Nuclear Energy 4

Nuclear Reactors
Promise of nuclear energy

- No $\text{CO}_2$ emissions
- No oil imports
- Plutonium “resource” huge
Getting Uranium

Uranium Ore

Yellowcake is a mixture of Uranium Oxides obtained from ore
World Production of Uranium
World Production of Uranium

- Canada: 28%
- Australia: 23%
- Kazakhstan: 11%
- Russia: 8%
- Namibia: 8%
- Nigeria: 7%
- Uzbekistan: 6%
- US: 3%
**Enriching Uranium**

- U-235 and U-238 are chemically the same.
- U-235 and U-238 have slight different masses.
- All enrichment processes use the mass difference to separate the two isotopes.
Enriching Uranium 2

- Gas centrifuges are the method of choice today
- Other methods available in particular gaseous diffusion (US)
- All methods use repeated processing to enrich

Gas Centrifuges
**Military/Scientific Use**

Depleted Uranium Slug

Atlas detector at CERN
Commercial Uses

Fiesta Ware

Uranium Glass or Vaseline Glass
The First Nuclear Pile: CP-1

University of Chicago
December 2nd, 1942
Chicago Pile 1

- Built by Enrico Fermi in a space for squash courts under Alonzo Stagg Field stadium
- Fuel: Uranium pellets
- Moderator: Graphite
- Control rods: Cadmium
Nuclear Reactors

Generic lay-out

- Heat Engine!
- Fuel source
- Heat generation
- Steam cycle
- Electricity from turbogenerator
Issue of Criticality

- Reactors work by chain reactions very close to $k=1$: no exponential growth. This is not stable; must be managed.
- Moderators increase the probability of neutron capture by slowing down neutrons. Moderators increase $k$.
- Control rods are made from materials that absorb neutrons; they decrease $k$.
- Coolants carry off the generated heat.
Nuclear Reactors in the US

Pressurized Water Reactor (PWR)
radioactive coolant water separate from steam circuit
higher pressure more effective heat transport
and less radioactive contamination
More on nuclear reactors in the US

Boiling Water Reactor (BWR): coolant also turned into steam
Reactor vessels

Vessel for boiling water reactor

- ~ 40 ft high
- control rods
- fuel rods
- water inlet / outlet
PWR Vessel

- 40 ft high
- control rods
- fuel rods
- water inlet/outlet
Nuclear Reactors Fuel Rods: Uranium

- Fuel Rods of UO₂ enriched to 3% $^{235}$U for PWR
  2.2% $^{235}$U for BWR
- 100-200 tons of UO₂ inside cladding of alloy which picks up the heat from the fission processes
  UO₂ at 1100 °C but “Zirc洛y” at 340 °C
- Moderator water for both PWR and BWR
- Coolant water
- Control rods to shut down reactor
- Containment large pressure vessel (PWR)
  containment building (concrete)
**Chain reaction issue: need for moderator**

Fission probability depends strongly on neutron energy!

- **thermal neutron** (neutron at room temperature)
  - $0.026 \text{ eV}$ (or any slow neutron $\sim 10^{-2} \text{ eV}$) induces fission $\sim 1000$ times more likely than fast neutrons (energy of $\sim \text{MeV}$) which emerge from fission events

**Consequence:** moderators designed to turn fast $n$ into slow $n$

$\Rightarrow$ **Thermal Reactors** (thermal neutrons)
Chain reaction for Nuclear Reactors

Issue: Fission probability depends on the energy of the bombarding neutron!

**Neutron Cross-Sections for Fission of Uranium and Plutonium**

**Fission Probability** vs **Neutron Energy (MeV)**


1 barn = $10^{-24}$ m², 1 MeV = $1.6 \times 10^{-13}$ J
Moderator material:
- water (e.g. in the US)
- heavy water (Canada)
- graphite (Chernobyl, Hanford)

Lighter moderators are better at slowing down neutrons

Demonstration ...

Another consequence of fission probability:

Naturally occurring Uranium:
- 99.3 % $^{238}\text{U}$
- 0.7 % $^{235}\text{U}$

So enrichment is an important issue

Reactor fuel in the US has 2-3% $^{235}\text{U}$

Enrichment is a technically difficult and usually a “visible” process with potentially ominous consequences ⇒ proliferation

Link between Uranium enrichment and weapons proliferation
Iraq’s secret nuclear weapons program

UN mandated inspections as a cease-fire condition at the end of Gulf War in February 1991 revealed:

• A clandestine nuclear materials production and weapons design program of unexpected size and sophistication.
• Value of program $5-10 billion
• Involved 7000 scientists and 20 000 workers

Nuclear inspections carried out by the International Atomic Energy Agency (IAEA) ⇒ UN body charged with management of nuclear safeguards, including those of the Non-Proliferation Treaty (which Iraq had joined)

• EMIS project: ElectroMagnetic Isotope Separation (calutron enrichment method)
• By 1992 relevant sites had been dismantled !!!!!!!
• Iraq was 18-30 months away from enough material for a bomb
Coolants & Heat Transport

• Heat can be used in several ways (see later): mostly to heat water into steam which is then used to generate electricity as in a coal plant

• In the US water is used *both* as moderator and for this heat transport ⇒ important safety aspect:

  too much heat ⇒ reactor core melts

  with possible release of enormous amounts of lethal radioactivity

but: when water is gone it no longer acts as moderator and the chain reaction will stop!

not the case when graphite is used as moderator as at Chernobyl (and Hanford)
Chain reaction in a reactor

- Control of the chain reaction is required

- Time scale for increase/decrease of neutron flux made to depend on the 0.7% “delayed” neutrons from secondary radioactive decays (involves tens of seconds ⇒ safety issue)

- Control of the neutron density by insertion of control rods (cadmium or boron) that absorb slow neutrons very efficiently

- Each fission event releases most of its 200 MeV in the form of kinetic energy of the large fragments. When these fragments are stopped in the fuel, heat is generated
History of nuclear reactors in US

1946 Atomic Energy Act establishes Atomic Energy Commission (AEC) with control of nuclear energy development

1951 Arco, Idaho first electricity from Experimental Breeder Reactor 1
More history

1952  Reactor at Chalk River (Canada) goes out of control
       ⇒ partial core meltdown
1954  updated Atomic Energy Act provides for private ownership with government supported R&D
1956  Pres. Eisenhower directs AEC to make 20,000 kg of $^{235}$U available for reactors in other countries
1957  AEC safety report (to relieve fears of accidents)
       LOCA in $10^5$ to $10^6$ per reactor per year
       3,400 fatalities & $7B$ damage
1957  Price-Anderson Act limits liability of nuclear reactor owners currently to $200M + 103 * $88M = $9.3B
1957  Shippingport, PA first commercial plant 60 MW$_e$
and more history...

1966  Fermi fast breeder (Detroit) has partial core meltdown
1973  Oil embargo furthers use of nuclear energy
1974  WASH-1400 “Rasmussen report”
       Core meltdown \(\Rightarrow 1\) in 20,000 per reactor year
       Catastrophe \(\Rightarrow 1\) in \(10^9\) /ry (with 3000 deaths)
1974  AEC \(\Rightarrow\) Nuclear Regulatory Commission (NRC)
1974  UCS suggest that Emergency Core Cooling Systems
       may not work
1975  APS report also critical & points out risk of terrorism
1976  61 plants in the US produce 8.3% of electricity
1979  Rasmussen report retracted
Why Plutonium?

- Uranium resources needed to fuel nuclear reactors are limited
- Lifetime reactors about 30 years
- A reactor then has used about 5000 tons of $\text{U}_3\text{O}_8$
- 100 reactors require 500,000 tons
- how much uranium is there?
  - depends on the $\$ amount one wants to spend
  - unenriched available in US perhaps 2.5 million ton
  - at most 500 reactors total so limited supply
- Hence interest in fast breeder reactors
- Plutonium is used to make more fuel!
Special role of Plutonium

• Possible reactions in reactor (remember 98% of U is $^{238}\text{U}$!)

\[ n + ^{238}\text{U} \rightarrow ^{239}\text{U} \text{ decays radioactively} \]
\[ ^{239}\text{U} \rightarrow ^{239}\text{Np} \quad \text{also decays radioactively} \]
\[ ^{239}\text{Np} \rightarrow ^{239}\text{Pu} \quad \text{decays very slowly } T_{1/2} \text{ 24,000 years} \]

and is very **fissile** itself and contributes to the energy release in the reactor

• In addition: it is quite possible to remove this Plutonium chemically from the reactor fuel

\[ \Rightarrow \text{reprocessing (not possible for “old” reactor fuel)} \]

• **Inevitable link** between nuclear reactors and nuclear weapons proliferation
Fast Breeder Reactors

• Alternative reactor design
  no moderators $\Rightarrow$ use fast neutrons
  require 20% fissile material at start-up
  use $^{238}\text{U}$ as fuel to “breed” $^{239}\text{Pu}$

• US commercial reprocessing was stopped by president Carter
  to help discourage nuclear weapons proliferation

• France and Russia employ fast-breeder technology

• Japan is reconsidering but India is committed

• Concerns:
  questionable economics
  more heat so less safe
  heat transport liquid Na (very corrosive)
  Pu theft $\Rightarrow$ terrorism; dirty bombs ...

  nuclear weapons proliferation
Fuel Cycle

dashed arrows
not yet or no longer available in US
Where are reactors in the US?
# Reactor Types

<table>
<thead>
<tr>
<th>Reactor Type</th>
<th>Main countries</th>
<th>#</th>
<th>GW</th>
<th>Coolant</th>
<th>Moderator</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWR</td>
<td>US, France, Japan, Russia</td>
<td>260</td>
<td>243</td>
<td>water</td>
<td>water</td>
</tr>
<tr>
<td>BWR</td>
<td>US, Japan</td>
<td>92</td>
<td>83</td>
<td>water</td>
<td>water</td>
</tr>
<tr>
<td>PHWR Canada</td>
<td></td>
<td>34</td>
<td>18</td>
<td>heavy</td>
<td>heavy</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>water</td>
<td>water</td>
</tr>
<tr>
<td>Gas-cooled</td>
<td>UK</td>
<td>32</td>
<td>12</td>
<td>CO₂</td>
<td>graphite</td>
</tr>
<tr>
<td>RBMK</td>
<td>Russia, Ukraine</td>
<td>13</td>
<td>4</td>
<td>water</td>
<td>graphite</td>
</tr>
<tr>
<td>Fast reactors</td>
<td>Japan, France, Russia</td>
<td>4</td>
<td>1.3</td>
<td>liquid Na</td>
<td>none</td>
</tr>
<tr>
<td>Other</td>
<td>Russia, Japan</td>
<td>5</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td>440</td>
<td>371</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- PHWR  P heavy WR
- RBMK  light-water graphite reactor
World Capacity

[Graph showing World Electrical Generating Capacity from Nuclear Power Plants, 1950-93]
### Electricity production from reactors in 2001

<table>
<thead>
<tr>
<th>Country</th>
<th>%</th>
<th>#reactors</th>
<th>$M Watt_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>US</td>
<td>20</td>
<td>104</td>
<td>98,488</td>
</tr>
<tr>
<td>Belgium</td>
<td>58</td>
<td>7</td>
<td>5,728</td>
</tr>
<tr>
<td>France</td>
<td>77</td>
<td>59</td>
<td>63,203</td>
</tr>
<tr>
<td>Germany</td>
<td>31</td>
<td>19</td>
<td>21,141</td>
</tr>
<tr>
<td>Japan</td>
<td>34</td>
<td>54</td>
<td>44,301</td>
</tr>
<tr>
<td>Russia</td>
<td>15</td>
<td>30</td>
<td>20,793</td>
</tr>
<tr>
<td>S Korea</td>
<td>39</td>
<td>17</td>
<td>13,920</td>
</tr>
<tr>
<td>Ukraine</td>
<td>46</td>
<td>13</td>
<td>11,195</td>
</tr>
</tbody>
</table>

Source: IAEA a.o.