BASIC FIGURES CONCERNING THE OPERATION OF A NUCLEAR REACTOR

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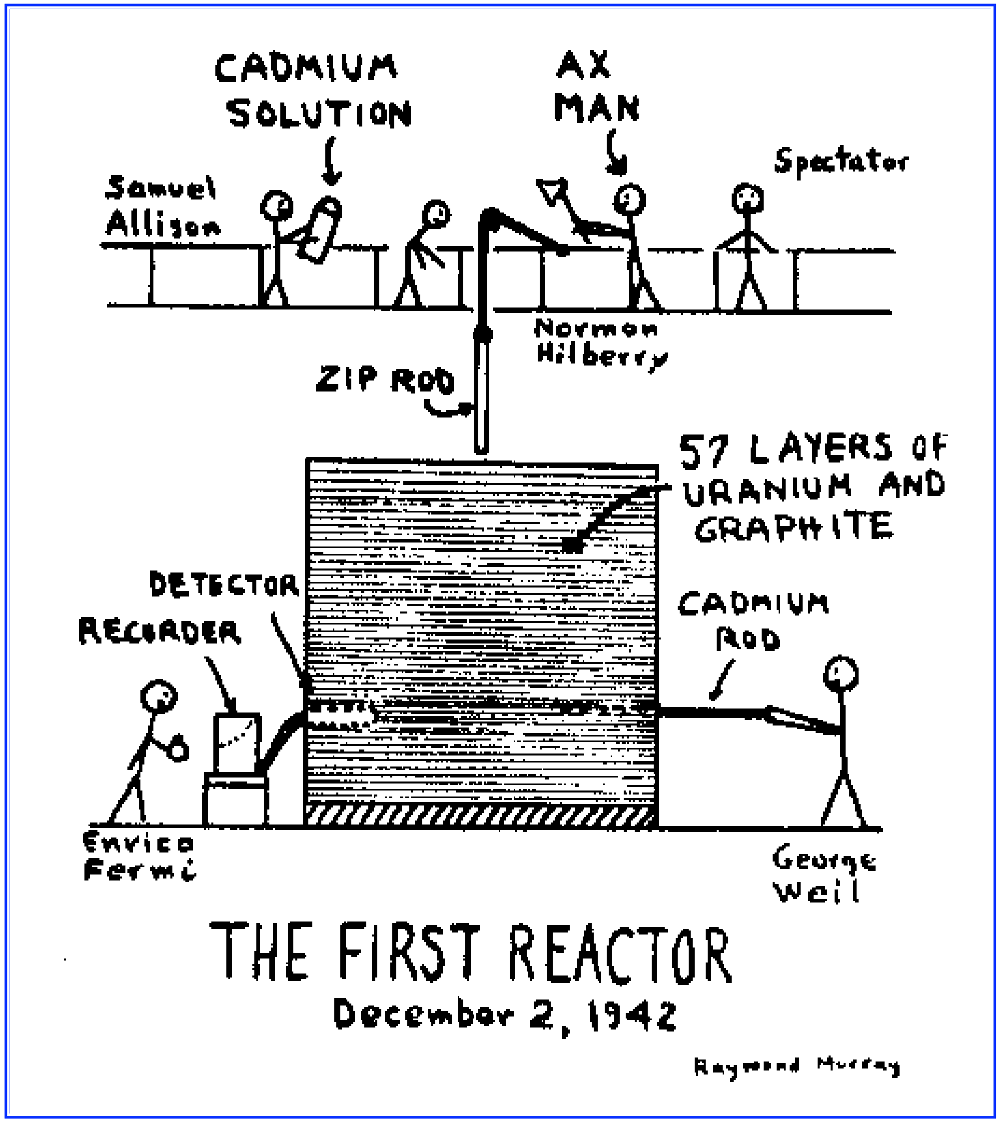


Enrico Fermi
1901-1954

Two types of nuclear fuels:

- **Fissile** ^{233}U ^{235}U ^{239}Pu ^{241}Pu
- **Fertile** ^{232}Th ($\rightarrow$ ^{233}U) ^{238}U ($\rightarrow$ ^{239}Pu)

Fraction of ^{235}U in natural Uranium

$$\delta_{nat} = 0.7\% \quad (= {}^{235}U/{}^{238}U)$$

Average energy of the emitted neutrons is 2 MeV (fast neutrons); slow neutrons are required for efficient use of ^{235}U.

Experiments with metallic Uranium show that the chain reaction starts if

$$\delta = {}^{235}U/{}^{238}U = 8.2\%$$

However:

when neutrons are thermalized

$T_n = 0.025$ eV

then $\sigma_{fission}(^{235}U) = 590 \times 10^{-24} cm^2$

while $\sigma_{reaction}(^{238}U) = 2.7 \times 10^{-24} cm^2$

Therefore:

$$\delta_{nat}\sigma_{fission}(^{235}U)/(1-\delta_{nat})\sigma_{reaction}(^{238}U) =$$

$$= 0.7 \times 590 / 99.3 \times 2.7 = 1.5$$

fraction of *n* interacting with ^{235}U =

$$= 1.5/(1.5 + 1.0) = 0.6$$

Since in a fission 2 new *n* are produced (on the average), then the average number of new *n* per thermal *n* in natural U is

$$\eta = 0.6 \times 2 = 1.2$$

If 17% of thermal *n* are lost (*n* absorption or geometrical losses)

$$\eta \times 0.83 = 1.2 \times 0.83 = 1$$

and the chain stops.

Thermalization

Needed : 2MeV → 0.025 eV (a reduction by $\approx 10^8$)

In elastic collisions with ^{A}M (moderator), fraction of energy lost is typically **1/(A+1)**, therefore the number N of collisions needed for thermalization:

$$\mathbf{N = 8/\log_{10}[(A+1)/A]}$$

A = 1 (Hydrogen) captures too many ***n***

A = 2 (Deuterium) is excellent

(also D_2O, Oxygen does not absorb too many ***n***)

A = 12 (Carbon) is excellent,

provided it is in the form of very pure graphite

(Bothe, Heisenberg and the nazi reactor at Hagerloch)

Light water reactors (LWR) can be used provided U is enriched: not less than 2.5%.

Actually, in LWR

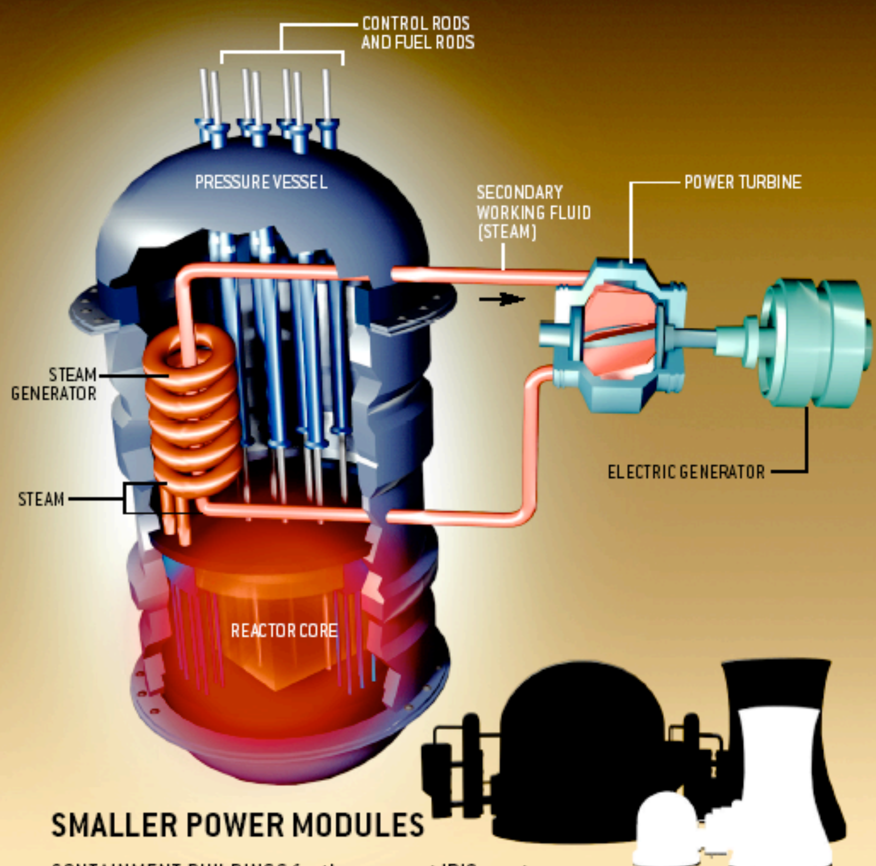
$$^{235}U/^{238}U = 3\%$$

As compared to graphite moderated, LWRs have some advantages: water is at a time moderator and refrigerator.

Enrichment costs because of chemical similarity of U isotopes.

WATER-COOLED NUCLEAR REACTOR

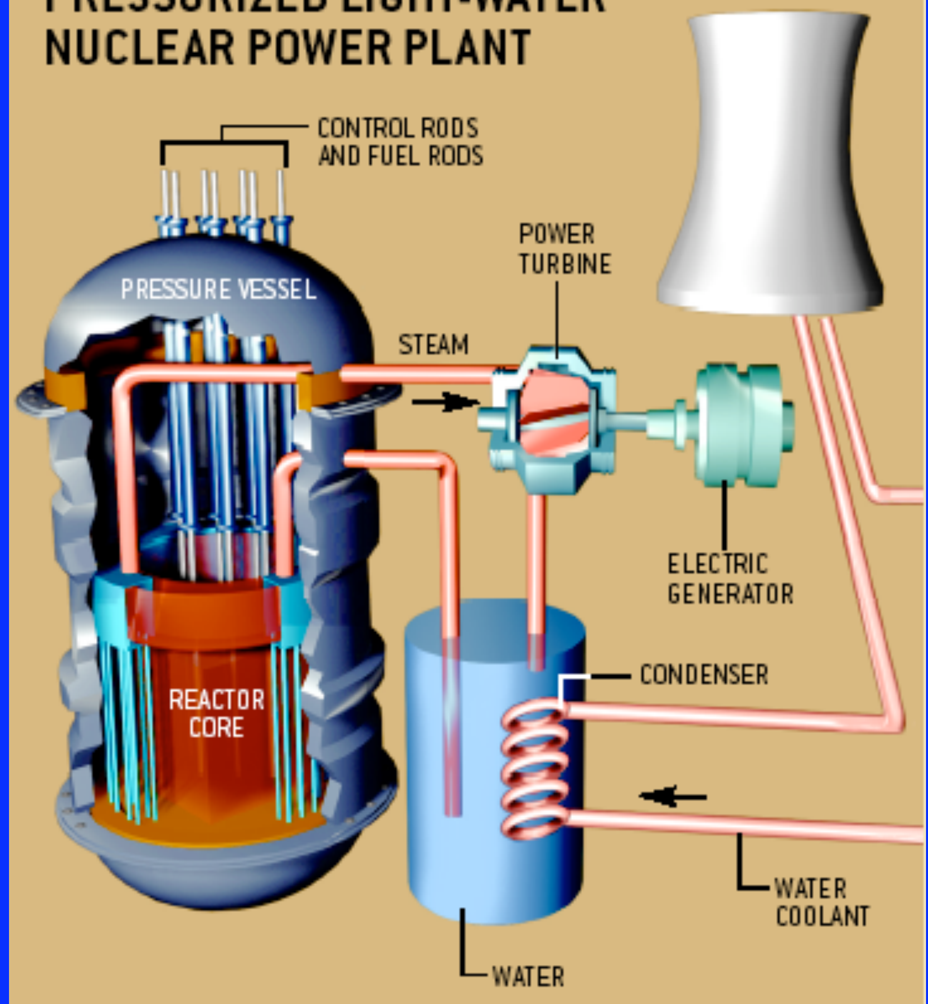
IRIS REACTOR DESIGN developed by Westinghouse Electric (*depicted in conceptual form*) is novel in that both the steam generator (heat exchanger) and the control rod actuator drives are enclosed within the thick steel pressure vessel.

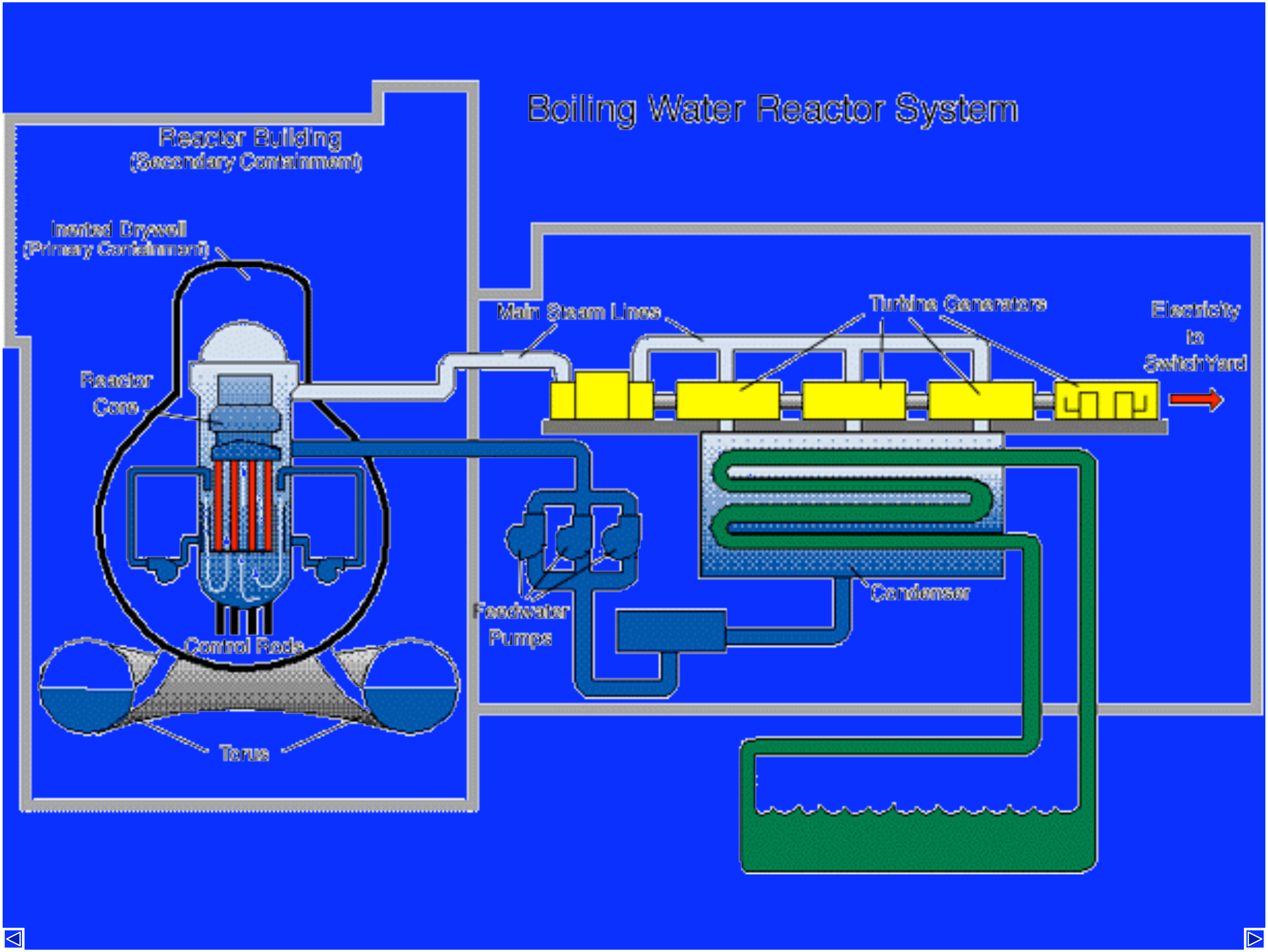


SMALLER POWER MODULES

CONTAINMENT BUILDINGS for the compact IRIS reactor can be reduced in size. The reactor's lower power output, ranging from 100 to 350 megawatts, can make these units more economical as well.

PRESSURIZED LIGHT-WATER NUCLEAR POWER PLANT




Boiling Water Reactor System
Reactor Building
(Secondary Containment)
Inerted Drywell
(Primary Containment)
Reactor
Core
Control Rods
Torus
Main Steam Lines
Turbine Generators
Electricity
to
Switch Yard
Feedwater
Pumps
Condenser

Graphite moderated reactors need no enriched U

Fast *n* produce $^{238}U + n \rightarrow {}^{239}U$
undergoing two β decays to ^{239}Pu

^{239}Pu is fissile
(1) easily separated from U due to chemical difference
(2) produces more *n* per fission than ^{235}U

The less the fuel is enriched,
the more it produces ^{239}Pu.

Therefore:

military interest for graphite moderated reactors
(plutonium bombs or H-bomb triggers).

Pu is very convenient since bombs require
weapon-grade enrichment ≈ 90% because energy must
be rapidly liberated. Pu is more economic.

However:

$$n + {}^{239}Pu \rightarrow {}^{240}Pu + \gamma$$

^{240}Pu is not fissile by ***n***,
but makes spontaneous fissions
with emission of many ***n***.

If too much **^{240}Pu** in a bomb, it fizzles.

Because of **^{240}Pu** , fuel bars must be extracted with a periodicity of no more than 30 days to utilize Pu for bombs.

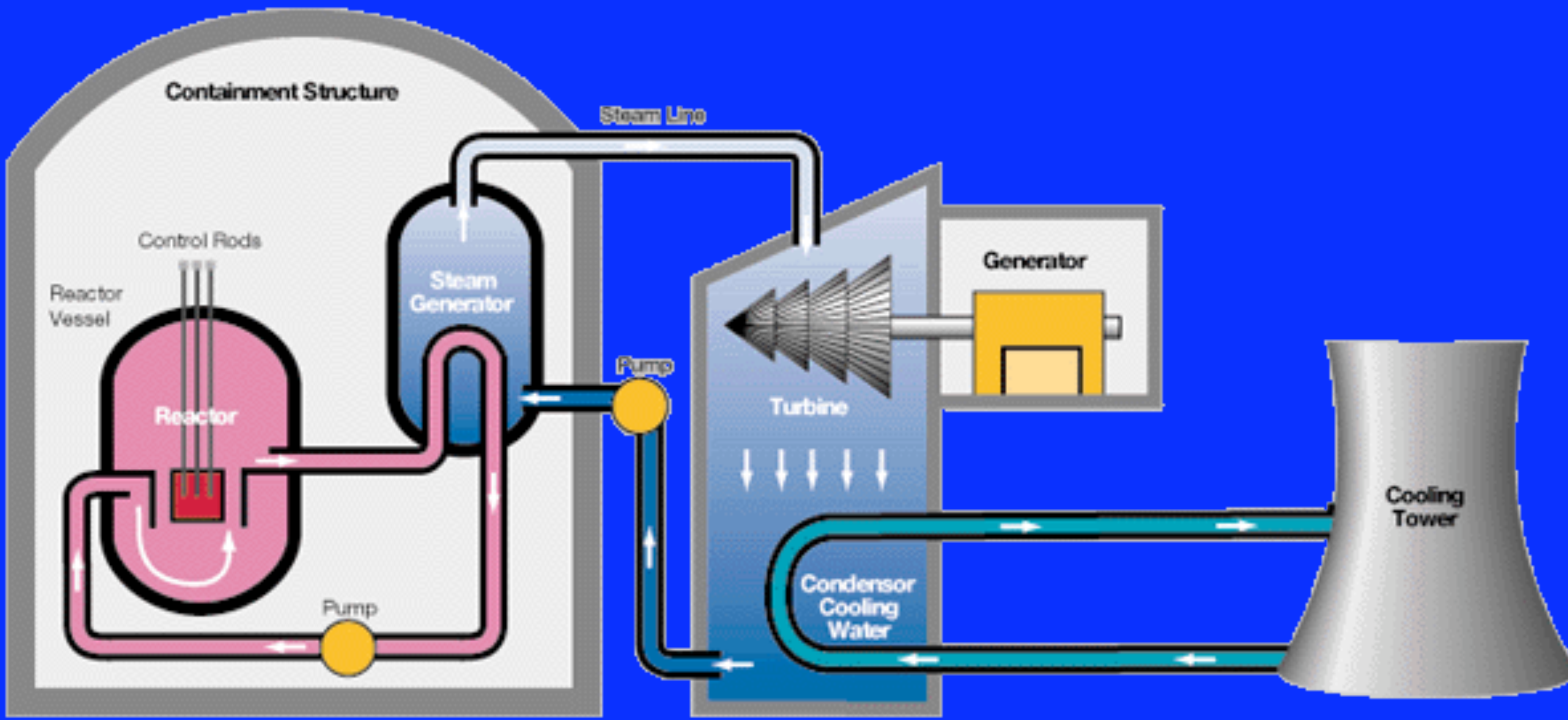
LWRs need 30 days just for replacing fuel: therefore refueling can be delayed up to every 1 or 2 years.

On the contrary, in graphite moderated (Hanford, Savannah River - USA, Cernobyl and many others - USSR)

the fuel can be replaced by extracting bars without stopping the plant; therefore they have no protection roof and are accessible from above.

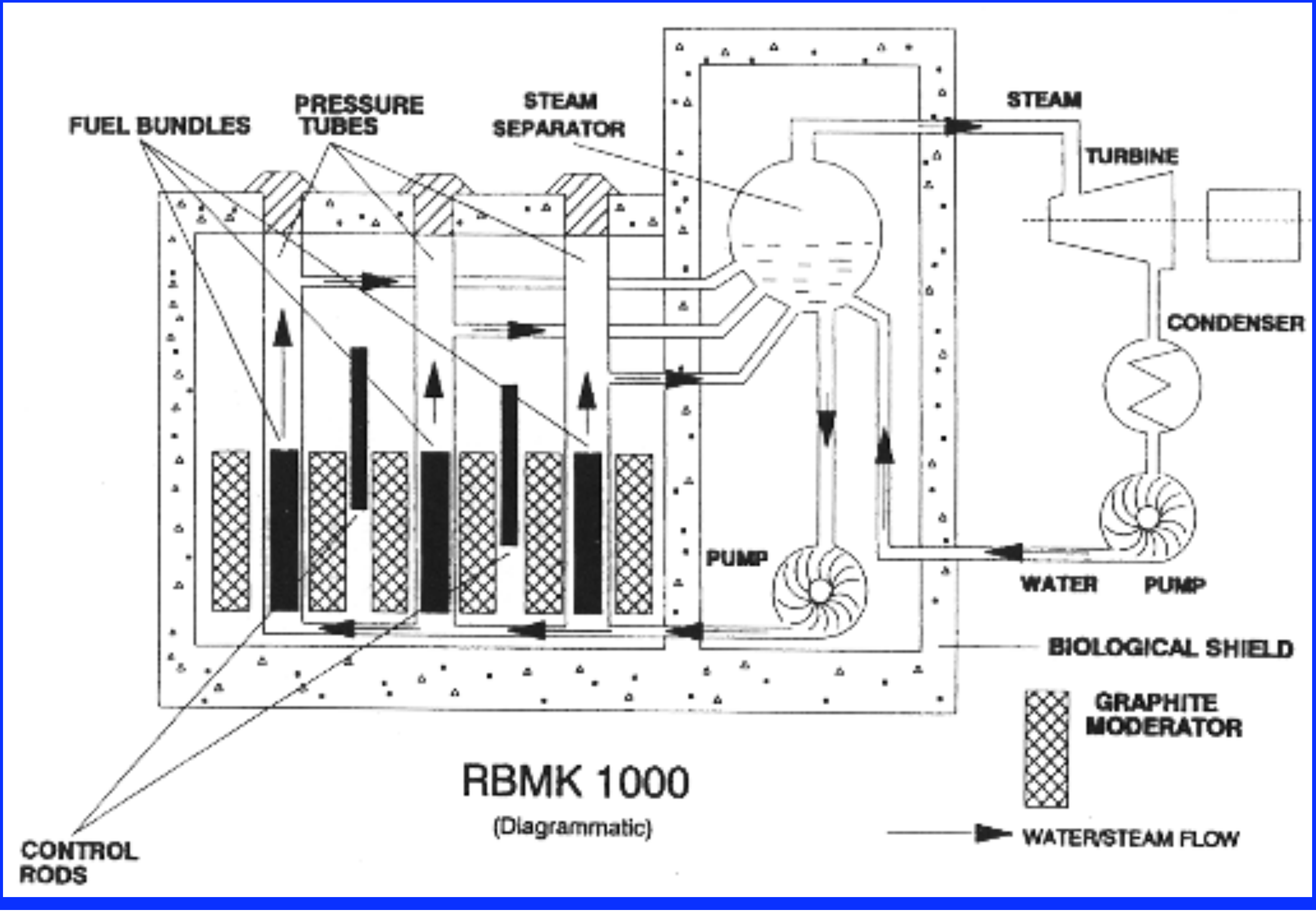
LWRs are thermally stable.
In case of LOCA
(Loss of Coolant Accident)
evaporation of water eliminates both the coolant and the moderator.
The chain stops. <u>However</u>: fuel melting problem. The residual activity of fission products (nuclear waste) amounts to ≈ 7% of the peak thermal power (≈ 3 times the peak electric power, typically 1000 MW).

This happened in 1979 at Three Mile Island, with no appreciable external consequences.



On the contrary, RBMK 1000 like Chernobyl, are thermally unstable: water is a “poison” because of *n* absorption. Therefore, LOCA is cathastrophic: the chain is less poisoned and accelerates, the produced power increases dramatically. Control must be “active”: control bars (cadmium) must intervene mechanically in the fuel mass. A too rapid temperature rise can impede the insertion by gravity of bars because of deformations of the seats.

Chernobyl


FUEL BUNDLES
PRESSURE TUBES
STEAM SEPARATOR
STEAM
TURBINE
CONDENSER
PUMP
WATER
PUMP
BIOLOGICAL SHIELD
GRAPHITE MODERATOR
WATER/STEAM FLOW
CONTROL RODS
RBMK 1000
(Diagrammatic)

Xenon interlude

Fission of ^{235}**U** produces ^{135}I, which β decays into ^{135}Xe in 6.7 hours. Xe in turn β decays into ^{135}Cs in 9.2 hours. The capture cross section of ***n*** by ^{135}Xe is $(2.6\times10^{6}) \times 10^{-24}$ cm^{2} !

The capture reaction is $\boldsymbol{n} + {}^{135}Xe \rightarrow {}^{136}Xe + \gamma$.

Capture is so frequent that ^{135}Xe not even decays into ^{135}Cs when the reactor works.

However, if reactor stops, ^{135}I decay continues to produce ^{135}Xe, which will not be destroyed any more and reaches such quantities as to empoison the fuel.

For the same reason , any power reduction is difficult to control and reactors must work at maximum power continuously.

The sequence of

Chernobyl accident on April 26, 1986

shows clearly that what happened was a thermal instability determined by the intention to avoid the Xe problem.

The control bars had no time to work: they did not fall into their seats because these were endamaged by excessive temperature.

The plant exploded.