Nuclear Energy – "But they blow up!"

John C. Bean

Outline

Tracking atomic Nuclei: What they contain, how that can change, and the energies involved

Nuclear Fission of abundant Uranium 238 vs. rare Uranium 235

Use of "moderators" to slow emitted neutrons => Sustained fission chain reactions

  vs. neutron "poisons" vs. neutron "mirrors"

Chain reactions in bombs vs. chain reactions in nuclear reactors

Common "light water" moderated reactors:

  Boiling Water Reactors (BWR) vs. Pressurized Water Reactors (PWR)

As opposed to carbon-moderated RBMK reactors

The Accidents:

  Three Mile Island / Chernobyl / Fukushima Daiichi

Does massive use of concrete severely undermine nuclear's claim of near zero greenhouse emissions?

(Heavily Revised & Expanded: Summer 2024)

On this website, my sequence of topics has been a bit strange:

I started by trying to explain the basic science behind electrical power

I then described **almost** all of the ways we traditionally produce electrical power

I followed that with descriptions of up-and-coming electrical power technologies

Then, running short of possibilities, I explored a range of exotic long-shot solutions

Only now am I returning to **our biggest source of nominally-carbon-free electricity**:

Nuclear Power

I followed this strange path because I suspect many of you are uneasy about nuclear power

So am I

And I may have a stronger personal reason to be uneasy than you:

Early in my marriage, when my wife and I were hoping for a first child

A nuclear reactor called Three Mile Island blew up

125 miles directly upwind from our home

And we had to decide whether to evacuate my possibly pregnant wife

So yes, I am uneasy about nuclear power, but following the path I've taken you along,
I've reluctantly concluded that greener technologies may not be ready
to have a big enough impact, in a short enough time

This has led me and many others (including major scientific & environmental organizations[1-4])
to not only ask if we might be able to **live** with nuclear reactors,
but if they can improved to the point that we feel **comfortable** living with them

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1) https://climatecoalition.org/union-of-concerned-scientists-support-nuclear-power/
2) https://www.ucsusa.org/sites/default/files/attach/2018/11/Nuclear-Power-Dilemma-full-report.pdf
3) https://virginia-recycles-snf.com/wp-content/uploads/2020/03/The-Activists-Who-Embrace-Nuclear-Power-_-The-New-Yorker.pdf
4) https://www.npr.org/2022/08/30/1119904819/nuclear-power-environmentalists-california-germany-japan

"But they blow up!"

Yes they (or at least three of them) have (sort of) blown up

Leading many to now fear not only similar future explosions,

but also the possibility of a future explosion reaching full nuclear bomb intensity

To address those concerns this note set will explore:

The science & technology of nuclear reactors

The sometimes similar / sometimes different technology of nuclear-fission "atomic" bombs [1]

The history of WWII nuclear atomic bomb development, which provides insights into

how "nuclear energy" initiatives can provide cover for nuclear weapons proliferation

This will, however, require a bit of Nuclear Physics background

Which may never have featured in any class you ever attended

(and never even surfaced in any class preparing me for an Applied Physics career)

Fortunately, we only need a **few concepts** PLUS a modest dose of **nomenclature and jargon**

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1) As opposed to later nuclear-fusion "Hydrogen" bombs - which are still triggered by nuclear-fission "Atomic" bombs

A Short(ish) Dive into Nuclear Physics:

Twentieth vs. Twenty-First Century Nuclear Physics

Nuclear Physicists of the last fifty years have been obsessed with sub-sub-nuclear particles

to which they delight in assigning weird names including:

up / down / top / bottom / strange / charmed quarks, leptons, bosons, gluons, . . . "god"

But Nuclear Reactors and Bombs can be explained by mid-twentieth century Nuclear Physics

in which sub-sub-nuclear particles still lurked secretly inside only **two nuclear particles:**

Positive Protons ("p" or ●) and Neutral Neutrons ("n" or ●)

Which DID, however, already exhibit a couple of weird behaviors:

1) They could **transform** into one another via incorporation or emission of negative electrons

1 Proton + 1 Electron → 1 Neutron OR 1 Neutron → 1 Proton + 1 Electron

2) These transformations DID NOT PRECISELY CONSERVE MASS

Instead, **Einstein's $E = mc^2$** demanded that:

Even minute **Gain of Mass** required HUGE ENERGY INPUT

Even minute **Loss of Mass** led to HUGE ENERGY OUTPUT

Nuclear physics requires tracking those protons, neutrons & electrons:

Electron tracking evolved first, when pioneering Chemists realized that inter-atomic bonding was driven by the different number of electrons "belonging" to each type of atom

Which led those Chemists to classify different atoms based on their:

Atomic Number = A lone un-ionized atom's **# of nucleus-surrounding electrons**

But in a lone un-ionized (charge neutral) atom,

the **# of nucleus-surrounding electrons** must equal the **# of nuclear protons**

implying **Atomic Number is** also defined by the **# of nuclear protons**

What about charge-less nuclear **neutrons**? Later more daunting science [1] revealed that:

Nuclei of small, light, common atoms tend to have **# of neutrons = # of protons**

Less common variants & heavy atoms tend to have **# of neutrons ≥ # of protons**

However, as neutrons are added, nuclei are held together more weakly,

developing a tendency to spontaneously fall apart (i.e., **radioactively fission**)

Neutron count is buried in a **nucleon count** = # of protons + # of neutrons in a nucleus,

used as a leading superscript - making common Hydrogen with a nucleus of 1 proton: ^{1}H

1) To learn more, I highly recommend: "The Making of the Atomic Bomb" by Richard Rhodes (ISBN978-1-4516-7761-4)

Applying (and expanding) those definitions for the special case of Carbon:

98.9% of Carbon nuclei have 6 protons (6 p) + 6 neutrons (6 n)

Giving Carbon an **atomic number** of 6

and a **nucleon count** of 12, as symbolized by ^{12}C, or called "Carbon 12"

Atomic Mass CAN be stated in normal MKS gram or kilogram units, but the resulting tiny & complex numbers led instead to the use of **Atomic Mass Units (AMU),**

defined as 1/12 th the mass of a lone ^{12}C atom in its resting energy state

That definition meant (uniquely) that, ^{12}C has **exactly**:

Atomic Number = 6 Nucleon Count = 12 Atomic Mass = 12

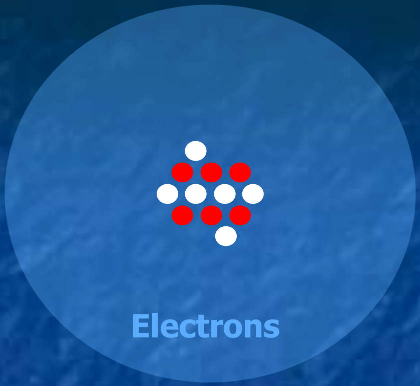
Why then does the periodic table show Carbon's mass as 12.011 AMU?

Because 1.06% of Carbon nuclei have instead 7 neutrons

And 10^{-10} % of Carbon nuclei have instead 8 neutrons

Together these are the ^{12}C, ^{13}C, and ^{14}C **isotopes** of carbon, with the small / tiny fraction of heavier isotopes boosting the **average** C mass to 12.011 AMU

For Carbon, trying to capture all of that visually: [1]



Protons, Electrons, Atomic # = **6**

Neutrons = **6**

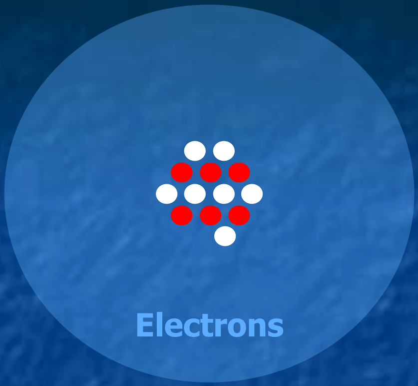
Nucleons = **12**

Symbol = **^{12}C**

Name = **Carbon 12**

Abundance = **98.9 %**

Mean Lifetime [2] = **Infinite**



Protons, Electrons, Atomic # = **6**

Neutrons = **7**

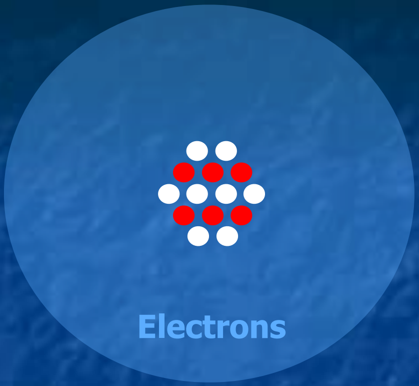
Nucleons = **13**

Symbol = **^{13}C**

Name = **Carbon 13**

Abundance = **1.06 %**

Mean Lifetime [2] = **Infinite**



Protons, Electrons, Atomic # = **6**

Neutrons = **8**

Nucleons = **14**

Symbol = **^{14}C**

Name = **Carbon 14**

Abundance = **10^{-10} %**

Mean Lifetime [2] = **5700 years**

1) Nuclear physic's tracking of protons, neutrons & electrons can easily confuse. In these notes I've thus put particular effort into my use of colors, tables and figures. Pause to study them - they may help you keep things straight.

2) Which nuclear physicists instead call radioactive ***Half-Life***

In nuclear reactors (and bombs) a few atoms play leading roles

Uranium (U), **Plutonium** (Pu) and, perhaps in the future, **Thorium** (Th)

Uranium, with an atomic mass of 238.02, is currently **the** major player

Its atomic mass suggests that Uranium's most common isotope is ^{238}U, which is indeed the case:

Uranium Isotope:	Abundance in Uranium Ore:	Radioactive Half-Life:
^{238}U	**99.27%**	**Half-life: 4.6 billion years**
^{235}U	**0.72%**	**Half-life: 703.8 million years**

Plus other isotopes, but all with natural abundance < 0.01%

Finite lifetimes mean these isotopes are ALL radioactive, eventually fissioning apart

But these extremely long lifetimes mean there is **minuscule decay within human lifespans**

In reactors OR bombs SOMETHING must vastly accelerate radioactive decay!

^{238}U *decay is strongly accelerated by collisions with* ***HIGH*** *energy neutrons:*

Also called **"hot"** or **"fast"** neutrons (which I will emphasize by using red text):

$^{238}\mathrm{U} + {}^{1}\mathrm{n}$ **(hot/fast)** → $^{239}\mathrm{U}$ → $^{239}\mathrm{Np} + \beta$ → $^{239}\mathrm{Pu} + \beta$

where **β ("beta")** is nuclear physics speak for a high energy electron

(which, like all electrons, have mass ~ 1/2000 that of protons and neutrons)

But ^{238}U fission CAN NOT SUSTAIN a nuclear chain reaction

Because while ONE hot neutron causes ONE ^{238}U atom to fission

that neutron is captured and no replacement neutrons are generated

Which helps explain why **^{238}U** survives as Uranium's most abundant isotope

But it doesn't explain high historical interest in **^{238}U's** dead-end radioactive decay

THAT interest focused instead on one of ^{238}U's nuclear fission products:

Plutonium 239 - Which produced the world's FIRST nuclear bomb explosion
at the 16 July 1945 "Trinity" test in Alamogordo New Mexico

*^{235}U decay is most strongly accelerated by collisions with **LOW** energy neutrons:*

Also called **"slow"** or **"thermal"** neutrons (which I will emphasize by using green text)

Its most likely fission decay path is:

^{235}U + ^{1}n (slow/thermal) → **^{236}U** → **^{89}Kr + ^{144}Ba + 2 ^{1}n (hot/fast)** + 200 MeV [1]

But it has many other possible but less likely decay paths, including: [2]

^{235}U + ^{1}n (slow/thermal) → **^{236}U** → **^{92}Kr + ^{141}Ba + 3 ^{1}n (hot/fast)** + 170 MeV

^{235}U + ^{1}n (slow/thermal) → **^{236}U** → **^{94}Zr + ^{139}Te + 3 ^{1}n (hot/fast)** + 197 MeV

The weighted average of all paths => **^{235}U fission produces ~ 2.4 (hot/fast) neutrons**

Incoming neutrons DO stimulate **^{235}U** fission, liberating larger numbers of outgoing neutrons

But this does NOT readily grow into a nuclear chain reaction

Because the liberated hot neutrons only weakly stimulate fission of other **^{235}U** atoms

(which, instead, interact strongly with only slow neutrons)

As circumvented in the Hiroshima Uranium Nuclear Bomb by means I'll discuss later

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1) "eV" = (charge on 1 proton or electron) x (1 Volt) = 1.6 x10 $^{-19}$ Coulomb - Volts = 1.6 x10 $^{-19}$ Joules of energy

2) http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/introduction/physics-of-nuclear-energy.aspx

Depictions summarizing ^{238}U and ^{235}U interactions with neutrons

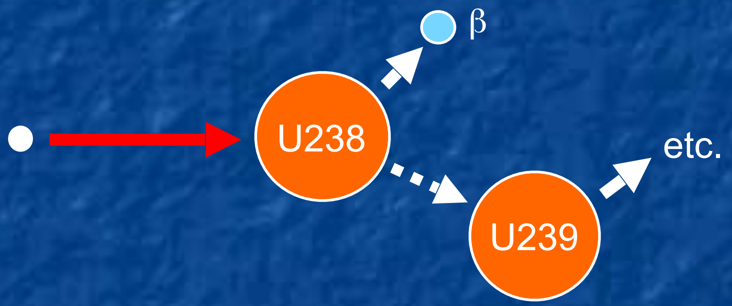
^{238}U:

Slow incoming neutron:

(Neutron just keeps on going)

Fast incoming neutron:

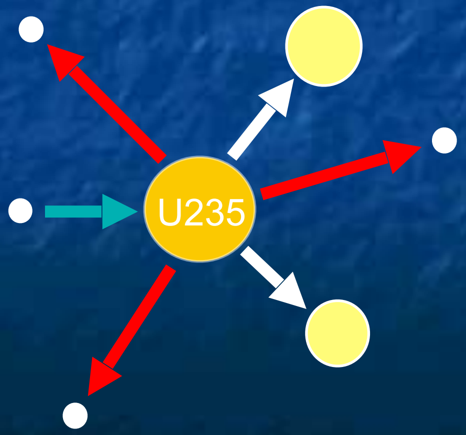
Neutron capture → Nuclear fission



^{235}U:

Slow incoming neutron:

Neutron capture → Nuclear fission



Fast incoming neutron:

(Most Neutrons just keep on going)

But what if a fissioning ^{235}U's fast neutrons could be slowed down?

THAT could sustain a rapid ^{235}U chain reaction, as neutrons emitted by one ^{235}U fission would then trigger fission of several more ^{235}U's (and so on and so on)

And, at least in principle, there is an simple way of doing this:

Just force the hot neutrons to first bounce off the nuclei of a bunch of light atoms,

where "light" means atoms with mass roughly comparable to that of the neutrons

Those light atoms will strongly rebound, each capturing part of the neutron's kinetic energy

Light atoms = NEUTRON "MODERATORS" (neutron energy absorbers)

Think of a fast cue ball slowed by bouncing repeatedly off other billiard balls

But in real-life there are a couple of other complicating possibilities:

Neutron collisions will hardly budge very heavy atoms

The neutrons WILL bounce off in another direction

But the heavier the target atom, the less Kinetic Energy it will siphon away

Heavy atoms = NEUTRON MIRRORS (redirecting but minimally slowing neutrons)

Which CAN be used to KEEP neutrons within the core of a nuclear reactor or bomb

Think of a fast cue ball bouncing off a big steel ball-bearing or small bowling ball

While the nuclei of certain atoms instead CAPTURE and HOLD neutrons

These, with many possible masses = **NEUTRON ABSORBERS / POISONS / SINKS**

Prominent examples include Xenon (Xe), Iodine (I), and Boron (B)

Their natural occurrence can hinder certain desired chain reactions, but in an emergency their deliberate introduction can quench a runaway nuclear reactor

Think of a cue ball NOT bouncing off other glue-covered billiard balls

*Depicting hot **neutron** interaction with **moderators**, **mirrors** and **poisons***

Before: **After:**

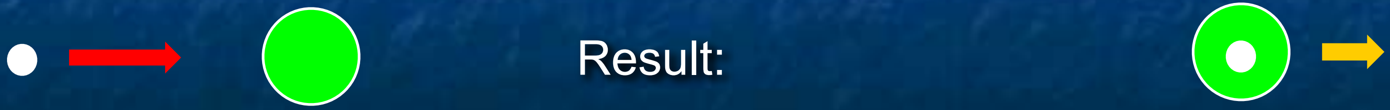
Neutron Moderator (light atom that absorbs some of neutron’s kinetic energy):


Result:

Neutron Mirror (heavy atom that absorbs very little of neutron’s kinetic energy):


Result:

Neutron Poison (atom that absorbs and then holds neutron inside its nucleus):


Result:

*But some atoms BOTH desirably **Moderate** AND undesirably **Poison***

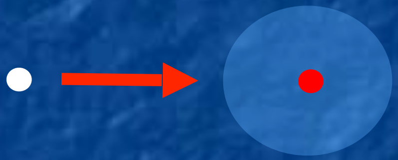
Most notably, **normal hydrogen (^{1}H)** with its nucleus of a single lone proton:

Because of the near match in proton and neutron masses

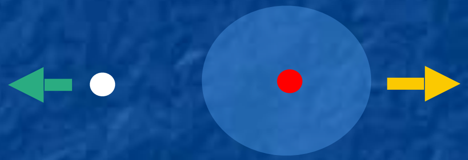
a neutron striking normal hydrogen can transfer a LOT of energy to it

Further, lots of such hydrogen atoms are readily available in water

Making normal hydrogen (and H_2O) a STRONG **Neutron Moderator:**

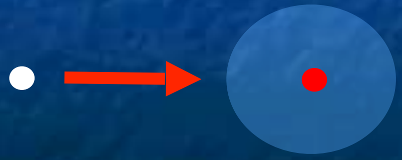


Producing:



But, while unlikely, ^{1}H's lone-proton nucleus can also absorb one or two neutrons

Making normal hydrogen a WEAK **Neutron Poison:**



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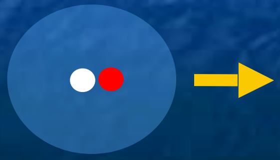
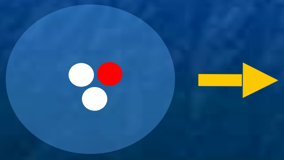


Or eventually:



^{1}H ^{2}H ^{3}H

But poisoning atoms can be largely filtered away via ***Isotope Separation*** *[1, 2]*

Which is an array of obscure, difficult and terribly expensive processes by which
DIFFERENT isotopes of the **SAME** atom can be separated from one another

For which conventional chemical refining is useless because all isotopes of the **same** atom
have the **same** number & arrangement of electrons
which makes those isotopes form **identical bonds with all other atoms**

But isotopes can be DIRECTLY separated by applying Electromagnetic or Centripetal forces
which, because F = ma, accelerate heavier isotopes more weakly thereby
sending them along *slightly* different paths, facilitating their sorting

Or, many early techniques exploited the fact that thermal equilibrium gives different isotopes
(or isotope-containing molecules) the **same** Kinetic Energy which, because K.E. = $1/2 \, mv^2$,
means the heavier isotopes (or isotopic molecules) must have lower v's
making both their migration and vibration are *minutely* slower

Which *minutely* slows heavier isotope **diffusion, decomposition** & **evaporation**
Not enough to separate isotopes quickly or immediately, but enough to **mostly**
separate them if the process is repeated over and over **thousands** of times

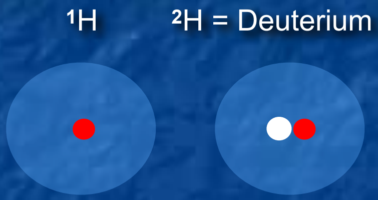
The development and proliferation of Nuclear Weapons and Reactors was
(and continues to be) gated by the design & construction of Isotope Separation facilities

1)) https://en.wikipedia.org/wiki/Isotope_separation *2) https://www.britannica.com/science/isotope/Isotope-separation-and-enrichment*

*Applying this to normal H_2O's dual **Neutron** Moderating & Poisoning tendencies*

To eliminate water's poisoning, use water with only H nuclei **already containing** neutrons
There is one such stable isotope, with 1 nuclear neutron, called Deuterium, or D:

Deuterium occurs naturally but it is very rare, with
only ~ 1 in 6400 H atoms of natural water being Deuterium [1]



But, per the preceding slide, D_2O's motion & vibration are minutely slower
which minutely slows D_2O's electrolytic decomposition into D_2 and O_2 gases

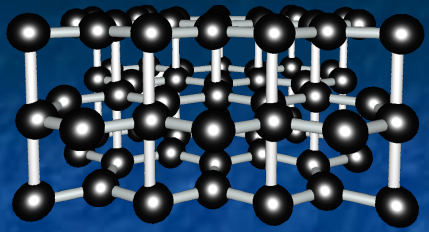
So, if natural H_2O is electrolyzed, gas emitted later has minutely enhanced D_2 concentration
If ONLY that later gas is retained, recombined, condensed, and that process repeated
THAT resulting water will have even higher D_2O concentrations

Repeat a HUGE number of times and almost pure D_20 = **"Heavy Water"** is produced
= A near ideal non-poisoning **neutron moderator**

As done by WWII Nazi nuclear bomb developers at the **Telemark** hydroelectric power plant
in occupied Norway - Only to then be sabotaged by Norwegian commando attacks [1]

1)) https://en.wikipedia.org/wiki/Norwegian_heavy_water_sabotage

*But one can **moderate** almost as well with the Carbon atoms of common Graphite*



Common Carbon atoms are 12 times heavier than neutrons

meaning they absorb less energy from colliding neutrons

than is absorbed by a Hydrogen atom of near-neutron mass

But they make up for this by seldom if ever **capturing** neutrons which makes Carbon,

like Deuterium, a non-poisoning **neutron moderator** (unlike common ^1H or ^1H_2O)

By using a Heavy Water OR Graphite Moderator, fission chain reactions can be sustained in naturally-occurring Uranium consisting of 0.7% ^{235}**U** + 99.3% ^{238}**U**

Heavy Water Reactors thus shift "obscure, difficult & terribly expensive" isotopic separation

from their fuel to their water (which IS a lot easier and safer to separate)

Graphite Moderated Reactors entirely eliminate the need for ANY isotope separation

But incorporate a flaw that would hugely expand the impact of the Chernobyl disaster:

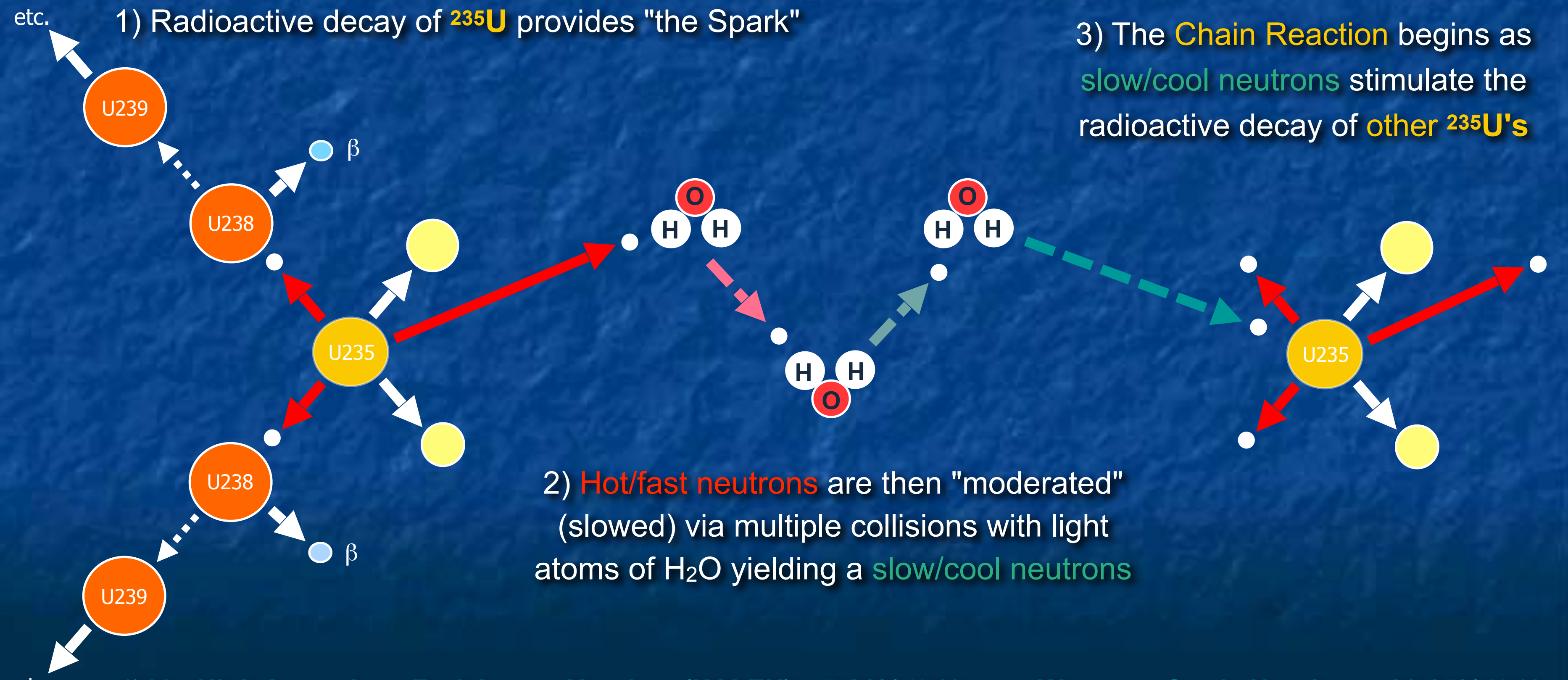
Superheated Graphite burns fiercely when suddenly exposed to air

Figure: Screenshot from my animation at: https://wecanfigurethisout.org/VL/Nanocarbon.htm/state/5

But reactors generally use a little bit of Uranium plus a WHOLE LOT of water

Thus, for easier and safer neutron moderation almost all "western" nuclear reactors now employ unenriched "**light water**" MODERATOR - despite its slight neutron poisoning effect - which is offset by the use of **Uranium fuel mildly enriched by isotope-separation to 4-5% ^{235}U**

In such **"Reactor Grade" / Low Enrichment Uranium (LEU)** [1] the chain reaction then becomes:



1) Radioactive decay of **^{235}U** provides "the Spark"

2) Hot/fast neutrons are then "moderated" (slowed) via multiple collisions with light atoms of H_2O yielding a slow/cool neutrons

3) The Chain Reaction begins as slow/cool neutrons stimulate the radioactive decay of other **^{235}U's**

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*[1] Vs. **High Assay Low Enrichment Uranium (HALEU)** = 5-20% ^{235}U vs. **Weapons Grade Uranium** = 20-85% ^{235}U (https://en.wikipedia.org/wiki/Enriched_uranium)*

In real life, the fission reaction products break down even farther:

The **^{235}U fission** path is depicted horizontally, including side branches into . . .

a **^{144}Ba fission** path: ↗

a **^{238}U fission** path: ↘

and a **^{89}Kr fission** path: ↓

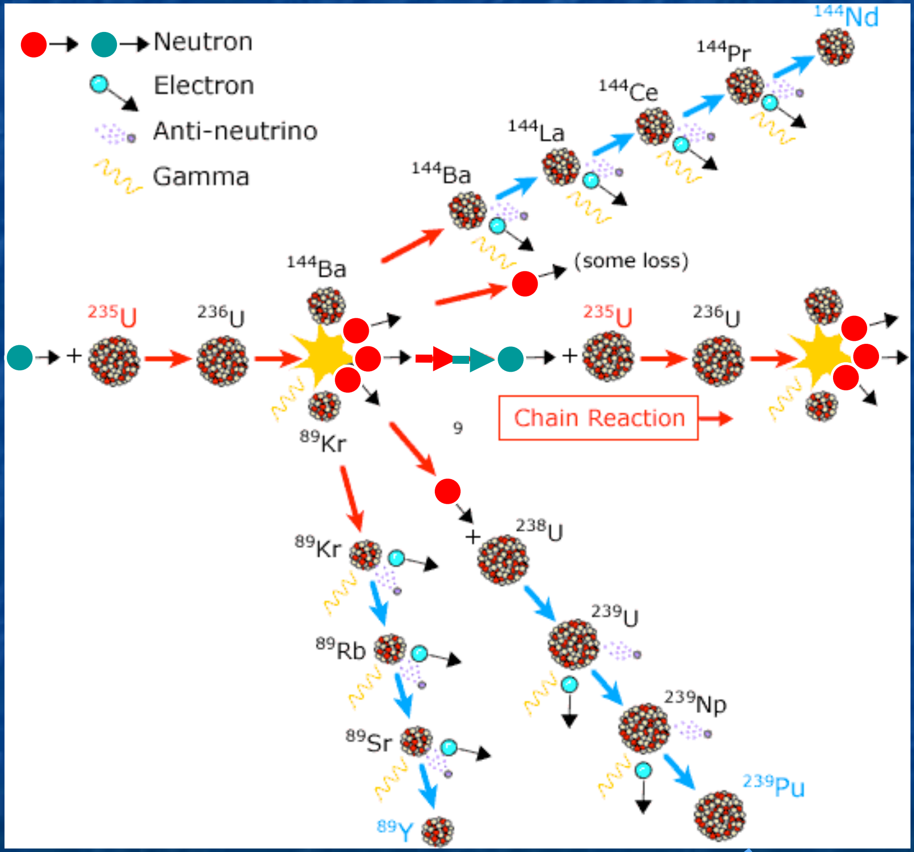
But all of these paths take TIME

And they extend right off the page!

Importantly:

EVEN AFTER ^{235}U FISSION STOPS its decay products continue fissioning for seconds, minutes or even hours!

Producing persistent intense HEAT that induced the NON-NUCLEAR explosions triggering 2 of 3 major Reactor Accidents



↘

Modification of figure found at: http://www.nobelprize.org/educational/physics/energy/fission_2.html

But could a full blown nuclear explosion instead be triggered?

Experts often rebut that possibility based on arguments citing **"Critical Mass"**

But their rebuttals are muddied by that simplistic and misleading term,

which actually obscures key differences between nuclear reactors and bombs

To sustain the chain reaction, a neutron released by one fissioning ^{235}U

MUST successfully induce the fission and neutron release from another ^{235}U

If probability is < 1 the chain reaction dies out, and state is labeled **Sub-Critical**

If probability = 1, the chain reaction continues at a constant rate labeled **Critical**

and the fuel involved is said to be of **Critical Mass**

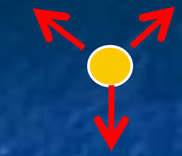
If probability is > 1, the chain reaction grows and the state is then **Super-Critical**

But exceeding the "Critical" probability of 1 requires far more than just fuel mass

As can be demonstrated by the following simple diagrams:

Consider these contrasting possibilities:

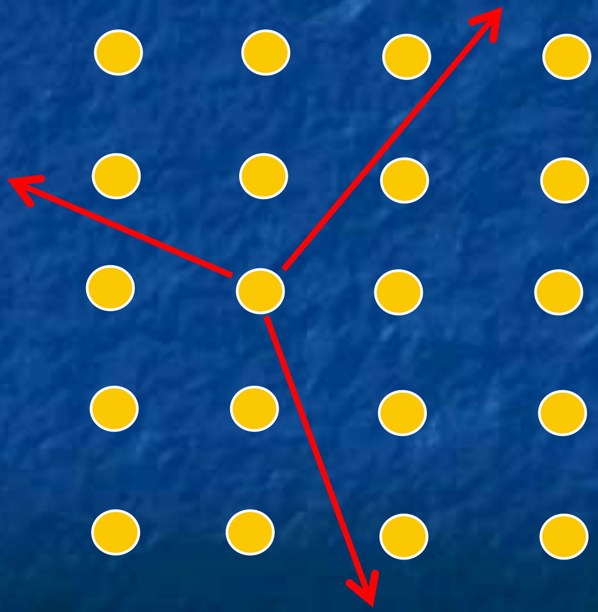
Say that (on average) one fissioning ^{235}U atom emits exactly 3 neutrons:



Then consider different ways of packing such atoms:

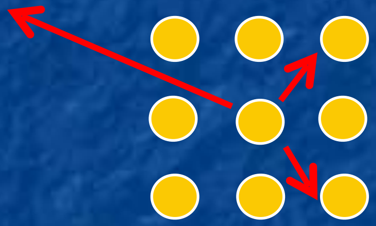
High total mass

No collisions → No chain reaction



Low total mass

Two Collisions → Rapidly growing chain reaction



BECAUSE tighter packing
makes collisions more probable!

Suggesting:

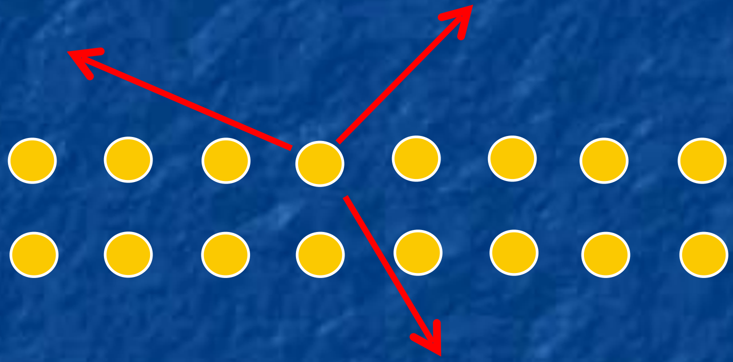
MASS / VOLUME or NUMBER / VOLUME

(a density) is instead the CRITICAL factor

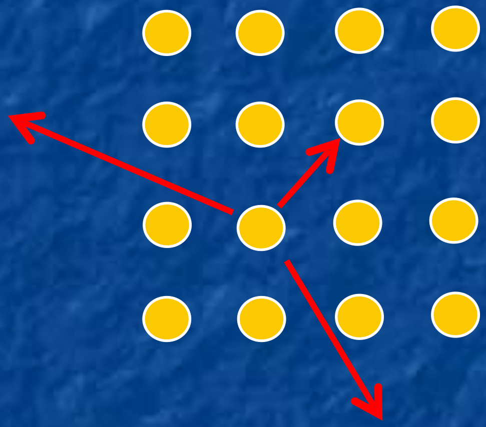
But high mass or number density (alone) might also be insufficient:

Consider two shapes, with same Mass, Mass / Volume, and Number / Volume:

NO collisions → No chain reaction:



One collision → Chain reaction:



Similar to heat, a shape with lower surface to volume ratio **traps** more neutrons

But high Total Mass AND Mass density AND Number density AND proper shape

may STILL not be enough to achieve "Critical Mass"

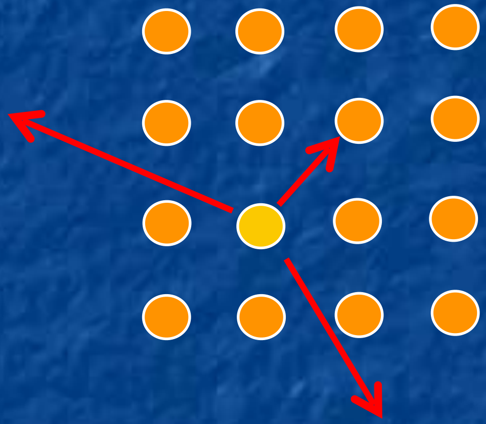
It also depends upon purity - Or what in this context is called "Enrichment"

Consider two Uranium shapes with different ^{235}U (🟡) to ^{238}U (🟠) ratios

Reactor Grade Uranium: 4-5% ^{235}U

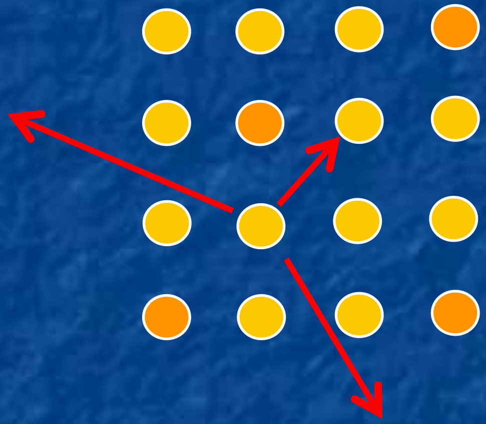
One ^{238}U collision → No neutron release

→ No chain reaction



Weapons Grade Uranium: > 80% ^{235}U

One ^{235}U collision → Chain reaction:



So "Critical Mass" is ACTUALLY about mass, density, shape, enrichment . . .

And is ANY combination producing a chain-reaction of CONSTANT intensity [1]

For additional information see, for example: https://en.wikipedia.org/wiki/Critical_mass

*Nuclear bombs require **growing** ("Super Critical") fission chain reactions,*

But a bomb's Super Critical chain reaction must also be what experts label **"Prompt"**

What is THAT all about?

In a "Super Critical Mass," the fission chain-reaction becomes increasingly intense

yielding ever more intense **heat** that begins to **fracture, melt & vaporize the fuel**

w**hich thereby flows, and increasingly blows, rapidly apart!**

But if that fissioning material **spreads too far apart,** **Super Criticality** is lost

Reverting to one of the preceding too dilute and/or too spread out configurations

in which the probability of propagating a fission chain reaction falls below 1

A situation scientists gave the very descriptive name of nuclear **FIZZLE**

But isn't "fizzle" just a euphemism for "a slow explosion"

NO! - Not in an all important way:

A nuclear fizzle releases immensely less energy than a nuclear explosion

Because:

A fizzle's slow **early** energy release, which IS due to nuclear fission,

drives away (via melting and vaporization) the remaining nuclear fuel

Which, spread out, is no longer of Super Critical Mass / Super Critical configuration

and not only does the chain reaction cease growing

but in much of the fuel the chain reaction is not even be sustained

In which case only a tiny fraction of the available fissionable material ever fissions

So a fizzle produces a much, much smaller net energy & radiation release

Which can be so weak that it ends up being more "meltdown" than explosion

*The Prompt in **Prompt Super Critical Mass** alludes to fizzle-beating speed*

According to Wikipedia's "Critical Mass" webpage data: [1]

To fission ~ all of a nuclear bomb's fuel requires at least 80 chain reaction cycles

which must be completed within the ~ **1 microsecond** before that

fuel is thrown so far apart that the chain reaction is largely extinguished

But, from above, ^{235}U fissions into all sorts of things over

sub-microsecond to 1000's of second time scales

Bombs need a fizzle-avoiding design & fuel producing

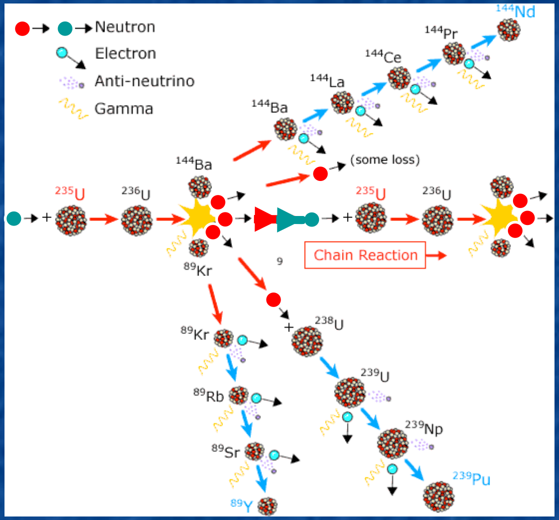
Prompt (submicrosecond) **Super Critical Mass**

Reactors instead target a stable chain reaction rate

which requires a slightly **Super Critical Mass** of fuel

but stays well below **Prompt Super Critical Mass** thereby slowing any

chain reaction rate variation to correctable second to minute timescales

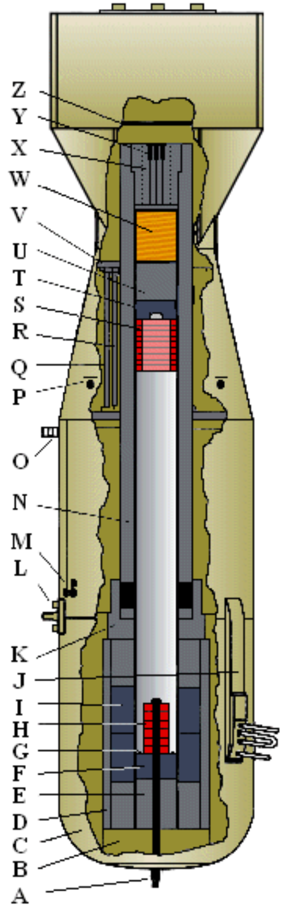


https://en.wikipedia.org/wiki/Critical_mass

But to give those concepts substance its time to dig into technologies, starting with:

The Technology of Nuclear-Fission "Atomic" Bombs

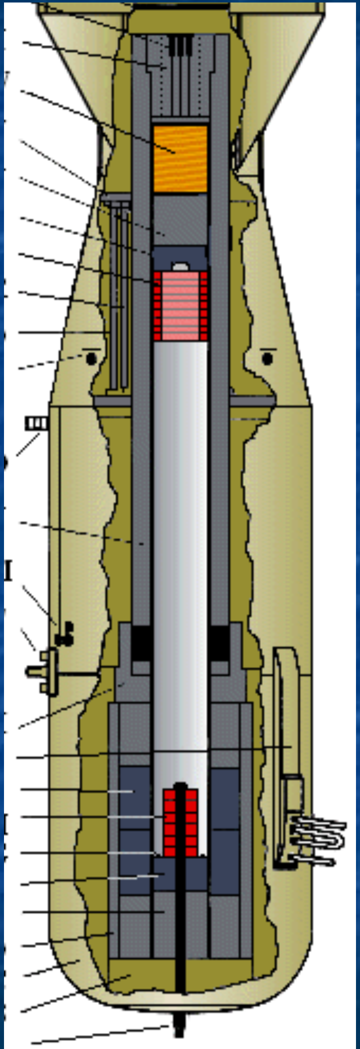
Producing a Prompt Super Critical Mass over Hiroshima required: "The Little Boy"



Cross-section drawing of Y-1852 Little Boy showing major mechanical component placement. Drawing is shown to scale. Numbers in ( ) indicate quantity of identical components. Not shown are the APS-13 radar units, clock box with pullout wires, baro switches and tubing, batteries, and electrical wiring. (John Coster-Mullen)

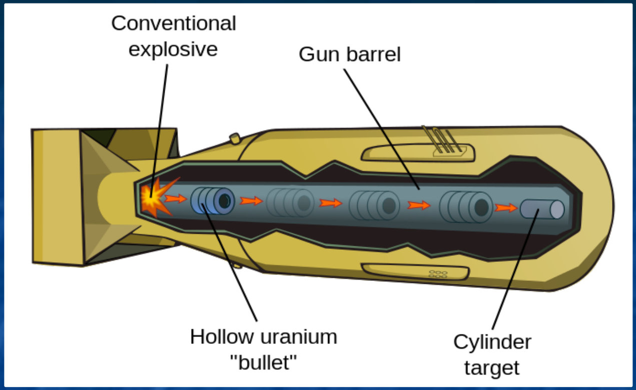
Z) Armor Plate
Y) Mark XV electric gun primers (3)
X) Gun breech with removable inner plug
W) Cordite powder bags (4)
V) Gun tube reinforcing sleeve
U) Projectile steel back
T) Projectile Tungsten-Carbide disk
S) U-235 projectile rings (9)
R) Alignment rod (3)
Q) Armored tube containing primer wiring (3)
P) Baro ports (8)
O) Electrical plugs (3)
N) 6.5" bore gun tube
M) Safing/arming plugs (3)
L) Lift lug
K) Target case gun tube adapter
J) Yagi antenna assembly (4)
I) Four-section 13" diameter Tungsten-Carbide tamper cylinder sleeve
H) U-235 target rings (6)
G) Polonium-Beryllium initiators (4)
F) Tungsten-Carbide tamper plug
E) Impact absorbing anvil
D) K-46 steel target liner sleeve
C) Target case forging
B) 15" diameter steel nose plug forging
A) Front nose locknut attached to 1" diameter main steel rod holding target components

"Atom Bombs: The Top Secret Inside Story of Little Boy and Fat Man," 2003, p 112.
John Coster-Mullen drawing used with permission



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

So named because it WAS little and relatively simple:

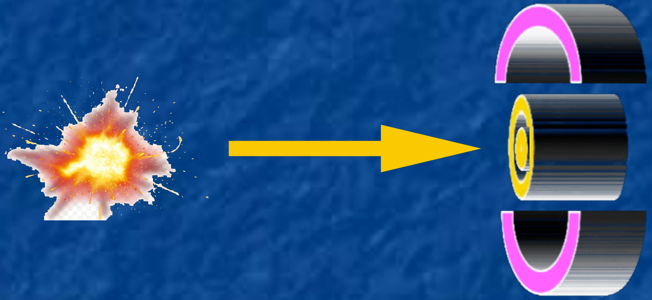


http://en.wikipedia.org/wiki/Little_Boy

An **80-90% ^{235}U Tube** was SHOT *thru a cannon* into place around a **cylinder of 80-90% ^{235}U**

Before cannon fired:

After cannon fired → ^{235}U Prompt Super Critical Mass:



Enhanced by a surrounding **Neutron Mirror** bouncing **back** neutrons leaking outward

which was the ONLY way it **BEAT** the initial heat starting to push things back apart,

avoiding fizzle, getting MOST of ^{235}U to fission → ~ Complete energy liberation

The Manhattan Project didn't even advance test the Little Boy design:

1) Because they were almost certain it's simple idea / implementation would work

2) Because they'd produced so little of the absolutely necessary 80-90% enriched ^{235}U

(to be contrasted with the 0.7-5.0% ^{235}U fueling common reactors)

Why had so little ^{235}U been produced? Because ^{235}U is SO HARD TO ENRICH!

As discussed earlier, ^{235}U is **chemically identical** to ^{238}U and

separation must instead somehow exploit their mere 1% mass difference

Requiring isotope separation plants repeatedly sending Uranium feedstock through

diffusion barriers OR mass spectrometers OR high-speed centrifuges OR . . .

Almost half of the WWII Manhattan Project's 27 billion dollar budget [1, 2]

was spent developing & building such Uranium isotope separation plants [2-4]

---

1) As expressed in equivalent 2023 U.S. dollars

2) https://en.wikipedia.org/wiki/Manhattan_Project

3) "The Making of the Atomic Bomb" by Richard Rhodes, 25th Anniversary Edition, Simon & Schuster (ISBN978-1-4516-7761-4)

4) https://www.nps.gov/mapr/learn/uranium.htm

Located in what had been the backwoods of Oak Ridge Tennessee:

Where, after being converted into UF_6, natural Uranium (99.3% ^{238}U + 0.7% ^{235}U)

was sent through these three plants, very, very gradually filtering out ^{238}U in favor of the ^{235}U

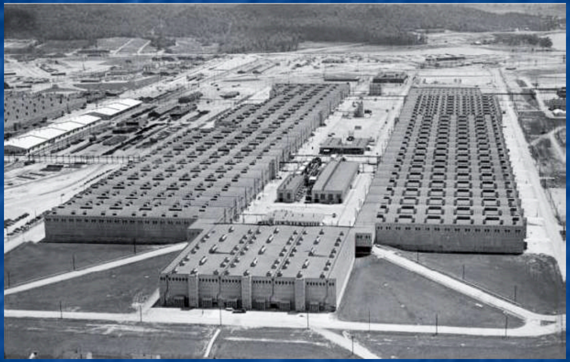
0.7% ^{235}U → 0.9% ^{235}U

Liquid Diffusion "S-50" Plant

Designed to house 1600 liquid thermal diffusion columns connected in progressive purification stages

https://en.wikipedia.org/wiki/S-50_(Manhattan_Project)

https://ahf.nuclearmuseum.org/ranger/tour-stop/s-50-plant/



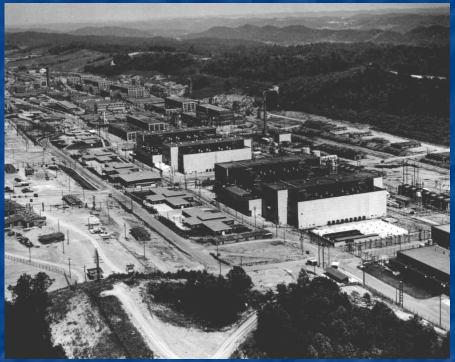
0.9% ^{235}U → 23% ^{235}U

Gaseous Diffusion "K-25" Plant

Housing 2892 gaseous diffusion tanks connected in progressive purification stages, inside of what was then the **world's largest building**: Four stories tall, half mile long, 42.6 acre footprint

https://en.wikipedia.org/wiki/K-25

Plus references given on the preceding slide



23% ^{235}U → 80-90% ^{235}U

Electromagnetic "Y-12" Plant

With **11** electromagnetic "racetracks" through which only ^{235}U could readily pass, organized into two progressive purification stages

https://en.wikipedia.org/wiki/Y-12_National_Security_Complex

https://teva.contentdm.oclc.org/digital/collection/p15138coll18/id/305/

As compared to the Plutonium required for the other WWII Nuclear Bomb:

Which was instead a direct product of ^{238}U fission decay within a nuclear reactor:

$$^{238}U + {}^{1}\mathbf{n}\ \text{(hot/fast)} \Rightarrow {}^{239}U \Rightarrow {}^{239}Np + \beta \Rightarrow {}^{239}Pu + \beta$$

Then easily separated from co-products because different numbers of electrons meant that those co-products chemically bonded to different things

(Remembering that while ^{239}U, ^{239}Np and ^{239}Pu share an atomic mass of 239 their electron counts = proton counts = atomic numbers are 92, 93 and 94)

The Manhattan Project hid its reactor in the badlands of Eastern Washington State within what was later named the "Hanford Nuclear Reservation" [1] now better known as the Hanford Superfund Nuclear Waste Cleanup site [2]

U.S. Government Accountability Office - 2022: [3]

"One of the largest and most expensive environmental cleanup projects in the world"

"estimated that completing cleanup of the entire site (will) cost between $300 billion and $640 billion [4] and take decades"

1) https://en.wikipedia.org/wiki/Hanford_Site

2) https://www.hanford.gov/page.cfm/AboutHanfordCleanup

3) https://www.gao.gov/assets/730/722024.pdf

*4) **Equaling 10-20 times the entire WWII cost of the Manhattan Project** [5]*

They had PLANNED to use that plutonium in the same Little Boy design

But they discovered that the plutonium fission reaction started up so much faster that

Pu would have begun blowing apart well BEFORE the canon

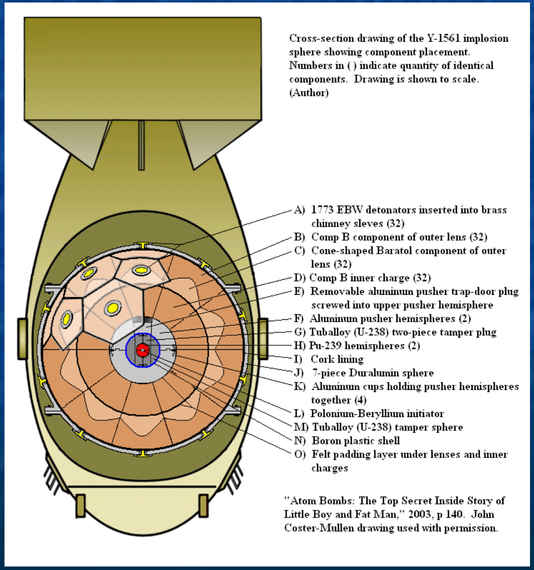
could fully merge the Pu tube and Pu cylinder, thereby producing a **FIZZLE**

So they were compelled to develop the much more complex "**Fat Man**" design:

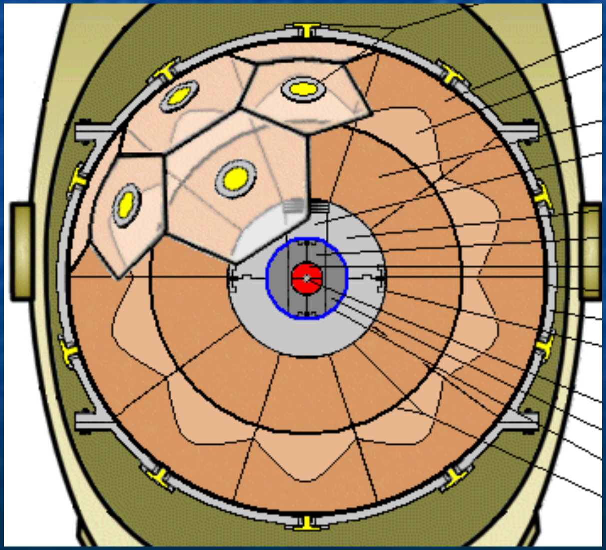
A spherical shell of explosives surrounding a spherical shell of Pu designed to

compress the Pu **shell** into a prompt supercritical **sphere** in < 1 micro-Sec [1]

THIS is what they tested at Alamogordo NM . . . and then dropped on Nagasaki


Cross-section drawing of the Y-1561 implosion sphere showing component placement. Numbers in ( ) indicate quantity of identical components. Drawing is shown to scale. (Author)

"Atom Bombs: The Top Secret Inside Story of Little Boy and Fat Man," 2003, p 140. John Coster-Mullen drawing used with permission.



"Shaped" conventional explosive shell

Smaller embedded Plutonium shell

Final prompt supercritical sphere (---)

← http://en.wikipedia.org/wiki/Fat_Man

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*1) Virtually **all sources** note that higher speed is needed for Pu vs. U, but I found **no source** actually giving comparative times*

Bomb vs. Reactor comparison up to this point:

Uranium Bombs:

Are fueled by 80-100% ^{235}U + 20-0% ^{238}U

Before triggering, that fuel is separated and/or distributed such that it remains sub-critical

Triggered chemical explosives then compress that fuel into a prompt super-critical condition

Rapidly growing fission reactions then produce heat working to counter that compression

But if the compression is forceful enough and fast enough (completed in ~ 1 microsecond)

virtually all of the fuel fissions before super-criticality is lost due to re-expansion

Reactors:

Are fueled by 0.7-5% ^{235}U + 99.3-85% ^{238}U

The Uranium fuel mass **alone** (even if lumped together via accidental meltdown) is sub-critical

But inside an operating reactor, a sustained critical reaction is **induced** by the addition of:

Neutron Moderation generally (in the West) via cooling / heat-transferring water

Balanced by Neutron Poisoning from within movable control rods

Understanding a reactor's induced sub-critical → critical transition calls for a deeper look into:

The Science & Technology of Nuclear (Fission) [1] Reactors:

---

*[1] The "**Fission**" clarifier is actually unnecessary because, after almost three-quarters of a century of intense and lavishly funded research, not a single practical **Nuclear "Fusion" Reactor** has yet been built [2]*

[2] For further discussion of Fusion Reactors see my note set: Exotic Power Technologies (pptx / pdf / key)

Think of it this way: A Reactor = Sub-Critical Mass + an Accelerator + a Brake

The **Accelerator** is the **neutron moderator** (light / common water in most reactors)

The **Brake** is **neutron poison** (absorbers) contained within movable "**control rods**"

The **GOAL** is to balance those competing effects to such that:

Exactly **one** neutron ejected by first ^{235}U is then absorbed by a second ^{235}U

Which then decays (and so on an so on) => **Constant energy release**

That balancing act is aided by an important characteristic of neutron emission:

Very few neutrons (~0.65%) are "prompt" = Released extremely quickly

Most neutrons instead take milliseconds to several seconds to emerge

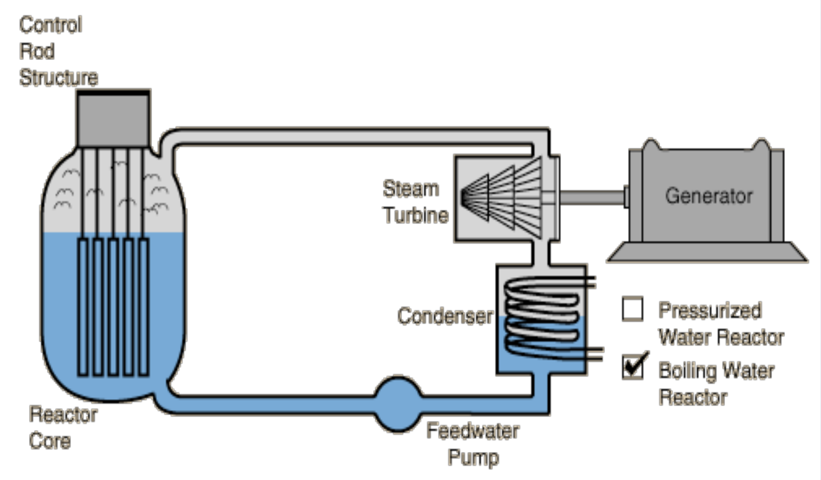
Which means that the reaction can only build over seconds to minutes

Giving "control rods" much more time to move (and thereby control)

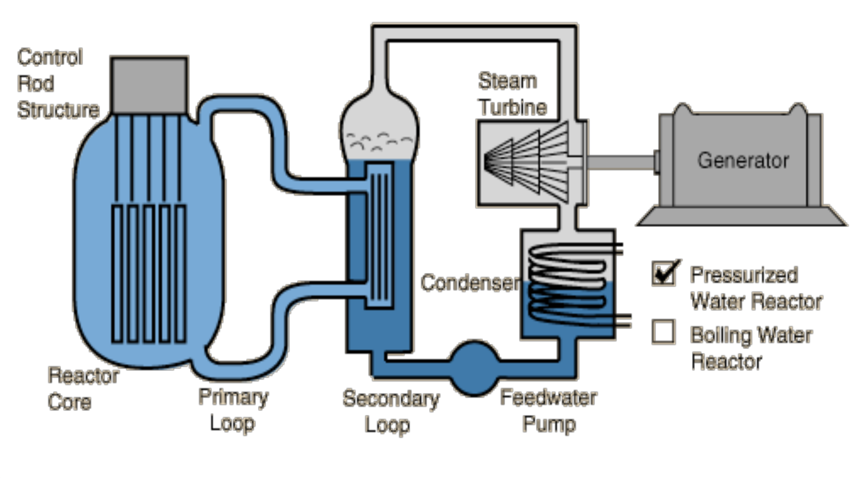
(Plus in many reactors, an additional **intrinsic** control mechanism - to be discussed shortly)

Light Water (normal water) Reactors come in two types:

Boiling Water Reactors (BWRs):



Pressurized Water Reactors (PWRs):



Both use uranium enriched to **4-5% ^{235}U**

Both use normal water to **moderate** some of the neutrons released by **^{235}U** fission

Both use neutrons (moderated & unmoderated) to stimulate further **^{235}U** + **^{238}U** fission

Both use fission heat to produce **steam** to spin turbines driving electrical generators

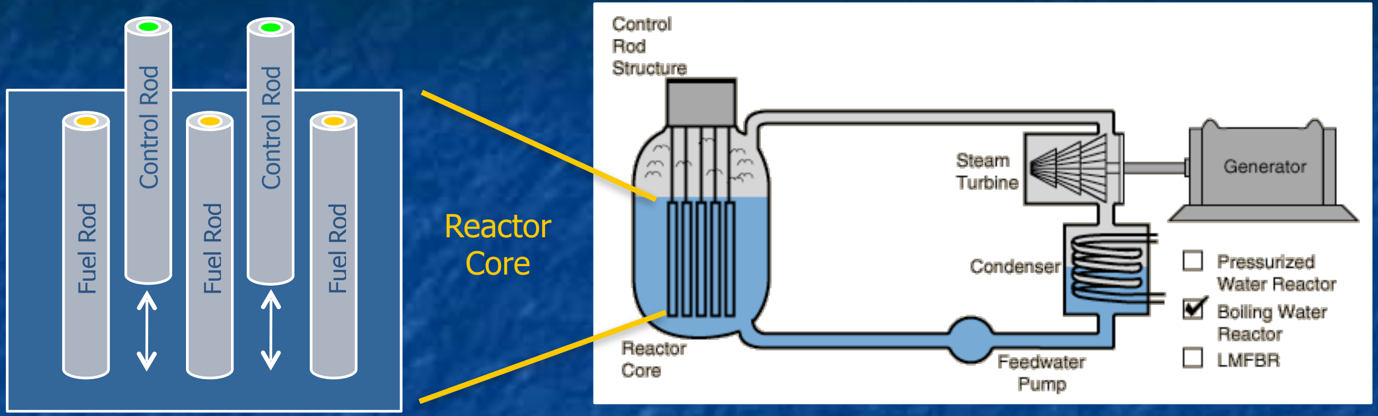
But they use **different** schemes to transfer that water-borne heat to produce that steam

Leading to their use of **different** control mechanisms & safety containment structures

Figures: http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/reactor.html

Details of Boiling Water Reactors (BWRs):

Which exploit both a mechanical AND a subtle intrinsic control mechanism:



Fixed-in-place **Fuel Rods** are immersed in the partially water-filled reactor core

These are extremely heat-resistant **zirconium tubes** (1-2 cm dia. / 3-4 m long)

containing tall stacks of cylindrical 4-5% **^{235}U + ^{238}U fuel pellets**

Interleaved with similar but movable **Control Rods** filled with **neutron poisons**

Which can be lowered to increasingly obstruct neutron paths between Fuel Rods,

absorbing more neutrons and thereby **"braking"** the fission reactions

While surrounding water provides **moderation** **"accelerating"** the fission reactions

As fission heat drives that boiling water's expansion into turbine-spinning steam

After driving the turbine, the steam is cooled, condensed & returned to the reactor

But what if water is somehow lost (and not replaced by automatic systems)?

This is where a subtle intrinsic BWR control mechanism can come into play

Use of enriched 4-5% ^{235}U adds more neutrons, countering water's mild poisoning of them
Water's strong effect is then moderating hot neutrons so that they split more ^{235}U atoms

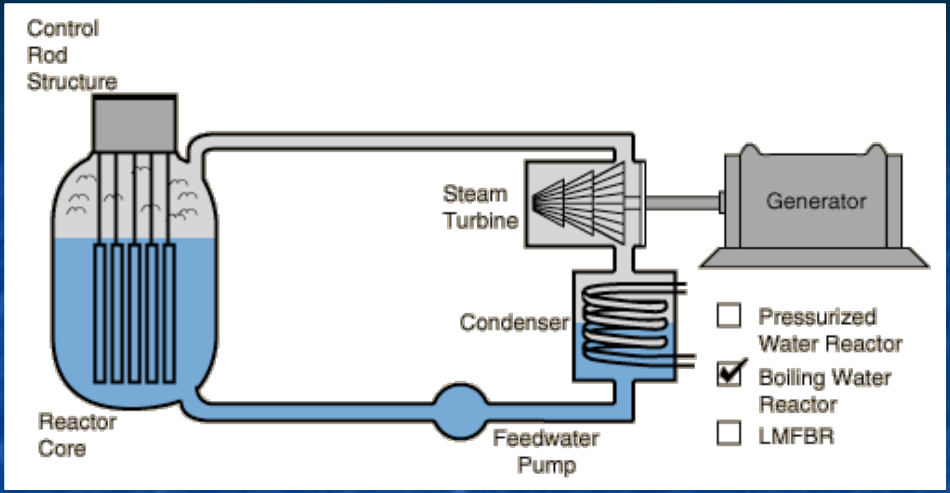
To start the reactor, its neutron-poisoning Control Rods are gradually withdrawn,
a fission chain reaction begins and the reactor core & surrounding water begin to heat,
until the water is hot enough that steam begins to bubble up out of it which is
then piped to the turbine-generator beginning production of electrical power

For MORE power, Control Rods are withdrawn further, the rate of Uranium fission increases,
the water boils more vigorously, the additional steam spins the turbine-generator faster

However: Because **steam bubbles** contain ~ 2000X less water/volume than **liquid water**,
there are fewer water molecules between the Fuel Rods, cutting **neutron** moderation
making it harder and harder to increase heat-producing fission within the reactor

Which SHOULD make an out-of-control BWR core meltdown much less likely

But there is an offsetting potential problem with Boiling Water Reactors:



The turbine-generators are located OUTSIDE the reactor safety containment structure

because they are complex machines requiring ongoing attention & maintenance

Meaning water from the very core of the nuclear reactor

must continuously cycle in & out of the safety containment structure

Fortunately, **pure water** ($^1H_2\,^{16}O$) cannot become strongly / persistently radioactive:

Neutron-induced ^2H (D) is stable while ^3H is only very weakly radioactive

Neutron-induced heavier oxygen isotopes (e.g. ^{17}O & ^{18}O) are stable

The alternative of Pressurized Water Reactors (PWRs):

Partially inspired by concerns about BWR reactor core water exiting its containment:

Because if that water picked up **impurities**, THEY could become **strongly** radioactive

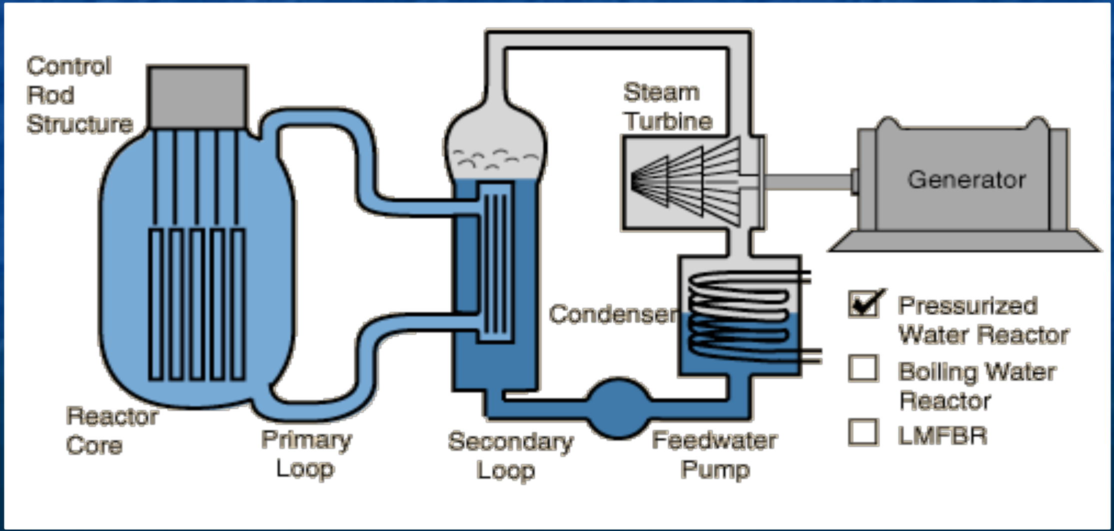
Or if the reactor Fuel Rods leaked, that water would transport **massive** radioactivity

So instead of the BWR's one water loop, in a PWR there are two water-cooling loops:

A highly-pressurized & superheated **Primary Water Loop** enters the reactor's core

Outside the core - **but still within the containment structure** - heat is transferred to

A **Secondary Water Loop** which exits the containment to drive the turbine-generator



http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/reactor.html

Subtleties of Pressurized Water Reactors (PWRs):

The Primary Loop's job is maximizing heat delivered to the Secondary Loop

In a PWR, that Primary Loop is therefore highly pressurized which allows its water to:

1) Be heated far above it's normal 100°C boiling temperature - carrying more heat

2) But still remain a dense liquid (rather than a dilute vapor) - carrying more heat

Both of which can enhance the overall "thermal efficiency" of PWRs, possibly yielding more generated electrical power per Uranium fuel input & nuclear waste output

But the water in the PWR's Primary Loop is ALSO its NEUTRON MODERATOR

Under pressurization, THAT liquid water cannot significantly expand or vaporize

So the degree of neutron moderation (which accelerates ^{235}U fission)

will **not** automatically decrease as the reactor core heats up

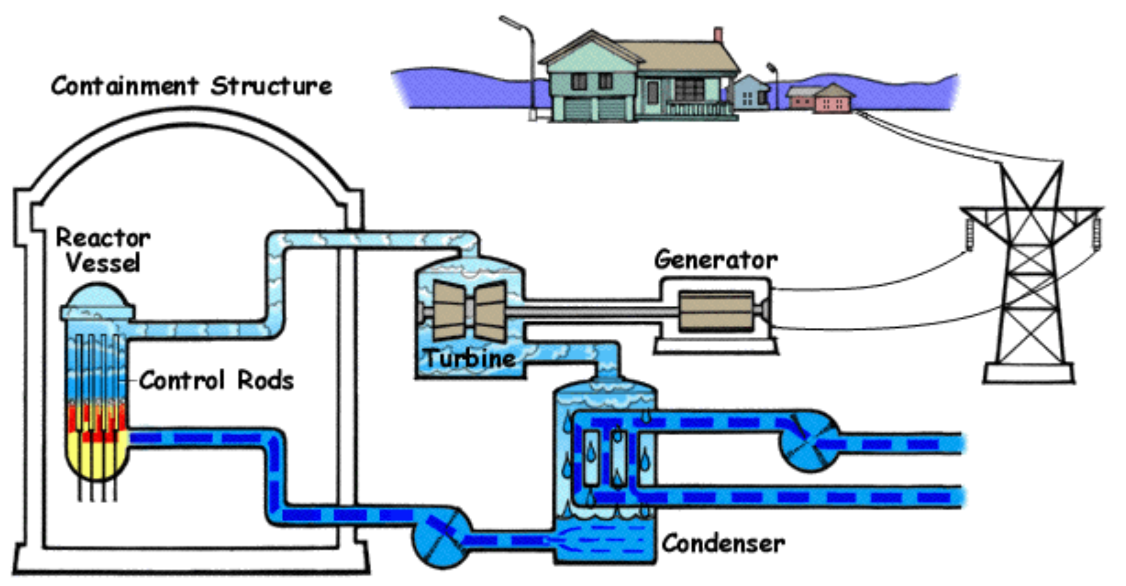
So Pressurized Water Reactors (PWRs) lack the intrinsic negative feedback mechanism

that enhances the stability of competing Boiling Water Reactors (BWRs)

Comparisons focusing on water's temperature, flow, liquid vs. steam state:

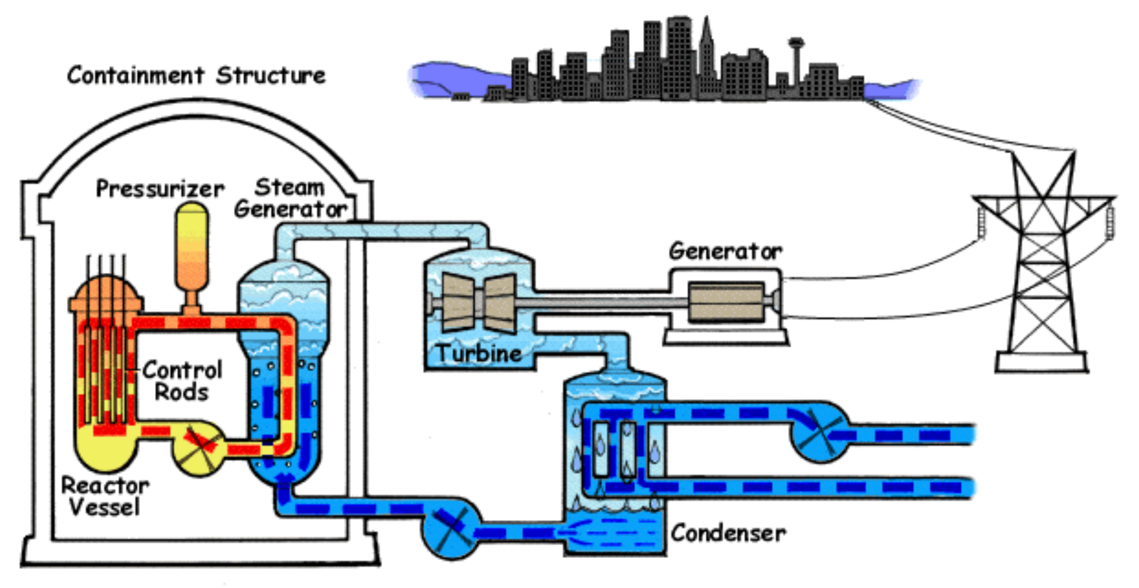
Boiling **W**ater **R**eactor:

www.nrc.gov/reading-rm/basic-ref/students/animated-bwr.html



Pressurized **W**ater **R**eactor:

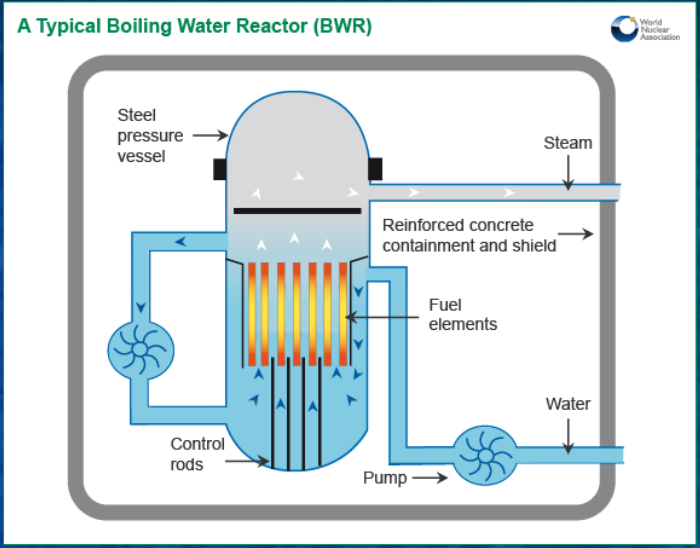
www.nrc.gov/reading-rm/basic-ref/students/animated-pwr.html



(These animations play within Powerpoint & Keynote)

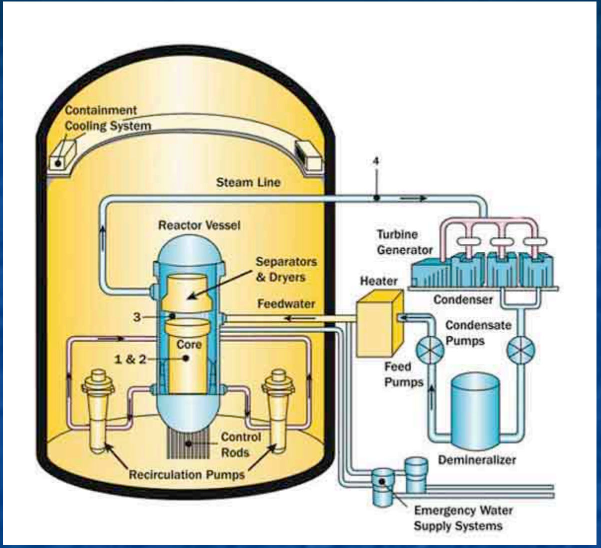
Comparisons focusing on details - but weak on big picture (such as containment)

Boiling **W**ater **R**eactor:

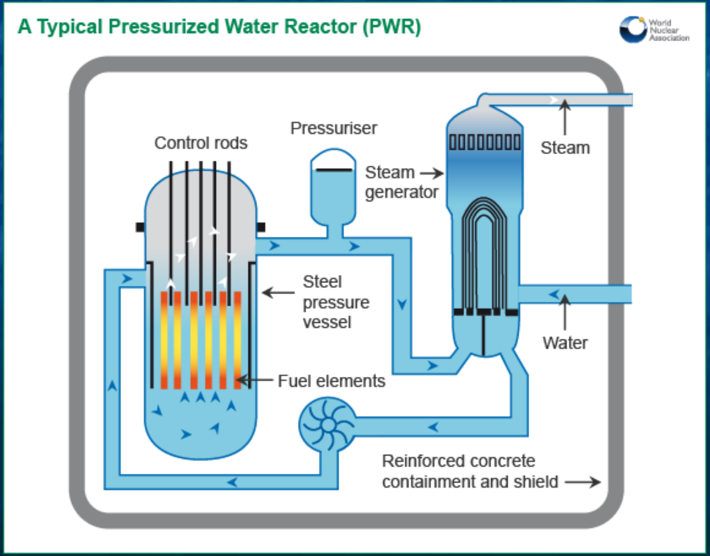


www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Power-Reactors/Nuclear-Power-Reactors/

www.nrc.gov/reactors/bwrs.html

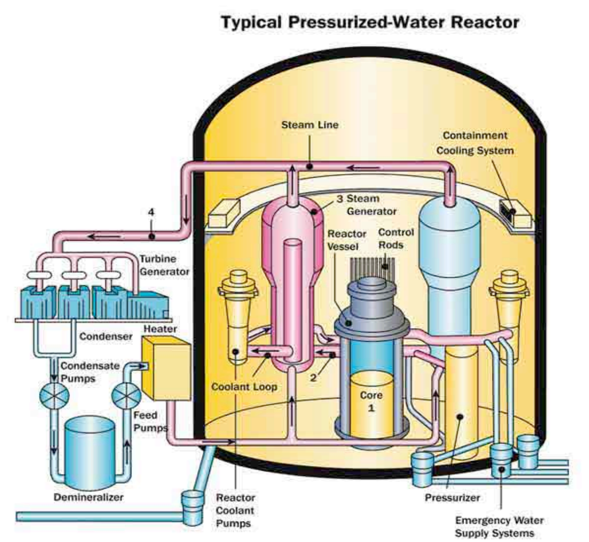


Pressurized **W**ater **R**eactor:



www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Power-Reactors/Nuclear-Power-Reactors/

www.nrc.gov/reactors/pwrs.html



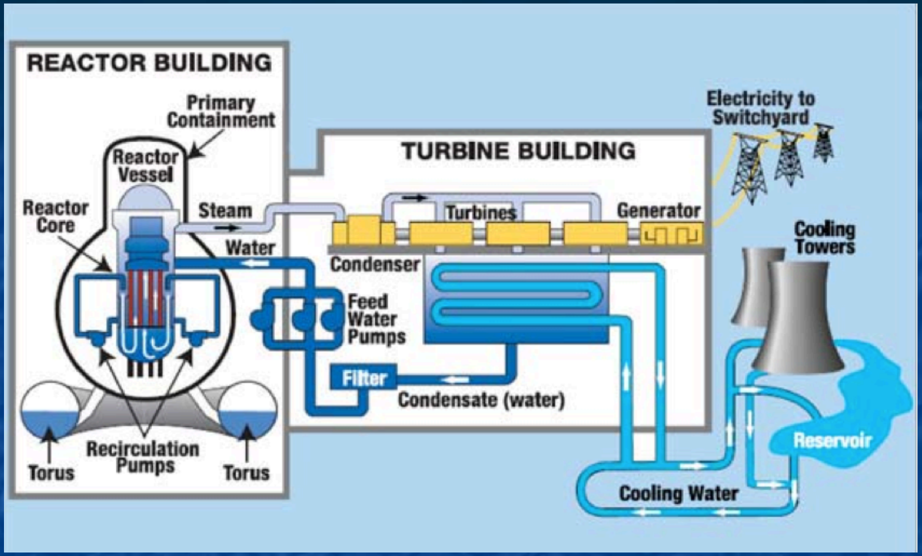
Finally, more accurate depictions of containment strategies & structures:

Boiling **W**ater **R**eactor:

Strong **reactor vessel** containment

Weak **reactor building** containment (often conventional flat walls & roofs)

No turbine building containment

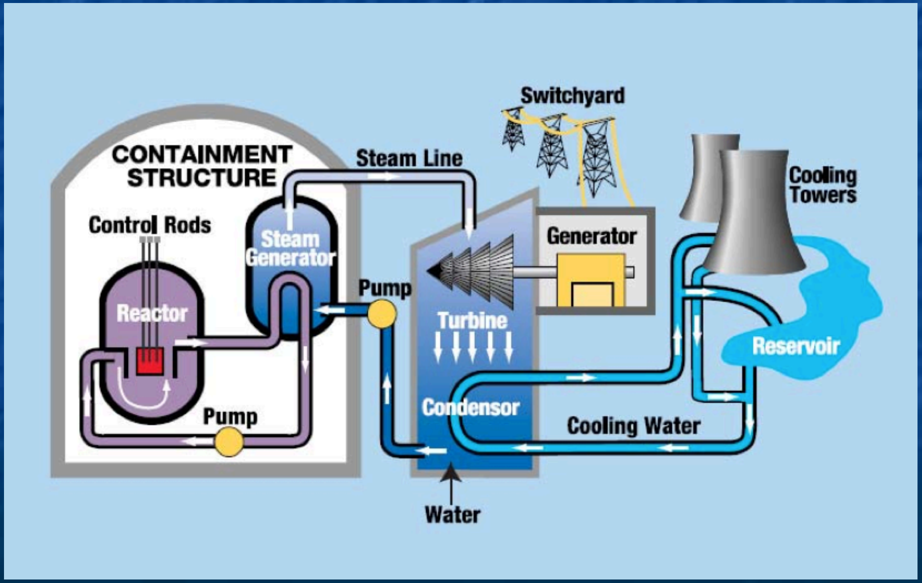


Pressurized **W**ater **R**eactor:

Weak **reactor vessel** containment

Strong **reactor building** containment of reactor vessel & steam generator (steel-reinforced concrete domes)

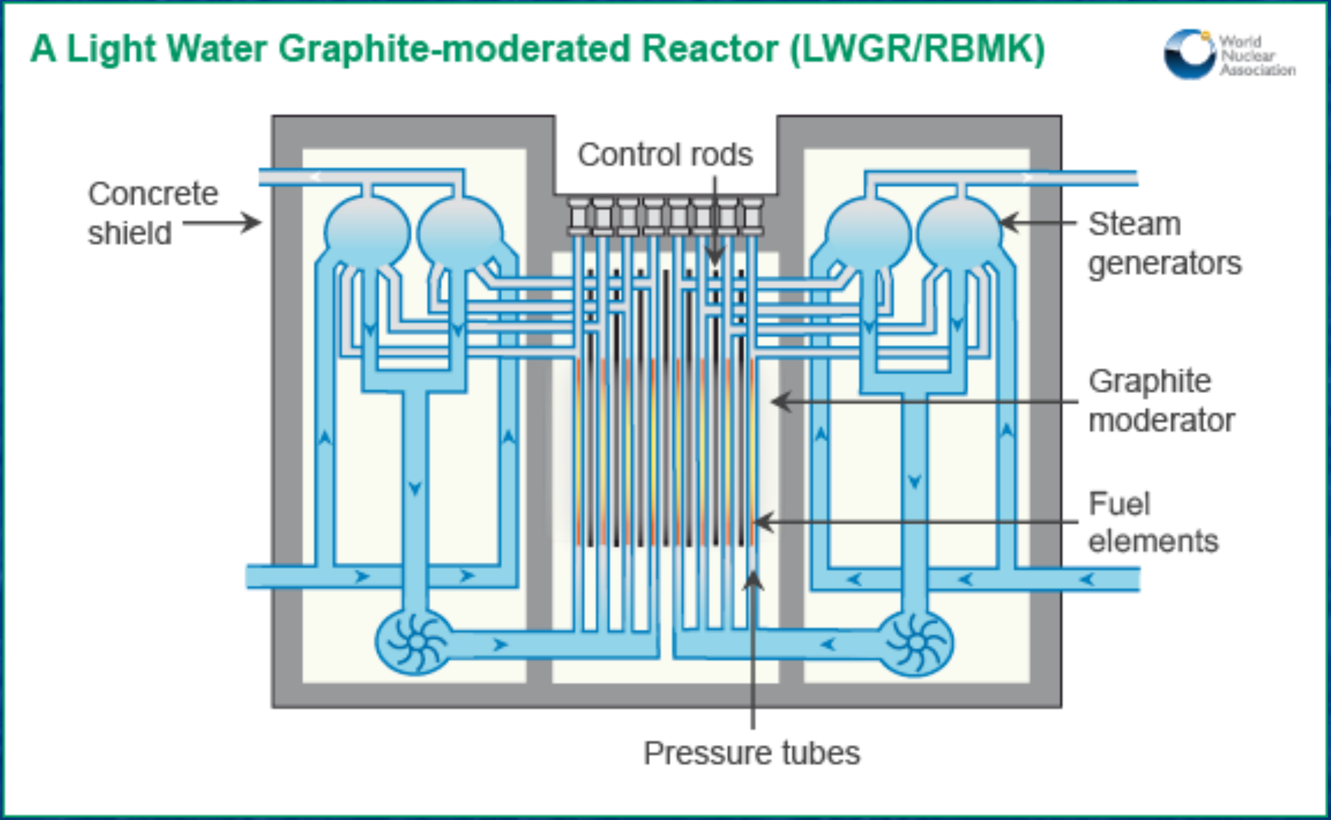
No turbine building containment



Source: CRS Report to Congress – "Power Plants: Characteristics and Costs" (November 13, 2008) - Order Code RL34746
https://fas.org/sgp/crs/misc/RL34746.pdf

But we also need to consider one other (non-Western) type of reactor:

The **RBMK** (Reaktor Bolshoy Moshchnosti Kanalnyy) reactor – as used at Chernobyl



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

RBMK Reactors

RBMKs use **partially** pressurized cooling water, that **is** allowed to boil

Putting them somewhere **between** the previous **BWR** and **PWR** designs

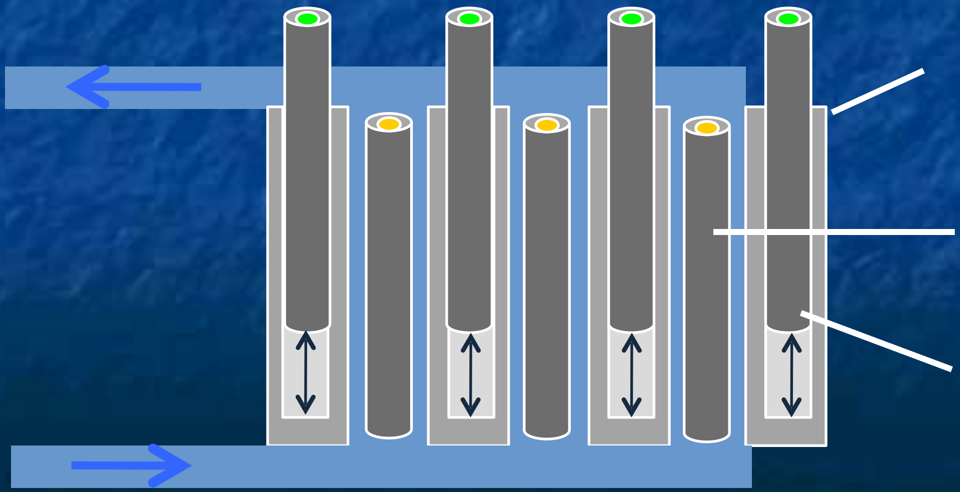
But they use **water ONLY for heat transfer** and **NOT for neutron moderation**

Instead, fuel rods rest in oversized metal-lined holes in blocks of **Graphite**

With thin layers of cooling water flowing between rods and liners

Plus gas flow for heat transfer between liner and block / block to block

The **graphite** (alone) produces near complete **neutron moderation**



Graphite blocks with holes/liners
for fuel rods and control rods

Fuel rods containing uranium

Control rods containing neutron poison

Unique design goals & characteristics of RMBK reactors:

Design goals were to:

- Use much cheaper un-enriched natural uranium: 0.7% ^{235}U + 99.3% ^{238}U

- Produce BOTH **electrical power** PLUS **plutonium for weapons**

- Build unusually large high power reactors, at unusually low costs

Which was accomplished via:

- Complex heat transfer scheme combining thin layers of water + inert gas flows

- Constant, heavy, neutron **moderation** provided by (flammable) graphite blocks

With neutrons **already** moderated, water's **moderation** becomes unimportant!

- **WITHOUT heavily reinforced reactor containment vessel / containment building**

As used in western reactors including both BWR and PWR designs above

The Three Major Nuclear Reactor Accidents:

The Three Mile Island Accident

Eastern Pennsylvania - 28 March 1979

Babcock & Wilcox Pressurized Water Reactor #2 (one of two on site)

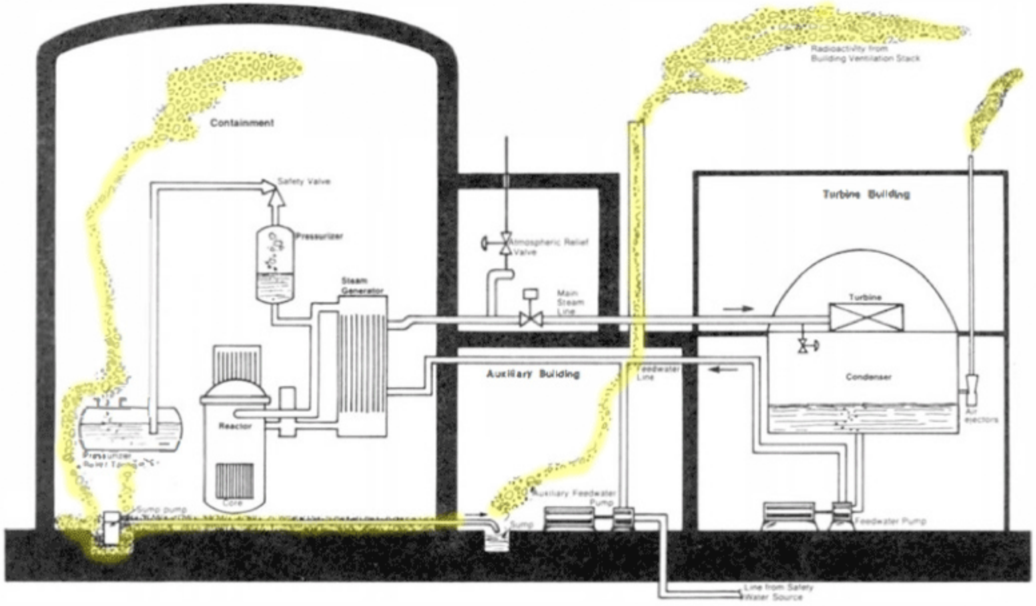
nuclear news®

Special Report—April 6, 1979

The ordeal at Three Mile Island

A combination of design deficiency, mechanical failure, and human error contributed to the ill-controlled accident that was touched off at about 4 a.m. on Wednesday, March 28, at Unit 2 of the Three Mile Island nuclear power station of Metropolitan Edison Company, a member company of General Public Utilities (GPU). The initial event at the unit, located near Harrisburg, Pa., has been characterized as a loss-of-normal-feedwater turbine trip—with complications. As Norman Rasmussen of M.I.T. explained the following Sunday on ABC's television program "Issues and Answers," the event could not be considered, in the parlance of reactor safety studies, a "major event" ("an event of major consequences" to the public health and safety, he quickly went on to clarify). The TMI-2 "event," however, certainly promises to have major consequences for the utilization of nuclear power in America and elsewhere—this in spite of the fact that the accident was contained and the amounts and forms of radioactivity that did escape from the plant, appeared, by most accounts, to have been of no major consequence.

Simplified PWR Showing Three Mile Island Release Paths



Yellow highlighting of Radiation Release Paths added

Figure from the "Nuclear Newswire" - American Nuclear Society Reports, 1979 & 2022:

1) https://www.ans.org/file/6411/TMI%20Report%20Featured%20Image.jpg

2) https://www.ans.org/news/article-3916/the-three-mile-island-special-report/

Drawing from Presidential, Nuclear Regulatory Commission & Press Reports: [1-3]

Initial fault was in the secondary water cooling loop (outside the containment):

A filter clogged, operators tried to clean it by injecting compressed air

The resulting over-pressurized water leaked into a pneumatic control line

Hours later the compromised pneumatic line caused secondary loop pumps to trip off

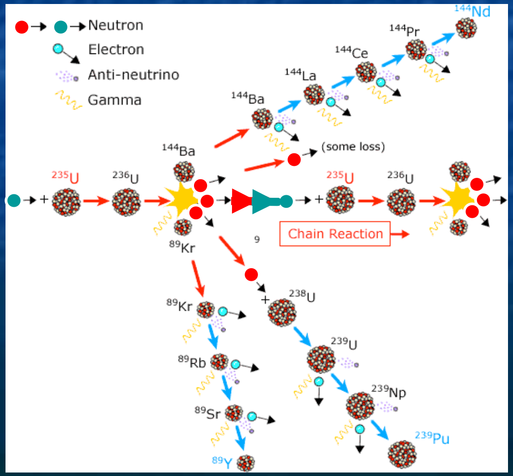
→ Secondary loop could no longer remove heat from the reactor core's primary loop

Primary cooling loop then overheated, initiating automatic "SCRAM" shutdown

Ramming control rods fully downward to quench ^{235}U fission in the reactor's core

But there was already a HUGE amount of latent heat within the reactor core

Plus heat **still being generated** by the continued breakdown of ^{235}U fission products:



1) https://www.osti.gov/biblio/6986994

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

3) https://www.graphicnews.com/en/pages/38900/us-40th-anniversary-of-the-three-mile-island-accident

With the SCRAM, three emergency pumps automatically turned on to cool the core

- But **two were blocked by manual shutoff valves left closed** after earlier maintenance
  - Thereby dramatically diminishing the emergency cooling system's effectiveness

The Primary loop heated to point its pressure relief valve (PORV) was energized to open

- When excess pressure was vented, that valve **should** have then closed
  - Stopping further loss of water from that primary cooling loop
- But the **pressure relief valve instead stuck open** continuing its release of cooling water
  - As PORV's had stuck open **nine** previous times on Babcock + Wilcox reactors [1]

But dark control room light indicated that power to open the valve had been removed

- And there was **no light** indicating whether or not valve HAD actually closed
- Operators **misinterpreted** dark "open" light as indicating PORV valve closure:
  - **U**ndetected stuck-open valve continued water release from primary cooling loop

Which operators did not notice because the reactor had been designed & built with

- **no direct way of measuring the cooling water level around the reactor core (!)** [1]

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1) Report of the President's Commission on the Accident at Three Mile Island - page 11: https://www.osti.gov/biblio/6986994

But instruments DID suggest water was in the Pressurizer ABOVE the reactor

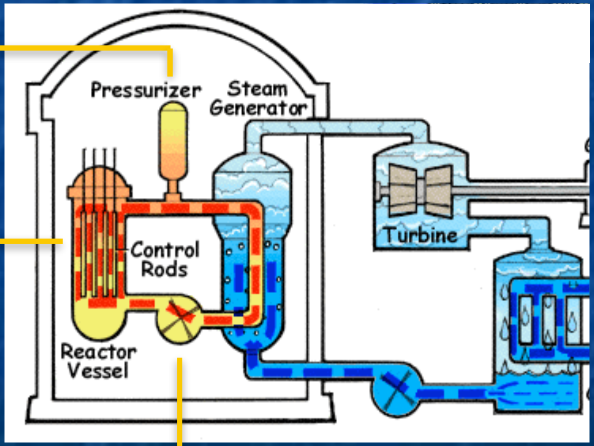
So operators **assumed** that the reactor below it must still be fully immersed in water

Then, because of pump vibrations, and fearing pressurizer would overfill (and fail):

Operators shut down automatic pumps trying to **add** water to the primary loop

In fact, the water level had already fallen below the top of the reactor's core, falling ever lower as steam continued to exit via the stuck-open valve

The water pumps had vibrated because they'd been trying to pump steam!



Pressure Relief Valve (PORV):
Stuck open / venting steam

Primary Cooling Loop:
Steam replacing water

Water-Adding Pumps:
Blocked or disabled by operators

Water Circulation Pumps:
Vibrating / pumping steam

Secondary Cooling Loop:
Shut down by filter-cleaning

Confusion reigned for four hours during which:

About half of the reactor's core melted down releasing uranium inside the containment

As in "The China Syndrome" movie which coincidentally debuted the very same week

The superheated Zr metal of the fuel rod tubes began **catalyzing** steam's decomposition:

$$2\ H_2O + \text{hot Zr} \rightarrow 2\ H_2 + O_2$$

Filling the containment building with H_2 and O_2

which eventually found an ignition source and explosively recombined [1]

(luckily) blowing only relatively small holes in the containment's walls,

venting proportionally small amounts of radioactivity to the surroundings

*The **same** mechanism that would produce Fukushima's explosions 32 years later*

Which continued until a fresh clearer-headed new shift of operators figured out that:

rather than needing LESS water, the reactor's core desperately needed MORE water,

thereby finally beginning to bring the TMI reactor accident under control

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1) Report of the President's Commission on the Accident at Three Mile Island - pages 87, 99 & 107: https://www.osti.gov/biblio/6986994

Partial list of faults and errors:

Equipment failures:

Stuck open primary loop pressure relief valve

Indicator giving only **intended** state of that valve and not its true state

Lack of dedicated indicator giving water level in core

Control system producing over 100 simultaneous alarms in first minutes of failure

Management / operator / training errors:

Initial procedure for cleaning out secondary cooling loop's clogged filter

Emergency cooling system manual valves left closed after earlier maintenance

Misinterpretation of badly designed pressure relief valve indicator

Operator mistrust of automatic safety systems (for cause?), leading to:

Operator misuse & override of water cooling systems, replicating errors that

18 months earlier **almost** brought down another Babcock & Wilcox reactor:

A previous near disaster about which TMI operators were never informed [1-3]

1) Report of the President's Commission on the Accident at Three Mile Island - page 10: https://www.osti.gov/biblio/6986994

1) https://en.wikipedia.org/wiki/Three_Mile_Island_accidentor.htm 2) https://en.wikipedia.org/wiki/Davis-Besse_Nuclear_Power_Station

Quoting directly from the

Report of the President's Commission on the Accident at Three Mile Island: [1]

Excerpt from "Handling of the Emergency" (page 17):

"The response to the emergency was dominated by an atmosphere of almost total confusion. There was lack of communication at all levels. Many key recommendations were made by individuals who were not in possession of accurate information, and those who managed the accident were slow to realize the significance and implications of the events that had taken place."

Excerpt from "Warning" (page 24):

"We have stated that fundamental changes must occur in organizations, procedures, and, above all, in the attitudes of people. No amount of technical "fixes" will cure this underlying problem. There have been many previous recommendations for greater safety for nuclear power plants, which have had limited impact. What we consider crucial is whether the proposed improvements are carried out by the same organizations (unchanged), with the same kinds of practices and the same attitudes that were prevalent prior to the accident. As long as proposed improvements are carried out in a "business as usual" atmosphere, the fundamental changes necessitated by the accident at Three Mile Island cannot be realized."

In light of the above, I must note that in researching modern TMI "information webpages"
posted by BOTH industry associations AND federal agencies
many (if not most) ***still*** *fail to mention central critical errors,*
some omitting even the egregious failure to reopen emergency valves after earlier maintenance.

Suggesting, sadly, that the Commission's final warning has fallen on largely deaf ears

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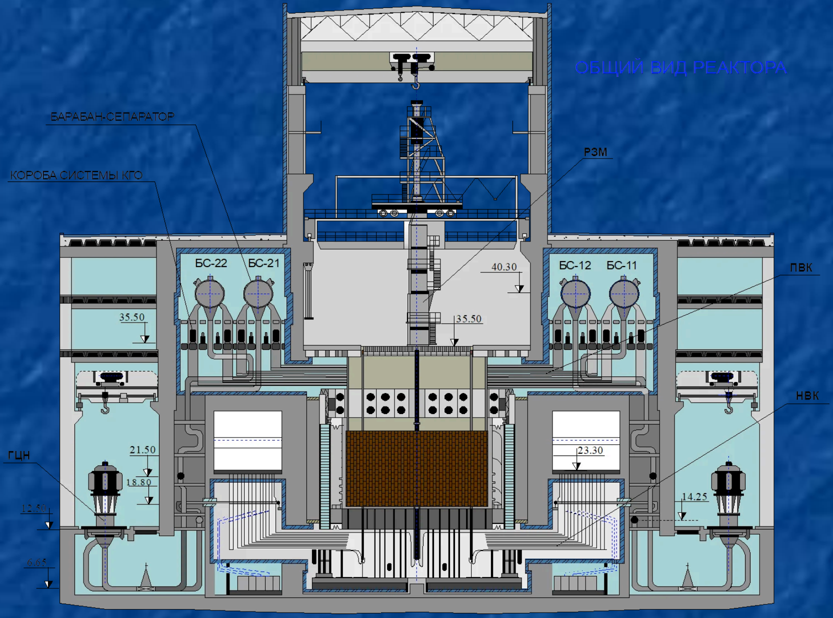
1) Report of the President's Commission on the Accident at Three Mile Island: https://www.osti.gov/biblio/6986994

The Chernobyl Accident

Ukraine (then Soviet Union) - 26 April 1986

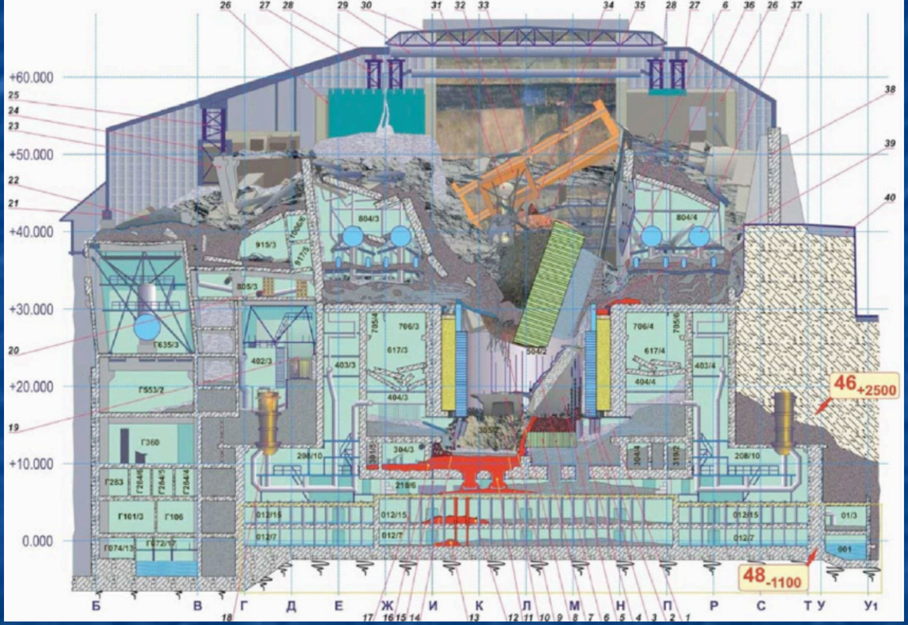
RBMK Reactor #4 (one of four on site)

Before:



After:

As now entombed inside a massive "sarcophagus"



https://hotcore.info/babki/chernobyl-nuclear-reactor.htm

https://www.researchgate.net/publication/353120989_Preliminary_results_on_dry_Cutting_FOR_Segmentation_of_non-homogeneous_FCM_at_ChNPP_Unit_4_with_advanced_laser-technologies

Unlike almost all Western Nuclear Power Plants . . .

Chernobyl's RBMK reactors use masses of Graphite as a Neutron Moderator

This solid does not expand and then boil away as temperature increases

Thus, as reactor power increases, its neutron moderation does not diminish

vs. moderating water whose loss would have dampened fission

Graphite cores produce strong, continuous, neutron moderation:

Initially **hot neutrons** with extremely high kinetic energy

undergo many, many collisions with cooler graphite (carbon) atoms

leading to neutron kinetic energy approaching that of the ambient atoms

So from then on, these cooled neutrons are almost as likely

to gain energy from atomic collisions as lose energy from atomic collisions

Leading to Chernobyl's 1st positive feedback loop:

Water no longer moderated these already slowed down neutrons

However, water did still **absorb** neutrons, **slowing nuclear fission reactions**

But then, when the reactor began to overheat and its water started to boil:

There was less water per volume →

There was less neutron absorption per volume →

Leaving more neutrons to **accelerate nuclear fission**

This acceleration of fission, upon creation of steam bubbles, is called a:

Positive void coefficient [1-3]

“Positive” in the sense that it provides positive feedback, stoking the fission reaction

So when Chernobyl **started** to overheat, this further **accelerated** the heating

1) https://en.wikipedia.org/wiki/Void_coefficient 2) https://en.wikipedia.org/wiki/RBMK 3) https://en.wikipedia.org/wiki/Chernobyl

Chernobyl's 2nd positive feedback loop: Its strange control rods

A control rod's job is to slow nuclear fission when it's pushed into the reactor core

But before a control rod enters the reactor core, its hole is filled with water

Which (per discussion above) already absorbs some neutrons

Designers wanted strongest possible drop in neutrons when the absorber entered

So they decided to kill off the initial absorption of the neutrons in water,

by first pushing out water, via a unique **Displacer** extension of the control rod

But that meant as a control rod entered reactor, **neutron population changed as**:

Medium (due to water) → High (no loss in displacer) → Low (due to absorber)

In the middle (with only displacer inserted) nuclear fission instead **accelerated**

Accelerating even **more** because displacer was made of neutron moderating graphite

Chernobyl's 3rd and 4th positive feedback loops: Involving Neutron "poisons"

I described earlier how things like Xenon, Boron & Iodine act as **neutron** **poisons**

Absorbing but not re-emitting any neutrons (taking them out of play)

But fission chain reactions themselves **produce** **poisons** within the fuel mass

Meaning Control Rods must be gradually withdrawn to maintain reactor power

But more subtly (and potentially deadly):

At HIGH reactor power strong neutron flux can make Control Rod **poisons** radioactive

Causing them to fission away into new **non-poison** elements

Diminishing the effectiveness of the Control Rods

→ Positive feedback loop driving the reactor power output even higher

At LOW reactor power neutron poisons tend to build back up (per first point above)

Which drives nuclear fission rate down even further

→ Positive feedback loop driving the reactor power output even lower

Before the accident, the Chernobyl Reactor had been running at low power

Meaning the fourth positive feedback loop had been in effect for a long period

leading to a higher than normal net amount of **neutron** **poison** within the reactor

As the operators now wanted to bring the reactor back to full power

they knew they would have to withdrawal control rods **farther** than normal

or withdraw **more** fuel rods than they would normally withdraw

But as the reactor heated up, accumulated poisons would begin to burn off (fission away)

meaning operators would have to drive control rods back to their normal operating depth

or increase the number of fully inserted control rods back to the normal number

This normal, carefully balancing Chernobyl reactor start-up procedure was spelled out

As similar careful start-up procedures are spelled out for reactors around the world

because they ALL suffer from this same poison build-up / burn-off phenomenon

But late at night, doing a much delayed test, in the absence of senior reactor staff,
these particular Chernobyl operators were in a hurry
and they withdrew many more than the recommended number of control rods

Four positive feedback loops → Instability → Sudden intense spike in fission

And, due to their abnormal procedures, they'd left themselves no margin for error

Likely leading to ("likely" because witnesses were dead and the damage overwhelming):

- A **Massive Steam explosion** blowing the lid right off the top of the reactor
- Which immediately exposed the super-hot reactor core to air (and its O_2)

  because RBMK's were built **without** western-style containment buildings
- Allowing air (w/ its oxygen) to reach the **super hot graphite moderator blocks**
- Causing those **graphite blocks** to **near instantaneously burst into flame**
- Producing the strong smoke plumes and thermal updrafts which, in short order,

  distributed radioactive debris & dust all across eastern Europe

Extraordinarily bad reactor design OR extraordinary human error?

I'd argue "both" - which I invite you to personally research [1-3]

But given RMBK's limited Western use, I'm instead going to move onward to . . .

1) https://en.wikipedia.org/wiki/RBMK *2) https://en.wikipedia.org/wiki/Chernobyl*

*3) Or my highly recommended **long read**: Adam Higginbotham's book **Midnight in Chernobyl** (ISBN 978-1-5011-3461-6)*

The Fukushima Daiichi Accident

Fukushima, Japan - 11 March 2011

General Electric Boiling Water Reactors #1 - #4

Figure: Institute for Science and International Security report (only one week after accident) [1]

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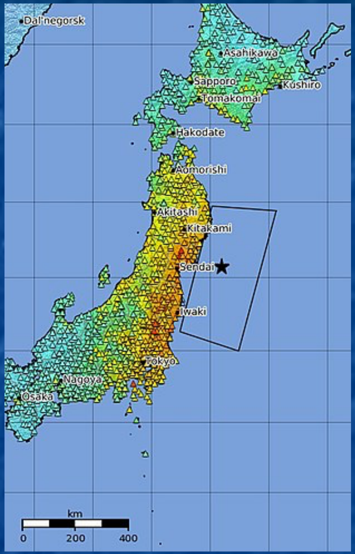
[1] *https://isis-online.org/isis-reports/detail/new-march-18-satellite-image-of-fukushima-daiichi-nuclear-site-in-japan/37*

Tōhoku Earthquake and Tsunami [1]

14:46 PM: **Richter 9.1 earthquake occurs ~ 70 km east of the Fukushima shore**



Local electric power grid crashes due to earthquake damage

But earthquake sensors automatically initiate shutdown of reactors

Activating reactor-site diesel backup generators which:

Power SCRAM insertion of control rods to quench ^{235}U fission

Energize emergency water cooling pumps

15:36 PM: Tsunami waves flood reactor sites

Shutting down diesel backup generators

Halting emergency shutdown procedures

Eliminating power to control room instruments

Leaving plant operators literally in the dark

(This video plays within Powerpoint & Keynote)

1) https://en.wikipedia.org/wiki/2011_Tōhoku_earthquake_and_tsunami

Video: Excerpt from PBS Nova's "Nuclear Meltdown Disaster" (2015)

Fukushima's TWO Reactor Complexes:

Fukushima Daiichi (Fukushima #1):

Six 1967 vintage General Electric BWR's, ~ 225 km northeast of Tokyo [1]

Three operating when 11 March 2011 tsunami struck, precipitating their destruction

Fukushima Daini (Fukushima #2) located 12 km to the south:

Four 1982 vintage reactors of same basic design, all four in operation that day [2]

But here, heroic and often inspired operator action prevented reactor destruction [3]

1) https://en.wikipedia.org/wiki/Fukushima_Daiichi_Nuclear_Power_Plant

2) https://en.wikipedia.org/wiki/Fukushima_Daini_Nuclear_Power_Plant 3) Upon which I will elaborate below

*I found **reams** of information about the Fukushima accident*

With much more detail & consensus than I found for the TMI & Chernobyl accidents

But in the end, it wasn't all necessary, because this accident was easy to figure out:

It wasn't due to unpredictable equipment breakdowns

It wasn't due to lack of operator training or operator errors

It was instead due to design shortcomings and compromises

that were well known and had been recognized for decades,

but which were accepted based on the cost reductions they facilitated

Accepted by reactor's owners: Tokyo Electric Power Company (TEPCO)

Accepted by the reactors' designers & builders: GE / Toshiba / Hitachi

And accepted by the responsible Japanese Government Regulators

Fukushima design shortcoming #1 (shared by all reactors):

As discussed earlier: **Turning off a reactor doesn't really turn it off**

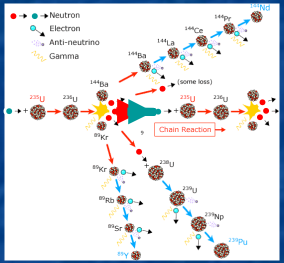
A reactor is "turned off" by inserting control rods containing **Neutron poisons**

absorbing so many neutrons that fission of ^{235}U **(but only ^{235}U)** is abruptly curtailed

But a rich population of previously created ^{235}U fission products continue fissioning,

releasing large amounts of heat, for additional seconds, minutes or hours,

adding to the heat that had already built up within the then operating reactor!



The **Reactor Core** itself may be able to withstand the resulting temperatures

because it's built with expensive & exotic high temperature materials, possibly including:

Melting Points (ºC): Titanium 1670 Zirconium 1854 Tantalum 2950 Tungsten 3400

But the reactor shell and piping can be substantially less temperature resistant:

Melting Points (ºC): Irons 1127-1204 Carbon Steels 1371-1593 Stainless Steel 1510

Metal melting point data from: https://fractory.com/melting-point-of-metals-chart/

The result: ***AFTER shutdown reactors MUST be cooled for DAYS***

Future reactors might be able to do this using only stored water + gravity

For instance, GE's ESBWR design and certain Small Modular Reactor (SMR) designs

But I have yet to learn of a single such **passively cooled** reactor in actual operation

Today's reactors are instead **actively cooled**, meaning that upon shutdown

electric pumps must circulate cooling water for the required multiple days

Shutting down a Nuclear Power Reactor thus requires days of Electrical Power

Which can't be supplied by the then shutting-down or already shut-down reactor

And if unavailable from a neighboring still operating reactor

it's imperative that electrical power remain available from **SOMEWHERE ELSE**

So how did the builders / owners / regulators of Fukushima address this challenge?

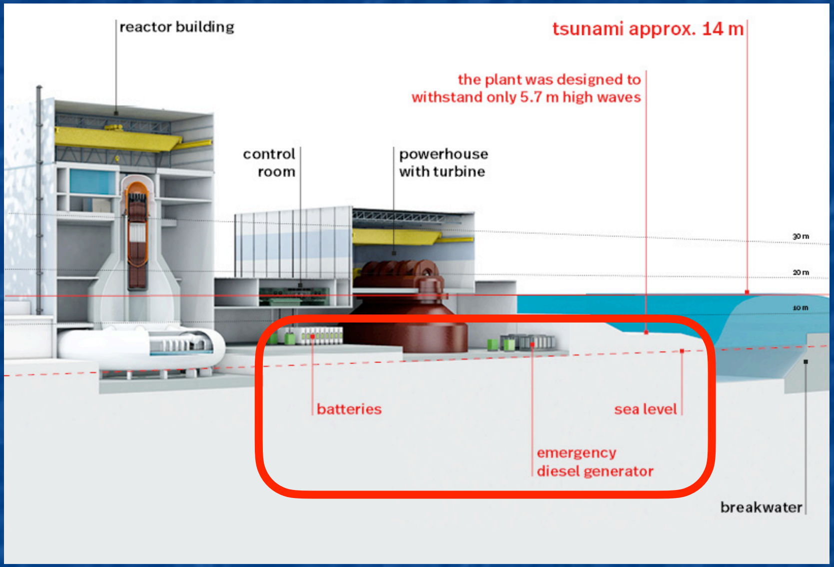
For backup shutdown electrical power they added to each reactor installation

banks of batteries AND diesel-powered electrical generators

But WHERE were those batteries & diesel electric generators placed?

On the edge of perhaps the world's most seismically active & tsunami prone coast

Indeed, on one of the coasts where "tsunamis" actually got their name!



Where these back-up batteries and diesel electric generators were built into

BASEMENTS . . . AT NORMAL SEA LEVEL (right figure, highlighted by red box)

WHY locate plant, pumps & generators AT sea level (vs. up the adjacent hill)?

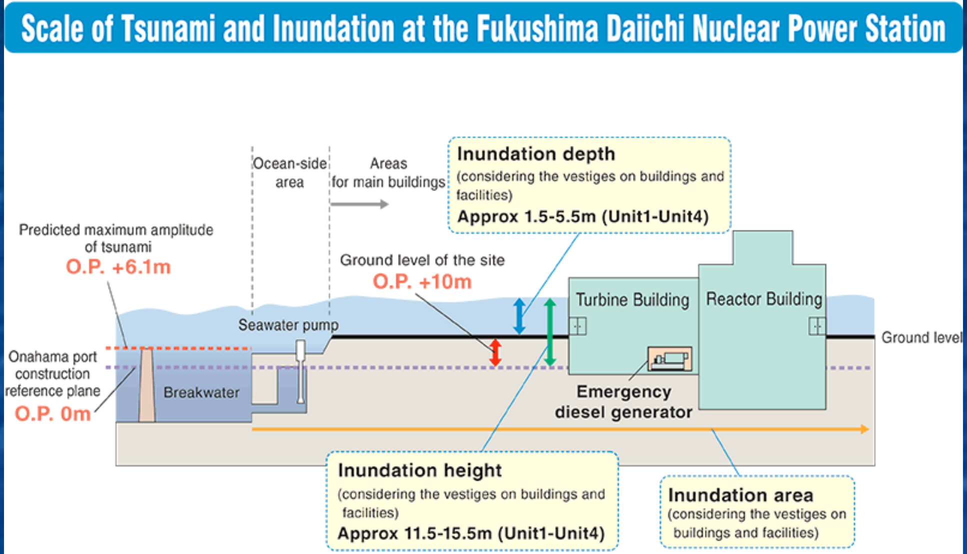
Likely only to allow use of cheaper pumps/pipes unable to pump water up/down that hill

Left) https://en.wikipedia.org/wiki/Fukushima_Daiichi_Nuclear_Power_Plant

Right) With title text hidden and emphasizing red box added: https://www.base.bund.de/EN/ns/accidents/fukushima/fukushima.html

Compounded by Fukushima design shortcoming #2: Inadequate Tsunami protection

From the summary of a later Federation of Electric Power Companies of Japan (FEPC) report: [1]



Scale of Tsunami and Inundation at the Fukushima Daiichi Nuclear Power Station

Inundation depth
(considering the vestiges on buildings and facilities)
Approx 1.5-5.5m (Unit1-Unit4)

Inundation height
(considering the vestiges on buildings and facilities)
Approx 11.5-15.5m (Unit1-Unit4)

Inundation area
(considering the vestiges on buildings and facilities)

Interpreting figure's O.P. ("Onahama port construction reference plane") as normal sea level:

- An offshore Tsunami Barrier was built reaching **6.1 meters above O.P.**

- Behind which the reactor complex's ground level was **10 meters above O.P.**

- But, according to **this** figure, the emergency diesel generators were actually **BELOW O.P.**

Meaning they **could even have been flooded by everyday groundwater seepage**

All mooted by the arrival of a Tsunami extending 15.5 METERS ABOVE above O.P.

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1) https://www.fepc.or.jp/english/nuclear/power_generation/overview/

But those shortcomings were actually identified well before the "accident" [1-3]

First, while the design's goal was to block tsunami's of **10 METERS** height

the **actual design** incorporated an only 6.5 meter high offshore barrier

apparently just **hoping** it would slow 10 meter high water enough that it would

not then flood up upon onto the 10 meter high ground around the reactors

But even that optimism-based scenario was undermined by subsequent studies

suggesting that the risk of even larger tsunamis was too high

and that the barrier height should be very significantly increased

TEPCO considered those studies but ultimately decided against higher barriers

Fearing that admission of their design error at Fukushima might lead to calls for

similar barriers, or barrier heightening, at other Japanese nuclear plants

(including at sites where the tsunami threat was less acute)

Instead, SOME of the backup generators were moved up to the top of the hill

But their power lines and circuit breakers were left down in those basements

where they were flooded and knocked out of service when the tsunami hit

1) https://www.base.bund.de/EN/ns/accidents/fukushima/fukushima.html
2) https://eta.lbl.gov/sites/default/files/seminars/fukushima1_technical_perspective_lbl_eedt_04052011-1.pdf
3) https://nap.nationalacademies.org/catalog/18294/lessons-learned-from-the-fukushima-nuclear-accident-for-improving-safety-of-us-nuclear-plants

Have we in the U.S. been any smarter, wiser, or less-penny pinching?

Humboldt Bay Nuclear Power Plant (first of three U.S. west coast Nuclear Plants):[1]

1960: Construction begun on the northern California coast,
with the plant was sited on the Pacific Ocean waterfront,
at essentially sea level, but behind a modest piled stone berm

1964: Record-breaking 1964 Alaskan Earthquake triggers tsunami
devastating the nearby Northern California town of Crescent City[2]

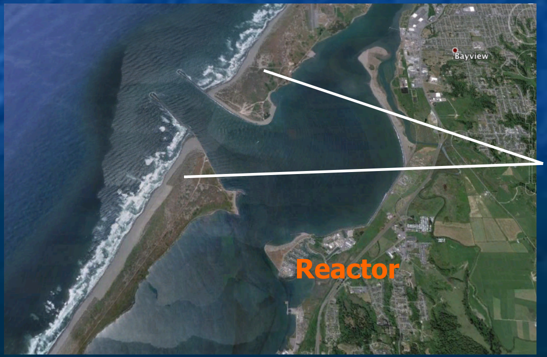
Subsequent study indicates that city had
"experienced tsunami conditions 31 times between the years 1933 and 2008"[2]

1963: Construction of the Nuclear Plant completed and plant commissioned

2004: Plant operator PG&E announces that it has lost three nuclear fuel rods

2020: Plant decommissioned, in part due to discovery of new nearby earthquake faults

Stone berm



Minor natural protection

(Google Earth)

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1) https://en.wikipedia.org/wiki/Humboldt_Bay_Nuclear_Power_Plant

2) https://en.wikipedia.org/wiki/Crescent_City,_California

San Onofre Nuclear Power Plant (second of three U.S. west coast Nuclear Plants): [1]

1964: Construction begun on the southern California coast, not far north of San Diego
with plant sandwiched between Interstate Highway 5 and Pacific Ocean waterfront,
immediately south of popular state park & beach (where I vacationed as a child)

Built at essentially sea level, **without natural or added artificial tsunami barriers**

2012: Both reactors shut down:

"after premature wear was found on more than 3,000 tubes in replacement steam generators that had been installed in 2010 and 2011"

2013: U.S. Senate Environment and Public Works Committee chairman claims plant:

"posed a danger to the eight million people living within 50 miles of the plant"

2013: Plant decommissioned

Left Photo: www.kpbs.org/news/2011/mar/24/san-onofre-operators-welcome-nrc-review/
Right photo and reference 1) https://en.wikipedia.org/wiki/San_Onofre_Nuclear_Generating_Station

Diablo Canyon Nuclear Power Plant (third of three U.S. west coast Nuclear Plants): [1]

1968: Construction begun on **very lightly populated** California coast roughly midway between San Francisco and Los Angelas, **atop a 26 meter tall cliff**

Later discovered that plant was within 5 km of two previously unknown earthquake faults

But Nuclear Regulatory Commission comparative review of U.S. nuclear power plants concluded that Diablo Canyon had "a high level of preparedness and strong capability in terms of equipment and procedures to respond to severe events"

2021: Among vigorous calls for plant's shutdown, a MIT / Stanford study concluded:

> "keeping Diablo Canyon running until 2035 would reduce the state's carbon emissions from electricity generation by 11% every year, save the state a cumulative $2.6 billion . . . and improve the reliability of the grid" [1]

Present Day: That debate continues

Photo: www.ojaipost.com/2011/03/diablo-canyon-nuclear-plant/

Photo: https://wonderfulengineering.com/wp-content/uploads/2021/10/diablo-canyon-exterior-2-2.jpg

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1) https://en.wikipedia.org/wiki/Diablo_Canyon_Power_Plant

Returning to Fukushima: where within minutes of the tsunami wave . . .

SEVEN operating Nuclear Reactors (3 at Fukushima Daiichi + 4 at Fukushima Daini)
have SCRAMMED, quenching ^{235}U fission within their cores

But products of earlier ^{235}U fission continue their fission decay
adding more and more heat energy into those reactor cores

Which have now lost both normal AND emergency backup cooling
due to massive basement-level tsunami flooding

Allowing the reactor cores to get hotter and hotter
AND for the spread of intense heat into other parts of the reactor
never intended to operate at such extreme high temperatures

Threats now compounded by . . .

Fukushima design shortcoming #3 (shared by many/most reactors): ***Spent Fuel***

"Spent fuel" is really not all that spent:

After two years in a reactor ≤ 25% of the ^{235}U actually fissions, but it must nevertheless then be replaced because ^{235}U fission can no longer be sustained (i.e., because what started as 4-5% ^{235}U fuel has become ~ 3-4% ^{235}U fuel)

Thus, rather than trying to immediately bury it for millennia, it makes much more sense that it be re-enriched (removing ^{238}U), boosting it back up to **reactor grade 4-5% ^{235}U**

However, rich in still-fissioning ^{235}U & ^{238}U products, spent fuel is **intensely radioactive** and rather than trying to move, and eventually ship away that fuel, the accepted practice is to **keep it at the reactor site for at least a few years** during which decay of shorter-lived fission products reduces its radioactivity

But to minimize its handling, and contain it while it IS STILL intensely radioactive,

spent fuel is now generally stored IMMEDIATELY ADJACENT to the reactor

The amount of STORED spent fuel can easily exceed that INSIDE the reactor

Thereby doubling, tripling, or even quadrupling the TOTAL amount of fuel

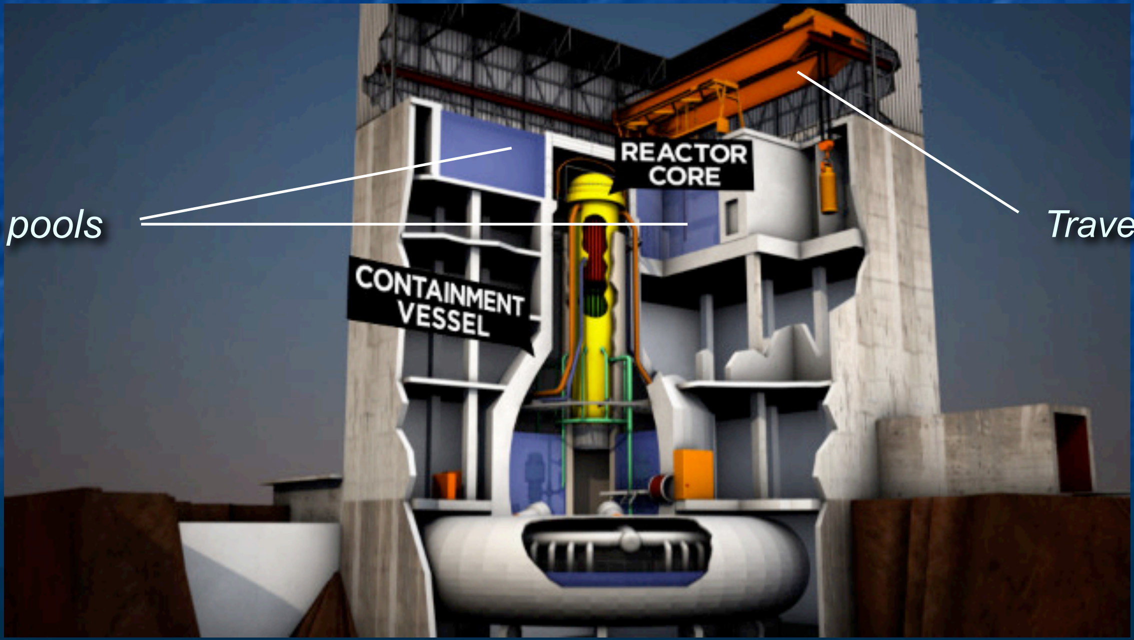
Further, because that "spent" fuel **is** still fissioning, it must also be cooled

typically via immersion in nearby pools of cooled water

To get that spent fuel out of the reactor core and into those water pools quickly & safely

in the GE-designed Fukushima reactor pools were placed **beside** the reactor's lid

allowing for a simple lift from the core, short sideways move, descent into a pool

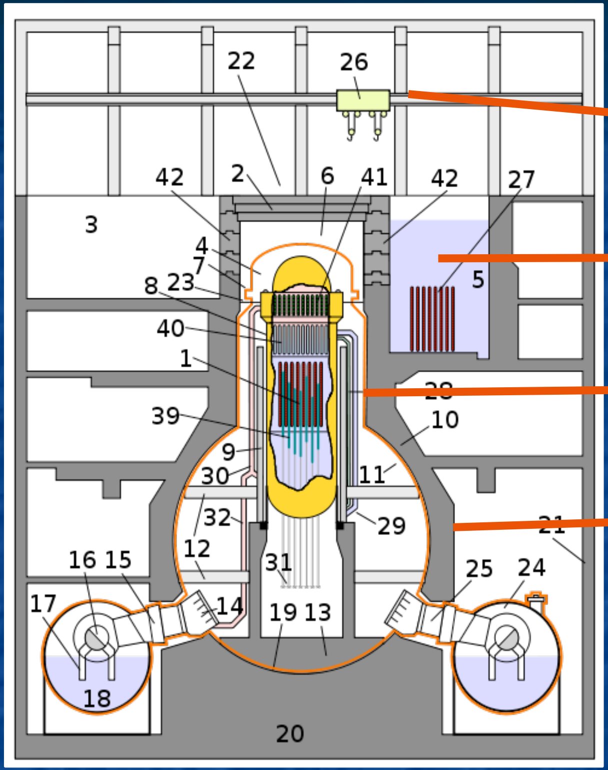


Spent fuel storage pools

Traveling beam crane

www.cnn.com/2012/02/17/us/us-nuclear-reactor-concerns/

Or diagrammatically:



Crane for fuel rod loading / unloading

"Spent" fuel rod storage pool

Reactor vessel

Reinforced reactor enclosure

The high position of storage pools DOES make them quicker and easier to reach

But they are already outside of the main reinforced reactor enclosure and,

above the reactor, they are susceptible to damage and cooling water loss

These three Fukushima design shortcomings set the stage for . . .

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

Fukushima design shortcoming #4 (shared by many/most reactors):

High temperature catalytic decomposition of H_2O by zirconium

Fuel rods hold enriched ^{235}U inside **zirconium metal** alloy tubes

because it's one of very few materials that can withstand full reactor core heat

At Fukushima Daini, operators had improvised an off-the-books way of cooling their 4 reactors

But the operators of the 4 Fukushima Daiichi reactors were less successful

The Fukushima Daiichi #1-3 reactors thus reached near 2000°C temperatures where

Zirconium catalyzes steam/water decomposition: **$2\ H_2O \Rightarrow 2\ H_2 + O_2$**

Those gases accumulated until within 3 Daiichi reactors,

they reached explosive levels, found an ignition source, and chemically recombined:

$2\ H_2 + O_2 \Rightarrow 2\ H_2O$ + large amount of energy (= explosion)

Despite meltdowns, to that point **radiation had been confined** within the reactor buildings

because the reactor's "containment structures" **had** still been doing their jobs!

But hydrogen + oxygen explosions now blew open those containment structures!

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

(This video plays within Powerpoint & Keynote)

But these were NOT "nuclear explosions"

They were NOT even "nuclear fizzles"

These were classic chemical explosions: $2\ H_2 + O_2 \Rightarrow 2\ H_2O$ + Heat Energy

And their energy release was **immensely less** than even the earliest nuclear bombs

(even though, yes, it was fission heat that had driven zirconium catalytic splitting of H_2O)

Only then were large quantities of radioactive materials widely dispersed →

"DIRTY BOMB" = Bomb using conventional explosives to spread radioactive materials

Video segment excerpted from: https://www.youtube.com/watch?v=IMVi-XmM-SU

Later insights from a 2015 PBS Nova investigative documentary: [1]

Of the six Fukushima Daiichi reactor "units" **only Units 1-3 had been in operation**

As shown in preceding video, **Unit 1** & **Unit 3** were blown open by hydrogen explosions

But mysteriously:

Unit 2 did not explode

Because, it was discovered, its building was punctured by the adjacent Unit 1 explosion

Which vented Unit 2's accumulated H_2 preventing its own explosion, but also

allowing its release of deadly radioactive Cesium into the countryside

But Unit 4 did explode

Despite its being out of operation, undergoing fuel rod replacement

Ultimately explained by the fact that it shared a venting chimney with Unit 3

Which allowed enough of Unit 3's pre-explosion H_2

to leak into unit 4, setting the stage for its explosion

1) PBS Nova's "Nuclear Meltdown Disaster" (2015)

A hydrogen explosion also occurred at Three Mile Island

(thirty two years earlier)

And high temperature zirconium catalysis of water was **also** identified as the cause.

even in the 1979 Presidential Commission Report about TMI

And once again, the hydrogen chemical explosion shifted the accident from

a **contained meltdown** to an external **radiation release**

That is, the explosion moved a problem **within a single reactor building**

into the beginnings of a **large area environmental disaster**

But fortunately, the TMI hydrogen + oxygen explosion was much, much smaller

and the damage to the containment was proportionally reduced

such that radiation leakage at TMI was minimal

And it took a 2nd go round (at Fukushima) to fully play out this disaster scenario

Producing this local damage:

Before:

After:

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

https://isis-online.org/isis-reports/detail/new-march-18-satellite-image-of-fukushima-daiichi-nuclear-site-in-japan/37

As well as this much broader eventual transformation:

Before: Barely discernible seaside reactors + surrounding countryside:

After: Barely discernible seaside reactors + massive clean-up / nuclear waste-storage

Left: http://metro.co.uk/2011/03/14/pictures-japan-earthquake-aftermath-3053782/combination-photo-shows-satellite-images-of-fukushima-daiichi-nuclear-power-plant-in-japan-taken-by-the-geoeye-1-satellite-on-november-15-2009-l-and-on-march-11-2011-after-magnitude-8-9-earthquak/

Right: http://www.gettyimages.de/ereignis/fukushima-daiichi-nuclear-power-plant-five-years-after-meltdown-610095217#in-this-aerial-image-tokyo-electric-power-cos-fukushima-daiichi-on-picture-id515572706

Fukushima shortcoming #5: Major Operator Errors (as at TMI & Chernobyl)?

No!

Multiple studies concluded that the operators met or exceeded training expectations

But for me the commitment, indeed the heroism of Fukushima operators

was driven home by the 2015 PBS Nova investigative documentary:

Nuclear Meltdown Disaster

Which retold the Fukushima story based almost entirely on interviews with

operators & experts on the ground at Fukushima as the disaster unfolded

That video HAD been available on U.S. Public Television (and via YouTube posted copies)

but as of 2024 it can apparently only be viewed via this Amazon Prime link

(Which I urge you to do)

In the interim I have re-viewed that documentary and offer these highlights:

When **BOTH** grid power and emergency onsite backup power failed at Diaichi and Daini
an event TEPCO never anticipated and for which they provided no operator training:

Operators ran up the hill to steal batteries from cars and trucks in the parking lots
with which they jury-rigged power to instruments in the blacked out control rooms
providing them with the first information about what was occurring inside the reactors

Which revealed the dire state of those reactors prompting operators at Daini (with less flooding)
to venture out into the countryside to find and tap hoses into an abandoned water line

And, when they eventually found one remote building that had regained power:

They managed to have shipped in **five miles** of heavy duty electrical cable
which would normally have taken a month to connect that building to the reactors
but as a crew of 200 they managed haul it on their shoulders into place in a day

Which put them in a position to finally energize pumps to deliver water to the reactors
but only after certain valves were opened, by hand, in reactor basements
where radiation was at lethal levels, but into which they nevertheless ventured

And when asked by the film's interviewers how they could take such a risk, their response was:

By then none of them expected to even **survive** the disaster
so in whatever time remained for them, why **not** do everything possible to save others?

*My **personal** conclusions regarding the Fukushima disaster:*

Fukushima's shortcomings were well known
and alternatives or fixes were obvious (if not always easily affordable)

Specifically, regarding tsunami protection at beachfront nuclear reactor sites:

I can't believe much higher tsunami barriers would have strongly impacted overall cost

Nor I can believe that placing batteries & diesel electric generators **OUT** of basements

and **UP** the hill behind would have greatly impacted the Fukushima sites' overall cost

But why was a beachfront reactor site **even considered** when, for half a century,

Diablo Canyon reactors had been successfully water-cooled atop a 26 meter tall bluff?

Finally, while I acknowledge the difficulty of eliminating hydrogen-catalyzing fuel rods,

I found no more than a few isolated & sporadic research efforts **even targeting** that goal

All of which reenforces the TMI Presidential Commission Report's prophetic:

"As long as proposed improvements are carried out in a 'business as usual' atmosphere,
fundamental changes necessitated by the accident (now accidents) . . . cannot be realized"

And finally:

What about Nuclear Energy's Supposedly Small Carbon Footprint?

*Which might **seem** an extreme change of topic*

But given this note set's focus on arguments for not even considering a Nuclear Future,

claims that Nuclear might NOT be a low Greenhouse Gas technology **are** relevant

Those claims parallel criticisms of Hydroelectric Energy, because both technologies

make massive use of concrete (as incorporated in their dams & reactor complexes)

Which I first analyzed in my note set about **Hydroelectric Power** (pptx / pdf / key),

but which I will here now slightly adapt to apply to reactors

(in the interest of keeping this note set about Nuclear largely self-contained)

Concrete: What is it?

Concrete consists of gravel ("aggregate") glued together with a cement

Portland cement is the most commonly used modern glue

It contains calcium silicates (e.g., Ca_3SiO_5 and Ca_2SiO_4) which,

when exposed to water, form hydrates that bind the gravel together [1]

The source of that Ca is naturally occurring limestone ($CaCO_3$)

Ca is liberated by heating the limestone at 1400-1600°C in **HUGE** rotating kilns: [2]

1) Portland cement science: http://matse1.matse.illinois.edu/concrete/prin.html

2) Photo: https://www.cemnet.com/Articles/story/39950/acc-s-mega-kiln-line-project.html

Concrete's Carbon Footprint:

The above process has a huge carbon footprint due to:

- Burning of carbon fossil fuels to produce the 1400-1600°C kiln temperatures
- The need to **constantly** heat those massive kilns, even when not in production
- The release of CO_2 that occurs as Ca is liberated from the limestone ($CaCO_3$)

The 2024 EPA Inventory of US Greenhouse Gas Emissions & Sinks reported [1]

that 2022 U.S. Portland cement production produced a carbon footprint of:

41.9 million metric tonnes CO_2 equivalent

Annual U.S. Portland cement production that year was ~ 95 million tonnes [2] and thus:

1 tonne of Portland cement => 0.44 tons of CO_2 equivalent released

Concrete (aggregate + Portland cement) is ~ 11% Portland cement by weight [3] =>

1 tonne of **Concrete** => 0.05 tonnes of CO_2 equivalent released OR

Concrete's Carbon Footprint = 0.05 tonnes CO_2 eq. / tonne Concrete

1) Sections 2.2 and 4.1 of: https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022

2) https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-cement.pdf

3) www.cement.org/cement-concrete-basics/concrete-materials

Using that to compute Nuclear's carbon footprint due to concrete:

A "typical**"** **nuclear plant** requires "**up to 350,000 cubic yards**" of concrete [1]

Which, given **concrete's density** [2] of 1.9 tons/yd^3 => 603,000 tonnes of **concrete**

But, using that same concrete, the reactor then operates for at least 40 years,

making the plant's time-averaged annual use of concrete **15,075 tonnes of concrete / yr**

Which, using the previous page's result for carbon footprint from concrete's manufacture,

(15,075 tonnes of concrete / yr) x (0.05 tonnes CO_2 eq. / tonne concrete) yields:

Nuclear plant carbon footprint = **754 tonnes CO_2 eq. / yr**

Nuclear plants typically output of about 1.5 GW of electrical power, so footprint per power is

(754 tonnes CO_2 eq. / yr) / (1,500,000 kW)

Nuclear power footprint = **0.0005 tonnes CO_2 eq. / kW-yr**

Total U.S. electrical power is now ~ ½ Tera-Watts of which Nuclear produces 19.7% = 9.8×10^7 kW,

with (9.8×10^7 kW) x (5×10^{-4} tonnes CO_2 eq. / kW-yr) then yielding:

Cumulative U.S. Nuclear power plant carbon footprint = **49,900 tonnes of CO_2 eq. / yr**

1) www.concreteconstruction.net/construction/construction-of-nuclear-power-stations.aspx
2) http://hypertextbook.com/facts/1999/KatrinaJones.shtml

Comparing that to Carbon Footprint of other U.S. Power Technologies

Using the **"Where Do We Go from Here?"** (pptx / pdf / key) note set's analyses:

Coal Plant Power:	0.001 metric tonne CO_2 eq. / kW-hr	= **8.8 tonne** CO_2 eq. / kW-yr
OCGT Gas Plant Power:	0.0007 metric tonne CO_2 eq. / kW-hr	= **6.1 tonne** CO_2 eq./ kW-yr
CCGT Gas Plant Power:	0.00045 metric tonne CO_2 eq. / kW-hr	= **3.9 tonne** CO_2 eq./ kW-yr

All hugely larger than Nuclear Power at 0.0005 tonne CO_2 eq. / kW-yr

In 2016 **Coal Power Plants** provided 30.4% of U.S. power => 1.52×10^8 kW

Carbon footprint = (1.52×10^8 kW) x (8.8 tonne/kW-yr) = 1.3×10^9 tonnes CO_2 / yr

= **26,000 times the cumulative Nuclear Plant carbon footprint**

In 2016 **Natural Gas Power Plants** provided 33.8% of U.S. power => 1.69×10^8 kW

Which, if it were produced using half OCGT and half CCGT, would represent

Carbon footprint = (1.69×10^8 kW) x (5.0 tonne/kW-yr) = 8.5×10^8 tonnes CO_2 / yr

= **17,000 times the cumulative Nuclear Plant carbon footprint**

Nuclear Power's CO_2 footprint is MINISCULE compared to fossil fuel power!

My personal takeaways?

As I stated in my opening, I too am uneasy about nuclear power

But in the face of accelerating of global warming,
and our still meager reductions in Greenhouse Gas emissions,
I wondered if low-emission Nuclear (as I just verified) might be an acceptable answer

I've now provided information & sources upon which you can reach your own conclusions

But, for myself, I am still uneasy:

Three Mile Island and Chernobyl seem like accidents that were just waiting to happen

Fukushima would never have happened if reactors were uphill just 100 meters to the west
Possibly encouraging, had their actual siting not been such an obviously terrible decision
on the part of the plants' owners, designers and government regulators

My plan is to now search for nuclear reactor designs that would not only passively shut down,
but do so in ways that are almost certainly both idiot-proof and natural-disaster-proof

And looking farther forward, for reactors producing radically less long-lived radioactive waste

I'll write up what I discover - Keep checking my WeCanFigureThisOut Energy Webpage

John C. Bean - Summer 2024

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This set of notes was authored by John C. Bean who also created all figures not explicitly credited above.