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Title: Fuel Fabrication and Nuclear Reactors

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Fuel Fabrication and Nuclear Reactors

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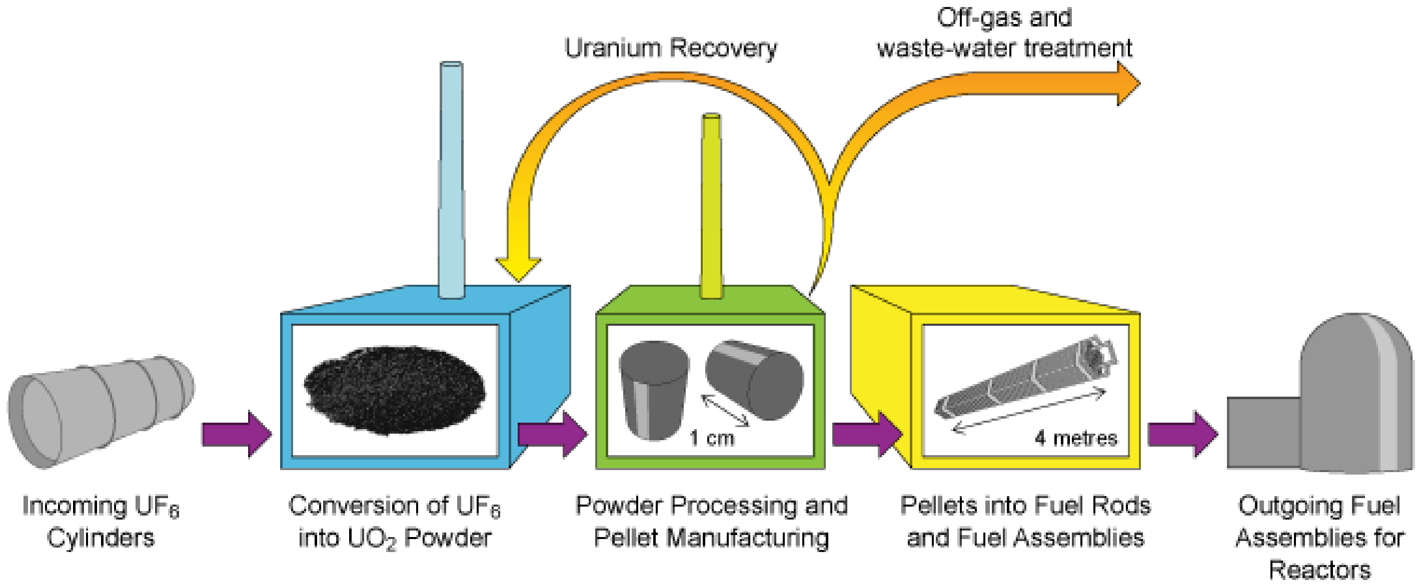
Fuel Fabrication Overview

- The uranium from the enrichment plant is still in the form of UF_6
- UF_6 is not suitable for use in a reactor due to its highly corrosive chemistry as well as its phase diagram
- UF_6 is converted into UO_2 fuel pellets, which are in turn placed in fuel rods and assemblies

Fuel Fabrication Overview

- Produce pure uranium dioxide (UO_2) from incoming UF_6 or UO_3.
- Produce high-density, accurately shaped ceramic UO_2 pellets.
- Fabricate the rigid metal framework for the fuel assembly



Steps in Fuel Fabrication – Part 1

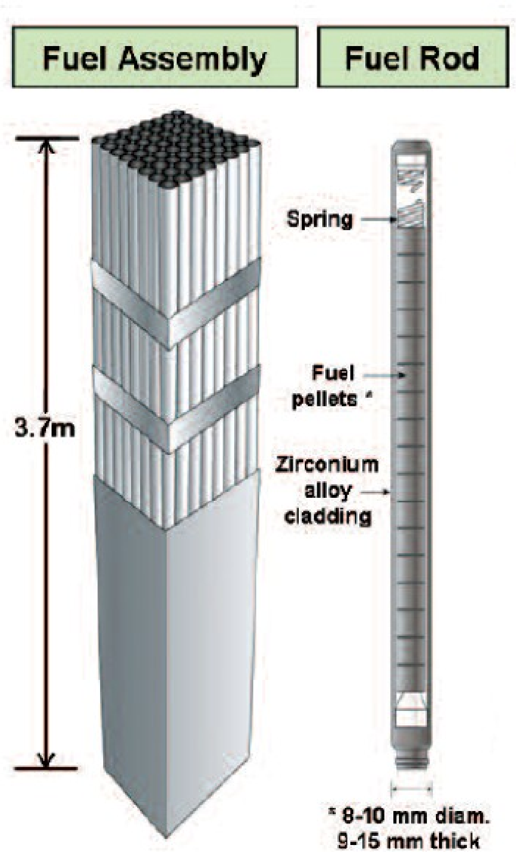
1. Heat cylinder of UF_6
2. Bubble UF_6 gas in water to make UO_2F_2
3. Mix with ammonia and water to get ammonium diuranate $(NH_4)_2U_2O_2$
4. Dry at high temp (calcine) to get U_3O_8
5. Further reduce with H to get UO_2
6. Grind into fine powder
7. Add adhesive and press into a cylindrical “green” pellet
8. Sinter green pellets at 1650° C in hydrogen atmosphere
9. Load into cladding (fuel rods)
10. Assemble fuel bundle

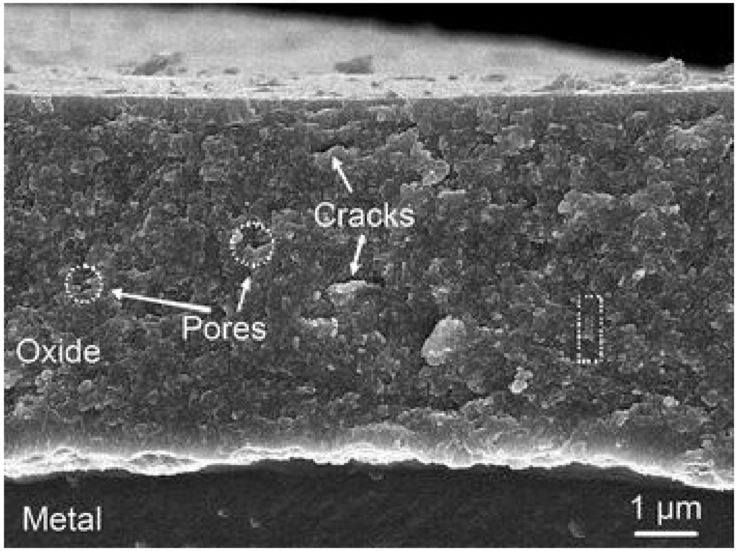
Steps in Fuel Fabrication – Part 2

1. Heat cylinder of UF_6
2. Bubble UF_6 gas in water to make UO_2F_2
3. Mix with ammonia and water to get ammonium diuranate $(NH_4)_2U_2O_2$
4. Dry at high temp (calcine) to get U_3O_8
5. Further reduce with H to get UO_2
6. Grind into fine powder
7. Add adhesive and press into a cylindrical "green" pellet
8. Sinter green pellets at 1650° C in hydrogen atmosphere
9. Load into cladding (fuel rods)
10. Assemble fuel bundle

Cladding

Fuel pellets are housed in zirconium-alloy coated fuel rods

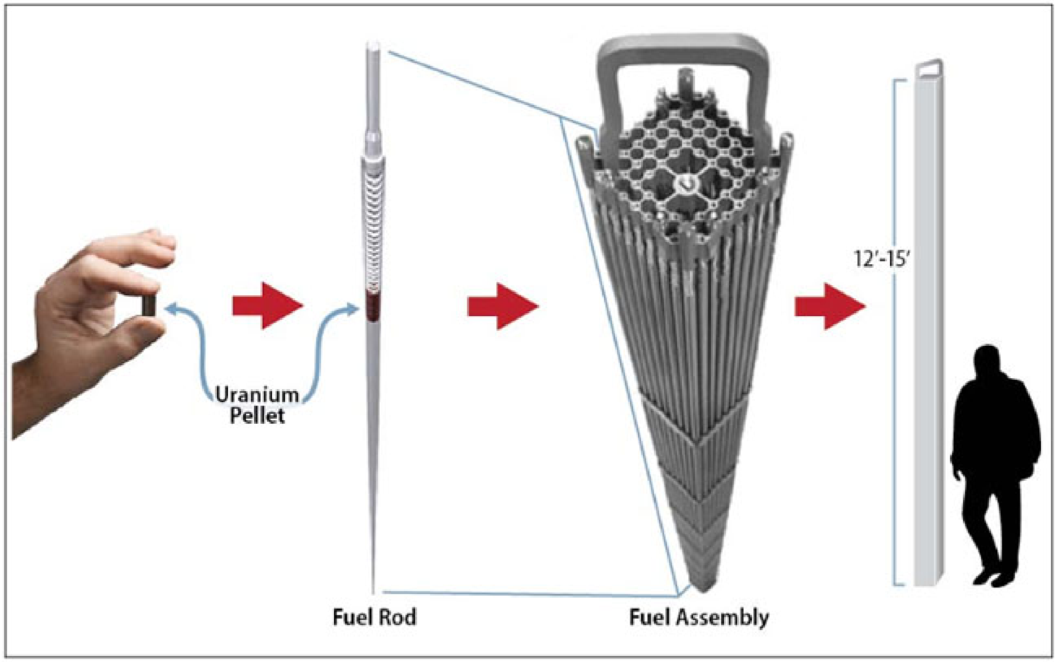




http://nucleotidings.com/article/nuclear-reactors-349-mit-researchers-working-improving-zirconium-cladding-nuclear-fuel-rods

In the extreme environment of the reactor the rods can exhibit signs of wear

Rods to Assemblies

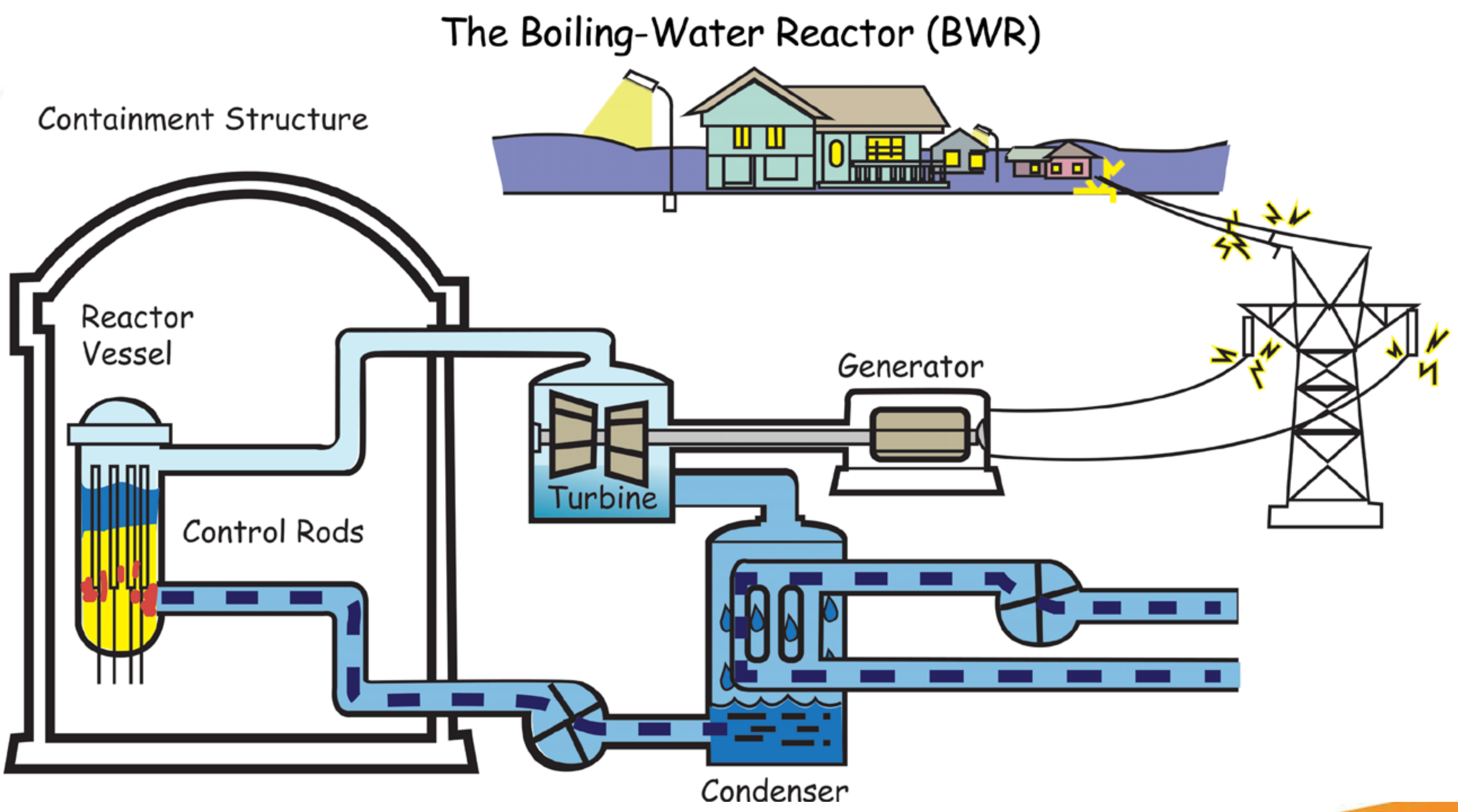


Nuclear Reactors

Types of Nuclear Reactors

- Categorize by Application
  - Power Reactors
  - Breeder Reactors
  - Research Reactors
- Categorize by Operation
  - Boiling Light-Water Reactors (BWR)
  - Pressurized Water Reactor (PWR)
  - Graphite Reactors
  - Other

Boiling Light-Water Reactors



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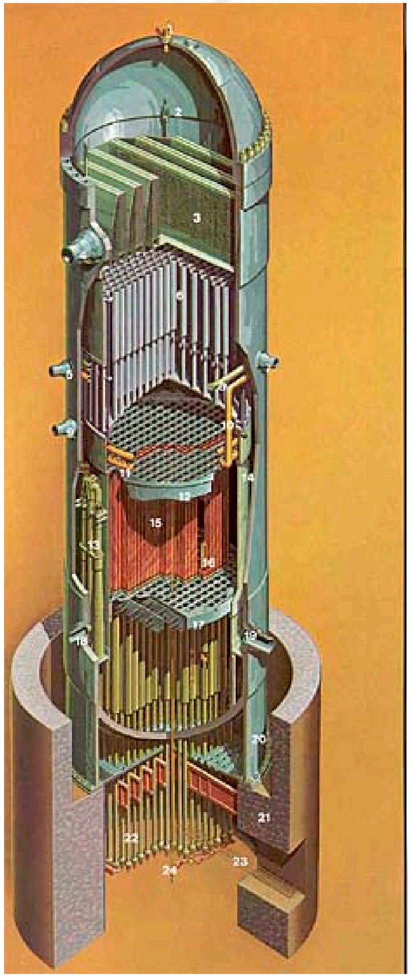
Boiling Light-Water Reactors



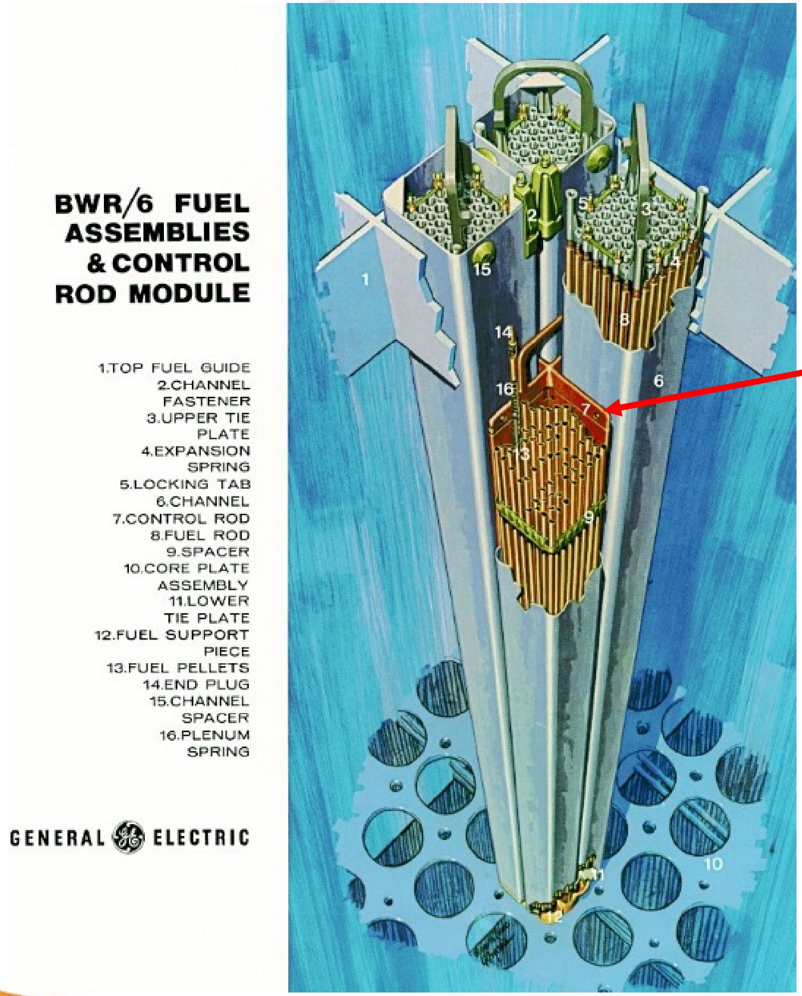
BWR/6
REACTOR ASSEMBLY

1. VENT AND HEAD SPRAY
2. STEAM DRYER LIFTING LUG
3. STEAM DRYER ASSEMBLY
4. STEAM OUTLET
5. CORE SPRAY INLET
6. STEAM SEPARATOR ASSEMBLY
7. FEEDWATER INLET
8. FEEDWATER SPARGER
9. LOW PRESSURE COOLANT INJECTION INLET
10. CORE SPRAY LINE
11. CORE SPRAY SPARGER
12. TOP GUIDE
13. JET PUMP ASSEMBLY
14. CORE SHROUD
15. FUEL ASSEMBLIES
16. CONTROL BLADE
17. CORE PLATE
18. JET PUMP / RECIRCULATION WATER INLET
19. RECIRCULATION WATER OUTLET
20. VESSEL SUPPORT SKIRT
21. SHIELD WALL
22. CONTROL ROD DRIVES
23. CONTROL ROD DRIVE HYDRAULIC LINES
24. IN-CORE FLUX MONITOR

GENERAL ELECTRIC

Water is both coolant and neutron moderator
Both water and steam exist in reactor vessel
Steam from reactor goes directly to turbine
Use LEU with 3 – 5 % ^{235}U
LEU Mass up to 140 tonnes
Pressures can be > 1000 psi
Core outlet temperatures > 286° C (~550 °F)
Thermal Efficiency ~ 33 - 37 %
Only use "chemical shim" as last resort
78 BWRs operating worldwide in Nov 2016

BWR Control Rods

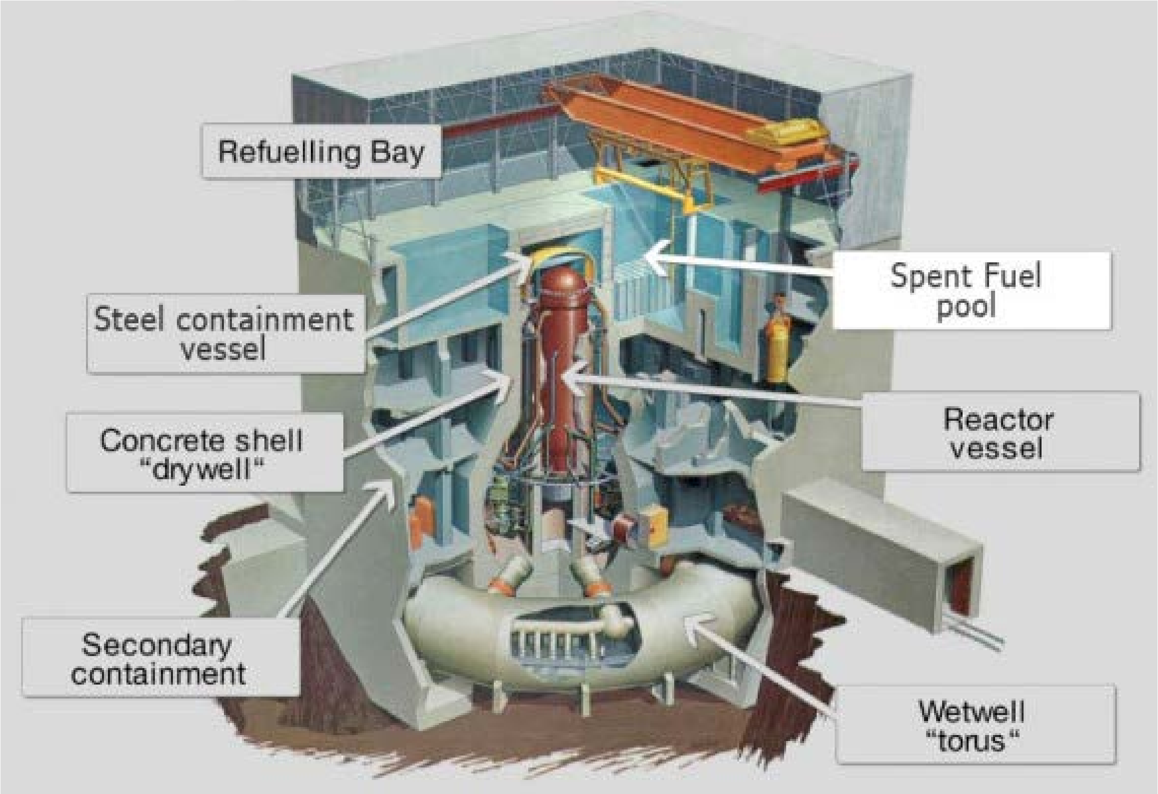


Control rods are used to control the fission rate in the reactor.

They are typically filled with neutron-absorbing material such as boron carbide.

In BWRs the control rods are cruciform blades between the fuel bundles and are hydraulically inserted from the bottom of the reactor.

Primary and Secondary Containment

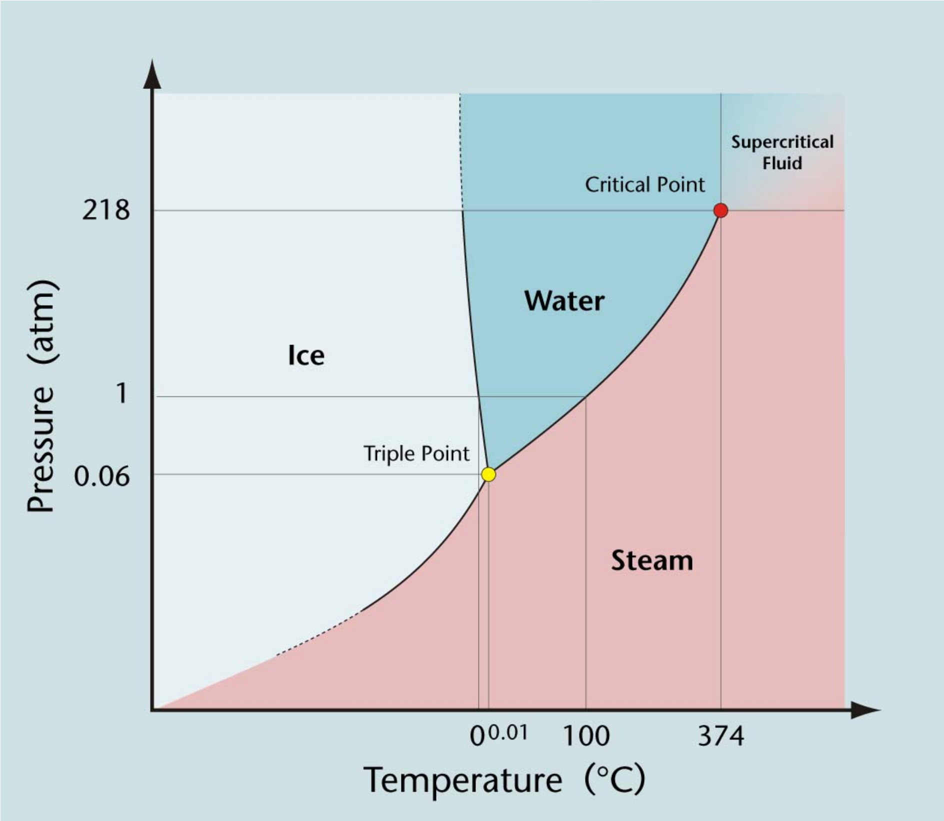


Phase Diagram for Water

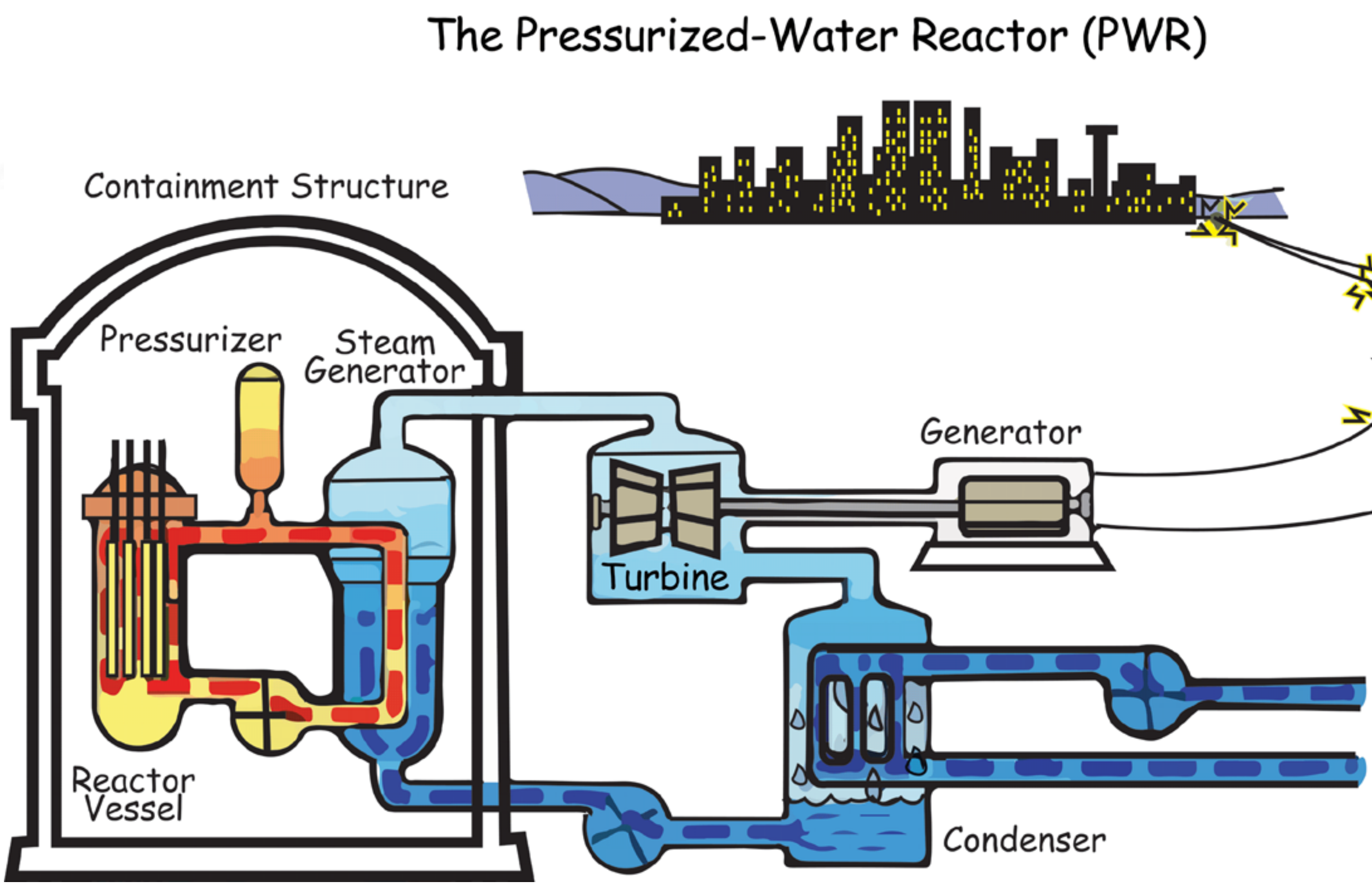
Water might boil at 100° C (212° F) at 1 atmosphere. But this is not always the case!

Even in a BWR, the temperature of the feed water to the reactor is well above 100° C - but it is at high pressure ~1000 psi (~68 atm).

In a PWR the pressure is even higher ~2250 psi (153 bar)



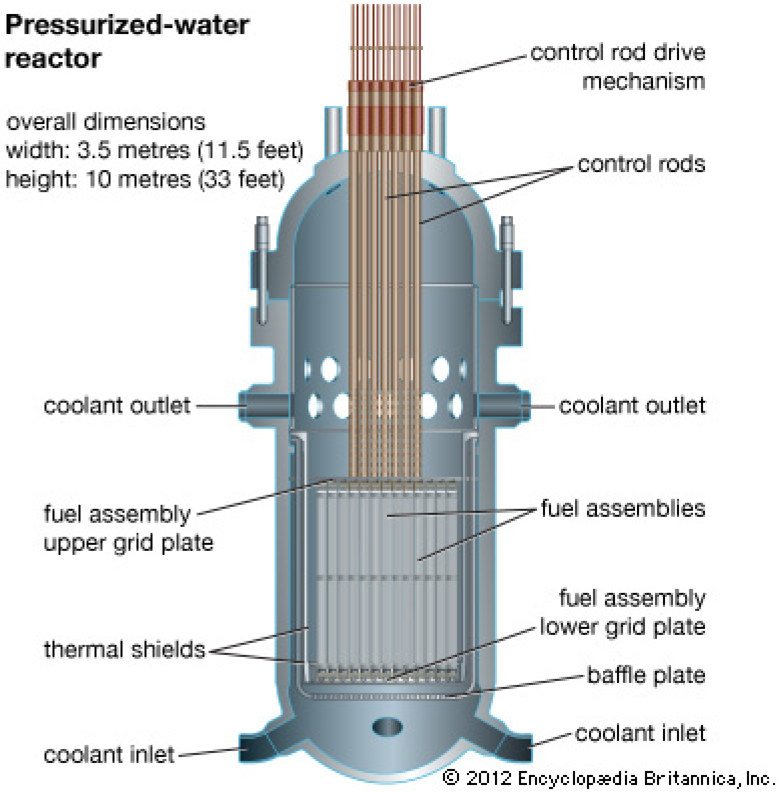
Pressurized Water Reactor



Unlike in a BWR, the reactor coolant does not flow through the turbine.

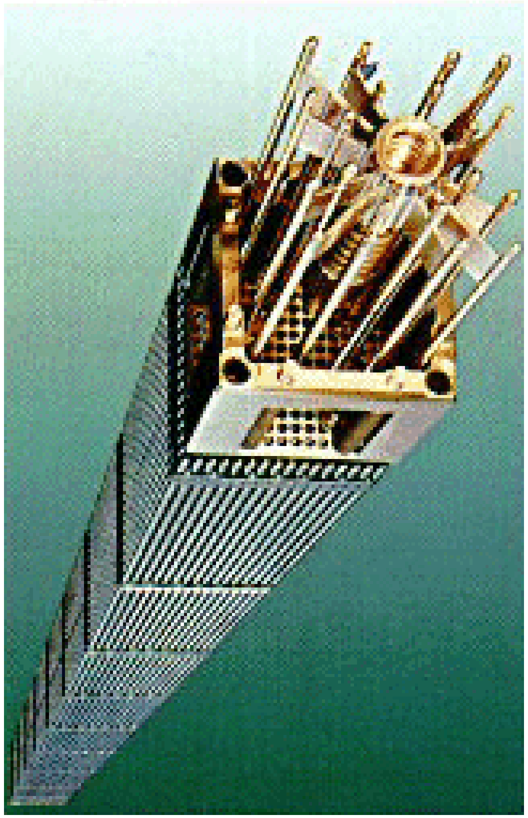
www.nrc.gov

Pressurized Water Reactors



Water is both coolant and neutron moderator
No steam exists in reactor vessel
Steam generator used in secondary loop
Use LEU with 3 – 5 % ^{235}U
LEU mass up to 100 tonnes
Pressures can be > 2200 psi
Core outlet temperatures ~ 315° C (~599 °F)
Thermal Efficiency ~ 33 %
“chemical shim” in primary coolant
291 BWRs operating worldwide in Nov 2016

PWR Control Rods



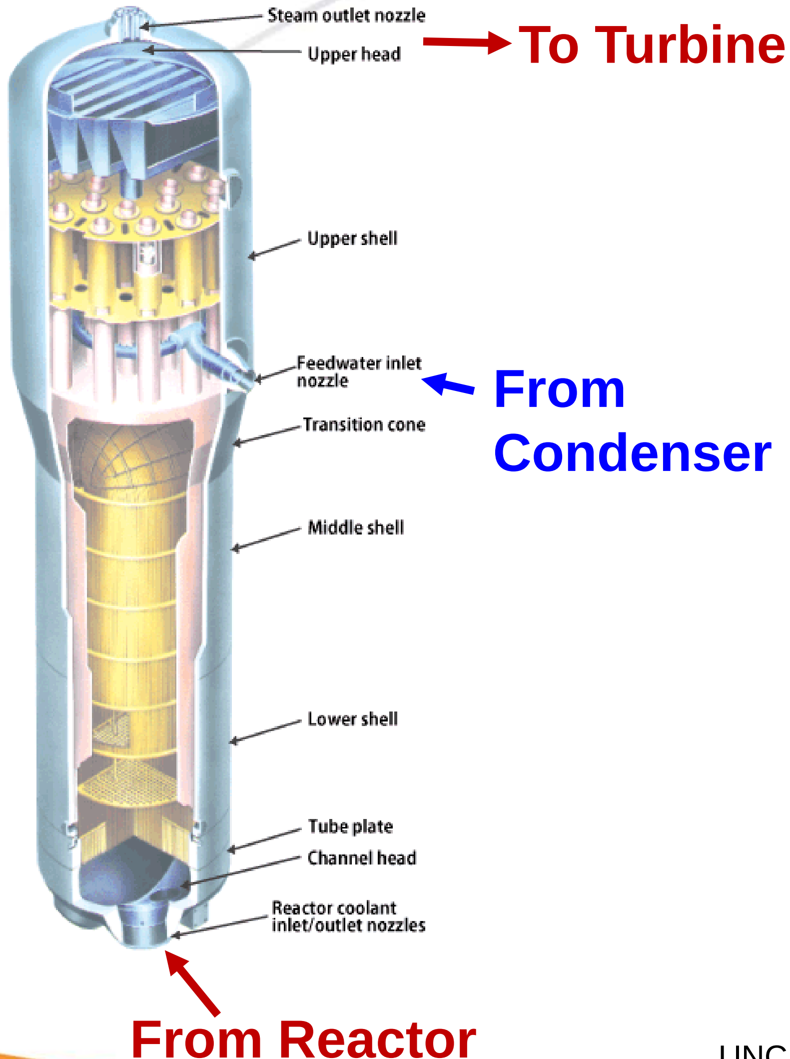
Just as in BWRs, control rods are used in PWRs to control the fission rate in the reactor.

Unlike the cruciform blades seen in BWRs the control rods in PWRs are inserted directly into the fuel bundles.

As there is no steam dryer over the core the controls rods can be inserted (electro-mechanically) from the above of the reactor.

Note that in PWRs, boric acid is normally mixed into the primary coolant as an additional control mechanism (chemical shim)

PWR Steam Generator



The steam generator is the link connecting the primary coolant loop of the reactor with the loop for the turbine generator.

The two basic sections are a lower U-tube heat exchanger and an upper steam drum section.

The reactor water remains water but the water from the turbine loop boils making steam that drives the turbine.

BWR vs. PWR

- BWRs have a higher thermal efficiency than PWRs
- BWRs do not use chemical shims
- BWR vessels are subjected to less radiation than PWRs
- But BWRs are more complex in design
- BWR’s require a larger reactor vessel
- BWR design allows a small amount of radioactive contamination to get into the turbine system.
- BWRs are more costly

Producing Plutonium

Los Alamos NATIONAL LABORATORY EST. 1943

- Plutonium is produced in a reactor via neutron absorption by and subsequent decay of ^{238}U

$$^{238}_{92}U + n \rightarrow {}^{239}_{92}U \xrightarrow[23.5m]{\beta-} {}^{239}_{93}Np \xrightarrow[2.35d]{\beta-} {}^{239}_{94}Pu$$

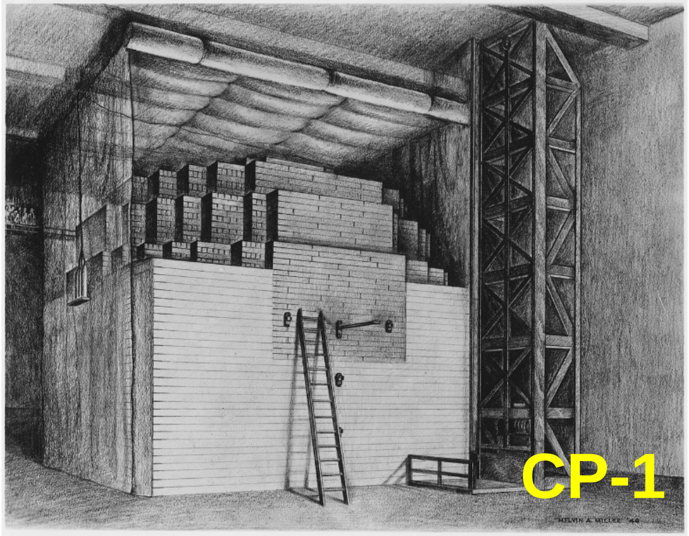
- Use natural uranium (>99% ^{238}U)
- Minimize Neutron-absorption by moderator
  - Water: 0.332 barns (Worst)
  - Graphite: 0.0035 barns
  - Heavy Water: 0.00052 barns (Best)

Grades of Plutonium

- Plutonium is always found as a mixture of nuclides where
  - ^{239}Pu and ^{240}Pu are the 'major isotopes'
  - ^{240}Pu is usually the dominant neutron emitter due to its abundance
  - ^{241}Am is a daughter of ^{241}Pu and is the dominant gamma emitter in unshielded or lightly shielded items
- Grades of Plutonium
  - Weapons Grade: < ~10% ^{240}Pu (US WGPu is 6% ^{240}Pu)
    - WGPu may also be called 'Low Burnup'
  - Reactor Grade: > ~10 % ^{240}Pu (may be > 25%)
    - RGPu may also be called 'High Burnup'

Graphite Reactors

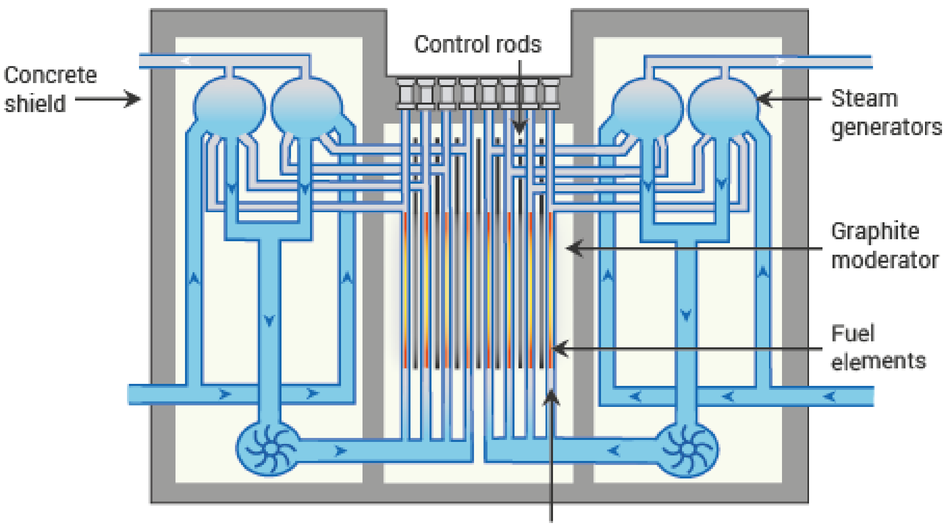
- Graphite is the neutron moderator
- Cooling media
  - Water (RBMK)
  - Gas (Magnox)
  - Molten Salt (MSRE)



- Approximately 30 graphite-moderated reactors operating worldwide

RBMK Graphite Reactor

A Light Water Graphite-moderated Reactor (LWGR/RBMK)



The RBMK is based on a Soviet-era design for plutonium production

It is the oldest reactor design still in wide use (11 operating in Russia only)

Core is made of 25cm^3 graphite blocks with holes for fuel and control rods

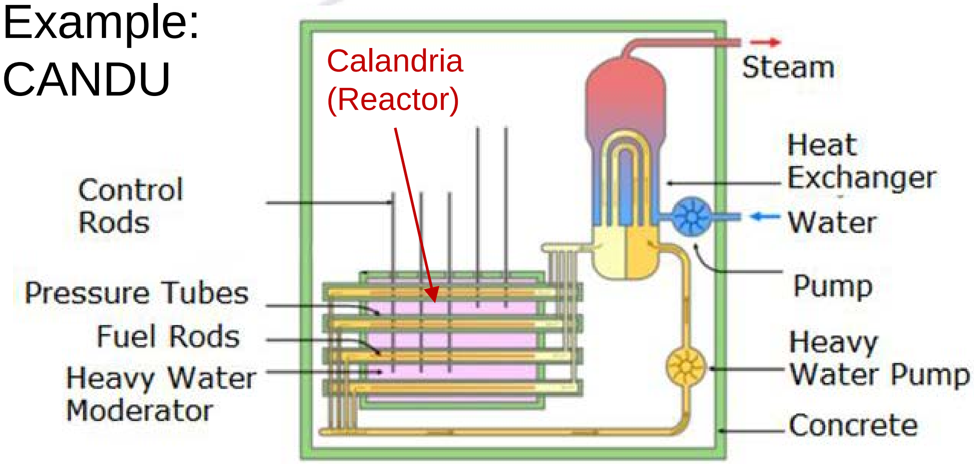
RBMK reactors in service since the time of the Chernobyl accident in 1986 have been retrofitted to address design flaws.

Gas-Cooled Graphite Reactor

- Magnox reactors were developed in the UK from the 1950's – 1970's
- Magnox is from magnesium-aluminum alloy cladding on fuel rods
- Coolant was carbon-dioxide
- Fuel was natural uranium
  - Initial mission was to produce plutonium
- North Korea also developed their own Magnox reactors, based on the UK design which was made public at an Atoms for Peace conference

Heavy-Water Reactors

Example:
CANDU



Heavy-Water reactors have a moderator that is D_2O.

The main advantage is that they can be fueled with natural uranium.

The main disadvantage is the greater proliferation risk due to plutonium production

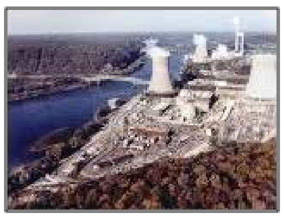
Generation IV Initiative

Los Alamos NATIONAL LABORATORY EST. 1943

Generation IV: Nuclear Energy Systems Deployable no later than 2030 and offering significant advances in sustainability, safety and reliability, and economics

Generation I

Early Prototype Reactors



- Shippingport
- Dresden, Fermi I
- Magnox

Generation II

Commercial Power Reactors

- LWR–PWR, BWR
- CANDU
- VVER/RBMK

Generation III

Advanced LWRs

- ABWR
- System 80+
- AP600
- EPR

Near-Term Deployment

Generation III+ Evolutionary Designs Offering Improved Economics

....

Generation IV

- Highly Economical
- Enhanced Safety
- Minimal Waste
- Proliferation Resistant

Gen I	Gen II	Gen III	Gen III+	Gen IV

1950 1960 1970 1980 1990 2000 2010 2020 2030

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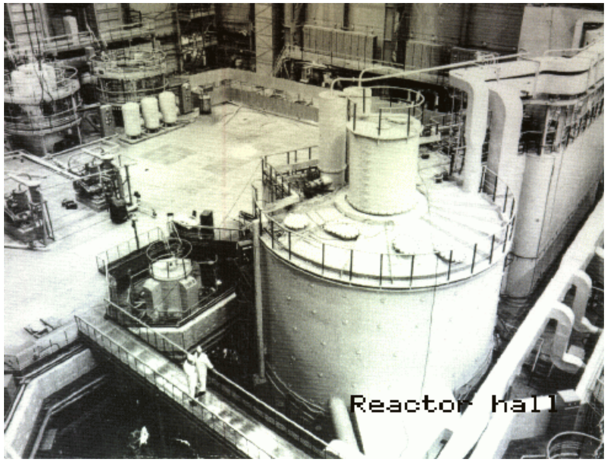
Fast vs. Slow Neutrons

Fission Probabilities of Selected Actinides, Thermal vs. Fast Neutrons[3][4][5][6][7]

Isotope	Thermal Fission Cross Section	Thermal Fission %	Fast Fission Cross Section	Fast Fission %
Th-232	nil	1 (non-fissile)	0.350 barn	3 (non-fissile)
U-232	76.66 barn	59	2.370 barn	95
U-233	531.2 barn	89	2.450 barn	93
U-235	584.4 barn	81	2.056 barn	80
U-238	11.77 microbarn	1 (non-fissile)	1.136 barn	11
Np-237	0.02249 barn	3 (non-fissile)	2.247 barn	27
Pu-238	17.89 barn	7	2.721 barn	70
Pu-239	747.4 barn	63	2.338 barn	85
Pu-240	58.77 barn	1 (non-fissile)	2.253 barn	55
Pu-241	1012 barn	75	2.298 barn	87
Pu-242	0.002557 barn	1 (non-fissile)	2.027 barn	53
Am-241	600.4 barn	1 (non-fissile)	0.2299 microbarn	21
Am-242m	6409 barn	75	2.550 barn	94
Am-243	0.1161 barn	1 (non-fissile)	2.140 barn	23
Cm-242	5.064 barn	1 (non-fissile)	2.907 barn	10
Cm-243	617.4 barn	78	2.500 barn	94
Cm-244	1.037 barn	4 (non-fissile)	0.08255 microbarn	33

https://en.wikipedia.org/wiki/Breeder_reactor

Fast-Neutron Reactors



BN-350 Aktau, Kazakhstan

Fast reactors do not have a moderator and therefore operate using fast neutrons for fission

Since ^{235}U fission cross section is lower for fast neutrons a higher enrichment is generally required.

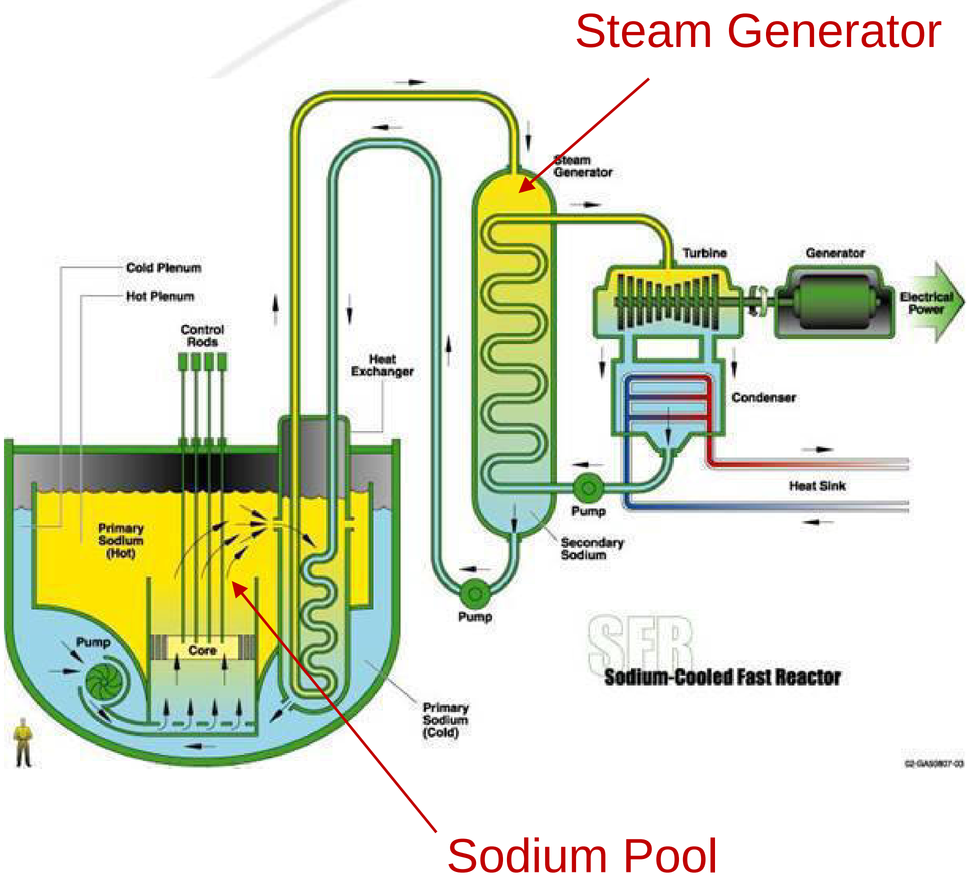
But fast neutrons can also fission ^{238}U

Fast neutrons are more likely to fission actinides than slow neutrons.

Fast reactors are often employed as ‘breeders’ with a ^{238}U blanket around the core to make ^{239}Pu

‘Clementine’ was the first fast reactor. It was built by LANL in 1946.

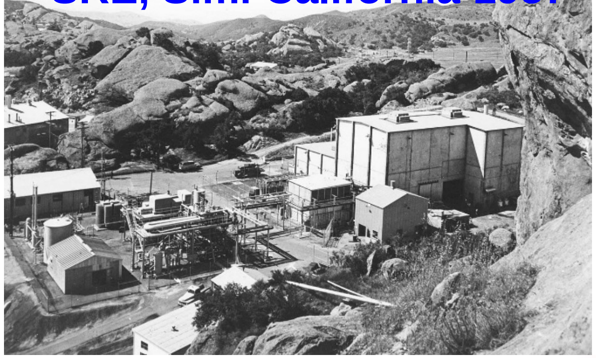
Sodium-Cooled Fast Reactors



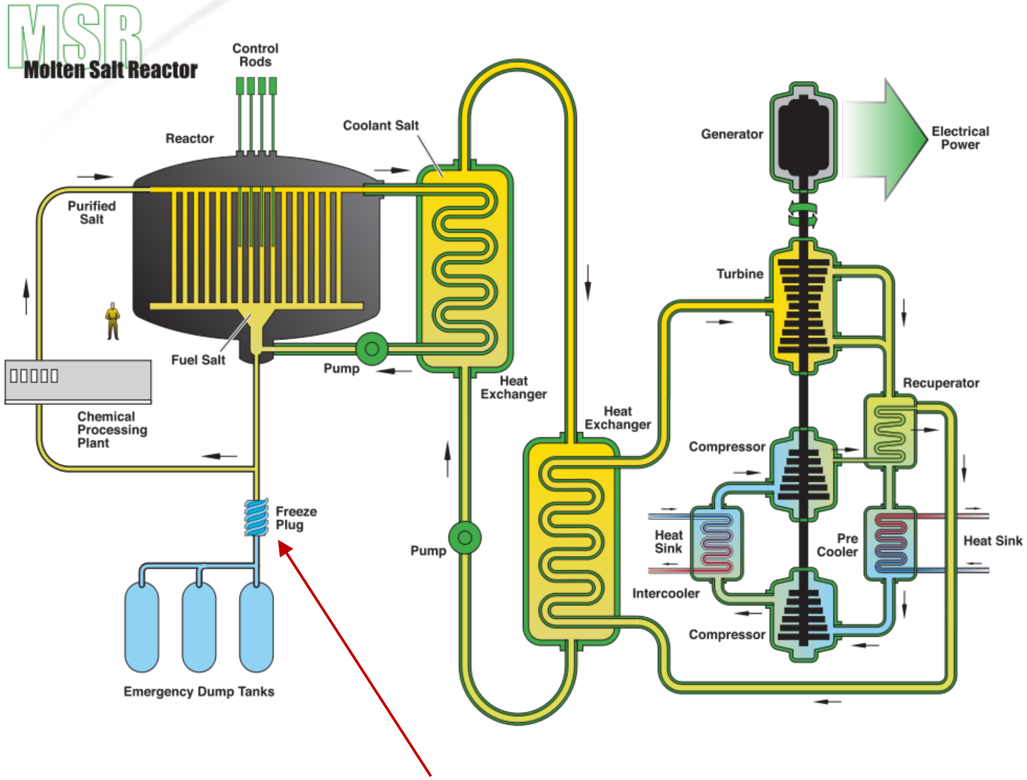
Coolant is liquid sodium (T_{boil} = 1621° F)
Na vapor pressure << H_2O vapor pressure
Na explodes when submerged in water

Pioneered by the US in the 1950's
New Generation IV designs are in the works by China, France, Russia
Fuel cycle would rely on recycling of actinides

SRE, Simi California 1957



Molten Salt Reactors



With power loss, the (salt) freeze plug coolers shut down, the freeze plug melts and the salt drains into dump tanks

Molten salt reactors have fuel dissolved in coolant as a 'fuel salt'

Thorium, uranium, and plutonium all form suitable fluoride salts that readily dissolve in the LiF-BeF2 (FLiBe)

MSRs were pioneered in the 1960's with the Molten Salt Reactor Experiment at ORNL

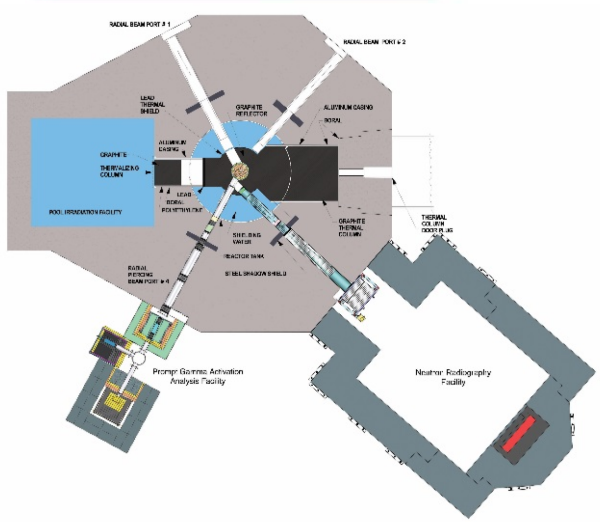
MSRs employ a 'freeze plug' as a safety mechanism

Salts are in a liquid state from 500 C to 1400° C at 1 atm

Can run with fast neutrons or graphite moderated

MSRs have large negative temperature and void coefficients

Research Reactors



Research reactors have been used around the world since

E.g. General Atomics TRIGA reactors were built in 66 facilities in 24 countries on five continents.

Used by universities and national laboratories for neutron scattering and activation analysis etc.

Some older reactors use HEU enriched to 93% but efforts have been underway for decades to convert these to LEU

About 243 research reactors operating in 55 countries in 2016

Three-Mile Island

March 28, 1979

Main feed water pumps stopped sending water to steam generator of TMI-2

Reactor shut down but pressure began to rise

Instruments did not indicate pressure rise

Relief opened to relieve pressure but stuck open draining coolant from the reactor

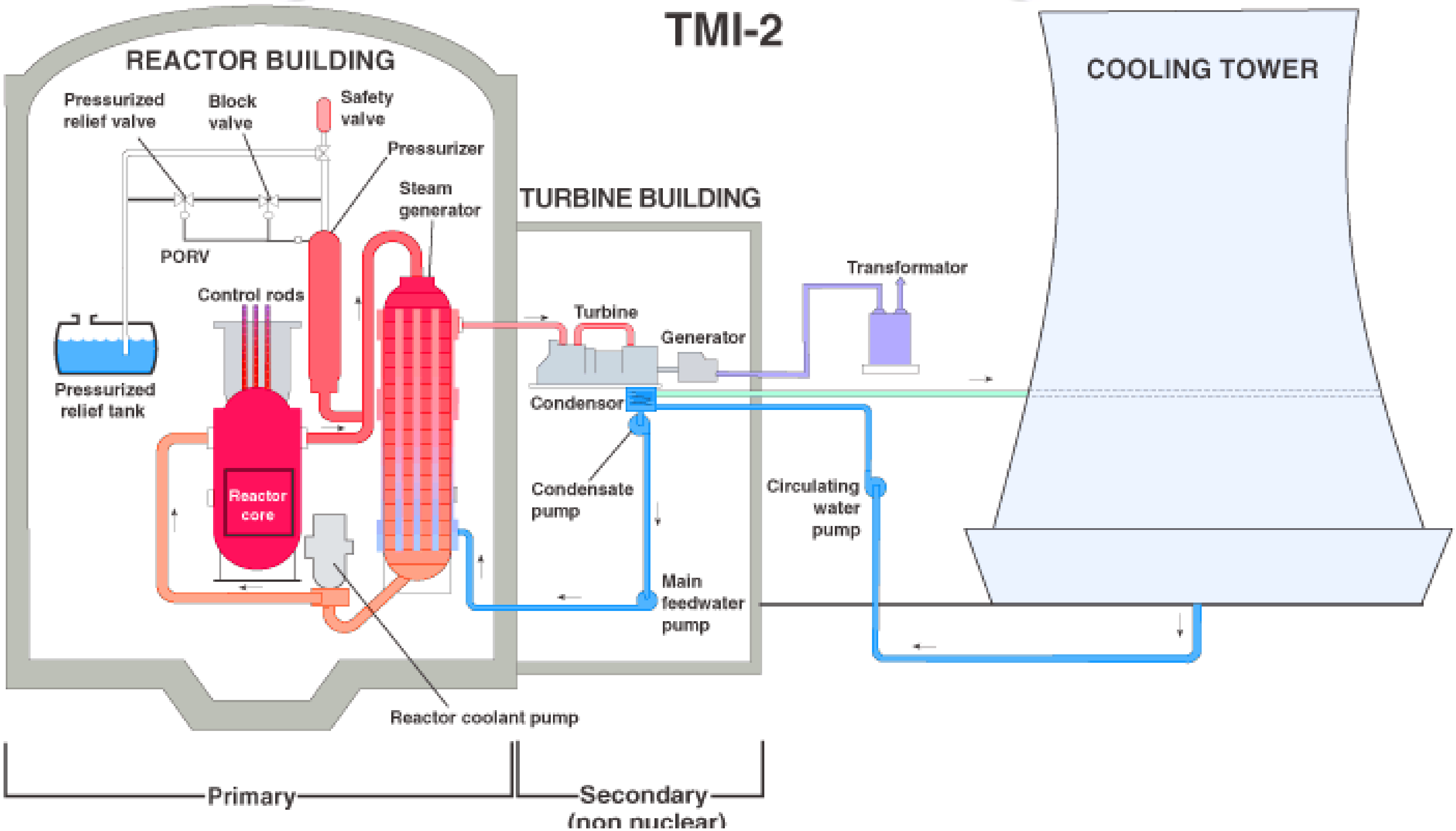
Instruments indicated valve was closed but other alarms sounded

Reactor coolant pumps, needed to be turned off to avoid dangerous vibrations

Fuel rod cladding ruptured, and fuel partially melted

https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html

Three-Mile Island



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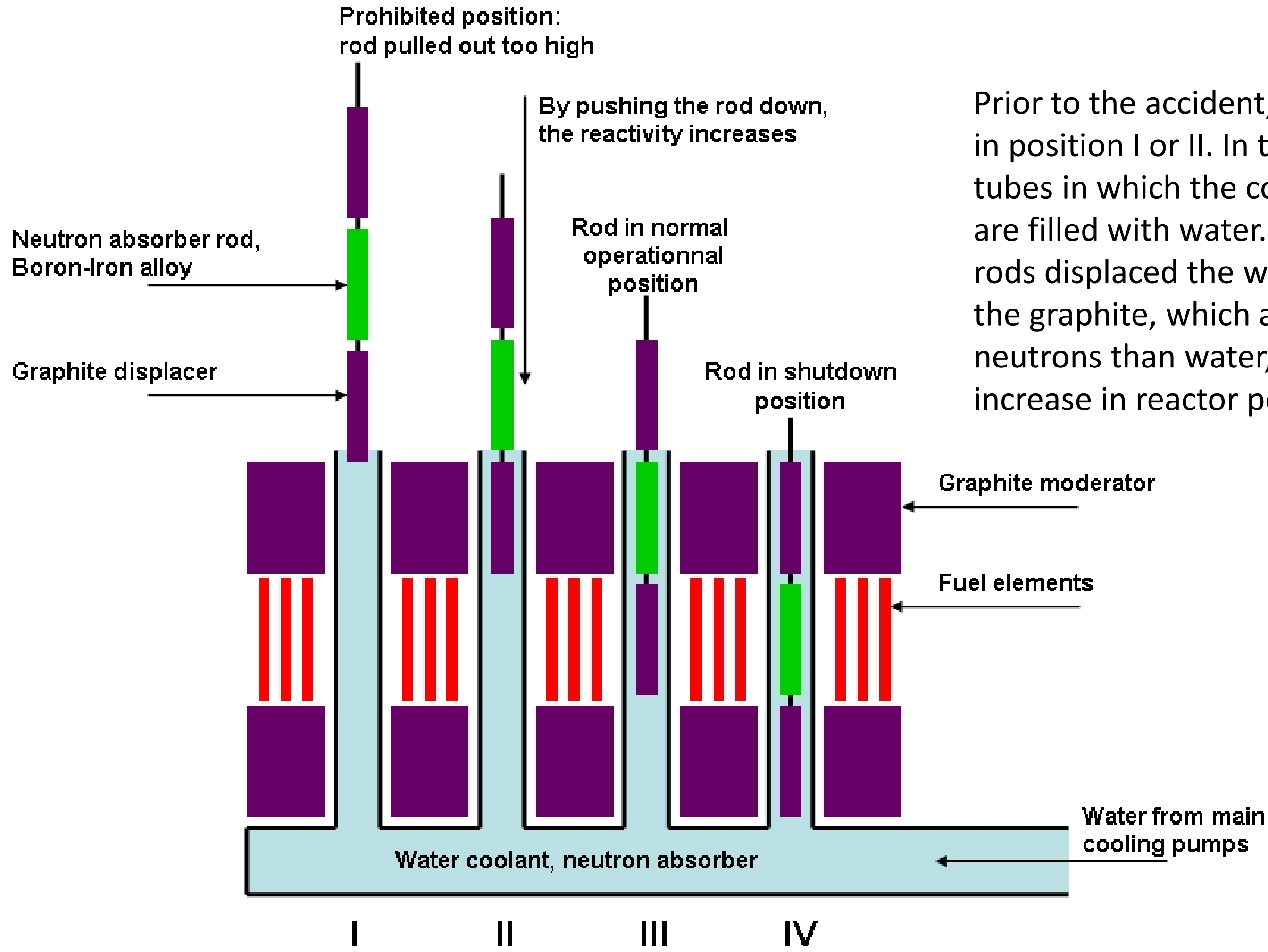
Chernobyl

- Void Coefficient
  - Steam bubbles in water are voids
  - Negative Void Coefficient:
    - When water is both coolant and moderator, excess steam reduces power
  - Positive Void Coefficient:
    - When water is the coolant and something else like graphite is the moderator, excess steam means less water to absorb neutrons – so power will increase.
    - This was a design flaw of early RBMK reactors

Chernobyl Control Rods



Prior to the accident, most of the rods were in position I or II. In these positions, the tubes in which the control rods slide down are filled with water. When inserted, the rods displaced the water and replace it with the graphite, which absorbs less the neutrons than water, thereby causing an increase in reactor power.

Chernobyl

April 4, 1986

Test of cooling system during a power loss was conducted

Reactor emergency cooling system was disabled

Power dropped more than expected and control rods were removed from the reactor (8 rods in vs. 15 min. allowed)

Various factors led to severe power increase and SCRAM was initiated at 1:23:43.

The graphite-tipped control rods were inserted and reactivity increased

Fuel elements overheated an ruptured, leading to a jamming of the control rods not yet fully in place

Steam increase exacerbated positive void coefficient

Steam and hydrogen explosions destroyed the containment.

Fukushima

March 11, 2011

A tsunami follows a magnitude 9.0 earthquake

Reactors shut down due to quake but the tsunami damaged seawater pumps, residual-heat-removal pumps, diesel generators, batteries etc. resulting in a station blackout

Steam and eventually hydrogen built up in the BWR vessels. The wet well torus could not compensate

Hydrogen explosion blew the roof off of Unit 1 on Mar 12th.

The fuel partially melted in Unit 1 but significantly so in Units 2 and 3

Leak of the primary containment of Unit 2 occurred releasing most of the radioactivity in the incident

Summary

- Reactor designs are variable in moderators, coolants, fuel, performance etc.
- The dream of energy ‘too-cheap to meter’ is no more but, even in the light of disasters like Fukushima, the nuclear power industry is pushing ahead with advanced reactor designs
- Thorium Fuel Cycle Reactors will be addressed in a later presentation.