Nuclear Energy – "But they blow up!"

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<u>Outline</u>

Nuclei: What they contain, how to keep track of this

Fission of abundant U238 vs. rare U235

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

As opposed to carbon moderated RBMK reactors

The Accidents:

Three Mile Island / Chernobyl / Fukushima Dai Ichi

The claim that massive use of concrete negates nuclear's ~ zero greenhouse emission

(Written / Revised: December 2017)

Nuclear Energy – "But the blow up!"

My sequence of topics has been a little strange:

I started with basic science

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

I followed this by descriptions of up and coming power technologies

Then, seemingly about to exhaust possibilities, described exotic long shots

And only now am I looping back to our biggest carbon-free technology:

Nuclear

I followed this path because I suspect many of you are uneasy with nuclear

So am I

And I probably have more 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, 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 environmentalists**)

To ask, not only if we might be able to **live** with nuclear,

but if it can improved to the point that we feel **comfortable** living with it

"But they blow up!"

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

So in this lecture we are going to learn **how nuclear reactors blow up**

AND, for comparison, **how nuclear bombs blow up**

Starting with a quick review of nuclear physics:

Nuclear physics is all about nuclei, which consist of protons plus neutrons

But protons and neutrons are capable of changing identities, for instance:

Neutron => proton + electron + ΔE **or** the reverse reaction

And that ΔE is **HUGE**, capable of boiling a lot of water, generating a lot of electricity

This all comes directly from Einstein's famous $E = mc^2$

Which says that mass can actually be converted to **immense** energy

as occurs when protons & neutrons slightly shift their masses

Keeping track of atom's protons, electrons and neutrons:

Atoms start with equal numbers of **protons** and **electrons**, balancing charge

Their count is encoded in the atom's name, and in it's **atomic number**

Most carbon atoms have 6 protons (6 p) + 6 neutrons (6 n)

Giving carbon an **atomic number** of 6 (≠ its **atomic mass** of ~ 12)

The number of **nucleons** = number of **protons** + **neutrons** in atom's nucleus

But the number of neutrons in an atom varies => **isotopes** of an atom

In light atoms, numbers of protons and neutrons tend to be equal

In heavier atoms, neutrons tend to outnumber protons

Nucleon count is given by a leading superscript, as in **^{13}C** for carbon

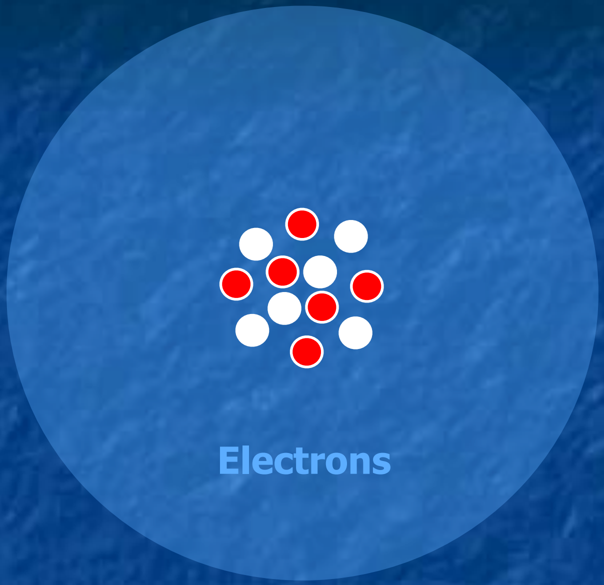
From this, number of **neutrons** = [number of nucleons – number of protons]:

For ^{13}C, neutron count = 13 – 6 = 7

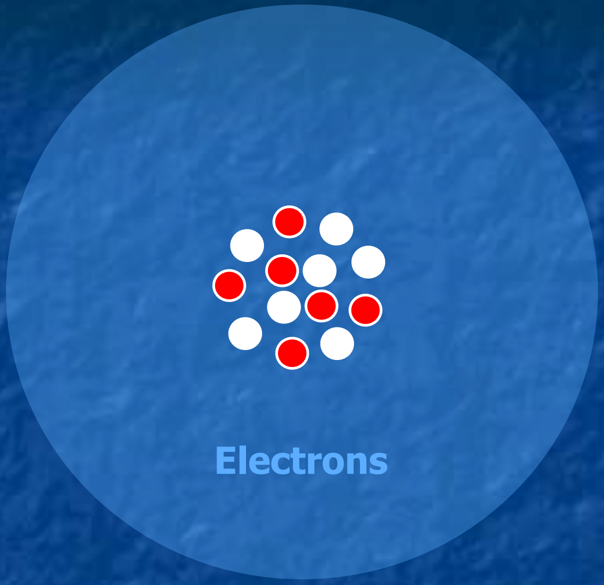
For ^{12}C (the more common isotope of carbon), neutron count = 12 – 6 = 6

Showing all of that schematically for ^{12}C and ^{13}C:

^{12}C:



^{13}C:



Protons = **6** = Electrons = Atomic Number

Neutrons = **6**

Protons = **6** = Electrons = Atomic Number

Neutrons = **7**

But natural atomic abundances are **98.93% ^{12}C**, and only **1.07% ^{13}C**

So (averaged) atomic mass in nature works out to be 12.0107

In nuclear reactors (and bombs) a few atoms play major 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

That mass suggests its main isotope is ^{238}U, which is indeed the case:

^{238}U: 99.27% Half-life: 4.6 billion years

^{235}U: 0.72% Half-life: 703.8 million years

Plus other much less abundant isotopes (<0.01%)

Finite lifetimes => They ARE radioactive, eventually falling apart (releasing energy)

Extremely long lifetimes mean that **very few decay in a given amount of time**

So in reactors OR bombs **something** must vastly speed up the process of decay

Decay is stimulated by capture of neutrons of particular energies:

The dominant ^{238}**U** isotope captures **high kinetic energy / "fast" neutrons**

^{238}U + ^{1}**n (hot/fast)** => ^{239}U => ^{239}Np + β => ^{239}Pu + β

where β ("beta") = a released high energy electron

Significantly: This decay sequence does NOT produce more neutrons

So while a neutron can CAUSE ^{238}U to fission, that neutron is thereby consumed

And because it is not replaced, you cannot get a ^{238}U chain reaction

Helping to explain ^{238}U's surviving abundance

However, ^{238}U's reaction DOES produce plutonium

Which works so well in bombs

Attracting would-be members of the "nuclear club"

Whereas:

^{235}U prefers capture of **low kinetic energy / "slow" / "thermal" neutrons**

^{235}U + ^{1}n **(slow/thermal)** => ^{236}U => ^{89}Kr + ^{144}Ba + **2 ^{1}n** + 200 MeV

With many other possible, but less likely, decay paths including: [1]

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

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

The weighted average of these paths => **^{235}U fission produces ~ 2.4 neutrons**

Because these neutrons tend to have lots of kinetic energy = hot / fast

they **don't** strongly stimulate **other ^{235}U** atoms to decay

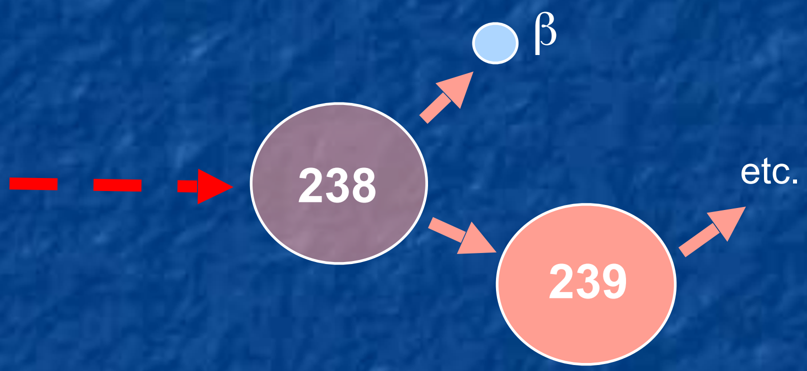
But as hot / fast neutrons, they DO stimulate **^{238}U** atoms to decay

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

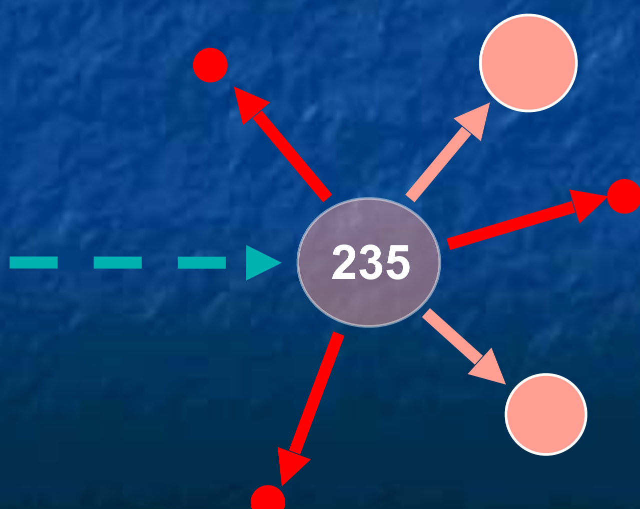
The ways ^{238}U and ^{235}U typically interact with neutrons:

^{238}U: Slow neutron incident

Fast neutron incident



^{235}U: Slow neutron incident



Fast neutron incident

However, hot / fast neutrons can be slowed down:

The simplest way is by just bouncing them off light atoms

Those atoms are accelerated, capturing part of the neutron's kinetic energy

Light atoms => NEUTRON MODERATORS (absorbing energy)

Whereas a neutron can hardly budge a very heavy atom and thus

Heavy atoms => NEUTRON MIRRORS (neutrons ricocheting off)

And another important player: **NEUTRON ABSORBERS / POISONS / SINKS**

Which, because they absorb but do not emit more, eliminate neutrons

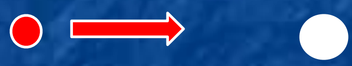
Xenon (Xe), Iodine (I), Boron (B) are examples of neutron poisons/sinks

To sustain nuclear fission there must be very few of these around!

Summary schematic of things affecting neutrons:

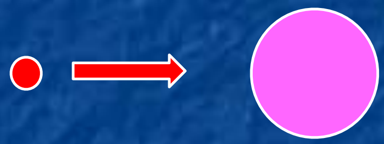
Before: **After:**

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

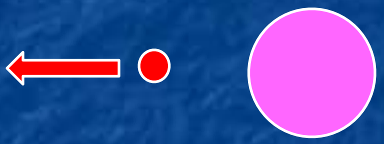


Result:

Neutron Mirror (heavy atom that absorbs ~ none of neutron’s kinetic energy):



Result:



Neutron Poison (an atom that absorbs a neutron into its **own** nucleus):

Result:

*But some atoms act as both **Moderator** and **Poison***

Most notably, normal hydrogen with its nucleus containing a single lone proton

Because of the near match in proton and neutron masses

A neutron striking hydrogen transfers a lot of energy to it

Making normal hydrogen a great **Neutron Moderator:**

But while unlikely, that nucleus can also absorb one (or even two) neutrons

Transmuting simple hydrogen into isotopes called **deuterium** or **tritium**

Making normal hydrogen at least a weak **Neutron Poison:**

But for pure moderation one can instead use:

Carbon (in the form of graphite) as a moderator

Its heavier mass makes it a somewhat less effective as a moderator

But its nucleus is far less likely to absorb neutrons

And critically, when one uses almost purely-moderating carbon:

A fission chain reaction can be set up and sustained

in even naturally occurring uranium ore of 0.7% ^{235}**U** + 99.3% ^{238}**U**

Which has the huge advantage of eliminating the need to pre-process uranium ore

in order to **enrich** its ^{235}U content, which is **impossible via chemistry**

because ^{235}U and ^{238}U have identical electron structures

However, as we shall see, Graphite has a deadly flaw: It is flammable

But there is one more alternative: "Heavy Water"

Which is water in with deuterium replaces normal hydrogen (then also called "D_2O")

Deuterium DOES occur naturally, but it is very rare:

As a result, only one water molecule in 3200 is normally D_2O [1]

But with heavier hydrogens, brownian motion & vibration of D_2O is slightly slower

Which minutely affects both its evaporation rate

and its electrically-induced decomposition (electrolysis)

Thus, if evaporation is followed by re-condensation over and over and over

or electrolysis is followed be recombination over and over and over

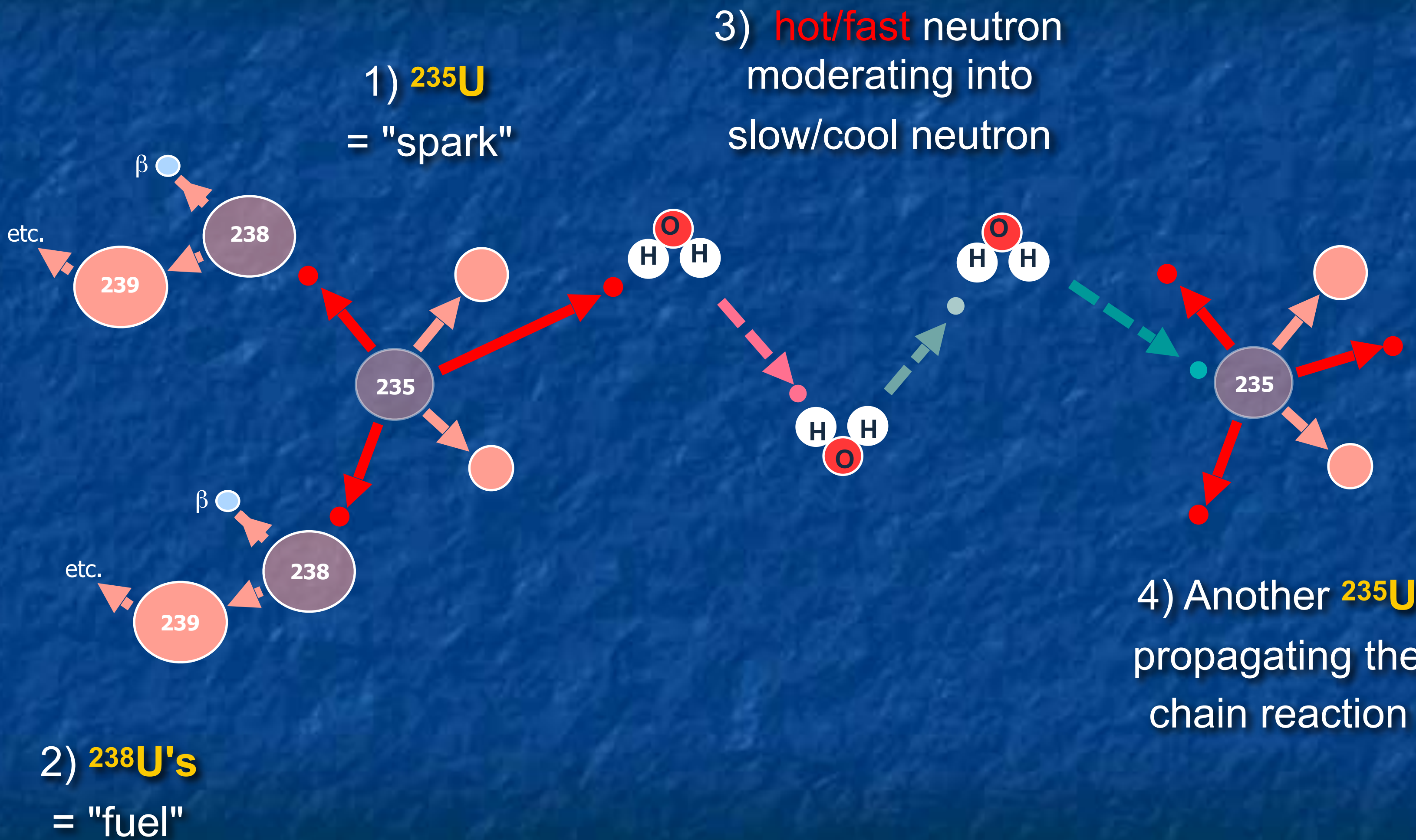
(separating what comes out early from what comes out late)

One can produce water that is almost pure D_20 = **Heavy Water**

Which, like C, allows for a fission chain reaction in natural 0.7% **^{235}U** + 99.3% **^{238}U**

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

Using either form of water, the uranium chain reaction has these steps:



But things really break down even further:

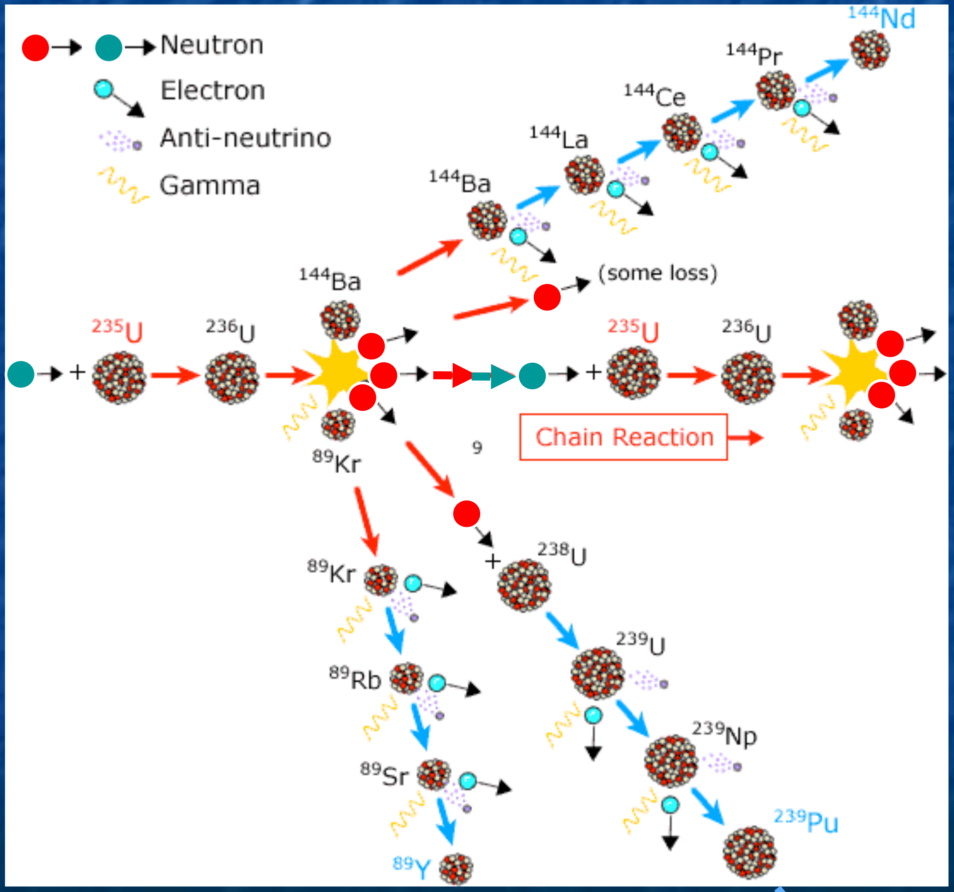
^{235}**U fission** fission path (displayed horizontally across the figure)

Ba & Kr fission paths (↗ & ↓)

^{238}**U fission** path (to lower right)

But all of these paths take time

And they continue right off the page!



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

BOTTOM LINES:

All SORTS OF THINGS continue fissioning LONG after initial ^{235}U / ^{238}U fission stops

=> Sustained heat + radiation!

=> 2 of 3 accidents I'll soon describe

On to how nuclear fission bombs and reactors are made:

BOTH bombs and reactors set up a sustained chain reaction of nuclear fission decay

But common REACTORS require BOTH a fission reaction:

$^{235}U + {}^{1}n$ **(slow/thermal)** => (byproducts) + ~ 3 ^{1}n **(fast/hot)**

And a moderation reaction:

^{1}n **(fast/hot)** + **Moderating Atom** => ^{1}n **(slow/thermal)**

Working together these two reactions enable a sustained chain reaction

But this multi-step process requires a fair bit of time - at least **milliseconds**

Nevertheless, per the preceding discussion, with an ideal moderator (C or D_2O),

This can occur in even natural uranium ore of 0.7% ^{235}U + 99.3% ^{238}U

But bombs are different:

VIOLENT explosions require EXTREMELY fast & dense release of energy

That argues against the use of neutron moderators because:

1) A separate moderator dilutes the density of energy-release

Because the moderating atoms must replace some fissionable atoms

2) Neutrons must collide multiples times with moderator to be fully moderated

And that takes too much time when mere **microseconds** are significant

Uranium bombs thus use only the single less efficient reaction of:

^{235}U + ^{1}**n (fast/hot)** => (byproducts) + ~ 3 ^{1}**n (fast/hot)**

Less efficient because other ^{235}U's don't like to absorb those fast/hot neutrons

But extremely fast because, when they DO absorb, it is all done in one step

Occurring in microseconds, but sustainable only with ≥ 80% ^{235}U

But chain reactions ALSO require something else:

To sustain a chain reaction, **EACH** liberated neutron must **FIND** other ^{235}U

If probability of finding another ^{235}U <1, reaction is NOT self-sustaining

If probability of finding another ^{235}U = 1, reaction becomes self-sustaining

If probability of finding ^{235}U >1, reaction is self-sustaining **and** growing

Leading to the important (but poorly named) concept of **CRITICAL MASS**

Which defines the mass above which a lump of radioactive material will chain react

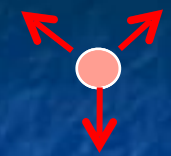
WRONG! Its actually much more complex . . . and much simpler

Simpler because it really does just boil down to:

The probability of a liberated neutron **finding another** ^{235}U:

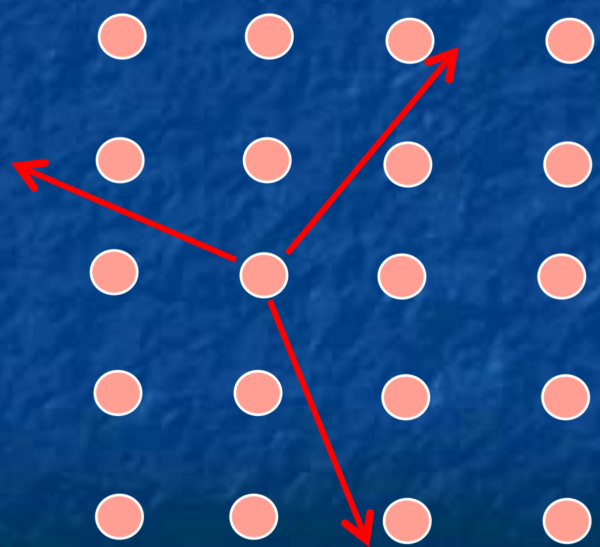
Illustrative Examples:

Say that a fissioning ^{235}U emitted exactly 3 neutrons:

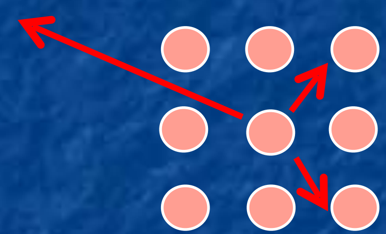


Then you could have:

High mass / NO CHAIN REACTION:



Low mass / CHAIN REACTION:



BECAUSE the tighter packing makes collisions more probable!

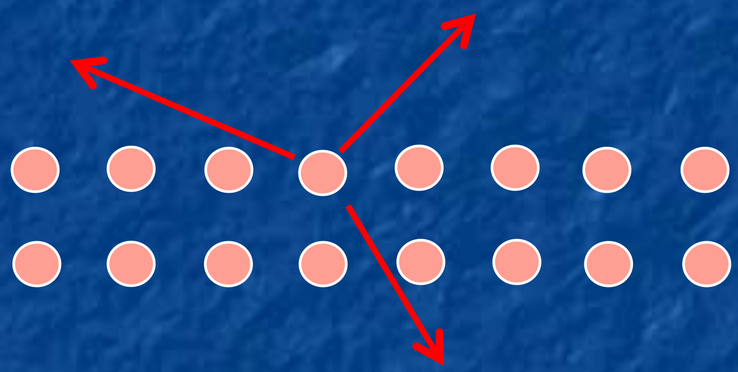
*So its more about the **critical concentration**?*

Partly

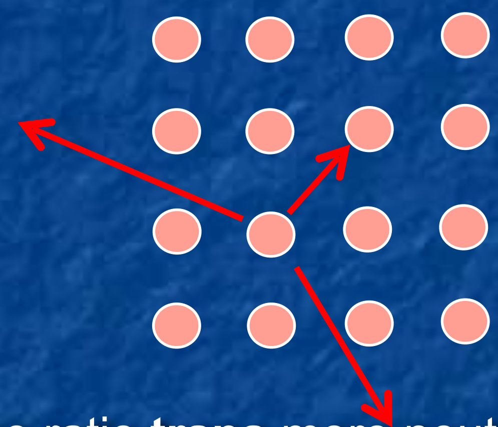
But it's also about **shape**:

Two objects with **identical concentrations** AND **same total mass** of ^{235}U:

NO chain reaction:



YES, chain reaction:



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

So "critical mass" is ACTUALLY about concentration, mass, shape . . .

= It’s about PROBABILITY of neutron collision with another ^{235}U

Nuclear bombs *require* ***hyper-fast assembly*** *of supercritical mass*

"Hyper-fast" because even as you approach critical mass,

the chain reaction starts up, beginning to yield **vast amounts of heat**

That **heat** then quickly, **fractures, melts and vaporizes things**

Which are thus propelled rapidly apart!

If/when fissioning material **spreads too far apart,** you loose **criticality**

Reverting to one of the above too dilute / too spread out configurations

And the chain reaction is then extinguished

All of which was given the very descriptive name of a **FIZZLE**

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

NO!

A nuclear fizzle releases immensely less energy than a nuclear explosion

Because (again):

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

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

Which, now spread out, is no longer of critical mass / critical configuration

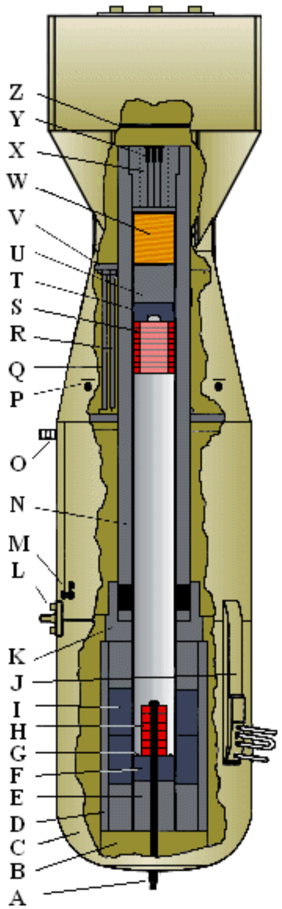
and thus can no longer sustain a fission chain reaction

Thus, only a tiny fraction of the available fissionable material ever fissions

So a fizzle produces a much, much smaller energy release

Which can be so weak it might be more "meltdown" than explosion

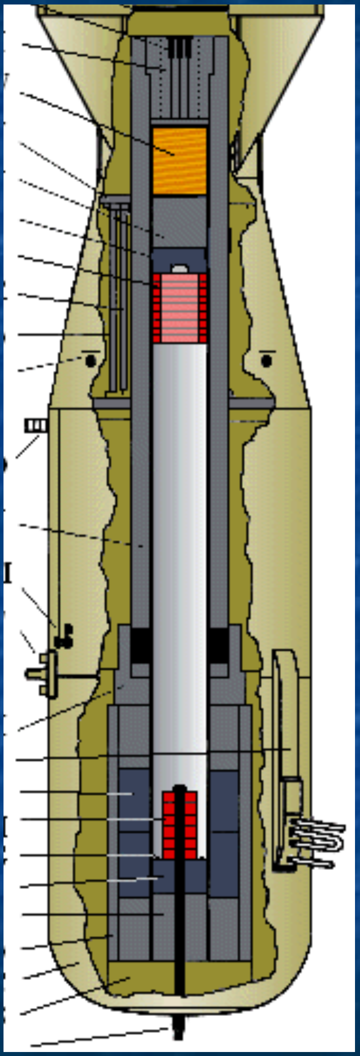
Beating that fizzle required this (over Hiroshima): "Little Boy"



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)

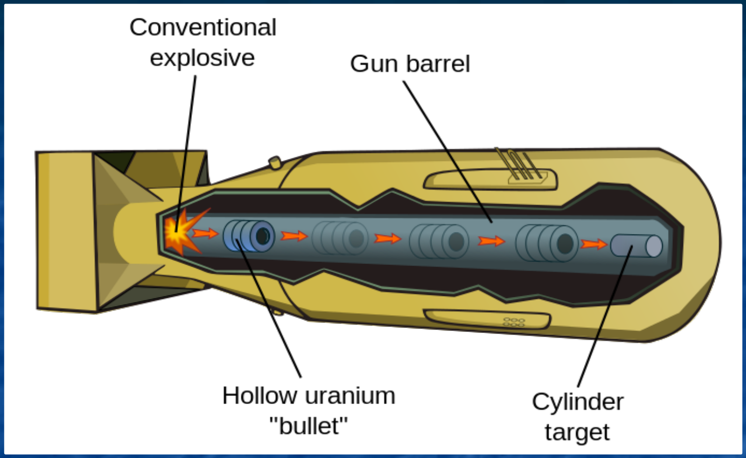
Z) Armor Plate
Y) Mark XV electric gun primers (3)
X) Gun breech with removable inner plug
W) Cordite powder bags (4)
V) Gun tube reinforcing sleeve
U) Projectile steel back
T) Projectile Tungsten-Carbide disk
S) U-235 projectile rings (9)
R) Alignment rod (3)
Q) Armored tube containing primer wiring (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



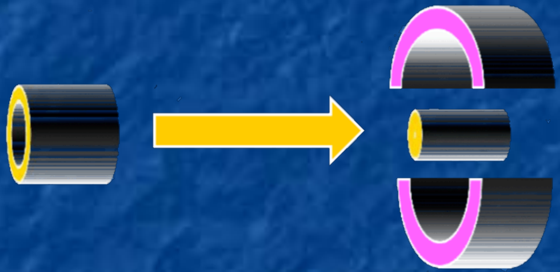
http://en.wikipedia.org/wiki/Little_Boy

So named because it was little and relatively simple:



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

Tube of 80% ^{235}U SHOT (by cannon!) into position around **cylinder of 80% ^{235}U**



With **Neutron Mirror** then also bouncing **back** neutrons leaking outward from tube

ONLY in this way could they **BEAT** the initial heat starting to push things back apart

Avoiding fizzle, getting MOST of ^{235}U to fission => ~ Complete energy liberation

They didn't even test the Little Boy in advance

Reason #1) Because they were almost certain it would work

Reason #2) Because they had so little ^{235}U

Why? Because ^{235}U is SO HARD TO ENRICH:

^{235}U is <u>electronically</u> identical to ^{238}U: So it **bonds** to all the same things!

Separation must instead exploit the 1% mass difference between ^{235}U and ^{238}U

Requiring huge factories in which ore is passed through **hundreds of cycles** of

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

Plutonium, obtained from ^{238}U decay, is much easier to separate:

^{238}U + ^{1}n (hot/fast) => ^{239}U => $^{239}Np + \beta$ => $^{239}Pu + \beta$

Pu and ^{238}U have different number of electrons, so bond to different things

^{239}Pu can thus be chemically separated from its uranium pre-cursors

They had PLANNED to use plutonium in same Little Boy design

But the plutonium fission reaction started up so much faster

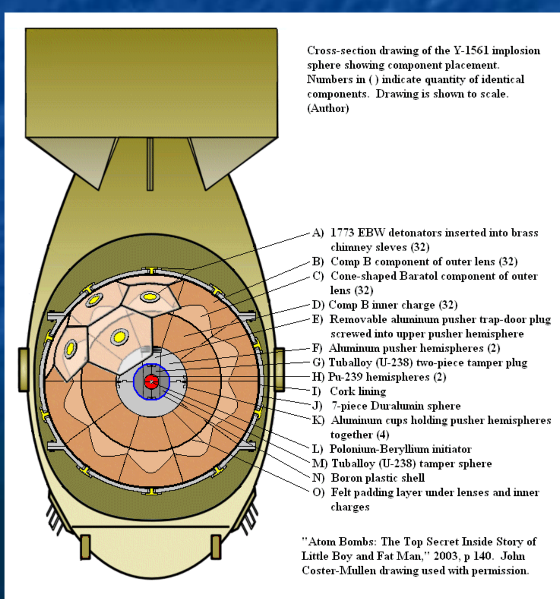
That mass would have begun blowing back apart too early

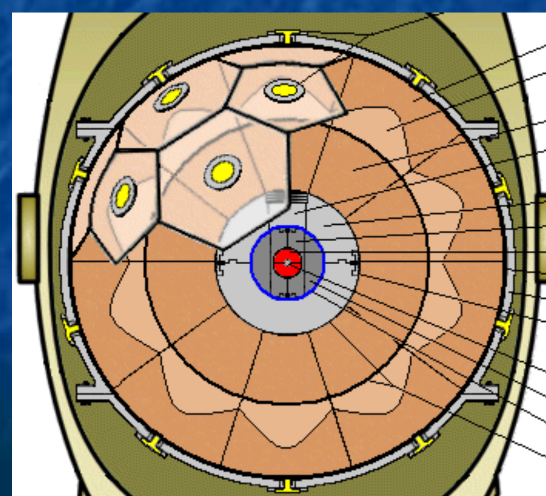
Before cannon could fully merge tube / cylinder => **FIZZLE**

So were driven to "**Fat Man**" = sphere of explosives surrounding sphere of Pu

They were still so unsure of it, that THIS is what was tested at Alamogordo NM

And then dropped on Nagasaki





Shaped conventional explosive

Hollow Plutonium Sphere

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

Nuclear bombs versus reactors:

SIMILARITY: Most common reactor designs DO use the SAME ^{235}U fission reaction

DISSIMILARITY: In **bombs**, when fissile masses are merged, they are **critical**

Facilitated by extremely rapid merge + 20X more concentrated ^{235}U

In **reactors**, even if fissile masses are merged, they are **subcritical**

HOLD IT! But then how does a nuclear reactor continue working?

That is, how do ^{235}U's **continue** fissioning at a rate higher than

the **natural rate** of 50% probability per 703.4 million years?

ANSWER: By deliberate addition of those NEUTRON MODERATORS

Which slow down (**thermalize**) neutrons liberated by one ^{235}U's decay

increasing likelihood that they will cause another ^{235}U to decay

So when I say <u>MODERATOR</u> think <u>ENHANCEMENT</u> of ^{235}U fission!

Reactor = Subcritical mass + Accelerator + Brake

Accelerator is the above mentioned **neutron moderator**

Brake is the added **neutron poison** (absorbers) contained in the "**control rods**"

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 greatly aided by a detail of neutron emission:

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

Most 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 react

Finally, moving on to U.S. reactors:

Which, like many/most of those used in the rest of the world, are:

Light Water Reactors (moderated and cooled by normal water)

Which cannot use **natural uranium ore of 0.7% ^{235}U + 97.3% ^{238}U**

As is possible with carbon (graphite) or heavy-water moderated designs

But which instead require the very expensive enrichment of ore to ~ **4% ^{235}U**

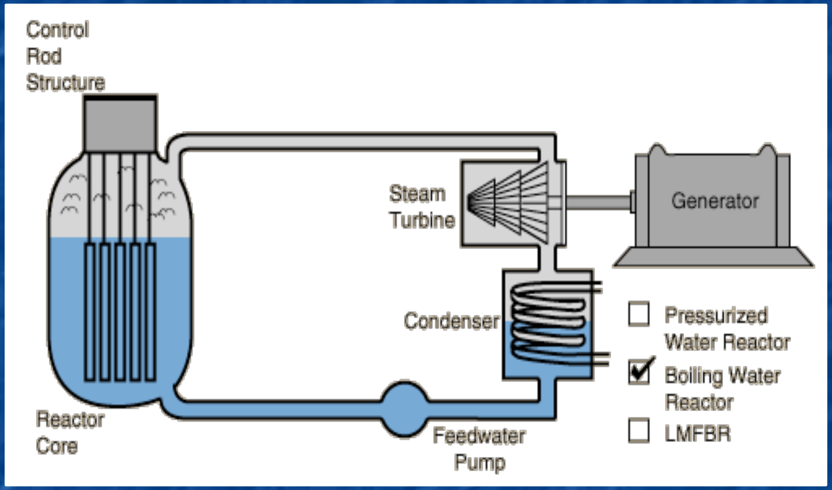
The cost and trouble of which can be balanced against:

The expensive and trouble of enriching heavy water

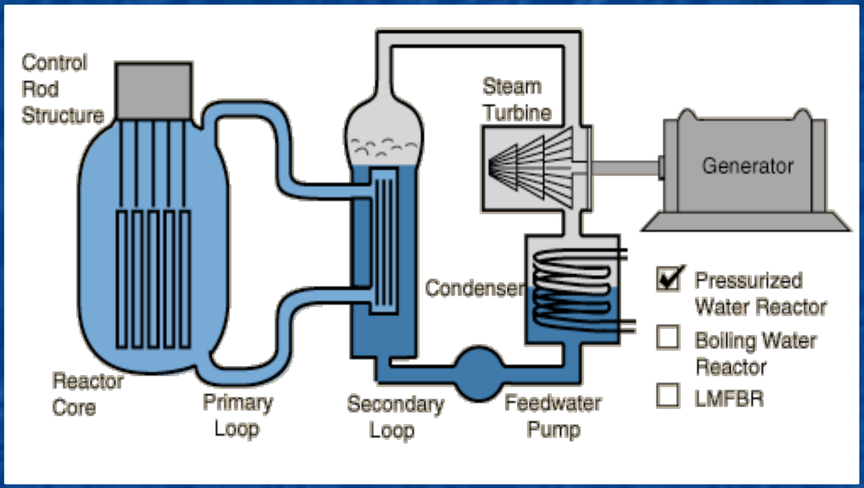
Or the-soon-to-be-discussed hazard of using flammable graphite

Our U.S. Light Water Reactors come in two types:

Boiling Water Reactors (BWR):



Pressurized Water Reactors (PWR):



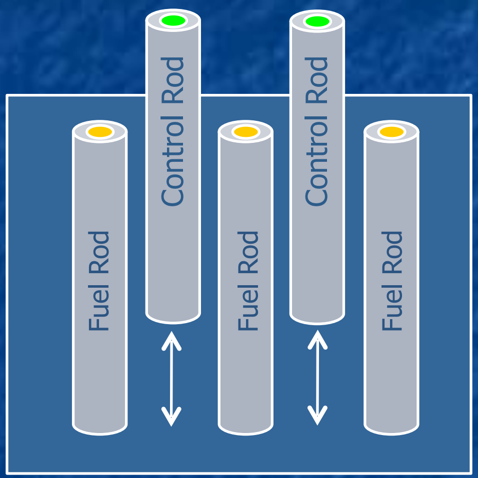
http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/reactor.html

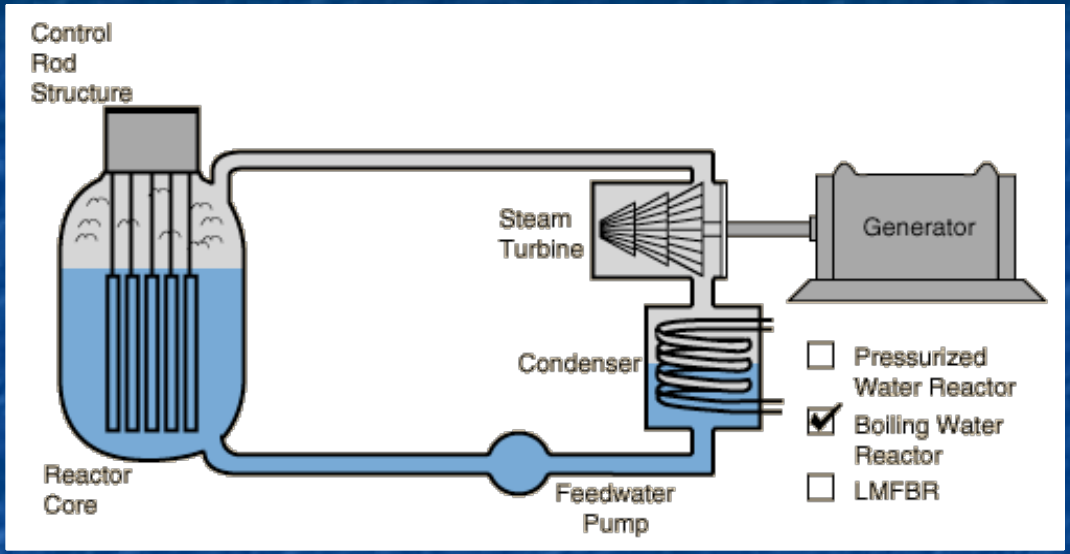
Both use the heat of ^{235}U + ^{238}U decay to boil water, driving a turbine generator

But their control schemes (and safety containment structures) differ as follows:

Details of boiling water reactor (BWR) design:

With the simpler control scheme which is, in a subtle sense, more sophisticated:





4% ^{235}U + ^{238}U **fuel pellets** inside **zirconium tubes** (1-2 cm dia. / 3-4 m long)

= "**Fuel Rods**"

Plus movable "**Control Rods**" containing **neutron poison/sink** (= "brake")

Plus neutron moderator supplied by surrounding **water** (= "accelerator")

Water ALSO absorbs heat, boiling into the steam that drives the turbine

*But recall that "light water" is **both** neutron moderator and absorber:*

Moderating because neutrons are so close in mass to water's hydrogens

That colliding neutrons transfer a lot of their kinetic energy to them

Where neutrons would instead just ricochet off much more massive nuclei

Thus light water transforms hot/fast neutrons into slow/thermal neutrons

So the **output** of one ^{235}U fission becomes ideal **input** for next ^{235}U fission

Based on moderation alone: More water should **accelerate** reaction

But light water (with neutron-free hydrogens) can also absorb neutrons

Converting hydrogen nuclei from from p to n+p (= ^{2}H = **deuterium**)

Based on absorption alone: More water should **decelerate** reaction

Most reactors are designed so that water "moderation" dominates:

Then, if a BWR reactor overheats, water first expands and then boils:

Both spread out water molecules (especially boiling) making it harder for

Hot/fast neutrons to **moderate** into **slow/thermal** neutrons

Fewer slowed neutrons makes it much harder for ^{235}**U** to fission

Which automatically turns the reactor back down!

A second level of control is added via the **control rods**

Which, absorbing neutrons, diminish the likelihood of fission

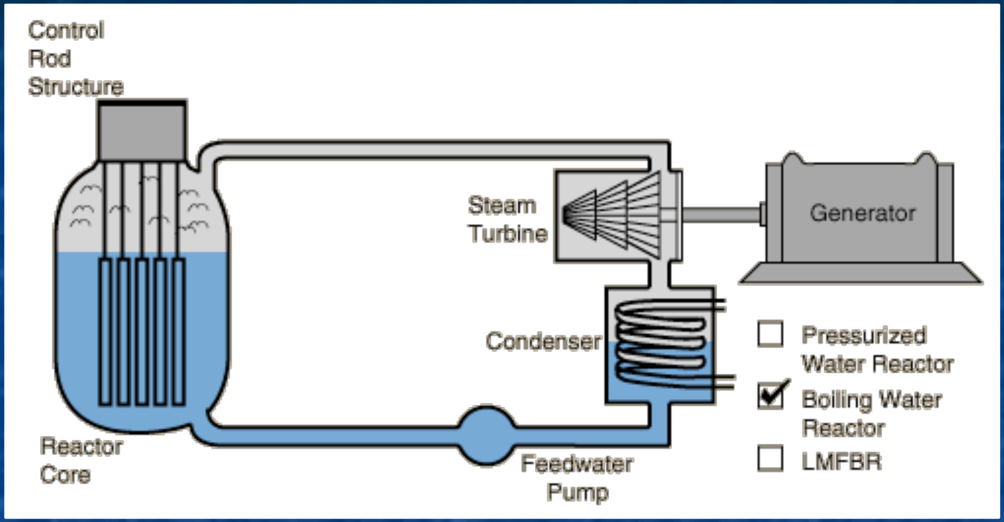
Third level of control added via **emergency ("scram") shutdown**

by injecting boric acid, the boron's of which **strongly** absorb neutrons

Because boiling water reactors DO allow water to boil (spreading vastly)

experts view it as being the most stable type of reactor

But there is a potential problem with boiling water reactors:



The turbine generators are located OUTSIDE the reactor containment structure

Because they must be more easily accessible for servicing, meaning:

Water from reactor (as steam) is allowed to exit the containment

Fortunately, **pure water** can become only slightly/mildly radioactive:

Some ^1H => ^3H (tritium) which decays relatively slowly and benignly

Alternate Pressurized Water Reactor (PWR):

Inspired, in part, by concern about reactor cooling water exiting containment

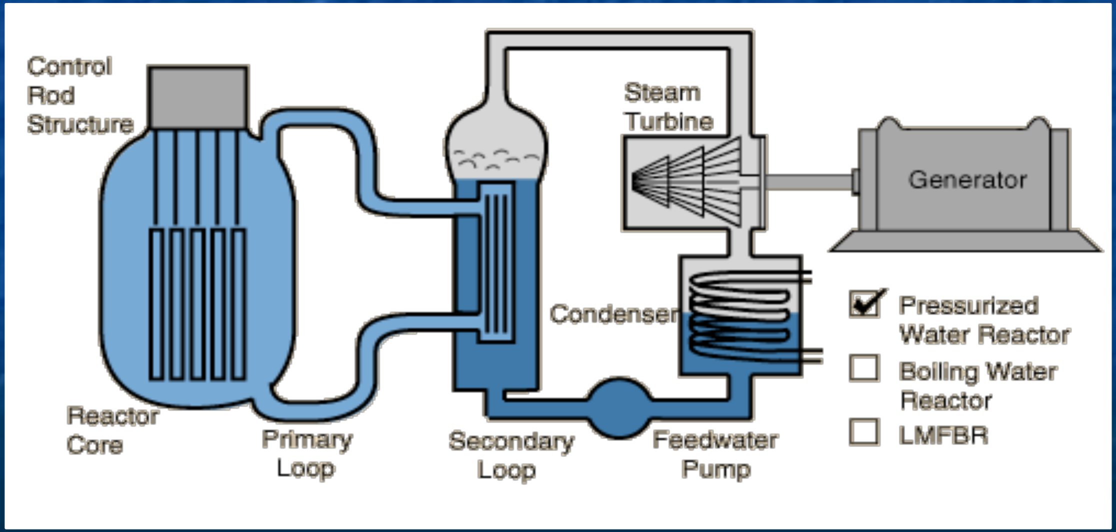
If water picks up impurities, THEY could become strongly radioactive

Or if fuel rods leaked, water could become massively radioactive

So instead of one water loop, there are two:

Primary loop enters reactor core then, via heat exchanger, transfers heat

ONLY secondary water/steam loop **exits containment** to drive turbines



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

Subtleties of Pressurized Water Reactor (PWR):

Primary loop's job is to supply enough heat to boil water in the secondary loop

It can carry a lot more heat energy if water in it remains a **dense** liquid (vs. vapor)

But it still has to reach temperatures ABOVE boiling so it must be **pressurized**

Keeping that water liquid even well above 100°C

However, the water in that primary loop is ALSO a NEUTRON MODERATOR

But, under pressurization, its water cannot expand much and can't vaporize

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

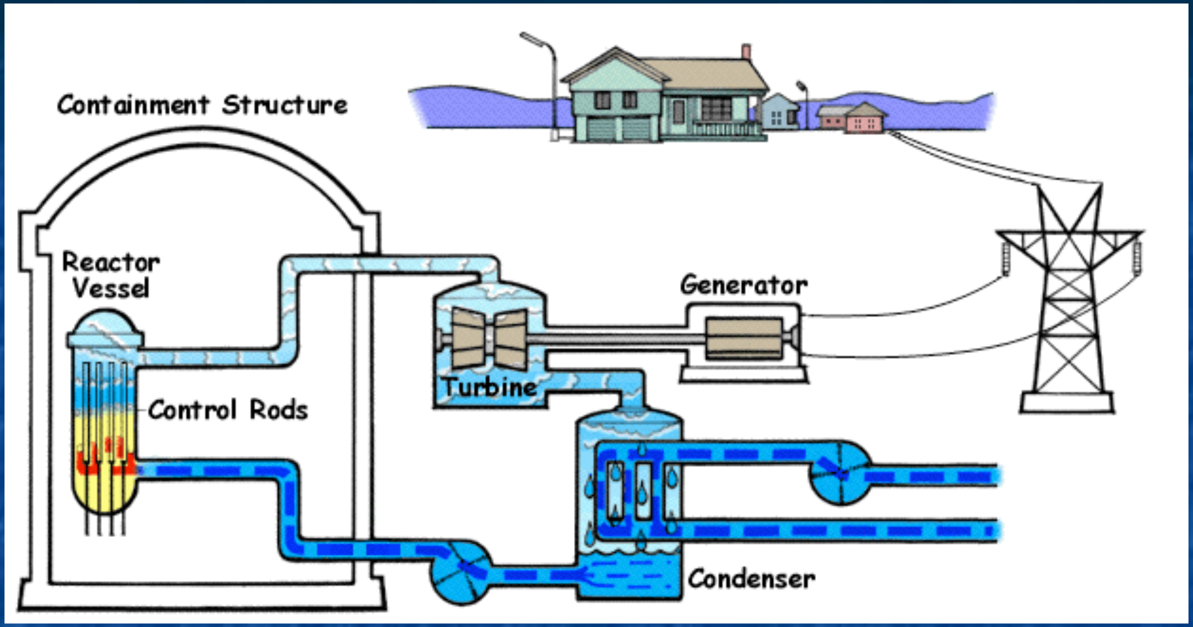
Will not automatically decrease sharply when reactor core heats up

So you loose a negative feedback mechanism that enhances
the stability of competing boiling water reactor (BWR) designs

Putting basic schematics of these two designs side by side:

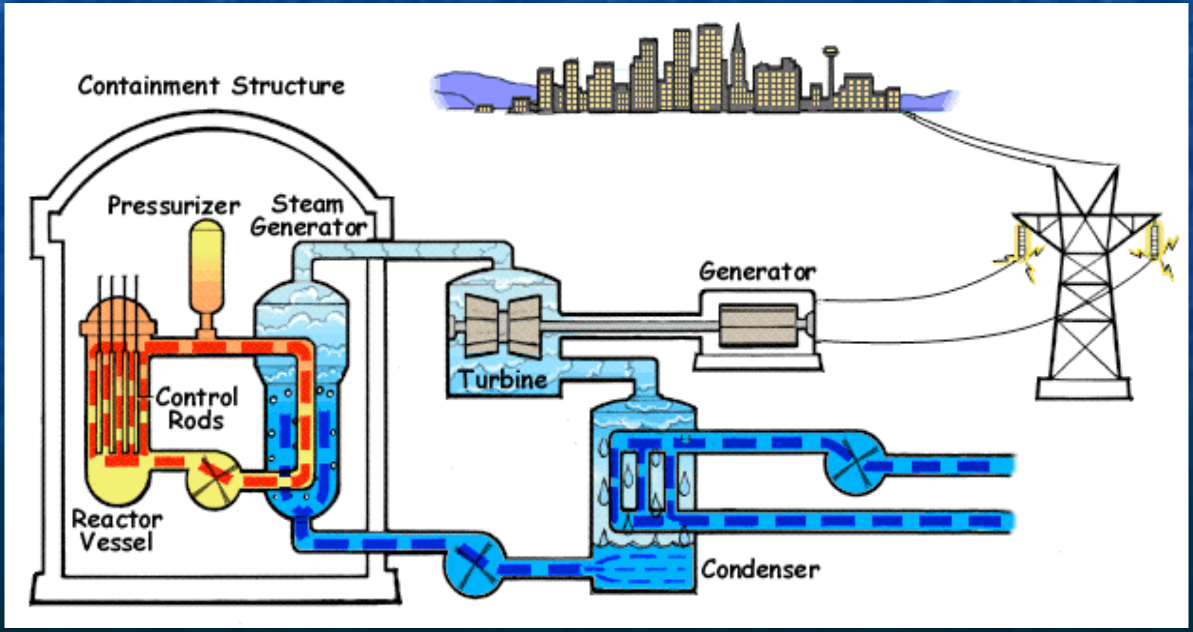
Boiling **W**ater **R**eactor:

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



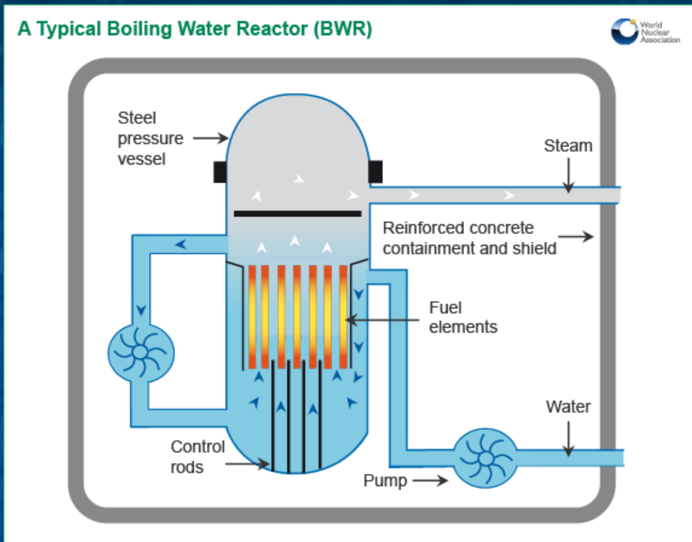
Pressurized **W**ater **R**eactor:

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



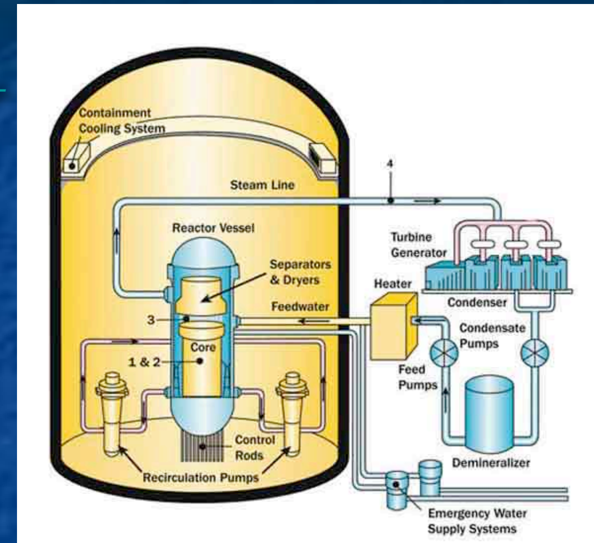
Adding a bit more technical detail:

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

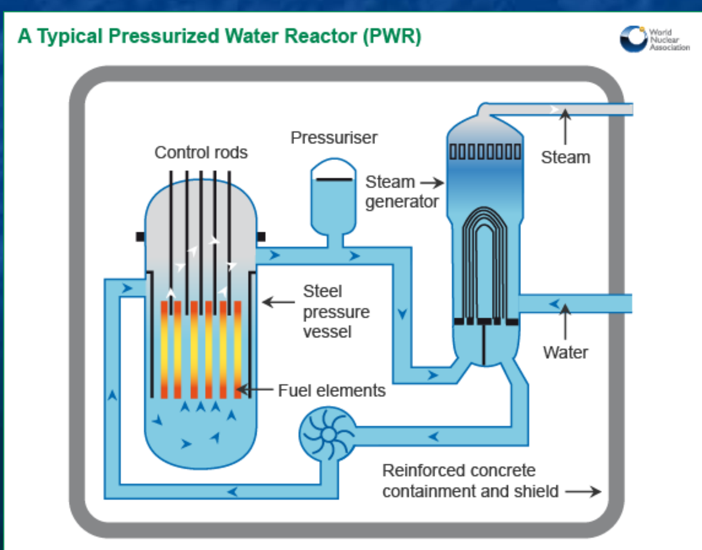


www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Power-Reactors/Nuclear-Power-Reactors/

www.nrc.gov/reactors/bwrs.html

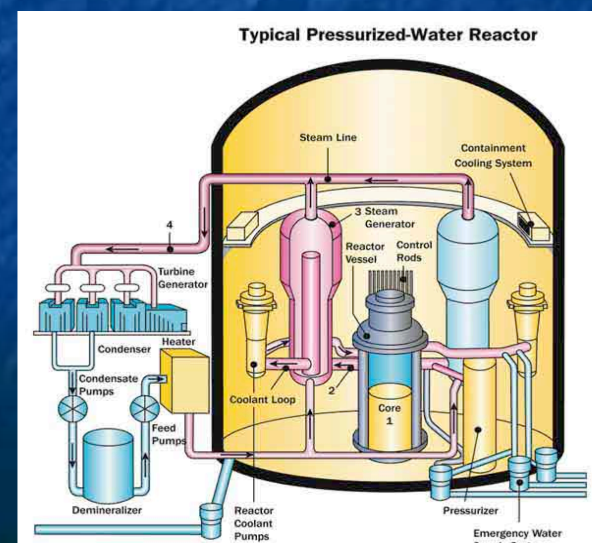


Pressurized **W**ater **R**eactor:



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

www.nrc.gov/reactors/pwrs.html

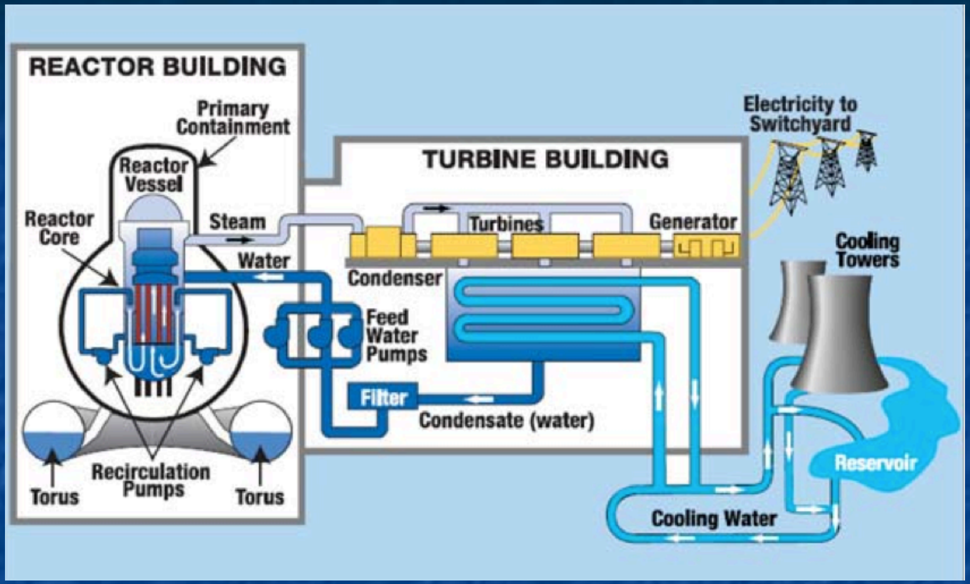


Finally: Different "hot zones" => Different containment strategies:

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

Strong reactor **vessel** containment

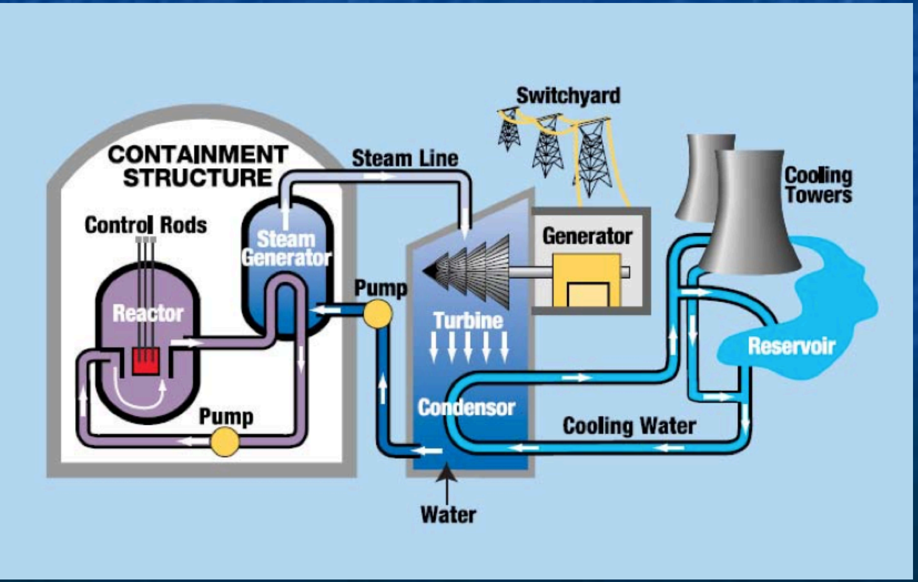
Weaker overall building containment
(=> conventional flat walls & roofs)



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

Strong building containment of reactor vessel & steam generator
(=> signature concrete domes)

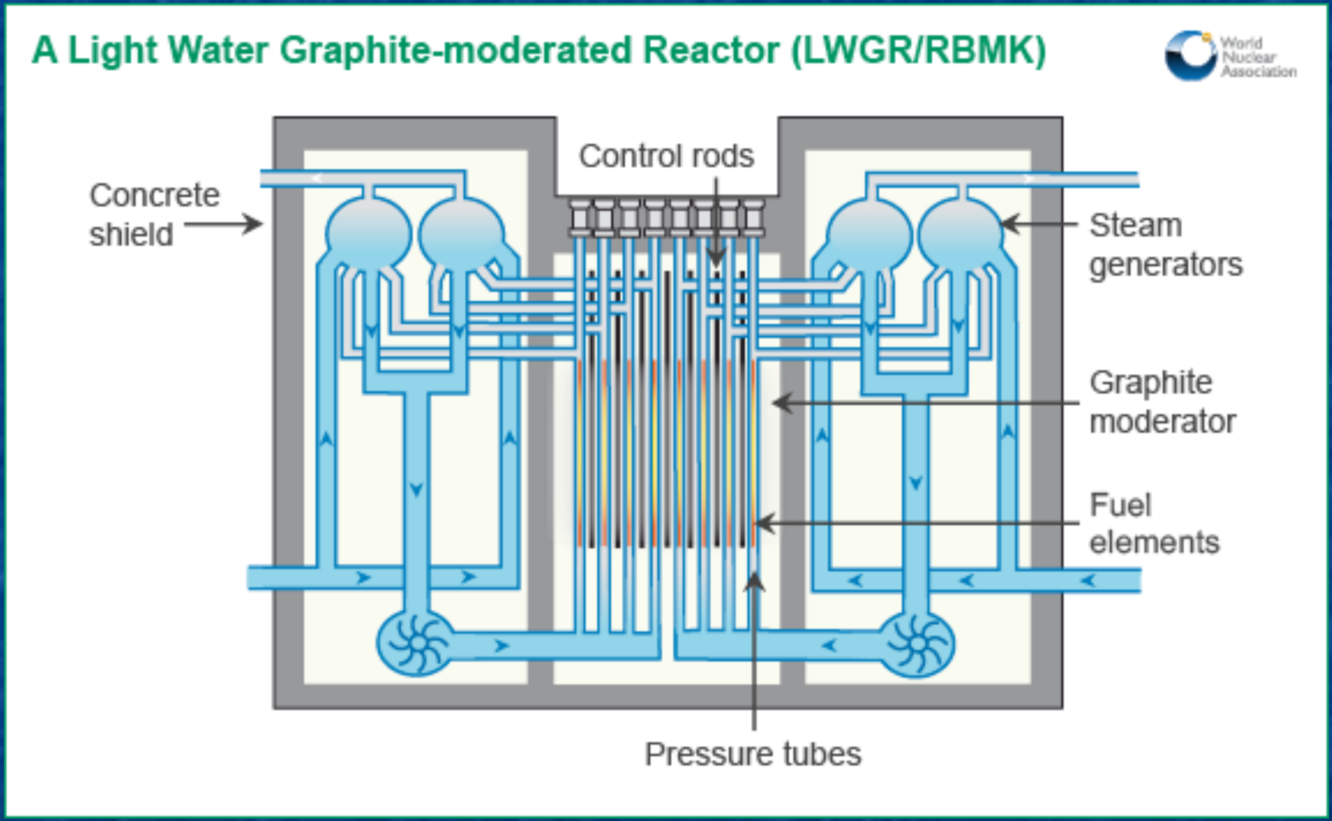
No turbine building containment



Source: CRS Report to Congress – "Power Plants: Characteristics and Costs" (November 13, 2008) - Order Code RL34746

But we need to include one more type of reactor:

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** previous **BWR** and **PWR** reactors

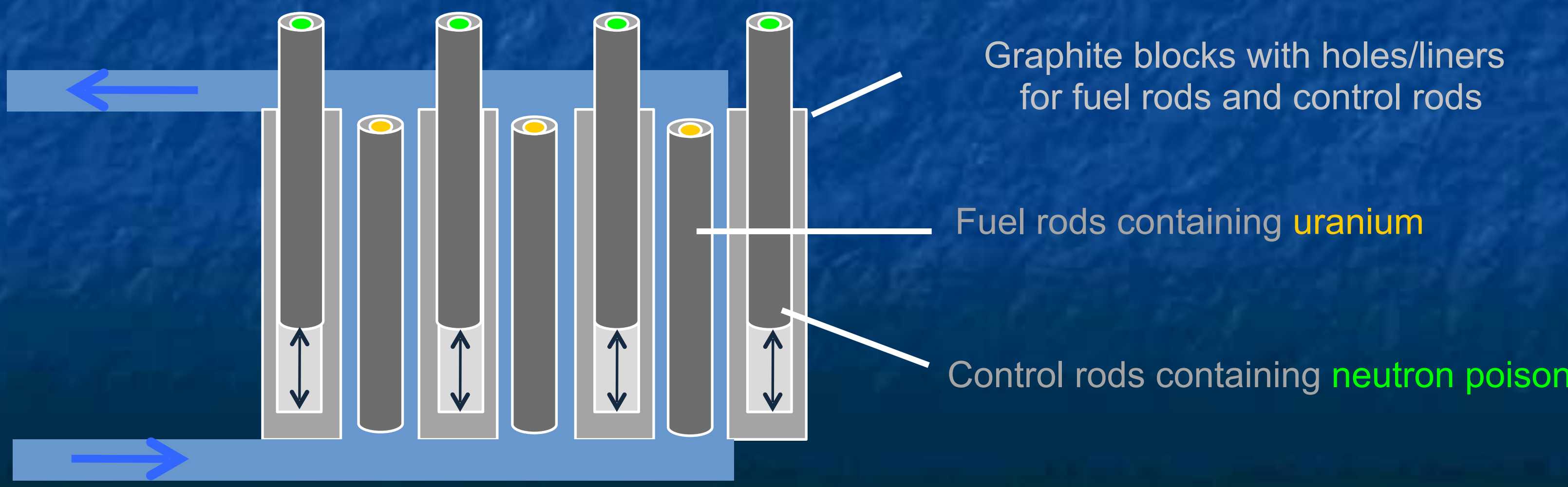
But they use **water** only for heat transfer, NOT for neutron moderation

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

With thin layer 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 ~ complete **neutron moderation/slowing**



Unique 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 w/ inert gas flows

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

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

- **WITHOUT a heavily reinforced reactor containment vessel**

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

With this background, let's figure out WHY three reactors "exploded"

THREE MILE ISLAND (TMI) – Eastern Pennsylvania - 28 March 1979

Reactor involved (TMI #2) = Pressurized Water Reactor (Babcock & Wilcox Corp.)

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

- A filter clogged, operators tried to clean it by injecting compressed air
- Resulting over-pressurized water leaked into air control line
- Hours later compromised air control line caused pumps to trip off
- => Secondary loop could no longer fully remove heat from primary loop

Primary loop then overheated, reactor automatically initiated "scram" shutdown

- Ramming in control rods to absorb neutron flux
- But there was still HUGE amount of heat energy in the reactor core
  - Which was no longer being carried away by the cooling loops

The TMI blow by blow analysis (continued):

But with the scram, three emergency pumps automatically turned on to cool core

- But **two of their valves had been left closed** after earlier maintenance
  - So effectiveness of emergency cooling system was vastly reduced

Primary loop then heated so much that pressure relief valve was energized to open

- When excess pressure was vented, that valve should then have closed
  - Limiting loss of water from that primary cooling loop
- But **valve instead stuck open**, allowing more water to escape

Dark control room light indicated that power to open valve had been removed

- But there was **no light** indicating whether or not valve HAD actually closed
- Operators **misinterpreted** dark "open" light as indicating valve closure

The TMI blow by blow analysis (further continued):

Operators had **NO instrument to directly read level of water around core**

But they knew that water was in the **"pressurizer"** located **above** the reactor

So they assumed that reactor core below was still fully immersed in water

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

Operators shut down pumps trying to add more water to the primary loop

But the reactor's core was **NOT** fully covered by cooling water

Water pumps were vibrating because they were pumping steam

Confusion reigned for four hours until

new shift of operators finally figured out situation and began to correct

By then **half of the reactor core had melted down** and**,** driven by hydrogen combustion, some radioactivity had already escaped from the containment vessel

Partial list of faults and errors:

Equipment failures:

Stuck primary loop vent 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 which produced over 100 alarms in first minutes of failure

Management / operator / training errors:

Initial procedure for cleaning out clogged filter

Emergency cooling system valves left closed after earlier maintenance

Misinterpretation of above (badly designed) relief valve indicator

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

Operator override of automatic water cooling system

Repeating error that almost caused **earlier** accident elsewhere:

TMI management knew of that near miss, but had not told operators!

Report Of The President's Commission On The Accident at Three Mile Island:

"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."

("Kemeny Report," Overview, p. 24)

In light of the above, note that in 2014 I found TMI "information webpages"

posted by BOTH a key industry association AND a key federal agency

that **still** fail to mention central critical errors,

including failure to reopen emergency cooling valves after earlier maintenance.

CHERNOBYL – then USSR now Ukraine – 26 April 1986

Chernobyl's RBMK reactor used **masses of graphite** as a neutron moderator

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

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

Vs. moderating water whose loss would have dampened fission

The graphite core produced strong, continuous, neutron moderation:

Initially hot neutrons with extremely high kinetic energy

=> Many, many collisions with cooler graphite (carbon) atoms

=> Neutron kinetic energy approached that of the ambient

From then on, these cooled neutrons were almost as likely

to **gain** energy from collisions as **lose** energy from 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 reaction**

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

There was less water per volume =>

There was less neutron absorption per volume =>

Leaving more neutrons to **accelerate nuclear fission**

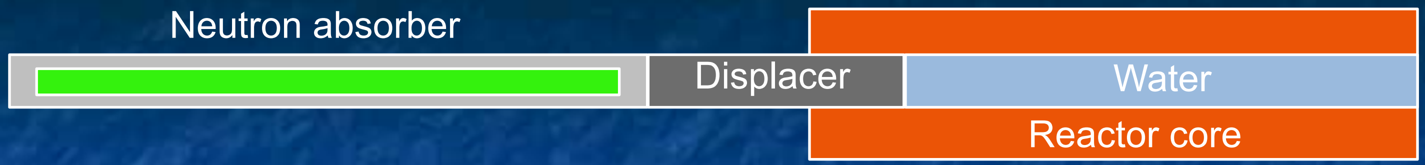
This acceleration of fission, upon creation of steam bubbles, is called a:

Positive void coefficient

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

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

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



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

- But before control rod enters reactor core, its hole is filled with water
- Which (per discussion above) already absorbs some neutrons

Designers wanted strongest possible drop in neutrons when absorber entered

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

- by first pushing out water (via a "Displacer" extension of the control rod)

But that meant as 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 accelerated

- because they made the displacer out of neutron moderating graphite

Chernobyl's 3rd positive feedback loop: Neutron "poisons"

- I mentioned earlier that things like Xenon, Boron & Iodine are **neutron poisons**
  - Absorbing but not re-emitting any neutrons (taking them out of play)
- Fission reactions themselves produce "poisons" such as these
  - As poisons accumulate, reactor control rods must be withdrawn farther
    - Compensating for poisons by reducing rod's neutron absorption
- But neutrons from the reactor can also make some of these **poisons** radioactive
  - Causing them to fission into new non-poison elements
    - Sort of like a hot furnace burning soot out of narrowing chimney
- But when reactor is turned down, neutron poisons tend to build back up
  - Which, in turn, drives nuclear fission rate down even further
    - => Positive feedback loop trying to shut reactor down

But this then works in reverse when turning up reactor

If reactor has been off, or running very low, neutron poisons build back up

Normal withdrawal of control rods will then not accelerate fission as intended

So they pull out **more** rods than normal (or rods further) to get running

But as fission reaction finally accelerates, neutrons begin to "burn off" poisons

Causing fission reaction to further **surge** upwards

(NOTE: These surges are also an issue in non-RBMK reactors)

Safe way to start reactor (done elsewhere, and **normally** done at Chernobyl):

Leave IN enough control rods that surge cannot go supercritical

But doing a much delayed test, missing key reactor experts, they were in a hurry

And withdrew many more than the recommended number of rods

Three positive feedback loops => Instability => Sudden 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 / damage overwhelming):

- Steam explosion blowing lid off reactor

- Which was enough to effectively open things up

  Because RBMK's were built **without** western-style containment

- Allowing air (w/ oxygen) to reach super hot graphite moderator blocks

  Which had, to that point, been bathed in inert cooling gasses

- Causing them to near instantaneously catch fire

- Producing strong smoke plumes and thermal updrafts

  Distributing radioactive debris and dust far and wide

Exceptionally bad reactor design? Or (once again): Key role of the "human factor?"

FUKUSHIMA DAI ICHI – 11 March 2011

Which is a location (140 miles Northeast of Tokyo) where there are SIX reactors

Four of which were involved in the accident (and critically damaged)

While the other two were shut down for maintenance at the time

I came up with reams of data on this accident, much more than on TMI or Chernobyl

But it really wasn't necessary, because this accident was easy to figure out:

It wasn't due to unpredictable equipment breakdowns

It wasn't due to operator errors

Both instead worked essentially as intended and as hoped for

It was instead due to design shortcomings

That were longstanding and well known (indeed known for decades!)

But accepted by designers, utility company, and government regulators

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

Turning a reactor off doesn't really turn it off

A reactor is turned off (including in emergency "scram") by inserting control rods

=> Neutron poisons absorb so many neutrons that ^{235}U stops fissioning

But firstly: There is still a huge amount of heat in the reactor core

And while the core itself may be able to withstand these temperatures

Because it employs exotic/expensive high temperature materials

Steels of reactor shell and piping may not withstand such temperatures

And secondly: Fission is not an instantaneous process

^{235}U does not => End products in one quick energy releasing step

It instead decays into something else, which decays to something else . . .

With each radioactive decay along the way releasing more energy

Meaning that while control rods stop ^{235}U + ^{238}U fission:

The overall fission decay process continues

Until ALL radioactive products

Have decayed into final NON-radioactive elements

Which means control rods cannot instantaneously cut energy release to zero

Instead, energy release may only fall by ~ 95%

With the remaining 5% (due to radioactive decay of fission products)

then taking hours or days to fall away

STORED ENERGY in core + FISSION ENERGY STILL BEING PRODUCED

=> Reactor MUST be actively cooled for additional day/days

"Active cooling" = Electrically powered, fully functioning cooling pumps

So with days of active cooling **essential**, *where was Fukushima built?*

On the edge of one of the world's most seismically active / tsunami prone coasts:

www.hsci2012.org/is-the-fukushima-daiichi-nuclear-disaster-a-threat-to-west-coast-usa/

And where were the back-up generators for these essential pumps placed?

In the basements (i.e. as close to sea level as you could possibly put them)

Why locate plant and pumps essentially AT sea level?

To save a **little money** by using smaller water cooling pumps and piping?

Tsunami protection (?)

Immediately offshore a system of barriers WAS built (at right edge of previous photo)

With design goal of blocking tsunami's of up to **10 METERS** in height

But subsequent studies suggested that risk of larger tsunamis was too high

And that barrier height should be significantly increased

TEPCO considered these studies but decided against higher barriers

Fearing that admission of error might lead to calls for

similar barriers, or barrier heightening, at nuclear plants elsewhere

(Including at sites where tsunami threat was less acute)

Instead they moved SOME of the backup generators to the top of the hill

But they left power lines / circuit breakers in the oceanside basements

Where they were flooded when the 14 METER tsunami hit

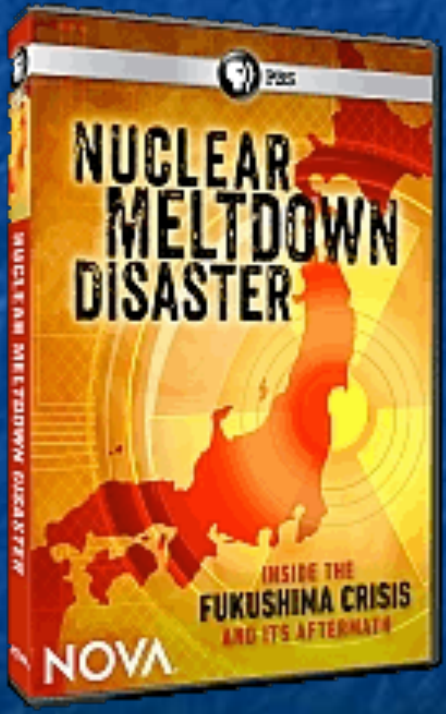
So three now uncooled reactors began to melt-down

A Short Digression:

To fully understand my **empathy** for the Fukushima plant operators,

and my **disgust** with TEPCO and Japanese Government "regulators"

I STRONGLY RECOMMEND viewing this PBS Nova documentary:



Available to Public TV members via their PBS station

Or viewable by all at this YouTube link

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

Beachfront / at sea level:

SAN ONOFRE CALIFORNIA (closing)
www.kpbs.org/news/2011/mar/24/san-onofre-operators-welcome-nrc-review/

Just above sea level:

***DIABLO CANYON CALIFORNIA** (closure planned)*
www.ojaipost.com/2011/03/diablo-canyon-nuclear-plant/

Beachfront / at sea level:

Minor natural protection

(Google Earth)

HUMBOLDT BAY CALIFORNIA (closing)
en.wikipedia.org/wiki/Humboldt_Bay_Nuclear_Power_Plant

Fukushima design shortcoming #2 (<u>shared by ~ all reactors</u>):

Spent nuclear fuel is stored inside the reactor enclosure

"Spent fuel" is really not all that spent:

Atoms are still fissioning (in ever decreasing numbers)

for hours, days, years, centuries and millennia afterwards

And no country has yet agreed upon a long term storage site for this "spent" fuel

Further, ≤ 25% of ^{235}U & ^{238}U fissions over the ~ 2 years it's in the reactor

Providing a reason to hold on to it for later re-enrichment and reuse

With no place to go, it is now generally stored AT the reactor site, indefinitely

It exits the reactor still highly radioactive, so one wants to minimize its handling

Leading to common practice of storing it in INSIDE the reactor building

Until, less radioactive, it's moved to another facility at the site

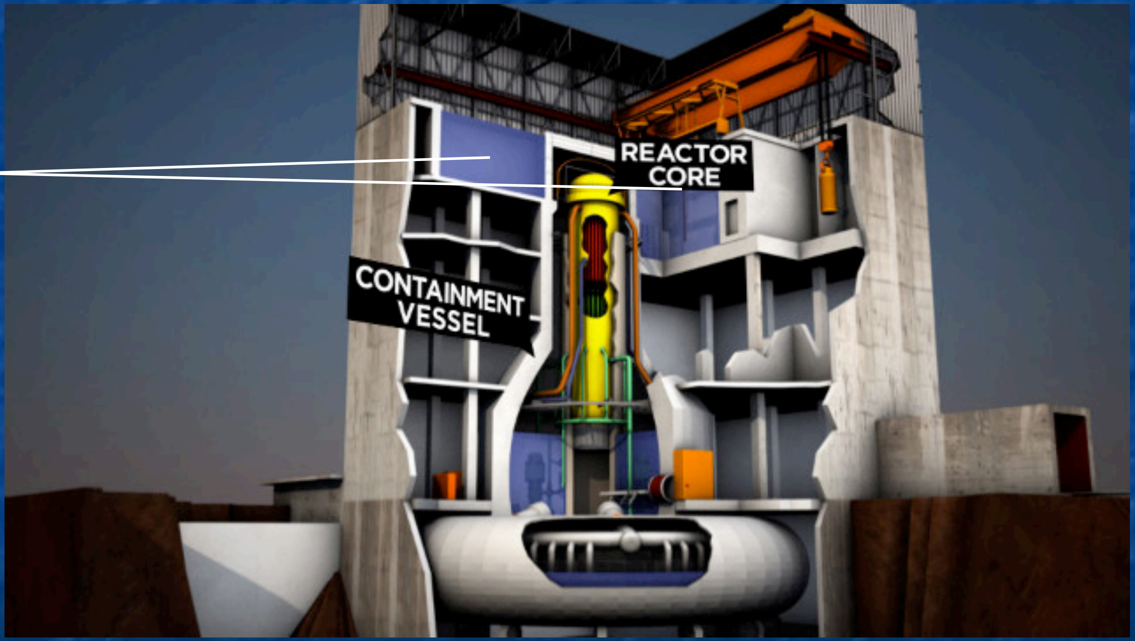
This increases radioactive material within the reactor building

Stored spent fuel can easily exceed the amount INSIDE the reactor

And thus total amount of radioactive material doubles, triples, quadruples . . .

That "spent" fuel, still fissioning, must also be cooled, so it is held in water pools:

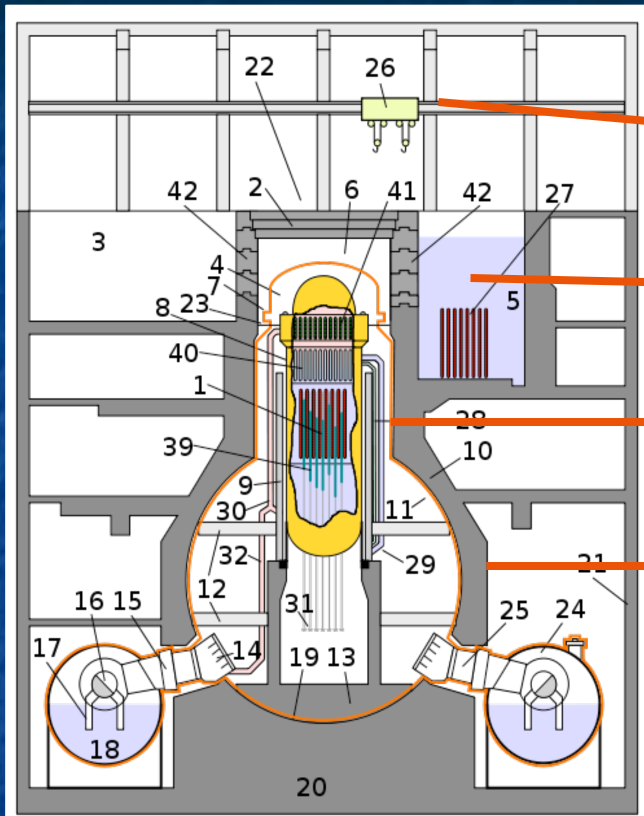
Spent fuel storage pools



Vermont Yankee Nuclear Plant with same GE BWR design as Fukushima

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

High position of storage pool DOES make it quicker and easier to reach

But it is already outside of the main reinforced reactor enclosure

And, being high above the reactor, it is susceptible to damage and water loss

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

Fukushima design shortcoming #3 (shared by ~ all reactors):

High temperature catalytic decomposition of H_2O by zirconium

Fuel rods consist of enriched ^{235}U held in **zirconium metal** alloy tubes

Because it's one of very few materials that can withstand full reactor heat!

But at the 2000°C temperatures of an approaching/ongoing meltdown

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

These gases accumulate inside reactor until they reach an explosive level

And then an abundance of hot things can cause them to ignite:

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

Despite the meltdowns, radiation **HAD** been confined to the reactor buildings

Because these "Containment Structures" **had** been doing their job!

But hydrogen + oxygen explosions now blew open the containments!

http://www.mirror.co.uk/news/uk-news/japan-nuclear-meltdown-fears-continue-176620

Were these "nuclear explosions?" NO!

Were "nuclear fizzles" NO!

These were classic chemical explosions, here: $2\ H_2 + O_2 \Rightarrow 2\ H_2O$

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

Even though fission heat drove zirconium to catalyze $H_2 + O_2$ liberation

And net effect was widespread dispersion of radioactive materials =

A DIRTY BOMB: Radioactive materials dispersed by conventional explosives

A hydrogen explosion **also** *occurred at Three Mile Island*
(thirty two years earlier)

High temperature zirconium catalysis of water was **also** identified as the cause

E.G. in the Presidential Commission's Report on TMI

And that hydrogen chemical explosion **also** moved the accident from
a **contained meltdown** to an external **radiation release**

That is, hydrogen explosion converted a problem **inside 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:

Fukushima: Before and After

Barely discernible seaside reactors + surrounding countryside:

Barely discernible seaside reactors + massive clean-up / waste-storage facility

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 in the context of the two earlier accidents:

All THREE of Fukushima's critical shortcomings were well known

Two (plant site / spent fuel storage) had easy (but not inexpensive) fixes

Third (zirconium catalysis of H_2O) had also caused TMI's radiation release

And while its elimination may indeed be difficult

32 years passed without any significant effort **to** eliminate it!

Making that 32 year old TMI Presidential Commission Report seem prophetic:

"No amount of technical 'fixes' will cure this underlying problem.

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"

A final criticism of nuclear: "It's carbon footprint is NOT really zero!"

Why? Because nuclear **reactors use massive amounts of concrete**

And the production of concrete liberates huge amounts of CO_2

This criticism is also leveled at hydroelectric dams

To test its validity for nuclear power plants,

let me now adapt the analysis I made in my **Hydro Power** (pptx / pdf / key) notes,

repeating some of its content in the interest

of keeping this note set on 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 now censored EPA Inventory of US Greenhouse Gas Emissions & Sinks reported [1] that 2012 U.S. Portland cement production produced a carbon footprint of:

35 million metric tonnes CO_2 equivalent = 38.5 million tons CO_2 equivalent

Annual U.S. Portland cement production is ~ 86 million tons [2] and thus:

1 ton of Portland cement => 0.45 tons of CO_2 equivalent released

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

1 ton of **Concrete** => 0.05 tons of CO_2 equivalent released

1) Deleted from the EPA website in April of 2017 "under the leadership of President Trump and Administrator Pruitt." (but my copy can still be viewed/downloaded at THIS LINK)

2) www.cement.org

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

Using this 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 => 665,000 tons **Concrete**

Which is 11% Portland cement => 73,000 tons **Portland cement**

That typical nuclear plant produces ~ 1.5 GW of electrical power

Ratio of nuclear plant Portland cement use to power produced:

= 73 kilo-tons cement /1.5 GW => 0.049 tons **Portland cement** / kW

And given that Nuclear plants operate for at least 40 years, this translates into:

= **0.0012 tons Portland cement / kW-yr for a nuclear plant**

Total U.S. power is ~ ½ Tera-Watts. Nuclear produces 19.7% => 9.8 x 10^7 kW

Which would require 117,600 tons **Portland cement** / yr, and thus:

Total U.S. nuclear footprint = 52,920 tons of CO_2 equivalent

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

Comparing this to Fossil Fuel power plant footprints:

Where Do We Go from Here? (pptx / pdf / key) analysis of carbon tax impact, found that:

Conventional Coal => 0.001 metric tonne CO_2 eq. / kW-hr => 9.6 ton / kW-yr

OCGT Natural Gas => 0.0007 metric tonne CO_2 eq. / kW-hr => 6.7 ton / kW-yr

CCGT Natural Gas => 0.00045 metric tonne CO_2 eq. / kW-hr => 4.3 ton / kW-yr

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

Carbon footprint = (1.52×10^8 kW)(9.6 ton/kW-yr) = 1.5×10^9 tons CO_2 / yr

= 28,300 times Nuclear's current carbon footprint

In 2016 **natural gas** 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)(5.5 ton/kW-yr) = 9.3×10^8 tons CO_2 / yr

= 17,600 times Nuclear's current carbon footprint

Nuclear's CO_2 footprint is MINISCULE compared to our fossil fuel plants!

Comparing carbon footprint for each kW-hour of power you consume:

From top of preceding page, converting kW-yr to kW-h, and ton to kg:

Conventional Coal Power:	9.6 ton CO_2 eq. / kW-yr=>	0.99 kg CO_2 eq. / kW-hr
OCGT Natural Gas Power:	6.7 ton CO_2 eq. / kW-yr =>	0.69 kg CO_2 eq. / kW-hr
CCGT Natural Gas Power:	4.3 ton CO_2 eq. / kW-yr =>	0.44 kg CO_2 eq. / kW-hr

From two pages ago, converting GW-yr to kW-h, and ton to kg:

Nuclear Power:	52,920 ton CO_2 eq. / 98 GW-yr =>	0.000055 kg CO_2 eq. / kW-hr

Nuclear's carbon footprint / kW-hr is ~ 10,000 lower than for fossil fuels

Other WeCanFigureThisOut.org note sets on nuclear energy:

A side trip to investigate a very strange possibility:

Prehistoric Natural Nuclear Reactors?

Plus three note sets on the possible future of nuclear energy:

Gen III/III+ Reactors: Confronting Cost & Operational Safety

Gen IV Reactors: Two Designs that Might Radically Reduce Nuclear Waste

Other Gen IV Nuclear Reactors

For links to these note sets (and their accompanying resources webpages) visit:

www.WeCanFigureThisOut.org/ENERGY/Energy_home.htm

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