Introduction
- No new nuclear power plants in the US since 1978, but recent surge in applications.
- Those concerned with greenhouse producing coal power plants note that nuclear plants do not emit greenhouse gases.
- Nuclear plants can operate during night and without wind, unlike wind and solar power.
- Is nuclear power the answer to our energy problems? If not nuclear then what?
- People fear nuclear bombs yet accept nuclear medicine.

Outline
1. Nuclear Fission
   1. Bombs
   2. Power plants
2. Nuclear Fusion
   1. Bombs
   2. Power
3. Natural Radioactive Decay
   1. Medical applications
   2. Medical imaging

7.2 Nuclear Fission
- When large atoms split into smaller atoms and release energy. \( E = mc^2 \) by Einstein true.
- Discovered in Germany 1938 by bombarding U with neutrons. (Hahn and Strassmann)
- This happens naturally or can be induced.
- Uranium-235 and Plutonium-239 can do this
  \[
  ^{235}_{92}U + ^{1}_{0}n \rightarrow ^{92}_{36}Kr + ^{141}_{56}Ba + 3 ^{1}_{0}n
  \]
- This reaction produces 3 neutrons which can go and start 3 more reactions which will make 9 neutrons, etc...
- So this is a chain reaction. It can continue to increase until it explodes IF there is critical mass.

Uranium
- U has _____ protons and _____ electrons.
- U comes in two isotopes
  - Uranium-238 is most abundant
  - Uranium-235 is least abundant
  - How many neutrons are in these?
- Write the atomic notation for these isotopes
  \[
  ^{238}_{92}U \quad \text{and} \quad ^{235}_{92}U
  \]
Uses of Fission

- Purposefully have critical mass (33 pounds) so there is an explosion = nuclear bomb (need 90% U-235 or weapons grade)
- Purposefully don’t have critical mass and get power from the reaction = power plant (need 3% U-235)
- Natural U is 0.7% U-235

Fission Bomb

- Aka Atomic Bomb
- Equivalent to 20,000 tons of TNT
- Used in WWII by USA
  - Aug 6, 1945 “Little Boy” dropped on Hiroshima (Uranium bomb)
  - Aug 9, 1945 “Fat Man” dropped on Nagasaki (Plutonium bomb)
- > 2000 test detonations total thus far
- Countries with bombs: US, UK, Russia, North Korea, China, India, France, Pakistan, Israel?

Nagasaki Bomb
Fat Man (11 miles high)

Fat Man – 11,000 lbs.

Little Boy – 9700 lbs., 10 ft long

How Fission Bombs Work

1. Gun type
2. Implosion

http://www.howstuffworks.com/nuclear-bomb.htm
**Fission Bomb Facts**
- Need enriched Uranium fuel, natural U is about 0.7% U-235
- U-235 is the atom that is used, not U-238
- Fuel kept in sub critical masses that are kept separate until time to explode
- Neutrons from a “generator” start the fission reaction, separated from the U fuel by foil
- Energy created is about 10 kilotons of TNT

**Test “Priscilla” June 24, 1957 near Las Vegas. 2 x energy of Little Boy!**

**7.1 Fission Power**
Controlled fission reaction without critical mass

**Nuclear Energy**
- 1 gram of U-235 has same energy as 12 million grams of gasoline
- So less transportation costs of fuel to power plant, less trucks, less gasoline, less pollution
- Exhausted fuel rods stored temporarily in underwater ponds or vaults, then stored in concrete casks
- Does not cause global warming unlike coal

**Worldwide Nuclear Power Reactors**
- First one in USSR 1954
- There are 440 nuclear power reactors in 31 countries.
- 30 more are under construction in China, Russia, India, South Korea.
- However Germany and Switzerland are phasing out nuclear power
- It is France’s primary energy source
- They account for 15% of the world’s electricity. (coal is 40%, gas is 20%)
World Nuclear Power Plants

<table>
<thead>
<tr>
<th>Region</th>
<th>Nuclear Electricity Production (Gigawatts)</th>
<th>Percent of Electricity</th>
</tr>
</thead>
<tbody>
<tr>
<td>US</td>
<td>97 GW</td>
<td></td>
</tr>
<tr>
<td>North America Region</td>
<td>109 GW</td>
<td></td>
</tr>
<tr>
<td>France</td>
<td>63 GW</td>
<td>Increasing</td>
</tr>
<tr>
<td>Germany</td>
<td>21.0</td>
<td>Being phased out</td>
</tr>
<tr>
<td>U.K.</td>
<td>12.0</td>
<td></td>
</tr>
<tr>
<td>Western Europe Region</td>
<td>126.0</td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>44.0</td>
<td>Increasing (India, China)</td>
</tr>
<tr>
<td>Asia Region</td>
<td>66.0</td>
<td></td>
</tr>
<tr>
<td>Eastern Europe Region</td>
<td>11.0</td>
<td></td>
</tr>
<tr>
<td>Former Soviet U. Region</td>
<td>34.0</td>
<td></td>
</tr>
</tbody>
</table>

Nuclear growth

- India had 17 reactors in 2009, is planning for 36 more plants.
- China had 11 reactors in 2009 with 17 under construction and plans for 110 more.

7.3 How a Nuclear Reactor works

- $^{235}\text{U}$ fissions by a controlled chain reaction
- $^{235}\text{U}$ is enriched from its 0.7% in nature to about 3%, and is contained in Uranium rods
- Boron control rods are inserted to absorb neutrons to slow the fission reaction if needed
- Water is boiled by the heat of the fission and turned to high pressure steam. The steam then turns the turbines that rotate within a magnetic field which generates electricity.

Inside a Nuclear Reactor

- Steam outlet
- Fuel Rods contain about 200 UO$_2$ pellets
- Boron control Rods which absorb neutrons

Typical Light Water Reactor
Coolant filled reactor core with red fuel rods and blue control rods. Moving the control rods controls the reaction rate and thus temperature.

Cold coolant pumps from the left side into the core, heats up, and leaves on the right. It enters the steam generator and heats up that water producing steam.

The steam then flows to the turbine.

The turbine turns, generates an electric field, and the steam cools down and is pumped back to the steam generator. The condenser water is sent to the cooling tower.

Production of Plutonium (Pu) in Nuclear Reactors

- $^{239}\text{Pu}$ is one of the products
- $^{239}\text{Pu}$ also fissions by absorbing a neutron, and can produce 1/3 of the energy.
- $^{239}\text{Pu}$ is relatively stable, with a half life of 24 thousand years.
- It is used in nuclear weapons – several countries reprocess spent fuel to obtain Pu for weapons
- It can be bred for use in other nuclear reactors
Liquid Metal Fast Breeder Reactor

- Uses neutrons from $^{235}\text{U}$ fission on surrounding $^{238}\text{U}$ to produce $^{239}\text{Pu}$
- In 10-20 years, enough Pu is produced to power another reactor
- No water coolant, must use liquid sodium coolant
- $U$ must be at 15%-30% enrichment to generate power with fast neutrons while breeding Pu
- This is close to weapons grade enrichment, however
- Super-Phenix in France operated for 20 years
- Extends the usefulness of mined U by 60 times
- Currently renewed interest in this type of reactor

Heavy Water Reactor

- Canada Deuterium Uranium reactor
- Heavy water is $D_2O$, used as coolant
- Uranium ore needs no enrichment (good) and can be used as mined
- Used in Canada, called CANDU reactors. 6 other countries have them as well.
- Overall CANDU reactors use 30–40% less mined uranium than light-water reactors per unit of electricity produced. This is a major advantage; it not only requires less fuel, but as the fuel does not have to be enriched, it is much less expensive as well.

Nuclear Weapons to Reactor Fuel

- We are buying highly enriched uranium (20% $^{235}\text{U}$) from the former Soviet Union’s nuclear weapons for 20 years from 1993–2013
- Converting it to low enriched uranium (3% $^{235}\text{U}$) for reactor fuel
- It will satisfy 9 years of US reactor fuel demand
- It comes from 6,855 Soviet nuclear warheads so far

7.7 How to enrich U

- Turn U ore into UF$_6$. $^{235}$UF$_6$ travels faster than $^{238}$UF$_6$. Separated by large gas centrifuges. The U-238 is called DU for depleted uranium.
- Nuclear Non-Proliferation Treaty of 1968 gives some countries the right to enrich U
  - Iran restarted up in 2005 despite protests
  - Nuclear weapons states = US, UK, Russia, China, France
  - North Korea withdrew in 2003
  - Non signers = India and Pakistan

7.5 Nuclear Plant Future

- The countries of the world are each planning their own course of nuclear plant development or decline
- Nuclear power is competitive with natural gas
- It is non-polluting
- It does not contribute to global warming
- Obtaining the fuel only takes 5% of the energy output
- Newer designs are much better
- Waste disposal still an issue being studied

Nuclear Problems

- Three Mile Island  March 1979
  - A stuck valve with no indicator released water, but containment vessel held
  - Small amount of radioactivity leaked
  - More sensors added, better communication to experts in Washington, don’t turn off emergency cooling liquid
  - 2002 study reported that cancer in the area was no different than the rest of the nation
  - Good US safety record since incident
  - Unlike Chernobyl, reinforced concrete dome must surround all US plants
Chernobyl, Ukraine April 1986
- Human stupidity turned off cooling system during a safety test
- Poor steam cooling reactor design allowed unstable steam pocket to explode chemically, not nuclear
- Boron rods got stuck
- Meltdown occurred, fire broke out, lasted 10 days
- Radioactive material blown out into the air
- Design not used in other countries
- 56 deaths from 1986 to 2006
- Thyroid cancer increased sharply, survival rate high
- 1000 square miles near site still not farmed

Fukushima, March 2011
- Followed a 9.0 earthquake and tsunami
- 6 light water reactors (4-6 not online)
- Reactors 1-3 automatically shut down after quake
- Fallowing tsunami wave flooded plant
- Power to the cooling system failed, reactors started to overheat
- Reactors 1, 2 and 3 experienced full meltdown. Heat destroyed the upper cladding of the buildings housing Reactors 1, 3, and 4; an explosion damaged the containment of reactor 2; multiple fires broke out at Reactor 4.
- Used fuel rod ponds overheated and water levels dropped

7.9 Nuclear Waste
- Biggest problem with nuclear power
- Waste contains Pu that could be used in a weapon
- Spent nuclear fuel (SNF) is the fuel rods after being used in the reactor
  - Mostly U-238, leftover U-235, fission products, Pu-239
  - At each US reactor 33% of fuel rods replaced per year, they are transferred to pools of water for a year, then dried and put in casks
  - Most waste is stored on site in casks in concrete vaults which were supposed to be temporary storage
  - US doesn’t reprocess their waste fuel the way France, Germany and Japan do

Fukushima, March 2011
- 5th largest quake recorded
- 12 million without power
- Generated 10 m tsunami
- Hundreds caught in landslide near Sendai (1 million population)
- 2nd worst nuclear power accident (Chernobyl was much worse)

Yucca Mountain Project: Nuclear Fuel and High Level Waste Repository
- More secure than leaving waste at reactor sites around the country
- On old atomic bomb testing base, inside a mountain
- The storage is above the water table
- The Yucca Mountain site would be 60% filled by present waste
- Site has been studied by scientists for over 20 years
- Will store waste during its 10,000 year decay time
- Questions of radioactive decay weakening storage containers
- A solution would be to build containers that can be opened and reincased, or to which surrounded casings could be added
- As of 2010 seems that Yucca project is dead
7.10 Benefits of Nuclear Power
- No coal miners dying unlike coal
- No greenhouse gas production unlike coal
- No NO\textsubscript{x} or SO\textsubscript{y} or pollutants unlike coal
- No coal ash produced unlike coal
- No mercury produced unlike coal
- No Thorium released unlike coal
- Less transportation costs

7.11 Nuclear Power Future?
- If 50 years from now the world uses twice as much energy, and half comes from nuclear power
- Need 4,000 nuclear reactors, using about a million tons of Uranium a year
- With higher cost ore, would last for 300 years
- Breeder reactors creating Plutonium could extend the supply to 200,000 years
- Nonpolluting, non-CO\textsubscript{2} producing source
- While nuclear reactors have to be on all day and night, and power use is less at night, they could be used to charge up electric cars.

Risks of Nuclear Power
- U mine worker safety
- Nuclear waste
- U mine tailings, these rock tailing contain U and thus emit Radon
- Meltdown error

Nuclear Fusion

What is Fusion?
- When two small atoms combine into a large single atom releasing energy
- Stars are basically fusion reactors
  - \( ^1_1H + ^1_1H \rightarrow ^2_2H + ^0_1e + E \)
  - \( ^2_1H + ^1_1H \rightarrow ^2_2He + E \)
- Harder to initiate reaction than fission (need extreme heat), produces more energy than fission, and produces very little radioactive waste
Fusion Uses

- Uncontrolled reaction for explosion (bomb)
- Controlled reaction for Power

Fusion Bomb Facts

- Aka H-bombs or thermonuclear warheads
- The fuel must be highly compressed and at high temperatures for fusion to begin
- A fission reaction (Pu-239) actually initiates the bomb by making tritium for the fusion and producing the needed high temps
- Lithium deuteride, main fuel, stable at low temp
- Deuterium-tritium fusion occurs once hot enough
- 700 times more powerful than Little Boy = 14 million tons of TNT equivalent

H Bomb

- Teller-Ulam design 1951
- Primary section is fission bomb, the trigger
- Secondary section compressed by primary explosion and it heats up starting the fusion

Mushroom cloud from the Soviet 50-megaton Tsar Bomba, the largest weapon ever detonated (1961)

Fusion Power

- Would be awesome
  - Plenty of Hydrogen for fuel
  - Releases helium
  - No pollution, little radioactivity
- To date, continuous fusion has not been achieved
- A fusion reactor is a “magnetic bottle” that contains small atoms heated to 10 million degrees Celsius by a laser.

7.4 Radioactivity

- Discovered by Becquerel in 1896 then studied by Marie Curie (won 2 Nobel prizes)
- Rutherford named alpha and beta radiation
  - Alpha is 2 protons + 2 neutrons thus a Helium nucleus, \( {}^4_2 \alpha \) (+2 charge)
  - Beta is a high speed electron \( {}^0_-1 \beta \) (-1 charge)
- Gamma rays are no charge no mass rays \( {}^0_0 \gamma \)
- Electromagnetic radiation is all types of light
- Nuclear radiation is emitted by the nucleus of an atom such as \( \alpha, \beta, \) and \( \gamma \) radiation.
Natural Radioactive Decay

- The emission of particles by unstable atoms, the atom changes its identity
- Many different atoms do this naturally and exist all around us
- We can use these atoms for medical purposes and other purposes
- (Decay reactions are aka emission reactions)

Alpha Decay

- $^{235}_{92}\text{U} \rightarrow 4\alpha + ^{231}_{90}\text{Th}$
- Alpha particle = He nucleus (2 pro + 2 neu)
- Alpha emitters = $^{226}_{88}\text{Ra}$, $^{222}_{86}\text{Rn}$, $^{210}_{84}\text{Po}$, $^{238}_{92}\text{Pu}$
- Can be stopped by skin, but very dangerous internally
- Note to balance the top numbers and bottom numbers must add up
- Americium-241 used in smoke detectors
- All elements above Bismuth are radioactive

Beta Decay

- $^{228}_{88}\text{Ra} \rightarrow 0\beta + ^{228}_{89}\text{Ac}$
- Beta particle = high E electron
- Beta emitters = $^{228}_{88}\text{Ra}$, $^{99}_{43}\text{Tc}$, $^{14}_{6}\text{C}$,
- Can be stopped by 30 cm of wood, Al foil
- Application is C-14 dating

Gamma Ray Decay

- $^{220}_{90}\text{Th} \rightarrow 0\gamma + ^{220}_{80}\text{Th}$
- Gamma ray = high E wave, or photon stream
- Gamma emitters = $^{233}_{91}\text{U}$, $^{222}\text{Rn}$, $^{60}_{27}\text{Co}$, $^{192}_{77}\text{Ir}$, $^{241}_{95}\text{Am}$
- Can be stopped by 10 cm of lead, 30 cm of concrete
- Often occurs with alpha or beta decay
- Uses include irradiation to sterilize medical equipment, killing bacteria on foods, cancer treatment

Positron Emission

- $^{22}_{11}\text{Na} \rightarrow 0\beta + ^{22}_{10}\text{Ne}$
- Positron particle = positive electron
- Positron emitters = $^{22}_{11}\text{Na}$, $^{30}_{16}\text{P}$, $^{11}_{5}\text{C}$, $^{40}_{19}\text{K}$, $^{13}_{6}\text{N}$, $^{13}_{7}\text{O}$, $^{18}_{8}\text{F}$, $^{121}_{50}\text{I}$
- These atoms may also undergo electron capture
- One use is PET scans
Writing reactions

- Alpha decay of Po-210
- Beta decay of C-14
- Gamma decay of Co-60

7.8 Half Life

- Half life, $t_{1/2}$ – time it takes for $\frac{1}{2}$ to react and turn into product (daughter)
  - U-238 is 4.5 billion years
  - I-131 is 8.04 days
  - Pu-231 is 8.5 minutes
  - C-14 is 5715 years and is used to date bones
- If you have 100 grams of Pu-231, how much remains after 34 minutes?

7.6 Radioactivity and You

- Ionizing radiation ($\alpha$, $\beta$, $\gamma$, X rays) has energy high enough to ionize molecules they hit which can kill cells.
- So this radiation can be used to kill certain cancer cells.
- Side effects = radiation sickness
- We protect ourselves from ionizing radiation with lead shields

Natural exposure

- 82% is natural
  - Radon is 55%, gas produced from U decay, very dense, accumulates in basements
  - U in rocks and soil is about 8%
  - Cosmic rays is about 8%
  - You have some radioactive atoms in your body 11% like K-40 and C-14 atoms
- 18% is human made
  - X rays is 11%
  - 4% is nuclear medicine
  - 3% is consumer products
  - Nuclear power plants is less than 0.1%

Measurements

- 1 curie = $3.7 \times 10^{10}$ particles / second
  - This is large so often use milli and micro curies
- A rad measures absorption of 0.01 J per kg
- A rem (roentgen equivalent man”) measures damage to human tissue
- A sievert (Sv) is 100 rems
- Single Radiation dose effects
  - 0-25 rems nothing
  - 25-50 rems lower white blood cell count
  - 50-100 rems large drop in white blood cell count
  - 100-200 rems nausea, vomiting, hair loss
  - 200-500 rems ulcers, hemorrhaging
  - 500+ death

Nuclear Medicine

- I-131 tablet measures thyroid gland activity
- Inhaled Xe-133 diagnose respiratory problems (healthy lung tissue uptakes Xe)
- Iron-59 diagnose anemia
- Tc-99 diagnose brain tumors
- Co-60 radiation destroys cancer cells
- Injected Ir-192 bead destroys breast cancer tissue
- Pu-238 powers pacemakers
Medical Imaging

- X rays
- Mammograms
- CT
- Fluoroscopy
- PET
- Ultrasound
- MRI

X Rays

- Aka projectional radiographs
- Uses ionizing radiation that is energetic enough to move electrons from atoms
- Ionizing radiation has sufficient energy to penetrate human tissue
- Commonly used to examine bones, fractures, chest, abdomen and teeth
- About 50% of radiation exposure is medical imaging for the average human

How X rays work

- Beam goes through patient, some radiation is absorbed (attenuation).
- Denser tissue absorbs more, so less passes through. (Bone absorbs more than organs)
- The more radiation that passes through = darker. So bones appear white on the image. Lungs which are mostly air appear black.

Mammograms

- Uses low energy X rays
- Lower energy than bone X rays
- Used to detect breast cancer
- New digital mammography uses less radiation

Left = normal, Right = cancer
**CAT or CT scans**

- Computer (axial) tomography
- Used for soft tissue examination
- Uses X rays at higher dose than plain X rays
- Used to scan head, lungs, heart, colon
- Abdominal CT = same radiation as 300 X rays
- Some estimate that 0.4% of cancers in the US are due to CT scans


**Fluoroscopy**

- Uses low doses of constant X rays
- Used for catheter or needle guidance, discography, orthopedic surgery guidance, placing metal implants
- Used for real-time images
- Patient placed between X ray source and camera which records image that plays on a monitor

**PET**

*Normal brain* *Alzheimer’s brain*
PET

- Positron emission tomography
- A positron emitter is injected usually into blood
- Wait while it concentrates in tissue of interest then scan
- The positron annihilates a nearby electron which produces gamma rays which are detected
- C-11, N-13, O-15, F-18 commonly used
- Often used for brain scans

Ultrasound

- High frequency sound waves transmitted to area of interest and the returning echoes recorded
- Most common application is use in sonography to produce image of fetus in womb
- Also used to visualize muscles, tendons and organs (heart, liver, gallbladder)
- Inexpensive and portable
- Does not use ionizing radiation
- Because it is real time scan, often used to guide needles for biopsies

MRI

- Magnetic resonance imaging
- Uses strong magnetic fields and radio waves
- Provides detailed images of the body's internal structures
MRI

- Magnetic resonance imaging
- Used for soft tissue images
- Uses powerful magnets and radio waves to excite H atoms in water to spin a certain way that is detectable and converted to images.
- Does NOT use ionizing radiation
- More H = white, so fat is white, hydrated discs are white, degenerated discs are black