Nuclear Reactors and Plutonium Production

ISIS Course-Week 4

October 23, 2014

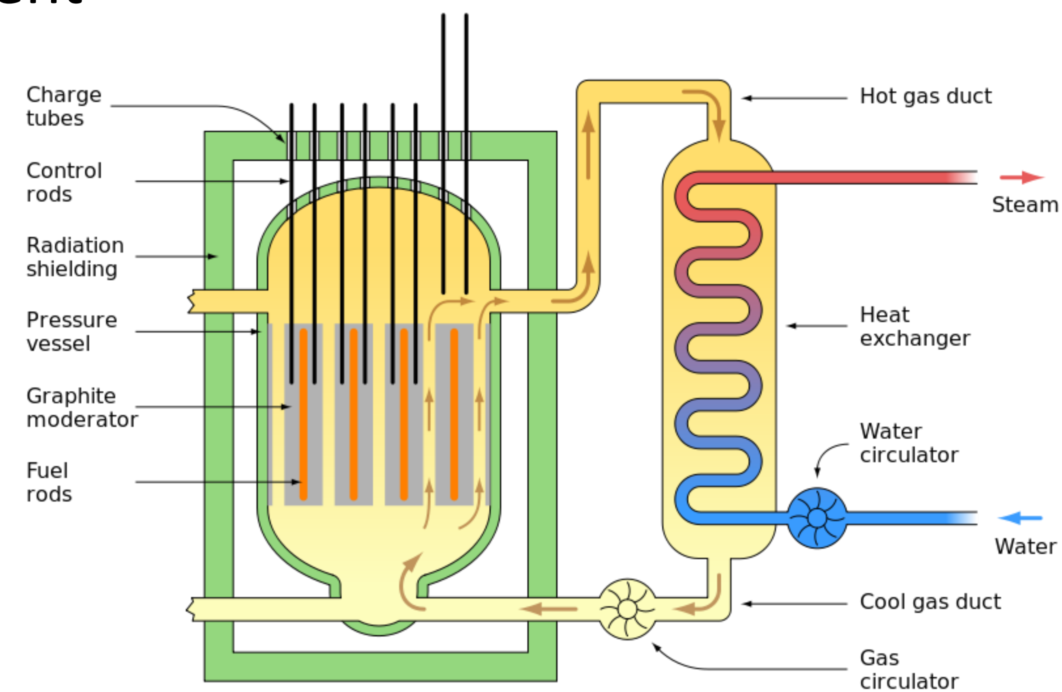
Nuclear Reactors

- A nuclear reactor is an apparatus or machine in which fissile material can be made to undergo a controlled, self-sustaining nuclear reaction with the consequent release of energy.

The Basic Parts of a Reactor

http://en.wikipedia.org/wiki/Magnox

- Fuel region
- Heat removal equipment
- Control system
- Refueling capability



Purposes of Reactors

- Nuclear reactors are used for civilian purposes to
  - generate electricity
  - produce heat via steam
  - produce isotopes for medical, industrial, or research purposes
  - conduct research
  - propel surface ships, such as ice-breakers
- Nuclear reactors are also used for military purposes to
  - produce plutonium for nuclear weapons
  - produce tritium for nuclear weapons
  - propel military submarines and surface ships
  - power aircraft and rockets (abandoned)

Classification of Reactors

- Power reactors
  - typically civilian, almost all now generate electricity. Some produced steam for district heating. Typically make large quantities of reactor-grade plutonium.
- Research reactors
  - typically civilian aimed at making isotopes or conducting research.
  - In non-proliferation context, ostensibly civilian research reactors have also been used to make plutonium for nuclear weapons, e.g. Cirus and Dhruva reactors in India. The misuse of the Taiwan research reactor was planned. Is the Arak reactor in Iran in this category, ostensibly a civilian research reactor but in reality it would also have produced plutonium for nuclear weapons?
- Propulsion reactors
  - either civilian or military
- Production reactors
  - almost always military and dedicated to plutonium and tritium production for nuclear weapons, which means that the goal is the production of weapon-grade plutonium.

Reactors

- Reactor types vary greatly, some are far simpler to build than others
- Production reactors and research reactors are the simplest to build.
- Graphite- and heavy water-moderated reactors use natural uranium fuel, so there is no need for uranium enrichment capabilities. These are usually the types sought by proliferant states to make plutonium for weapons.
- Typically, commercial reactors use LEU fuels and have much more advanced control and safety systems than production reactors

We will consider three types of reactors in more detail

I. Production Reactors
II. Research Reactors
III. Power Reactors

I. Production Reactors

- There have been many types of production reactors, almost all of which are shut down. The few remaining operational ones are in India, Pakistan, and Israel.
- Their initial goal was to make weapon-grade plutonium for nuclear weapons. Later, some also have made tritium.
- They typically were designed to use natural uranium fuel. Some types, such as the Savannah River production reactors shifted to highly enriched uranium fuel in a driver/target system.
- Fuel was simple, often uranium metal with simple cladding
- They have been cooled by water, carbon dioxide, or even air
- Moderated typically by graphite or heavy water
- Some also produced electricity

Hanford B Reactor:

Graphite moderated, water cooled, natural uranium metal fuel

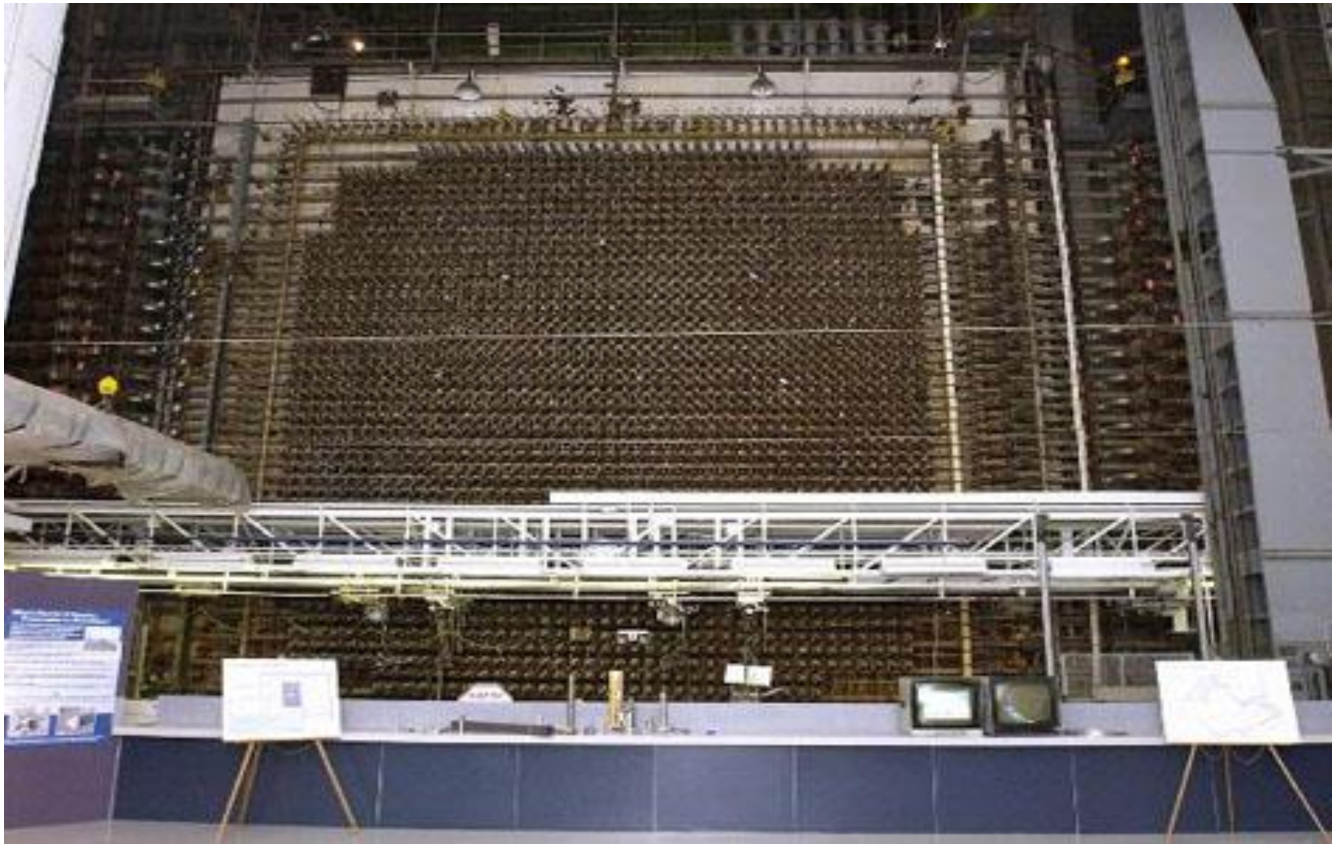
http://www.hanford.gov/page.cfm/BReactor#BReactor

Hanford B Reactor
Initial power was 250 MWth

http://www.hanford.gov/page.cfm/BReactor#BReactor

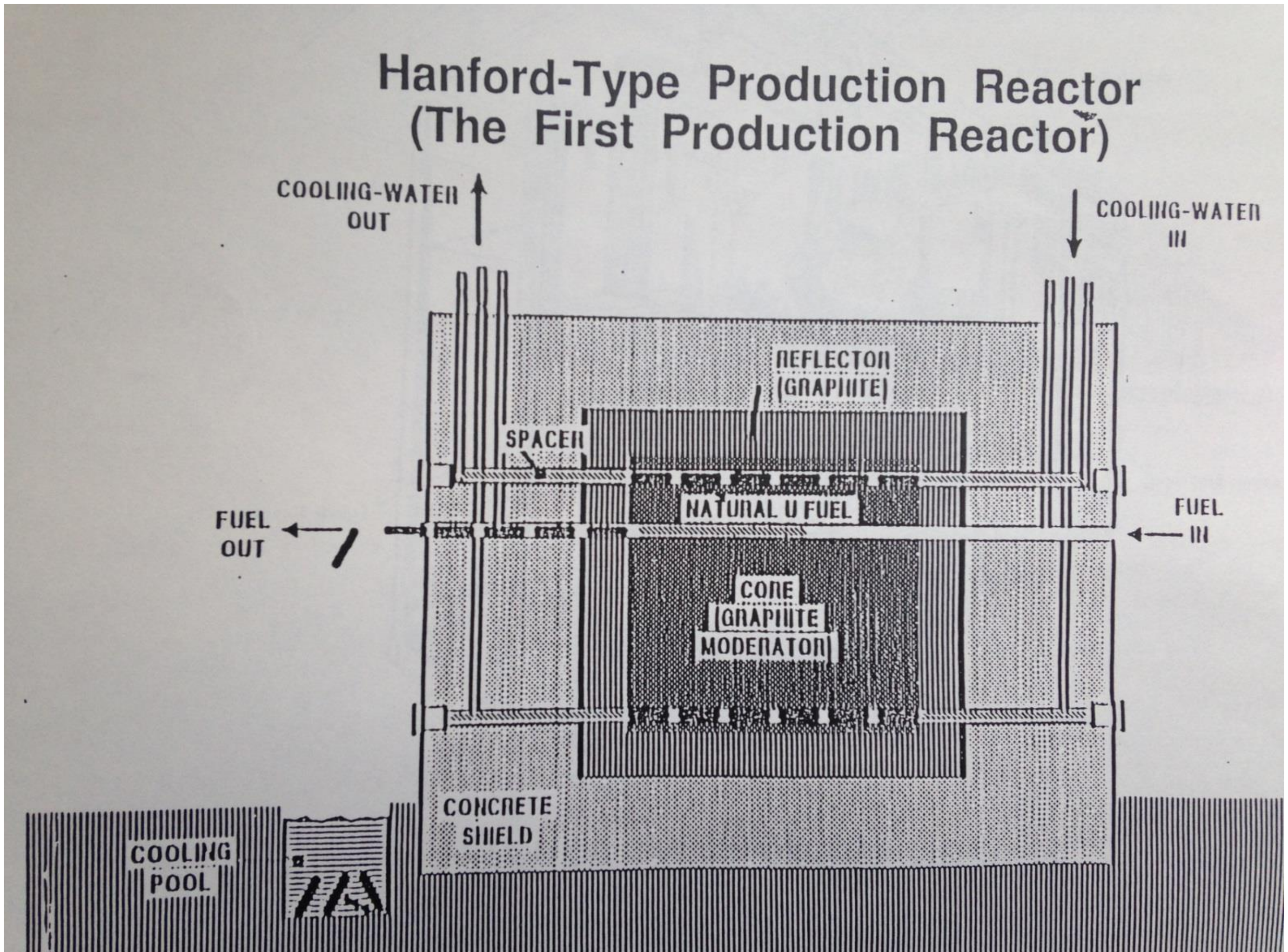
Hanford B Reactor Core Face

http://response.restoration.noaa.gov/about/media/restoration-amid-hanfords-nuclear-waste-and-largest-environmental-cleanup-us.html



Hanford Type Reactor: The design of First Plutonium Production Reactor

Source DOE



French G-2 Reactors, 250 MWth each

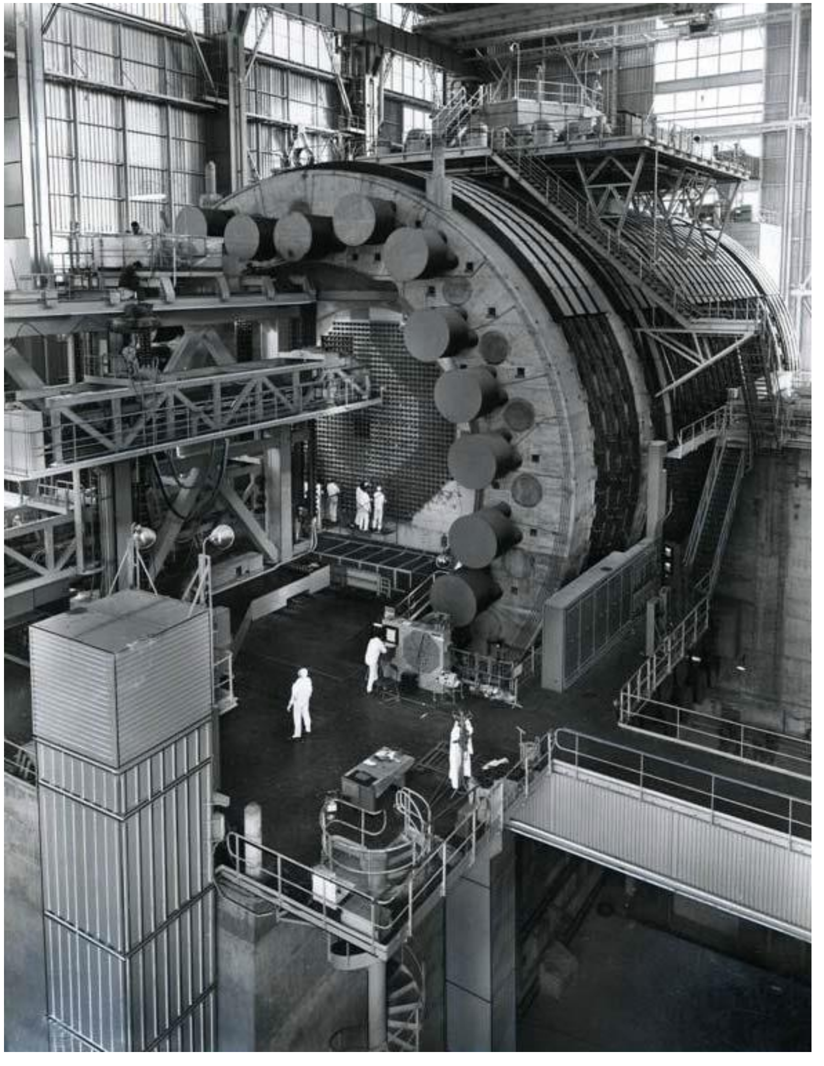
Graphite moderated, carbon dioxide fuel

http://www.francetnp.fr/IMG/pdf/C-MAR_G1_G2_G3.pdf

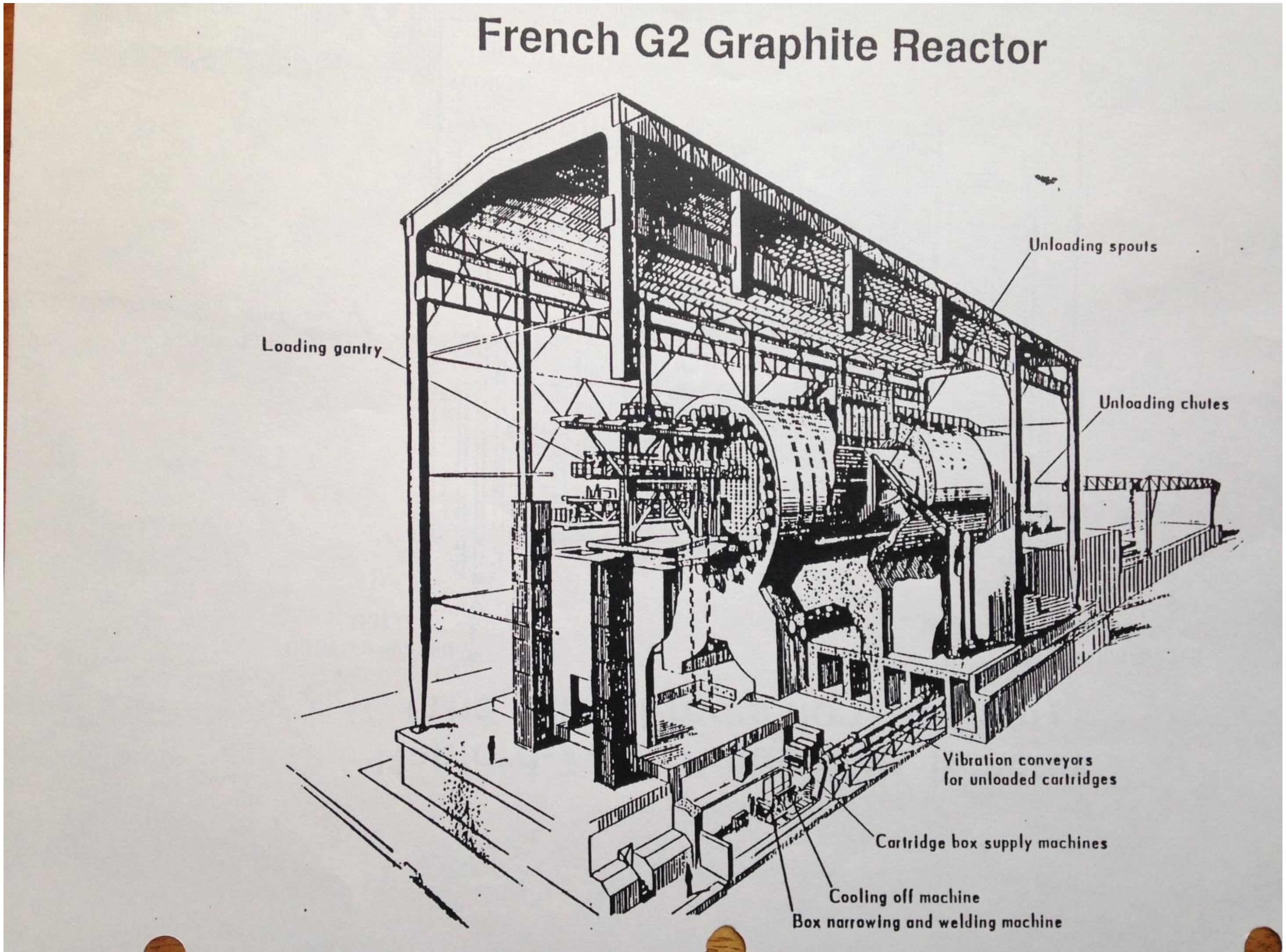
The G2 and G3 reactors on the Marcoule site

View of the G-2 reactor unit, with the fuel loading system in the foreground and the platform for the control rod winches above the reactor

http://www.francetnp.fr/IMG/pdf/C-MAR_G1_G2_G3.pdf



French G-2 Reactor

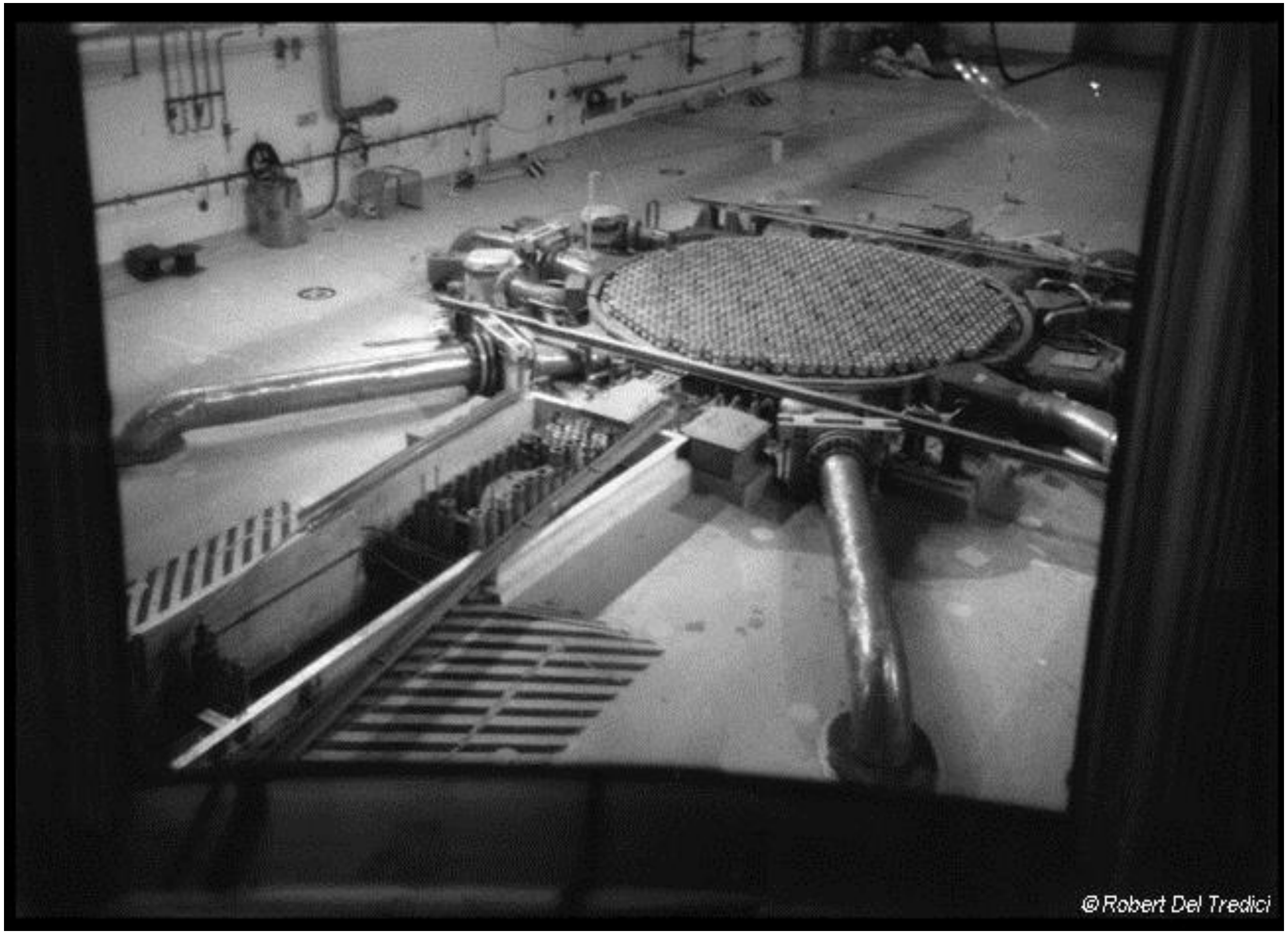


Savannah River Production Reactor

http://www.nationalregister.sc.gov/SurveyReports/HC02005.pdf

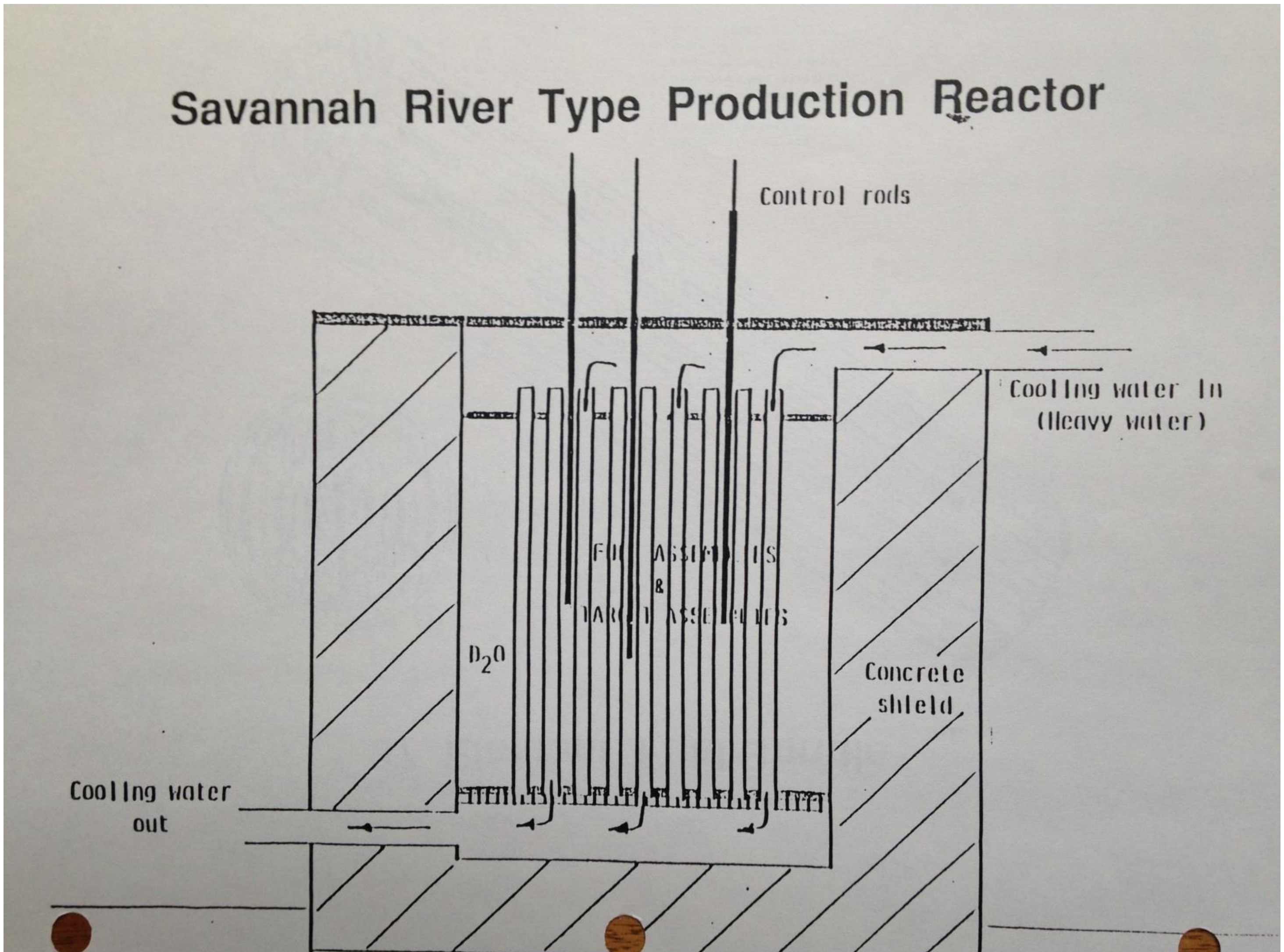
Savannah River Production Reactor (K Reactor)

http://nonuclear.se/deltredici.f5.k.reactr.head.html



Savannah River Production Reactor

Source DOE



II. Research Reactors

- Design and construction is relatively easy.
- Some are similar to production reactors
- Far simpler to build than power reactors
- Fueled with LEU or HEU
- Many can be used to make plutonium via a driver/target system

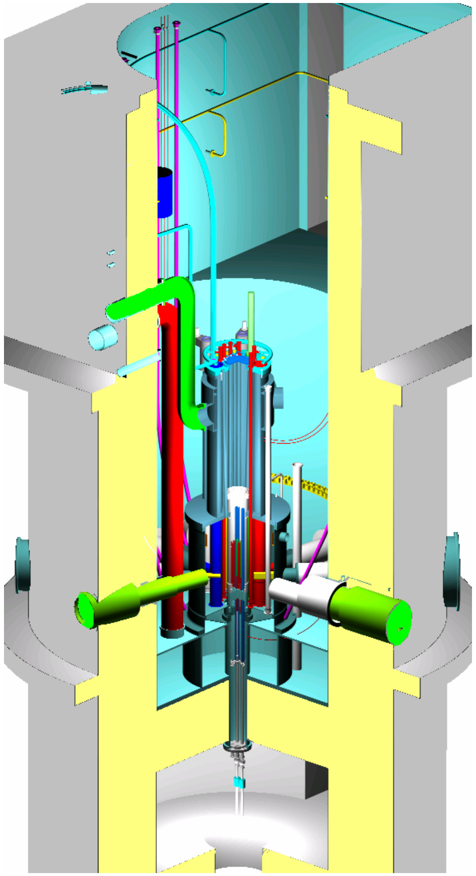
China Advanced Research Reactor (CARR) is a tank in pool, light water cooled, heavy water reflected, near 20% LEU fuel

http://www.world-nuclear-news.org/NN-Chinese_research_reactor_starts_up-1805107.html

18 May 2010

A new Chinese-designed and built research reactor has reached first criticality at the China Institute of Atomic Energy (CIAE)'s Fangshan, Beijing site.

The pool hall at CARR (Image: CIAE)



Tehran Research Reactor

http://www.pbs.org/wgbh/pages/frontline/tehranbureau/2011/04/iran-plans-4-new-research-reactors-mousavi-aide-pressed-to-confess.html

Tehran Research Reactor: Pool type, light water cooled and moderated

http://www.nti.org/gsn/article/israel-would-not-warn-us-impending-iran-attack-official/

Arak Heavy Water Reactor

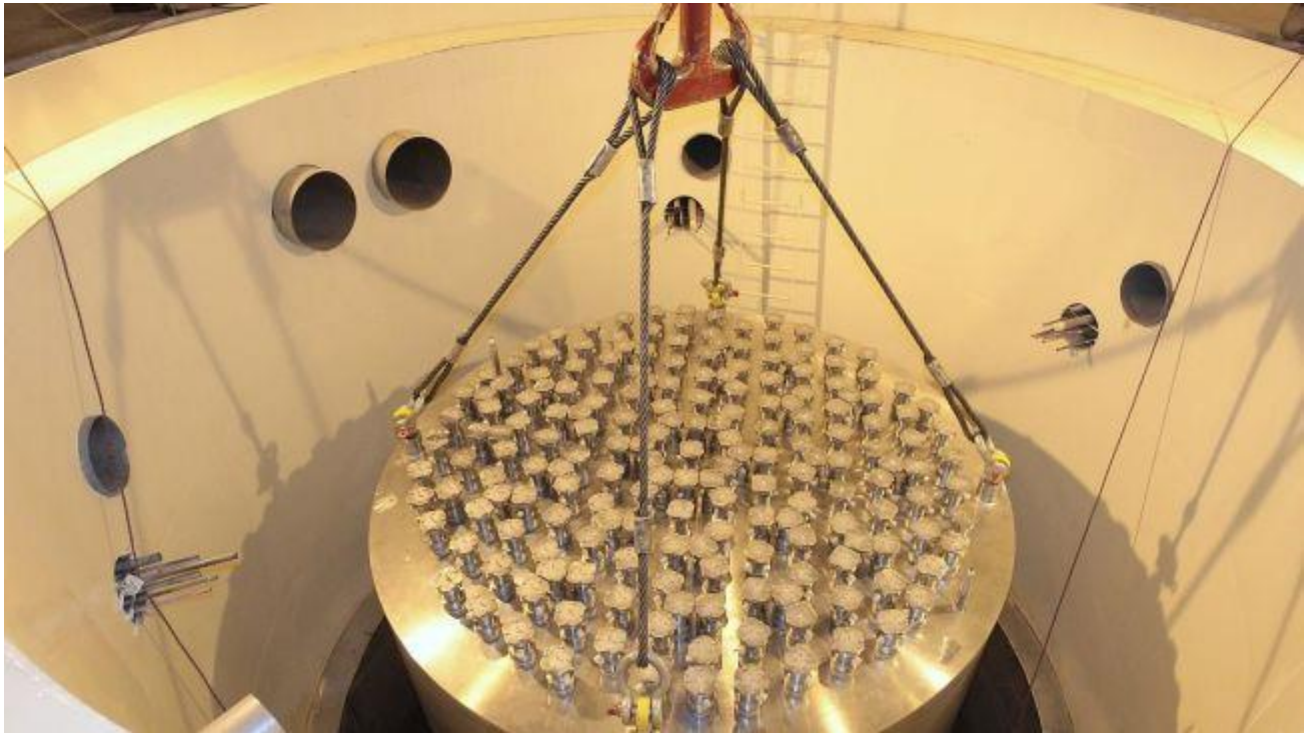
http://www.isisnucleariran.org/images/gallery/arak/25Nov2009.jpg

Arak Heavy Water Reactor

http://en.wikipedia.org/wiki/File:Arak_Heavy_Water4.JPG

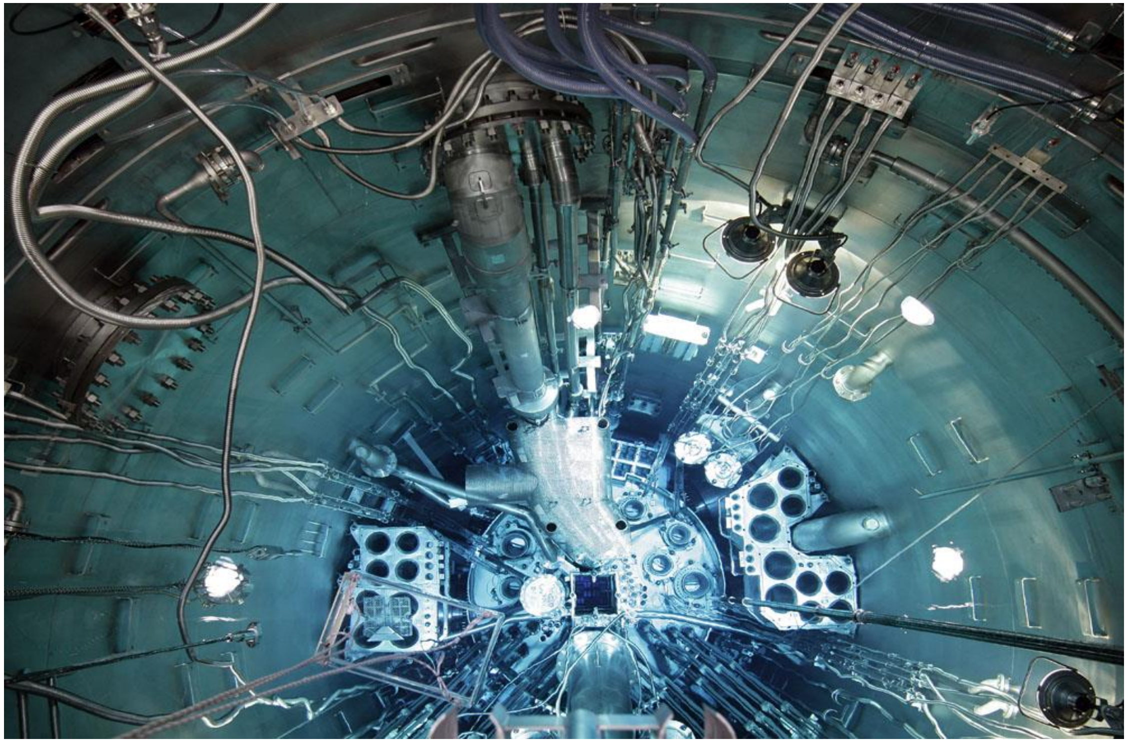
Arak Heavy Water Reactor

http://www.presstv.ir/detail/2013/06/12/308556/arak-reactor-under-constant-iaea-watch/



Pool Type Research Reactor

http://www.ansto.gov.au/BusinessServices/OtherSpecialisedServices/Neutronactiviationanalysis/



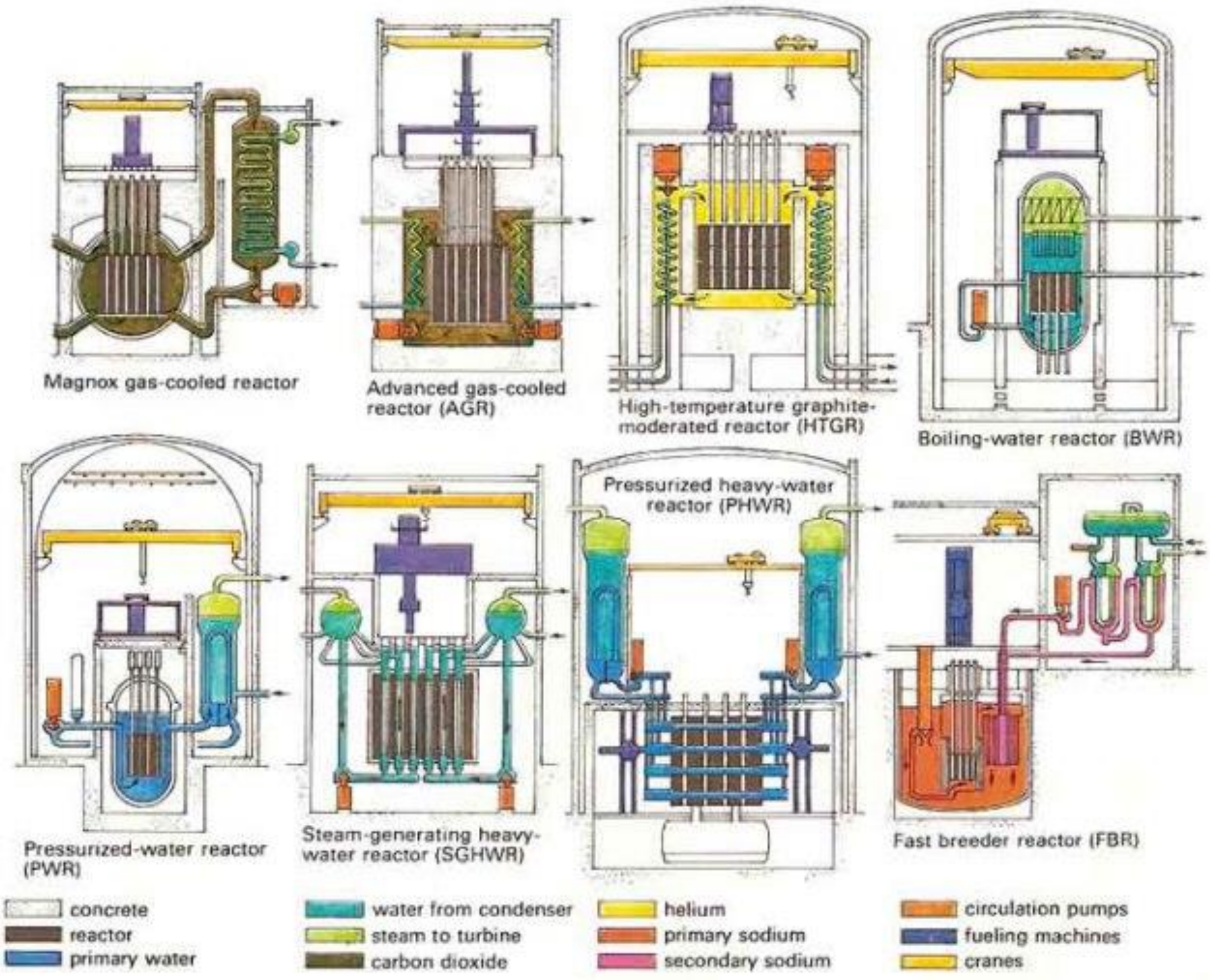
Interior of OPAL reactor Australia

III. Nuclear Power Reactors

- There are many types of nuclear power reactors
- The dominant types today are water-cooled and moderated, namely Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs). They both use LEU fuel and are expensive.
- Another major type is the heavy water moderated and cooled CANDU reactor, which uses natural uranium fuel.
- Older types include the Magnox reactor, advanced gas reactor, and the Russian RBMK reactor.
- Breeder reactors have been built but have operated poorly.
- Excluding breeder reactors, nuclear power reactors are an inefficient means of making weapon-grade plutonium, although they routinely make large quantities of reactor-grade plutonium, i.e. they discharge high burnup fuel.
- However, weapon-grade plutonium production is possible, albeit inefficient, in power reactors.

Overview of Major Types of Power Reactors

http://www.daviddarling.info/encyclopedia/N/nuclear_reactor.htm



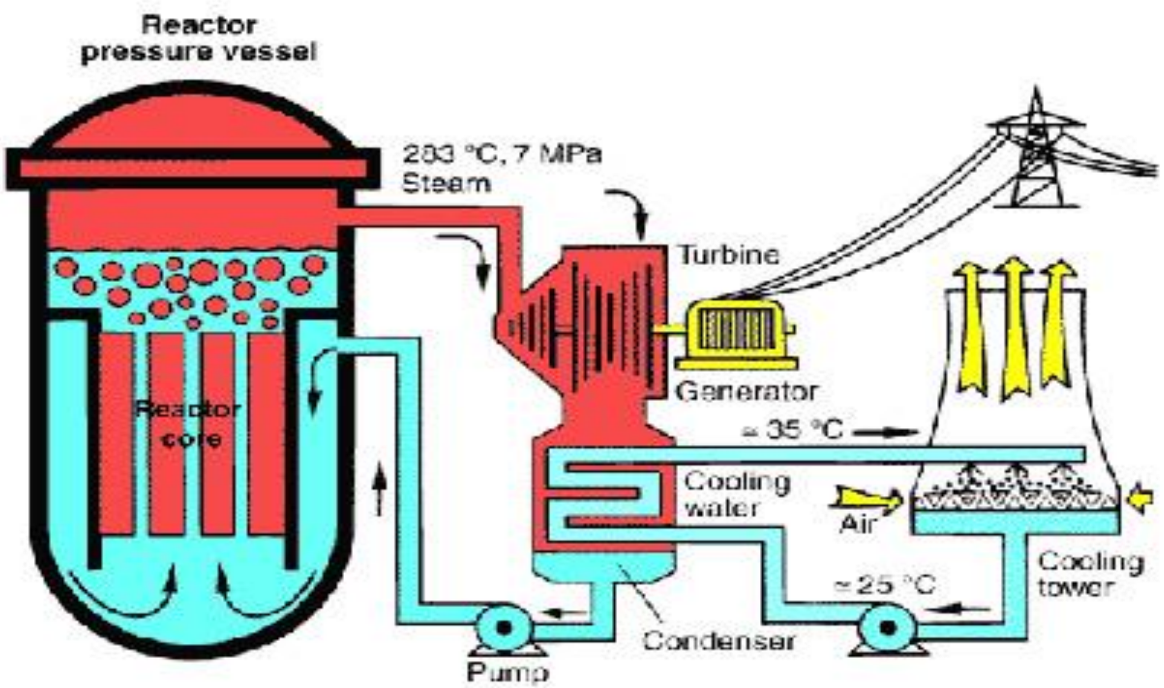
Boiling Water Reactors

https://www.asme.org/about-asme/who-we-are/engineering-history/landmarks/128-vallecitos-boiling-water-reactor

Vallecitos Boiling Water Reactor

Boiling Water Reactor

http://www.euronuclear.org/info/encyclopedia/boilingwaterreactor.htm



Pressurized Water Reactor

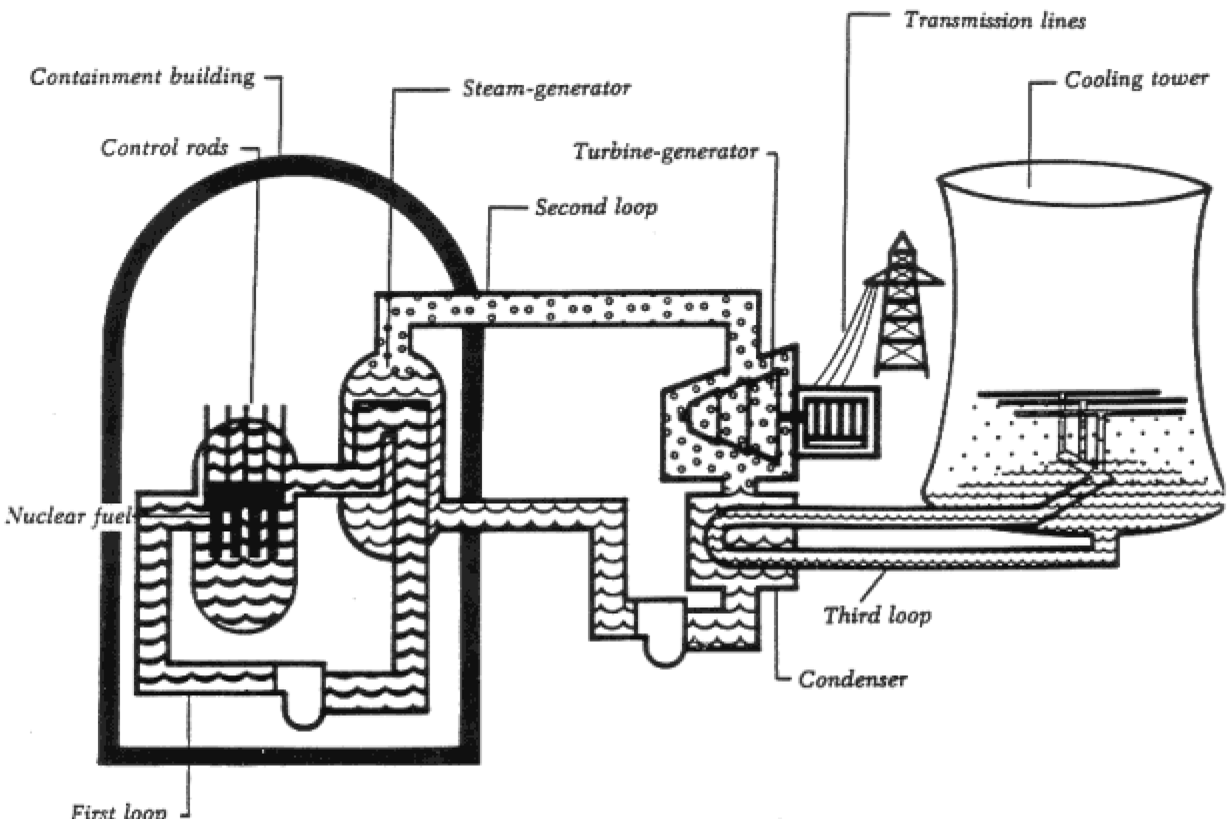
http://che.nelson.wisc.edu/cool_stuff/energy/nuclear.shtml

Figure 8: *Three Mile Island Nuclear Power Plant. Note the domed containment silos (center) and separate fuel-containment building (left of silos) distinct to pressurized water reactors, and the natural-draft cooling towers. The reactors must be housed in these external silos rather than in the single facility used in boiling water reactors (see Figure 7) because the reactors are themselves much larger.*

(U.S. Department of Energy, http://commons.wikimedia.org/wiki/File:Three_Mile_Island_(color)-2.jpg)

Pressurized Water Reactor

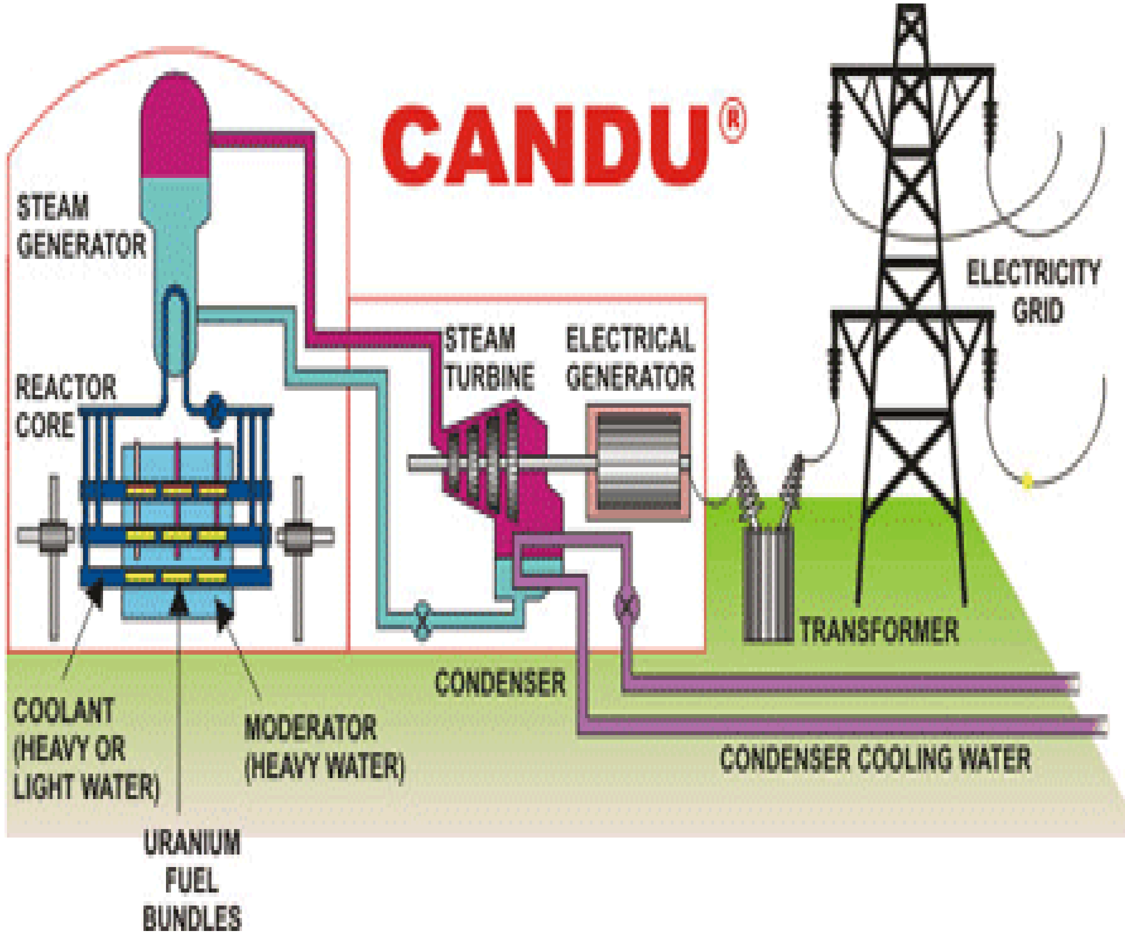
http://www.nrc.gov/reading-rm/basic-ref/teachers/pwr-schematic.html



Pressurized Water Reactor

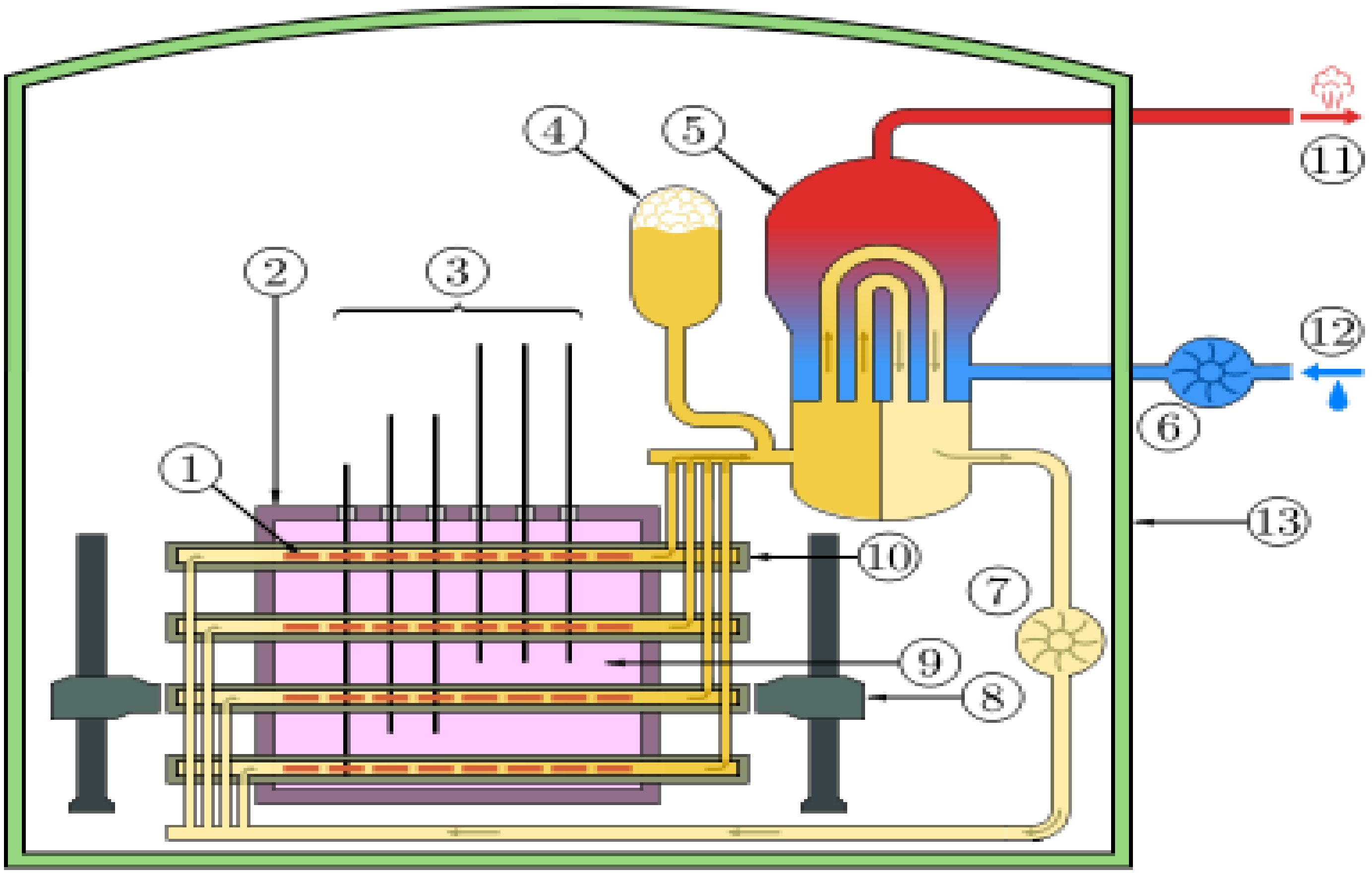
CANDU Power Reactor

http://www.cna.ca/how_works/candu_technology/



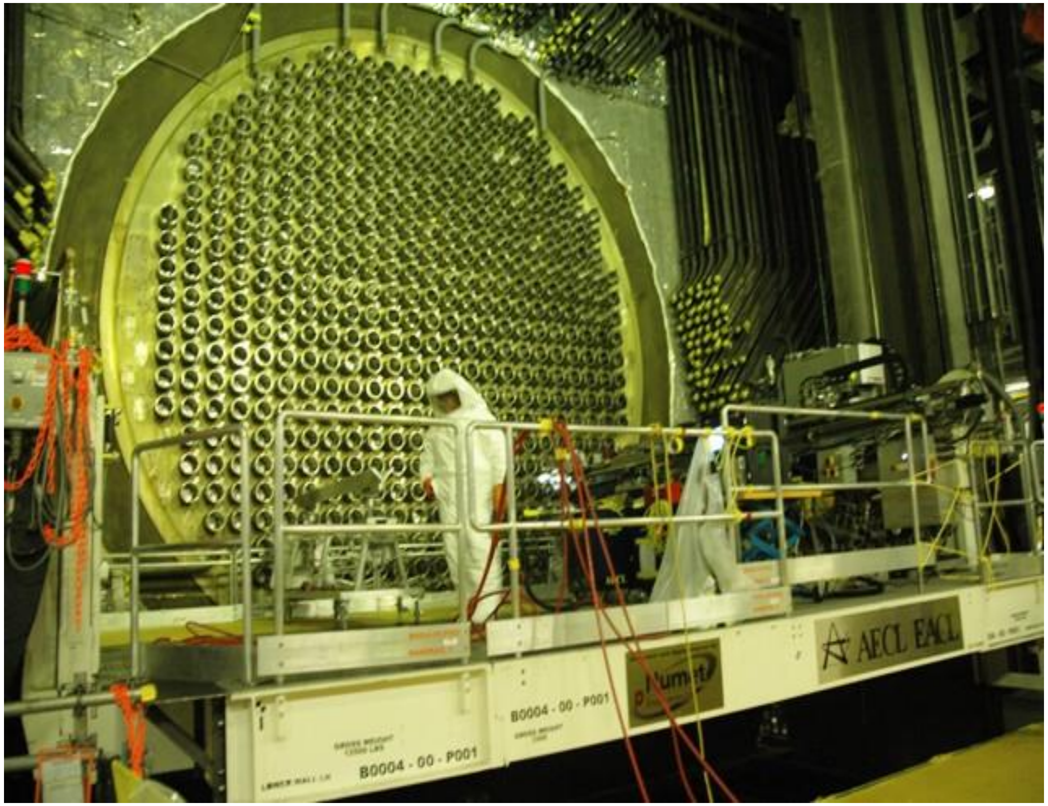
CANDU Power Reactor

http://en.wikipedia.org/wiki/CANDU_reactor



CANDU Power Reactor

http://www.newbrunswickbeacon.ca/29433/decade-refurbishment-nightmares-point-lepreau-online/



Point Lepreau nuclear power plant

CANDU Power Reactor

http://www.world-nuclear-news.org/C-Restart_of_Bruce_reactor_delayed-2105124.html

The turbine hall of Bruce A unit 2 (Image: Bruce Power)

British Magnox Power Reactor

http://www.nda.gov.uk/news/oldbury-shutdown.cfm

Reactor 1 Oldbury Power Station

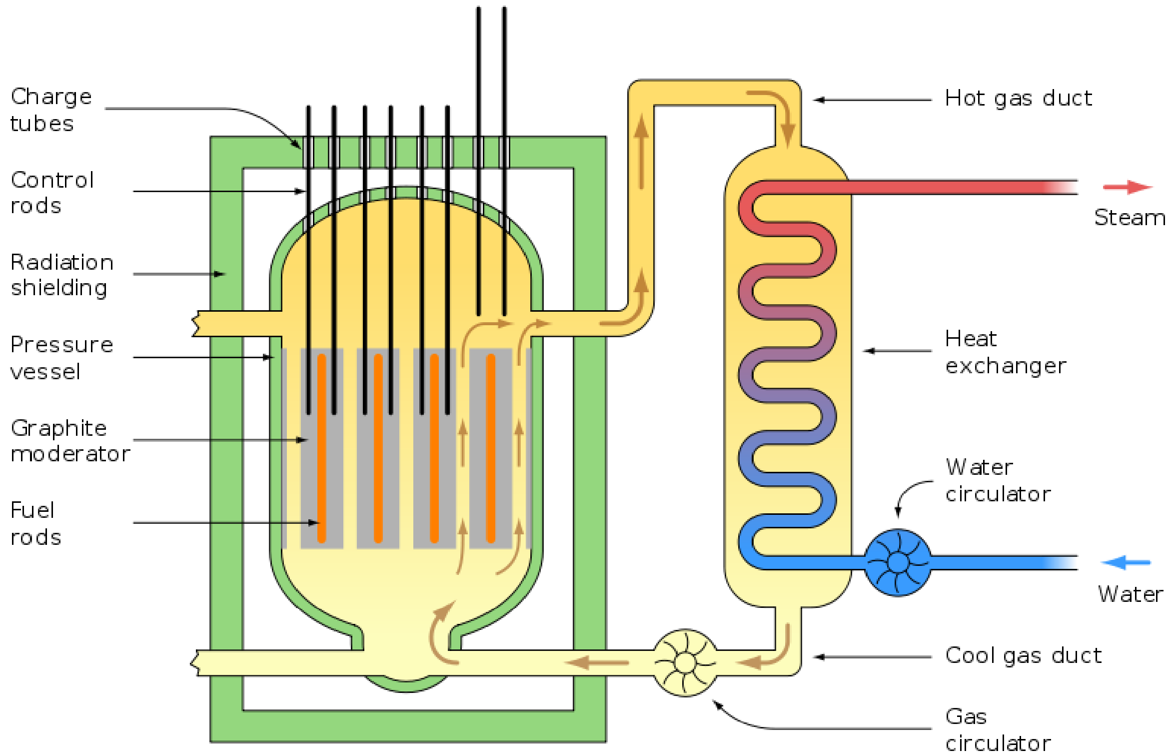
British Magnox Power Reactor

http://www.world-nuclear-news.org/RS-Fuel_transfer_to_keep_Wylfa_1_running-0908124.html

Wylfa 1, the UK's last operating Magnox reactor

British Magnox Power Reactor

http://en.wikipedia.org/wiki/Magnox



Russian RBMK Power Reactor

http://large.stanford.edu/courses/2013/ph241/kallman1/docs/nuclear_reactors.pdf

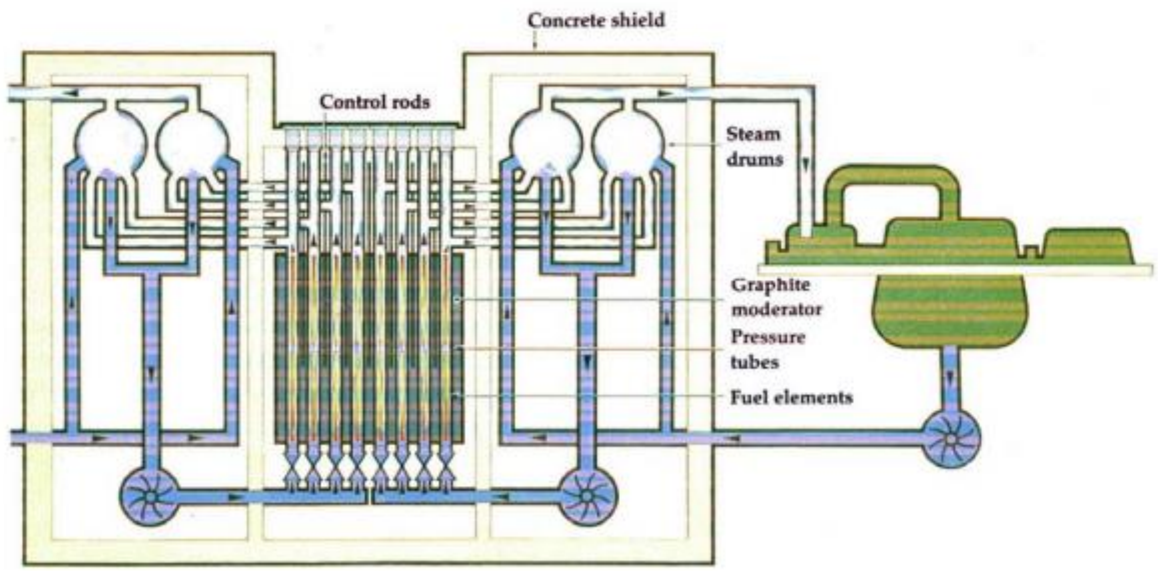
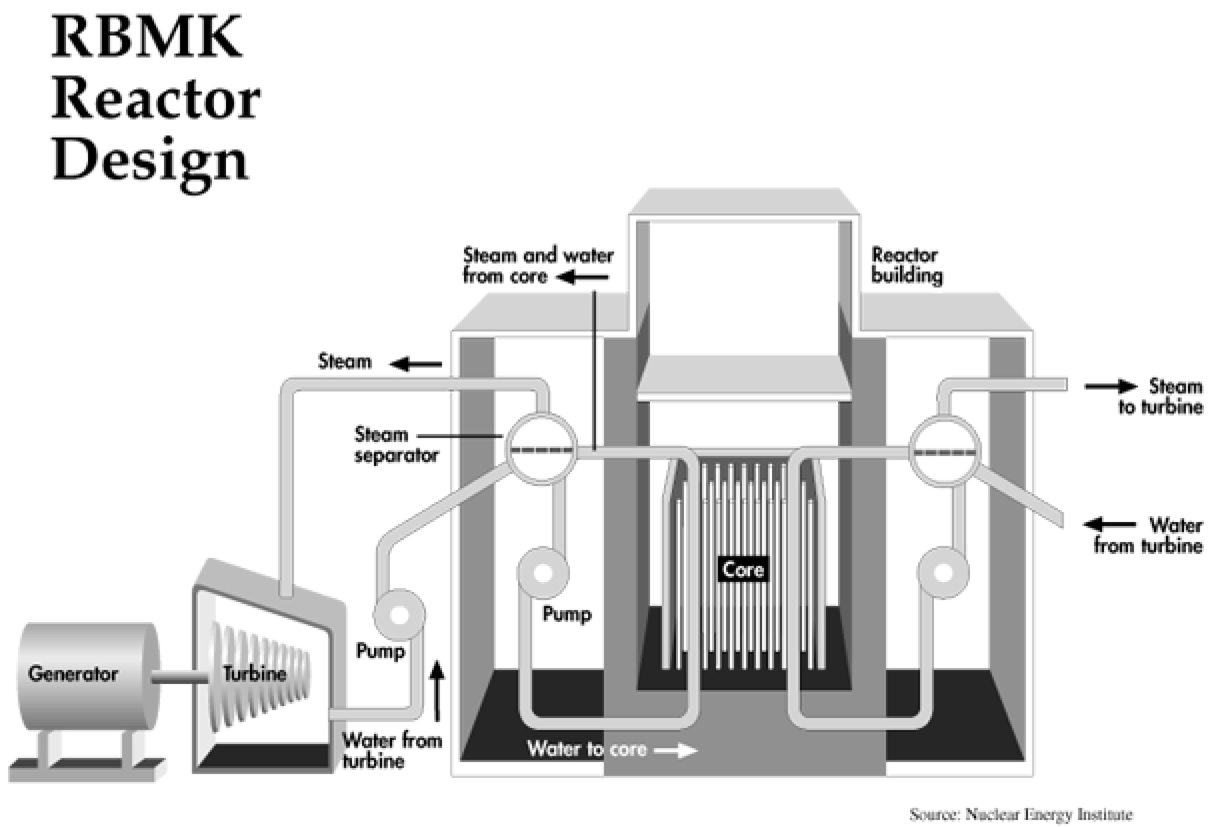


Figure 1.4 Schematic: RBMK REACTOR Boiling Light Water, Graphite Moderated Reactor

Russian RBMK Power Reactor

http://www.globalsecurity.org/jhtml/jframe.html#http://www.globalsecurity.org/wmd/world/russia/images/rbmk-design.gif|||



Russian RBMK Power Reactor

http://en.wikipedia.org/wiki/RBMK

Reactor hall of the RBMK-1500 at Ignalina Nuclear Power Plant, Lithuania – the upper biological shield (UBS) lies several meters below the floor of the reactor hall.

Plutonium Production in Reactors

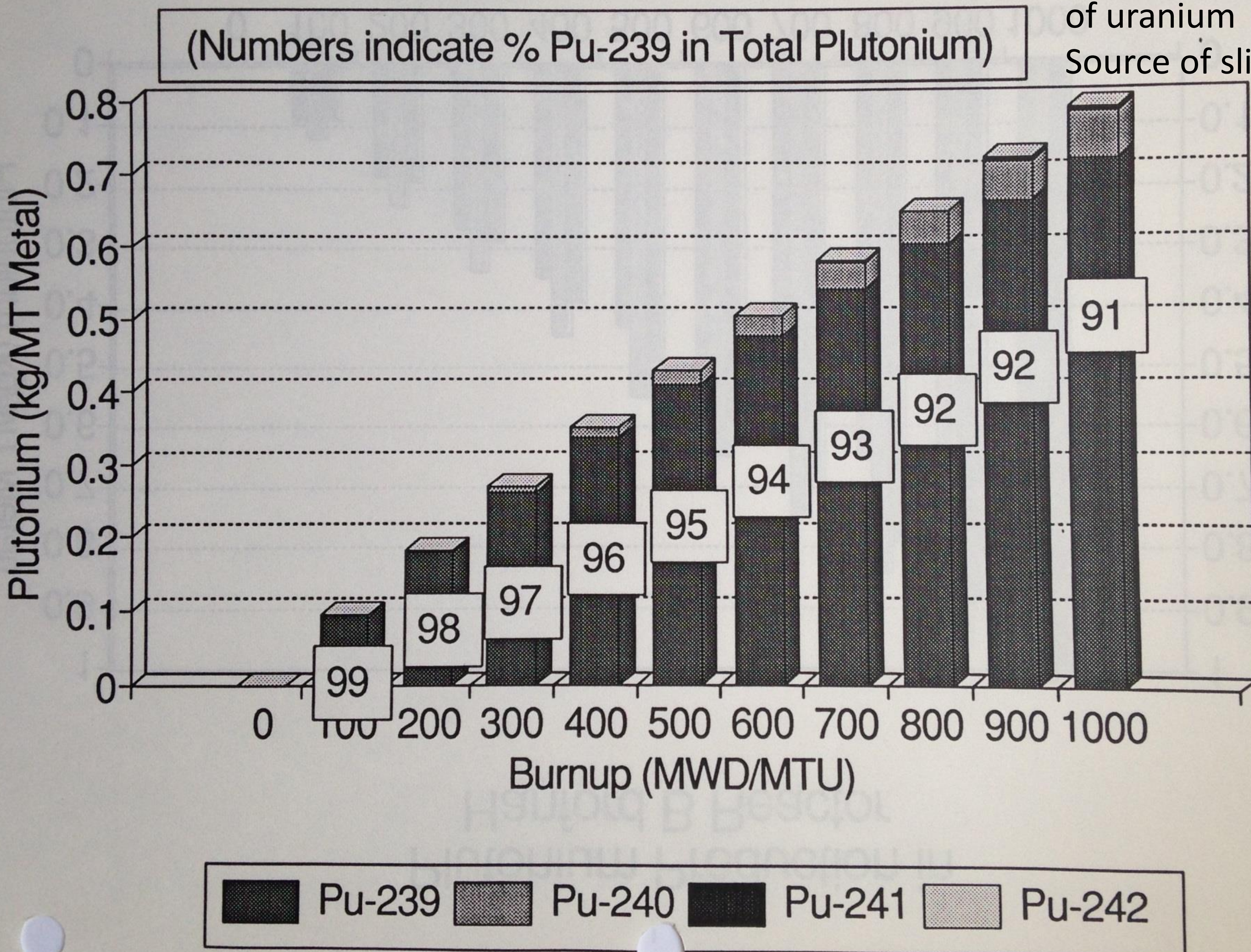
- Reactors are the principal method to make plutonium, whether deliberately or inadvertently.
- The amount of plutonium produced in a reactor varies
- Some reactors produce weapon-grade plutonium during normal operation; others produce reactor grade plutonium when operating normally.
- All reactors can be used to make weapon-grade plutonium.

Burnup of Irradiated Fuel and Plutonium Production

- Burnup is a measure of the extent that uranium fuel has been irradiated in a reactor.
- It is a measure of how much energy is extracted from a primary nuclear fuel source, such as uranium, via fission. It is measured both as the fraction of fuel atoms that underwent fission and as the actual energy released per mass of initial fuel.
- We will use the latter, namely the amount of energy released per unit of uranium. Its units are megawatt-thermal-days per tonne of uranium, e.g. MWth-d/tonne U, MWth-d/tonne, or MWth-d/t.
- Be careful not to confuse MWth with MWe. MWe measures only a fraction of the total energy produced in the reactor.
- Low burnup fuel, with values such as 500-1,000 MWth-d/tonne, would typically contain weapon-grade plutonium
- High burnup fuel, with values such as 30,000 MWth-d/tonne typically would contain reactor-grade plutonium.

Plutonium Production in Hanford B Reactor

(Note: MWD/MTU is same as MWth-d/t; and MTU equates to tonnes of uranium
Source of slide: DOE



Plutonium (Pu) Production at Normal Burnups

(grams Pu per MWth-d, here called g Pu/MWD)

Source: DOE

Reactor Comparison: Pu in Fuel at Normal Discharge

Reactor Type	Burnup	Pu, kg/MT	%Pu-239 in Pu	g Pu/MWD
Hanford B	600 MWD/MT	0.51	94.2	0.85
Magnox GCR	4000	2.49	76.4	0.62
Heavy Water	7000	3.76	65.9	0.54
RBMK	18000	4.96	51.8	0.28
Advanced GCR	18000	3.38	57.5	0.19
PWR	40000	10.65	53.8	0.27
FBR (blanket)	8000	22.96	98.7	2.87

(calculated data)

Plutonium (Pu) Production at a fixed, but low burnup, 1000 MWth-d/tonne

Source: DOE

Reactor Comparison: Pu in Fuel at 1000 MWD/MT

Reactor Type	Pu, kg/MT	%Pu-239 in Pu
Hanford B	0.79	90.8
Magnox GCR	0.88	93.1
Heavy Water	0.90	93.8
RBMK	0.54	96.2
Advanced GCR	0.28	97.5
PWR	0.51	98.5
FBR (blanket)	3.77	99.8

(calculated data)

Simple Approximation of Annual Weapon-Grade Plutonium Production

- In non-proliferation, it is useful to have a simple formula to estimate the amount of weapon-grade plutonium (about 93-95% plutonium 239) produced in natural uranium fueled reactors found in proliferant states, such as India, North Korea, and Iran.
- This calculation is an approximation limited to weapon-grade plutonium production, i.e. low burnup irradiated fuel, and to reactors that use natural uranium fuel.
- It should not be applied to nuclear power reactors using enriched uranium or to cases when higher burnup irradiated fuels are generated.
- But with these limitations, the approximation is useful to understand the threat posed by the types of reactors encountered in non-proliferation cases.
- When considering different reactors, the burnups associated with weapon-grade plutonium production can vary. For example, the burnup of the irradiated fuel from the Hanford B reactor would have a burnup of about 500-600 MWth-d/tonne while a heavy water reactor would have a burnup of about 1000 MWth-d/tonne; yet both would produce weapon-grade plutonium with about the same fraction of plutonium 239.

Simple Formula of Annual WGPu Production

$$Pu_{\text{yearly total}} = P_{\text{thermal power}} \times C \times 365 \text{ Days} \times PF$$

- $P_{\text{thermal power}}$ equals the total energy ouput of the reactor, given as units of megawatt-thermal (MWth)
  - Yongbyon reactor- 10-20 MWth
  - Arak reactor in Iran – 40 MWth
- C, or capacity factor, is the total amount of energy produced by the reactor during a period of time divided by the amount of energy the plant would have produced at full power
  - Typical capacity factors are 0.5 or 50 percent, or 0.7, or 70 percent
- PF, or plutonium conversion factor, converts the energy produced by the reactor into the amount of weapon-grade plutonium produced in the uranium fuel. The units are the mass of plutonium produced per energy produced by the reactor, i.e grams of plutonium per MWth-d, or grams/MWth-d.
  - For the production of weapon-grade plutonium, values of about 0.85-0.9 grams/MWth-d are typical for a variety of reactors. Burnups will vary based on reactor type.

Example of Annual WGPu Production

$$P_{thermal\ power} \times C \times 365\ Days \times PF$$

- 20 MWth x 0.5 x 365 days x 0.9 grams/MWth-d
- Answer = 3,285 grams/year, or 3.285 kilograms/year
- Rounded to 3.3 kg/year

Your Turn

- Yongbyon reactor, 10 MWth, 0.7 capacity factor, 365 days, 0.9 grams/MWth-d
- Answer: 2,299 grams/year, or 2.3 kg/year
- Arak reactor, 40 MWth, 0.7 capacity factor, 365 days, 0.9 grams/MWth-d
- Answer: 9,198 grams/year (or about 9 kg/year)

This book uses two main approaches to estimating the amount of weapon-grade plutonium produced in production reactors. The first approach involves a simple approximation of average annual weapon-grade plutonium production. It can be represented by the following equation:

$$Pu_{\text{yearly total}} = P_{\text{thermal power}} \times C \times (365 \text{ days}) \times F$$

where *P* is the nominal thermal power of the reactor and *C*, often called the capacity or 'innage' factor, represents the ratio of the total annual heat output to the annual heat output based on continual full-power operation. This ratio is often stated to be the fraction of the year the reactor operates at full power. The last factor in the equation, *F*, represents a plutonium conversion factor which gives the amount of plutonium produced per megawatt-day of thermal output (MWth-d) from the reactor. For weapon-grade plutonium produced in a graphite-moderated, natural uranium reactor, the factor is about 0.9 g weapon-grade plutonium per MWth-d (g/MWth-d).[1] Because weapon-grade plutonium includes all plutonium with more than 93 per cent ^{239}Pu, this conversion factor can vary by up to 10 per cent (ignoring the uncertainty of the estimate itself). This variation reflects the range of burnup for irradiated fuel containing weapon-grade plutonium. Table A.1 contains typical conversion factors for several types of reactor.

[1] Turner, S. E., *et al.*, *Criticality Studies of Graphite-Moderated Production Reactors*, Report prepared for the US Arms Control and Disarmament Agency, SSA-125, Southern Sciences Applications, Washington, DC, Jan. 1980.

From Plutonium and Highly Enriched Uranium, 1996