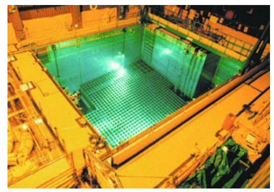

Realities of Nuclear Energy

Resources

Waste and Disasters

The Promise of Fusion?

Summary of fission

- ^{235}U will undergo spontaneous fission if a neutron happens by, resulting in:
  - two sizable nuclear fragments flying out
  - a few extra neutrons
  - gamma rays from excited states of daughter nuclei
  - energetic electrons from beta-decay of daughters
- The net result: lots of banging around
  - generates heat locally (kinetic energy of tiny particles)
  - for every gram of ^{235}U, get 65 billion Joules, or about 16 million kilocalories
  - compare to gasoline at roughly 10 kcal per gram
    - a tank of gas could be replaced by a 1-mm pellet of ^{235}U!!

Enrichment

- Natural uranium is 99.27% ^{238}U, and only 0.72% ^{235}U
  - ^{238}U is not fissile, and absorbs wandering neutrons
- In order for nuclear reaction to self-sustain, must enrich fraction of ^{235}U to 3–5%
  - interestingly, it was so 3 billion years ago
  - now probability of wandering neutron hitting ^{235}U is sufficiently high to keep reaction crawling forward
- Enrichment is hard to do: a huge technical roadblock to nuclear ambitions

Nuclear Fission Reactors

- 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 familiar Carnot efficiency:

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

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Nuclear Plant Layout

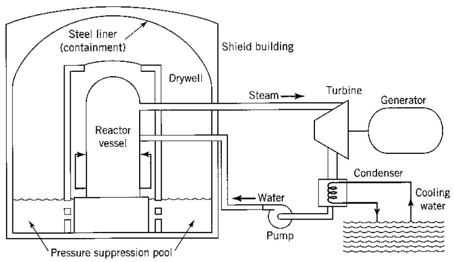

Figure 6.3 A diagram of a boiling water reactor power plant. Steam is produced in the reactor vessel and flows at high pressure to the turbine. After the steam is condensed to water at the low-pressure side of the turbine, the water is recirculated through a pump to the reactor core. The components of 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

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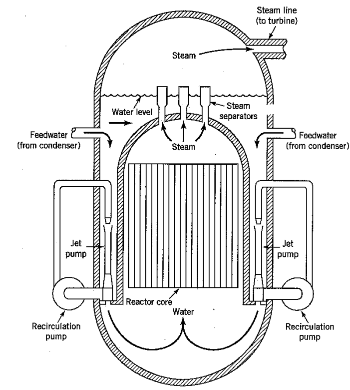
The core of the reactor



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.)

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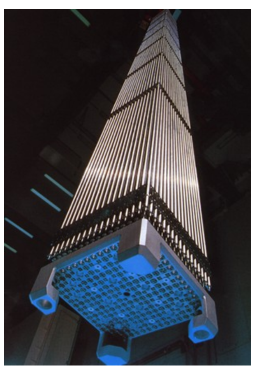
Fuel Packaging



- 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

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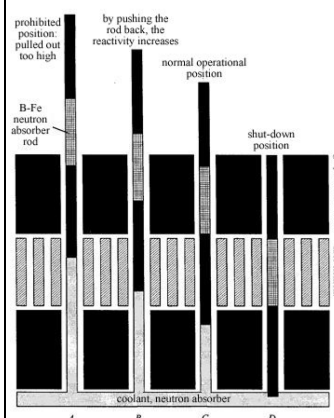
Control rod action



- 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

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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
- Offline since January 2012
  - premature wear in steam tubes installed 2010, 2011
  - likely will restart this year

CA has 74 GW electricity generating capacity
Produces 23 GW on average (198,000 GWh/yr)

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The relative cost of nuclear power

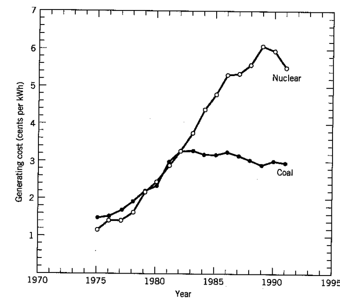

Figure 6.7 Comparison of U. S. coal and nuclear mean generating costs, 1975–1991. Generating costs are taken primarily from Department of Energy reports and are expressed in current dollars. (From: D. Bodansky, *Nuclear Energy: Principles, Practices, and Prospects*. 1996.)

safety regulations tend to drive cost

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The finite uranium resource

- Uranium cost is about $80/kg
  - just a few percent of cost of nuclear power
- As we go for more, it's more expensive to get
  - depleted the easy spots
- 3 million tons available at cost < $230/kg
- Need 200 tons per GW-yr
- Now have 100 GW of nuclear power generation
  - in about 100 plants; 1 GW each
- 3 million tons will last 150 years at present rate
  - only 30 years if nuclear replaced all electricity prod.

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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

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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!!
  - Pu is pre-enriched to 100%; need less for bomb

Reactor Risk

- Once a vigorous program in the U.S.
  - still so in France: 80% of their electricity is nuclear
- Orders for reactors in U.S. stopped in late 70's
  - not coincidentally on the heels of Three-Mile Island
  - only recently did it pick back up: 5 under construction
- Failure modes:
  - criticality accident: runaway chain reaction → meltdown
  - loss of cooling: not runaway, but overheats → meltdown
  - reactors are incapable of nuclear explosion
  - steam or chemical explosions are not ruled out → meltdown

Risk Assessment

- 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
- 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 Accident, 1979

- The worst nuclear reactor accident in U.S. history
- Loss-of-cooling accident in six-month-old plant
- Combination of human and mechanical errors
- Severe damage to core
  - but containment vessel held
- No major release of radioactive material to environment
- Less than 1 mrem to nearby population
  - less than 100 mrem to on-site personnel
  - compare to 300 mrem yearly dose from natural environment
- Instilled fear in American public, fueled by movies like *The China Syndrome*

The Chernobyl Disaster

- Blatant disregard for safety plus inherently unstable design spelled disaster
- Chernobyl was a boiling-water, graphite-moderated design
  - unlike any in the U.S.
  - used for ^{239}Pu weapons production
  - frequent exchange of rods to harvest Pu meant lack of containment vessel like the ones in U.S.
  - positive-feedback built in: gets too hot, it runs hotter: runaway possible
  - once runaway initiated, control rods not effective

Chernobyl, continued

- On April 25, 1986, operators decided to do an “experiment” as the reactor was powering down for routine maintenance
  - disabled emergency cooling system
    - blatant violation of safety rules
  - withdrew control rods completely
  - powered off cooling pumps
  - reactor went out of control, caused steam explosion that ripped open the reactor
  - many fires, exposed core, major radioactive release

Chernobyl after-effects

- Total of 100 million people exposed (135,000 lived within 30 km) to radioactivity much above natural levels
- Expect from 25,000 to 50,000 cancer deaths as a result
  - compared to 20 million total worldwide from other causes
  - 20,000,000 becomes 20,050,000 (hard to notice…
  - …unless you’re one of those 50,000
- 31 died from acute radiation exposure at site
  - 200 got acute radiation sickness

Fukushima Accident

- Sendai earthquake in March 2011 caused reactors to shut down
  - Generators activated to maintain cooling flow during few-day shutdown process
  - Tsunami ruined this plan, flooding generator rooms and causing them to fail
  - all three operational cores melted down, creating hydrogen gas explosions
- Designed by GE and operated by high-tech society, this is troubling failure
  - can happen to the best

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.!!

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
- Huge variety of radioactive products, with a whole range of half-lives
  - 1GW 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

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
- Worldwide, *nobody* has worked out a storage solution

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Burial Issues

- Radioactive emissions themselves are not radioactive
  - just light, electrons/positrons and helium nuclei
  - but they *are* ionizing: they rip apart atoms/molecules they encounter
- Absorb emissions in concrete/earth and no effect on biology
  - so burial is good solution
- Problem is the patience of time
  - half lives can be long
  - geography, water table changes
  - nature always outlasts human structures
  - imagine building something to last 10,000 years!!

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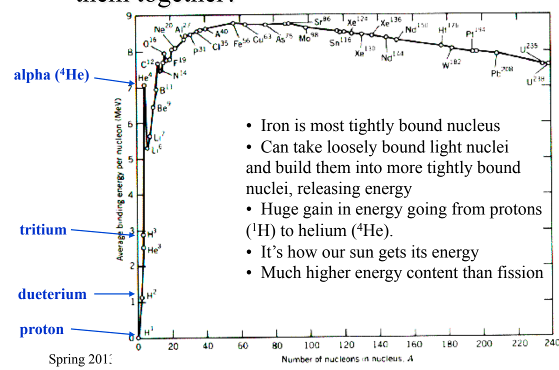
Fusion: The big nuclear hope

- 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

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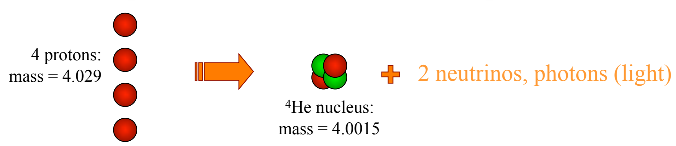
Thermonuclear fusion in the sun

- 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



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$E=mc^2$ 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 kilocalories per gram
    - compare to 16 million kcal/g uranium, 10 kcal/g gasoline

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Artificial fusion

- 16 million degrees in sun's center is *just* enough to keep the process going
  - but sun is *huge*, so it seems prodigious
- 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
  - but give up some energy: starting higher on binding energy graph
- Then:
  $^2H + {}^3H \rightarrow {}^4He + n + 17.6$ MeV (leads to 81 MCal/g)

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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!!!

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Tritium nowhere

- Tritium is unstable, with half-life of 12.32 years
  - thus none naturally available
- Can make it by bombarding ^6Li 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

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Nasty by-products?

- Far less than radioactive fission products
- Building stable nuclei (like ^4He)
  - maybe our voices would be higher…
- Tritium is only radioactive substance
  - energy is low, half-life short: not much worry here
- Main concern is extra neutrons tagging onto local metal nuclei (in surrounding structure) and become radioactive
  - smaller effect than fission, still problematic
  - key worry is structural degradation of containment

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Why don't we embrace fusion, then?

- Believe me, we *would* if we *could*
- It's a huge technological challenge, seemingly always 50 years from fruition
  - must confine plasma at 50 million degrees!!!
    - 100 million degrees for D-D reaction
  - all the while providing fuel flow, heat extraction, tritium supply, etc.
  - hurdles in plasma dynamics: turbulence, etc.
- Still pursued, but with decreased enthusiasm, increased skepticism
  - but man, the payoff is huge: clean, unlimited energy

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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
- 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

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ITER

- An international collaboration is building a Tokamak in France with the following goals
  - First plasma 2020
  - Maintain a fusion pulse for 480 seconds
  - Start D-T fusion in 2027
- Tens of billions of dollars; no resulting power plant
  - experimental to try to work out numerous kinks
- Would appear to be an expensive, exceedingly complex way to make electricity
  - got lots of ways to do that
  - not without safety/radioactivity issues

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References and Assignments

- Extra Credit on TED: adds 2% to final grade
  - enough to cross grade boundary!
- More on Three Mile Island:
  - www.nrc.gov/reading-rm/doc-collections/fact-sheets/
- More on Chernobyl:
  - http://en.wikipedia.org/wiki/Chernobyl_disaster
  - also NRC link as above
- Optional reading at Do the Math:
  - 29. Nuclear Options
  - 33. Nuclear Fusion
- HW #6 due 5/24; HW #7 (short) due 5/31
- Quiz by Friday midnight

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