Byron Nuclear Power Plant

Nuclear Power

Summary

- Currently about 100 nuclear plants in U.S. giving us about 20% of our electricity. France is 80% nuclear, Japan similar
- No new nuclear plants in U.S. since 1978
  - Economics most important; also regulations, legal liabilitly, radioactive waste, siting problems, etc.
- All current plants use fission; fusion being worked on
- Energy comes from nuclear bonds in Uranium

Fission of Uranium

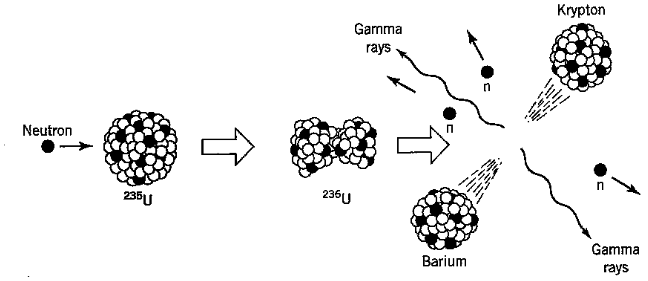
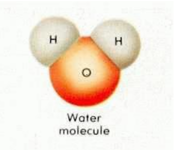
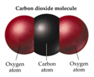


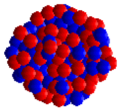
Figure 6.1 Three steps in the neutron-induced fission of ^{235}U. The combination of a neutron and ^{235}U forms ^{236}U in a highly excited state, that promptly fissions into two lighter nuclei, emitting neutrons and gamma rays in the process.

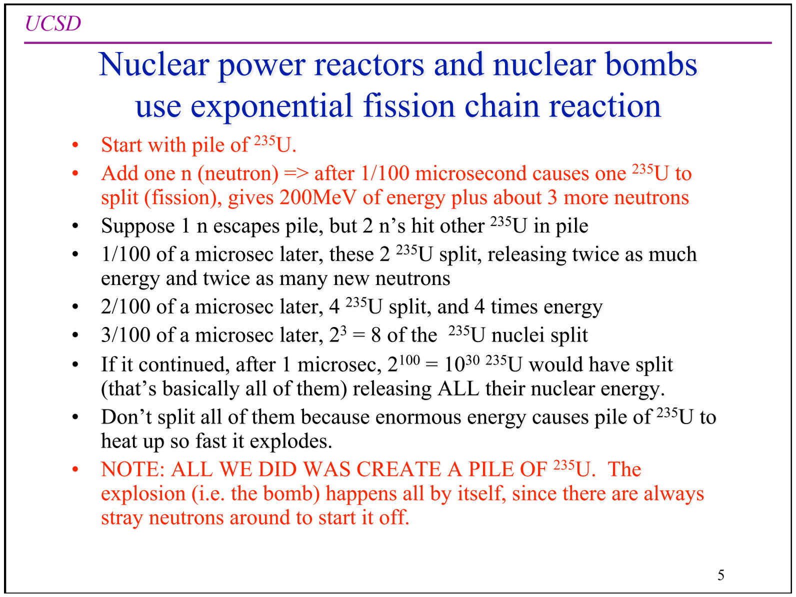
Barium and Krypton represent just one of many potential outcomes

- Original ^{235}U nucleus is heavier than Barium+Kypton+neutrons! Lost mass is converted to kinetic energy and electromagnetic radiation (light). Amount? $E= mc^2$
- About 0.07% of mass of ^{235}U is converted this way.
- Energy is from nuclear bond which is much stronger than chemical bond.
  - Energy between electrons is electric force: just a few eV; between nucleus many MeV => millio times more energy (eV = electron volt = 1.6×10^{19} J)
  - Energy between nuclei is strong nuclear force (like velco) it is millions of times stronger; hundreds of millions of eV (MeV). Needs to keep protons in nuclei together! Otherwise nucleus would fly apart
- Nucleus is 2000 times smaller than atom; tiny dot smaller than . at center of O in water molecule below



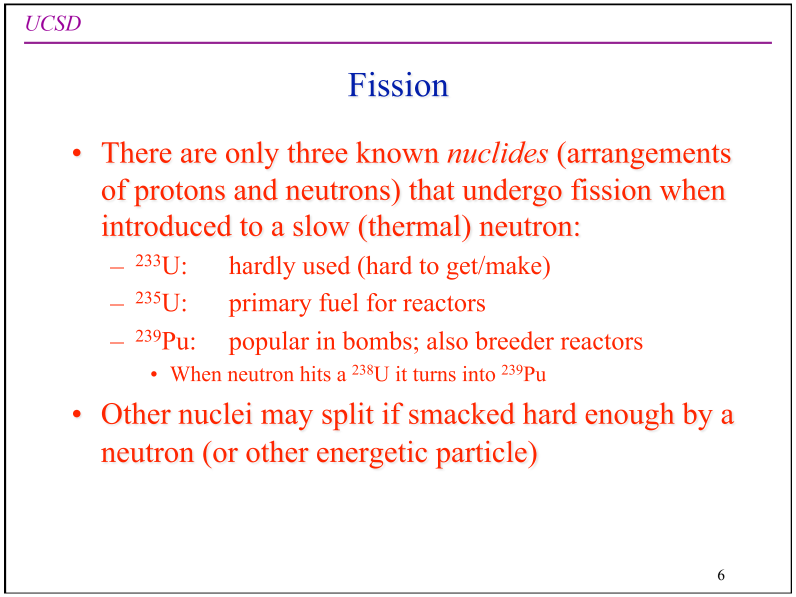






Nuclear power reactors and nuclear bombs use exponential fission chain reaction

- Start with pile of ^{235}U.
- Add one n (neutron) => after 1/100 microsecond causes one ^{235}U to split (fission), gives 200MeV of energy plus about 3 more neutrons
- Suppose 1 n escapes pile, but 2 n's hit other ^{235}U in pile
- 1/100 of a microsec later, these 2 ^{235}U split, releasing twice as much energy and twice as many new neutrons
- 2/100 of a microsec later, 4 ^{235}U split, and 4 times energy
- 3/100 of a microsec later, $2^3 = 8$ of the ^{235}U nuclei split
- If it continued, after 1 microsec, $2^{100} = 10^{30}$ ^{235}U would have split (that's basically all of them) releasing ALL their nuclear energy.
- Don't split all of them because enormous energy causes pile of ^{235}U to heat up so fast it explodes.
- NOTE: ALL WE DID WAS CREATE A PILE OF ^{235}U. The explosion (i.e. the bomb) happens all by itself, since there are always stray neutrons around to start it off.



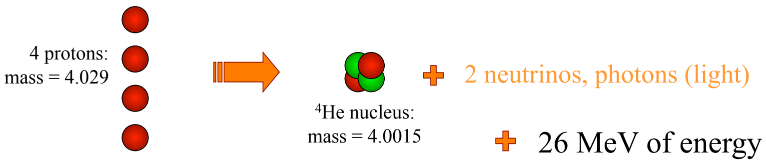
Fission

- There are only three known *nuclides* (arrangements of protons and neutrons) that undergo fission when introduced to a slow (thermal) neutron:
  - ^{233}U: hardly used (hard to get/make)
  - ^{235}U: primary fuel for reactors
  - ^{239}Pu: popular in bombs; also breeder reactors
    - When neutron hits a ^{238}U it turns into ^{239}Pu
- Other nuclei may split if smacked hard enough by a neutron (or other energetic particle)

- Fission was discovered in 1938/39 by Germans: Hahn, Frisch, Meitner. World War II started and many Jewish German physicists fled.
- Einstein (at urging of others) wrote letter to Roosevelt, saying Germans could create "super" bomb; Manhatten project started (Marshall Rosenbluth in our department was there)
- Fermi got small chain reaction going at University of Chicago in 1942
- U.S. made 3 bombs:
  1. Tested in New Mexico, July 1945: 6 kg of ^{239}Pu
  2. Hiroshima: 60 kg of 235U (gun type) (equiv to 12,000 tons TNT)
  3. Nagasaki: 6 kg of 239Pu (equiv to 22,000 tons of TNT)
- Note that modern Hydrogen Thermonuclear fusion bomb can give equiv to 50 million tons TNT, thousands of times more energy and destructive power

Can also have fusion: even more powerful

- Helium nucleus is *lighter* than the four protons!
- Mass difference is 4.029 – 4.0015 = 0.0276 a.m.u.
- 0.7% of mass is converted into energy via $E=mc^2$
- Reaction ~20 million times more energetic than chemical reactions, in general
  - Fusion works out to 150 million Calories per gram
  - compare to 16 million Cal/g uranium fission
  - Compare to 10 Cal/g gasoline



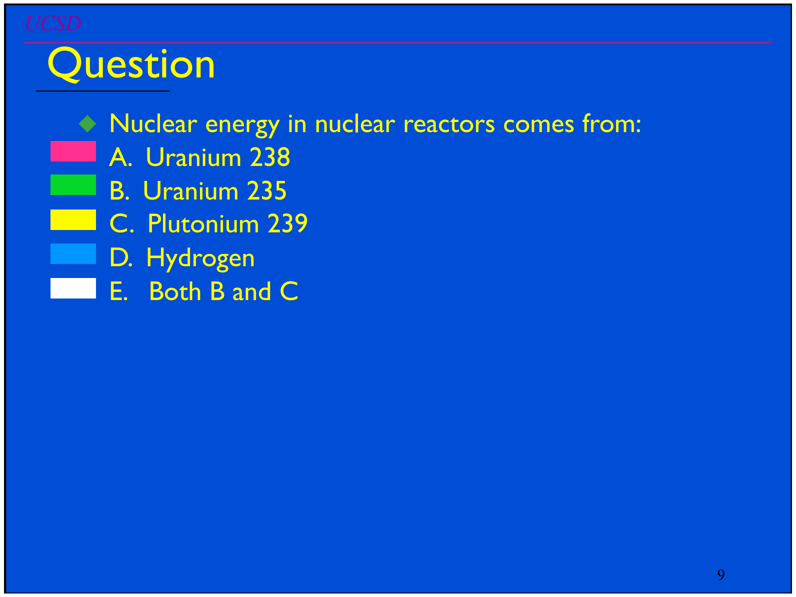
4 protons: mass = 4.029

^{4}He nucleus: mass = 4.0015

+ 2 neutrinos, photons (light)

+ 26 MeV of energy

THIS FUSION IS THE SOURCE OF THE SUN'S ENERGY, (and of energy in thermonuclear hydrogen bombs)



Question

◆ Nuclear energy in nuclear reactors comes from:

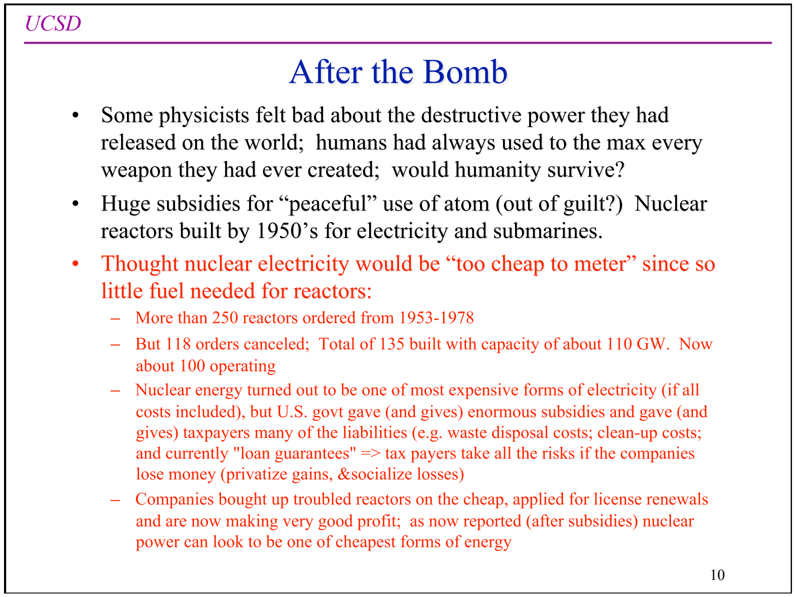
🟥 A. Uranium 238

🟩 B. Uranium 235

🟨 C. Plutonium 239

🟦 D. Hydrogen

⬜ E. Both B and C



After the Bomb

- Some physicists felt bad about the destructive power they had released on the world; humans had always used to the max every weapon they had ever created; would humanity survive?
- Huge subsidies for "peaceful" use of atom (out of guilt?) Nuclear reactors built by 1950's for electricity and submarines.
- Thought nuclear electricity would be "too cheap to meter" since so little fuel needed for reactors:
  - More than 250 reactors ordered from 1953-1978
  - But 118 orders canceled; Total of 135 built with capacity of about 110 GW. Now about 100 operating
  - Nuclear energy turned out to be one of most expensive forms of electricity (if all costs included), but U.S. govt gave (and gives) enormous subsidies and gave (and gives) taxpayers many of the liabilities (e.g. waste disposal costs; clean-up costs; and currently "loan guarantees" => tax payers take all the risks if the companies lose money (privatize gains, &socialize losses)
  - Companies bought up troubled reactors on the cheap, applied for license renewals and are now making very good profit; as now reported (after subsidies) nuclear power can look to be one of cheapest forms of energy

The relative cost of nuclear power

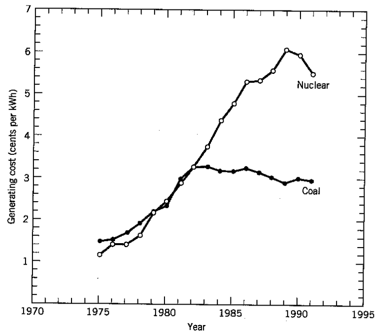
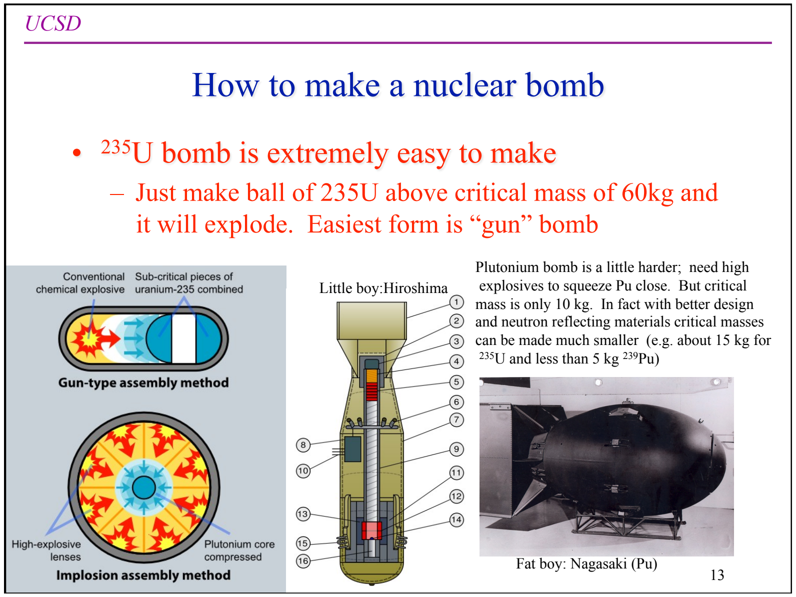


Figure 6.7 Comparison of U. S. coal and nuclear mean generating costs, 1975–1991. Generating costs are taken primarily from Department of Energy reports and are expressed in current dollars. (From: D. Bodansky, *Nuclear Energy: Principles, Practices, and Prospects.* 1996.)

- France and Japan also heavily subsidized their reactors: wanted energy independence
- Huge new push for nuclear energy for both reasons of climate change and energy independence; but still not clear whether it is too expensive and there are also other problems we will talk about such as safety, nuclear waste, and the ability to use waste for nuclear bombs
- Currently billions of government subsidies available (e.g. govt will pick up more than half of cost of building!) but very few companies want to build; Warren Buffett recently shut down his nuclear energy company.



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How to make a nuclear bomb

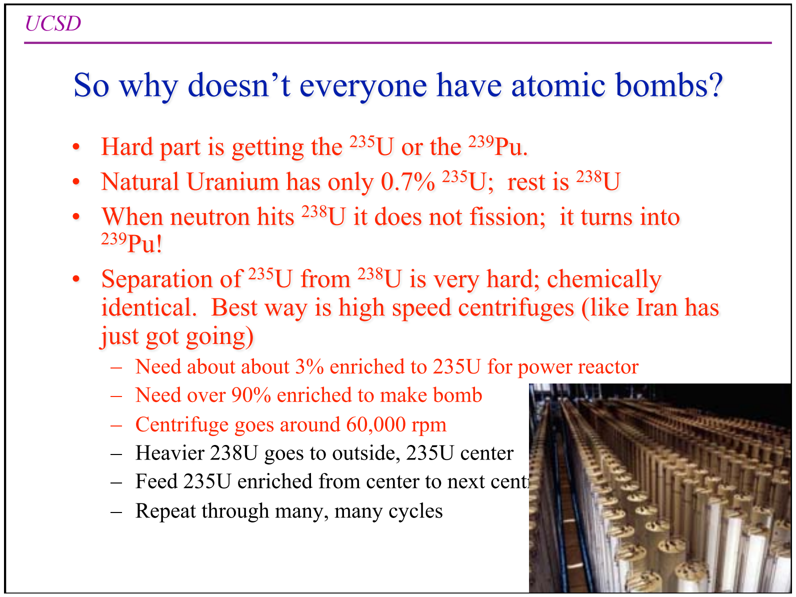
- ^{235}U bomb is extremely easy to make
  - Just make ball of 235U above critical mass of 60kg and it will explode. Easiest form is "gun" bomb

Little boy:Hiroshima

Plutonium bomb is a little harder; need high explosives to squeeze Pu close. But critical mass is only 10 kg. In fact with better design and neutron reflecting materials critical masses can be made much smaller (e.g. about 15 kg for ^{235}U and less than 5 kg ^{239}Pu)

Fat boy: Nagasaki (Pu)

13



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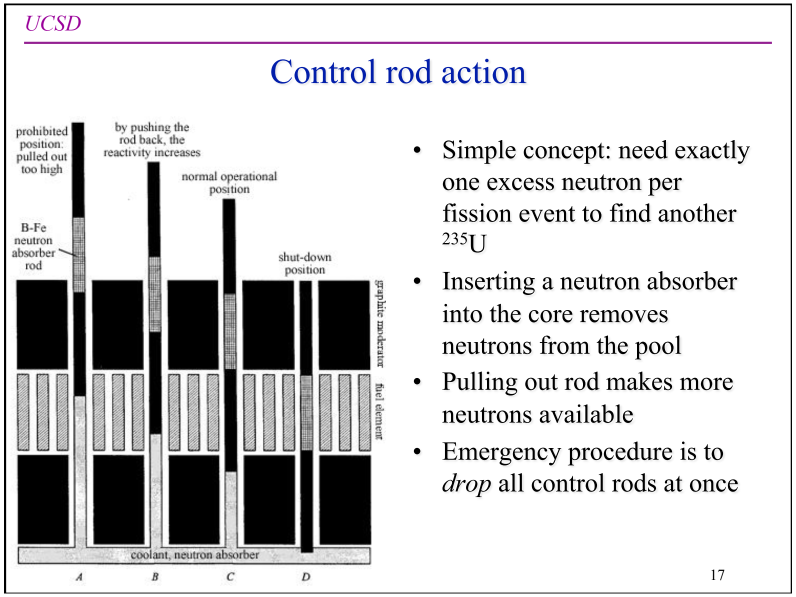
So why doesn't everyone have atomic bombs?

- Hard part is getting the ^{235}U or the ^{239}Pu.
- Natural Uranium has only 0.7% ^{235}U; rest is ^{238}U
- When neutron hits ^{238}U it does not fission; it turns into ^{239}Pu!
- Separation of ^{235}U from ^{238}U is very hard; chemically identical. Best way is high speed centrifuges (like Iran has just got going)
  - Need about about 3% enriched to 235U for power reactor
  - Need over 90% enriched to make bomb
  - Centrifuge goes around 60,000 rpm
  - Heavier 238U goes to outside, 235U center
  - Feed 235U enriched from center to next cent
  - Repeat through many, many cycles

- Getting Plutonium is somewhat easier, but still hard
- ^{239}Pu does not occur naturally on Earth; it is created in nuclear power reactors
  - A 1 GW nuclear power plant (like San Onofre) creates enough ^{239}Pu for a nuclear bomb every 6 days!
  - Separation is done chemically (easy) but very radioactive environment (this is what North Korea has done) and you need your own nuclear power plant
- So there are two main routes to an atomic bomb; very high tech centrifuges to get ^{235}U for simple gun bomb, or reprocessing nuclear waste from regular nuclear power plant to get ^{239}Pu for a more sophisticated implosion bomb

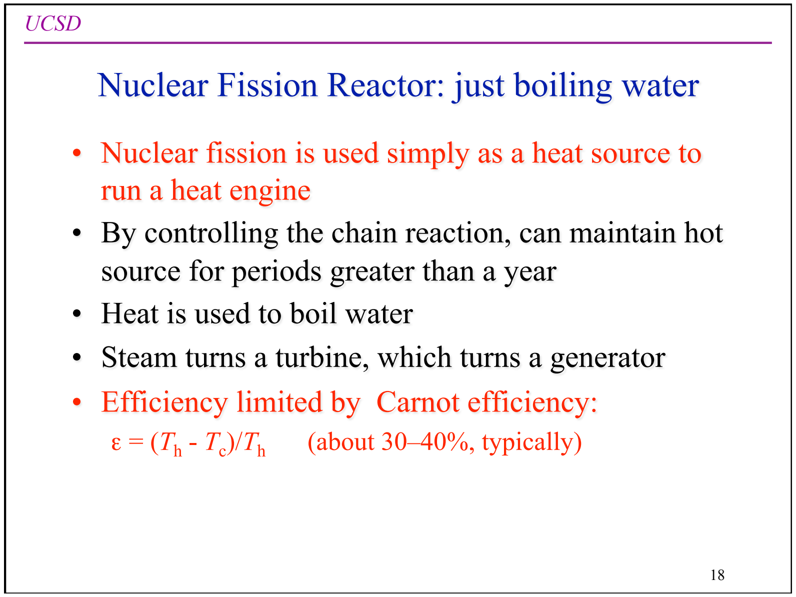
Why don’t nuclear reactors explode?

- Need to get exactly one neutron per fission
  - If more than 1 then will explode
    - e.g. if 1% more, after 1 millisec $N=(1.01)^{1ms/.00001ms} = 10^{234}$ (all nuclei split => explosion) (even 1% is exponential growth)
    - If less (e.g. 0.99) then after 1 millisec ($.99^{234} \sim 0$) turned off
- Use control rods made of Boron in between U fuel to capture neutrons. Pull them in and out to adjust rate of nuclear reactions.
- In emergency push control rods all the way in to stop reaction
  - But “delayed neutrons” will still be produced; cannot actually turn a nuclear reactor off!



Control rod action

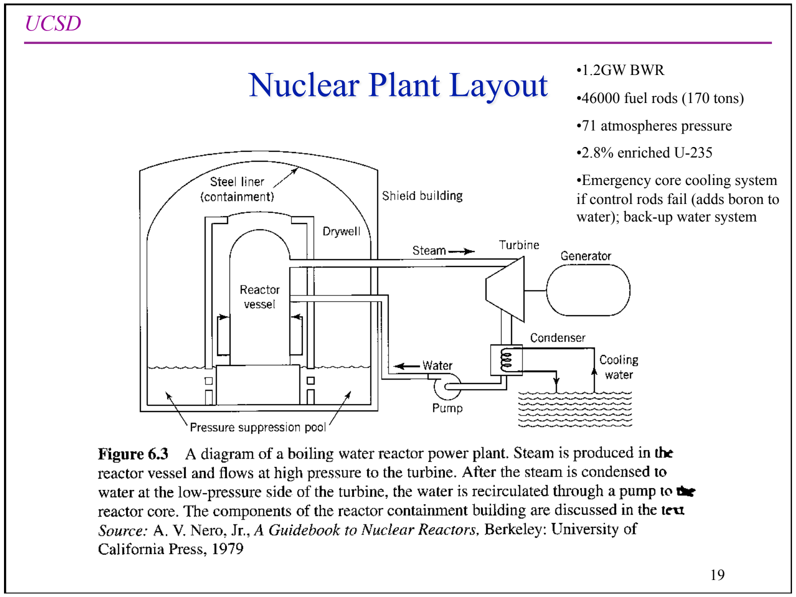
- Simple concept: need exactly one excess neutron per fission event to find another ^{235}U
- Inserting a neutron absorber into the core removes neutrons from the pool
- Pulling out rod makes more neutrons available
- Emergency procedure is to *drop* all control rods at once



Nuclear Fission Reactor: just boiling water

- Nuclear fission is used simply as a heat source to run a heat engine
- By controlling the chain reaction, can maintain hot source for periods greater than a year
- Heat is used to boil water
- Steam turns a turbine, which turns a generator
- Efficiency limited by Carnot efficiency:

  $\varepsilon = (T_h - T_c)/T_h$ (about 30–40%, typically)



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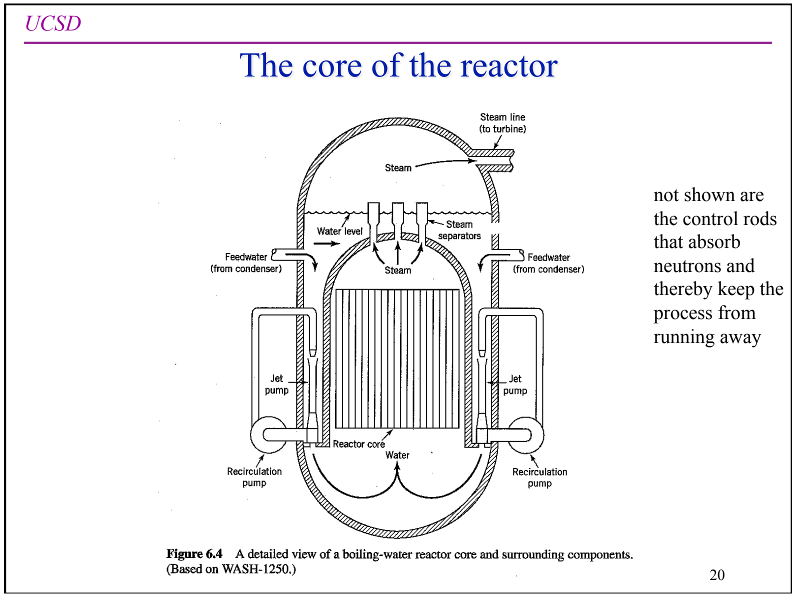
Nuclear Plant Layout

- 1.2GW BWR
- 46000 fuel rods (170 tons)
- 71 atmospheres pressure
- 2.8% enriched U-235
- Emergency core cooling system if control rods fail (adds boron to water); back-up water system

Figure 6.3 A diagram of a boiling water reactor power plant. Steam is produced in the reactor vessel and flows at high pressure to the turbine. After the steam is condensed to water at the low-pressure side of the turbine, the water is recirculated through a pump to the reactor core. The components of the reactor containment building are discussed in the text. *Source:* A. V. Nero, Jr., *A Guidebook to Nuclear Reactors.* Berkeley: University of California Press, 1979

19



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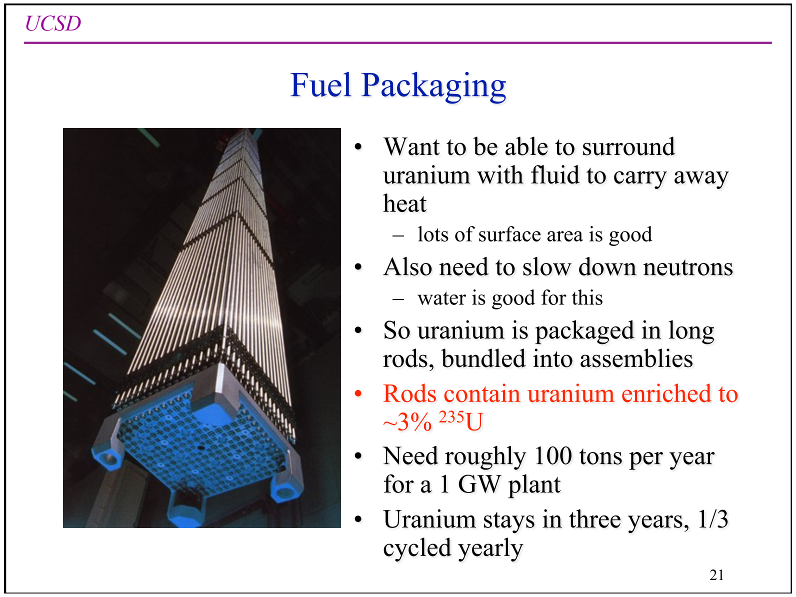
The core of the reactor

not shown are the control rods that absorb neutrons and thereby keep the process from running away

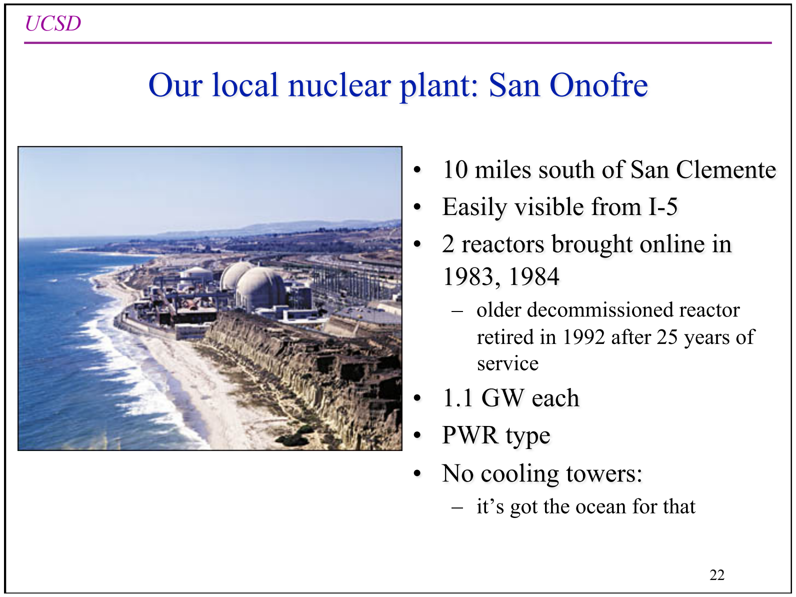
Figure 6.4 A detailed view of a boiling-water reactor core and surrounding components. (Based on WASH-1250.)

20



Fuel Packaging

- Want to be able to surround uranium with fluid to carry away heat
  - lots of surface area is good
- Also need to slow down neutrons
  - water is good for this
- So uranium is packaged in long rods, bundled into assemblies
- Rods contain uranium enriched to ~3% ^{235}U
- Need roughly 100 tons per year for a 1 GW plant
- Uranium stays in three years, 1/3 cycled yearly



Our local nuclear plant: San Onofre

- 10 miles south of San Clemente
- Easily visible from I-5
- 2 reactors brought online in 1983, 1984
  - older decommissioned reactor retired in 1992 after 25 years of service
- 1.1 GW each
- PWR type
- No cooling towers:
  - it's got the ocean for that

Symbols used in nuclear physics

- A nucleus has a definite number of protons (Z), a definite number of neutrons (N), and a definite total number of *nucleons*: $A = Z + N$
  - example, the most common *isotope* of carbon has 6 protons and 6 neutrons (denoted ^{12}C; 98.9% abundance)
    - $Z = 6$; $N = 6$; $A = 12$
  - another stable *isotope* of carbon has 6 protons and 7 neutrons (denoted ^{13}C; 1.1% abundance)
    - $Z = 6$; $N = 7$; $A = 13$
  - an unstable *isotope* of carbon has 6 protons and 8 neutrons (denoted ^{14}C; half-life is 5730 years)
    - decays via beta decay to ^{14}N
- Isotopes of an element have same Z, differing N

Full notation

- A fully annotated nucleon symbol has the total nucleon number, A, the proton number, Z, and the neutron number, N positioned around the symbol

$$^{A}_{Z}X_{N}$$

  - redundancy in that $A = Z + N$
- Examples:
  - carbon-12: $^{12}_{6}C_{6}$
  - carbon-14: $^{14}_{6}C_{8}$
  - uranium-235: $^{235}_{92}U_{143}$
  - uranium-238: $^{238}_{92}U_{146}$
  - plutonium-239: $^{239}_{94}Pu_{145}$

Radioactivity

- Any time a nucleus spontaneously emits a particle…
  - electron through beta (β^-) decay
  - positron (anti-electron) through beta (β^+) decay
  - alpha (α) particle (^{4}He nucleus)
  - gamma (γ) ray (high-energy photon of light)
- …we say it underwent a *radioactive* transformation
- Certain isotopes of nuclei are radioactively unstable
  - they will eventually change flavor by a radioactive particle emission
  - α, β, γ emission constitutes a minor change to the nucleus
    - not as dramatic as splitting the entire nucleus in two large parts

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Nuclear equations

- ${}^{137}_{55}\mathrm{Cs}_{82} \rightarrow {}^{137}_{56}\mathrm{Ba}_{81}$ + e- + neutrino, $t_{1/2} = 30$ yr
- ${}^{239}_{94}\mathrm{Pu}_{145} \rightarrow {}^{235}_{92}\mathrm{U} + {}^{4}_{2}\mathrm{He}_{2}$, $t_{1/2} = 24{,}000$ yr
- Excess mass→comes out in kinetic energy
- Different radioactive elements have different halflives (after $t_{1/2}$ 1/2 of original nuclei have decayed)
  - ^{15}O, $t_{1/2}$=12 seconds
  - ^{14}C (Carbon-14), $t_{1/2}$=5730 years
  - ^{3}He (tritium), 12.4 years
  - ^{238}U (U-238), 4.6 billion years
  - ^{235}U (U-235), 704 million years
  - ^{89}Sr (strontium-89), 50 days
  - ^{90}Sr (strontium-90), 29 years
  - ^{131}I (iodine-131), 8 days
  - ^{137}Cs (cesium-137), 30 years
- Half life is extremely important: tells how much radioactivity (how dangerous) and how long radioactively will last (how long wastes must be stored)

Examples

- Carbon-14 is used to date things that once were alive
  - Cosmic rays turn ^{14}N into ^{14}C. Plants breathe $^{14}CO_2$; animals eat plants. All living things have ^{14}C in them at known concentration (ratio of ^{14}C to ^{12}C is same for all living things; given by ratio in air)
  - Things die. No more ^{14}C intake, so ^{14}C decays in dead body materials; ratio of ^{14}C to ^{12}C decreases with time.
  - After 5730 years, half of ^{14}C is gone; after 11,400 years only 1/4 left.
  - Measure ratio of ^{14}C to ^{12}C and find out how long since that plant or animal died
  - Will it work for things 10 million years old? No: 10,000,000/5730 =1745 half lives. So only $1/2^{1745} \sim 0$ of ^{14}C left. Not even one nucleus left. But other elements with longer half lives can be used for longer times

Another example

- ^{131}I is waste product of nuclear power plants; if reactor melts down lots of ^{131}I could escape in atmosphere (happened in Chernobyl and Fukushima)
- Iodine is eagerly absorbed by humans (especially kids); stored in thyroid gland
- $t_{1/2}$ is only 8 days => down by factor of $1/2^{10} \sim 1/1000$ in 10 times 8halflives = 80 days, or down to $1/2^{100} \sim 0$ in 800 days
- So is it dangerous? YES VERY; short half life means in first two weeks almost all of nuclei decay, giving out huge amounts of cancer causing radiation; all concentrated in people's throats.
- This is why in San Diego emergency crews have huge supplies of iodine pills. If San Onofre melts down, they will very quickly distribute these pills to everyone. Want everyone's thyroid to get saturated with iodine so that the radioactive ^{181}I won't be absorbed
- Long half life => around for a long time, but not very radioactive
- Short half life => around for a short time, but very radioactive

Can Date the Earth this way!

- Uranium is made in supernova explosions; nuclear physics predicts roughly equal amounts of ^{238}U and ^{235}U. But today ^{235}U is only 0.7%. Explained because ^{235}U has $t_{1/2}$ = t235 =704x10^6 years and ^{238}U has $t_{1/2}$ = t238= 4.6x10^9 years.
- Today N239/N235 = 0.7/99.3 = $2^{(t/t235)}$/ $2^{(t/t238)}$
- You can solve this equation to find out what value of t will satisfy it. Find t = ln(0.7/99.3)/[ln2 (1/t238 - 1/t235)] ~ 6.7 billion years. One of several ways to find the time the Solar System was created. (Actually this is time when supernova when off)

Uranium isotopes and others of interest

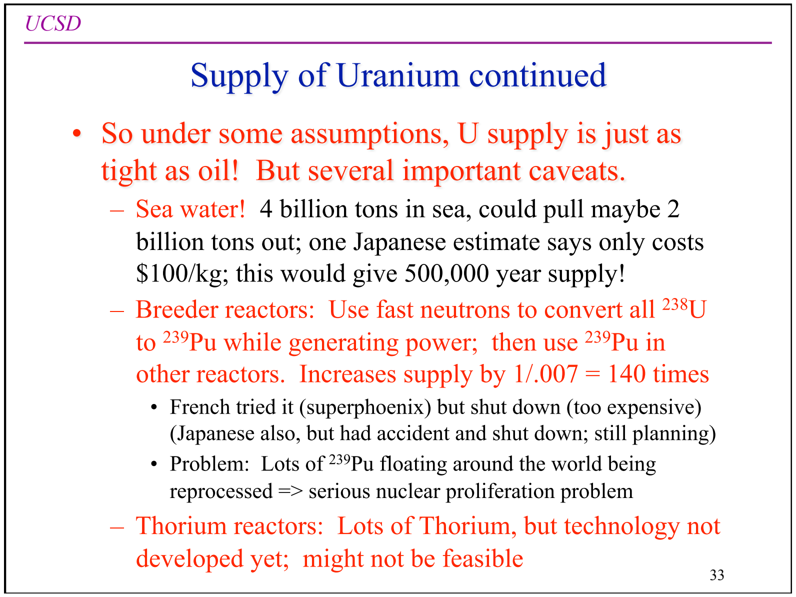
Isotope	**Abundance (%)**	**half-life**	**decays by:**
^{233}U	0	159,000 yr	α
^{234}U	0.0055	246,000 yr	α
^{235}U	0.720	704 Myr	α
^{236}U	0	23 Myr	α
^{237}U	0	6.8 days	β^-
^{238}U	99.2745	4.47 Gyr	α
^{239}Pu	no natural Pu	24,000 yr	α
^{232}Th	100	14 Gyr	α

Uranium decay

- The natural abundance of uranium today suggests that it was created about 6 billion years ago
  - assumes ^{235}U and ^{238}U originally equally abundant
  - Now have 39.8% of original ^{238}U and 0.29% of original ^{235}U
  - works out to 0.72% ^{235}U abundance today
- Plutonium-239 half-life is way too short (24,000 yr) to have any naturally available
- Thorium-232 is *very* long-lived, and holds primary responsibility for geothermal heat; could be used for a non-chain reaction, nuclear power plant!

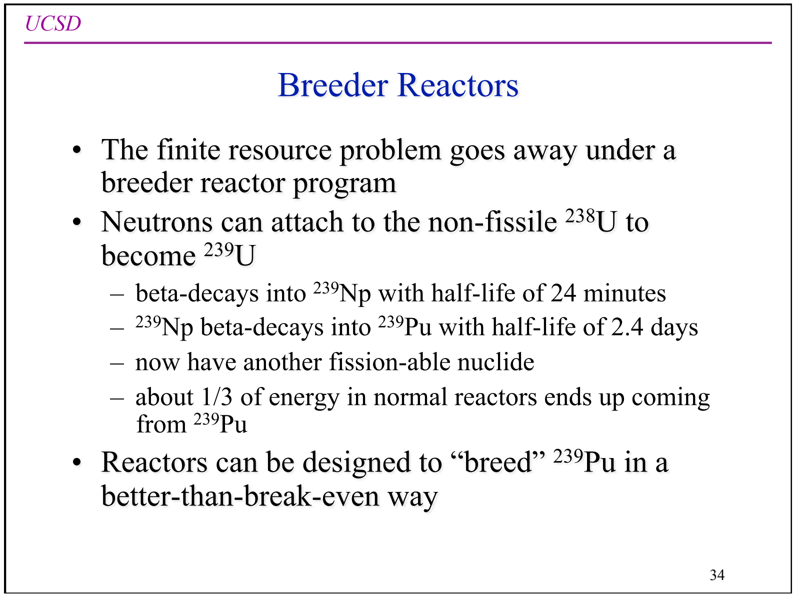
Will we run out of Uranium?

- Our book says current reserves ~2 Mton in U.S. 6 Mton in world (with cost < $150/kg)
- Uranium current cost is about $23/kg
  - Only about 1% of cost of nuclear power
- At double cost ($300/kg) there is rougly twice as much
  - (and who cares since fuel in nukes is not main cost)
- Need 200 tons per year for 1 GW reactor
  - (actually only ~1 ton ^{235}U, but that means 200 tons natural U)
- Garwin (Megawatts & Megatons author) says much more: ~ 100Mton in world at economic price
- In U.S. have 100 GW plants now, ~430 GW in world (Maybe need 2000GW in coming decades if switching to nuclear power)
  - If 10 Mton & 434 reactors: U lasts 115 years
  - If 10 Mton & 2000 reactors: U lasts 25 years
  - If 100 Mton & 434 reactors: U lasts 1150 year
  - If 100 Mton & 2000 reactors: U lasts 250 years
- For just U.S. & book numbers, U.S. now has about 150 years of U supply, or 30 years if we switch all electricity to nuclear



Supply of Uranium continued

- So under some assumptions, U supply is just as tight as oil! But several important caveats.
  - Sea water! 4 billion tons in sea, could pull maybe 2 billion tons out; one Japanese estimate says only costs \$100/kg; this would give 500,000 year supply!
  - Breeder reactors: Use fast neutrons to convert all ^{238}U to ^{239}Pu while generating power; then use ^{239}Pu in other reactors. Increases supply by 1/.007 = 140 times
    - French tried it (superphoenix) but shut down (too expensive) (Japanese also, but had accident and shut down; still planning)
    - Problem: Lots of ^{239}Pu floating around the world being reprocessed => serious nuclear proliferation problem
  - Thorium reactors: Lots of Thorium, but technology not developed yet; might not be feasible



Breeder Reactors

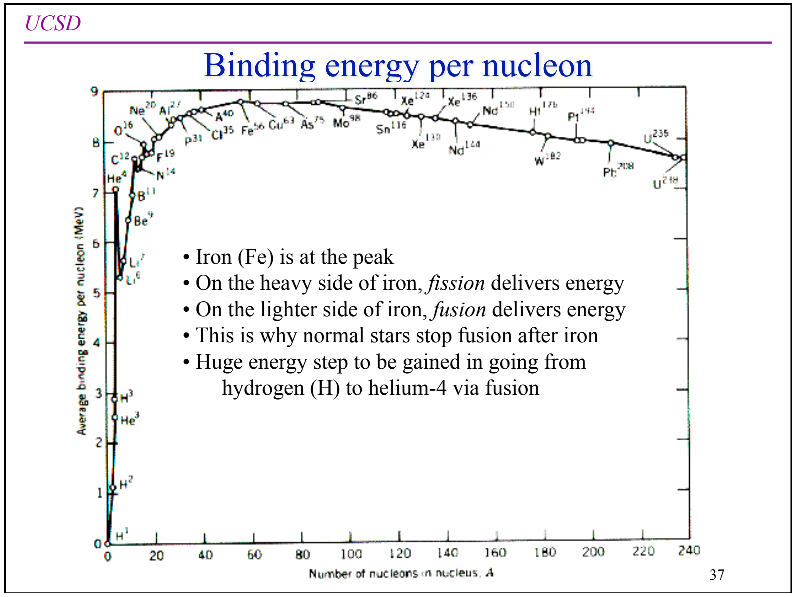
- The finite resource problem goes away under a breeder reactor program
- Neutrons can attach to the non-fissile ^{238}U to become ^{239}U
  - beta-decays into ^{239}Np with half-life of 24 minutes
  - ^{239}Np beta-decays into ^{239}Pu with half-life of 2.4 days
  - now have another fission-able nuclide
  - about 1/3 of energy in normal reactors ends up coming from ^{239}Pu
- Reactors can be designed to “breed” ^{239}Pu in a better-than-break-even way

Breeders, continued

- Could use breeders to convert all available ^{238}U into ^{239}Pu
  - all the while getting electrical power out
- Now 30 year resource is 140 times as much (not restricted to 0.7% of natural uranium), or 4200 yr
- Technological hurdle: need liquid sodium or other molten metal to be the coolant
  - but four are running in the world
- Enough ^{239}Pu falling into the wrong hands spells:
  - BOOM!!

Why uranium?

- Why mess with “rare-earth” materials? Why not force lighter, more abundant nuclei to split?
  - though only three “slow-neutron” fissile nuclei are known, what about using fast neutrons to force nuclei apart and get their mass energy?
- Turns out, you would actually *loose* energy in splitting lighter nuclei
- Iron is about the most tightly bound of the nuclides
  - and it’s the release of binding energy that we harvest
  - so we want to drive toward iron to get the most out



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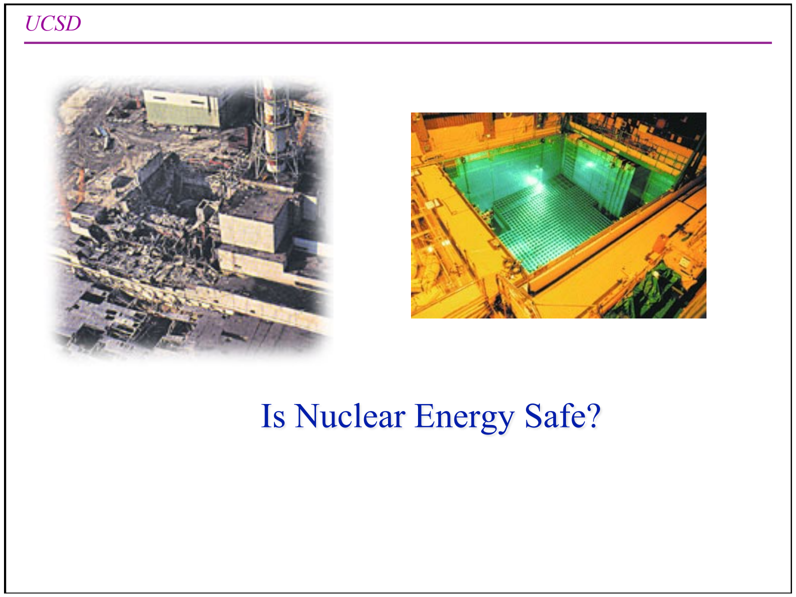
Binding energy per nucleon

- Iron (Fe) is at the peak
- On the heavy side of iron, *fission* delivers energy
- On the lighter side of iron, *fusion* delivers energy
- This is why normal stars stop fusion after iron
- Huge energy step to be gained in going from hydrogen (H) to helium-4 via fusion

37



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Is Nuclear Energy Safe?

How does radioactivity affect people?

- Basic unit of radioactivity is Curie (or Becquerel (Bq) in metric)
  - 1 Bq is one radioactive decay/second
  - 1 Ci = 3.7 x 10^{10} decays/sec = 37 Gbq
- But only particles that hit you cause damage; Units of radioactive dose
  - Gray = 1 Joule/kg absorbed in body (metric)
  - Rad = .01 J/kg absorbed in body (Gray = 100 rads)
- But some particles are more dangerous than others
  - Sievert (Sv) = RBE x Gray (metric)
  - Rem = RBE X rad (Sv = 100 rems)
- RBE = 1 for x-ray, gamma-ray
- RBE = 1-1.5 for electrons
- RBE = 3-5 for neutrons, 10 for protons, 20 for alpha particles
- I will use rems ~ rads for x-ray, gamma-ray and electrons

What do these units mean?

- 10,000 rems => complete destruction of tissue (100 Sv)
- 500 rems => death within days or weeks (5 Sv)
- 250 rems = LD50 (2.5 Sv)
- 20 rems => no immediate effect (0.2 Sv)
- U.S. radiation worker limited to < 5 rem/year (Europe says < 1.5 rem/year, and international recommendation < 2 rem/year) (U.S. 50 mSv/yr; Europe 15mSv/y; NEW JAPAN LIMIT: 150mSv/year)
- Average American gets 0.25 rem/year (2.5 mSv/yr)
- Chest X-ray gives .02-.04 rem (0.25 mSv)
- Round trip flight to Europe: 7 mrem (0.07 mSv)
- Inside Fukushima reactor 3 building: 140 rem/day (1.4 Sv/day)

Everyone gets radiated!

- Sources of radiation exposure

Body itself	~ 0.02 rem/year (K-40/C-14)
Breathing radon gas	~ 0.13 rem/year
Rocks, soil, buildings	~0.05 rem/year
Cosmic rays	~0.03 rem/year (sea level)

[~0.05 at Denver (5000ft), ~0.13 (Leadville, CO),
~0.20 at La Paz, Bolivia (3.9 km),
~1.5 in plane (37,000ft)]

Dental X-ray	~0.014 (but not whole body)
Medical X-ray	~0.02 - 0.1 rem

- Total of about 0.25rem/year (not counting X-rays)
  - This is conservative; other independent estimates get slightly higher numbers (e.g. 0.3 - 0.4 rem/year)

Are low levels of exposure dangerous?

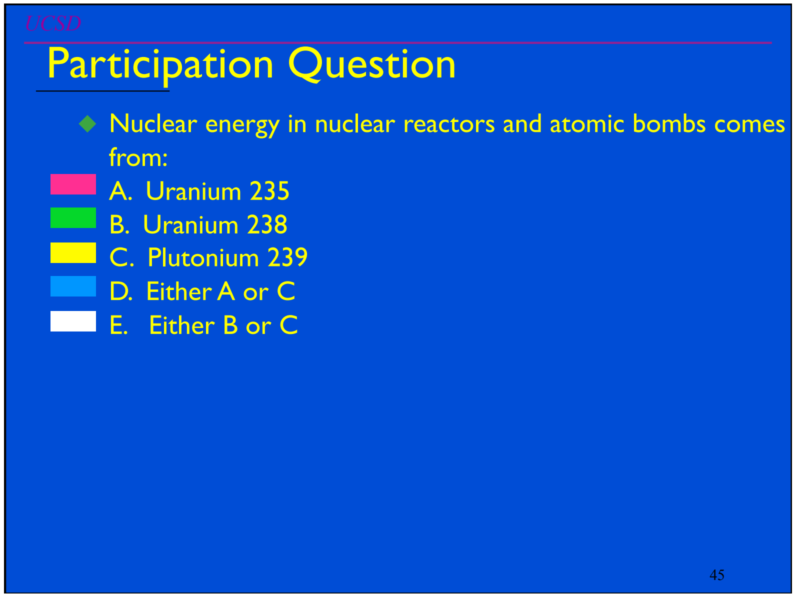
- Some debate on whether they are or not. Recent studies (U.N. sponsored) show ALL exposure increases chance of cancer. Conclusion of current best studies:
  - 1 fatal cancer in population for every 2500 rem of exposure
  - Average of 0.25 rem/year => 1 out of 10,000 in U.S. get cancer due to natural radiation! These deaths have nothing to do with nuclear power; medical X-rays are substantial contributor!
- Why? DNA replication: radiation ionizes an atom and breaks molecular bond; if just right one is hit => cancer
- We can use this number to calculate risk associated with nuclear power

Compare to Coal power plants

- Coal powered plants put out radioactivity (could be scrubbed, but mostly not) Coal is few ppm U and Th (Radon & Radium). U.N. estimates 0.8 lethal cancers per GW coal plant. For 400 such plants worldwide => 320 deaths/year. If include fly ash from plants used in concrete (5% used this way) increases to 5 deaths/plant or 2000 total deaths/year
- Nuclear plants (operating properly) put out very little radiation. U.N. estimates about 6 deaths/plant/year; almost all from Uranium mine tailing radioactivity over 10,000 years! With Pu reprocessing (breeders) it goes to 14 death/plant/year
- So nuclear and coal cause about same radiation exposure!

How about compared to other risks?
U.S.Deaths per year per 100,000 persons (1994)

Cause of death	total number	rate per 100,000
Cardiovascular disease	2,300,000	876
Cancer	534,000	205
Accidents	90,000	34
Motor vehicles	42,000	16
Errors in hospitals	2700-50,000!	1-35
Poisoning by drugs & medicine	7,828	3
Fire & flame	3986	1.53
Drowning	3404	1.3
Inhalation & ingestion of objects	3065	1.17
Firearms and handguns	1356	0.51
Air transport	1075	0.41
Water transport	725	0.28
Railway	635	0.26
Gases and vapors	605	0.28
Electric current	561	0.21
Nuclear power plants	~50	0.02



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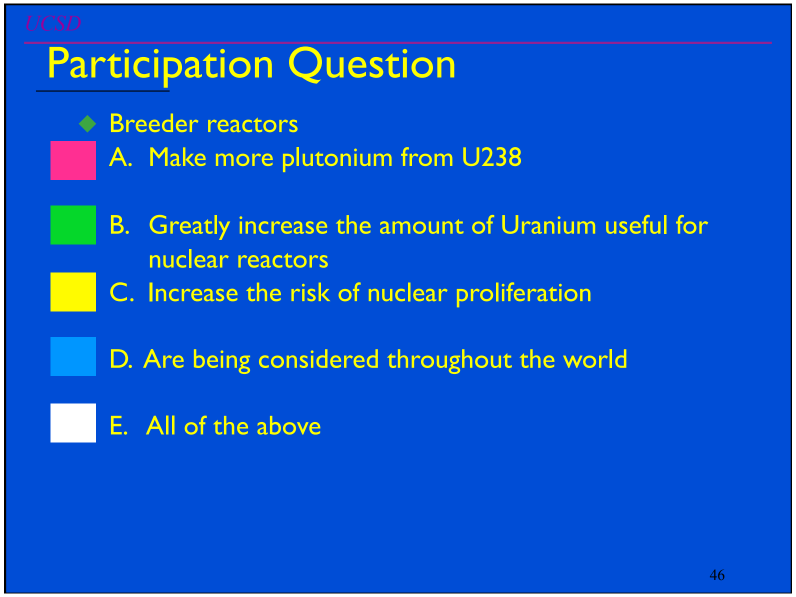
Participation Question

- Nuclear energy in nuclear reactors and atomic bombs comes from:

🟥 A. Uranium 235
🟩 B. Uranium 238
🟨 C. Plutonium 239
🟦 D. Either A or C
⬜ E. Either B or C



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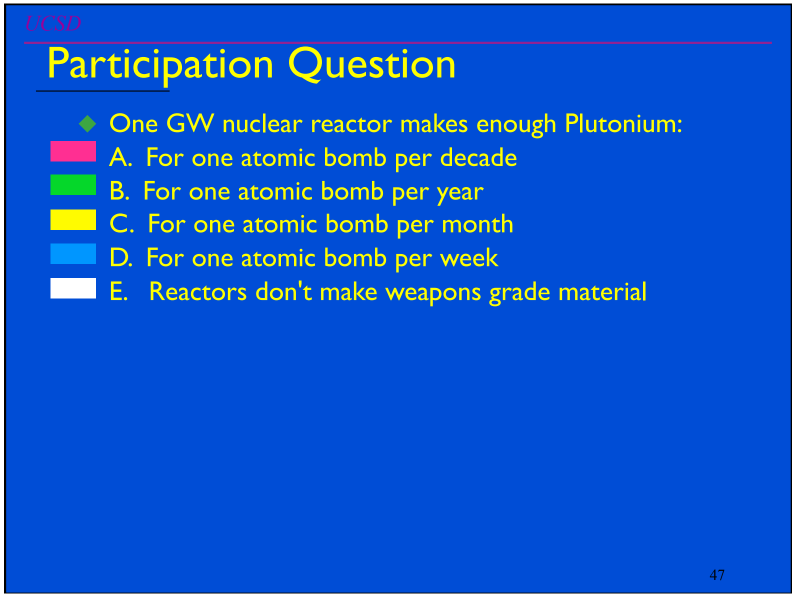
Participation Question

- Breeder reactors

🟥 A. Make more plutonium from U238
🟩 B. Greatly increase the amount of Uranium useful for nuclear reactors
🟨 C. Increase the risk of nuclear proliferation
🟦 D. Are being considered throughout the world
⬜ E. All of the above



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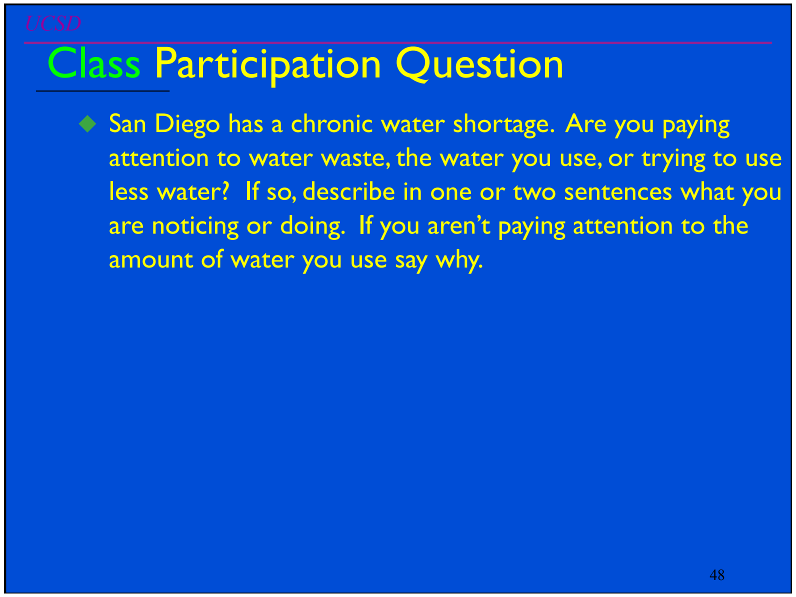
Participation Question

◆ One GW nuclear reactor makes enough Plutonium:

- 🟥 A. For one atomic bomb per decade
- 🟩 B. For one atomic bomb per year
- 🟨 C. For one atomic bomb per month
- 🟦 D. For one atomic bomb per week
- ⬜ E. Reactors don't make weapons grade material



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Class Participation Question

◆ San Diego has a chronic water shortage. Are you paying attention to water waste, the water you use, or trying to use less water? If so, describe in one or two sentences what you are noticing or doing. If you aren't paying attention to the amount of water you use say why.

Issues for nuclear power

- Is it excessively polluting?
- Are plants safe?
- Will it contribute to nuclear war?
- Is it economically viable?

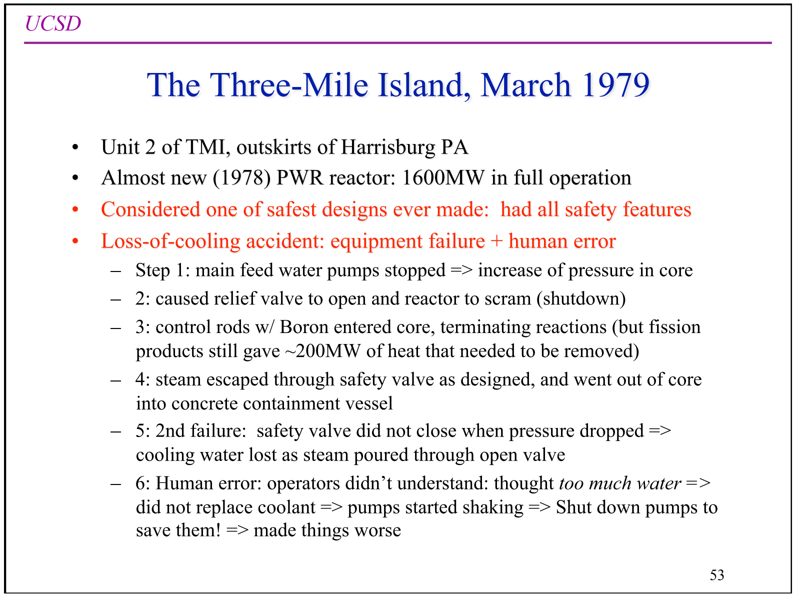
What about risk of nuclear accident?

- Must consider abnormal accidental conditions to prevent release of radioactivity:
  - Failure modes: electrical failure, pipes bursting, earthquakes, airplane crash, human error, enemy bomb, etc.
  - Worst thing is melt-down: fuel rods melt and release radioactivity to surroundings
- Nuclear Reg. Comm. (NRC) is very bad at considering these things
  - e.g. report by Union of Concerned Scientists
- One measure is SCRAMS: (plant suddenly taken off-line)
  - 1980: 7 scrams/plant/year
  - 1999: 1 scram/plant/year => plants getting safer
- Current plants require redundancy and safety features
  - 3 independent sets of control rods
  - Concrete containment shell outside of all
  - Emergency core cooling system (in case of loss of cooling accident)
  - Automatic water spray system
- But still Three Mile Island and Chernobyl and Fukushima accidents happened

What is risk of melt-down?

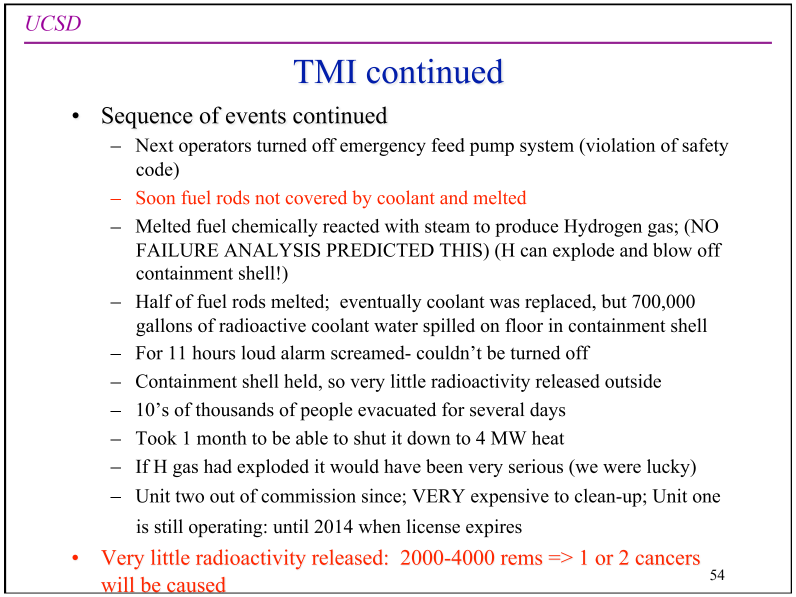
- Extensive studies by agencies like the NRC
- 1975 report concluded that:
  - loss-of-cooling probability was 1/2000 per reactor year
  - significant release of radioactivity 1/1,000,000 per RY
  - chance of killing 100 people in an accident about the same as killing 100 people by a falling meteor; but still Chernobyl happened!
- 1990 NRC report accounts for external disasters (fire, earthquake, etc.)
  - large release probability 1/250,000 per RY
  - 109 reactors, each 30 year lifetime → 1% chance

Close to home: Three Mile Island



The Three-Mile Island, March 1979

- Unit 2 of TMI, outskirts of Harrisburg PA
- Almost new (1978) PWR reactor: 1600MW in full operation
- Considered one of safest designs ever made: had all safety features
- Loss-of-cooling accident: equipment failure + human error
  - Step 1: main feed water pumps stopped => increase of pressure in core
  - 2: caused relief valve to open and reactor to scram (shutdown)
  - 3: control rods w/ Boron entered core, terminating reactions (but fission products still gave ~200MW of heat that needed to be removed)
  - 4: steam escaped through safety valve as designed, and went out of core into concrete containment vessel
  - 5: 2nd failure: safety valve did not close when pressure dropped => cooling water lost as steam poured through open valve
  - 6: Human error: operators didn't understand: thought *too much water* => did not replace coolant => pumps started shaking => Shut down pumps to save them! => made things worse



TMI continued

- Sequence of events continued
  - Next operators turned off emergency feed pump system (violation of safety code)
  - Soon fuel rods not covered by coolant and melted
  - Melted fuel chemically reacted with steam to produce Hydrogen gas; (NO FAILURE ANALYSIS PREDICTED THIS) (H can explode and blow off containment shell!)
  - Half of fuel rods melted; eventually coolant was replaced, but 700,000 gallons of radioactive coolant water spilled on floor in containment shell
  - For 11 hours loud alarm screamed- couldn't be turned off
  - Containment shell held, so very little radioactivity released outside
  - 10's of thousands of people evacuated for several days
  - Took 1 month to be able to shut it down to 4 MW heat
  - If H gas had exploded it would have been very serious (we were lucky)
  - Unit two out of commission since; VERY expensive to clean-up; Unit one is still operating: until 2014 when license expires
- Very little radioactivity released: 2000-4000 rems => 1 or 2 cancers will be caused

Chernobyl, April 26, 1986, in Urkraine

- 4 reactors, graphite cooled; no containment dome
- Plant managers testing ability of plant to give electricity when plant was being shut down => running plant at very low power
- Added Xe to absorb neutrons and pulled control rods all the way out
- Team running experiment were completely clueless! Many deviations from plant safety specs; also design flaws in reactor
  - Did not know that loss of coolant accident would lead to uncontrolled chain reaction and meltdown, so for convenience they turned off all safety devices!
- 1-year before, Soviet minister of energy issued decree: “Information on unfavorable ecological impacts shall not be reported” => secrecy about all accidents => nobody know about them

Chernobyl, continued

- Loss of coolant happened => fission chain reaction => fuel rods melted, then exploded => lifted 1000 ton cover off top of reactor => ruptured rest of 1600 pressure tubes => another explosion => radioactive core exposed to environment
- Reactor was like a volcano
  - Radioactive cloud rose to 11,000 meters; for weeks airplanes arrived thoughout Europe radioactive
  - Fifty tons of nuclear fuel was dispersed: workers were putting out visible fires: after 1/2 hour they were walking corpses; Workers tanned as if spent 2 weeks in Sun!
- Were some heroes:
  - 50 year old Lelachintov went 3 times to electrolysis room to disconnect hydrogen, sparing other the task and saving their lives. (Lethal dose in 2-6 minutes) (Died agonizing death few days later)

Chernobyl, continued

- Plant directors told Moscow that reactor had not been destroyed
  - While whole neighborhood was strewn with graphite pieces from the core!
- Moscow said: “don’t create a panic”, officials refused to order an evacuation!
- Official, Shcherbina, finally arrived and was furious when he learned only rational solution was to bury entire reactor under tons of sand dropped from helicopters (pilots all died)
- Chernobyl released 10 times more radioactivity than Hiroshima, plus 1/2 ton of Plutonium.
- Evacuations happened April 27-29; radioactive dogs were shot

---

Chernobyl after-effects

- Cloud of ^{137}Cs and ^{131}I rained down
  - Within a year thyroid cancers increased more than 100 times (and continue to this day)
- People 400 km away had to be evacuated
- Exposure
  - ~300 people seriously exposed (~ 30 died within 3 months, rest hospitalized with serious disorders)
  - 200,000 clean-up workers received unknown high doses; in general population (Using rubric of 1 death per 2500 rems find)
  - 135,000 received > .5 rem => 27 deaths
  - 270,000 received 0.2-0.5 rem => 38 deaths
  - 580,000 received 0.1-0.2 rem => 35 deaths
  - 4 million received > 0.1 rem =>160 deaths
- So expect at least 250 more deaths, plus some of the radiation workers plus some from continued exposure over time
- Experts disagree on total: some say 30,000 eventual, some say 0, some say 300,000

Safety, Nuclear Accidents, and Industrial Hazards

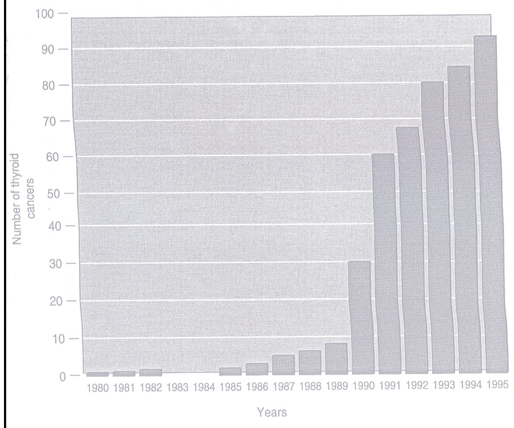


Fig. 7.1. Annual increase in thyroid cancer in Belarus.

Nuclear Proliferation

- The presence of nuclear reactors means there will be plutonium in the world
  - and enriched uranium
- If the world goes to large-scale nuclear power production (especially breeder programs), it will be easy to divert Pu into nefarious purposes
- But other techniques for enriching uranium may become easy/ economical
  - and therefore the terrorist’s top choice
- Should the U.S. abandon nuclear energy for this reason?
  - perhaps a bigger concern is all the weapons-grade Pu already stockpiled in the U.S. and former U.S.S.R.!!

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Nuclear Waste

- Big Problem; originally unappreciated
- Each reactor has storage pool, meant as temporary holding place
  - originally thought to be 150 days; 35 years and counting!
  - Reason? Nuclear proliferation (Don’t want Plutonium moving around)
- Huge variety of radioactive products, with a whole range of half-lives
  - 1 GW plant waste is 70 MCi after one year; 14 MCi after 10 years; 1.4 MCi after 100 years; 0.002 MCi after 100,000 years
  - 1 Ci (Curie) is 37 billion radioactive decays per second

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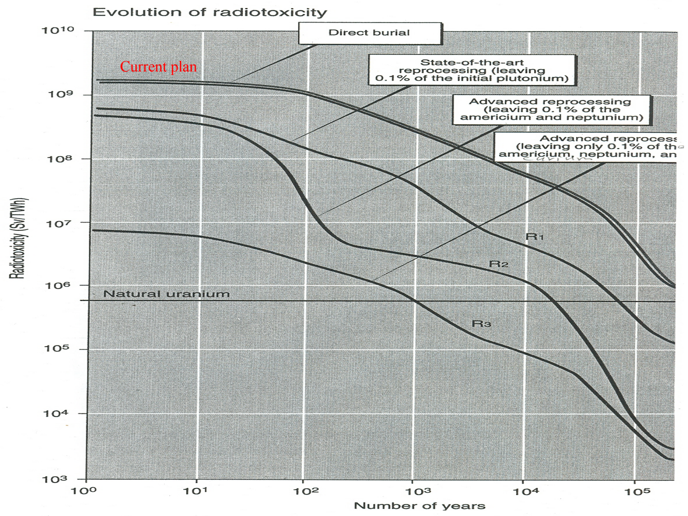
How long does nuclear waste have to be stored?

MEGAWATTS AND MEGATONS

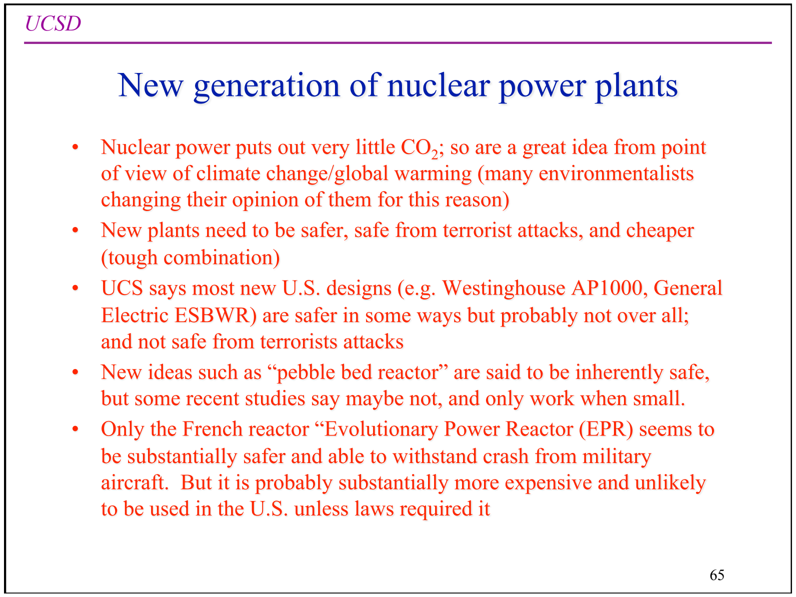


Should reprocessing be done?

- Advantages:
  - Last slide shows one advantages; don't need to store waste as long
  - Lower volume means less geologic storage needed
  - plus can use Pu for fuel
- Problems:
  - Heat, not Radioactivity limits storage volumes: PUREX reprocessing separates but does not reduce heat content => just as much area needed; still need hundreds of years for shorter lived isotopes
  - Separated Pu can be used in nuclear weapons => requires much more careful guarding for very long periods of time
- UCS recommends that U.S. drop plans for reprocessing and instead find better storage facility; Recommends "once through" waste disposal at site better than Yucca mountain

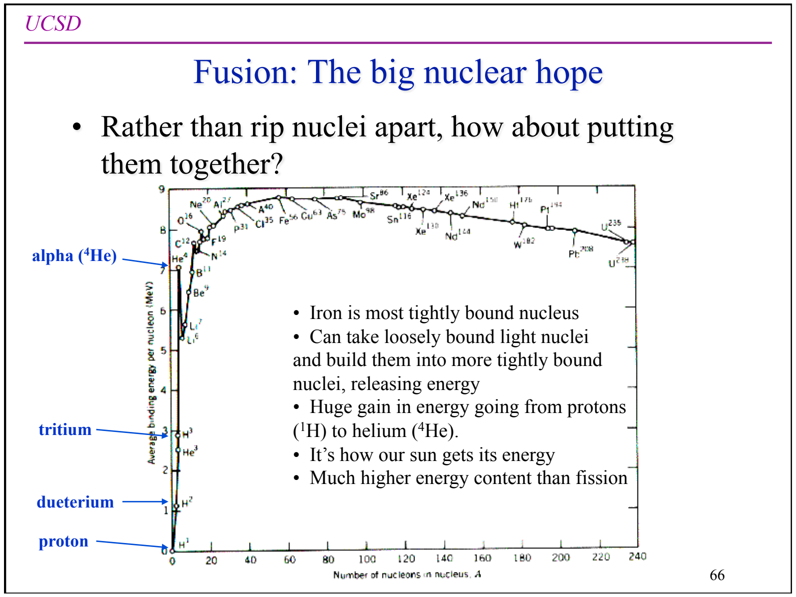
Storage Solutions

- There are none…yet
- EPA demands less than 1000 premature cancer deaths over 10,000 years!!
  - incredibly hard to design/account
- Proposed site at Yucca Mountain, NV
  - Very bad choice, geologically: cracks and unstable, storage area is above the water table => any leaks can get into water and migrate far
  - Could find a better site (e.g. below water table)
- Worldwide, *nobody* has worked out a storage solution



New generation of nuclear power plants

- Nuclear power puts out very little CO_2; so are a great idea from point of view of climate change/global warming (many environmentalists changing their opinion of them for this reason)
- New plants need to be safer, safe from terrorist attacks, and cheaper (tough combination)
- UCS says most new U.S. designs (e.g. Westinghouse AP1000, General Electric ESBWR) are safer in some ways but probably not over all; and not safe from terrorists attacks
- New ideas such as "pebble bed reactor" are said to be inherently safe, but some recent studies say maybe not, and only work when small.
- Only the French reactor "Evolutionary Power Reactor (EPR) seems to be substantially safer and able to withstand crash from military aircraft. But it is probably substantially more expensive and unlikely to be used in the U.S. unless laws required it



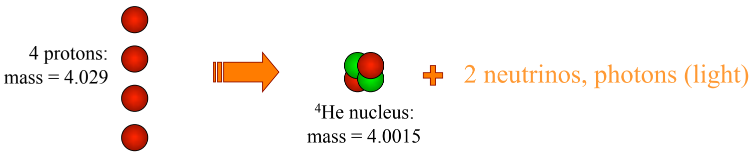
Fusion: The big nuclear hope

- Rather than rip nuclei apart, how about putting them together?

- Iron is most tightly bound nucleus
- Can take loosely bound light nuclei and build them into more tightly bound nuclei, releasing energy
- Huge gain in energy going from protons (^{1}H) to helium (^{4}He).
- It's how our sun gets its energy
- Much higher energy content than fission

Thermonuclear fusion in the sun

- Sun is 16 million degrees Celsius in center
- Enough energy to ram protons together (despite mutual repulsion) and make deuterium, then helium
- Reaction per mole ~20 million times more energetic than chemical reactions, in general



4 protons:
mass = 4.029

^{4}He nucleus:
mass = 4.0015

+ 2 neutrinos, photons (light)

$E=mc^2$ balance sheets

- Helium nucleus is *lighter* than the four protons!
- Mass difference is 4.029 – 4.0015 = 0.0276 a.m.u.
  - 0.7% of mass disappears, transforming to energy
  - 1 a.m.u. (atomic mass unit) is 1.6605×10^{-27} kg
  - difference of 4.58×10^{-29} kg
  - multiply by c^2 to get 4.12×10^{-12} J
  - 1 mole (6.022×10^{23} particles) of protons → 2.5×10^{12} J
  - typical chemical reactions are 100–200 kJ/mole
  - nuclear fusion is ~20 million times more potent stuff!
  - works out to 150 million Calories per gram
    - compare to 16 million Cal/g uranium, 10 Cal/g gasoline

Artificial fusion

- 16 million degrees in sun's center is *just* enough to keep the process going
- In laboratory, need higher temperatures still to get worthwhile rate of fusion events
  - like 100 million degrees
- Bottleneck in process is the reaction:

  $^1H + ^1H \rightarrow ^2H + e^+ + \nu$ (or proton-proton → deuteron)
- Better off starting with deuterium plus tritium
  - ^2H and ^3H, sometimes called ^2D and ^3T
- Then:

  $^2H + ^3H \rightarrow ^4He + n + 17.6$ MeV (leads to 81 MCal/g)
- But what kind of machine can hold something at 100 million degrees?
  - Answer: Nothing material; need magnetic fields

Deuterium everywhere

- Natural hydrogen is 0.0115% deuterium
  - Lots of hydrogen in sea water (H_2O)
- Total U.S. energy budget (100 QBtu = 10^{20} J per year) covered by sea water contained in cubic volume 170 meters on a side
  - corresponds to 0.15 cubic meters per second
  - about 1,000 showers at two gallons per minute each
  - about one-millionth of rainfall amount on U.S.
  - 4 gallons per person per year!!!

Tritium nowhere

- Tritium is unstable, with half-life of 12.32 years
  - thus none naturally available
- Can make it by bombarding ^{6}Li with neutrons
  - extra n in D-T reaction can be used for this, if reaction core is surrounded by “lithium blanket”
- Lithium on land in U.S. would limit D-T to a hundred years or so
  - maybe a few thousand if we get lithium from ocean
- D-D reaction requires higher temperature, but could be sustained for *many* millennia

Nasty by-products? Safety?

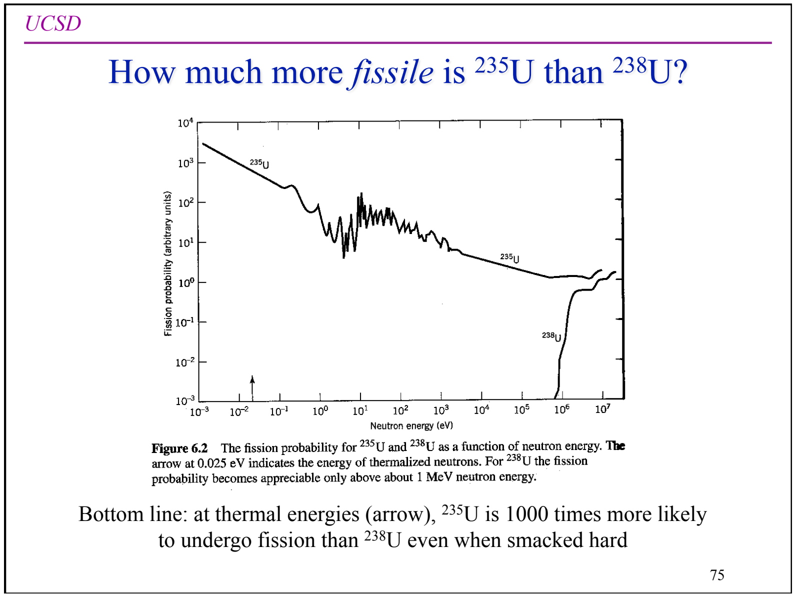
- Nuclear waster? Practically none: not like radioactive fission products
  - Tritium is only direct radioactive substance; but energy is low, half-life short: not much worry here
- Extra neutrons do hit nuclei (in surrounding structure) and become radioactive, so not totally clean radioactivity speaking
- Can’t have chain reaction; will turn itself off when things go wrong

Why don’t we embrace fusion, then?

- We *would* if we *could*
- It’s a huge technological challenge, always 50 years from fruition
  - must confine plasma at 50 million degrees! Magnetic confinement always seems to be unstable and stuff leaks out and hits inside walls
- Still pursued, but with decreased enthusiasm, increased skepticism
  - payoff is huge: relatively clean, unlimited energy
  - ITER: UCSD Physicists working on it; looks like working fusion reactors will be have to be extremely large; i.e. just one or two for whole U.S.

Fusion Successes?

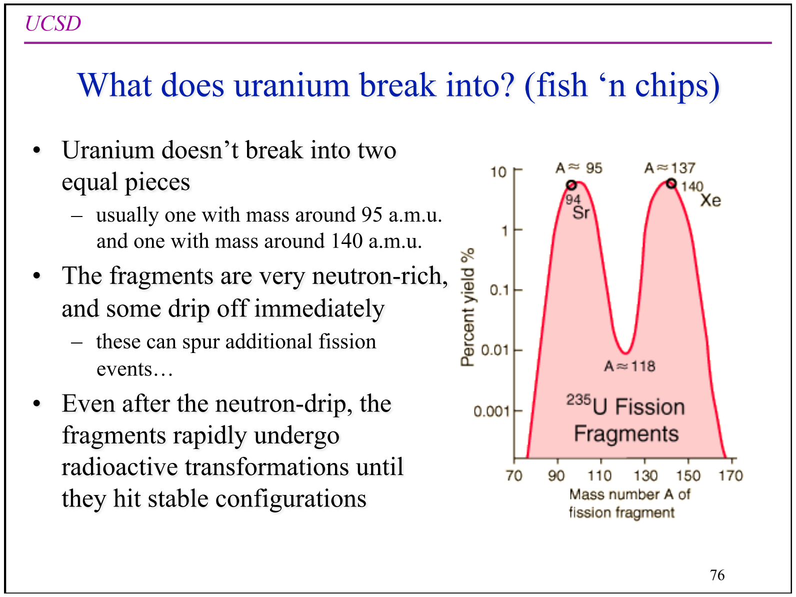
- Fusion *has* been accomplished in labs, in big plasma machines called *Tokamaks*
  - got ~6 MW out of Princeton Tokamak in 1993
  - but put ~12 MW *in* to sustain reaction
  - General Atomics in La Jolla has largest tokamak
- Hydrogen bomb also employs fusion
  - fission bomb (e.g., ^{239}Pu) used to generate extreme temperatures and pressures necessary for fusion
  - LiD (lithium-deuteride) placed in bomb
  - fission neutrons convert lithium to tritium
  - tritium fuses with deuterium



How much more *fissile* is ^{235}U than ^{238}U?

Figure 6.2 The fission probability for ^{235}U and ^{238}U as a function of neutron energy. The arrow at 0.025 eV indicates the energy of thermalized neutrons. For ^{238}U the fission probability becomes appreciable only above about 1 MeV neutron energy.

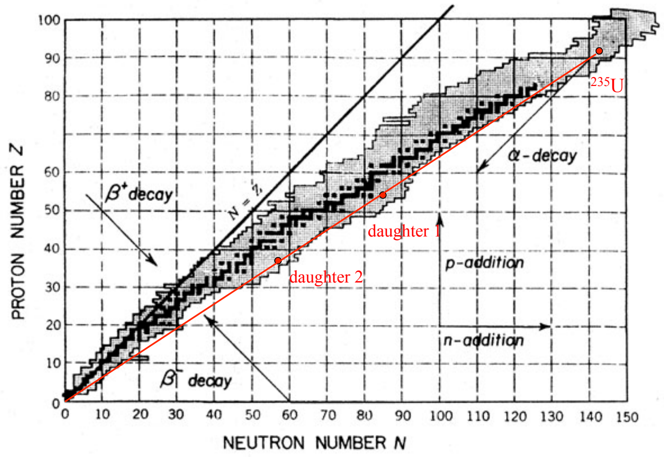
Bottom line: at thermal energies (arrow), ^{235}U is 1000 times more likely to undergo fission than ^{238}U even when smacked hard



What does uranium break into? (fish 'n chips)

- Uranium doesn't break into two equal pieces
  - usually one with mass around 95 a.m.u. and one with mass around 140 a.m.u.
- The fragments are very neutron-rich, and some drip off immediately
  - these can spur additional fission events…
- Even after the neutron-drip, the fragments rapidly undergo radioactive transformations until they hit stable configurations

Chart of the nuclides



■ stable nuclide ▨ radioactive (unstable) nuclide

Natural radioactive dose in rem/year

Source	**Sea Level**	**Denver**
cosmic rays	.028	.055
terrestrial (rock)	.046	.09
food and water	.04	
air (mostly radon)	.2	
air travel	.001 per 1,000 miles traveled	
house	.007 if made of stone/brick/concrete	
medical X-ray	.04 each (airport X-ray negligible)	
nuclear med. treatment	.014 each	
within 50 miles of nuclear plant	0.000009	
within 50 miles of coal plant	0.00003	
total for no travel/medical	**.316**	**.387**

source: www.epa.gov/radiation/students/calculate.html