A Human Turning Point
– Nuclear Energy

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Man-Made Reactors
First in World and First in Canada

CP1 – University of Chicago
December 2, 1942

ZEEP – Chalk River Laboratory
September 5, 1945
First Try – NRC Ottawa, 1941-42

Dr. G.C. Laurence was the first to assemble a reactor using uranium and carbon.
Nature’s Reactors

- Remains of at least six natural reactors were found in Oklo, Gabon, West Africa on June 2, 1972
- As oxygen built up in earth’s atmosphere, uranium from a river in East Africa was dissolved and carried to the river delta
- Uranium precipitated at high concentration in the river silt and sand
- Some time later, the uranium-sand-silt mixture was soaked with water. Natural reactors were created. They worked for thousands of years.

http://www.iaea.org/programmes/inis/index.html
Uranium Through History

Heavy elements probably were produced in supernova explosions

Decay constants: \( \text{U235} = 9.8 \times 10^{-10} \) per year, \( \text{U238} = 1.5 \times 10^{-10} \) per year

<table>
<thead>
<tr>
<th>TIME</th>
<th>-4 b.yr.</th>
<th>-2 b.yr.</th>
<th>0 (now)</th>
<th>+2 b.yr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n_5 )</td>
<td>35.3</td>
<td>5.0</td>
<td>0.72</td>
<td>0.10</td>
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<tr>
<td>( n_8 )</td>
<td>183.8</td>
<td>135.1</td>
<td>99.28</td>
<td>73.0</td>
</tr>
<tr>
<td>( n_5/(n_5+n_8) )</td>
<td>0.162</td>
<td>0.036</td>
<td>0.0072</td>
<td>0.0014</td>
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</table>

(uranium enrichment)

Fast Reactor | Thermal Reactor | Thermal Reactor (Graphite or D2O) | Enrichment of Fuel Required
Possible (LWR)
Bombs and Reactors

• The idea of fission energy production emerged just before World War II.
• US made their decision to develop nuclear weapons in ~1941.
• US, Soviet Union, UK, France, China developed weapon arsenals.
• Intense hostility (Cold War) maintained military emphasis until ~ 1990.

• The “Atoms for Peace” idea offered peaceful nuclear technology in return for a promise not to make weapons.
• The future is, as always, uncertain. Many nuclear weapons now are obsolete – replaced by even more effective, non-nuclear offensive weapons.

• In early 1944, Canada was assigned task of building a high-power heavy water reactor (NRX) for production of Pu239 and U233 for weapons.

• Canada retired the Bomarc and Genie nuclear-tipped missile systems in ~1972
A Quick Peek

The McMaster Nuclear Reactor

Reactor Core
A Modern Nuclear Power Plant

- Darlington NGS, East of Oshawa. Four units, total power output of 3524 megawatts
# Reactor Types: Prototypes and Successes

## THERMAL MODERATOR

<table>
<thead>
<tr>
<th>Graphite</th>
<th>Water</th>
<th>Heavy Water</th>
<th>Fast</th>
<th>Class</th>
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<tbody>
<tr>
<td>Molten Salt</td>
<td>Na</td>
<td>CO₂</td>
<td>H₂O</td>
<td>He</td>
</tr>
<tr>
<td>Hallam</td>
<td>MAG-NOX</td>
<td></td>
<td>BLW</td>
<td>CANDU</td>
</tr>
<tr>
<td>AGR</td>
<td>RBMK</td>
<td>HTGR</td>
<td>PBMR</td>
<td>PWR</td>
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<tr>
<td>MSBR</td>
<td></td>
<td>THTR</td>
<td>LWBR</td>
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</table>
Success is Not Permanent

- Three Mile Island Unit 2 (a modern US pressurized water reactor)
  - Errors committed by operators, designers, and regulators
  - Zero environmental or health effects, but large losses (>5 b$)
  - “Unjustified self-confidence” can be seen as the root cause
- Darlington station (designed, built by experienced companies)
  - Delays during construction – OH senior management and government
  - Errors in generator design – Swiss design organization
  - Error in heat transport system design - designers
- Chernobyl (USSR built several plants, and some of them operated well for years)
  - Errors were committed by government, designers, regulators, managers, operators
  - About 40 people were killed (operators, firemen, rescue workers)
  - Huge cost (>10 b$)
- Ontario Hydro Operational Breakdown
  - Errors committed by management, directors, government, unions
  - Staff reduced drastically by management, without proper care
  - Maintenance neglected, units understaffed, so 7 units were forced to shut down
  - Pickering A (then Bruce) units will be extensively refurbished
Fundamentals of Power Generation

**COAL-FIRED POWER PLANT**
- **COAL**
- **AIR**
- **HEAT ENERGY**
- **CONTROL**
- **FLY ASH**
- **CARBON DIOXIDE**
- **BOTTOM ASH**

**URANIUM-FIRED POWER PLANT**
- **HEAT ENERGY**
- **NEUTRONS**
- **CONTROL ABSORBERS**
- **URANIUM**
- **SPENT FUEL**
Offshore Adventures

- **India**
  - AECL exported two units in early 1970’s; Indian nuclear explosion led to isolation
  - Indian industry is now operating 10-12 small units, two larger units under construction
  - Fully mature industry, good performance

- **Pakistan**
  - One small unit operating (KANUPP, designed by Canadian General Electric)

- **Korea**
  - First CANDU6 unit started in 1983. Four units now operating. Two being considered
  - Fully mature industry. Both PWR and CANDU types
  - CANDU performance is excellent – several times at the top of world charts

- **Argentina**
  - Mature industry
  - One CANDU 6 unit started in 1983. An above-average performer

- **Romania**
  - One CANDU 6 unit started in 1986 – excellent performance. Second unit to be completed

- **China**
  - Growing industry – 2 operating, 8 under construction
  - Two CANDU 6 units under construction, for startup in 2002

- **Turkey**
  - Project cancelled by Turkish national government in 2000
Today’s Viewpoint

World Market Status
- Continued fierce opposition from much of the green movement
  - Some interesting recent exceptions – e.g. Sweden, Switzerland
- Low rate of ordering for new nuclear plants
  - Difficult to sustain experienced design and research staff
  - Low intake of new, young staff
- Improving performance of, and reliance on, existing plants
  - Especially US and India
  - Service business is good – older plants are being refurbished
- Extreme competition from remaining international competitors
  - UK, US, Russia, France, Germany

Main Short-term Issues
- Public acceptance
  - Governments follow; people lead
  - Recovery from a bad reputation takes time
- Economics
  - High capital cost – a barrier
  - The “eternal supply of fossil fuel at low price” myth
- Confusion in the electricity supply industry
  - Deregulation, privatization, mismanagement – most rates are rising
  - Instability of fossil fuel prices
Questions For Our Grandchildren

- Big Systems
  - How many people?
  - How much wealth do you need?
  - How much wealth do you want?
  - What wealth can be sustained?
  - Do you care about the welfare of foreign people?