Chapter 12
Nuclear Energy
I. Introduction to Nuclear Energy

- A. Nuclear Energy - the energy released by nuclear fission or fusion
  - Albert Einstein – $E=mc^2$ – suggested that nuclear reactions had the potential to release a vast amount of heat
  - Henri Becquerel – 1896 discovered that uranium-containing minerals spontaneously and continually give off invisible rays of energy called radiation
  - Marie Curie (right) – discovered that radiation came from inside the atoms
  - Ernest Rutherford – radiation consists of high energy particles
• B. Nuclear energy
  – Energy released by nuclear fission or fusion

• C. Nuclear fission
  – Splitting of an atomic nucleus into two smaller fragments, accompanied by the release of a large amount of energy – used by nuclear power plants – used to make nuclear bombs

• D. Nuclear fusion
  – Joining of two lightweight atomic nuclei into a single, heavier nucleus, accompanied by the release of a large amount of energy – used by the sun and stars
II. Atoms and Radioactivity

• A. Nucleus
  – Comprised of protons (+) and neutrons (neutral)
• B. Electrons (−) orbit around nucleus
• C. Neutral atoms
  – Same # of protons and electrons
• D. Atomic mass
  – Sum of the protons and neutrons in an atom

• E. Atomic number
  – Number of protons per atom
  – Each element has its own atomic number

• F. Isotope
  – Atom where the number of neutrons is greater than the number of protons
• F. Radioactive Isotope
  – 1. Unstable isotope
  – 2. Radioactive Decay
    • Emission of energetic particles or rays from unstable atomic nuclei
  – 3. Example
    • Uranium (U-235) decays over time to lead (Pb-207)
  – 4. Each isotope decays based on its own half-life
Radioactive Isotope Half-lives

Table 12.1 Some Common Radioactive Isotopes Associated with the Fission of Uranium

<table>
<thead>
<tr>
<th>Radioisotope</th>
<th>Half-Life (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iodine-131</td>
<td>0.02 (8.1 days)</td>
</tr>
<tr>
<td>Xenon-133</td>
<td>0.04 (15.3) days</td>
</tr>
<tr>
<td>Cerium-144</td>
<td>0.80</td>
</tr>
<tr>
<td>Ruthenium-106</td>
<td>1.00</td>
</tr>
<tr>
<td>Krypton-85</td>
<td>10.40</td>
</tr>
<tr>
<td>Tritium</td>
<td>12.30</td>
</tr>
<tr>
<td>Strontium-90</td>
<td>28.00</td>
</tr>
<tr>
<td>Cesium-137</td>
<td>30.00</td>
</tr>
<tr>
<td>Radium-226</td>
<td>1,600.00</td>
</tr>
<tr>
<td>Plutonium-240</td>
<td>6,600.00</td>
</tr>
<tr>
<td>Plutonium-239</td>
<td>24,400.00</td>
</tr>
<tr>
<td>Neptunium-237</td>
<td>2,130,000.00</td>
</tr>
</tbody>
</table>
III. Nuclear Fission

• A. Nuclear Fuel Cycle
  – processes involved in producing the fuel used in nuclear reactors and in disposing of radioactive (nuclear) wastes
Nuclear Fission
How Electricity is Produced

- Containment building
- Control rod
- Uranium fuel assembly
- Reactor vessel
- Reactor core
- Liquid water under high pressure carries heat to steam generator
- Steam turbine
- Steam generator
- Heat exchanger
- Condenser
- Electric generator
- Lake or cooling tower
- Electricity
• B. Basic parts of the nuclear power plants
  water reactors
  – 1. reactor core – where fission occurs
  – 2. steam generator – heat produced by nuclear
    fission is used to produce steam from liquid water
  – 3. turbine – uses the steam to generate electricity
  – 4. condenser – cools the steam and converts it
    back to a liquid
• C. Details of the nuclear fission process
  – 1. the reactor core contains the fuel assemblies
  – 2. above each fuel assembly is a control rod made of a special metal alloy that absorbs neutrons
  – 3. the plant operator signals the control rod to move either up out of or down into the fuel assembly – if the rod is out of the assembly, then free neutrons collide with uranium atoms in the fuel rods
4. Three water circuits

- a. primary water circuit – heats water, using the energy produced by the fission reaction – this is a closed system that circulates water under high pressure through the reactor core – because of the intense pressure this water cannot expand to become steam so it remains in the liquid state

- b. secondary water circuit – water is held here and heated from the water from the primary water circuit – the water in the secondary water circuit is converted to steam which turns the turbine which spins a generator to produce electricity – water then goes to a condenser where it becomes a liquid again

- c. tertiary water circuit – provides cool water to the condenser which cools the steam from the secondary water circuit – the water from the tertiary water unit must move to a lake or cooling tower where it is cooled before returning to the condenser
– 5. reactor vessel – huge steal reactor vessel surrounds the reactor core where fission occurs – a safety feature designed to prevent the accidental release of radiation into the environment

– 6. containment building – holds the reactor vessel and the steam generator – steel reinforced concrete walls about 1 to 1.5 m thick and are build to withstand severe earthquakes and the high winds of hurricanes and tornadoes – additional line of defense against accidental radiation leaks
IV. Breeder Nuclear Fission

• A. A type of nuclear fission in which non-fissile U-238 is converted into fissile Pu-239 – can generate larger quantities of energy from uranium ore than nuclear fission using U-235 – has potential to supply the country with electricity for several centuries

• B. Problems –
  • 1. use liquid sodium instead of water as a coolant – sodium is highly reactive that will explode when mixed with water and burns spontaneously in air – could rip open a containment building
  • 2. easier to process into a weapons-grade material
Breeder Nuclear Fission

1. Neutron
2. Plutonium 238
3. Neutron
4. Plutonium 239
5. Neutron

Breeder reaction

ENERGY

Uranium 238

Atomic fragment
V. MOX – mixed oxide fuel reactors

• A. MOX reactors – common in Europe – spent fuel from standard uranium-based reactors is reprocessed, and the extracted plutonium and U-235 are used as fuel
VI. Pros and Cons of Nuclear Energy

• A. Pros
  – Less of an immediate environmental impact compared to fossil fuels
  – Carbon-free source of electricity
  – May be able to generate H-fuel

• B. Cons
  – Generates radioactive waste
  – Many steps require fossil fuels (mining and disposal)
  – Expensive
## Pros and Cons of Nuclear Energy

### Table 12.2 Comparison of Environmental Impacts of 1000-MW Coal and Nuclear Power Plants*

<table>
<thead>
<tr>
<th>Impact</th>
<th>Coal</th>
<th>Nuclear (Conventional Fission)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land use</td>
<td>17,000 acres</td>
<td>1900 acres</td>
</tr>
<tr>
<td>Daily fuel requirement</td>
<td>9000 tons/day</td>
<td>3 kg/day</td>
</tr>
<tr>
<td>Availability of fuel, based on</td>
<td>A few hundred years</td>
<td>100 years, maybe longer (much</td>
</tr>
<tr>
<td>present economics</td>
<td></td>
<td>longer with breeder fission)</td>
</tr>
<tr>
<td>Air pollution</td>
<td>Moderate to severe, depending</td>
<td>Low**</td>
</tr>
<tr>
<td></td>
<td>on pollution controls</td>
<td></td>
</tr>
<tr>
<td>Climate change risk (carbon</td>
<td>Severe</td>
<td>Relatively small**</td>
</tr>
<tr>
<td>dioxide emissions)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radioactive emissions, routine</td>
<td>1 curie</td>
<td>28,000 curies</td>
</tr>
<tr>
<td>Water pollution</td>
<td>Often severe at mines</td>
<td>Potentially severe at nuclear</td>
</tr>
<tr>
<td></td>
<td></td>
<td>waste disposal sites</td>
</tr>
<tr>
<td>Risk from catastrophic accidents</td>
<td>Short-term local risk</td>
<td>Long-term risk over large areas</td>
</tr>
<tr>
<td>Link to nuclear weapons</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Annual occupational deaths</td>
<td>0.5 to 5</td>
<td>0.1 to 1</td>
</tr>
<tr>
<td>Certainty about risks</td>
<td>Well known</td>
<td>Highly uncertain</td>
</tr>
</tbody>
</table>

*Impacts include extraction, processing, transportation, and conversion. Assumes coal is strip-mined. (A 1000-MW utility, as a 60% load factor, produces enough electricity for a city of 1 million people.)

**While nuclear electricity generation does not generate air pollution and carbon dioxide directly, many of the steps (mining, construction, and waste disposal, for example) require fossil fuels.
VII. Cost of Electricity from Nuclear Energy

• A. Cost is very high
• B. 20% of US electricity is from Nuclear Energy
  – Affordable due to government subsidies
• C. Expensive to build nuclear power plants
  – Long cost-recovery time
• D. Fixing technical and safety issues in existing plants is expensive
VIII. Safety Issues in Nuclear Power Plants

A. Meltdown
   - At high temperatures the metal encasing the uranium fuel can melt, releasing radiation

B. Probability of meltdown is low

C. Public perception is that nuclear power is not safe

D. Sites of major accidents:
   - Three Mile Island
   - Chernobyl (Ukraine)
E. Three-Mile Island

• 1. 1979 - most serious reactor accident in US
• 2. 50% meltdown of reactor core
  – Containment building kept radiation from escaping
  – No substantial environmental damage
  – No human casualties
• 3. Elevated public apprehension of nuclear energy
  – Led to cancellation of many new plants in US
F. Chernobyl

• 1. 1986 - worst accident in history
• 2. 1 or 2 explosions destroyed the nuclear reactor
  – Large amounts of radiation escaped into atmosphere
• 3. Spread across large portions of Europe
• 4. Radiation spread was unpredictable and uneven
• 5. Death toll was around 10,000 but might be higher
G. Fukushima Disaster

1. Following a major earthquake, a 15-metre tsunami disabled the power supply and cooling of three Fukushima Daiichi reactors, causing a nuclear accident on March 11, 2011.

2. All three cores largely melted in the first three days.

3. The accident was rated 7 on the INES scale, due to high radioactive releases in the first few days.

4. After two weeks the three reactors (units 1-3) were stable with water addition but no proper heat sink for removal of decay heat from fuel. By July they were being cooled with recycled water from the new treatment plant. Reactor temperatures had fallen to below 80ºC at the end of October, and official 'cold shutdown condition' was announced in mid December.

5. Apart from cooling, the basic ongoing task was to prevent release of radioactive materials, particularly in contaminated water leaked from the three units.

6. There have been no deaths or cases of radiation sickness from the nuclear accident, but over 100,000 people had to be evacuated from their homes to ensure this.
IX. Nuclear Energy and Nuclear Weapons

- A. 31 countries use nuclear energy to create electricity
- B. These countries have access to spent fuel needed to make nuclear weapons
- C. Safe storage and handling of these weapons is a concern
X. Radioactive Wastes

• A. Low-level radioactive waste
  – Radioactive solids, liquids, or gases that give off small amounts of ionizing radiation

• B. High-level radioactive waste
  – Radioactive solids, liquids, or gases that give off large amounts of ionizing radiation
• C. Long term solution to waste
  – Deep geologic burial – Yucca Mountain
  – As of 2004, site must meet EPA million year standard (compared to previous 10,000 year standard)
  – Possibilities:
    • Above ground mausoleums
    • Arctic ice sheets
    • Beneath ocean floor
• D. Temporary storage solutions
  – In nuclear plant facility (require high security)
    • Under water storage
    • Above ground concrete and steel casks
• E. Need approved permanent options soon.
F. Case-In-Point Yucca Mountain

- 70,000 tons of high-level radioactive waste
- Tectonic issues have been identified
XI. Decommissioning Nuclear Power Plants

• A. Licensed to operate for 40 years
  – Several have received 20-year extensions

• B. Power plants cannot be abandoned when they are shut down

• C. Three solutions
  – Storage
  – Entombment
  – Decommissioning (dismantling)
XII. Attitudes Towards Nuclear Power

• A. NIMBY - Not In My BackYard
  – Citizens do not want a nuclear facility or waste disposal site near their home

• B. Dad- Decide, Announce, Defend
  – Pronuclear advocates
  – Based on the science, not fears
XIII. Fusion

- A. Fuel = isotopes of hydrogen

Deuterium → Helium-4
Tritium → Free neutron

ENERGY
• B. Way of the future?
  – Produces no high-level waste
  – Fuel is hydrogen

• C. Problems
  – It takes very high temperatures (millions of degrees) to make atoms fuse
  – Confining the plasma after it is formed

• D. Scientists have yet to be able to create energy from fusion