Everybody’s talking about nuclear energy but what exactly is it?

John Roberts
Dalton Nuclear Institute
The University of Manchester
Electricity

- Nuclear energy is used to produce electricity
  - ~15% UK,
  - ~20% USA
  - ~80% France
  - ~32% Switzerland
  - ~30% Japan
  - ~16% Russia
  - ~5% Mexico
  - ~2.5% Brazil
  - ~16% Worldwide
Electrical Generator

- Converts mechanical to electrical energy
- 86% of all worldwide electrical generation uses steam turbines
- Need a source of energy to convert water into steam
- Could be coal, oil, gas or nuclear fission
Uranium

- Nuclear Fission reactors use uranium as the fuel
- Use of U as an oxide dates back many years - used to colour glass
- Discovered as a metal in pitchblende in 1789
- Named after the planet discovered in 1781
- Radioactive properties discovered by Henri Becquerel in 1896
Nuclear Fission

- Discovered in 1938 by Hahn and Strassman
- Theoretically calculated by Meitner and Frisch
- Bombardment of uranium by neutrons causes the nucleus to split into two main fragments
- Mass decrease due to this reaction is appreciable
- Crucially other neutrons are emitted
- \( n + {}^{235}\text{U} \rightarrow {}^{144}\text{Ba} + {}^{90}\text{Kr} + 2n \)
Nuclei are bound together due to attractive nuclear force which overcomes the repulsive coulomb force.
Binding Energy

- Energy has to be expended to release a nucleon
- This is known as the Binding Energy
- The value is roughly independent of the size of the nucleus but the small variation is responsible for the possibility of nuclear energy
- Nuclei can be fissioned apart or fused together
Variation of Binding Energy
Units

- 1 MeV = 1 Mega Electron volt = One million eV
- 1 eV = $1.6 \times 10^{-19}$ joule
- 1 J = $6.2 \times 10^{18}$ eV = $6.2 \times 10^{12}$ MeV
Energy Release in Nuclear Fission

- $n + ^{235}\text{U} \rightarrow ^{144}\text{Ba} + ^{90}\text{Kr} + 2n$
- Energy released is $\sim 200$ MeV
  - Kinetic energy from fission fragments $165 \pm 5$
  - Prompt $\gamma$-ray energy $7 \pm 1$
  - Kinetic Energy of fission neutron $5 \pm 0.5$
  - $\beta$-rays from fission products $7 \pm 1$
  - $\alpha$-rays from fission products $6 \pm 1$
  - Neutrino’s from fission products $10 \pm 1$
Massive Source of Energy

• In an AGR reactor 1 tonne of U is equivalent to 20,000 tonnes of coal

• In a fast reactor - equivalent to 2,000,000 tonnes of coal

• A typical nuclear power station requires 40 tonnes of fuel per year - one lorry load per fortnight

• An equivalent coal power station requires 3,000,000 tonnes per year - two train loads per day
The role of Neutrons

- Neutron is uncharged so can approach nucleus at low energies without coulomb repulsion
- Cross section of interaction is greater at low energies
- ~200 MeV is released per fission which is 45 million times greater per atom of fuel than in a chemical reaction
- ~2.5 neutrons are released per fission
- Release of new neutrons give possibility of a chain reaction
Chain Reaction

1st Neutron Generation

2nd Neutron Generation

3rd Neutron Generation
Stable or Non-Stable Reactions

• Define a reproduction constant

\[ k = \frac{\text{no. of neutrons in one generation}}{\text{no of neutrons in previous generation}} \]

• \( k > 1 \) supercritical - bomb

• \( k < 1 \) subcritical - reaction dies out

• \( k = 1 \) critical - stable chain reaction
Reactor Ingredients

- **Fuel** - Originally uranium metal but now many variations
- **Moderators** - carbon, H$_2$O, D$_2$O
- **Cladding** - contains fuel and prevents release of radioactive fission products
- **Coolant** - gas of liquid circulated through core of reactor for heat extraction
- **Control Rods** - usually boron or cadmium with large capture cross section to maintain $k=1$
- **Shield** - usually steel and concrete used for radiation protection and pressure vessel
Build A Nuclear Reactor

Fuel Rods  Control Rods  Moderator  Shielding
Shielding
Sizewell B PWR
Torness AGR
Generic Nuclear Reactor
So that’s the theory - how does it happen in the real world?
UK Nuclear Industry
Worldwide Nuclear Industry
Nuclear Fuel Cycle

- Depleted uranium
- Enrichment
- Conversion to UF₆
- Fuel fabrication
- Reactor
- Spent fuel
- Storage
- Reprocessing
- Vitrification
- Storage
- Disposal
- Mining
- Tailings
Uranium Mining

10 countries are responsible for 95% of global production
Uranium Mining

- 28% of Earth’s supply is in Australia
- Currently 3 working mines
- Milled at the mine and leached with sulphuric acid to separate out the uranium
- Recovered from solution and dried as $\text{U}_3\text{O}_8$ - yellowcake
- Approx. 200 tonnes required for 1000 MWe reactor for one year
Conversion

- Uranium needs to be in the form of a gas before it can be enriched
- $U_3O_8$ is converted into $UF_6$ - uranium hexafluoride
Enrichment

- Most Nuclear Reactors need enriched uranium to operate - notable exceptions are Magnox and Candu
- $^{235}\text{U}$ is increased from 0.7% to 3 - 4%
- Centrifuges are used to separate the two streams
- Two streams are produced enriched and depleted
- Depleted uranium is 1.7 times denser than lead
Enrichment
Enrichment
Fuel Fabrication

- Enriched UF$_6$ is converted to UO$_2$ powder and pressed into pellets
- In a PWR reactor the pellets are put into thin tubes made of zircalloy to form fuel rods
PWR Fuel Assembly

264 fuel rods per assembly, Zircaloy cladding, $\text{UO}_2$ fuel
PWR Fuel Assembly
Magnox Fuel Assembly

1 fuel rod per assembly, Magnox cladding, U metal fuel
First Commercial Reactor
Calder Hall 1956
Magnox Reactors

- Berkeley in Gloucestershire, 2 units 138 MWe each, first grid connection 1962, **shut down 1989**
- Bradwell near Southminster, Essex, 2 units 123 MWe each, first grid connection 1962, **shut down 2002**
- Calder Hall near Whitehaven, Cumbria - 4 units 50 MWe each, first grid connection 1956, **shut down 2003**
- Chapelcross near Annan, Dumfriesshire, 4 units 50 MWe each, first grid connection 1959, **shut down 2003**
- Hunterston near West Kilbride, 2 units 160 MWe each, first grid connection 1964, **shut down 1990**
Magnox Reactors

- Hinkley Point near Bridgwater, Somerset, 2 units 235 MWe each, first grid connection 1965, shut down 1999
- Trawsfynydd in Gwynedd, 2 units 195 MWe each, first grid connection 1965, shut down 1991
- Dungeness A in Kent, 2 units 220 MWe each, first grid connection 1965, shut down 2006
- Sizewell A near Leiston, Suffolk, 2 units 210 MWe each, first grid connection 1966, shut down 2006
- Oldbury near Thornbury, South Gloucestershire, 2 units 217 MWe each, first grid connection 1967, decommissioning due 2008 but extended
- Wylfa on Anglesey, 2 units 495 MWe each, first grid connection 1971, decommissioning due for 2010 but probably extended
Advanced Gas-Cooled Reactors

- Dungeness, in Kent, 2 units Connected in 1983 and 1985
  Decommissioning due 2008
- Heysham in Lancashire, 4 units connected in 1983, 1984 and 1988
  Decommissioning due 2014 - 2023
- Hunterston in Ayrshire, 2 units connected in 1976 and 1977
  Decommissioning due 2011
- Hartlepool in Durham, 2 units connected in 1983 and 1984
  Decommissioning due 2014
- Hinkley Point in Somerset, 2 units connected in 1976
  Decommissioning due 2011
- Torness in East Lothian, 2 units connected in 1988 and 1989
  Decommissioning due 2023
Other UK Reactors

- Dounreay Fast Reactor, 14 MW, connected in 1962
  shut down in 1977

- Dounreay Prototype Fast Reactor, 250 MW, connected in 1975
  shut down in 1994

- Sizewell B in Suffolk, 1188 MW, connected in 1995
  Decommissioning due 2035
UK Decommissioning
## European Nuclear Power 2009

<table>
<thead>
<tr>
<th>Country</th>
<th>Operational Reactors</th>
<th>Net Capacity MWe</th>
<th>% Nuclear</th>
</tr>
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<tbody>
<tr>
<td>Belgium</td>
<td>7</td>
<td>5,728</td>
<td>54</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>2</td>
<td>1,906</td>
<td>32</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>6</td>
<td>3,472</td>
<td>30</td>
</tr>
<tr>
<td>Finland</td>
<td>4</td>
<td>2,696</td>
<td>29</td>
</tr>
<tr>
<td>France</td>
<td>59</td>
<td>63,473</td>
<td>77</td>
</tr>
<tr>
<td>Germany</td>
<td>17</td>
<td>20,339</td>
<td>26</td>
</tr>
<tr>
<td>Hungary</td>
<td>4</td>
<td>1,826</td>
<td>37</td>
</tr>
<tr>
<td>Lithuania</td>
<td>1</td>
<td>1,185</td>
<td>64</td>
</tr>
<tr>
<td>Netherlands</td>
<td>1</td>
<td>485</td>
<td>4</td>
</tr>
<tr>
<td>Romania</td>
<td>2</td>
<td>1,310</td>
<td>13</td>
</tr>
<tr>
<td>Russia</td>
<td>31</td>
<td>21,743</td>
<td>16</td>
</tr>
<tr>
<td>Slovakia</td>
<td>4</td>
<td>1,686</td>
<td>54</td>
</tr>
<tr>
<td>Slovenia</td>
<td>1</td>
<td>696</td>
<td>42</td>
</tr>
<tr>
<td>Spain</td>
<td>8</td>
<td>7,448</td>
<td>17</td>
</tr>
<tr>
<td>Sweden</td>
<td>10</td>
<td>9016</td>
<td>46</td>
</tr>
<tr>
<td>Switzerland</td>
<td>5</td>
<td>3,220</td>
<td>43</td>
</tr>
<tr>
<td>Ukraine</td>
<td>15</td>
<td>13,168</td>
<td>48</td>
</tr>
<tr>
<td><strong>UK</strong></td>
<td>19</td>
<td><strong>11,035</strong></td>
<td><strong>15</strong></td>
</tr>
</tbody>
</table>
Perceived Problems with Nuclear Energy

- Economic
- Safety
- Proliferation
- Waste
Is nuclear energy too expensive?
Cost of Electricity Generation

The bar chart illustrates the cost of generating electricity for various sources. The x-axis represents different types of power generation methods, including Coal-fired PF, Coal-fired CFB, Coal-fired IGCC, Gas-fired OCGT, Gas-fired CCCT, Nuclear, Poultry-litter BFB, Onshore Wind-Farm, Offshore Wind-Farm, and Wave & Marine. The y-axis indicates the cost of generating electricity (p/kWh).

Key points:
- **Standby generation cost** is indicated by the red portion of the bars.
- **Cost of generating electricity** is indicated by the blue portion of the bars.
- Offshore Wind-Farm has the highest cost, followed by Wave & Marine.
- Nuclear has the lowest cost among the listed sources.
Modern Improvements

- Greater efficiency
- Higher burn-up
- Longer Fuel Cycles
Is Radiation A Danger?
Average Annual Radiation Dose to UK Population

- **Natural 85%**
  - 50% Radon gas from the ground
- **Artificial 15%**
  - 14% Gamma rays from the ground and buildings
  - 14% Medical
  - <0.1% Nuclear discharges
  - <0.1% Products
  - 0.2% Fallout
  - 0.3% Occupational
  - 10% Cosmic rays
  - 11.5% From food and drink

**2.6 mSv overall**
UK Radon Potential
# Radiological Dose

<table>
<thead>
<tr>
<th>Activity</th>
<th>Dose (mSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Living in Cornwall</td>
<td>7.8</td>
</tr>
<tr>
<td>From a brain scan</td>
<td>5</td>
</tr>
<tr>
<td>Average UK dose</td>
<td>2.6</td>
</tr>
<tr>
<td>Average additional dose for airline crews</td>
<td>2</td>
</tr>
<tr>
<td>Average annual dose received by coal miner</td>
<td>1.2</td>
</tr>
<tr>
<td>Dose from return flight from London to Los Angeles</td>
<td>0.14</td>
</tr>
<tr>
<td>Dose from return flight from London to Spain</td>
<td>0.02</td>
</tr>
<tr>
<td>Dose from 1 week holiday in Cornwall</td>
<td>0.1</td>
</tr>
<tr>
<td>Dose from drinking a glass of mineral water every day for 1 year</td>
<td>0.065</td>
</tr>
<tr>
<td>Dose from a single X-ray</td>
<td>0.02</td>
</tr>
</tbody>
</table>
# $^{238}\text{U}$ Decay Series

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-Life</th>
<th>Principal Decay Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}\text{U}$</td>
<td>$4.5 \times 10^9$ a</td>
<td>alpha</td>
</tr>
<tr>
<td>$^{234}\text{Th}$</td>
<td>24 d</td>
<td>beta</td>
</tr>
<tr>
<td>$^{234}\text{Pa}$</td>
<td>6.8 h</td>
<td>beta</td>
</tr>
<tr>
<td>$^{234}\text{U}$</td>
<td>$2.4 \times 10^5$ a</td>
<td>alpha</td>
</tr>
<tr>
<td>$^{230}\text{Th}$</td>
<td>$7.3 \times 10^3$ a</td>
<td>alpha</td>
</tr>
<tr>
<td>$^{226}\text{Ra}$</td>
<td>$1.6 \times 10^3$ a</td>
<td>alpha</td>
</tr>
<tr>
<td>$^{222}\text{Rn}$</td>
<td>3.8 d</td>
<td>alpha</td>
</tr>
<tr>
<td>$^{218}\text{Po}$</td>
<td>3.1 m</td>
<td>alpha</td>
</tr>
<tr>
<td>$^{214}\text{Pb}$</td>
<td>27 m</td>
<td>beta</td>
</tr>
<tr>
<td>$^{214}\text{Bi}$</td>
<td>20 m</td>
<td>beta</td>
</tr>
<tr>
<td>$^{214}\text{Po}$</td>
<td>160 µs</td>
<td>alpha</td>
</tr>
<tr>
<td>$^{210}\text{Pb}$</td>
<td>22 a</td>
<td>beta</td>
</tr>
<tr>
<td>$^{210}\text{Bi}$</td>
<td>5.0 d</td>
<td>beta</td>
</tr>
<tr>
<td>$^{210}\text{Po}$</td>
<td>138 d</td>
<td>alpha</td>
</tr>
<tr>
<td>$^{206}\text{Pb}$</td>
<td>stable</td>
<td></td>
</tr>
</tbody>
</table>
Decay Chains
Nuclear technology will inevitably lead to nuclear bombs
Nuclear Non-Proliferation Treaty

• Established since 1970
• Signed by 187 states worldwide
  • Including the five declared Nuclear Weapons States
    • China, France, Russian Federation, UK, USA
• Extended indefinitely in 1995
Reactor Innovation
What can we do with the radioactive waste?
Radioactive Waste

• Three main reasons for waste
  • mining and milling of uranium ores
  • reprocessing of fuel discharged from reactors
  • decommissioning

• Three categories of waste
  • LLW - discarded equipment, tools, protective clothing
  • ILW - stripped/leached remains of cladding or PCM
  • HLW - fission products
Storage of Spent Fuel

- Spent fuel is highly radioactive and very (thermally) hot
- Initially stored in ponds at the reactor site
- Water cools the rods and acts as shielding
- Can also be stored in dry stores with air cooling
Storage Pond

THORP storage pond at Sellafield
Reprocessing

- Only about 4% of U is burnt up
- $^{235}\text{U}$ content reduced to less than 1%
- Some Pu remains from fission reactions
- Reprocessing separates the U and Pu from waste products by chopping up the fuel rods and dissolving them in acid
- U can be returned to the conversion stage for re-enrichment
- Pu can blended with enriched U to produce MOX fuel
High Level Waste

80 year lifetime use of electricity for 1 person generates this much high level waste
Vitrification

- Highly active liquid waste concentrate is essentially a solution of metal nitrates
- The spent fuel is dissolved in nitric acid
- This can be converted into mixed oxides and reacted at ~1050 °C with glass forming materials to form a vitreous product
Vitrification

Continuous Vitrification Process

Highly Active Liquid Waste
Calcination Additives

Feed Control

Off Gas Equipment
Scrubbers
Condensers
Effluent Treatment

Glass Forming Additives

Calciner
Melter

Container for Glass
Lid Welding
Surface Decontamination

Storage

Swab Machine
Vitrification
Fuel Rod De-canning
Magnox Swarf
Intermediate Level Waste
Low Level Waste
Low Level Waste
# Wastes in Storage

<table>
<thead>
<tr>
<th>Waste Type</th>
<th>Volume (m$^3$)</th>
<th>% Volume</th>
<th>Activity (TBq)</th>
<th>% Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>LLW</td>
<td>2,100,000 ~ (128m)$^3$</td>
<td>91</td>
<td>21</td>
<td>0.00003</td>
</tr>
<tr>
<td>ILW</td>
<td>220,000 ~ (60m)$^3$</td>
<td>9</td>
<td>4.5M</td>
<td>6</td>
</tr>
<tr>
<td>HLW</td>
<td>1,300 ~ (11m)$^3$</td>
<td>0.1</td>
<td>75M</td>
<td>94</td>
</tr>
</tbody>
</table>
Future Waste

- Legacy
- 60 year operation of 10 AP1000 units

**HLW and ILW**
- 10% of 23,000 m³
- 90% of 216,000 m³

**LLW**
- 3% of 80,000 m³
- 97% of 2,750,000 m³
Future Reactors ??
Planning Timeline

NEW NUCLEAR - GOVERNMENT DECISION TO GENERATION IN 10 YEARS

1. **Licensing**
   - Generic design assessment (NII)
   - Site licensing (NII)

2. **NPS**
   - Justification (Government)
   - Strategic Siting Assessment up to Stage 2 (Government)
   - National Policy Statement - SSA Stage 3 (Government)

3. **Planning**
   - Planning application (developer)
   - Planning approvals granted (IPC)

4. **Construction**
   - Preparatory works (developer)
   - Construction (developer)
   - Electricity generated from new nuclear

Timeline:
- 2007
- 2008
- 2009
- 2010
- 2011
- 2012
- 2013
- 2014
- 2015
- 2016
- 2017

Government decision on new nuclear
Reactor Pressure Vessel
Land Sale
EPR in Finland
New UK Reactors

NOMINATED SITES FOR NEW NUCLEAR POWER STATIONS

- Sites currently generating
- Shut-down sites
- Nominated new sites

*Shut-down site known as Calder Hall

SOURCE: DECC
Natural Reactors

- Most famous is in Oklo, Gabon. Discovered in 1972 by Francis Perrin
- Water trickling through moderated the neutrons allowing fission of the uranium
- A chain reaction occurred until the water was boiled away
- Reactor worked on and off for more than a million years
- HLW created held in place by the rocks, Pu had only travelled 3m in almost two billion years