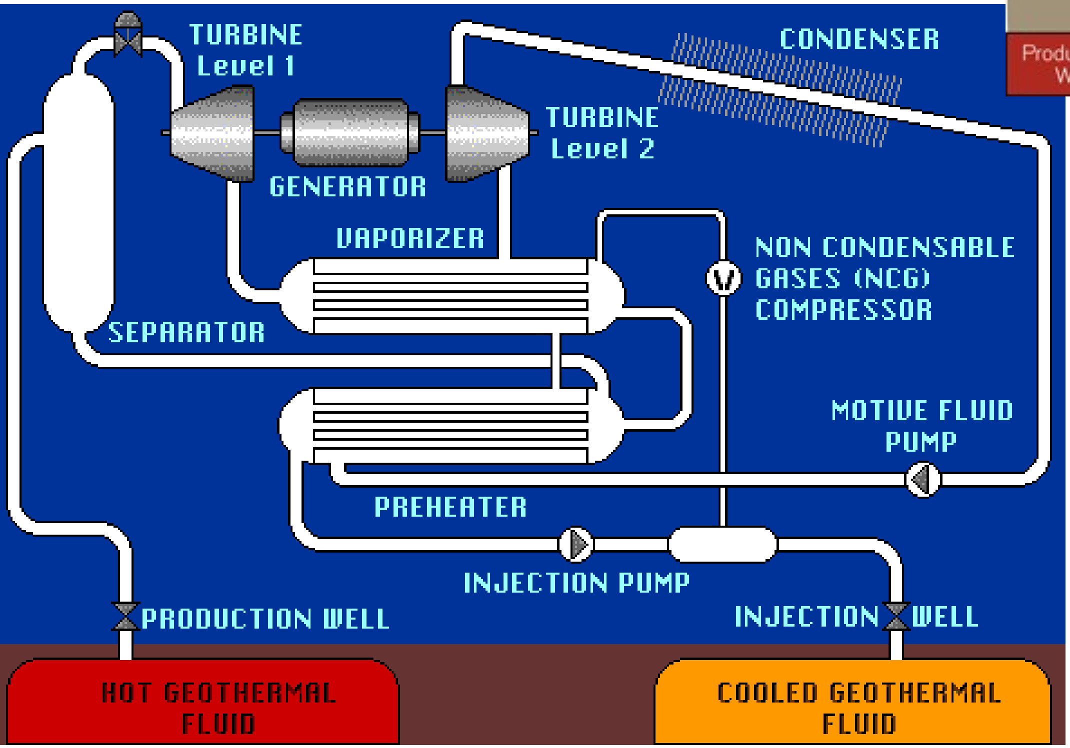
Geothermal Power Plant



Geothermal power plant where the condensed steam is reinjected into the reservoir to sustain the field's life.

Geothermal Plant operation





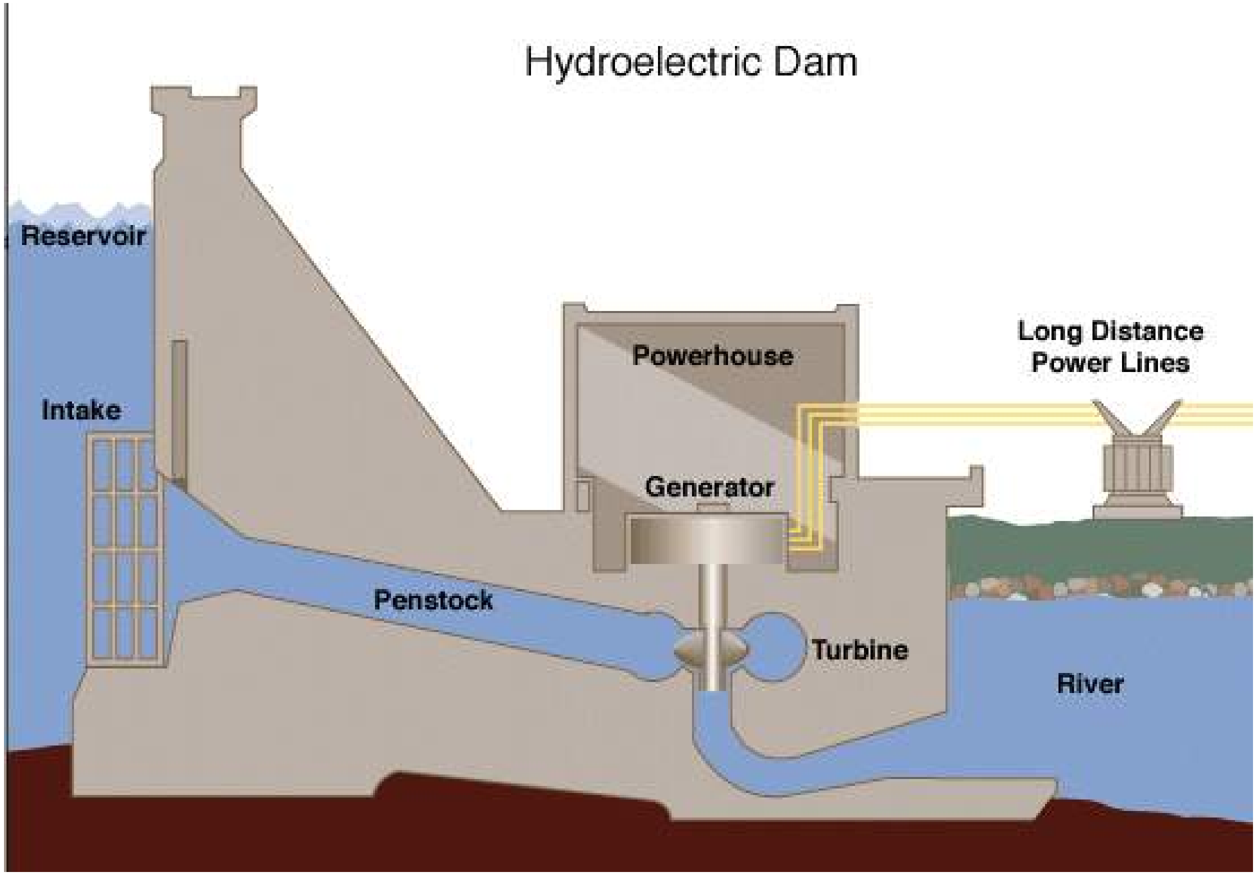
http://thefraserdomain.typepad.com/photos/uncategorized/ormat_combined_cycle_plant.gif

Greenearth Energy Ltd. http://www.greenearthenergy.com.au/geothermal/

Iceland

Inhabitat.com

Hydroelectric Power Plant



Water from the reservoir rushes through the penstock into the powerhouse. The water spins the turbine, which drives the generator. Inside the generator is a large electromagnet that spins within a coil of wire, producing electricity.

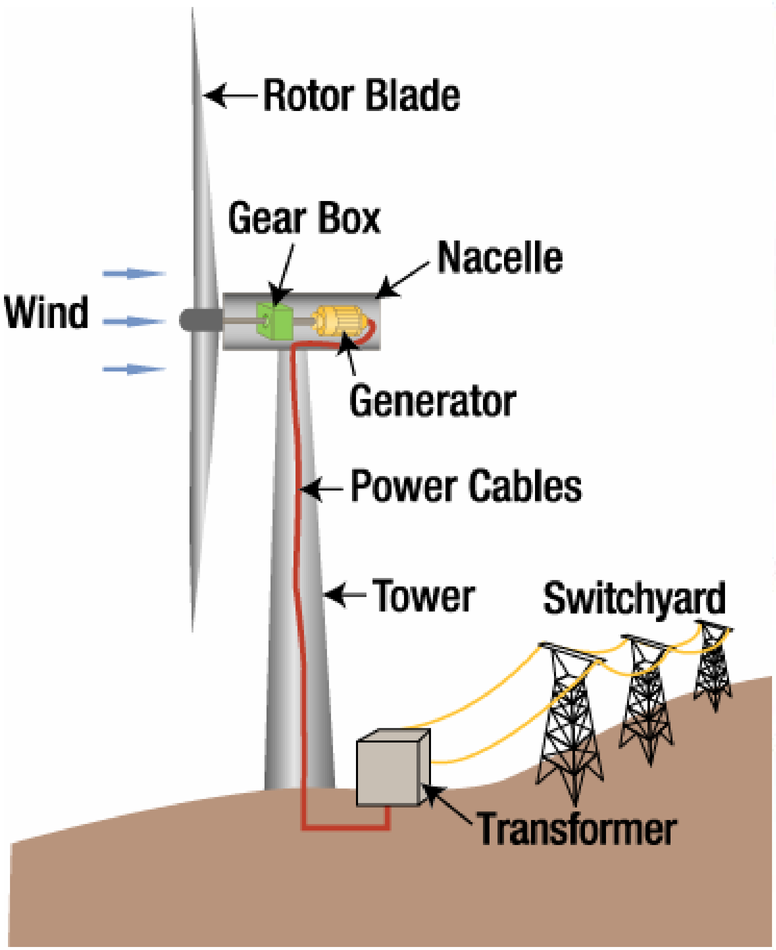
Source: Tennessee Valley Authority (TVA), http://www.tva.gov

Watts Bar Dam
Construction 1939 - 1942.
112 feet high and stretches 2,960 feet across the Tennessee River.

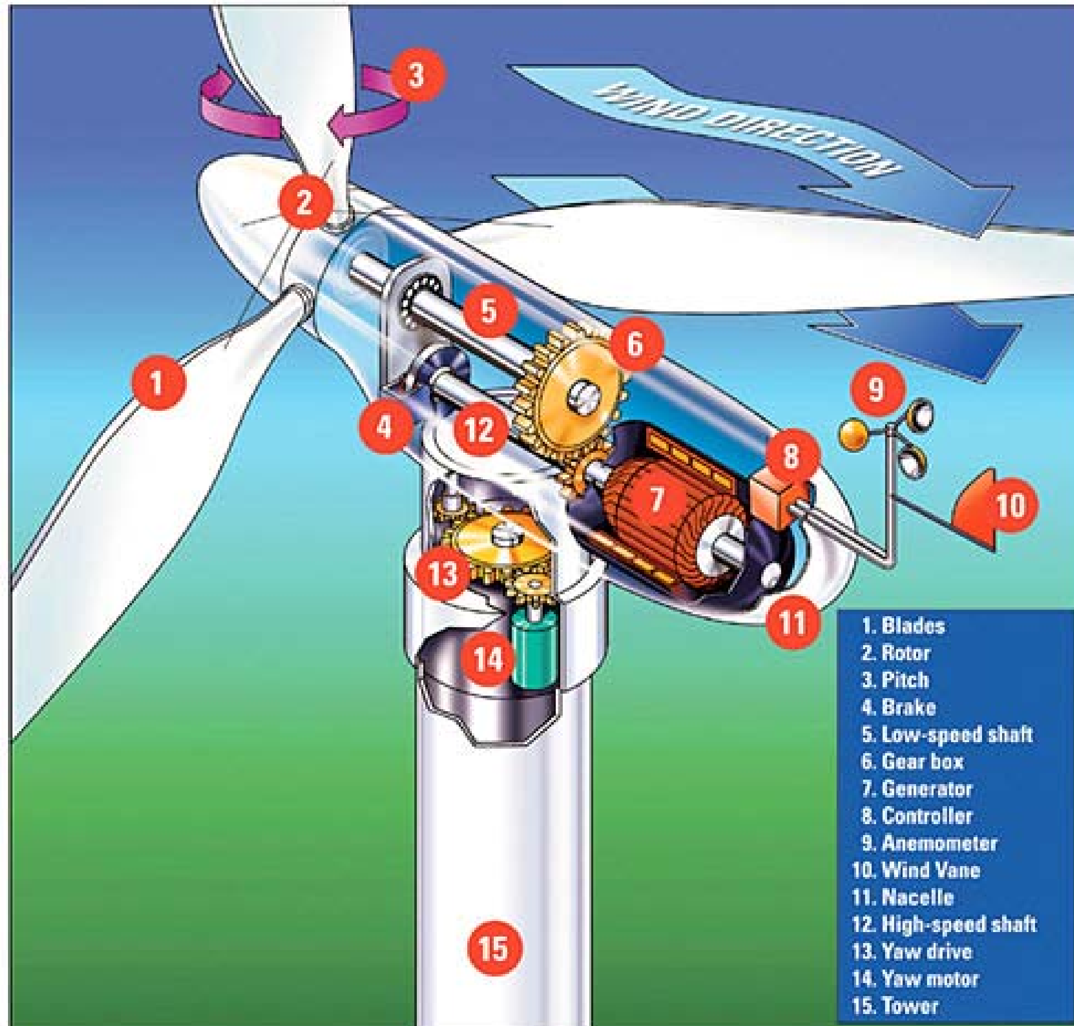
Tva.gov

Official name	Hoover Dam
Impounds	Colorado River
Creates	Lake Mead
Locale	Nevada-Arizona US
Length	1244 ft (379 m)
Height	726.4 ft (221 m)
Construction	1931-1936

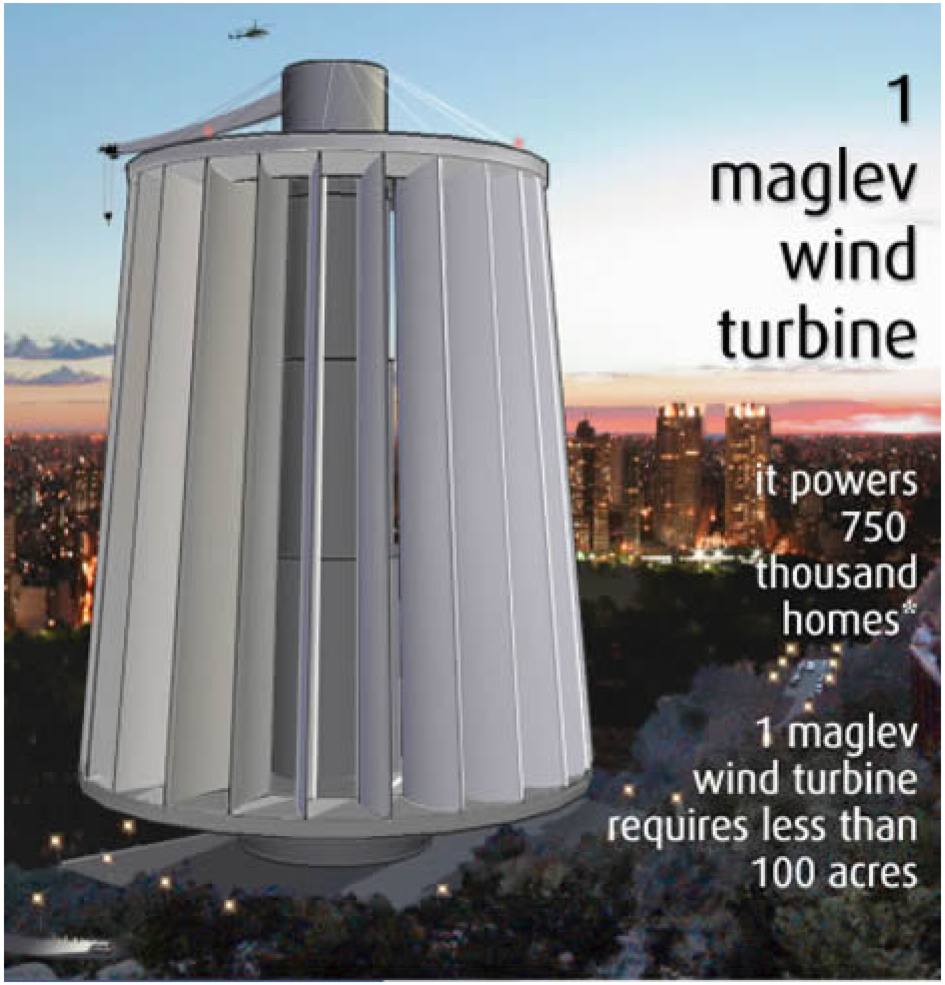
Wind Turbine Electric Generator



Source: TVA, http://www.tva.gov

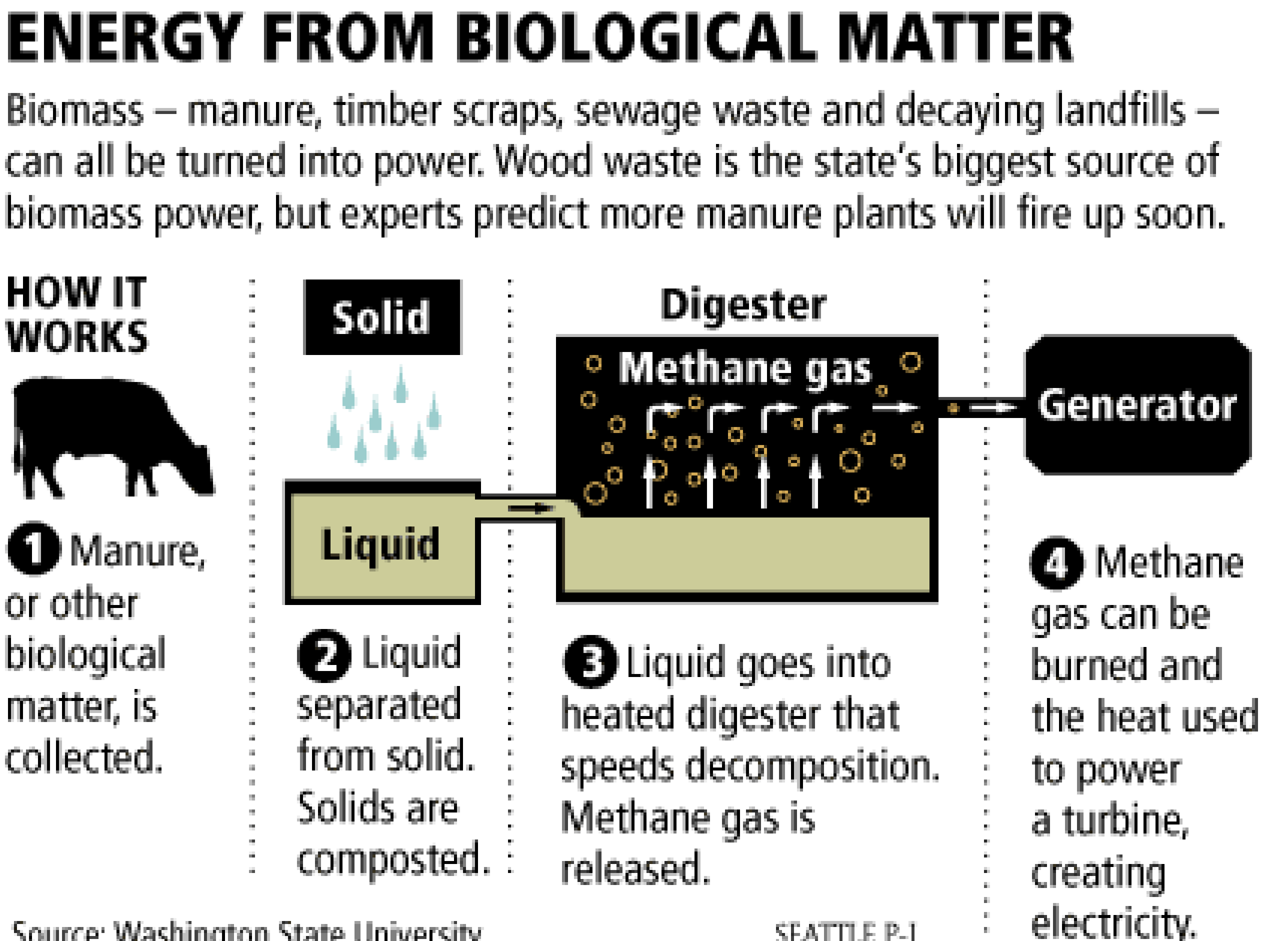


http://www.alternative-energy-news.info/images/technical/wind-turbine.jpg

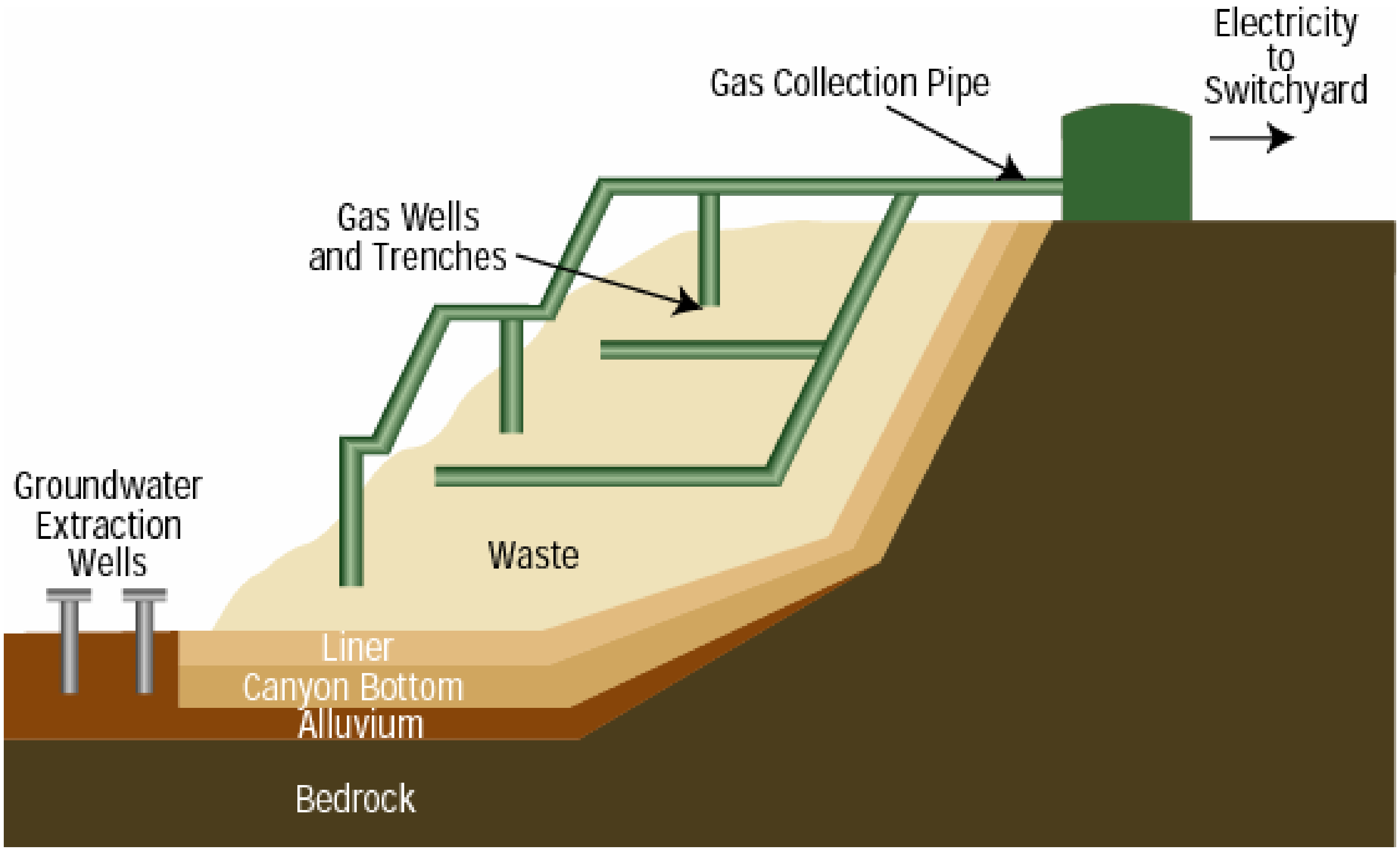


http://www.worldproutassembly.org/maglev_wind_turbine.jpg

Biomass


ENERGY FROM BIOLOGICAL MATTER
Biomass – manure, timber scraps, sewage waste and decaying landfills – can all be turned into power. Wood waste is the state's biggest source of biomass power, but experts predict more manure plants will fire up soon.
HOW IT WORKS
Solid
Liquid
Digester
Methane gas
Generator
1 Manure, or other biological matter, is collected.
2 Liquid separated from solid. Solids are composted.
3 Liquid goes into heated digester that speeds decomposition. Methane gas is released.
4 Methane gas can be burned and the heat used to power a turbine, creating electricity.
Source: Washington State University
SEATTLE P-I

Methane Gas Power Plant

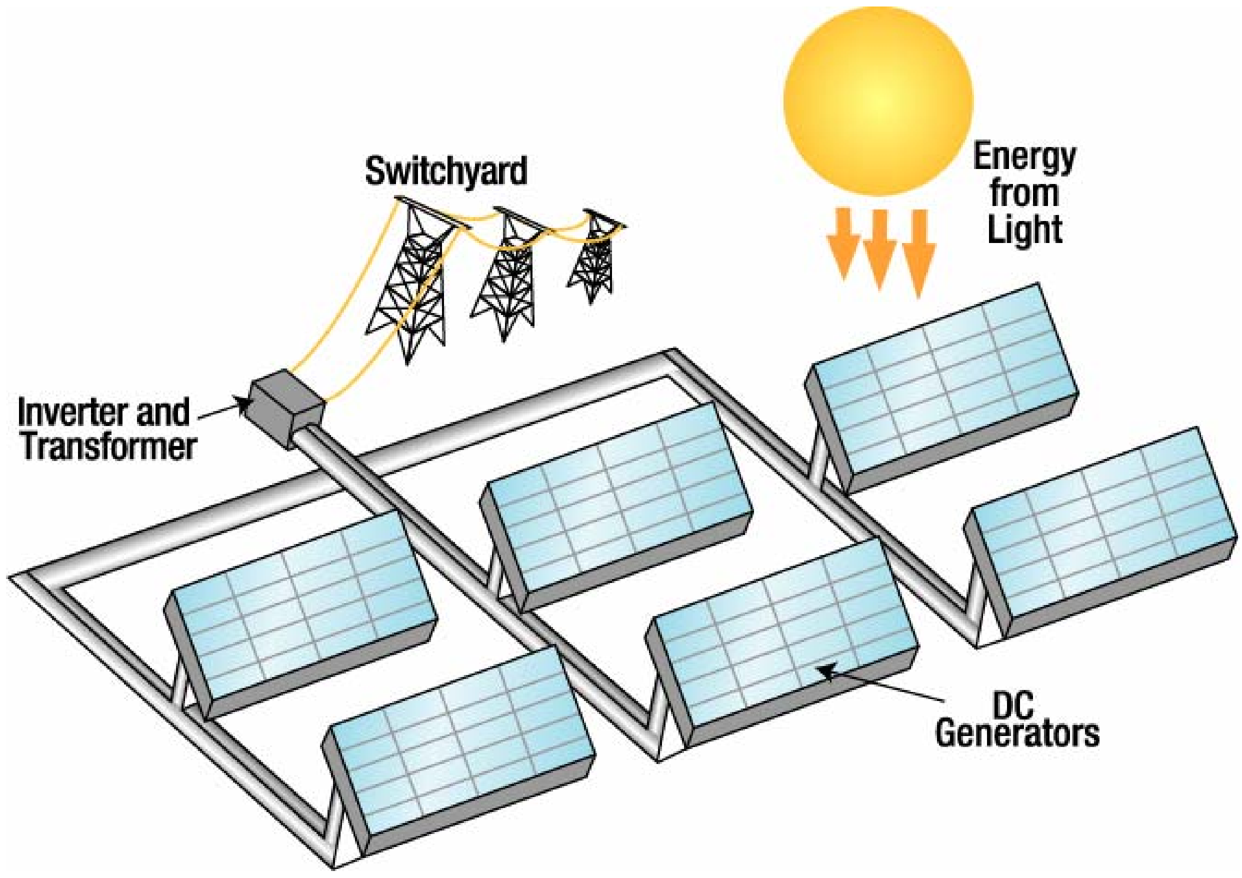


Pipes collect methane gas produced by decaying waste, and the gas is burned to generate electricity.

Source: Tennessee Valley Authority (TVA), http://www.tva.gov

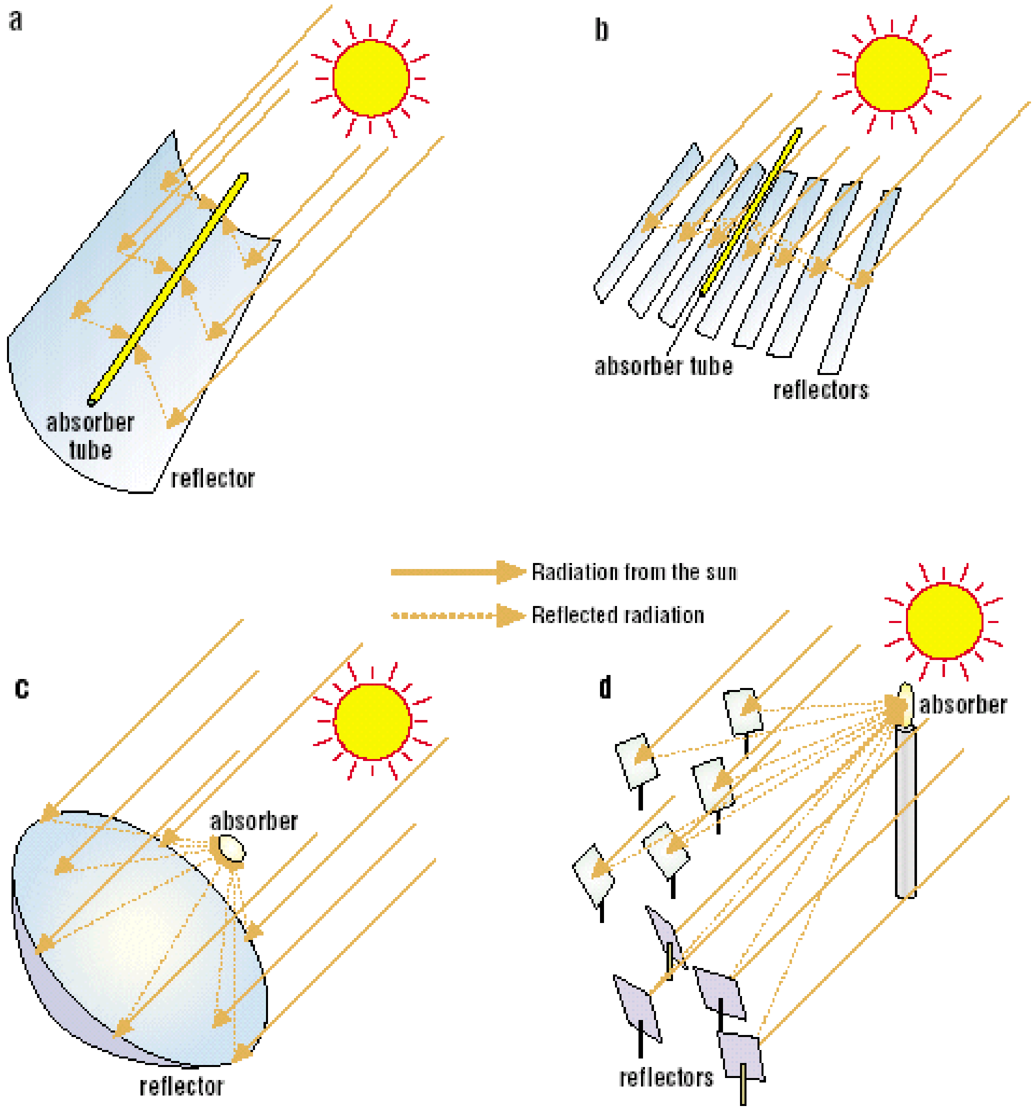
A general view of the 50-megawatt landfill gas power plant, newly built and claimed by South Korea to be the world's largest one, at a mammoth garbage dumping site in Incheon, west of Seoul, 11 December 2006. The Plant uses only methane gas, naturally generated from the site, to produce electricity for more than 180,000 households.

Solar Power Plant



Photovoltaic (PV) systems use semiconductor cells that convert sunlight directly into electricity. Direct current from the PV cells, which are arrayed in flat panels, flows to inverters that change it to alternating current.

Source: Tennessee Valley Authority (TVA), http://www.tva.gov

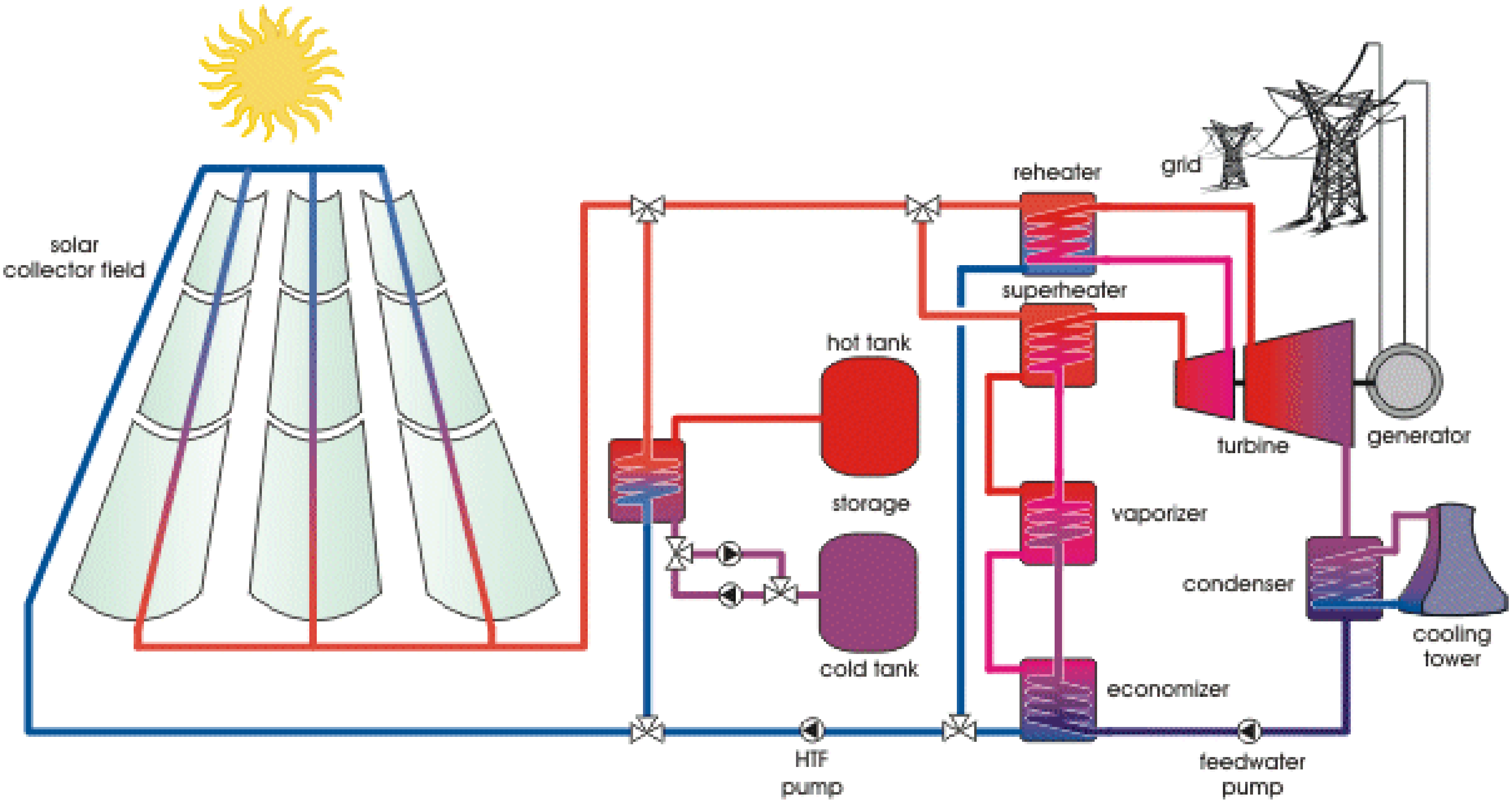


Concentration of sunlight using (a) parabolic trough collector (b) linear Fresnel collector (c) central receiver system with dish collector and (d) central receiver system with distributed reflectors

http://www.volker-quaschning.de/articles/fundamentals2/index_e.html

Operational in 2011 in Arizona.

Solar Thermal Power Plant



Schematic of a concentrated solar thermal trough power plant with thermal storage
http://www.volker-quaschning.de/articles/fundamentals2/index_e.html

Nuclear Power

Fission Power

- Generation I: 1950s-1970s
- Generation II: 1970s-1980s
  - Currently in use today; LWR (BWR, PWR), CANDU HWR
- Generation III (Not in U.S.)
  - Advanced evolutionary design; ABWR, APWR, passive reactor
- Generation III+ : By 2010
  - Pebble bed reactor, larger passive reactors
- Generation IV: conceptual, by 2030?
  - Economic
  - Safe
  - Minimal waste
  - Publically acceptable

Summary of Power Reactor Types

Reactor Type	Coolant	Moderator	Current Deployment
Pressurized water reactors (PWR, VVER)	Light water	Light water	Most countries, 259 *Steam generated in secondary loop*
Boiling water reactors (BWR)	Light water	Light water	*Steam from boiling water fed to turbine* Most countries, 92
Pressurized heavy water reactor (PHWR)	Heavy water	Heavy water	Argentina, Canada, China, India, Korea, Pakistan, Romania, 43
Gas-cooled reactors (Magnox, AGR, UNGG)	CO_2, Helium	Graphite	UK, Russia, 32
Liquid Metal-cooled (LMFBR)	Sodium, lead, Bismuth	None	France, Japan, Russia, India, 2
Light water graphite reactors (RBMK)	Pressurized boiling water	Graphite	Former USSR, 13

Sustainable Energy, MIT 2005; Britannica.

Table 1: Power densities and core volumes in fission power reactors.

Type	Description	Core Average Power Density [MWth/m^3]	Core Volume [m^3]
PWR	Pressurized Water Reactor, H_2O	75.0	40.0
BWR	Boiling Water Reactor, H_2O	50.0	60.0
HTGR	High temperature Gas-cooled Reactor, Graphite moderated, He cooled	7.0	428.6
GCFR	Gas Cooled Fast Reactor, He cooled, Fast neutron Breeder	280.0	10.7
LMFBR	Liquid Metal Fast Breeder Reactor, Na cooled, Fast neutron Breeder	530.0	5.7

Thanks to Dr. Magdi Ragheb, University of Illinois at Urbana-Champaign, Nuclear, Plasma and Radiaion Science: Inventing the Future, https://netfiles.uiuc.edu/mragheb/www .

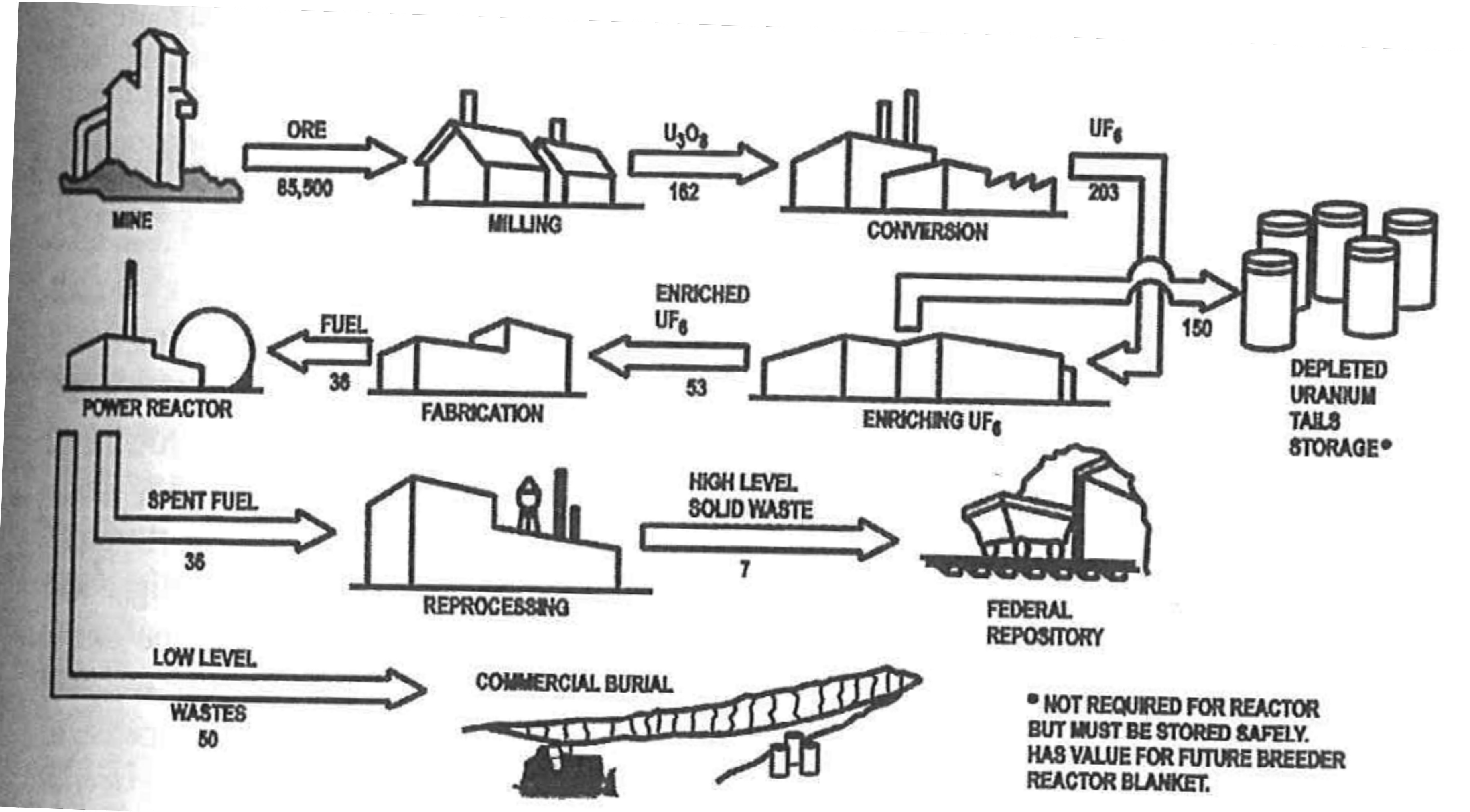
Light Water Reactors

- Most common type in use
  - 25% BWR
  - 75% PWR
- Ordinary water = moderator

Number of operating U.S. reactors: 104 (35 boiling water reactors, 69 pressurized water reactors)

14 BWR plants have one reactor; nine have two reactors; one has three reactors

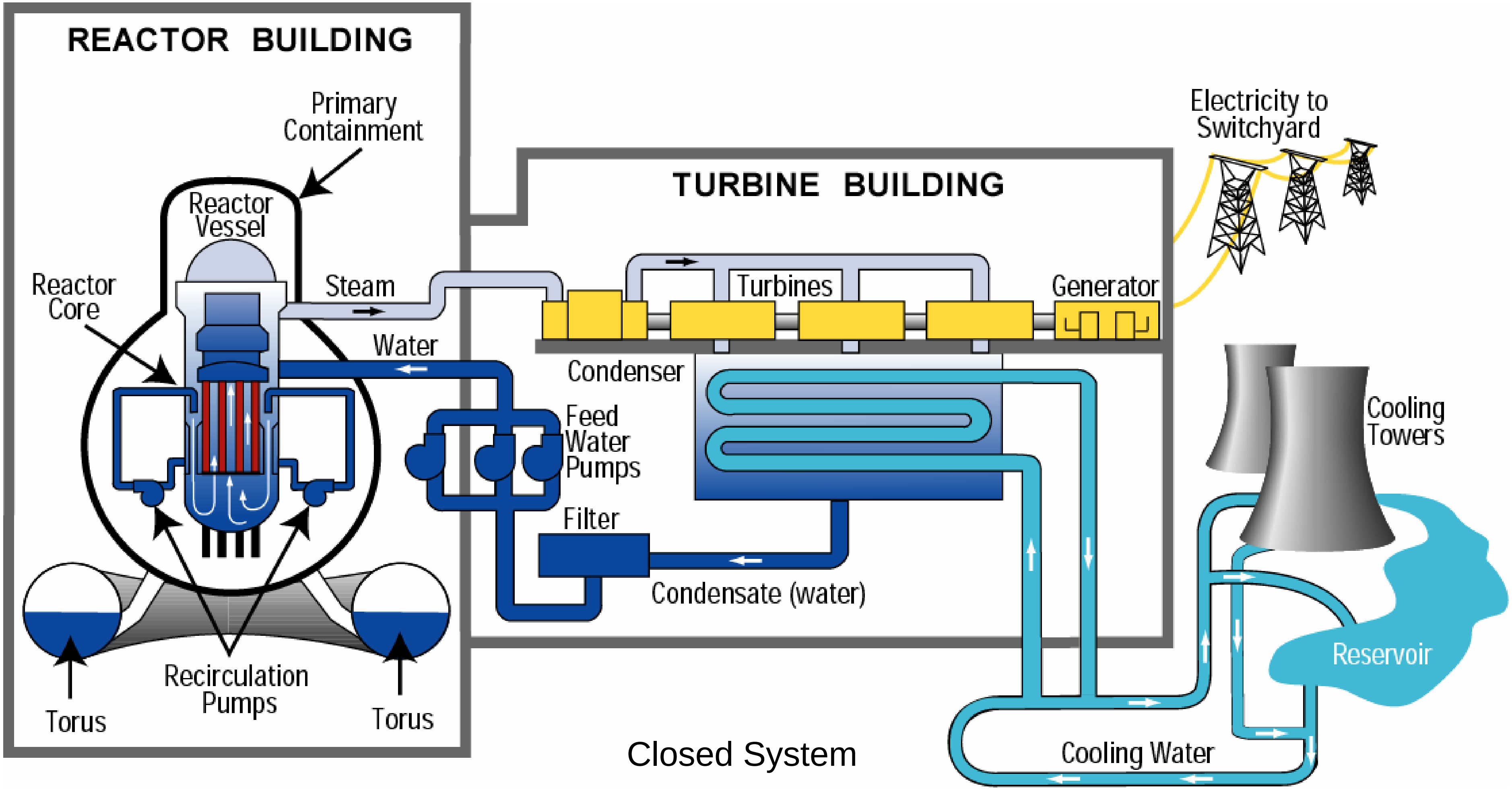
15 PWR plants have one reactor; 24 have two reactors; two have three reactors



1000MW LWR Fuel Cycle with Reprocessing

Sustainable Energy, MIT 2005.

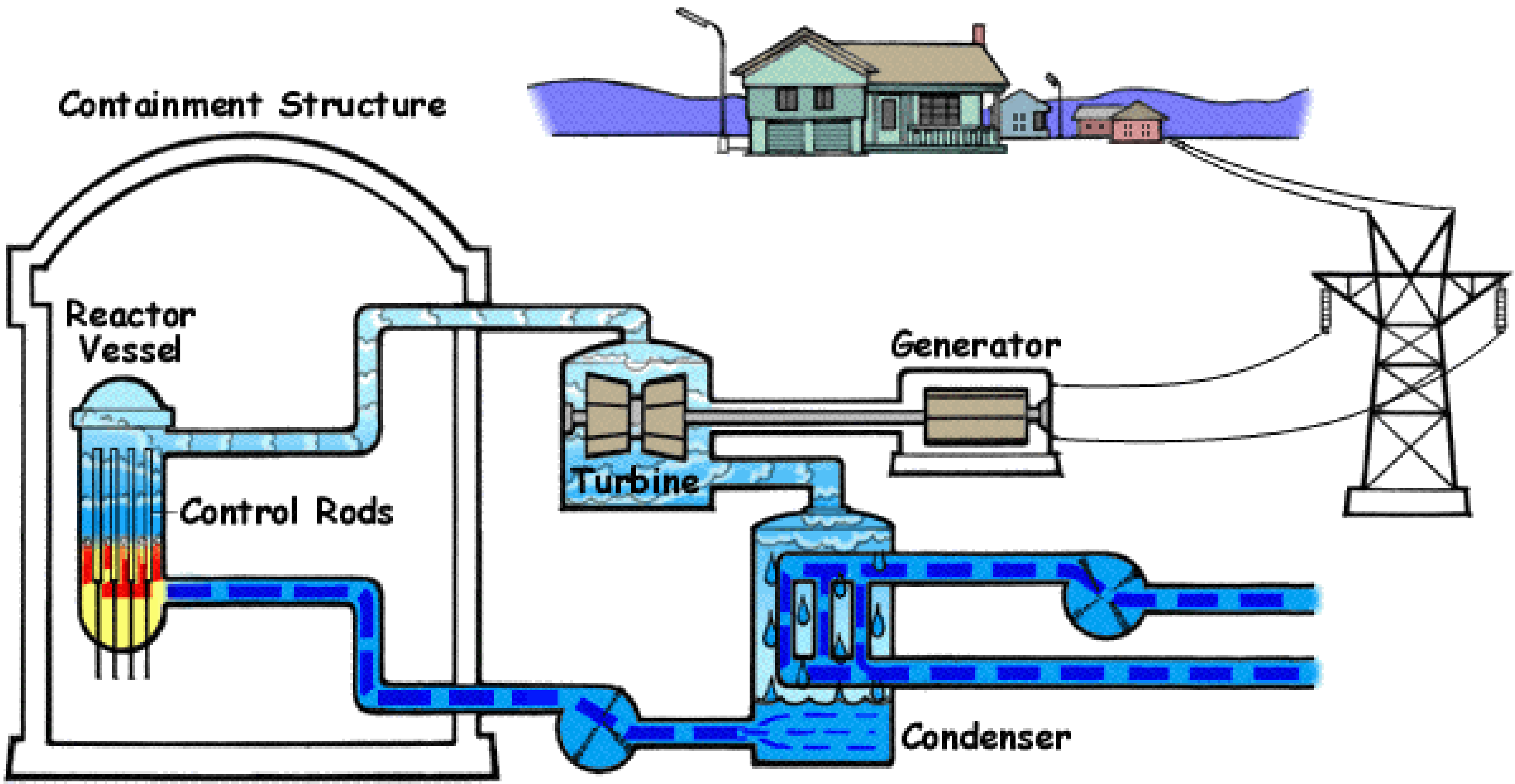
Nuclear Boiling Water Power Plant



Water is heated through the controlled splitting of uranium atoms in the reactor core and turns to steam. Pumps force the water through the reactor at top speed, maximizing steam production. Steam drives the turbines that turn the generator that makes electricity. Cooling water from the river condenses the steam back into water. The river water is either discharged directly back to the river or cooled in the cooling towers and reused in the plant.

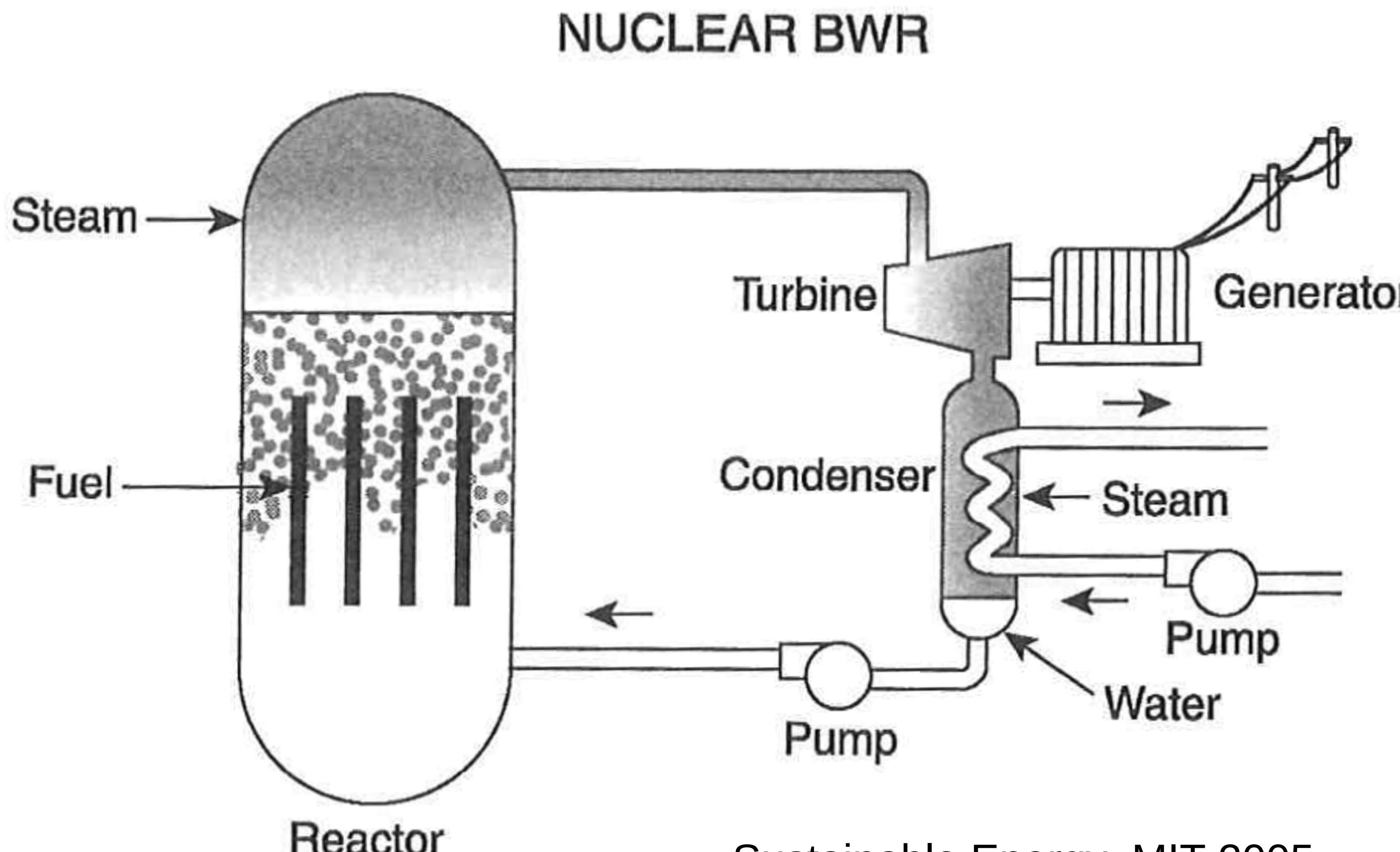
Source: Tennessee Valley Authority (TVA), http://www.tva.gov

BWR



NRC → Wikipedia

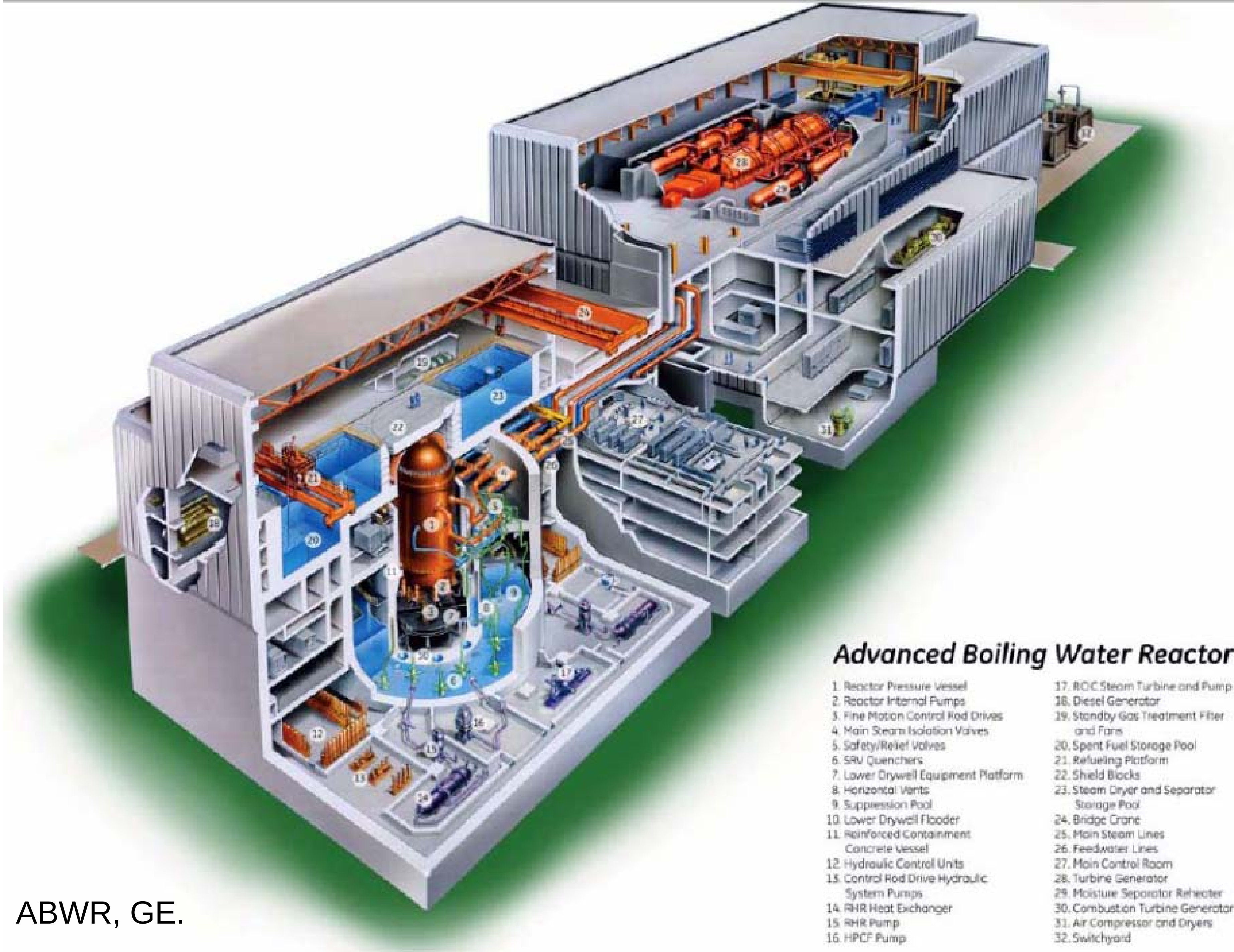
- 1040 psia
- No pressurizer or steam generator
- Usually control rods from bottom



Sustainable Energy, MIT 2005.

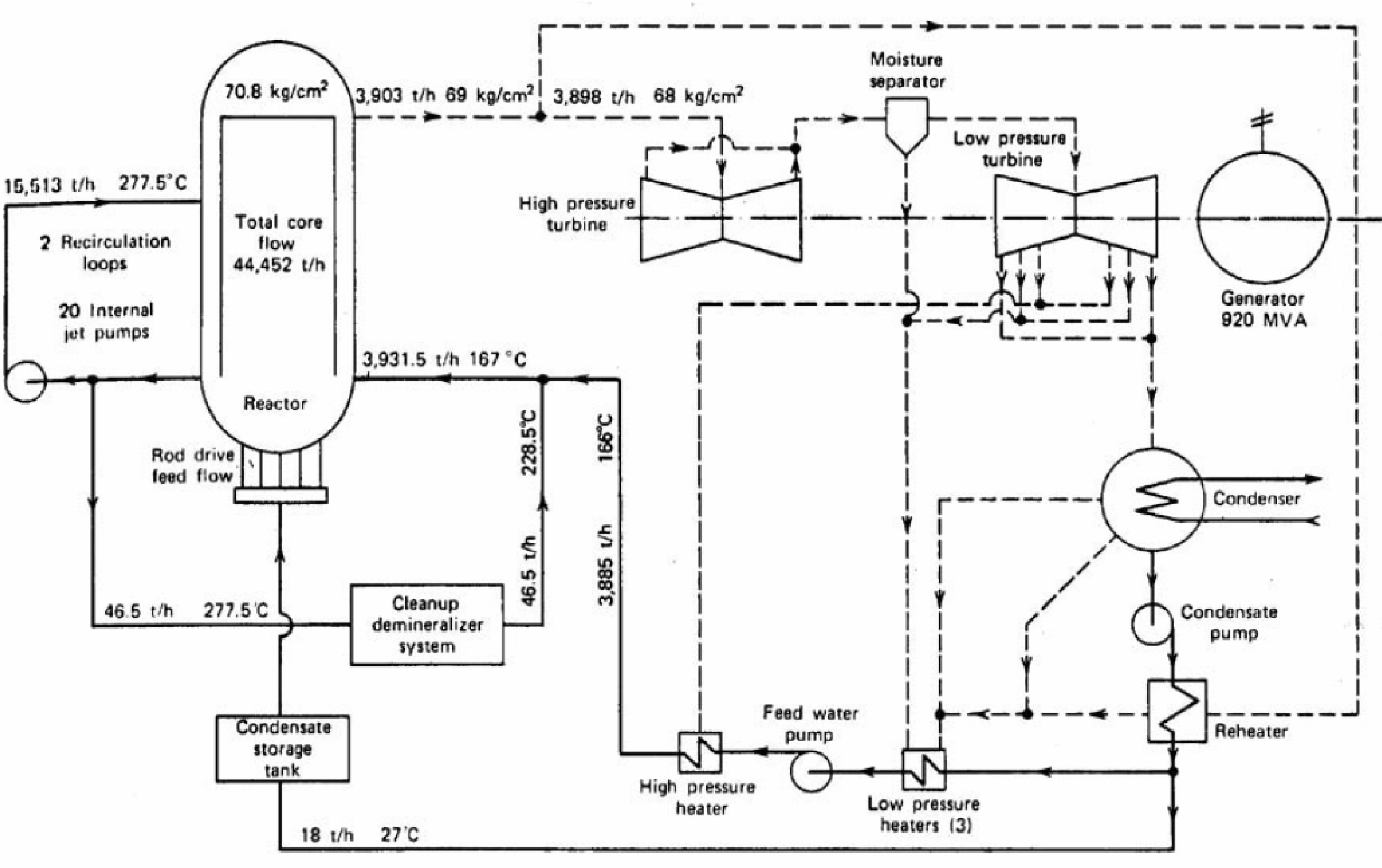
Operational Characteristics of a typical BWR

Characteristic	Value
Thermal Power output	3,579 MWth
System pressure	1,040 psia
Fuel enrichment	2.2-2.7 %
Coolant flow	1.05×10^8 lbs/hr
Core inlet enthalpy	527.9 Btu/lb
Average exit quality	14.6 %
Core average void fraction	42.6 %
Maximum exit void fraction	76 %
Average inlet velocity	7.1 ft/sec
Core pressure drop	25.9 psi
Inlet temperature, feed water	420 ^oF
Core inlet temperature	532 ^oF
Outlet temperature	547 ^oF
Maximum fuel temperature	3,500 ^oF
Average linear heat rate	6.0 kW/ft
Maximum linear heat rate	13.4 kW/ft
Average heat flux	159,000 BTU/(hr.ft^2)
Maximum heat flux	354,000 BTU/(hr.ft^2)
Minimum CHFR	>1.9
Active height	148 inches
Equivalent active diameter	144 inches
Height to diameter ratio	1.03
Active core volume	2260 ft^3
Average core power density	1580 kW/ft^3
Fuel weight	138,000 kgs
Specific power	25.9 kW/kg U
Burnup	27,500 MW.days/MTU
Conversion ratio	0.5
Number of fuel assemblies	732
Fuel element array	8x8
Assembly dimensions	5.52 in x 5.52 in
Assembly pitch	6.0 in
Number of fuel rods per assembly	62
Total number of fuel rods	45,384
Fuel rod outer diameter	0.493 in
Fuel rod pitch	0.64 in
Pitch to diameter ratio	1.3
Cladding thickness	0.034 in
Fuel pellet diameter	0.416 in
Pellet to clad gap size	0.0045 in
Pellet density, percent of theoretical	94 %
Fission gas plenum length	12 in


Advanced Boiling Water Reactor
1. Reactor Pressure Vessel
2. Reactor Internal Pumps
3. Fine Motion Control Rod Drives
4. Main Steam Isolation Valves
5. Safety/Relief Valves
6. SRV Quenchers
7. Lower Drywell Equipment Platform
8. Horizontal Vents
9. Suppression Pool
10. Lower Drywell Flooder
11. Reinforced Containment Concrete Vessel
12. Hydraulic Control Units
13. Control Rod Drive Hydraulic System Pumps
14. RHR Heat Exchanger
15. RHR Pump
16. HPCF Pump
17. RCIC Steam Turbine and Pump
18. Diesel Generator
19. Standby Gas Treatment Filter and Fans
20. Spent Fuel Storage Pool
21. Refueling Platform
22. Shield Blocks
23. Steam Dryer and Separator Storage Pool
24. Bridge Crane
25. Main Steam Lines
26. Feedwater Lines
27. Main Control Room
28. Turbine Generator
29. Moisture Separator Reheater
30. Combustion Turbine Generator
31. Air Compressor and Dryers
32. Switchyard

ABWR, GE.

BWR Flow Diagram

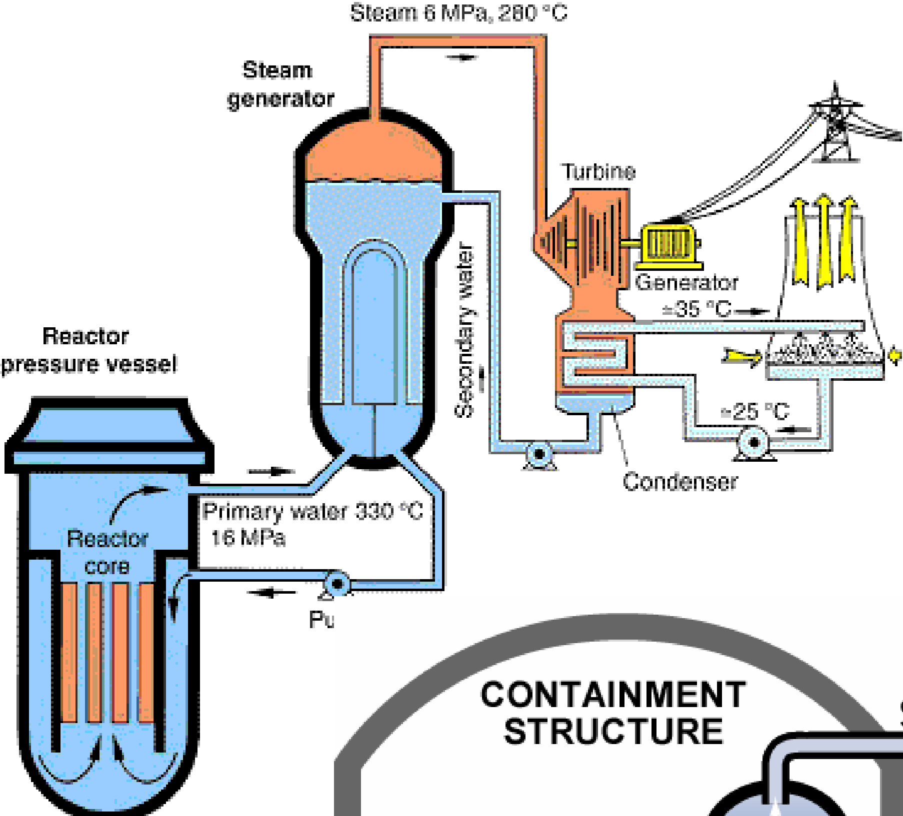


BWR Engineered Safety Features

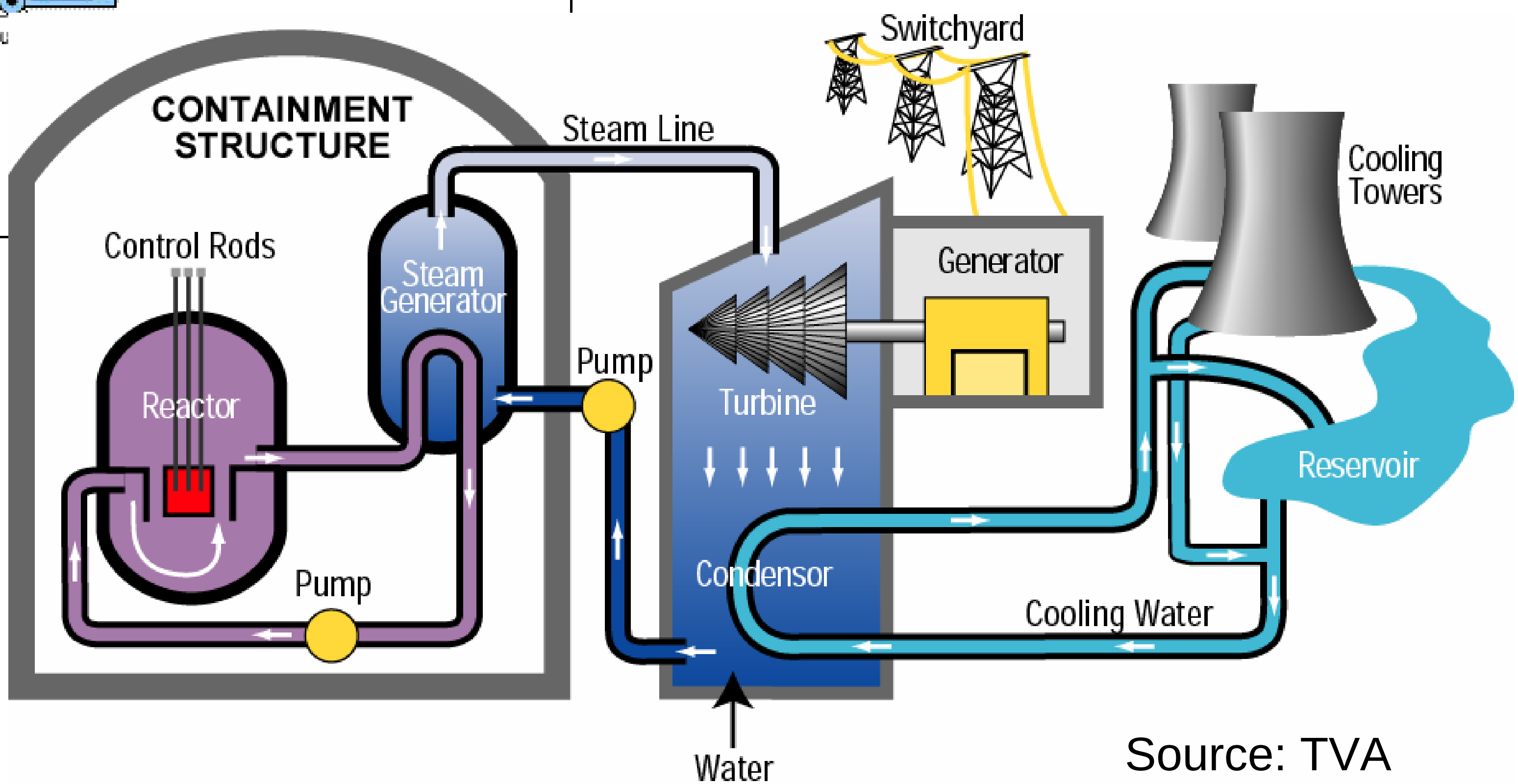
1. The control rods, to shut down the chain reaction.
2. The containment spray system, to quench any steam released under abnormal conditions.
3. The pressure suppression pool to condense any steam leaking into the containment vessel.
4. A residual heat removal system heat exchanger.
5. A High Pressure Coolant Injection system, HPCI.
6. A Low Pressure Coolant Injection system, LPCI.
7. A boron injection tank to shut down the chain reaction in case the control rods are not capable of being inserted into the core.
8. An extra supply of cooling water in the condensate storage tank.
9. An internal core spray system.

- Stability: tolerates mechanical malfunctions and human errors
- Controls are redundant and automated

Nuclear Pressurized Water Power Plant

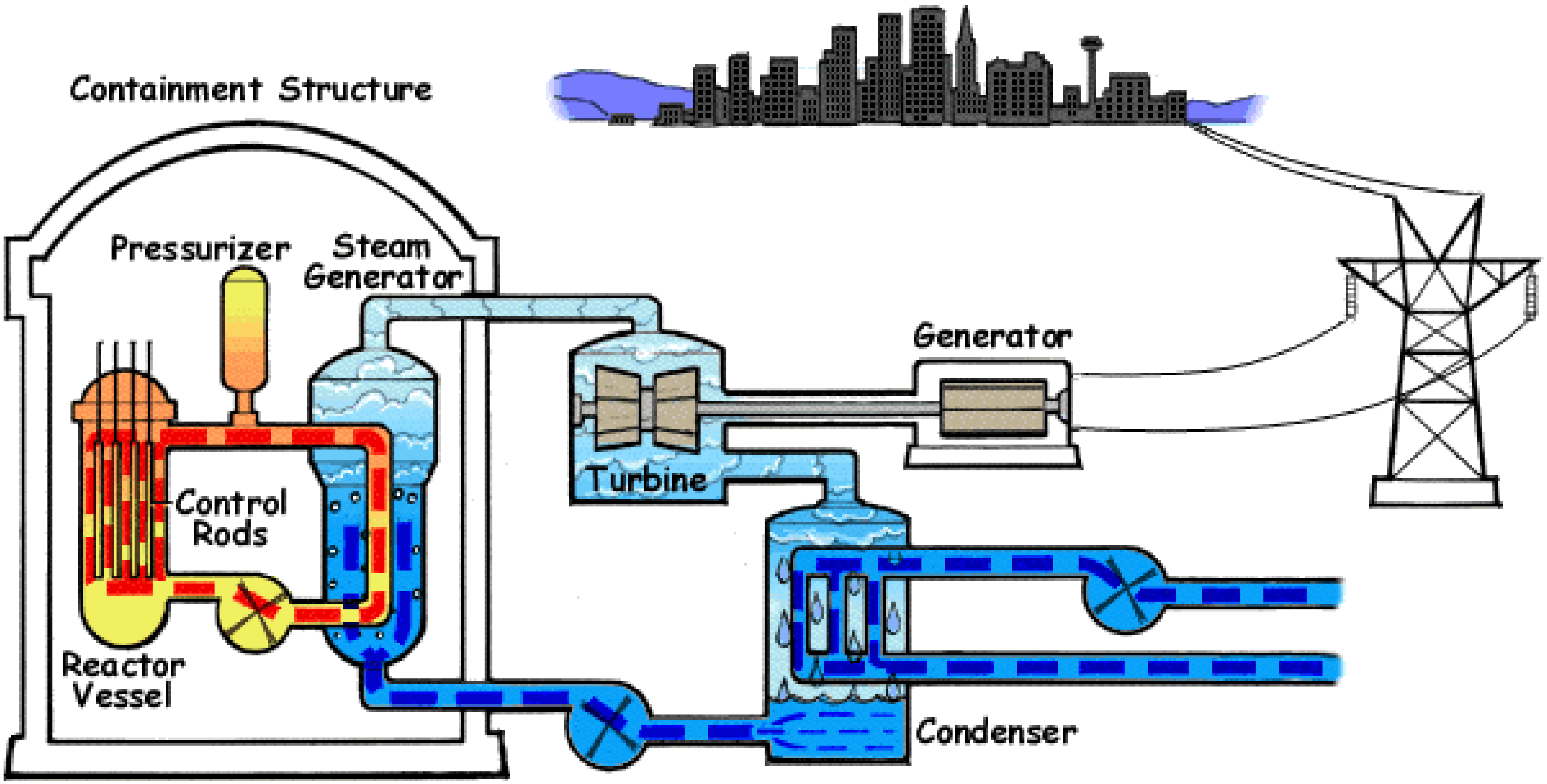


Britannica



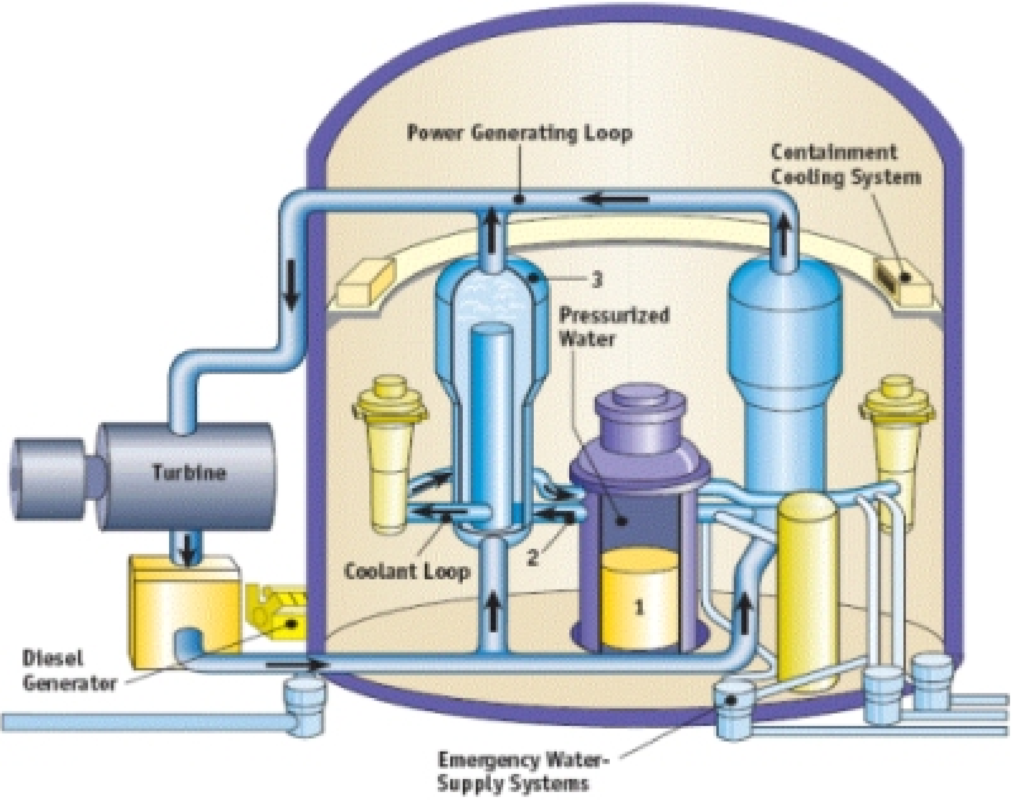
Source: TVA

PWR

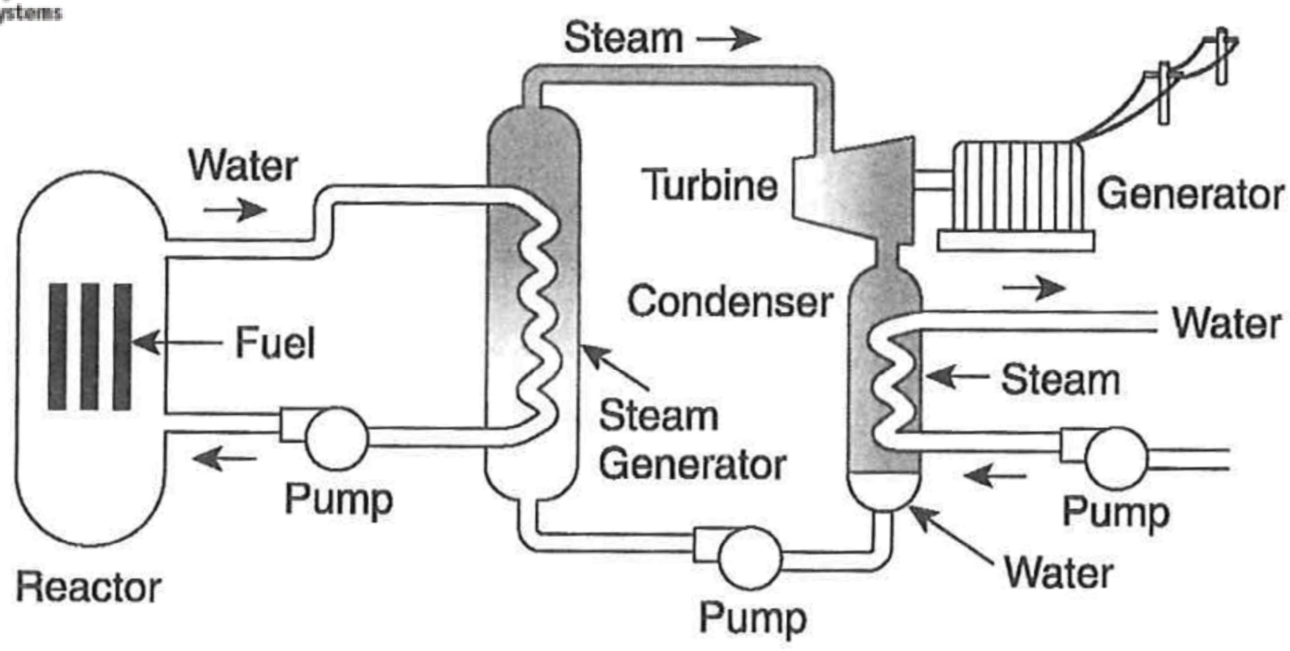


NRC → Wikipedia

PWR



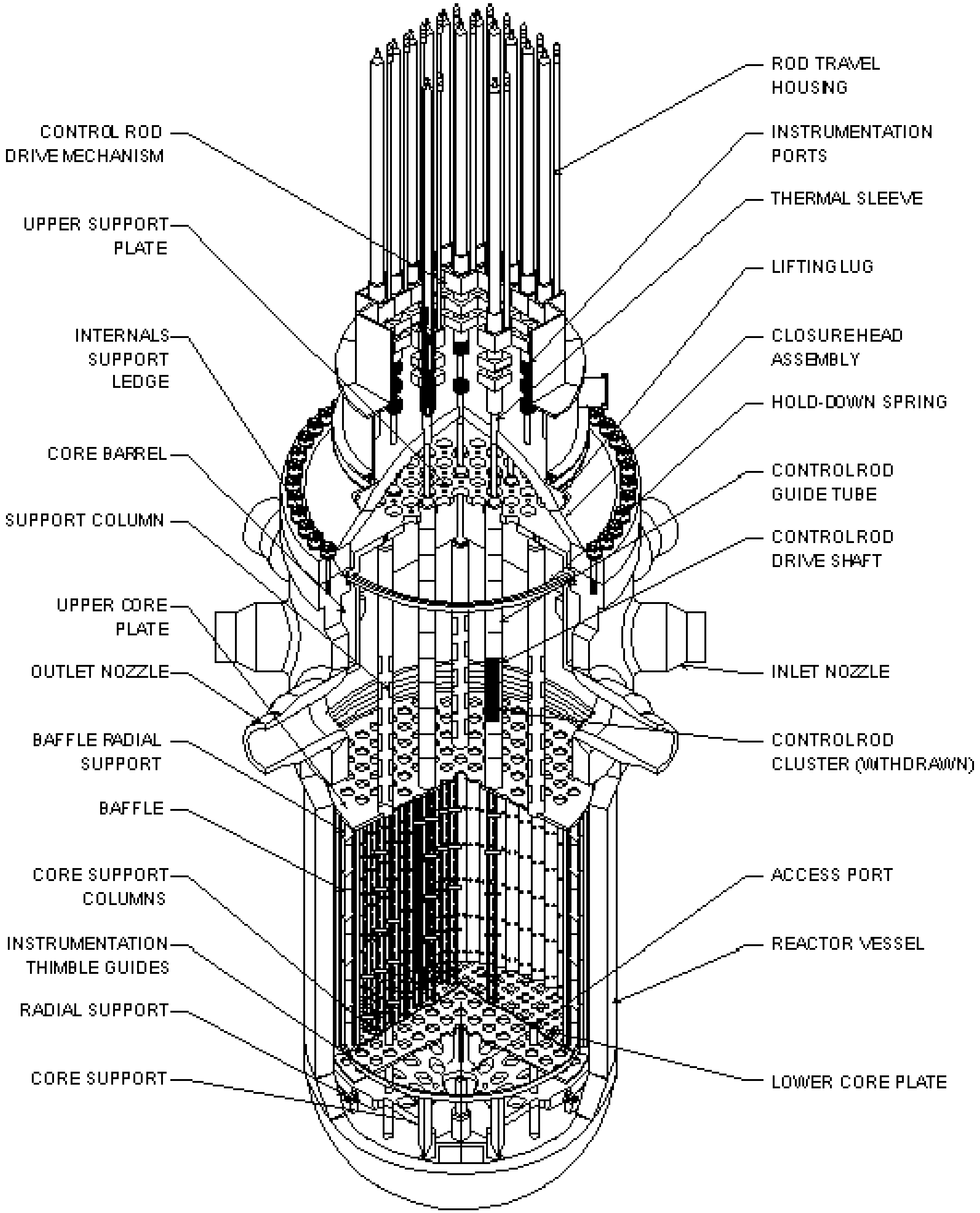
Sustainable Energy, MIT 2005.



PWR

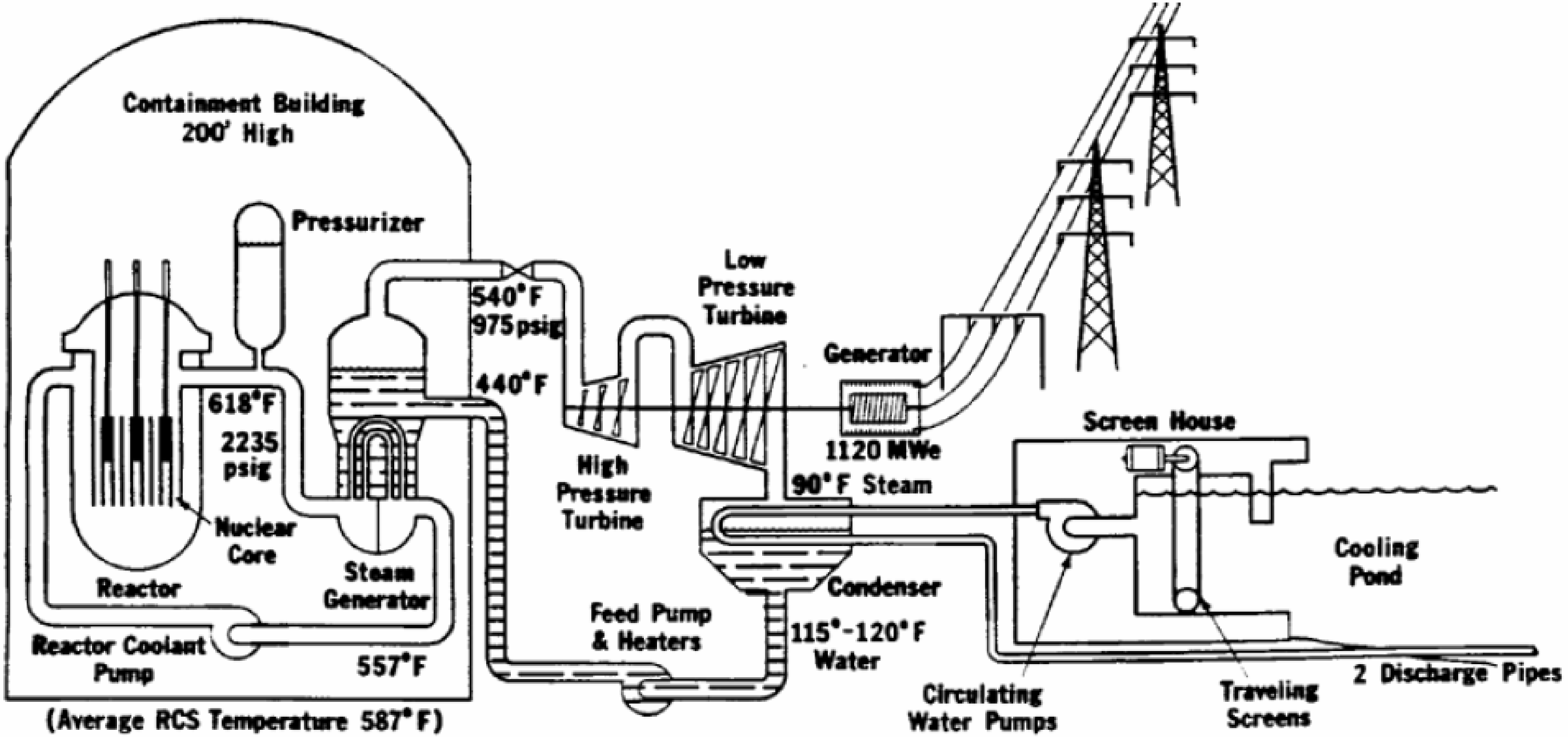
- 2200 psia/150 bars
- No boiling

- Efficiency = 32%
- Low capital cost



Operational Characteristics of a Typical PWR

Characteristic	Value
Thermal Power output	3,800 MWth
System pressure	2,250 psia
Fuel enrichment	1.9/2.4/2.9
Coolant flow	1.59×10^8 lbs/hr
Inlet temperature	565 °F
Outlet temperature	622.4 °F
Maximum fuel temperature	3,420 °F
Average linear heat rate	5.34 kW/ft
Maximum linear heat rate	12.51 kW/ft
Average heat flux	206,000 BTU/(hr.ft^2)
Maximum heat flux	550,000 BTU/(hr.ft^2)
Minimum Departure from Nucleate Boiling ratio (DNBR)	1.3
Active height	150 inches
Equivalent active diameter	142.9 inches
Height to diameter ratio	1.05
Active core volume	1413 ft^3
Average core power density	2,690 kW/ft^3
Fuel weight	103,000 kgs
Specific power	36.9 kW/kg U
Burnup	33,000 Mwdays/MTU
Conversion ratio	0.5
Number of fuel assemblies	241
Fuel element array	16x16
Assembly dimensions	8 in X 8 in
Number of fuel rods per assembly	236
Total number of fuel rods	56,876
Fuel element pitch	0.504 in
Fuel element outer diameter	0.382 in
Pitch to diameter ratio	1.33
Cladding thickness	0.025 in
Fuel pellet diameter	0.325 in
Pellet to clad gap size	0.0035 in



Typical PWR circuit.

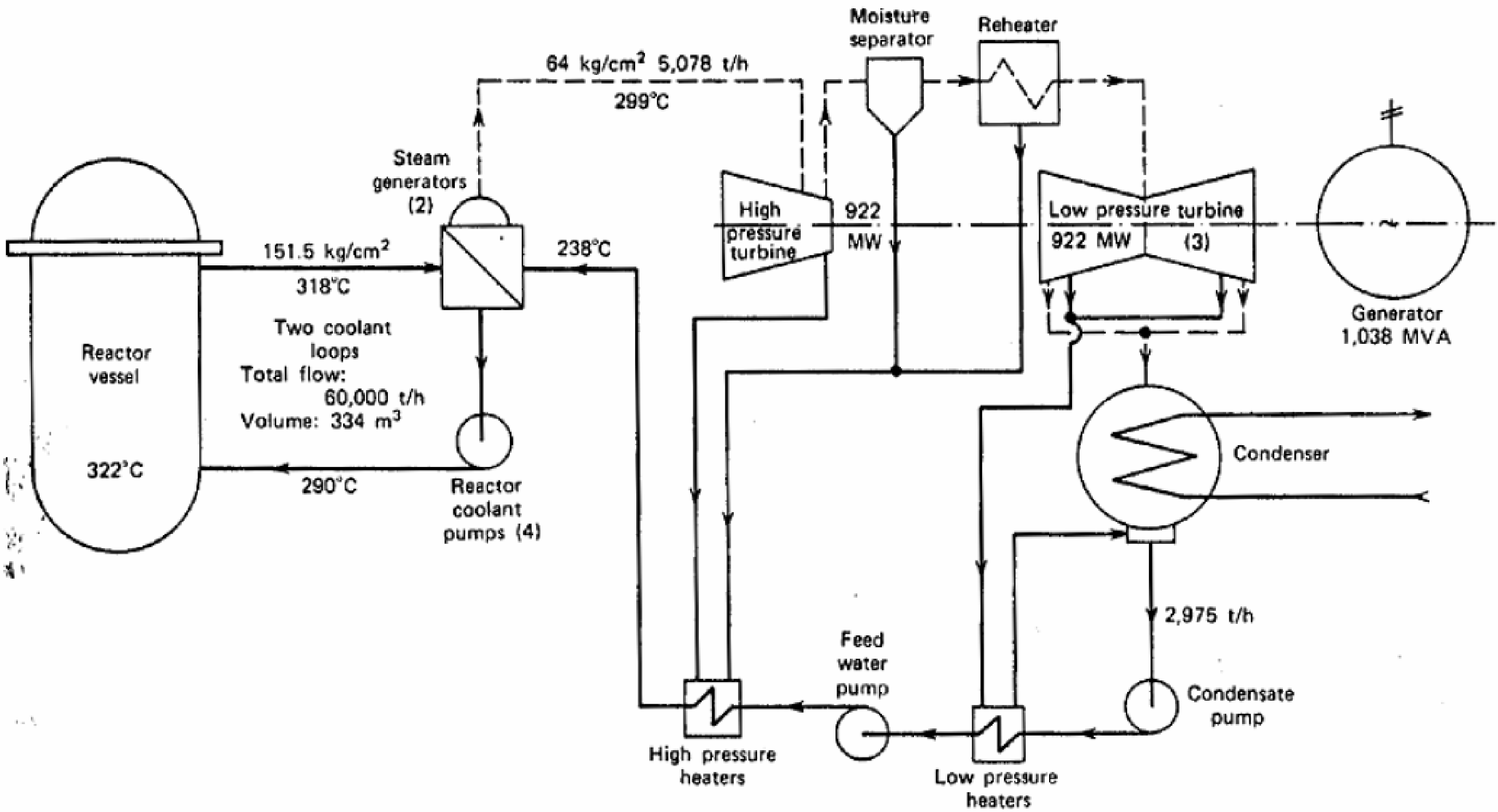


Fig. 7: Typical PWR flow diagram.

PWR Engineered Safety Features

1. The control rods, to shut down the chain reaction.
2. The containment vessel and its spray system, to quench any steam released into the containment.
3. The accumulator tanks containing a supply of water under nitrogen pressure for emergency cooling.
4. A residual heat removal system heat exchanger.
5. A High Pressure Coolant Injection system, HPCI.
6. A Low Pressure Coolant Injection system, LPCI.
7. A boron injection tank to shut down the chain reaction in case the control rods are not capable of being inserted into the core.
8. An extra supply of cooling water in the refueling storage tank.

Heavy Water Reactor

- 2nd most popular type of reactor in use
- CANDU
- Online refueling
- Use natural uranium without enrichment, but needs heavy water D_2O production
- Less spent fuel storage

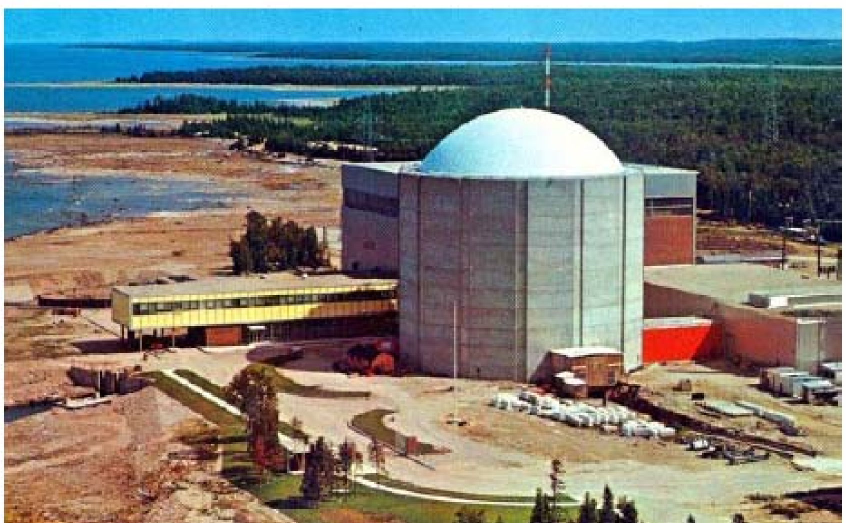
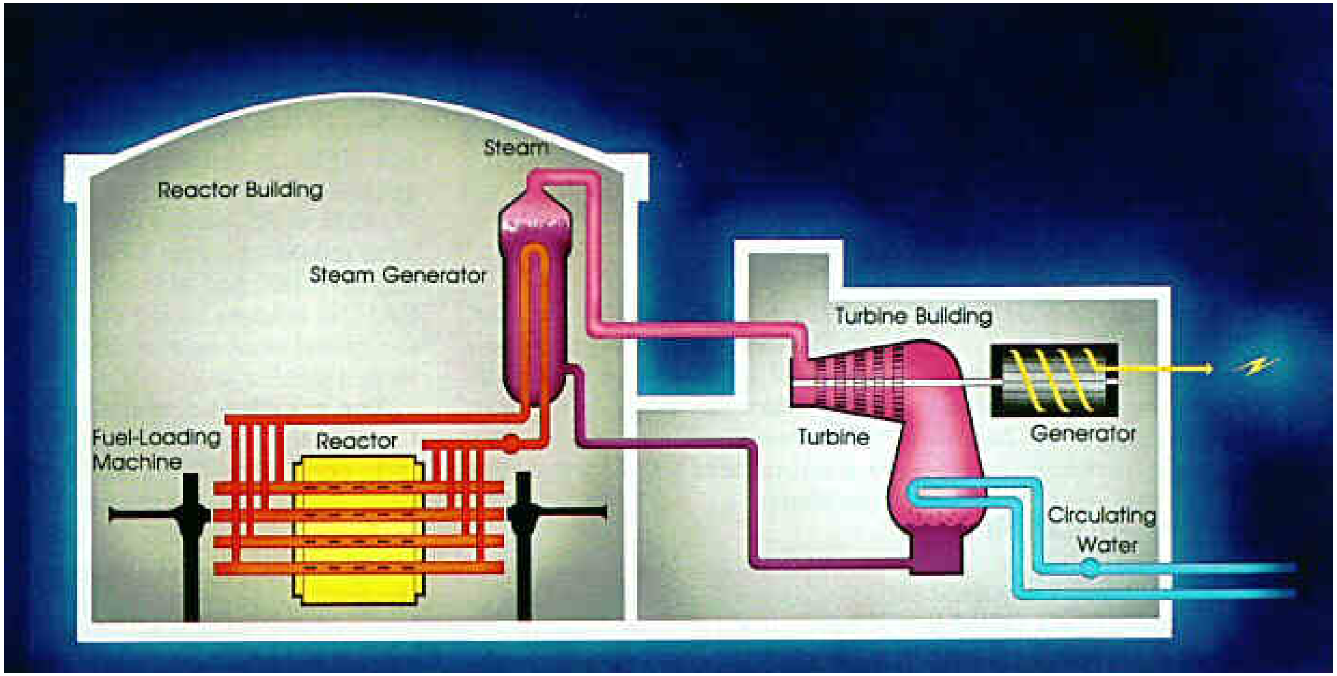
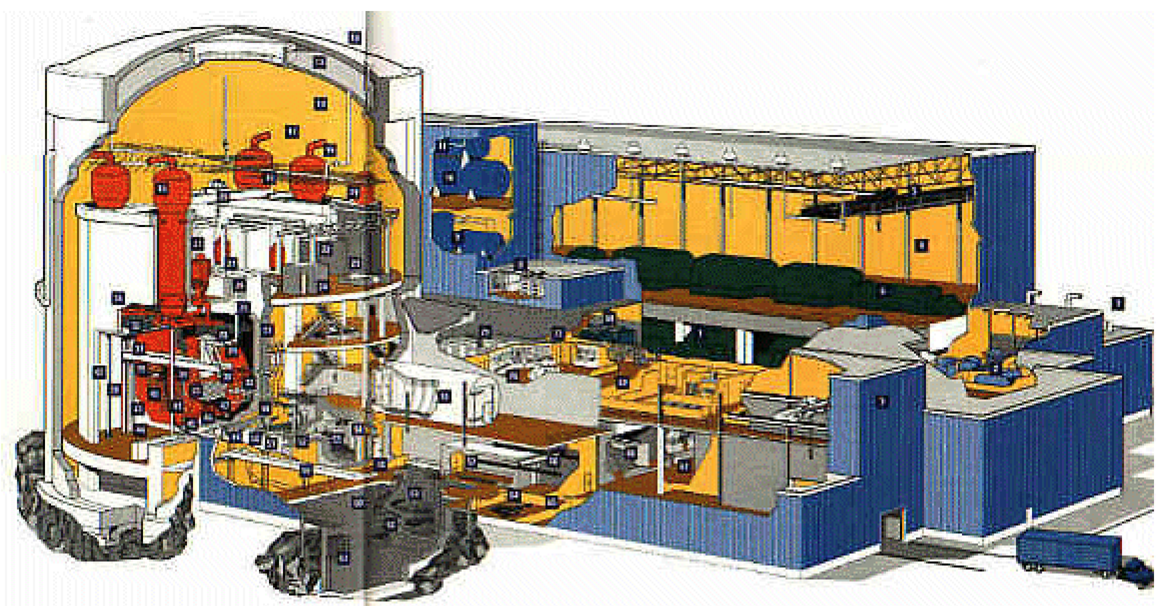


Fig. 1: First Generation Douglas Point on a stamp face, first HWR of the Candu design, now decommissioned, was part of a nuclear complex including the Bruce HWRs.

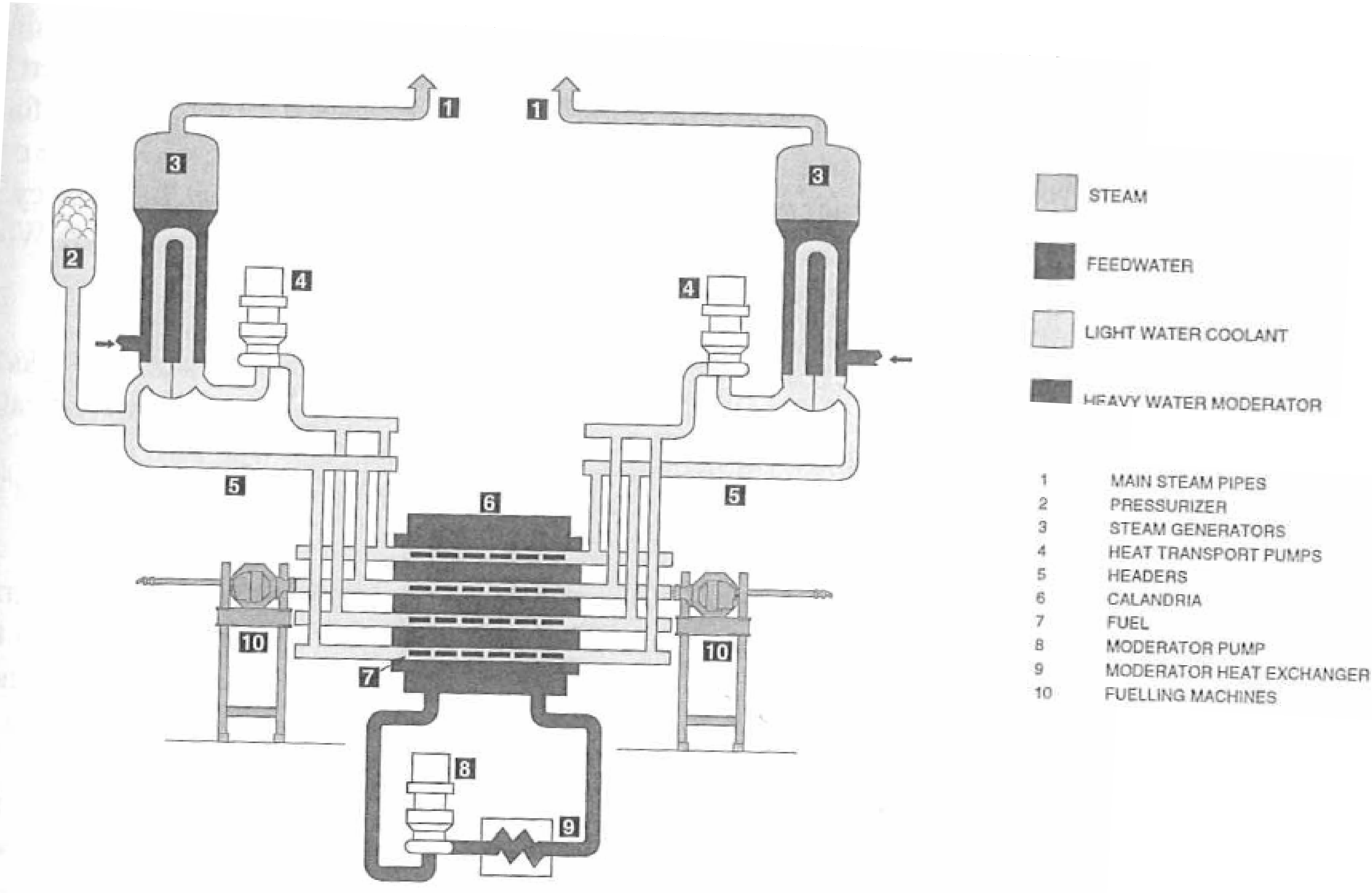
CANDU Pressurized Heavy Water Reactor





Nukeworker.com

CANDU Gas-Cooled Reactor



Sustainable Energy, MIT 2005.

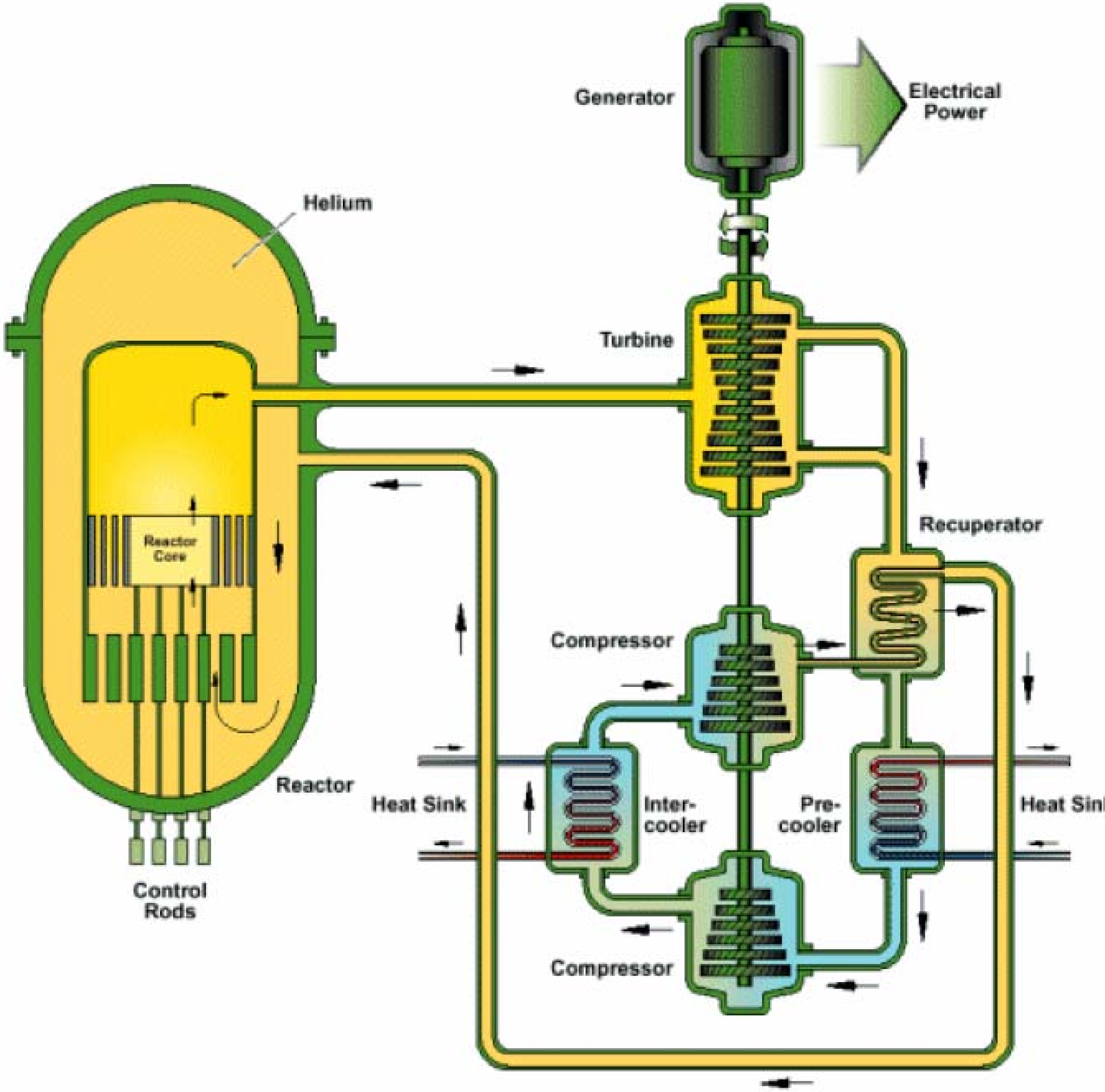


Fig. 5: Brayton or Joule gas turbine Gas cooled Fast Reactor, GFR.

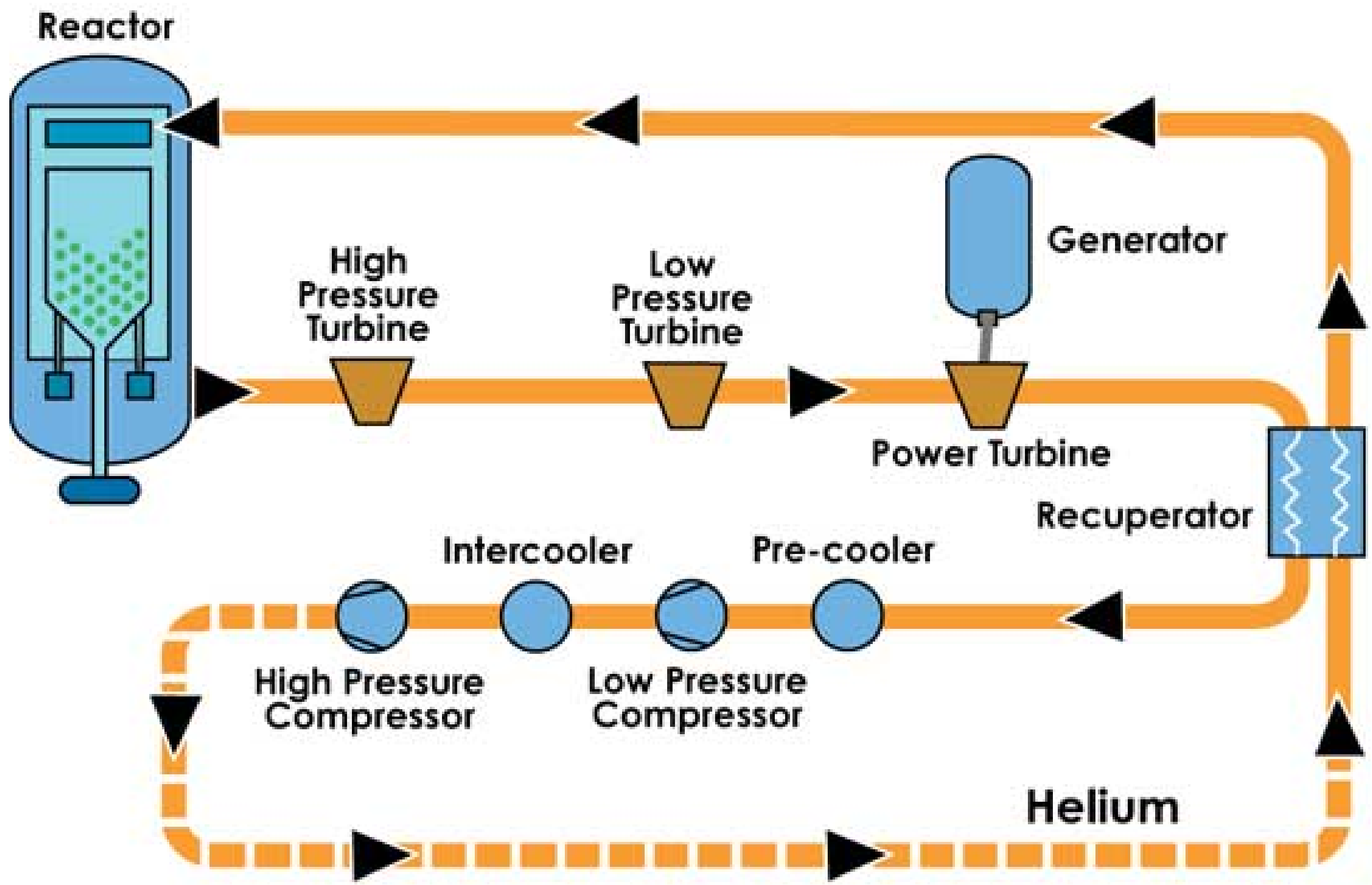
“Next” Generations

- Generation III and III+
  - ABWR - Advanced Boiling Water Reactor
  - System 80+ APWR - Advanced Pressurized Water Reactor
  - Passive reactor design

- Generation IV
  - GFR – Gas-Cooled Fast Reactor System
  - LFR – Lead-Cooled Fast Reactor System
  - MSR – Molten Salt Reactor System
  - SFR – Sodium-Cooled Fast Reactor System
  - SCWR – Supercritical-Water-Cooled Reactor System
  - VHTR – Very-High-Temperature Reactor System

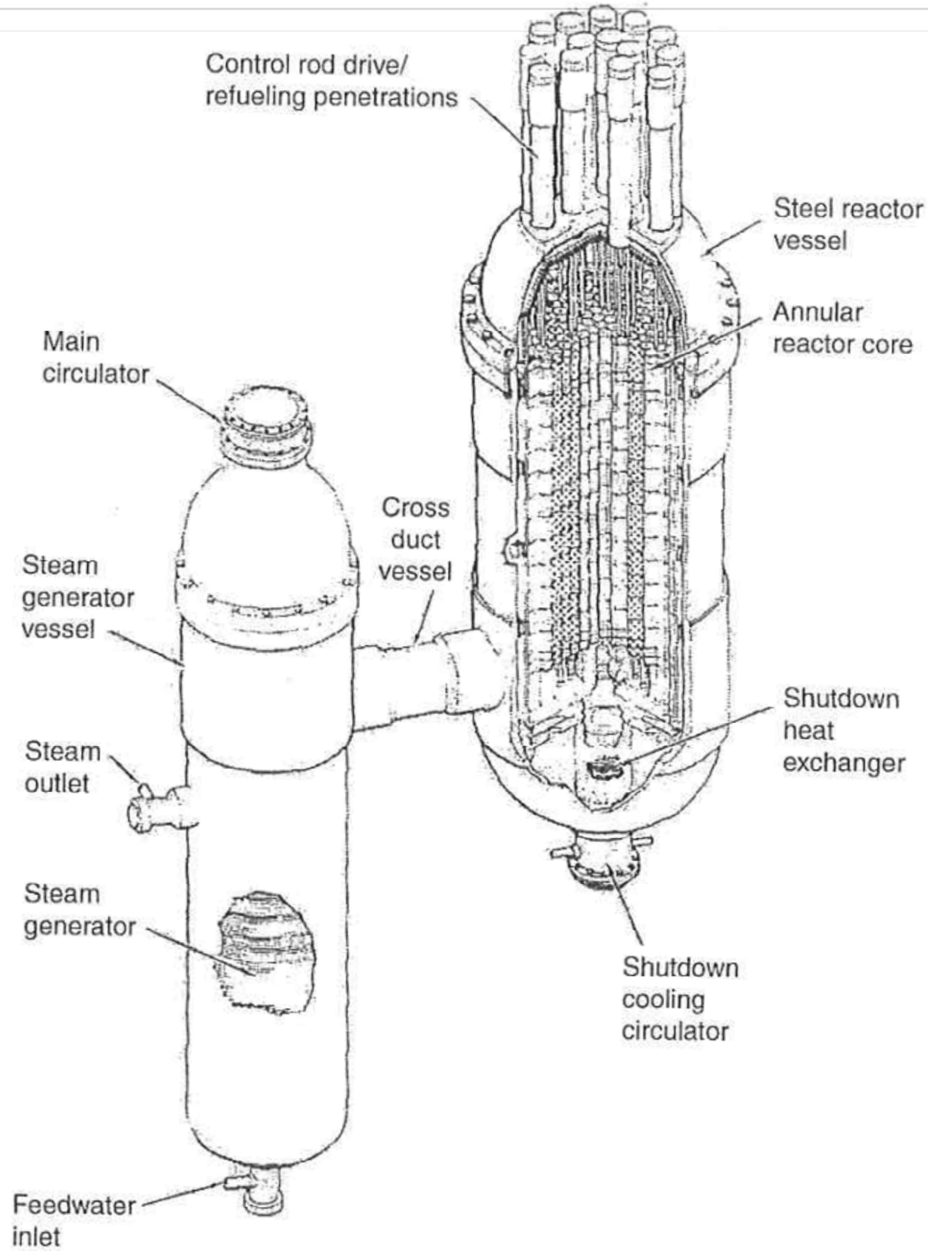
High Temperature Gas-Cooled Reactor

- Japan and China; >900 deg C

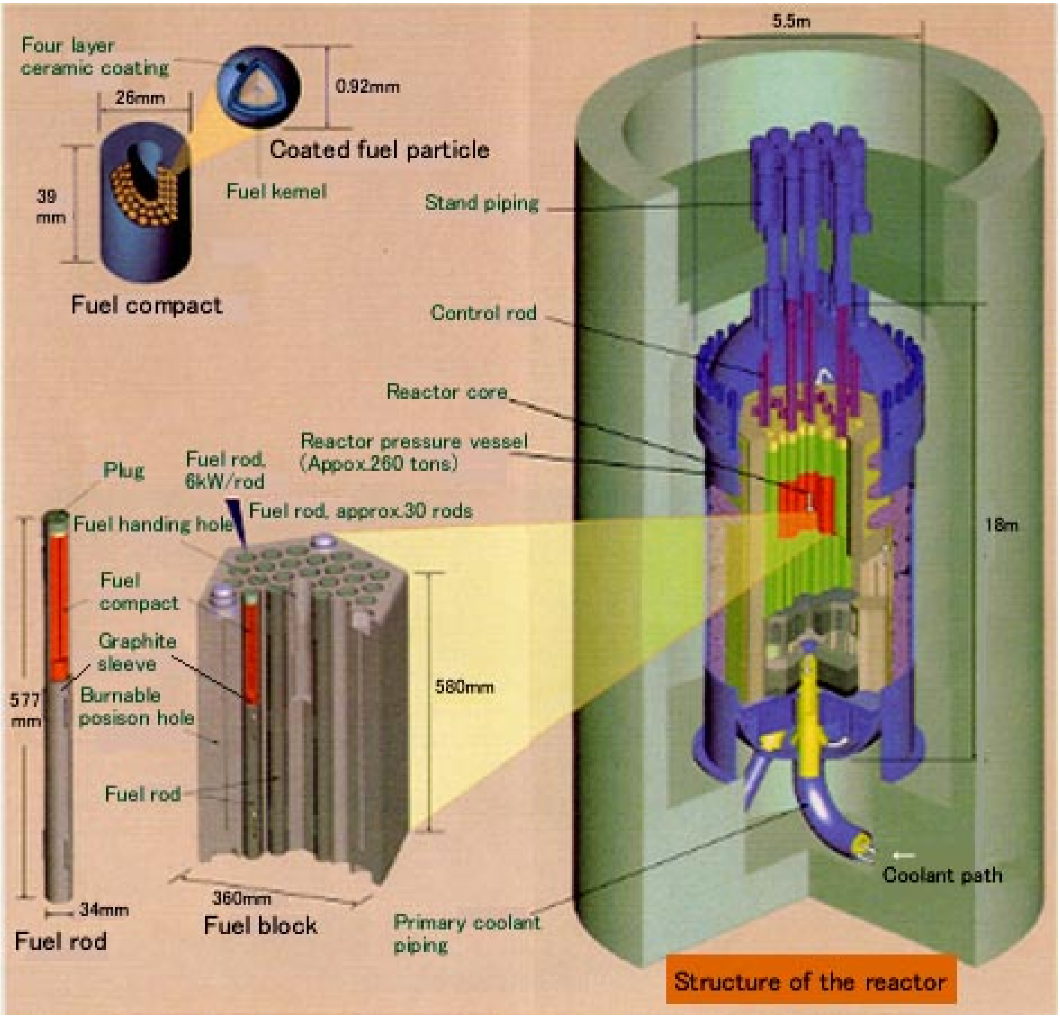


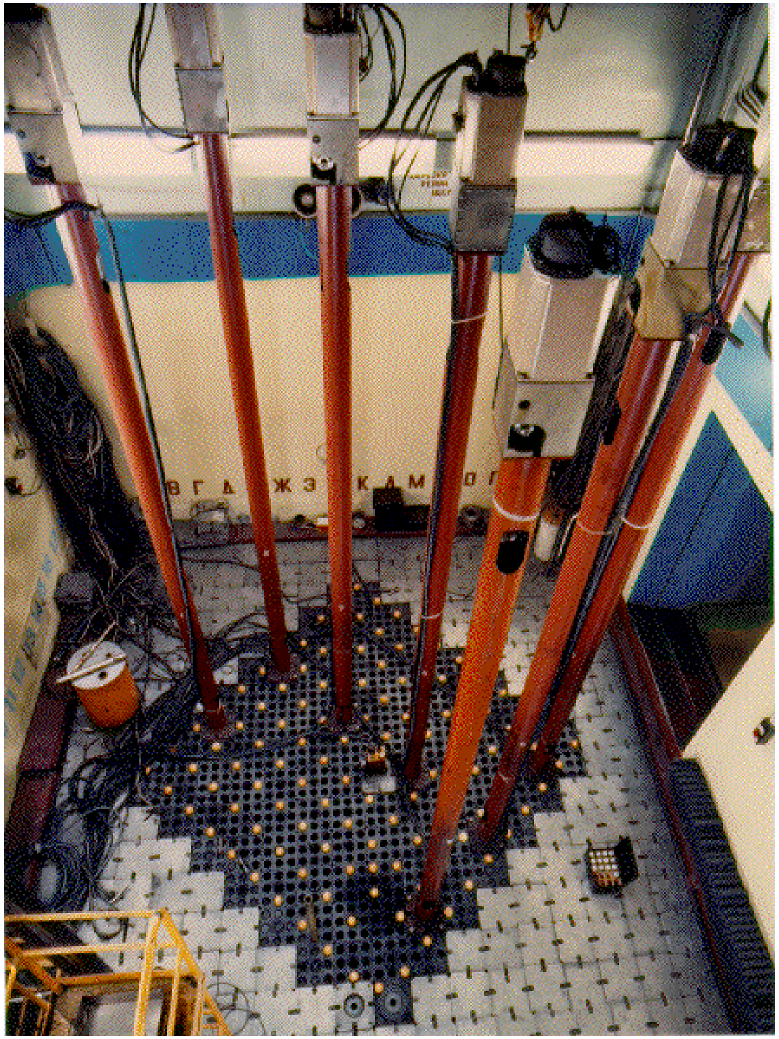
Nukeworker.com

HGTR


Control rod drive/
refueling penetrations
Steel reactor
vessel
Annular
reactor core
Main
circulator
Cross
duct
vessel
Steam
generator
vessel
Steam
outlet
Shutdown
heat
exchanger
Steam
generator
Shutdown
cooling
circulator
Feedwater
inlet

High Temperature Gas-Cooled Reactor





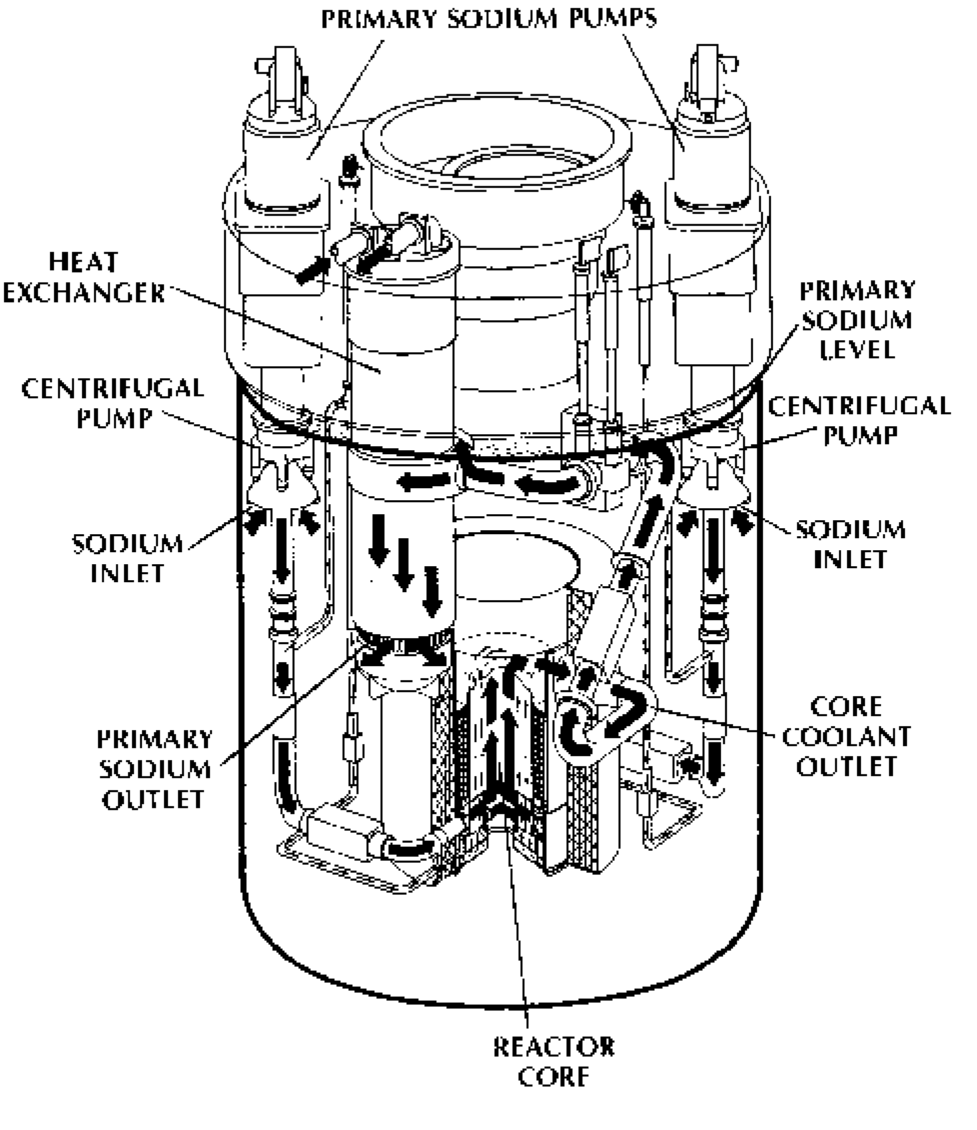
Passive Reactors

- Passively safe reactors rely on nature to keep them cool
- Cooling with a sodium pool
- The pool design passively removes decay heat if normal heat-removal systems fail.
- Sodium
  - Highly efficient heat-transfer material
  - Operates at normal atmospheric pressure
  - Increases reliability of components because it does not corrode common structural materials
  - Tends to bind chemically with radioactive fission products, which reduces radioactive releases if fuel fails.
- Metallic Fuel: an alloy of uranium and other metals.
- The safety bottom line: natural feedback mechanisms tend to maintain coolant temperature near its normal 500 degrees C (930 degrees F) operating value — well below sodium's 900 C (1,650 F) boiling point — even when the reactor loses its engineered cooling systems.

Argonne National Lab

Diagram of major components in an advanced fast reactor.

(passive reactor)



Argonne National Lab, ANL

Passive Reactor Designs

- AP600 and AP1000

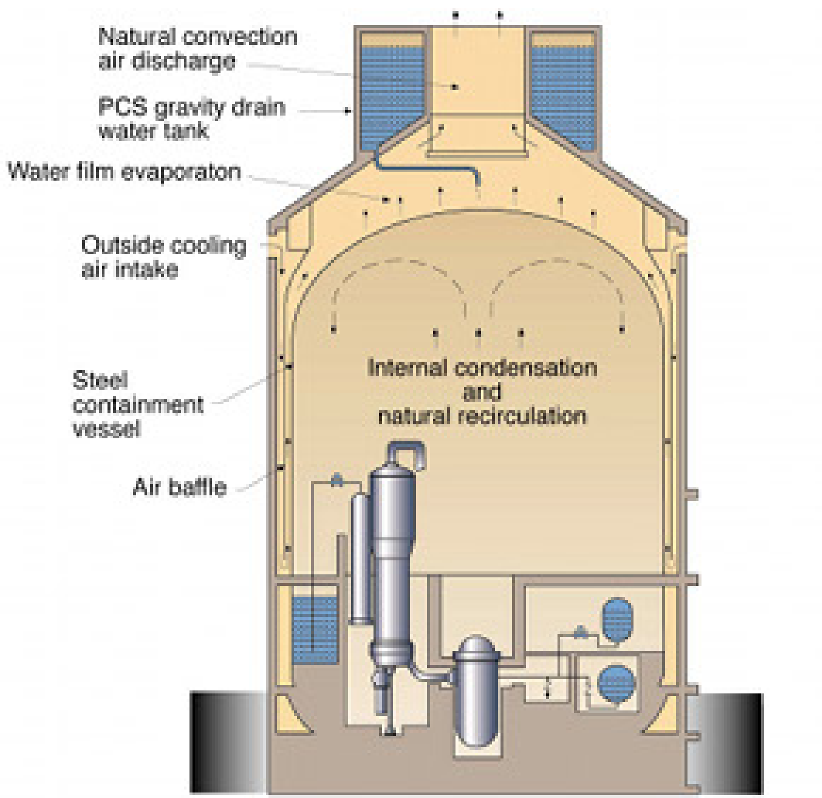
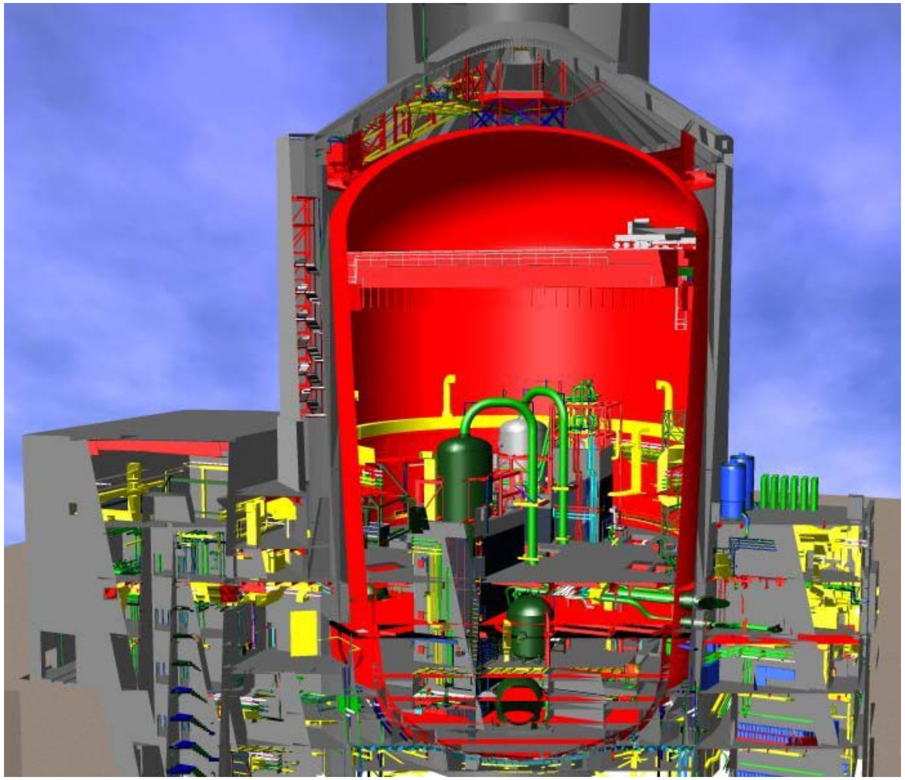
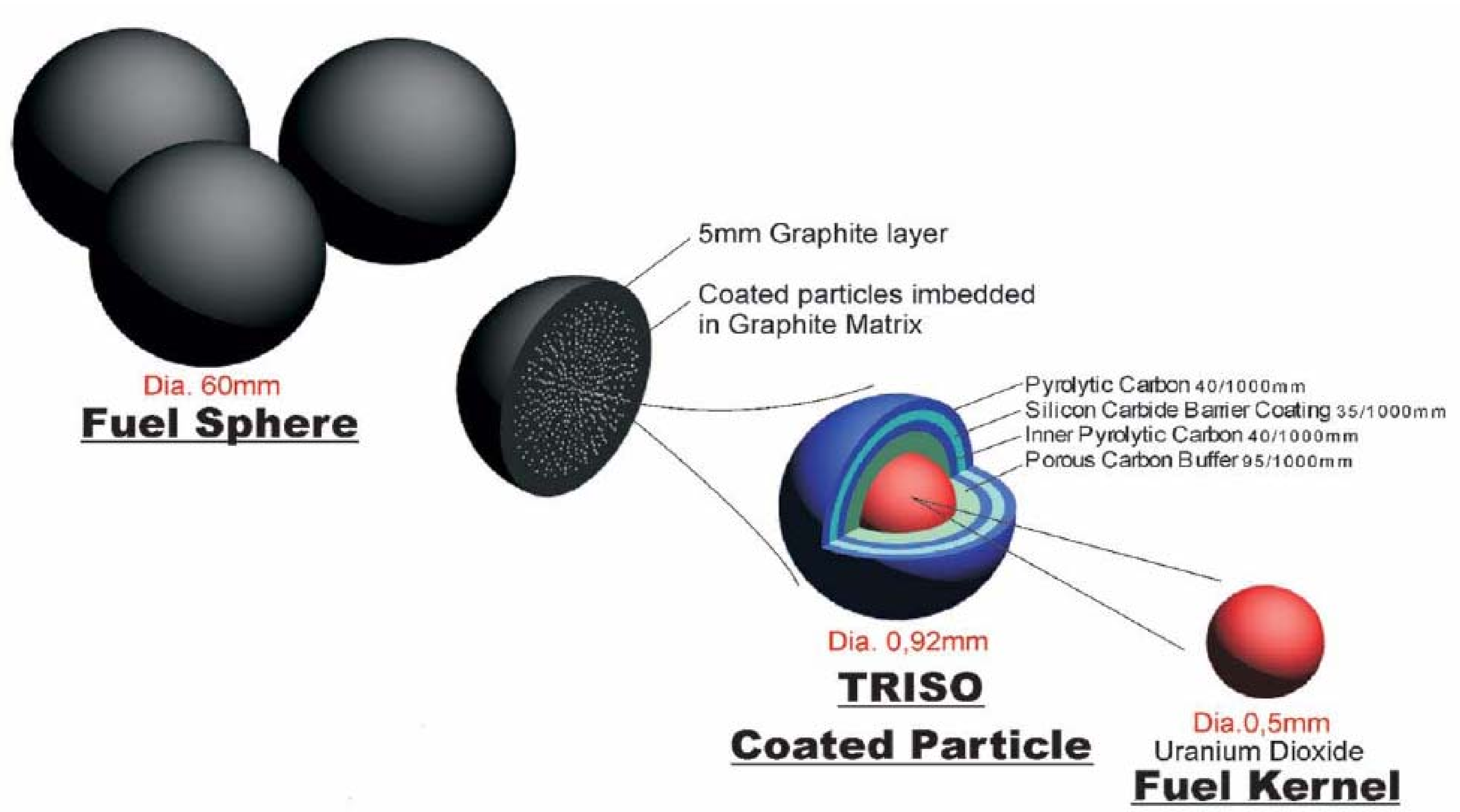


Figure 3. AP600 Passive Containment Cooling System

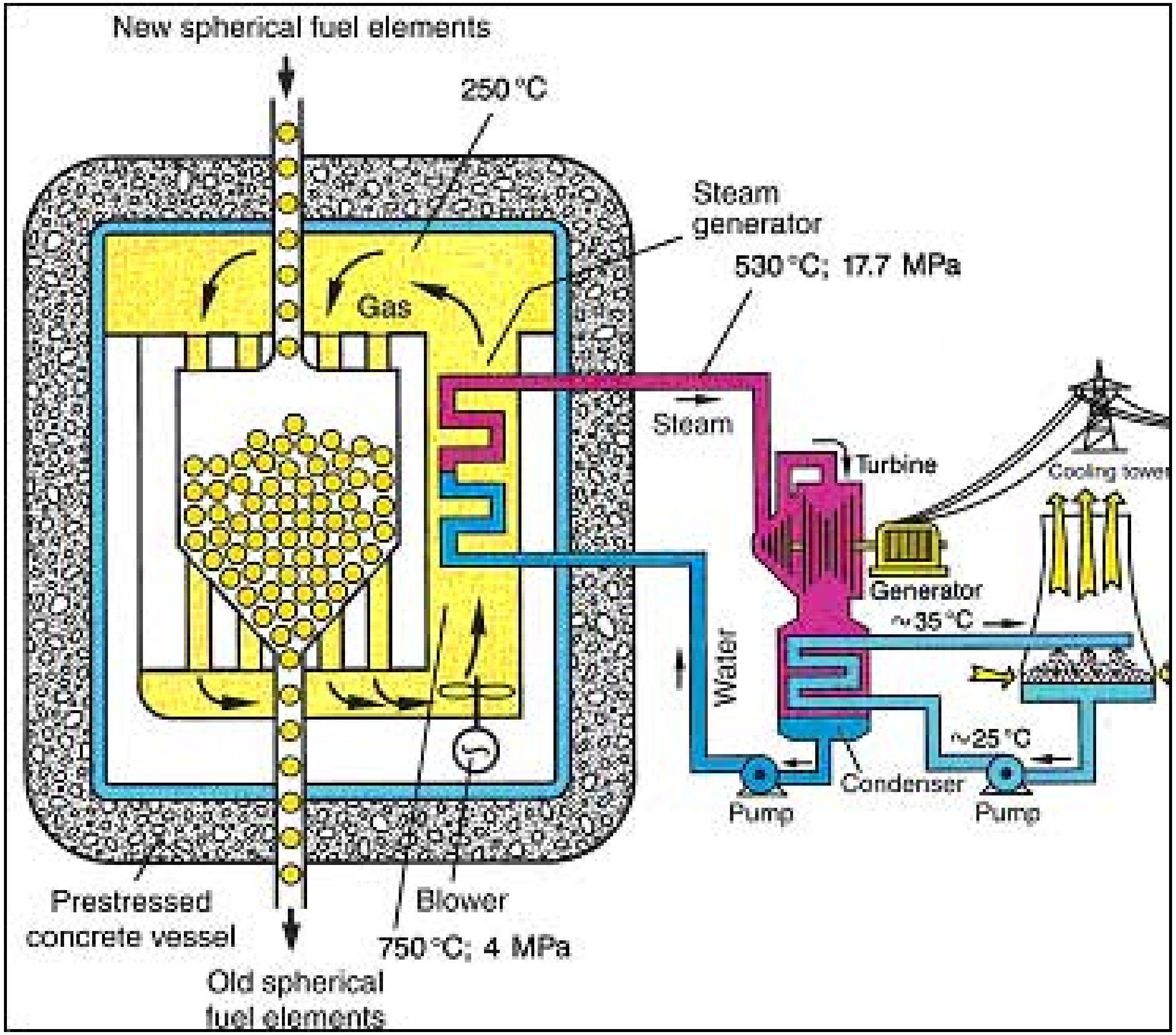


Pebble Bed Reactor

- Spherical pellets, Brayton cycle
- 110 MW output



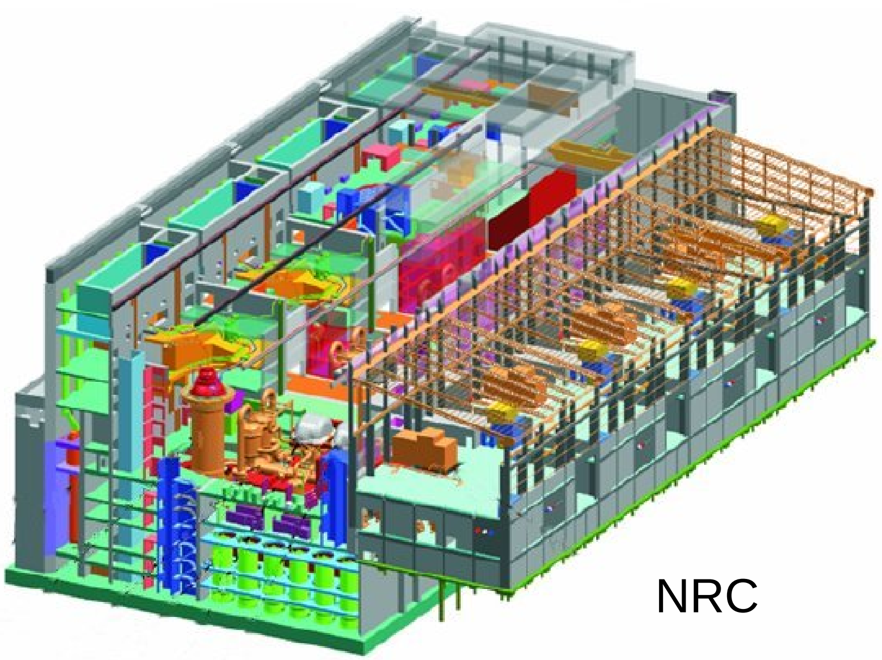
Pebble Bed Reactor



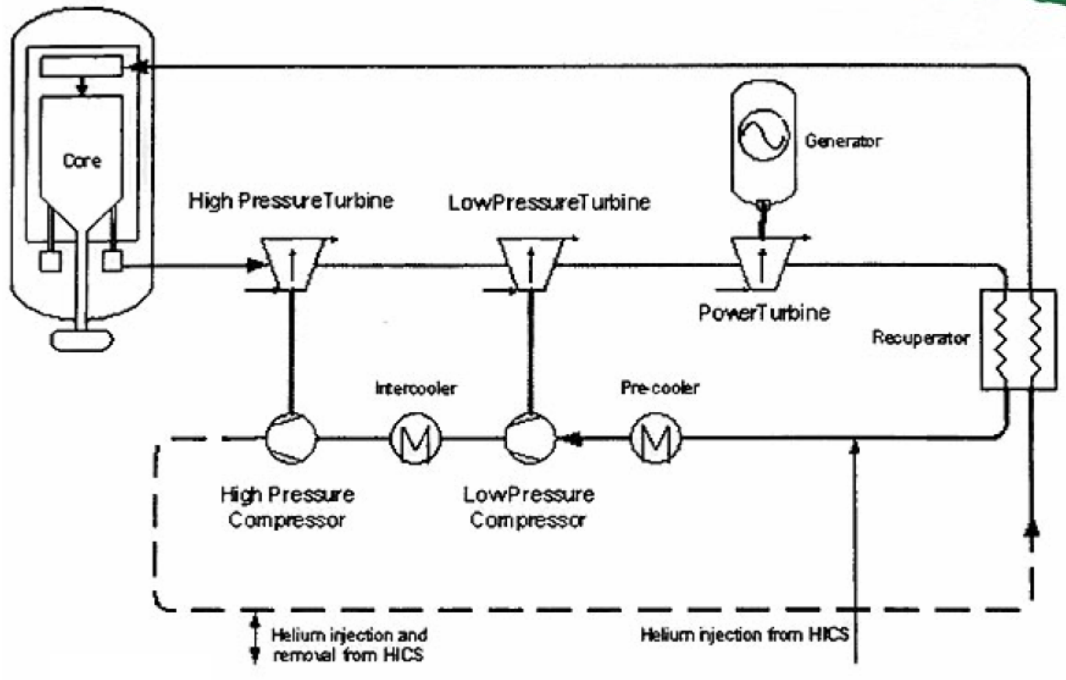
Schema-root.org

- South Africa as leaders
- Helium (500 deg C, 9MPa) cooled
- 450,000 fuel spheres
- Helium is now 900 deg C

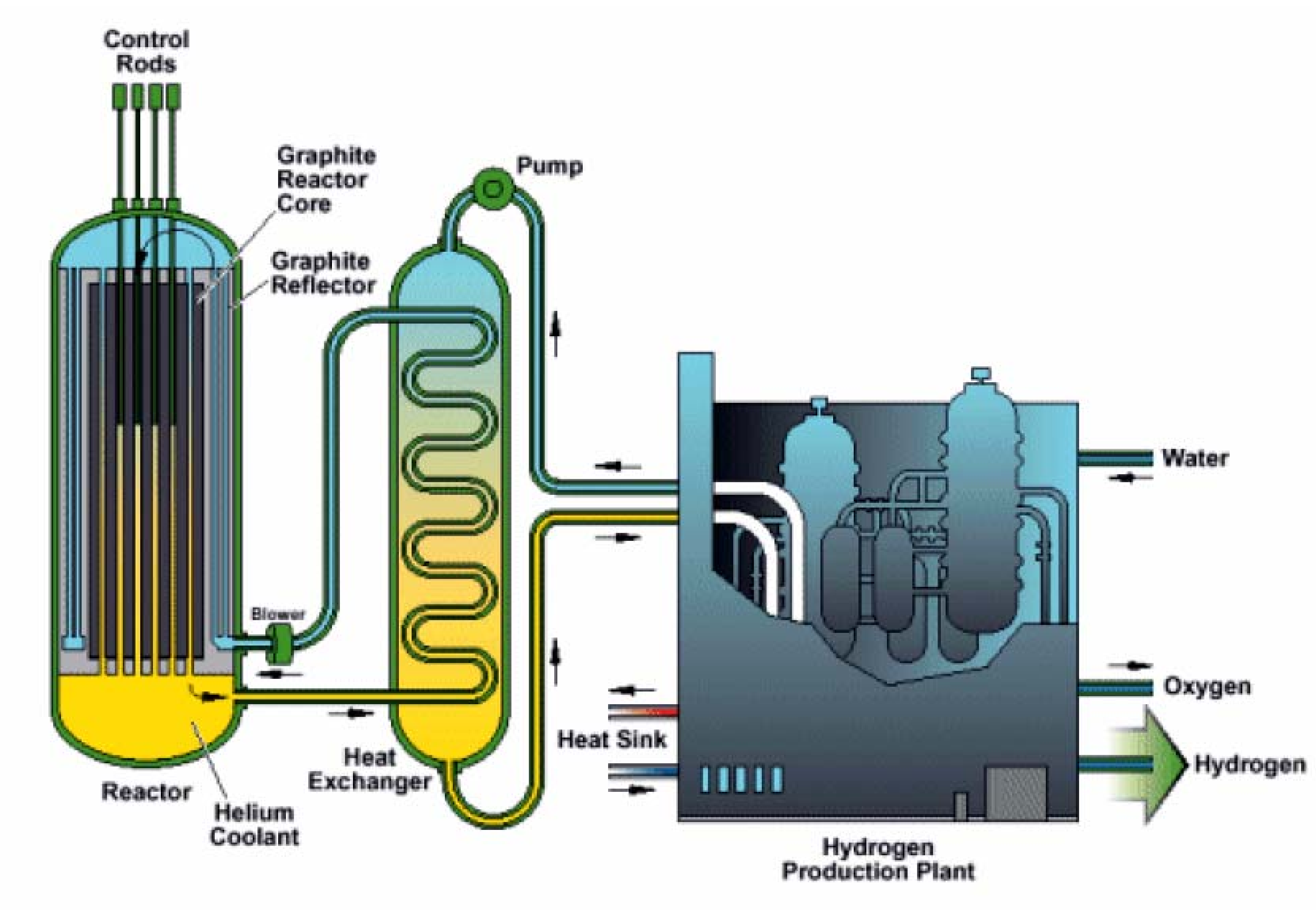
Pebble Bed Reactor



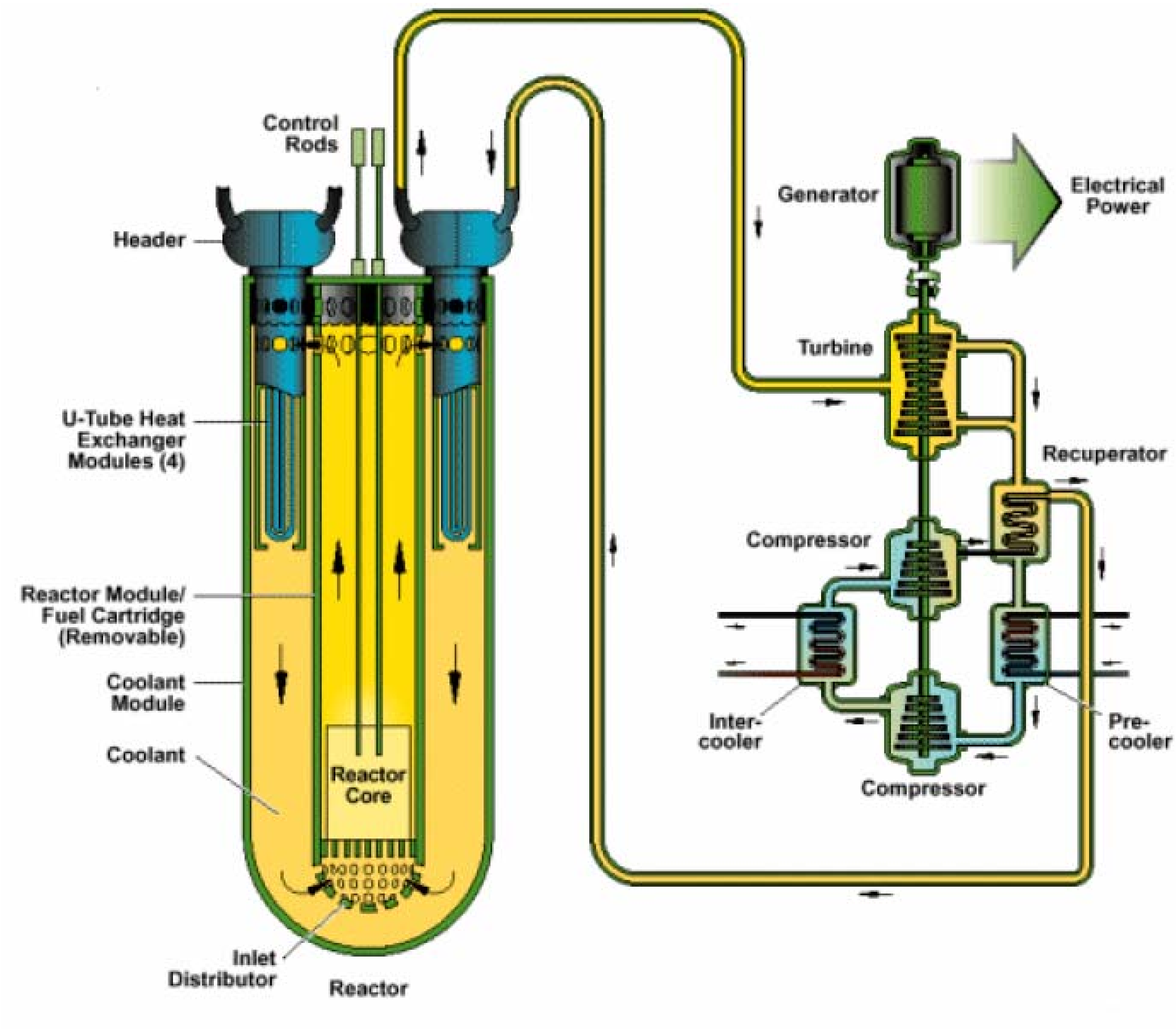
NRC



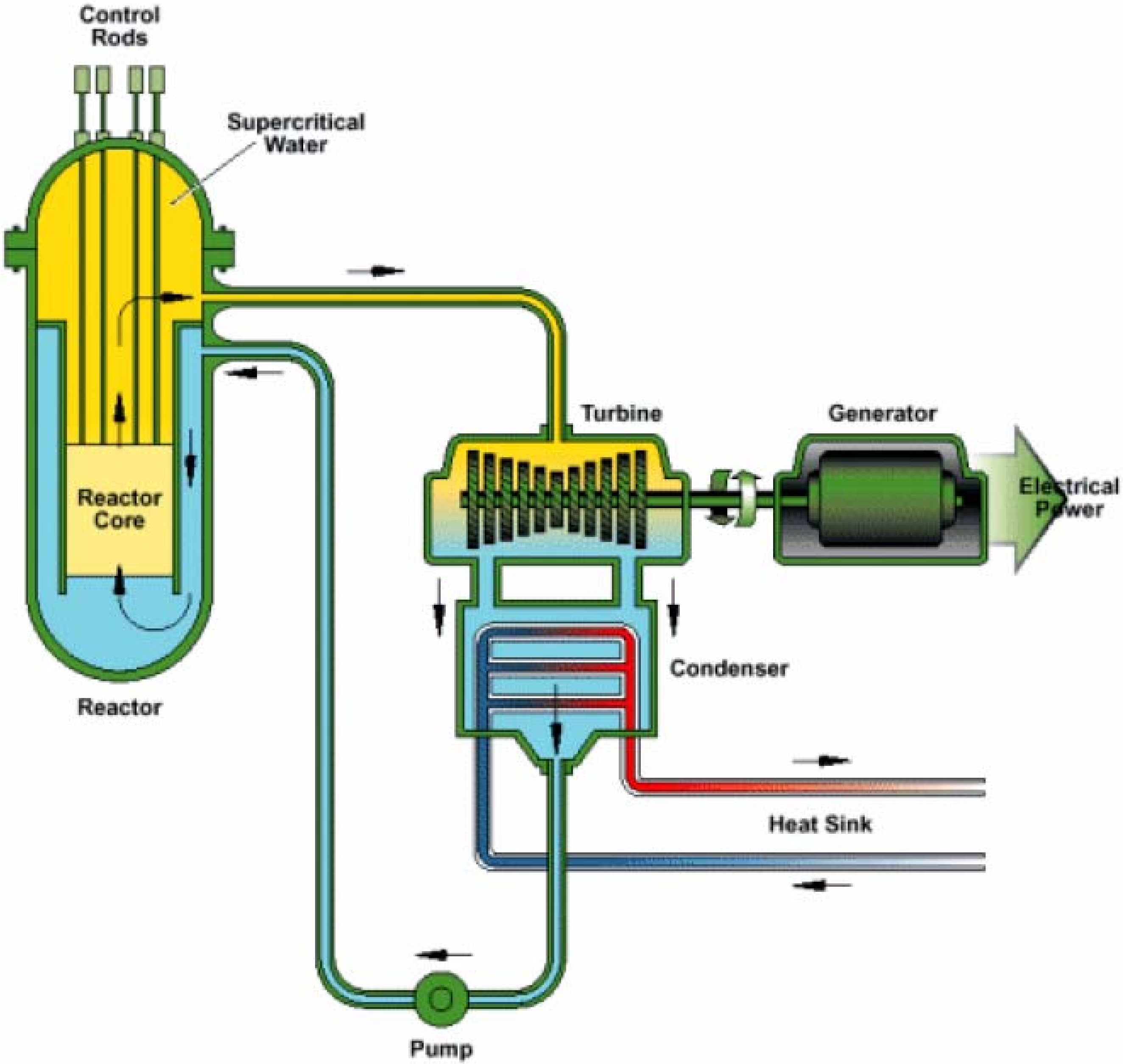
: Flow Diagram of the Pebble Bed Modular Reactor (PBMR)



Very High Temperature Hydrogen and Electricity (VHTR) design.



Lead cooled Fast Reactor with Brayton, Joule gas turbine cycle.

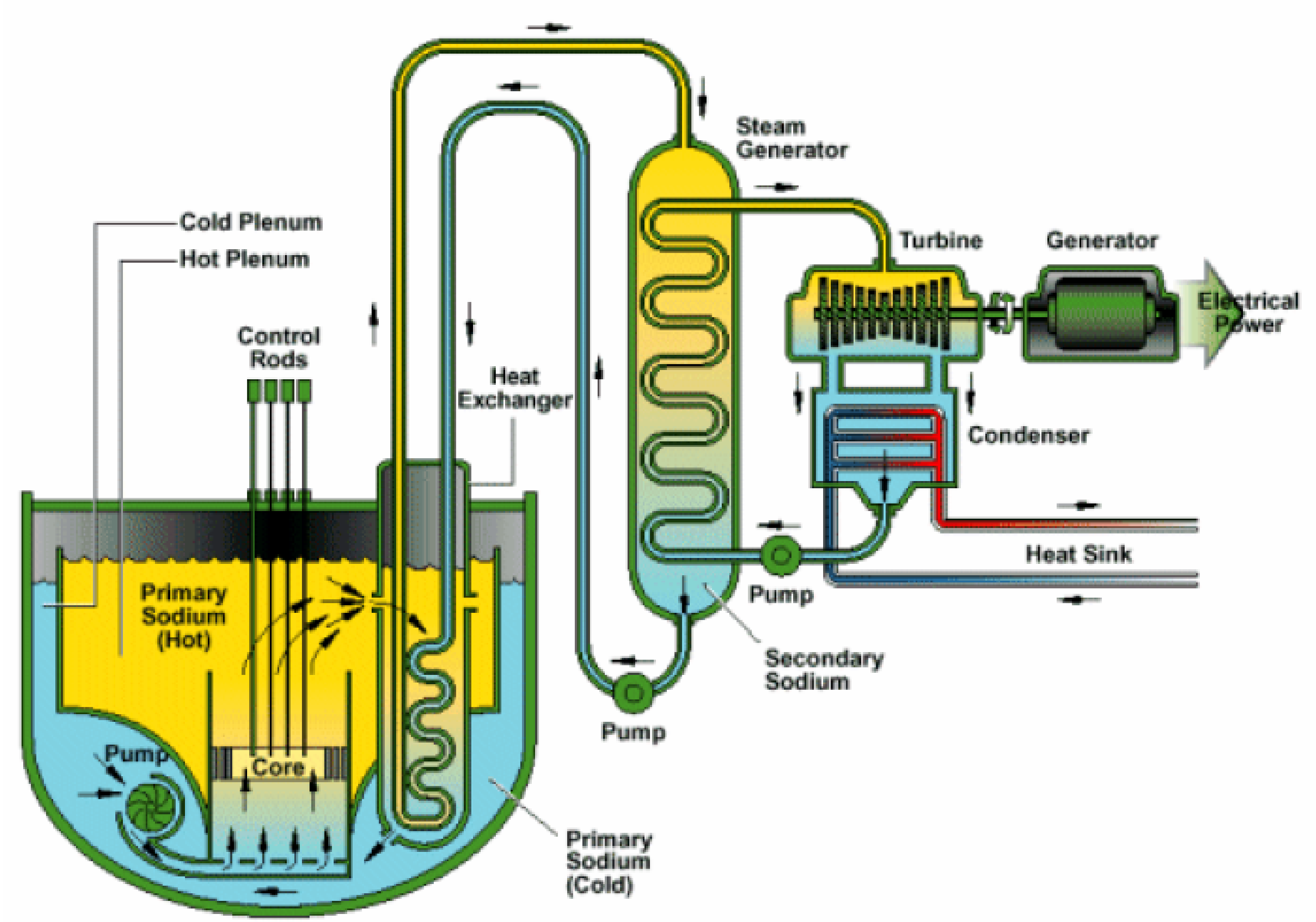


Supercritical Water Cooled Reactor (SWCR) using the Rankine steam cycle.

Molten Salt Advanced High Temperature Reactor

- Low pressure molten salt cooled (vs. high pressure helium)
- 150-500MW or 500-1500MW
- Fuel: Uranium/Plutonium/minoractinide/zirconium
- 550 deg C outlet temp

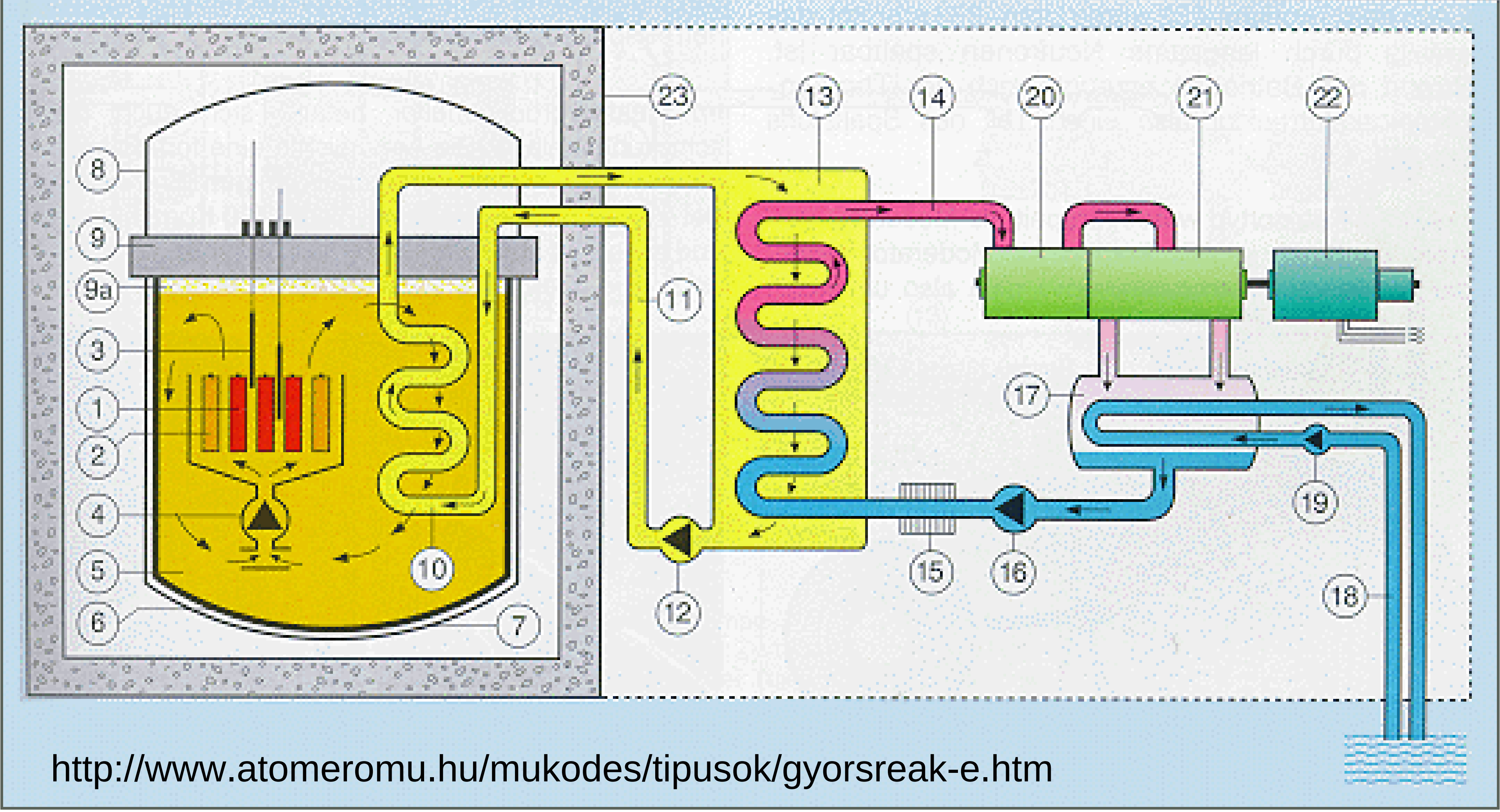
Molten Salt Advanced High Temperature Reactor



Breeder Reactors

- a nuclear reactor that generates new fissile material at a greater rate than it consumes such material
- French Phénix: for 100 fission reactions there are 115 newly produced fissile nuclei
- Two types of traditional breeder reactor have been proposed:
  - fast breeder reactor: plutonium, natural (or even depleted) uranium
  - thermal breeder reactor: thorium-232 → uranium-233

The heat of primary sodium is transferred to the secondary sodium in an intermediate heat exchanger, while the third heat exchanger is the steam generator. Three loops are needed for safety (liquid sodium is very dangerous: the primary sodium is highly radioactive because of neutrons activation, which results in Na-24; the second sodium loop prevents radioactive sodium from accidental contact with water.)



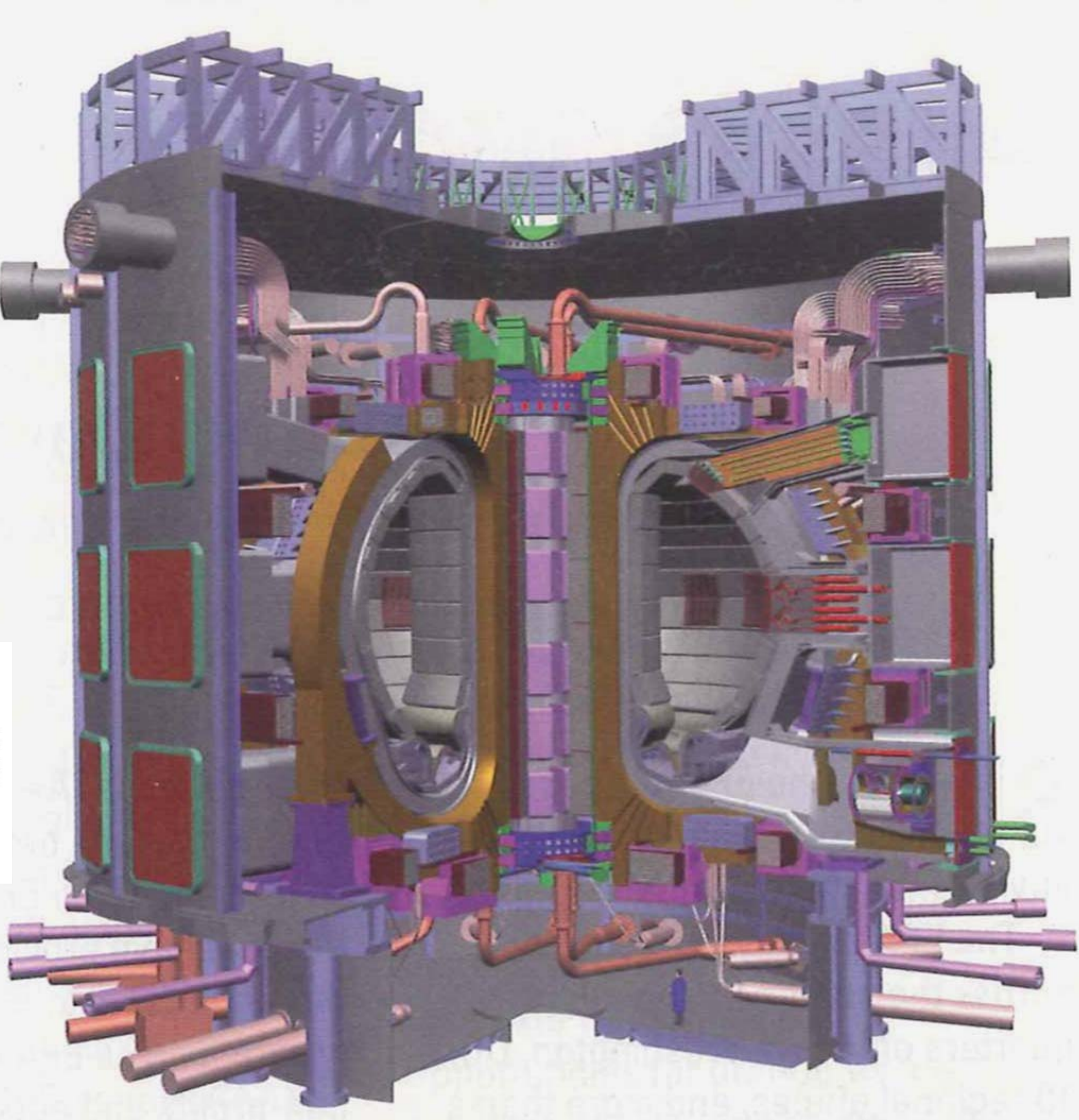
1 Fuel (fissile material)
2 Fuel (breeder material)
3 Control rods
4 Primary Na pump
5 Primary Na coolant
6 Reactor vessel
7 Protective vessel
8 Reactor cover

9 Cover
10 Na/Na heat exchanger
11 Secondary Na
12 Secondary Na pump
13 Steam generator
14 Fresh steam
15 Feedwater pre-heater
16 Feedwater pump

17 Condenser
18 Cooling water
19 Cooling water pump
20 High pressure turbine
21 Low pressure turbine
22 Generator
23 Reactor building

Nuclear Fusion Power

Done by 2018?



The ITER project is sited at Cadarache in the South of France. Europe will contribute almost half of the costs of its construction, while the other six Members to this joint international venture (China, Japan, India, the Republic of Korea, the Russian Federation and the USA), will contribute equally to the rest.

Graduating Engineer magazine, Back-to-School 2008.