The Leibstadt Nuclear Power Plant in Switzerland, on the Rhine river.

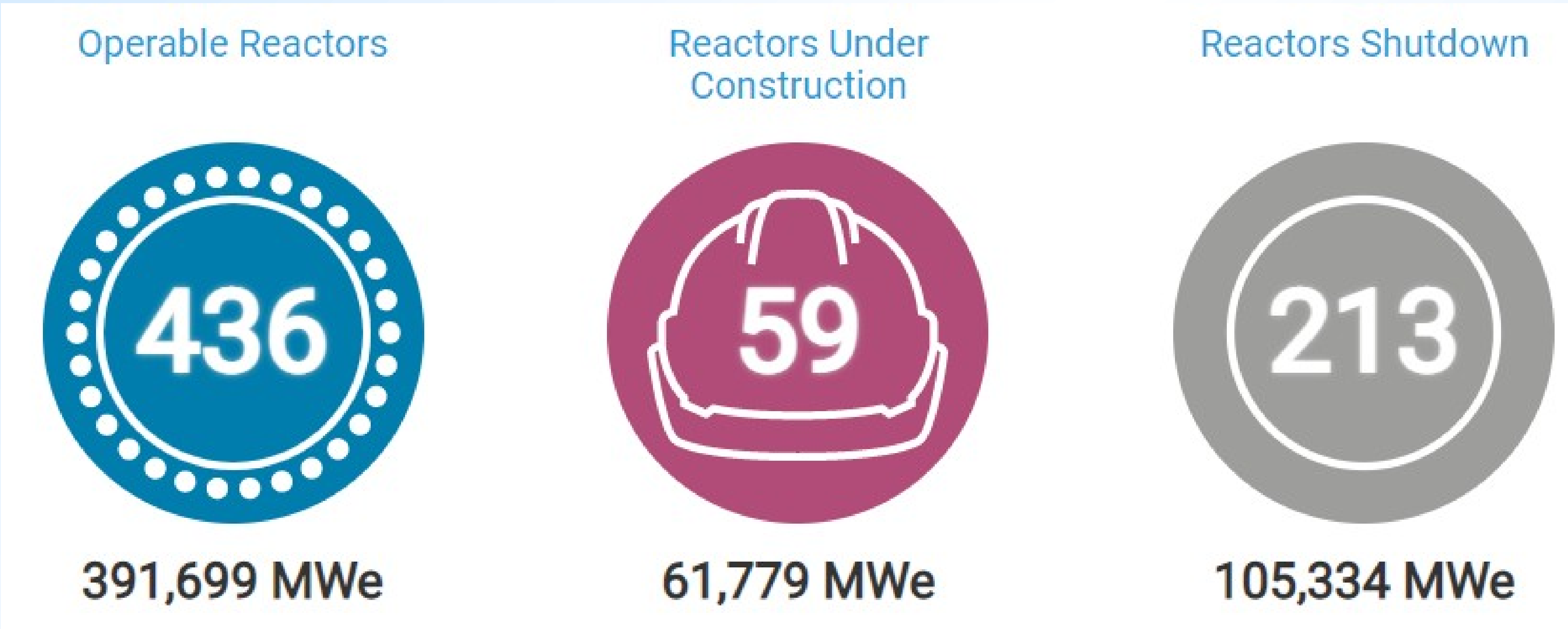
BWR (Boiling Water Reactor); Commissioned in 1984

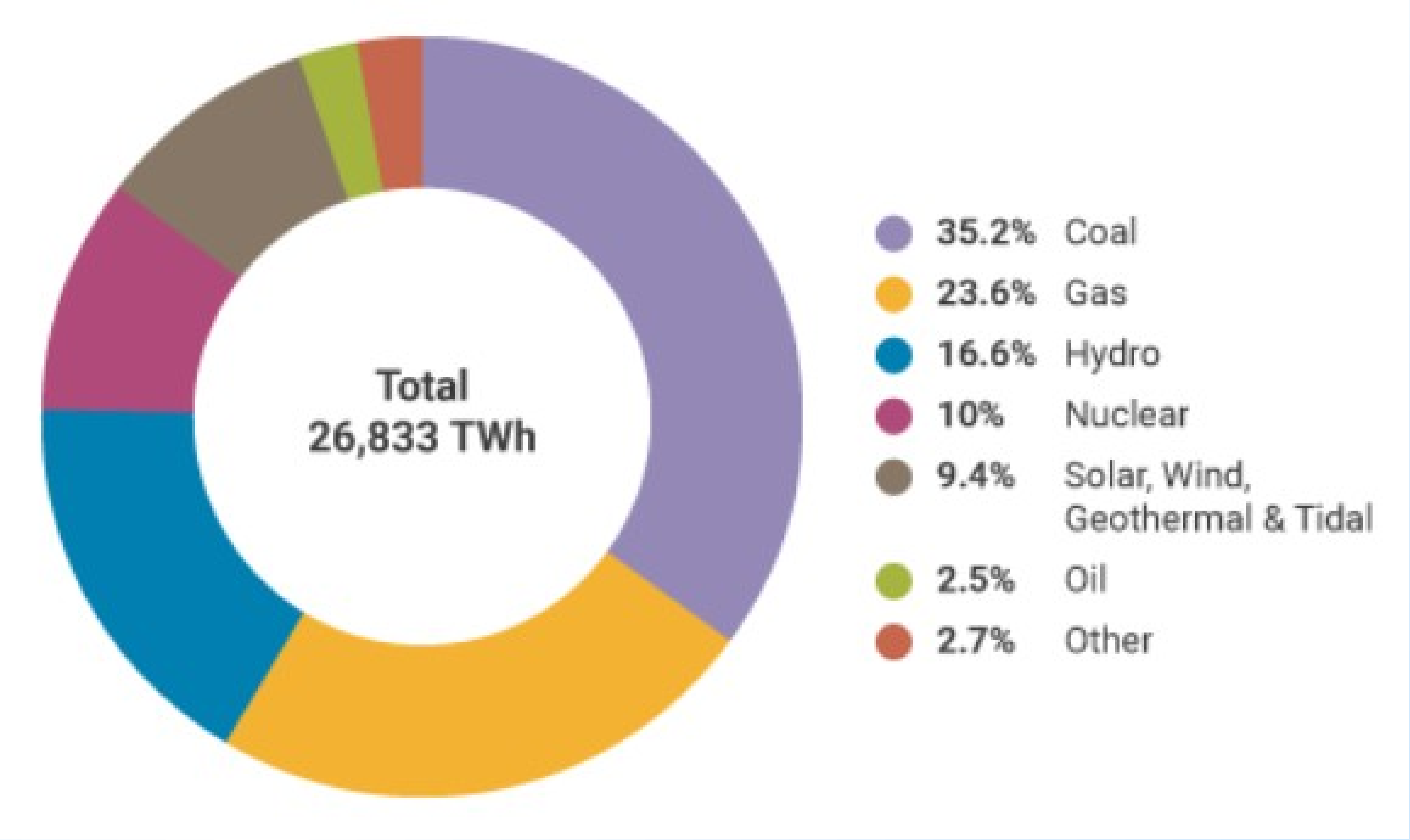
1220 MW

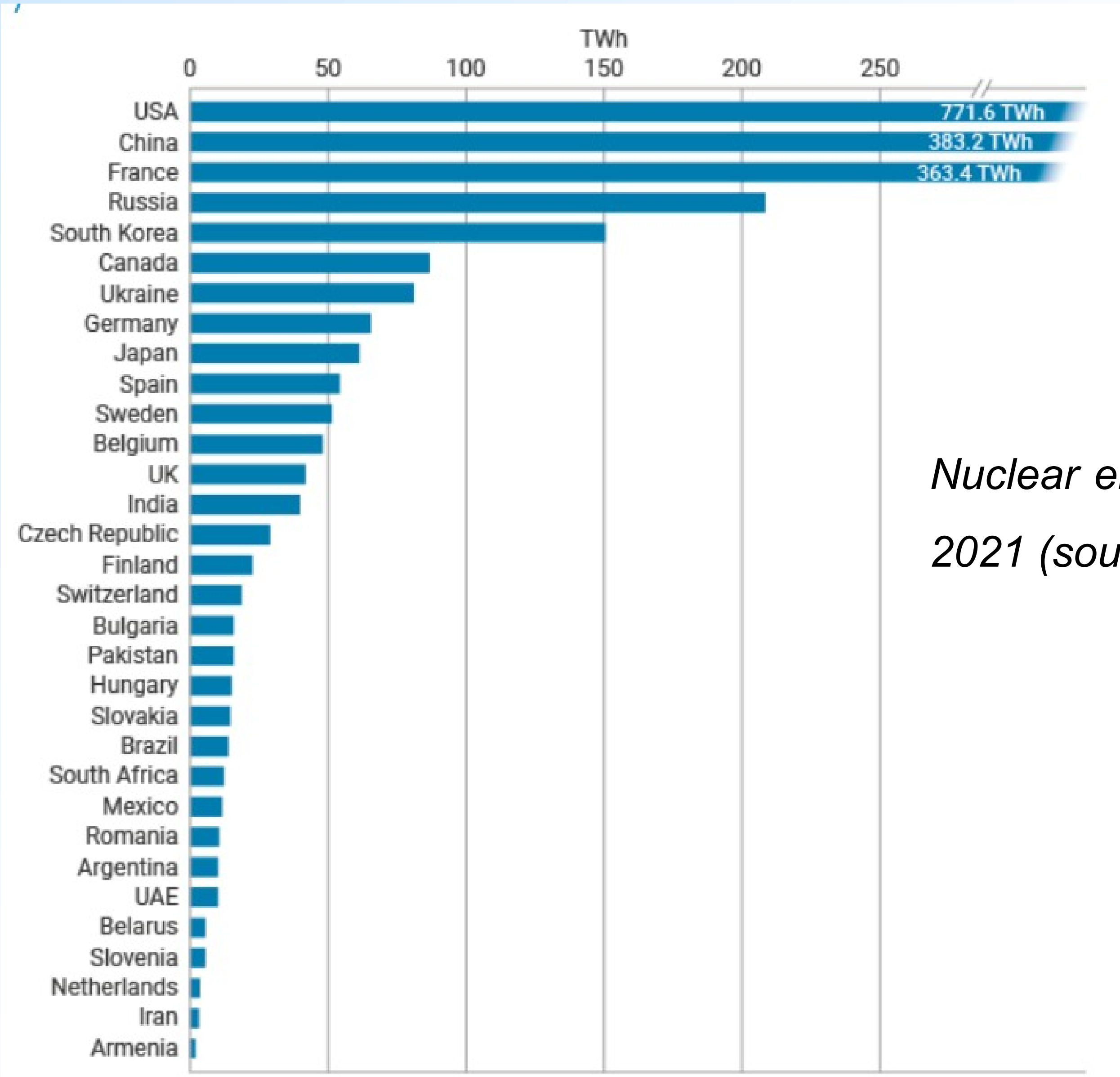
The Ikata Nuclear Power Plant, a pressurized water reactor (PWR) that cools by utilizing a secondary coolant heat exchanger with a large body of water, an alternative cooling approach to large cooling towers..

NUCLEAR POWER IN THE WORLD TODAY (MAY 2023)

- The first commercial nuclear power stations started operation in the 1950s.
- Nuclear energy now provides about 10% of the world's electricity from about 440 power reactors.
- Nuclear is the world's second largest source of low-carbon power (26 % of the total in 2020).
- Over 50 countries utilize nuclear energy in about 220 research reactors. In addition to research, these reactors are used for the production of medical and industrial isotopes, as well as for training.

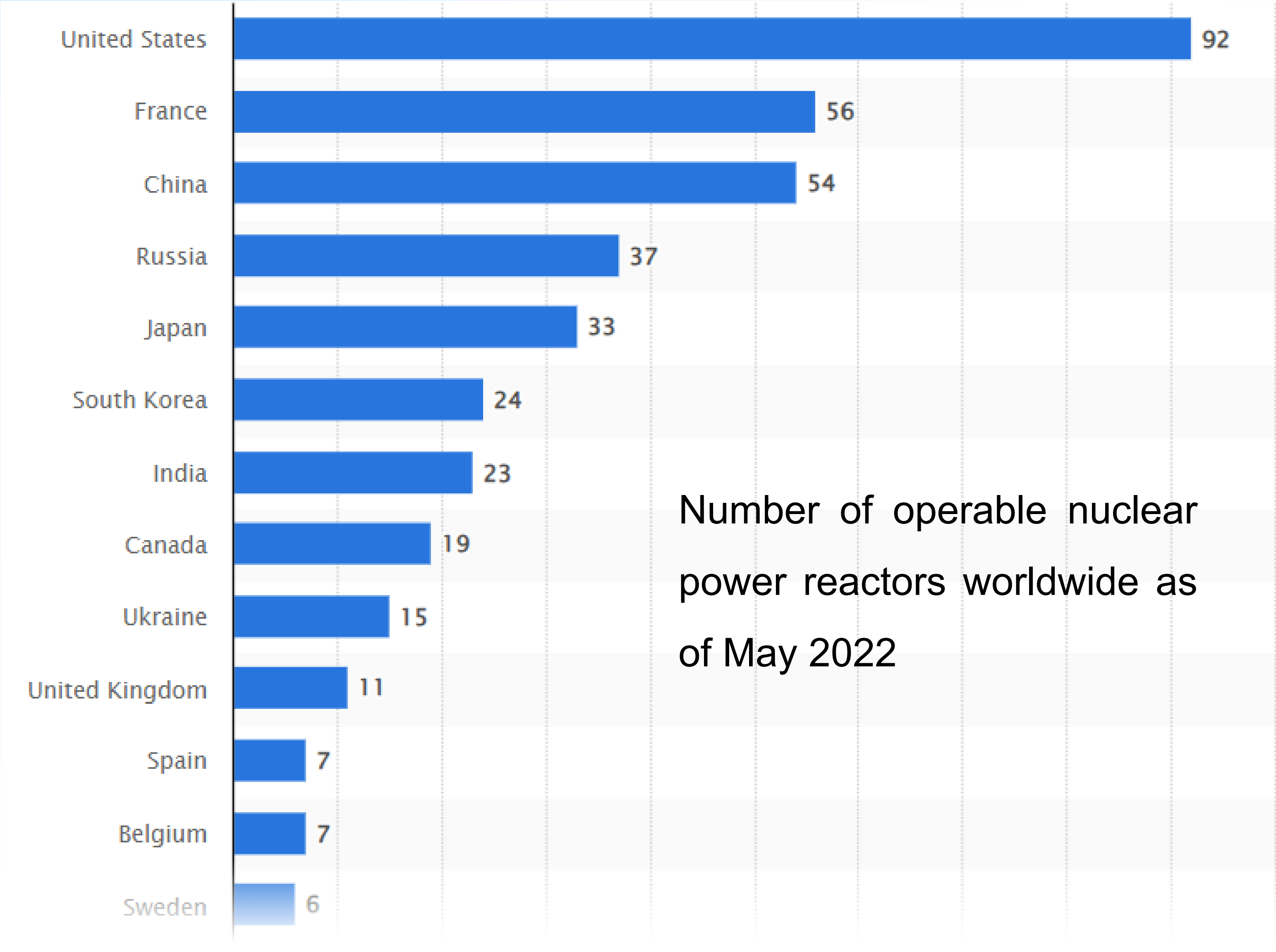

Operable Reactors
436
391,699 MWe
Reactors Under Construction
59
61,779 MWe
Reactors Shutdown
213
105,334 MWe


Total
26,833 TWh
35.2% Coal
23.6% Gas
16.6% Hydro
10% Nuclear
9.4% Solar, Wind, Geothermal & Tidal
2.5% Oil
2.7% Other



Nuclear electricity generation by coun

2021 (source: IAEA PRIS)



Number of operable nuclear power reactors worldwide as of May 2022

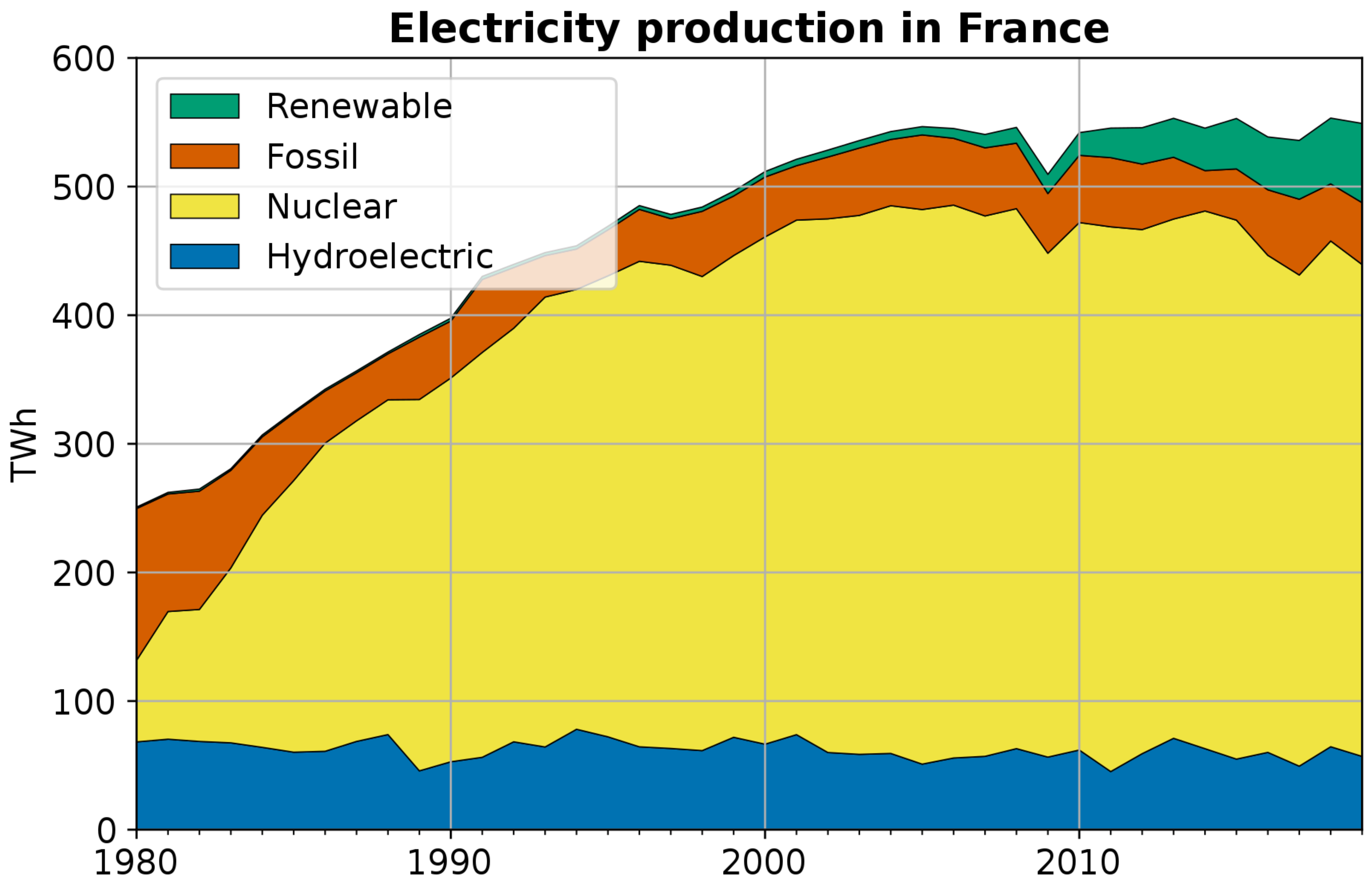

Electricity production in France
Renewable
Fossil
Nuclear
Hydroelectric
TWh
600
500
400
300
200
100
0
1980
1990
2000
2010

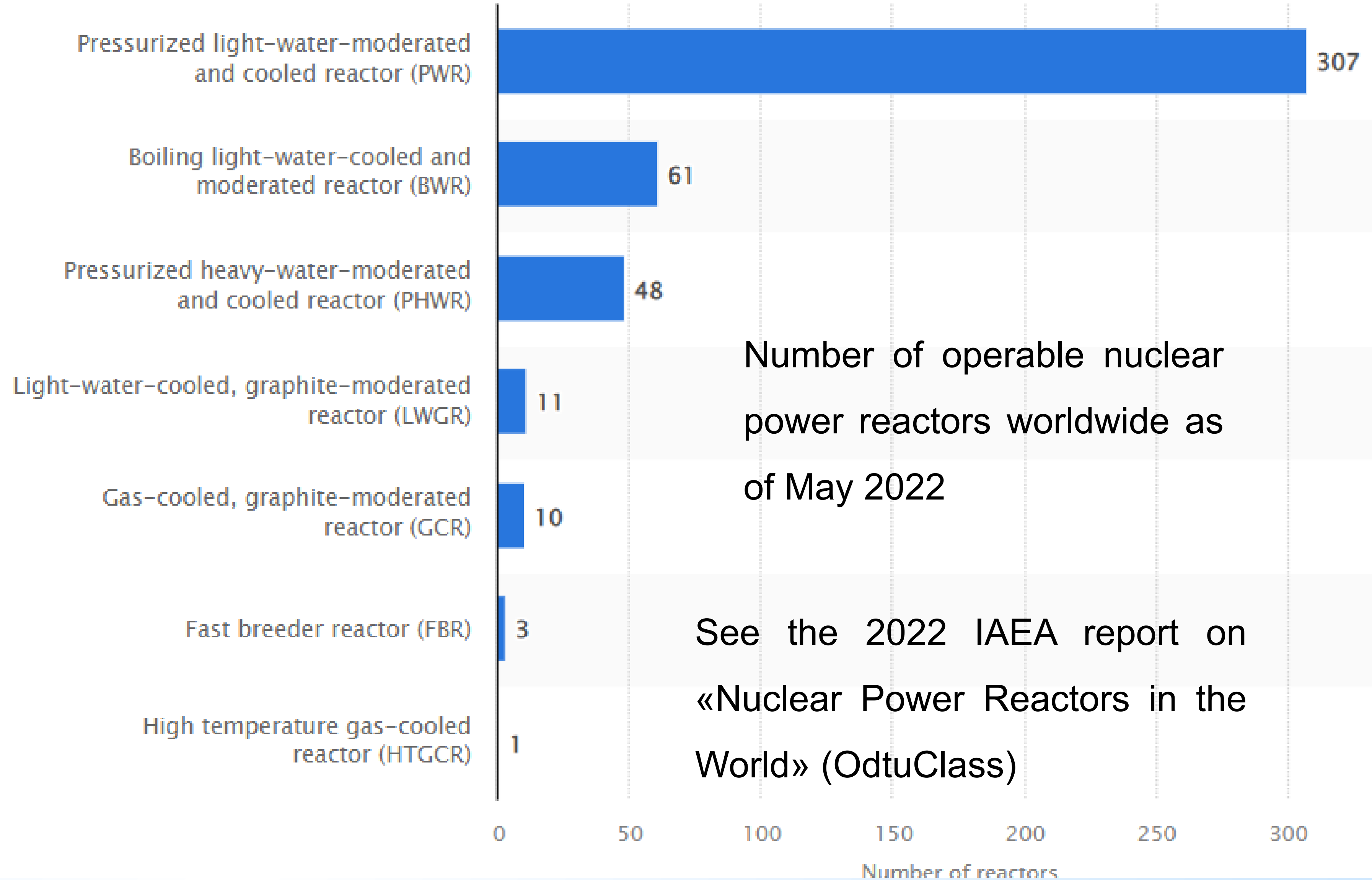
Table 8-4. Distribution of world reactors by type, 2004 and 2011

Reactor Type	Main Countries	Number	
		2004	2011
PWR	CN, FR, JP, KR, US	252	221
BWR	JP, KR, US	93	82
Heavy water	AR, CD, CN, KR	33	47
Gas-cooled	UK	34	14
Fast breeder*	RU	3	1
Other*	Various	14	75
Total		429	440

**Note*: IAEA reported one FBR each in Japan and France in 2004, but not in 2011. Change in number of "other" reactors is partially due to recategorization of some reactors.

Code: AR = Argentina, CD = Canada, CN = China, FR = France, JP = Japan, KR = S. Korea, RU = Russia, PWR = Pressurized Water Reactor, BWR = Boiling Water Reactor.

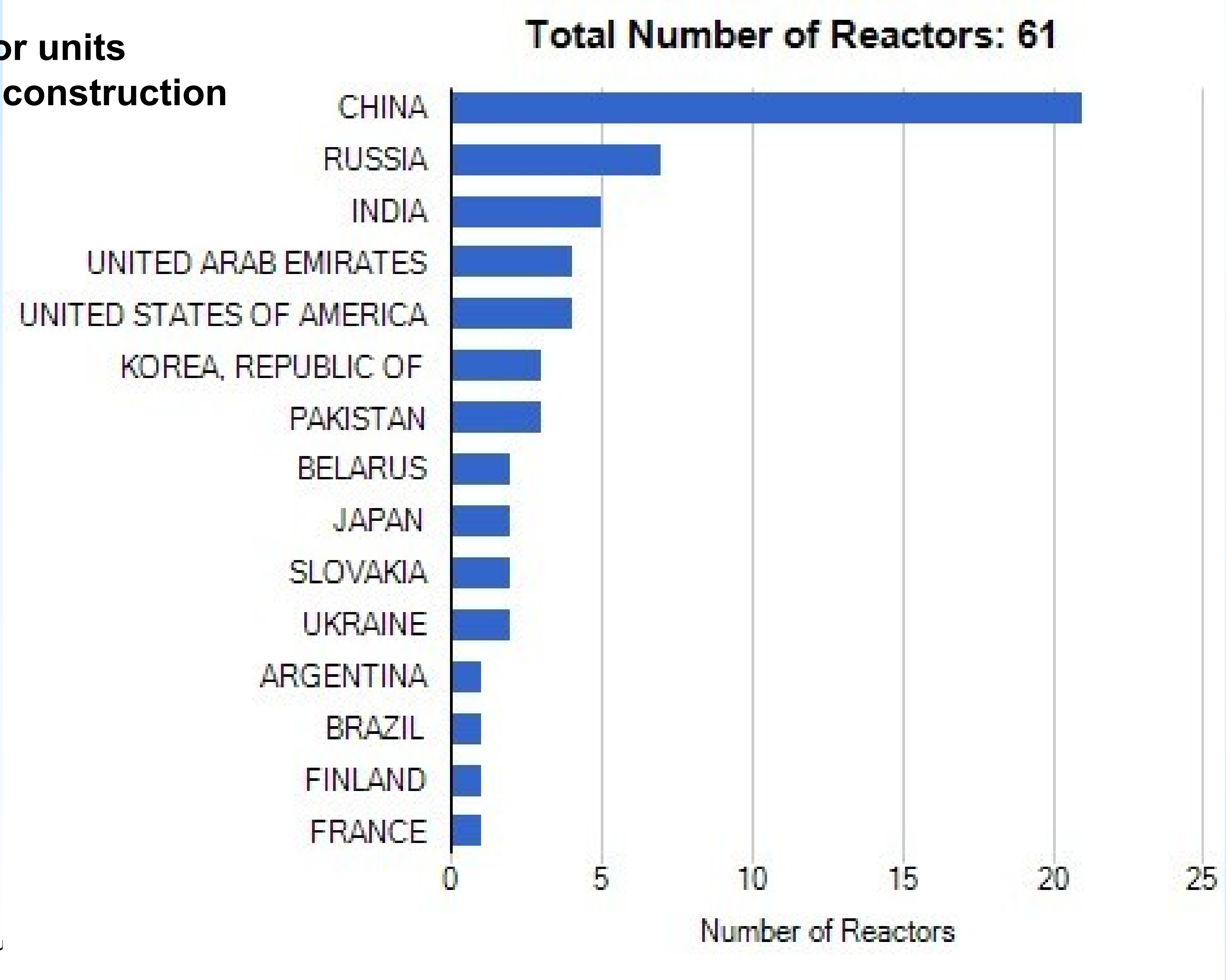
Source: IAEA



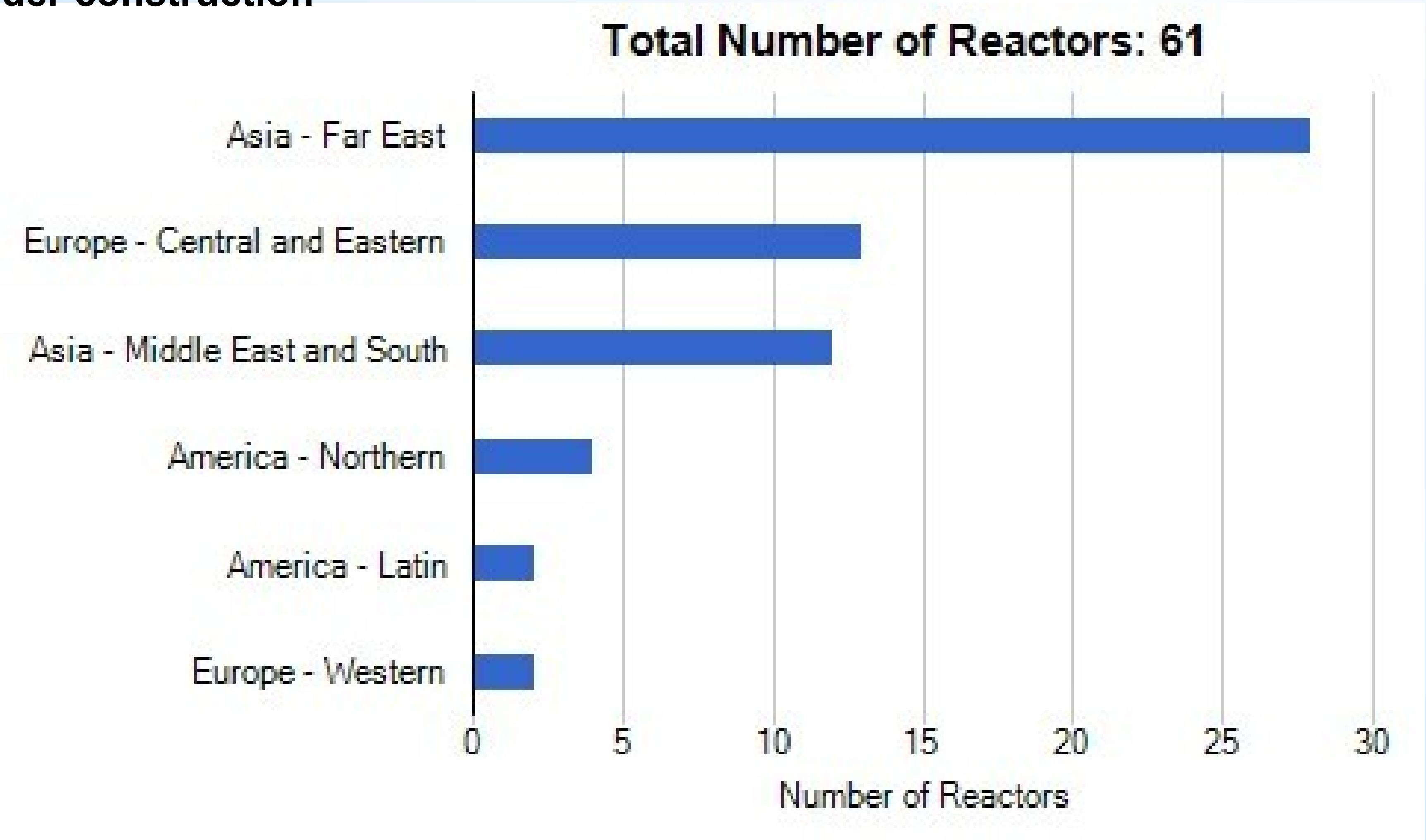
Number of operable nuclear power reactors worldwide as of May 2022

See the 2022 IAEA report on «Nuclear Power Reactors in the World» (OdtuClass)

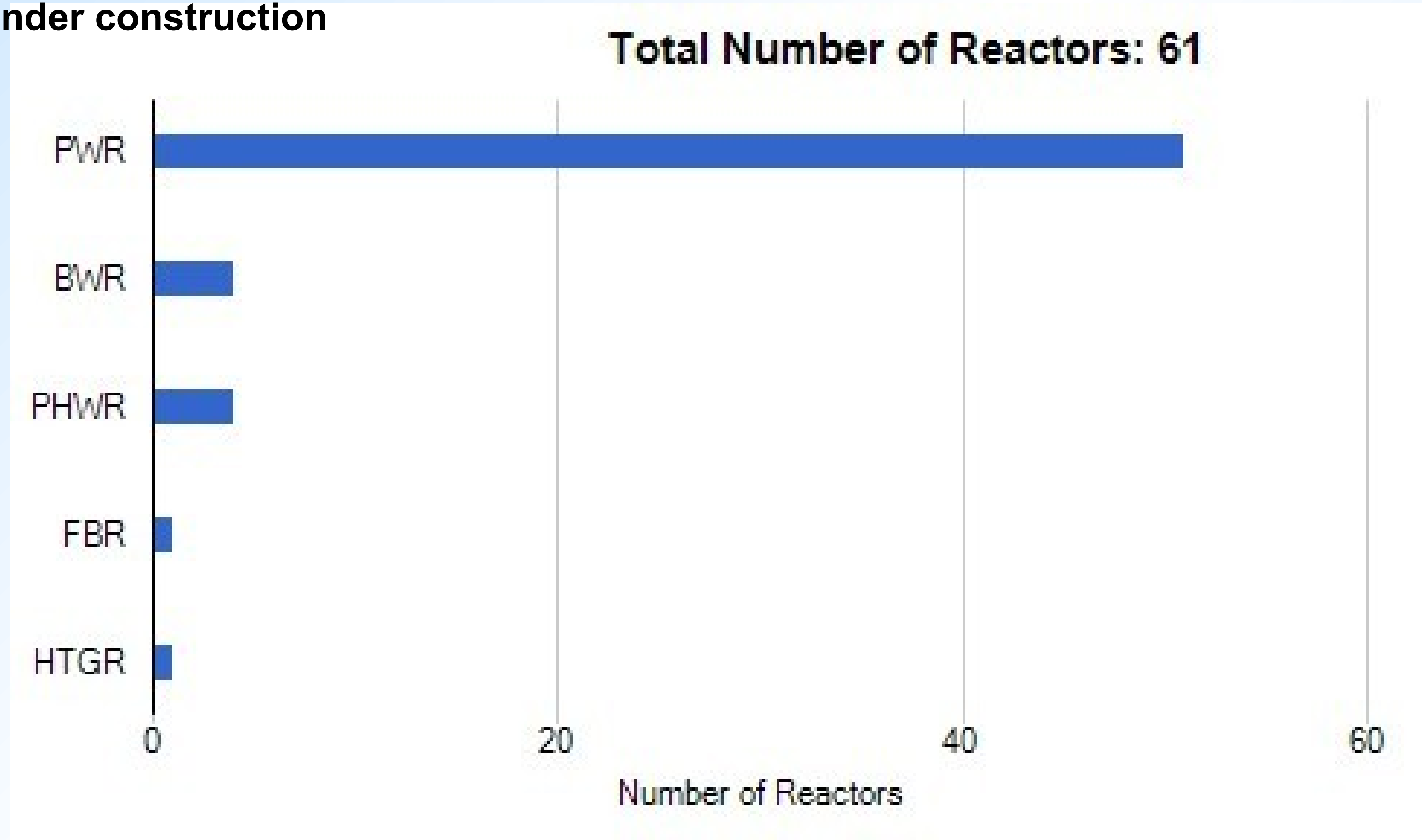
Reactor units under construction



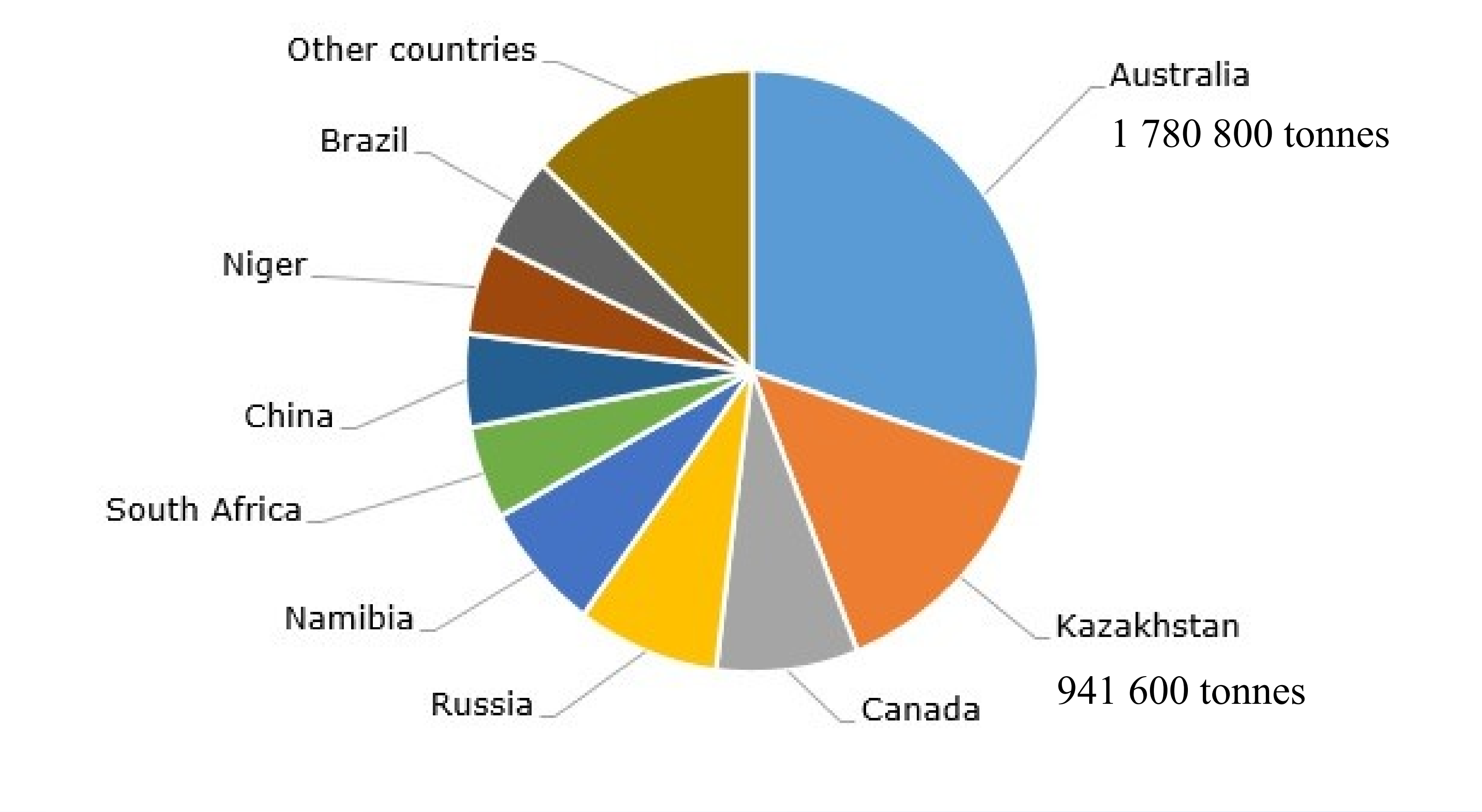
Reactor units under construction

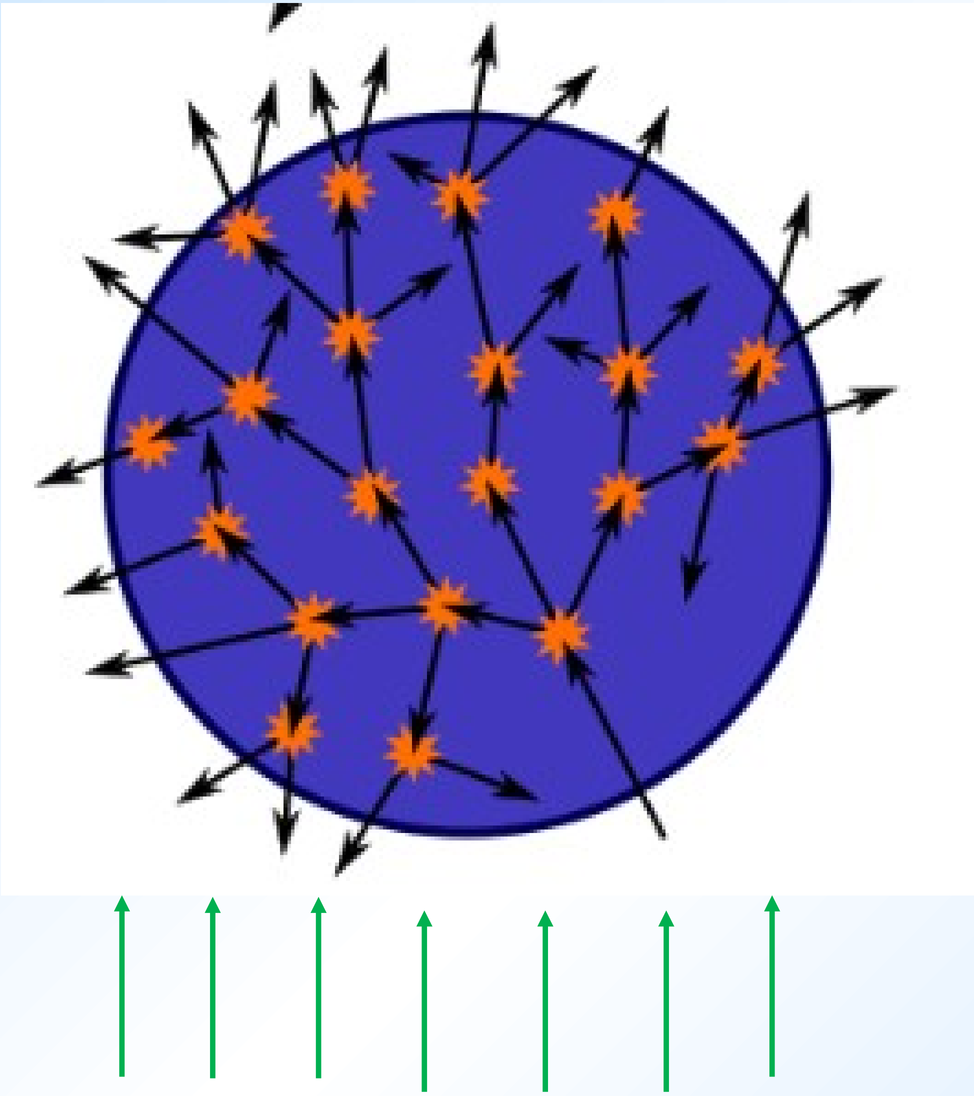


Reactor units under construction



Uranium Reserves





U-235 (with U-238)

Neutrons

Moderator material (neutron slower)

Control material (neutron absorber)

Fission producs

Coolant

Neutron Cross Section

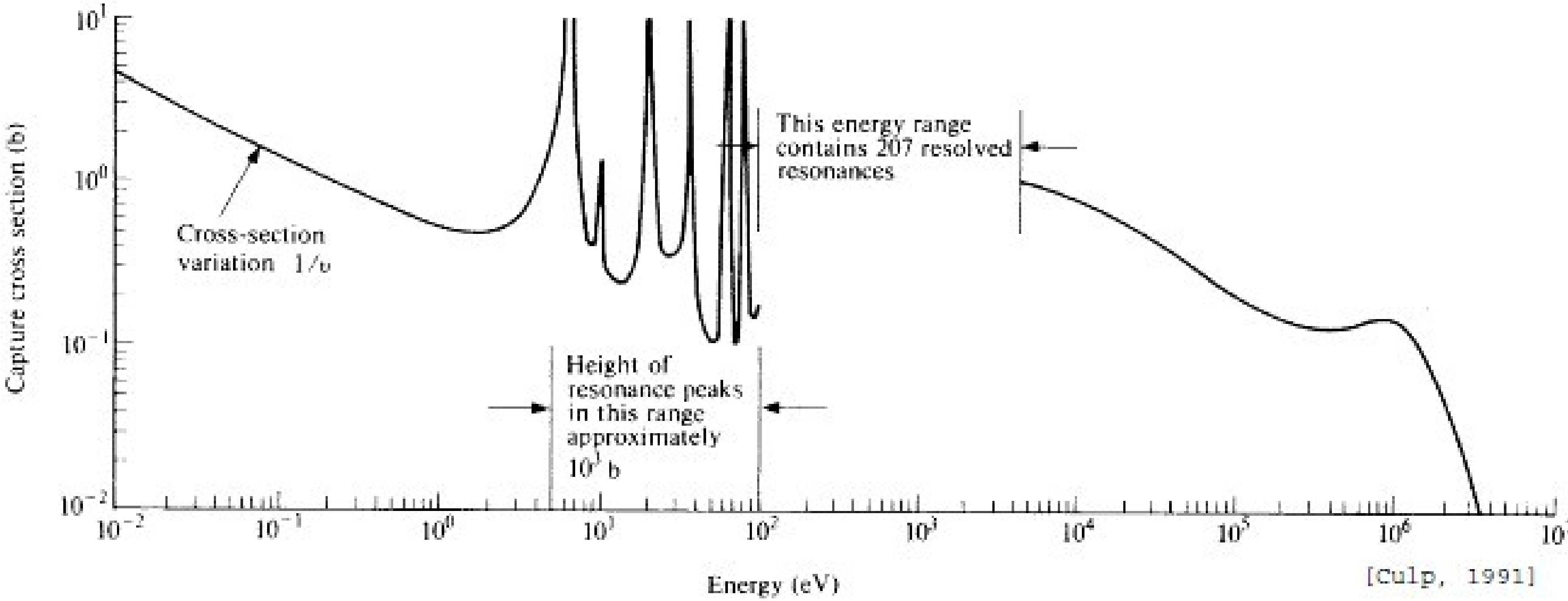
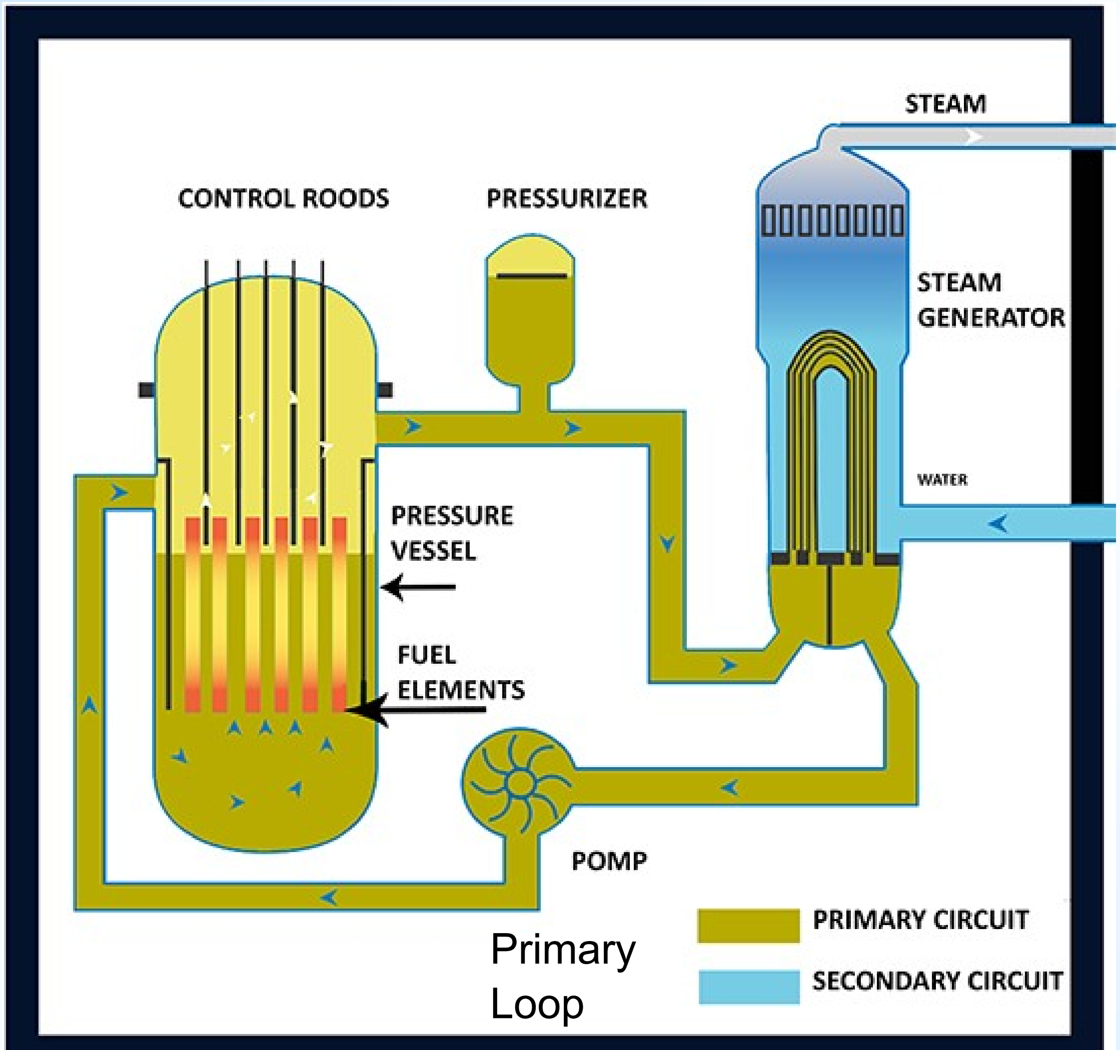


FIGURE 3.2
The microscopic neutron-absorption cross section for U-238. (*From Steam: Its Generation and Use, 1972.*)

Pressured Water Reactor - PWR



Fuel: Pellets of enriched UO_2 2-3 % U-235, stacked end-to end in a tube (rod) to a length of 3.6 m and clad

Cladding: Zircaloy

Fuel assembly; square array of fuel rods – up to 17x17

Coolant: Light water

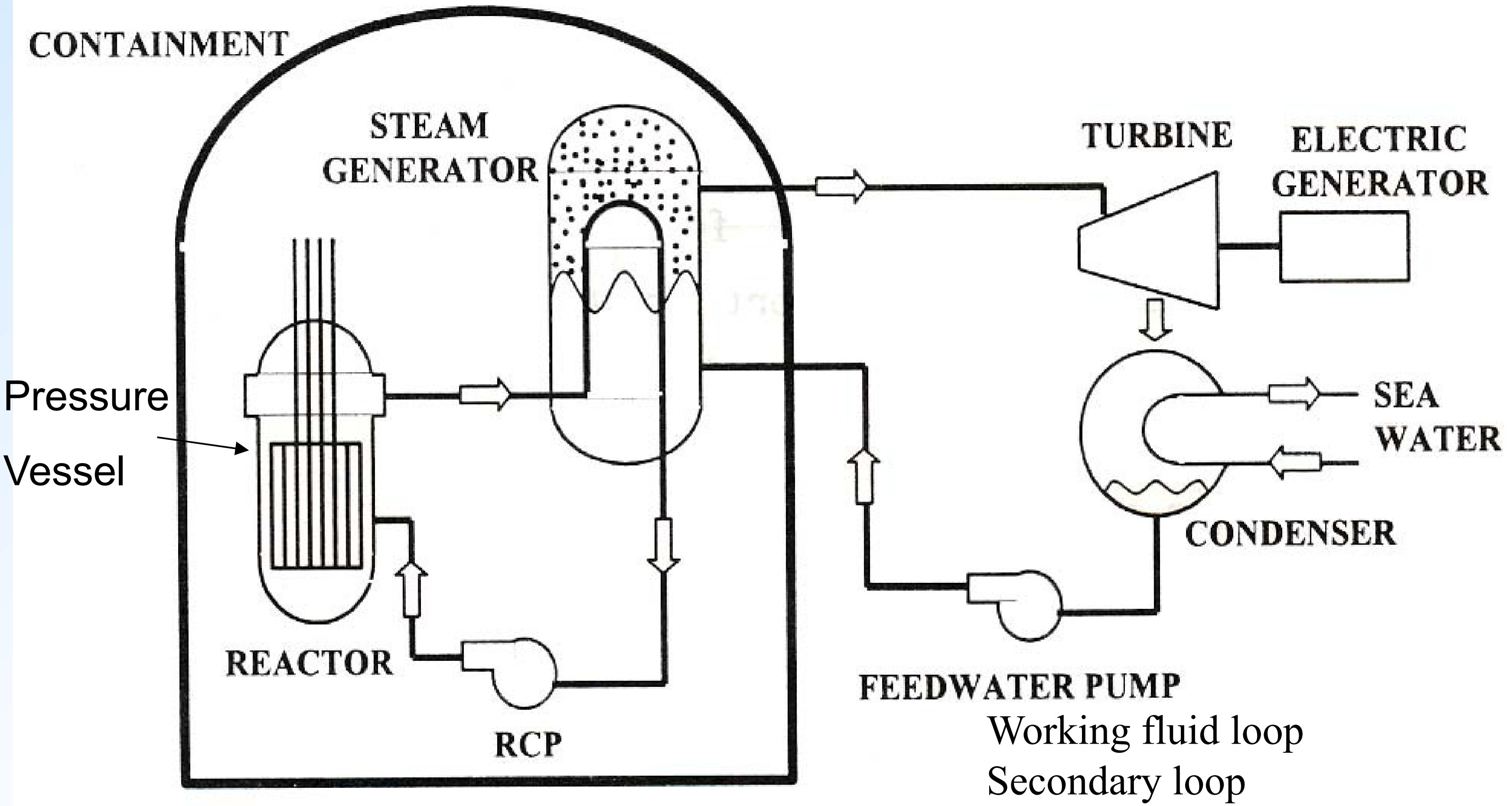
Moderator: Coolant

Control: Boric acid in the first loop and control rods

Control rods: Silver-Indium-Cadmium alloy

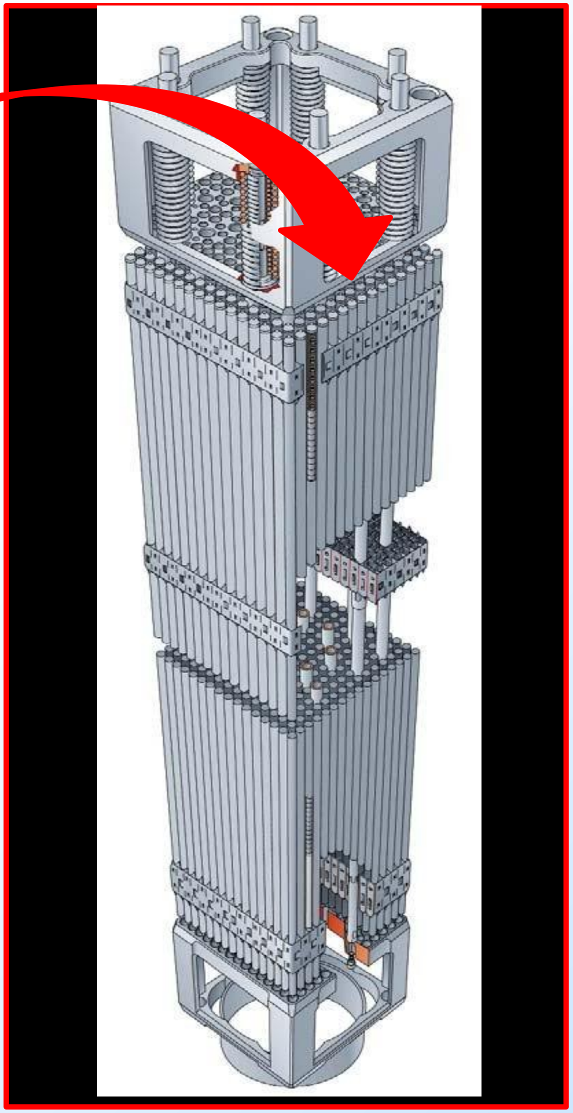
2-4 parallel independent steam generation loops

One of the loops has the pressurizer



Pellet

Fuel Assembly



Fuel Rod

Square array of rods; up to 17x17 (289) rods; Each rod is in a zircaloy cladding

ONE uranium fuel pellet weighs ~7 grams and generates as much energy as…

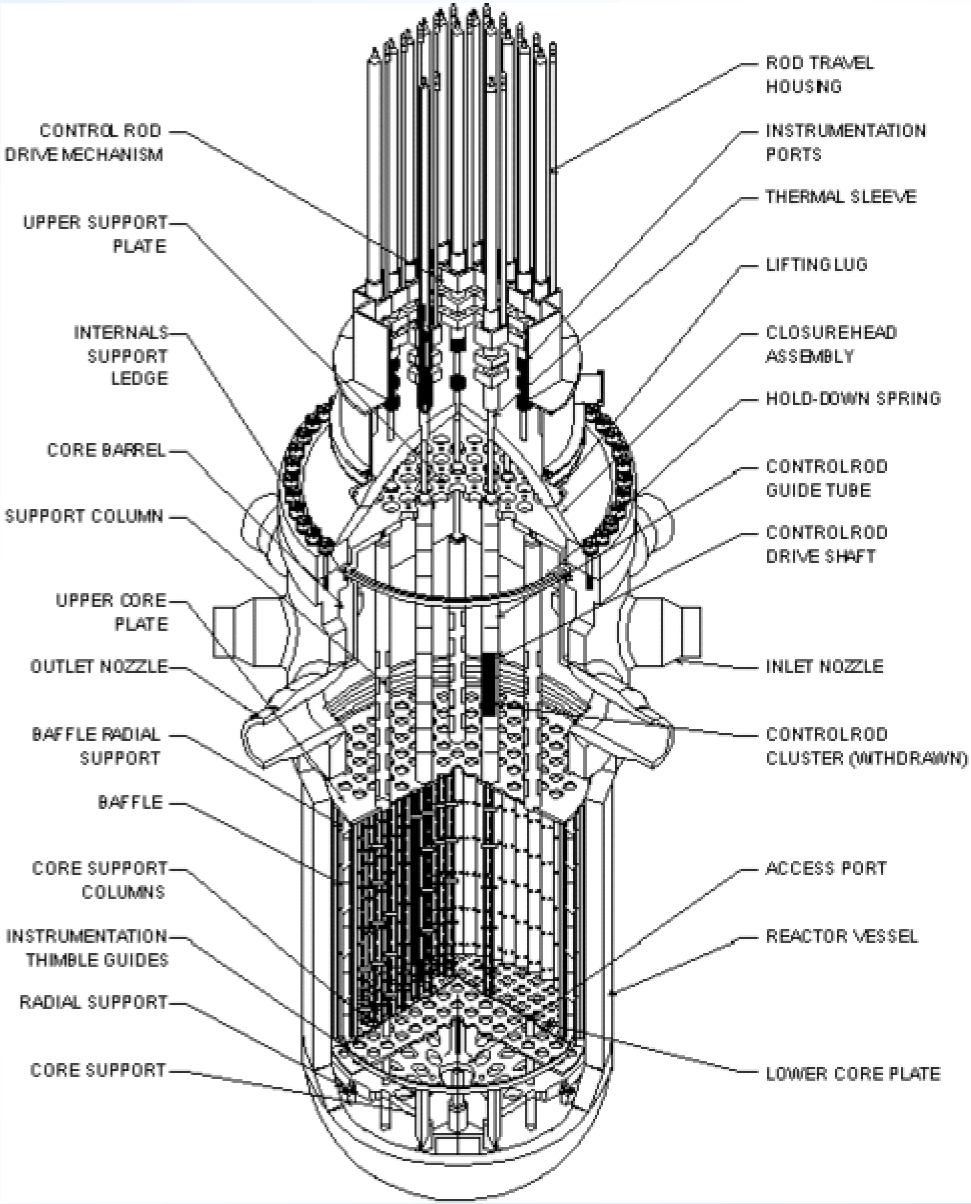
One Ton of Coal

149 Gallons of Oil

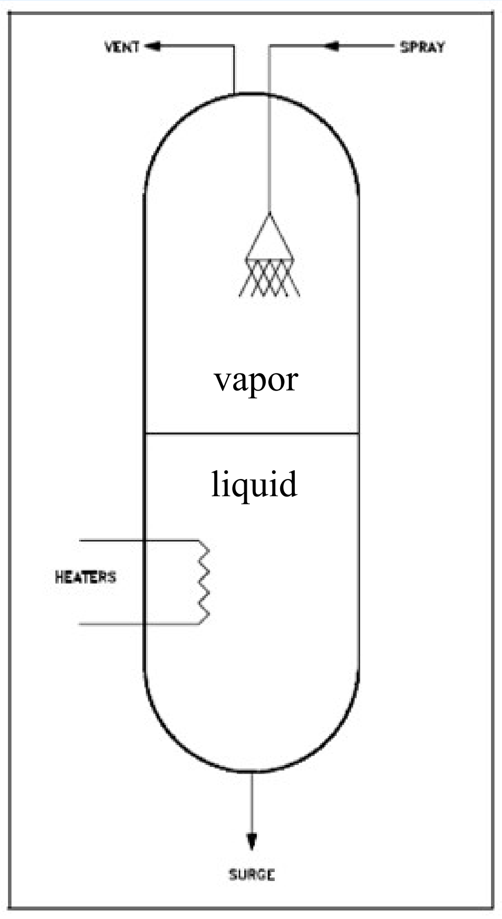
17,000 Cubic Feet of Natural Gas

PWR Reactor

Vessel steel, 15 cm thick, 15 m high, 3 m diameter



Pressurizer



Maintains coolant pressure to suppress boiling

Because liquids are nearly incompressible, small volume changes from change in coolant temperature, unforeseen expansions/contractions in loop components

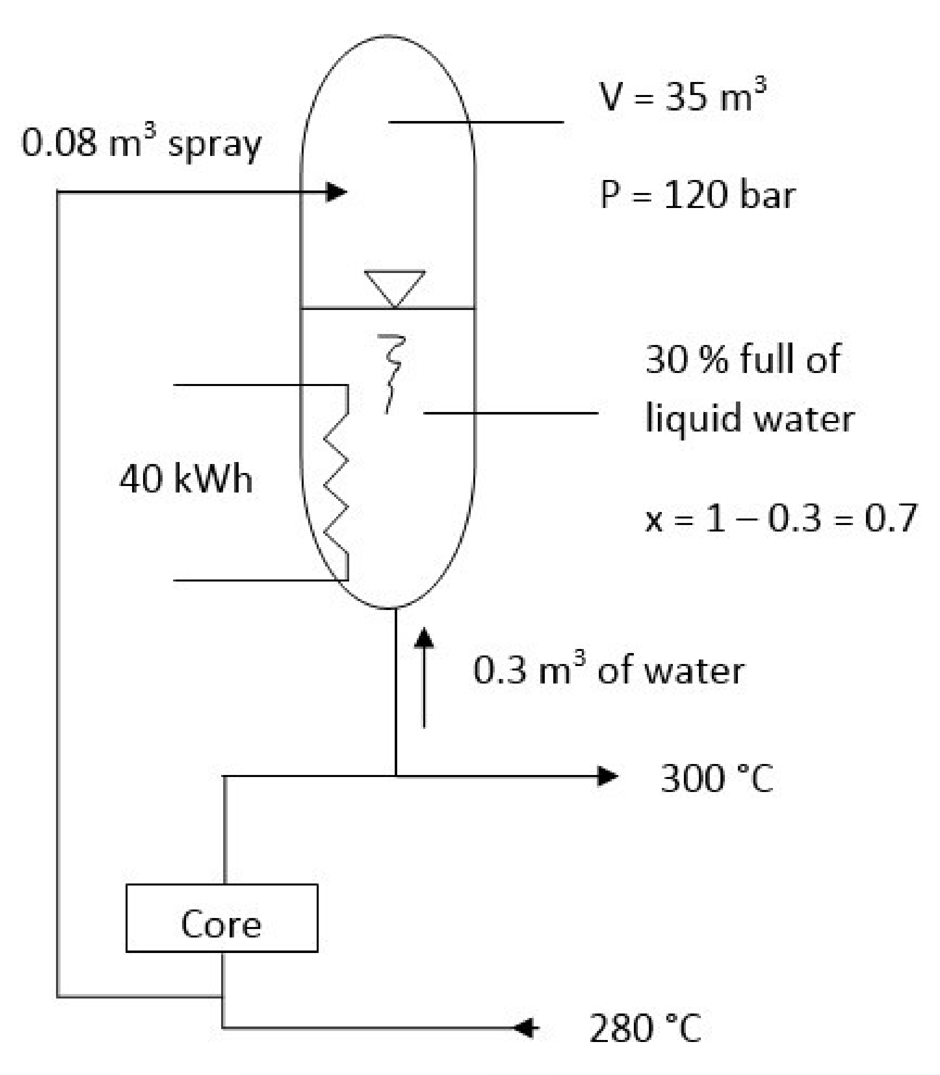
- Can cause severe or oscillatory pressure changes
- Can result in flashing & possible core burnout, pump cavitation, etc.

2 Types : Vapor pressurizers (LWR) and gas pressurizers (LMFBR)

+ surge: vapor is compressed and condenses; spray helps condensation

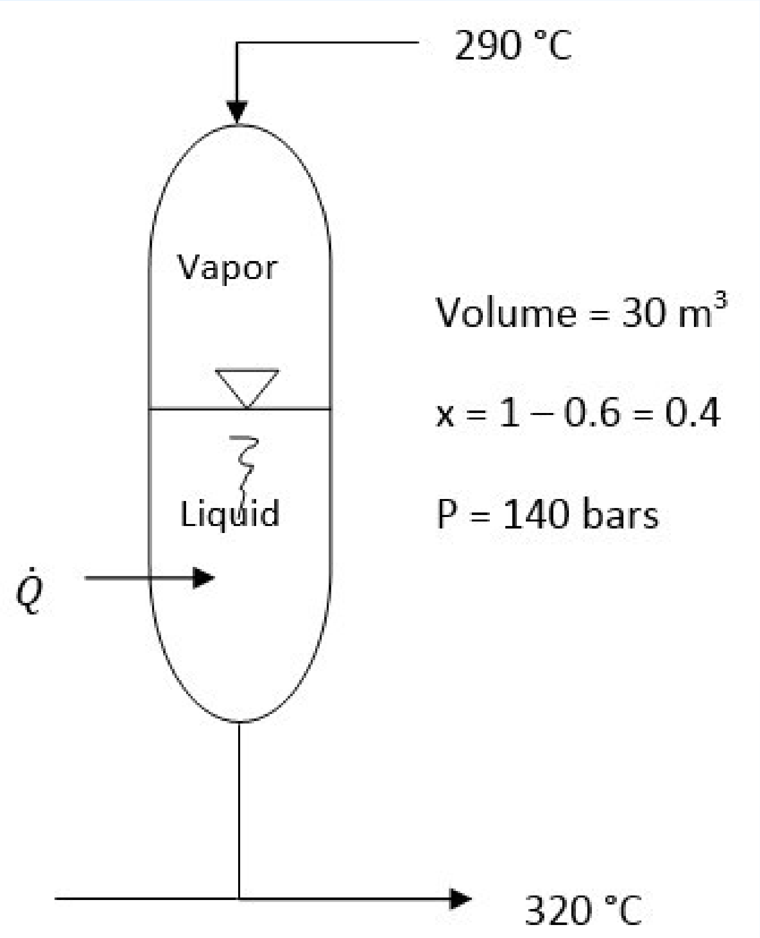
- surge: vapor expands and evaporates; electric heaters help

Example 7



Find the internal energy before and after.

Example 8

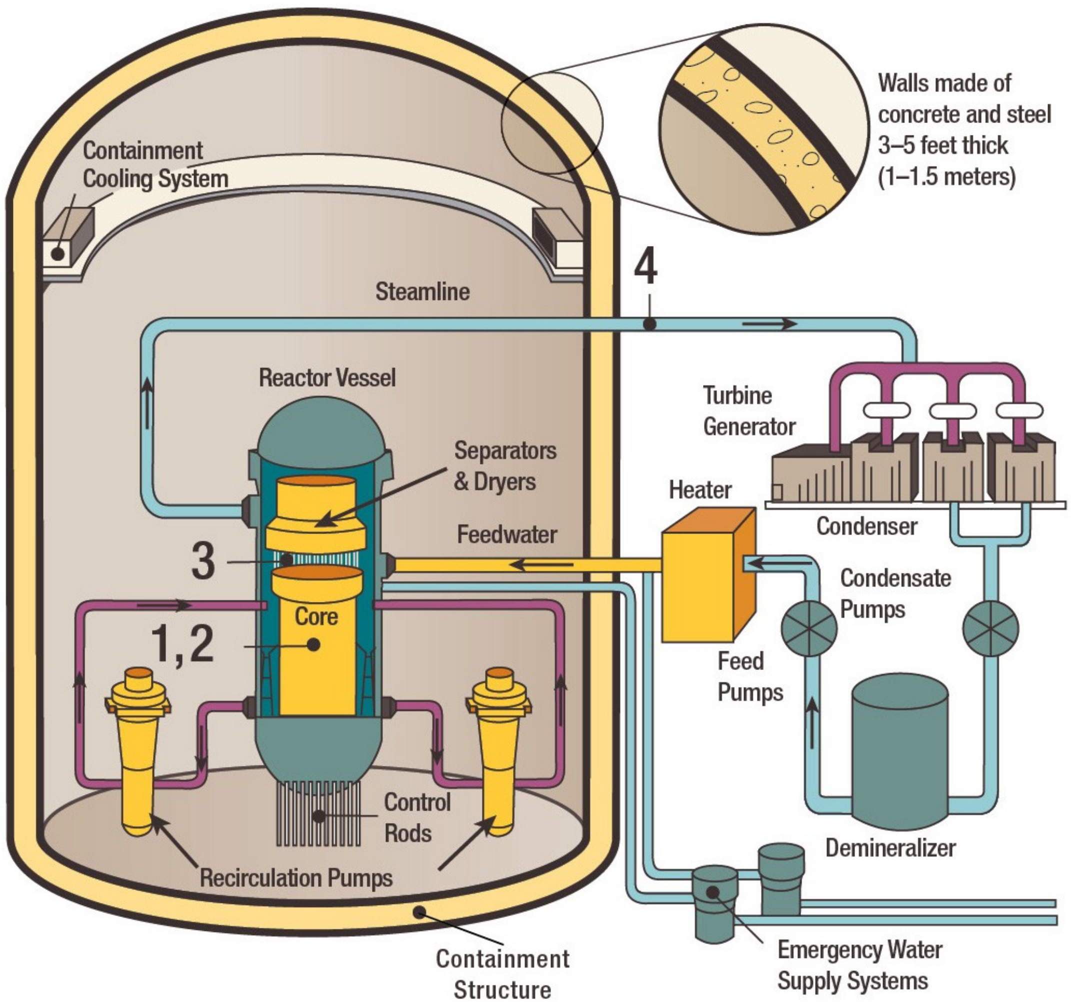


A PWR has inlet and exit water at 290 °C and 320 °C, respectively. It has a 30 m^3 vapor pressurizer which is normally 60 % full of water at a pressure of 140 bar.

A case of an insurge occurred during which 0.25 m^3 of water entered the pressurizer from the primary circuit hot leg, 0.05 m^3 entered through spray, and 50 kWh was added by the electric heaters. Determine the internal energy of the pressurizer contents before and after the event, in kJ. Ignore heat losses to the ambient.

Properties of water (from thermodynamic tables)						
	v_f, m^3/kg	v_g, m^3/kg	u_f, kJ/kg	u_g, kJ/kg	h_f, kJ/kg	h_g, kJ/kg
At 140 bar	0.001611	0.011485	1548.60	2476.8	1571.10	2637.6
At 320 °C	0.001472	0.015488	1444.60	2525.5	1461.50	2700.1
At 290 °C	0.001366	0.02557	1278.92	2576.0	1289.07	2766.2

Typical Boiling-Water Reactor - BWR



Fuel: Pellets of enriched UO_2

Cladding: Zircaloy

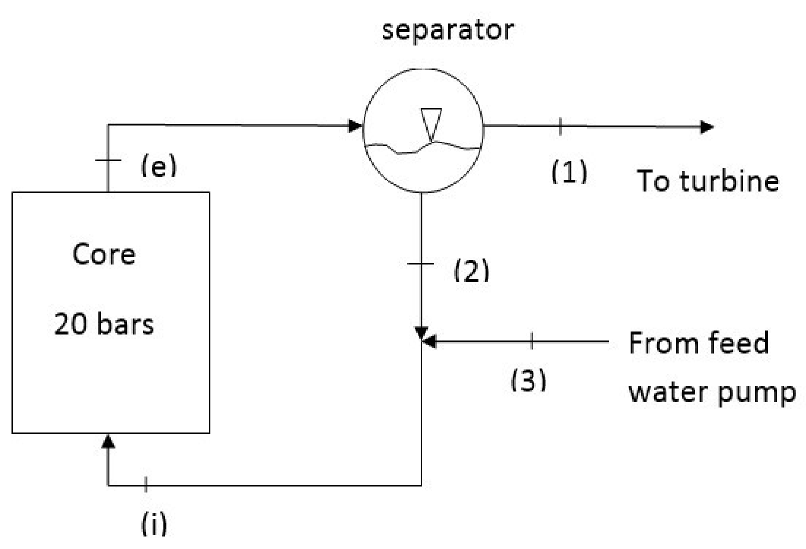
Moderator: Coolant

Coolant: Light water

Control: Boric acid in the first loop and control rods

Control rods: Silver-Indium-Cadmium alloy

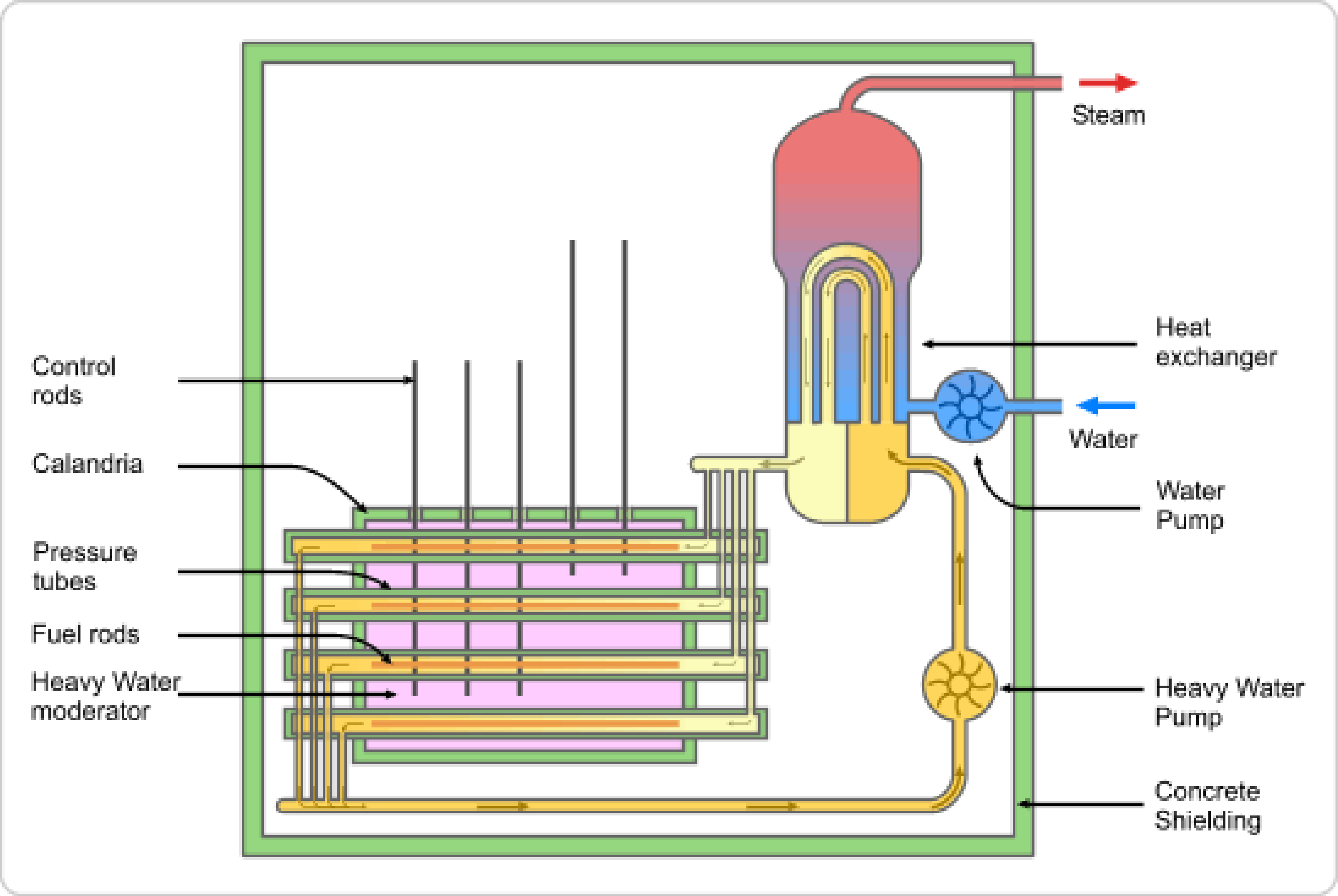
Example 9

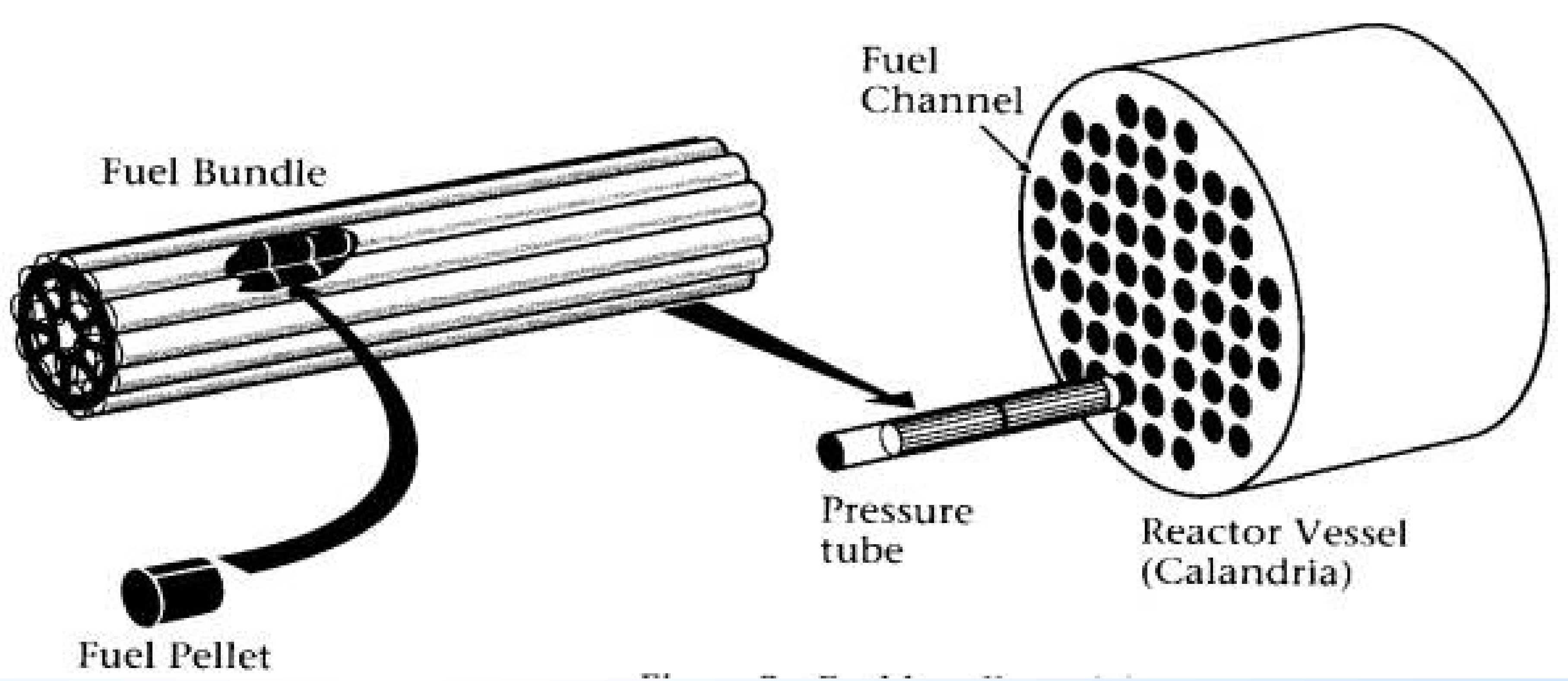


A 1000 MW BWR power plant with 33 % efficiency was operating at 75 % of rated load with a mass flow rate of 1150 kg/s, a reactor core pressure of 70 bar, and an average exit quality of 13.6 %. The plant uses recirculation control. Find

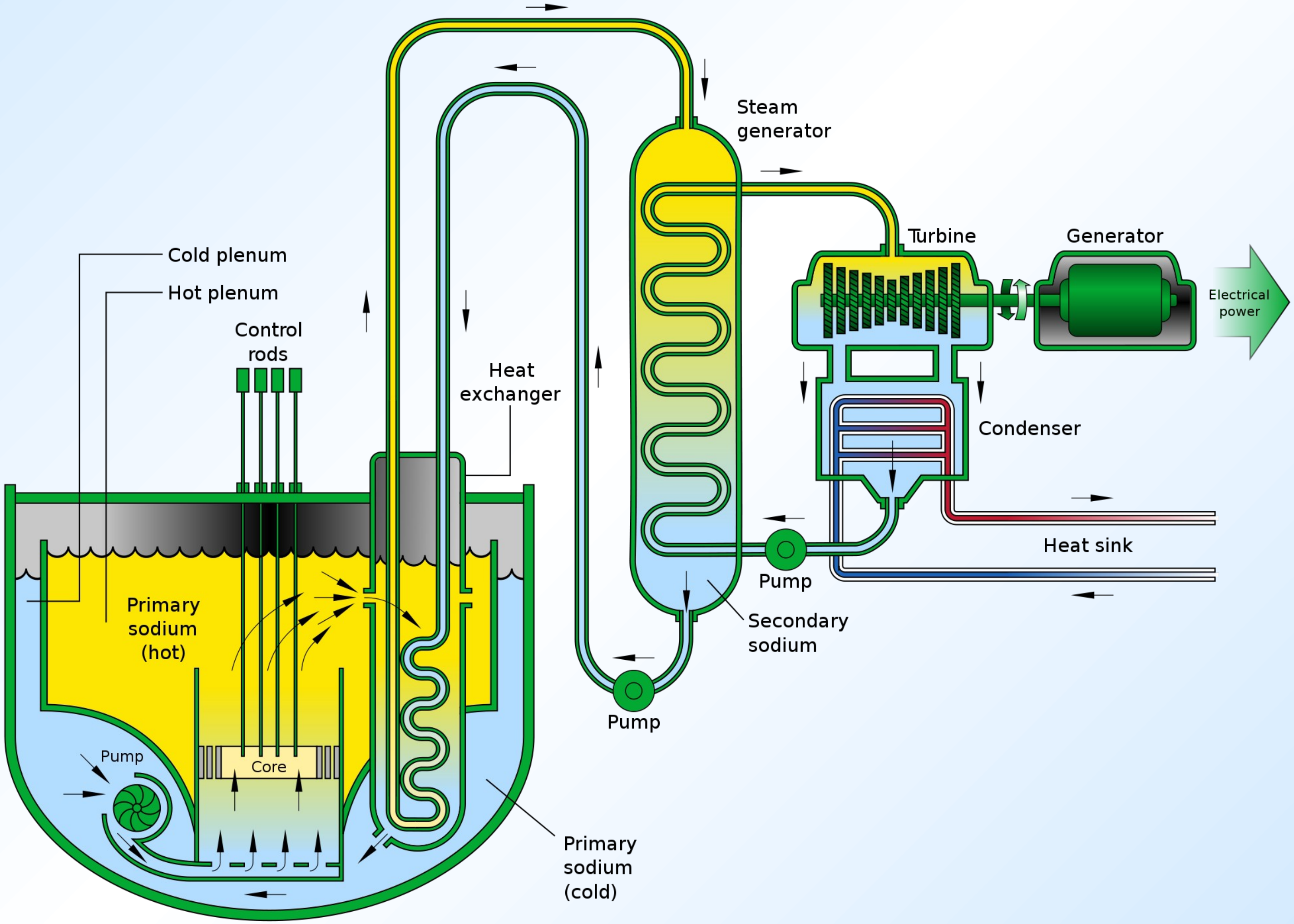
- The feed water temperature in °C
- The core degree of subcooling in °C
- The downcomer flow at 75 % load
- The average exit quality immediately after initiation of a load change to 80 %, and when the load has changed to 80 %
- The steam and downcomer flows, in kg/s, after load change

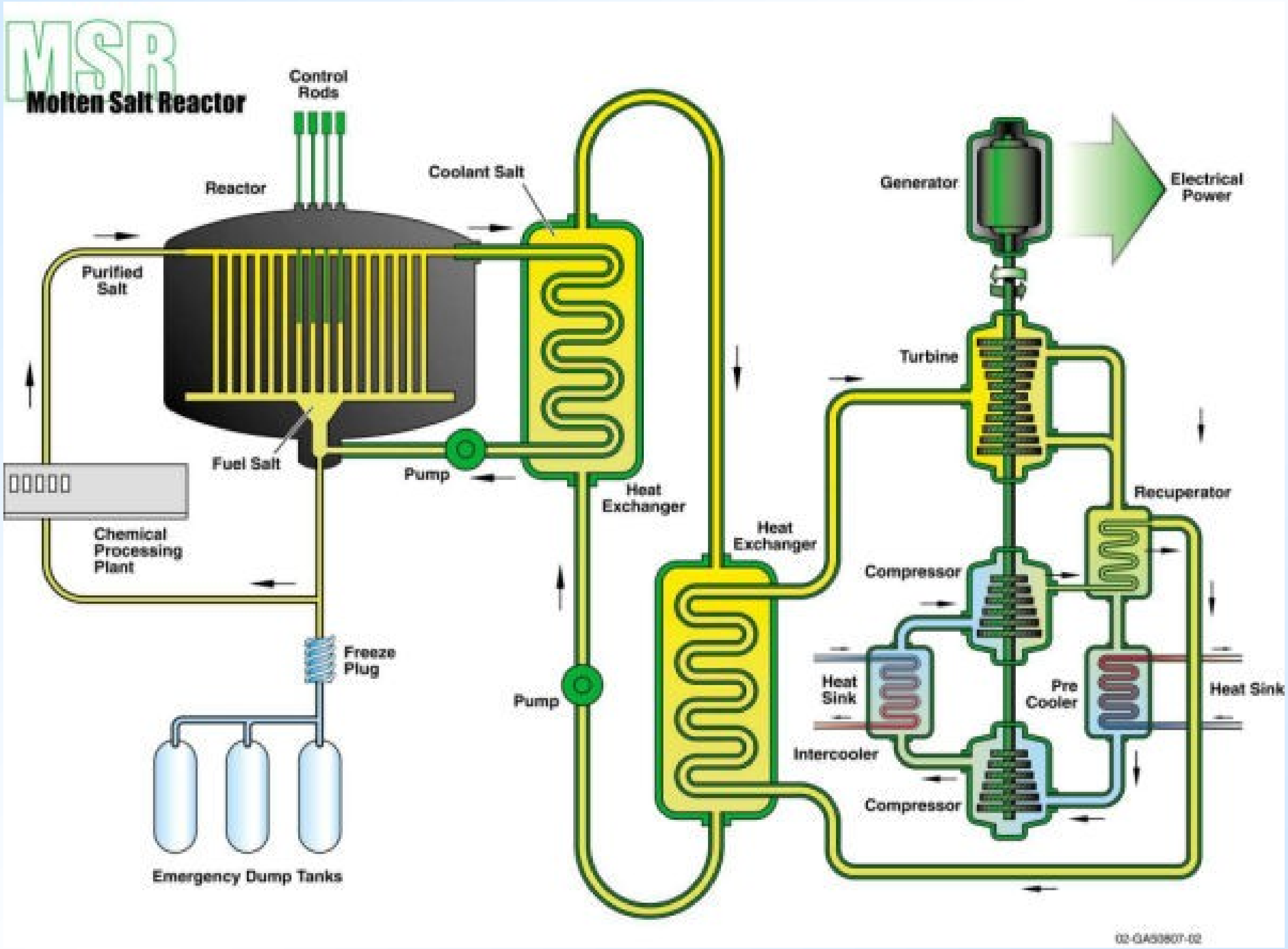
CANDU Reactor




Fuel Channel
Fuel Bundle
Pressure tube
Reactor Vessel (Calandria)
Fuel Pellet

Sodium-cooled Fast Reactor



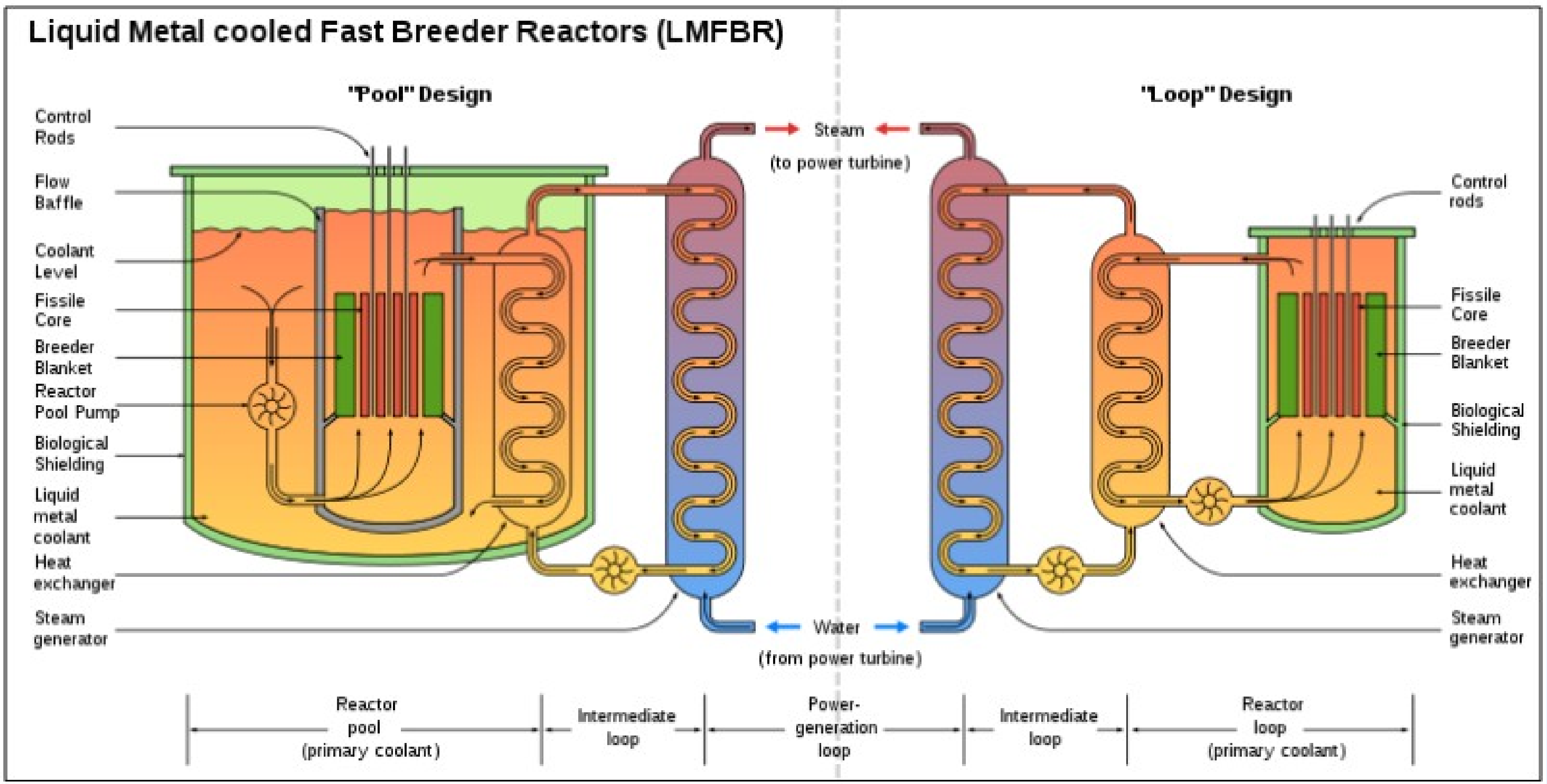


See: http://en.wikipedia.org/wiki/Molten_salt_reactor

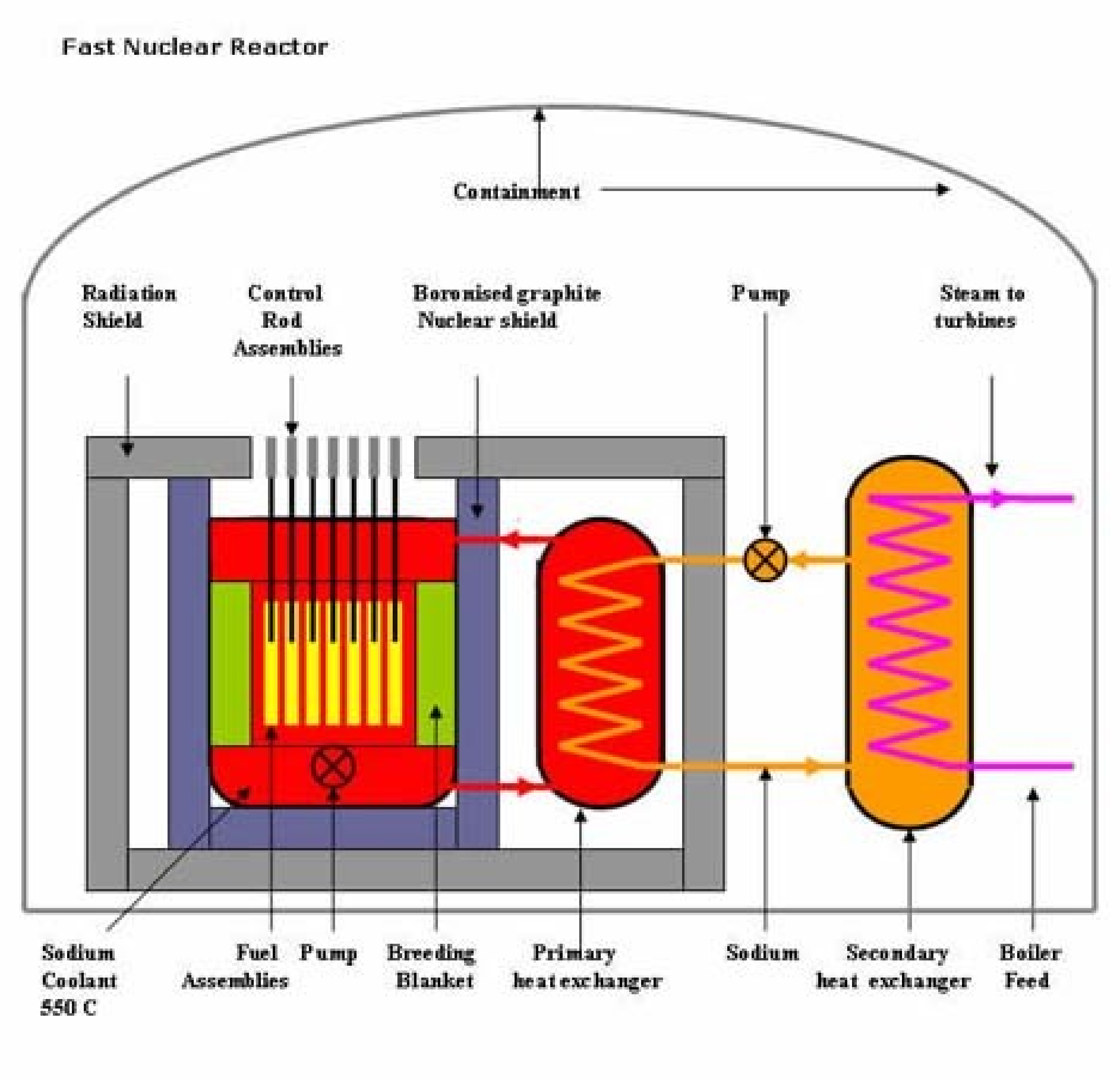
Characteristics of One-Fluid, Two-Region
Molten-Salt Breeder Reactors

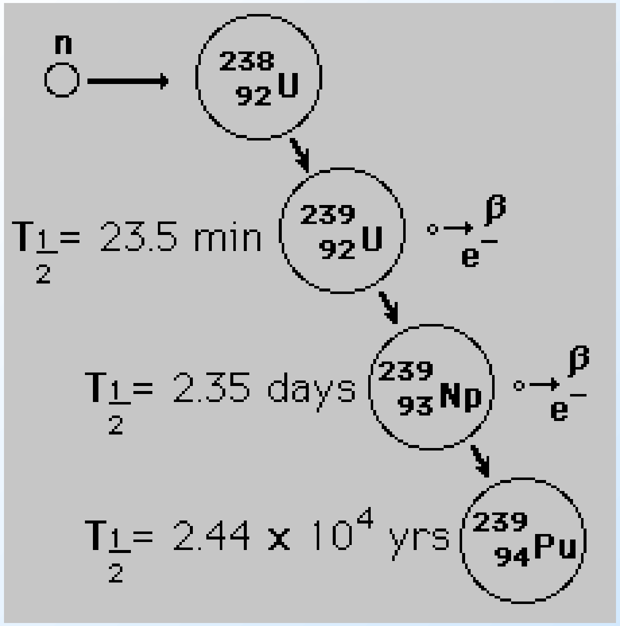
Fuel-fertile salt, mole %	72 ^7LiF, 16 BeF_2, 12 ThF_4, 0.3UF_4 Melting point, 770 K
Moderator	Graphite (bare)
Salt volume fractions, %	Core, 13, blanket, 40
Core temperatures, K	Inlet, 840, outlet, 980
Reactor power, MWe	1000-2000
Steam system	240 bar, 810 K, 44% net cycle efficiency
Breeding ratio	1.05-1.07
Specific fissile fuel inventory[a], kg/MWe	1.0-1.5
Doubling time[a] (compound interest), year	15-25
Fuel cycle cost[a], mills/kWh (including graphite replacement)	0.6-0.7

[a]The lower values are associated with the higher reactor powers.

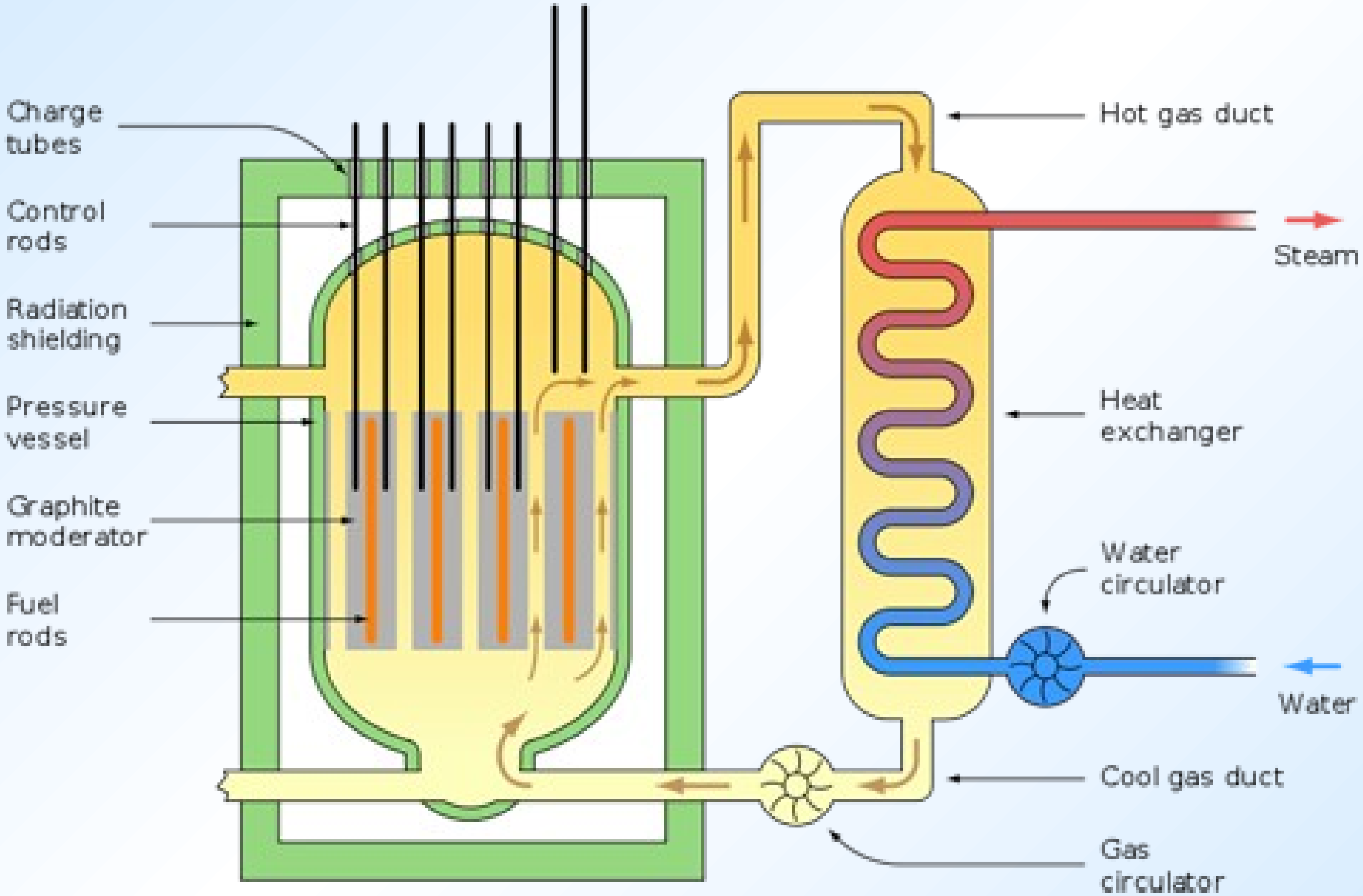


See: http://www.ati.ac.at/fileadmin/files/research_areas/ssnm/nmkt/11_LMFBR.pdf


Fast Nuclear Reactor
Containment
Radiation Shield
Control Rod Assemblies
Boronised graphite Nuclear shield
Pump
Steam to turbines
Sodium Coolant 550 C
Fuel Assemblies
Pump
Breeding Blanket
Primary heat exchanger
Sodium
Secondary heat exchanger
Boiler Feed


n
238
92 U
T1/2 = 23.5 min
239
92 U
β
e−
T1/2 = 2.35 days
239
93 Np
β
e−
T1/2 = 2.44 x 10^4 yrs
239
94 Pu

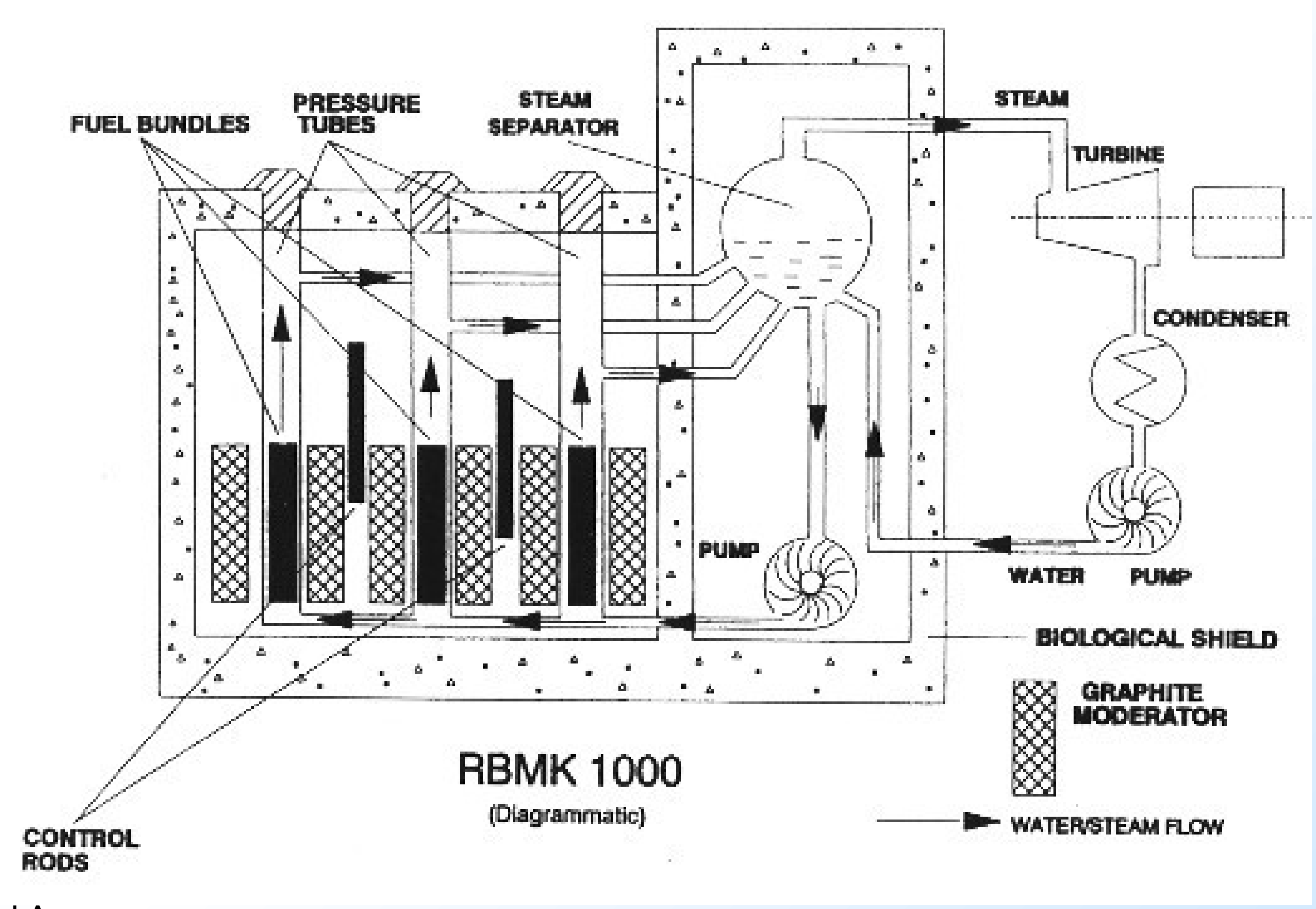
Gas-cooled Reactor



See: http://en.wikipedia.org/wiki/Gas-cooled_reactor

Boiling-Water Graphite-Moderated Reactor

[Reactor Bolshoy Moshchnosty Kanalny] (RMBK)



The reactor design at Chernobyl is a 1000-MWe Boiling-Water Graphite-Moderated Reactor [Reactor Bolshoy Moshchnosty Kanalny (RMBK)]. RMBK reactors are designed to produce Pu-239 for nuclear weapons as well as produce electrical power; unlike any reactors in most other places.

The reactor uses water as a coolant and a working fluid; directly boiling water in tubes passing through the core. The moderator is graphite and heat is transferred from the graphite into the water via conduction. This combination of graphite moderation and water coolant is not found in any other reactor design. The RMBK reactor is very unstable at low power.

See: http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/PowerReactors /Appendices/ RBMK-Reactors/

In order to maximize production of Pu-239 from U-238 and to minimize production of Pu-240 which is not suitable for nuclear warheads, the fuel rods must be removed every 30 days without shutting down the reactor. This requires a large open space above the reactor. The RMBK reactor design does not include a reinforced concrete or steel containment vessel.

See: http://www.world-nuclear.org/info/Safety-and-Security/Safety-of-Plants/Chernobyl-Accident/

See: «Advanced Nuclear Reactors - Technology Overview and Current Issues», Congressional Research Service Report, updated February 17, 2023

Problems of Nuclear Reactors

Concerns about the safety of nuclear fission reactors include the possibility of radiation-releasing nuclear accidents, the problems of radioactive waste disposal, and the possibility of contributing to nuclear weapon proliferation.

Although most technical analyses have rated nuclear electricity generation as comparable in safety to coal-powered generation, the low public confidence in nuclear power has blocked further development of nuclear power in the United States. No new nuclear power plants have been ordered since the Three Mile Island accident, and some partially completed projects have been abandoned.

Reactor Accidents

The nuclear accident at Chernobyl was the worst nuclear accident to date, spewing about 100 million Curies of radioactive material into the environment. By contrast, the accident at Three Mile Island released only some 15 Curies. Though its health effects were minimal, Three Mile Island did perhaps irreparable damage to the level of public confidence in nuclear reactors for electric power production in the United States.

Preceding these two high-profile accidents are a number of nuclear accidents with radiation release. These include accidents at the Fermi I reactor near Detroit, at the NRX reactor at Chalk River, Canada, at the Windscale reactor in England, and the SL-1 Reactor at Idaho Falls.

Radioactive Waste Disposal

The nuclear fission of uranium-235 produces large quantities of intermediate mass radioisotopes. The mass distribution of these radioisotopes peaks at about mass numbers 95 and 137 , and most of them are radioactive. The most dangerous for environmental release are probably Cesium and Strontium because of their intermediate half-lives and propensity for re-concentration in the food chain.

When spent fuel assemblies are removed from nuclear reactors, they are transported to "swimming pool" storage facilities to dissipate the heat of decay of short-lived isotopes as well as for isolation from the environment. The long term disposal of these wastes remains a major problem. It was assumed that these wastes would be encased in glass and placed in geologic disposal sites in underground salt domes. The site at Yucca Mountain was chosen as a first site, but both technical and political problems have thus far blocked its implementation.

Nuclear Weapons Proliferation

One concern about nuclear reactors is that the fuel could be diverted for the production of nuclear weapons. While the uranium fuel is enriched to only 3-5 % and could not easily be further separated to the >90 % U-235 needed to produce a bomb, the spent fuel elements contain Plutonium-239. The plutonium could be separated chemically and diverted to nuclear weapons production. Security concerns about the plutonium has thus far blocked any reprocessing of fuel from nuclear power plants.

A similar concern exists for fast breeder reactors, where the breeding process produces plutonium-239 for future generations of reactors.

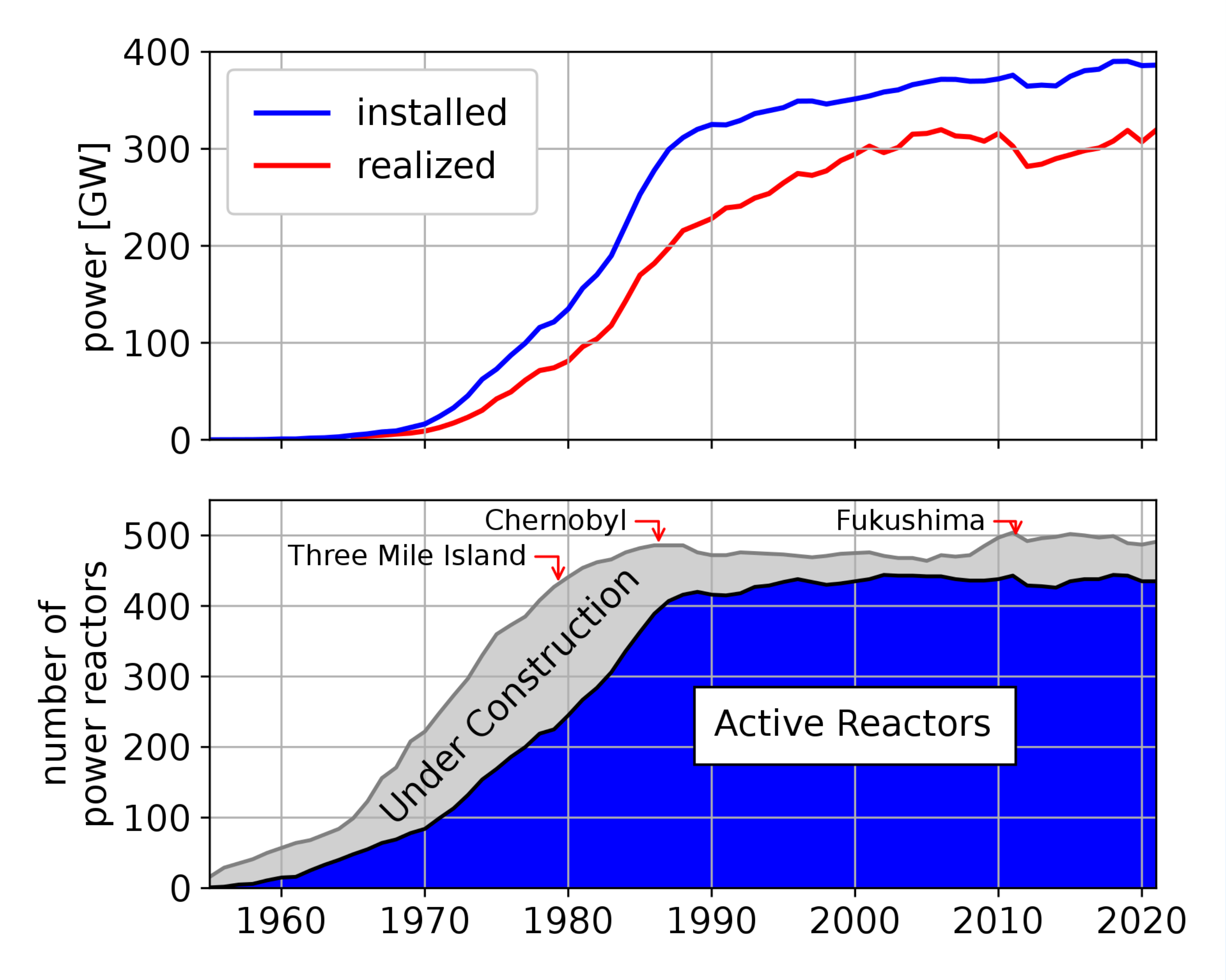
Three major accidents involving full-scale civilian nuclear power plants:

The first occurred in 1979 at Three Mile Island Unit 2 in Pennsylvania. Due mechanical failure, the main water pumps stopped running, leading to a partial meltdown of the fuel rods. Excessive heat caused a fracture in one of the reactors, allowing a small amount of radioactive steam into the atmosphere. Fortunately, no one was killed or even injured. This incident also lead to heightened regulation and safety precautions of nuclear reactors in the United States.

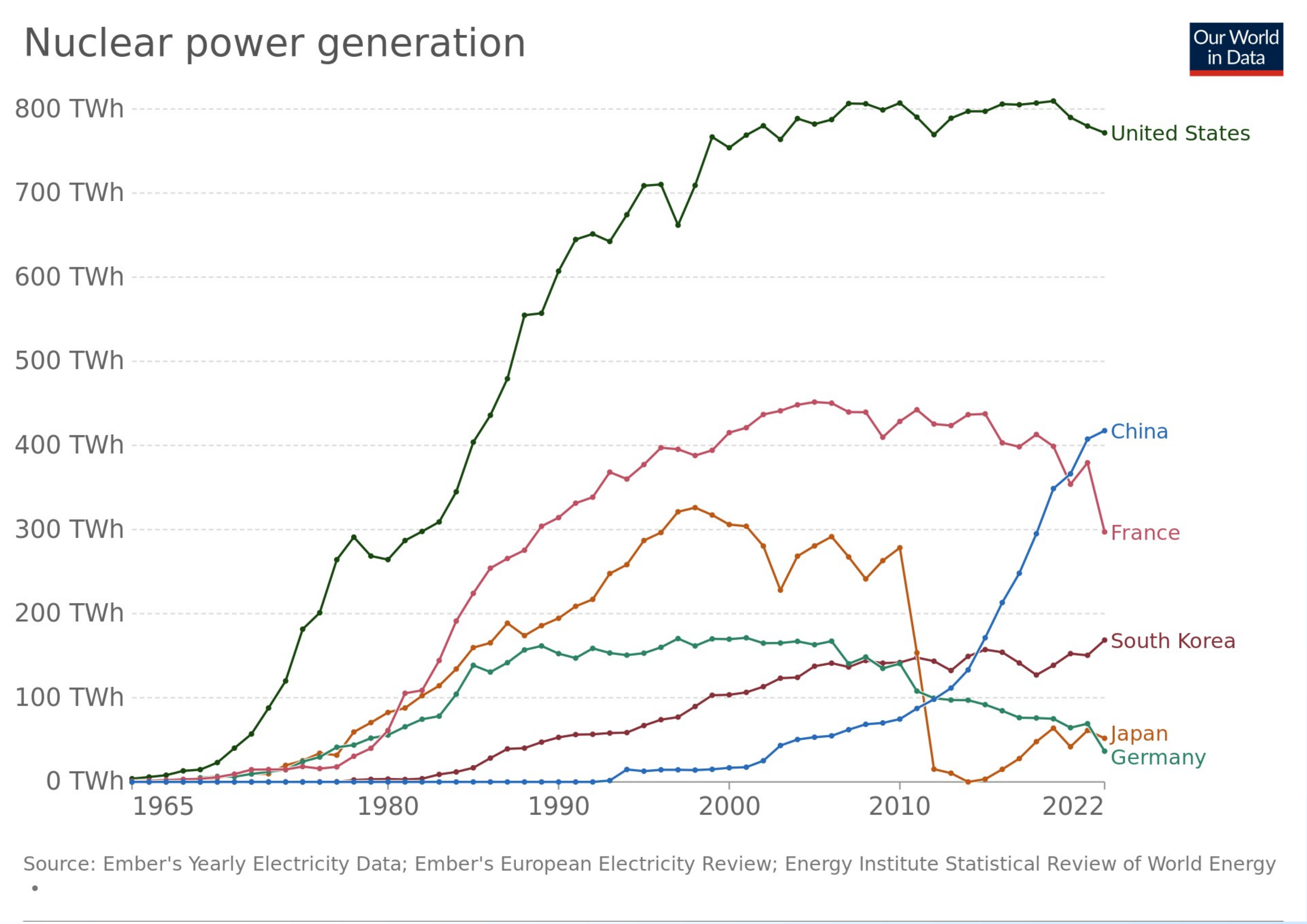
On April 26, 1986, the worst accident in nuclear history occurred in Chernobyl, Ukraine. During a routine test, an uncontrollable power surge burned the control rods, and massive amounts of radioactive smoke were released. 237 people suffered from acute radiation sickness, and 31 died within the first three months of the accident

Other effects of the radiation included an increase in down's syndrome, chromosomal aberrations, neural tube defects, and thyroid cancer. Perhaps the most important effect was psychological as the accident caused severe anxiety for the survivors and a general lack of trust in the government.

Due to a severe earthquake and tsunami in Japan in March 11, 2011, several BWR (Boiling Water Reactor) nuclear reactors at the Fukushima power plant lost electrical power for cooling, underwent explosions, and suffered reactor core damage from post-shutdown decay heat coming from highly radioactive fission products. Workers eventually pumped seawater into the reactors to cool them down and limit any further damage.



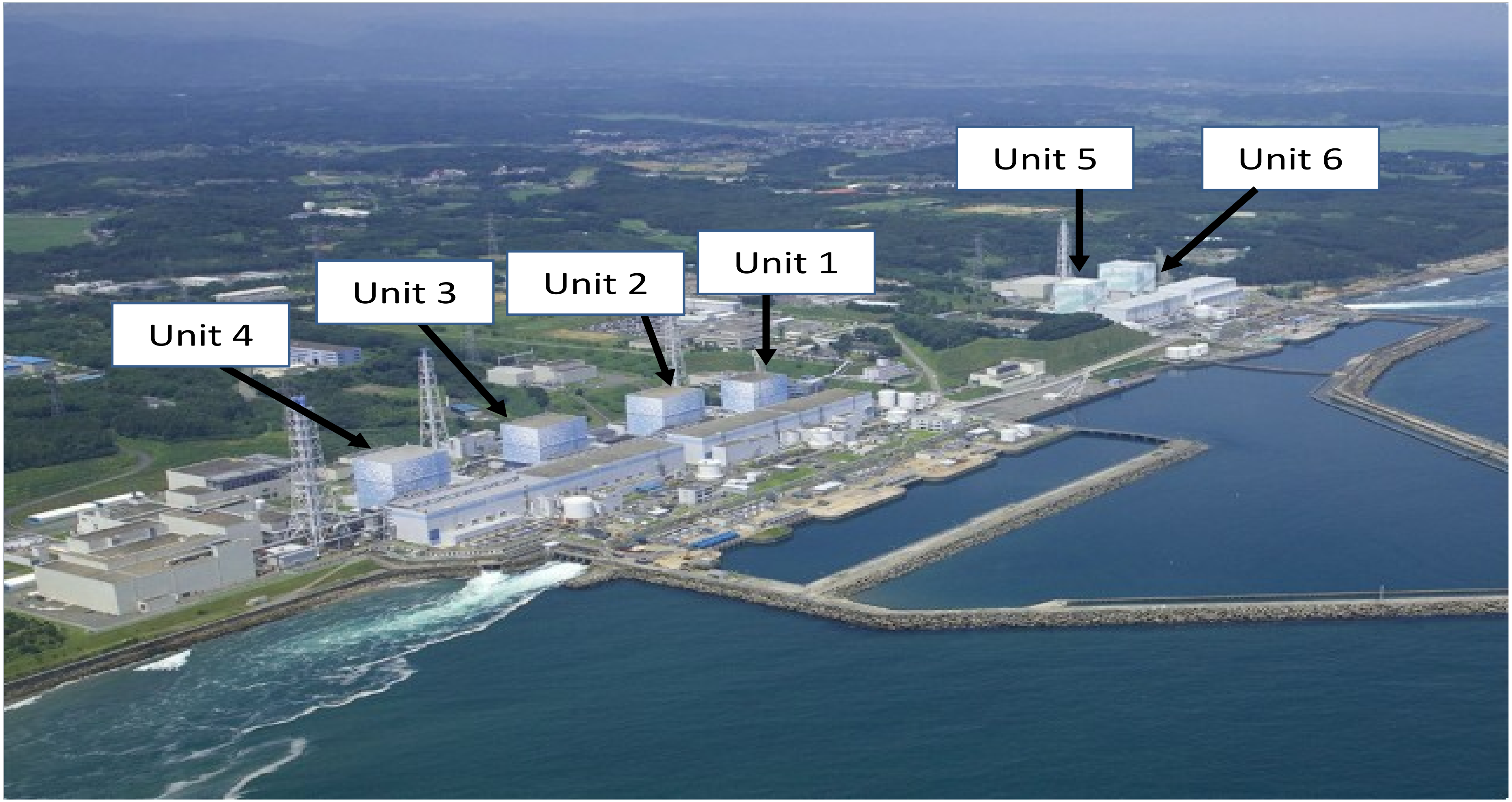
400
300
200
100
0
power [GW]
installed
realized
500
400
300
200
100
0
number of
power reactors
Chernobyl
Three Mile Island
Fukushima
Under Construction
Active Reactors
1960
1970
1980
1990
2000
2010
2020


Nuclear power generation
Our World in Data
800 TWh
700 TWh
600 TWh
500 TWh
400 TWh
300 TWh
200 TWh
100 TWh
0 TWh
1965
1980
1990
2000
2010
2022
United States
China
France
South Korea
Japan
Germany
Source: Ember's Yearly Electricity Data; Ember's European Electricity Review; Energy Institute Statistical Review of World Energy

Dry cask storage vessels storing spent nuclear fuel assemblies

The town of Pripyat abandoned since 1986, with the Chernobyl plant and the Chernobyl New Safe Confinement arch in the distance

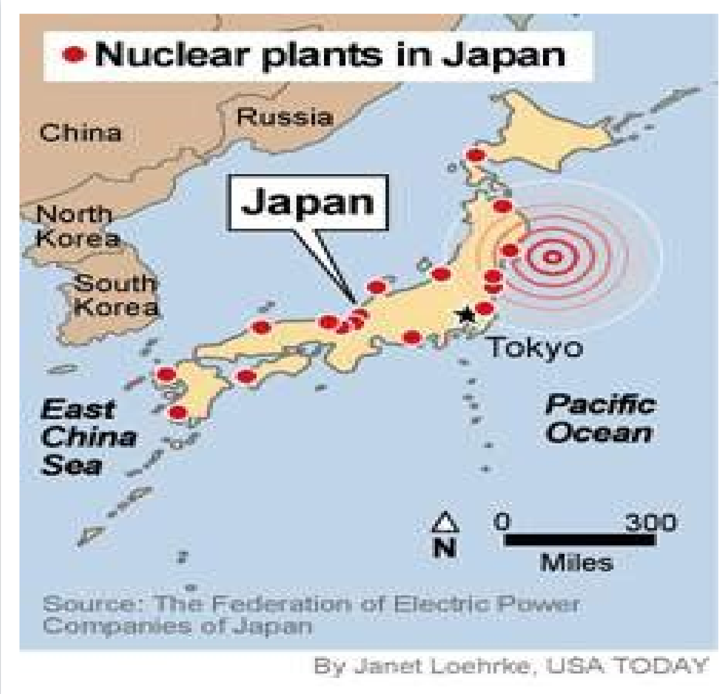
Fukushima



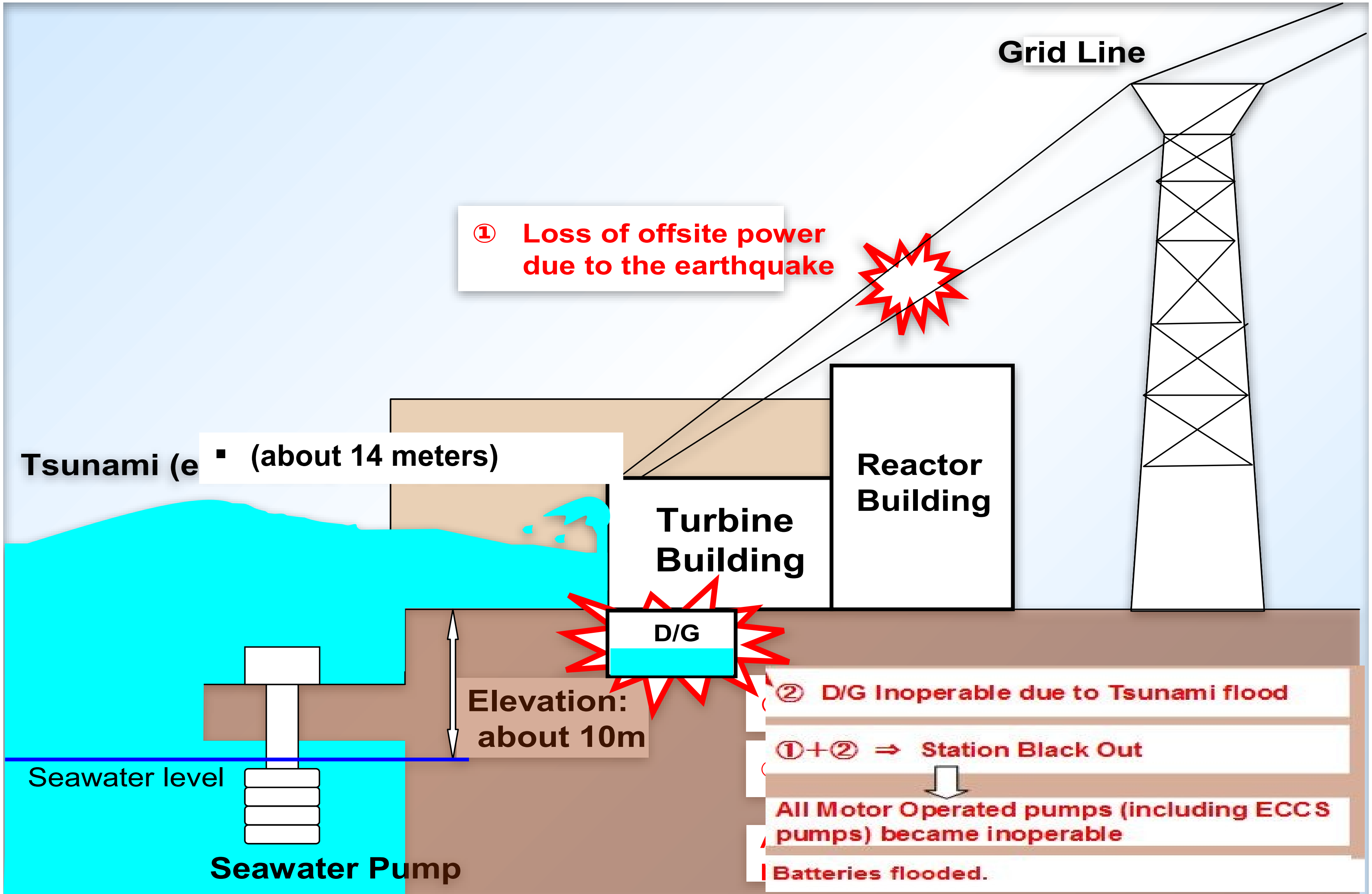
The Fukushima nuclear facilities were damaged in a magnitude 9.0 earthquake on March 11 (Japan time), centered offshore of the Sendai region, which contains the capital Tokyo.

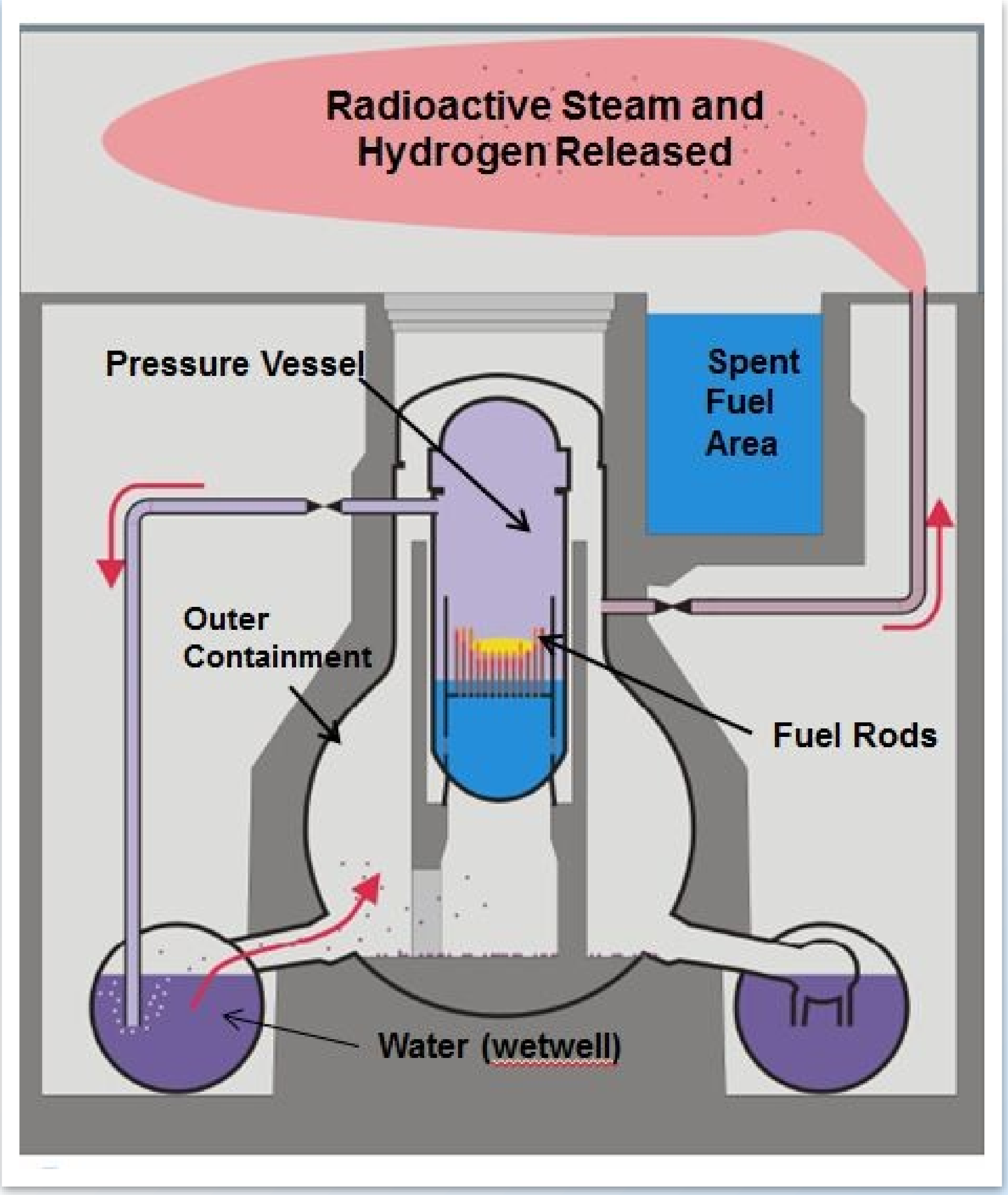
- Plant designed for magnitude 8.2 earthquake. An 9.0 magnitude quake is 8 times greater in magnitude.

Serious secondary effects followed including a significant tsunami, significant aftershocks and a major fire at a fossil fuel installation.



Fukushima


Grid Line
① Loss of offsite power
due to the earthquake
Tsunami (e
▪ (about 14 meters)
Turbine Building
Reactor Building
D/G
Elevation:
about 10m
Seawater level
Seawater Pump
② D/G Inoperable due to Tsunami flood
①+② ⇒ Station Black Out
All Motor Operated pumps (including ECCS
pumps) became inoperable
Batteries flooded.


Radioactive Steam and
Hydrogen Released
Pressure Vessel
Spent
Fuel
Area
Outer
Containment
Fuel Rods
Water (wetwell)

See: http://www.world-nuclear.org/info/Safety-and-Security/Safety-of-Plants/Fukushima-Accident/

See: http://www.iflscience.com/technology/new-nuclear-reactor-could-hold-secret-lasting-fusion