Nuclear Energy – The Facts Behind The Fuss

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Electrical Generator
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, gas or nuclear fission
How a Fission Reactor Works:

A Pressurised Water Reactor

- Reactor Vessel
- Control Rods
- Pressuriser
- Steam Generator
- Containment Structure
- Condenser
- Turbine
- Generator
How a Fission Reactor Works:

A Boiling Water Reactor

- Reactor Vessel
- Control Rods
- Containment Structure
- Turbine
- Condenser
- Generator
Nuclear Fission

\[ E = mc^2 \]

- The total energy released per fission is about 200 MeV or 32 pJ
  - 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 \( 6 \pm 1 \)
  - Neutrinos from fission products \( 10 \pm 1 \)

- One nuclear fuel pellet undergoes \( 6 \times 10^{12} \) fissions per second
- Each cubic micron has 10 fissions per second

\[
\text{neutron} + ^{235}\text{Uranium} \rightarrow ^{144}\text{Barium} + ^{90}\text{Krypton} + 2 \text{ neutrons} \\
\text{n} + ^{235}\text{U} \rightarrow ^{144}\text{Ba} + ^{90}\text{Kr} + 2\text{n}
\]
Variation of Binding Energy
Nuclear Energy

- For 1 1150 MWe reactor (Sizewell B in the UK)
  - 33% thermal efficiency ~ 3000 MWth
  - 200 17x17 assemblies, 300 pellets/rod
  - 3 GW is generated by 17,340,000 pellets
  - 200 W/pellet
- Pellets are ~ 1 cm in length
  - linear power ~ 200 W/cm ~ 20 kW/m
- Pellets weigh ~ 5g
  - specific power ~ 40 W/g
Nuclear Energy

- If the Fuel Pellet remains in the reactor for three years then the total energy produced by one pellet is given by:
  \[ 3 \times 365.25 \times 24 \times 3600 \times 200 \text{ W or J s}^{-1} \approx 20 \text{ GJ} \]

- Total energy per unit mass
  \[ = \frac{20 \text{ GJ}}{5 \text{ g}} = 4 \text{ GJ g}^{-1} = 4000 \text{ GJ kg}^{-1} = 4000 \text{ TJ tonne}^{-1} \]
  \[ = 46,000 \text{ MW day tonne}^{-1} \text{ (MW per day per tonne)} \]
  \[ = 1.1 \text{ Billion kW hour tonne}^{-1} \]

- Burning Gas = 0.4 MW day tonne\(^{-1}\)

- Eating Chocolate = 0.2 MW day tonne\(^{-1}\)

t = tonne
First Issue

Is Nuclear Energy safe?
Is Coal Energy Safe?

Is Hydro Electricity Safe?

etc
Vajont Dam, Italy

2,000 deaths
1963
Sayano-Shushenskaya Hydro Plant
Russia

75 deaths
2009
Chernobyl

28 + 19 deaths
1986
Deaths per TWh

Source: IBM
How dangerous is radiation?
# Radioactive Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 kg of granite</td>
<td>1,000 Bq</td>
</tr>
<tr>
<td>1 kg of coal ash</td>
<td>2,000 Bq</td>
</tr>
<tr>
<td>1 kg of coffee</td>
<td>1,000 Bq</td>
</tr>
<tr>
<td>1 kg of fertiliser</td>
<td>5,000 Bq</td>
</tr>
<tr>
<td>1 smoke detector</td>
<td>30,000 Bq</td>
</tr>
<tr>
<td>1 adult human (70 kg)</td>
<td>7,000 Bq</td>
</tr>
</tbody>
</table>

1 Bq = 1 disintegration per second
Humans are Radioactive

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Average Weight</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>90 µg</td>
<td>1.1 Bq</td>
</tr>
<tr>
<td>Th</td>
<td>30 µg</td>
<td>0.11 Bq</td>
</tr>
<tr>
<td>(^{40})K</td>
<td>17 mg</td>
<td>4.4 kBq</td>
</tr>
<tr>
<td>Ra</td>
<td>31 pg</td>
<td>1.1 Bq</td>
</tr>
<tr>
<td>(^{14})C</td>
<td>22 ng</td>
<td>3.7 kBq</td>
</tr>
<tr>
<td>(^{3})H</td>
<td>0.06 pg</td>
<td>23 Bq</td>
</tr>
<tr>
<td>(^{210})Po</td>
<td>0.2 pg</td>
<td>37 Bq</td>
</tr>
</tbody>
</table>

Yukiya Amano
IAEA Director General
## Effects of Radiation Exposure

<table>
<thead>
<tr>
<th>Dose (Whole Body Irradiation)</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.25 Sv</td>
<td>No clinically recognisable damage</td>
</tr>
<tr>
<td>0.25 Sv</td>
<td>Decrease in white blood cells</td>
</tr>
<tr>
<td>0.5 Sv</td>
<td>Increasing destruction of the leukocyte-forming organs (causing decreasing resistance to infection)</td>
</tr>
<tr>
<td>1 Sv</td>
<td>Marked changes in the blood pressure (decrease in the leukocytes and neutrophils)</td>
</tr>
<tr>
<td>2 Sv</td>
<td>Nausea and other symptoms</td>
</tr>
<tr>
<td>5 Sv</td>
<td>Damage to the gastrointestinal tract causing bleeding ~ 50% death</td>
</tr>
<tr>
<td>10 Sv</td>
<td>Destruction of the neurological system ~ 100% death within 24 hours</td>
</tr>
</tbody>
</table>
Chernobyl Background Rate

Lifetime radiation doses in various regions of Europe
Ch. High-50 Ci/km2, Medium-15 Ci/km2, Low-5 Ci/km2

- Chernobyl effects
- Natural background

Dose, mSv per 70 years

Austria, Finland, France, Greece, Spain, Poland, Switz, Sweden, UK

Ch. High, Ch. Medium, Ch. Low

Chernobyl region
Fukushima Fallout

Air dose rates at 1m from the ground (μSv/h)

Not measured
The natural radionuclides are included.

0.5 μSv.h⁻¹ = 4.4 mSv.year⁻¹
166 μSv.h⁻¹ = 83 mSv.year⁻¹
Fukushima-Daiichi, Japan

Image: TEPCO
Tohoku Earthquake
Second Issue

Is Nuclear Energy too expensive?
EDF Energy

Hinkley investment decision soon, says EDF chief after finance director resigns

Thomas Piquemal's departure intensifies the feeling of crisis surrounding the project
EPR Safety Systems

- Double-wall containment with ventilation and filtering system
- Molten core spreading area
- Containment heat removal system
- Water tank inside containment
- 4-train redundancy of main safeguard systems
Protection Against Airplane Crash

- A thick highly reinforced concrete shell protects the inner walls and structures from direct impact and resulting vibrations
- Protection is provided for the reactor, fuel and safeguard buildings including the Main Control Room
Costs of Electricity

Source NEA/IEA 2010
Cost per Power Plant

Source NEA/IEA 2010
Nuclear Costs

- Construction 55%
- Decommissioning 1 - 5%
- O & M 20%
- Uranium 5%
- Conversion 1%
- Enrichment 6%
- Fuel Fabrication 3%
- Back End 5%
Cost Structures

- Nuclear
- Coal
- CCGT
Westinghouse looks to UK for vessel manufacture

03 March 2016

Westinghouse Electric Company has announced a manufacturing study to investigate the production of reactor pressure vessels for its small modular reactor in the UK through a collaboration with the Nuclear Advanced Manufacturing Research Centre.

The NAMRC will provide an independent assessment of the current Westinghouse SMR RPV design, and determine an optimal manufacturing solution. A key component of the study will be the identification of efficiencies within the advanced manufacturing process to significantly reduce capital costs and drive project savings. Westinghouse said that the study will "utilise expert knowledge of local manufacturing capabilities to identify potential suppliers for when the Westinghouse SMR enters production."

The NAMRC is a collaboration of academic and industrial partners from across the civil nuclear manufacturing supply chain, and was established in 2012 with the mission of helping UK manufacturers win work at home and worldwide. With extensive experience in design for the manufacture of large complex parts for safety-critical applications, the centre can draw on broad academic and industry knowledge, to address challenges ranging from research and development to product and process improvement.
Third Issue

Radioactive Waste
Composition of Conventional Nuclear Fuel

(17x17 Westinghouse, 3% enr., 1100 day irrad, 33000 MWD/MTU, discharge composition, Origen Arp analysis)

0%

1%

2%

3%

4%

5%

6%

Fresh fuel  1 year  2 years  3 years

- uranium-235 (0.73%)
- uranium-236 (0.39%)
- xenon (0.54%)
- zirconium (0.35%)
- neodymium (0.37%)
- cerium (0.27%)
- cesium (0.28%)
- ruthenium (0.25%)
- barium (0.14%)
- lanthanum (0.12%)
- praseodymium (0.11%)
- other fission products (0.65%)

Very-low radioactivity, unused uranium fuel

Highly radioactive, but rapidly decaying fission products with a variety of potential applications

Long-lived, fairly radioactive "transuranic" isotopes, with potential for consumption in a reactor; drives disposal concerns

Very-low radioactivity, unused uranium

Source: Kurt Sorensen
$^{235}\text{U}$ Fission Products

- Y/rare earths: 53%
- Zr/Nb: 30%
- Ru/Tc/Rh/Pd: 26%
- Xe/Kr: 25%
- Mo: 24%
- Cs/Rb: 23%
- Ba/Sr: 15%
- I/Te: 1%
- others: 3%
- total: ~200%

\[ \text{n} + ^{235}\text{U} \rightarrow ^{144}\text{Ba} + ^{90}\text{Kr} + 2\text{n} \]
# $^{238}$U Decay Series

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-Life</th>
<th>Principal Decay Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}$U</td>
<td>$4.5 \times 10^9$ a</td>
<td>alpha</td>
</tr>
<tr>
<td>$^{234}$Th</td>
<td>24 d</td>
<td>beta</td>
</tr>
<tr>
<td>$^{234}$Pa</td>
<td>6.8 h</td>
<td>beta</td>
</tr>
<tr>
<td>$^{234}$U</td>
<td>$2.4 \times 10^5$ a</td>
<td>alpha</td>
</tr>
<tr>
<td>$^{230}$Th</td>
<td>$7.3 \times 10^3$ a</td>
<td>alpha</td>
</tr>
<tr>
<td>$^{226}$Ra</td>
<td>$1.6 \times 10^3$ a</td>
<td>alpha</td>
</tr>
<tr>
<td>$^{222}$Rn</td>
<td>3.8 d</td>
<td>alpha</td>
</tr>
<tr>
<td>$^{218}$Po</td>
<td>3.1 m</td>
<td>alpha</td>
</tr>
<tr>
<td>$^{214}$Pb</td>
<td>27 m</td>
<td>beta</td>
</tr>
<tr>
<td>$^{214}$Bi</td>
<td>20 m</td>
<td>beta</td>
</tr>
<tr>
<td>$^{214}$Po</td>
<td>160 µs</td>
<td>alpha</td>
</tr>
<tr>
<td>$^{210}$Pb</td>
<td>22 a</td>
<td>beta</td>
</tr>
<tr>
<td>$^{210}$Bi</td>
<td>5.0 d</td>
<td>beta</td>
</tr>
<tr>
<td>$^{210}$Po</td>
<td>138 d</td>
<td>alpha</td>
</tr>
<tr>
<td>$^{206}$Pb</td>
<td>stable</td>
<td></td>
</tr>
</tbody>
</table>
# Volumes of Radioactive Waste

<table>
<thead>
<tr>
<th></th>
<th>Volume (m³)</th>
<th>% Volume</th>
<th>Activity (TBq)</th>
<th>% Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLLW &amp; LLW</td>
<td>4,200,000 ~ (161m³)</td>
<td>94</td>
<td>21</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>ILW</td>
<td>290,000 ~ (66m³)</td>
<td>6</td>
<td>4.5M</td>
<td>5</td>
</tr>
<tr>
<td>HLW</td>
<td>1,100 ~ (10m³)</td>
<td>0.1</td>
<td>75M</td>
<td>95</td>
</tr>
</tbody>
</table>

Source: NDA
New LLW Container
LLW Repository near Drigg
ILW
Nuclear Power Generation

80 year lifetime use of electricity for 1 person generates this much high level waste
Storage of Canisters
Multibarrier Concept
Forsmark, Sweden
So, what of the future?
UK Nuclear Sites

DECOMMISSIONING
26 Magnox Reactors
2 Fast Reactors

OPERATIONAL
14 AGRs
1 PWR

9.6 GWe Total Capacity
21st Century UK Reactors

EDF (Areva, CGN, CNNC)
Horizon (Hitachi)
NuGeneration (Toshiba and Engie)

Bradwell, Essex
Hartlepool
Heysham, Lancashire
**Hinkley Point, Somerset**
Oldbury, South Gloucestershire
Moorside, Cumbria
Sizewell, Suffolk
Wylfa, North Wales

~ 16 GW (?) of new capacity
~ 3 GW on each of the five sites
2 EPR or 3 AP1000 or ABWRs
Hinkley Point C nuclear power station gets government green light

Theresa May gives £18bn scheme go-ahead but announces new safeguards for foreign investment in infrastructure

Work continues at the Hinkley Point C nuclear power station site near Bridgwater, Somerset. Photograph: Darren Staples/Reuters
www.uknucleareducation.net

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