Structure of the course

• Nuclear power today
  – how it works
  – why do we need it
  – what countries use it

• Public perception
  – radiation, radioactive contamination
  – nuclear waste
  – nuclear bombs and reactors
  – accidents

• Technology explained
  – types of nuclear reactors
  – safety features

• Future
  – advanced nuclear power reactors
  – nuclear fusion
Nuclear energy originates from the splitting of atomic nuclei in a process called fission.

At a power plant, the energy produced from controlled fission generates heat to produce steam, which is then used in a turbine to generate electricity.

Each fissioning $^{235}$U nucleus releases:
- prompt gamma radiation
- beta radiation from fission fragments
- approximately 200 MeV of energy

This energy ends up as thermal, i.e. ultimately heat.
A $^{235}\text{U}$ nucleus captures a neutron and fissions

2-3 fast neutrons are released

the neutrons are slowed down in the moderator

any of these neutrons can be absorbed by another $^{235}\text{U}$ nucleus which will fission ...

... and so forth
How does it work?

A simplified scheme of a nuclear power plant
Why do we need nuclear energy?

- We need more and more energy: in the next 50 years, it is estimated that the population of the world will use *more energy than the total consumed in all previous history*.
- Most of the energy generated today comes from **burning** fossil fuels to make electricity, power vehicles or heat buildings.
- When *fossil fuels* are burned, waste products are dispersed directly into the atmosphere.
- This waste takes the form of carbon dioxide CO₂ and particulates, which contribute to the greenhouse effect.
- Some numbers:
  - 30,000,000,000 tonnes of CO₂ each year, or
  - 80,000,000 tonnes each day or
  - 950 tonnes per second
  - North Americans release 54 kg CO₂ per person per day
  - Europeans release 23 kg CO₂ per person per day
### Heat content of various fuels

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Heat value</th>
<th>% Carbon</th>
<th>CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry firewood</td>
<td>16 MJ/kg</td>
<td>42</td>
<td>94 g/MJ</td>
</tr>
<tr>
<td>Gasoline/Diesel fuel</td>
<td>44-46 MJ/kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crude oil</td>
<td>42-44 MJ/kg</td>
<td>89</td>
<td>70-73 g/MJ</td>
</tr>
<tr>
<td>Methanol</td>
<td>20 MJ/kg</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>Natural gas</td>
<td>38 MJ/m³</td>
<td>76</td>
<td>52 g/MJ</td>
</tr>
<tr>
<td>Hard black coal</td>
<td>25 MJ/kg</td>
<td>67</td>
<td>90 g/MJ</td>
</tr>
<tr>
<td>Sub-bituminous coal</td>
<td>18 MJ/kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lignite/brown coal</td>
<td>10 MJ/kg</td>
<td>25</td>
<td>116 g/MJ (1250 g/kWh)</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>121 MJ/kg</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Natural Uranium in LWR</td>
<td>500,000 MJ/kg</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Natural Uranium in LWR with Uranium and Plutonium recycle</td>
<td>650,000 MJ/kg</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Uranium enriched to 3.5% in LWR</td>
<td>3,900,000 MJ/kg</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Natural Uranium in FNR</td>
<td>28,000,000 MJ/kg</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
**CO₂ emission comparisons**

- **Lignite**: 1069 Tonnes CO₂e/GWh
- **Coal**: 888 Tonnes CO₂e/GWh
- **Oil**: 735 Tonnes CO₂e/GWh
- **Natural Gas**: 500 Tonnes CO₂e/GWh
- **Solar PV**: 85 Tonnes CO₂e/GWh
- **Biomass**: 45 Tonnes CO₂e/GWh
- **Nuclear**: 28 Tonnes CO₂e/GWh
- **Hydroelectric**: 26 Tonnes CO₂e/GWh
- **Wind**: 26 Tonnes CO₂e/GWh

*Note: Average Emissions Intensity vs. Range Between Studies.*
Pollution comparisons

Power Plant Emissions
(pounds per MWh of electricity)

- **Nitrogen Oxides**
- **Sulfur Dioxide**

**Coal**
- 6 pounds

**Oil**
- 4 pounds

**Natural Gas**
- 1.7 pounds

**Nuclear**
- 0 pounds
- 0.1 pounds

*Power plant emissions only, not including small emissions from mining, transportation and refining or enriching fuel.

Source: [www.epa.gov](http://www.epa.gov)
Coal and oil vs. nuclear
How many wind turbines?

- Sizewell B reactor: 1195 MWe
- Offshore wind turbine: 7.5 MW

1 PWR = 160 WT
The International Energy Agency projects that renewables can provide only 6% of the world electricity needs by 2030.

Nuclear energy is the only proven option with the capacity to provide scalable clean electricity on a global scale.
Nuclear Power

Biggest nuclear-electricity producers
Terawatt hours*, 2009

<table>
<thead>
<tr>
<th>Country</th>
<th>Terawatt Hours</th>
<th>% of total domestic production</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>799</td>
<td>20</td>
</tr>
<tr>
<td>France</td>
<td></td>
<td>75</td>
</tr>
<tr>
<td>Japan</td>
<td></td>
<td>29</td>
</tr>
<tr>
<td>Russia</td>
<td></td>
<td>18</td>
</tr>
<tr>
<td>South Korea</td>
<td></td>
<td>35</td>
</tr>
<tr>
<td>Germany</td>
<td></td>
<td>26</td>
</tr>
<tr>
<td>Canada</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>Ukraine</td>
<td></td>
<td>49</td>
</tr>
<tr>
<td>China</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Britain</td>
<td></td>
<td>18</td>
</tr>
</tbody>
</table>

Source: World Nuclear Association

*1 terawatt hour = 1 trillion watt hours
Uranium mining

- Extracted via open-pit mining
- Then *milled*: ground into a fine powder and chemically treated to leach out uranium
- What is commercialised is $\text{U}_3\text{O}_8$ - the so-called *yellowcake*
- This is converted to gaseous UF$_6$, enriched to a specific $^{235}\text{U}$ concentration, then converted to oxide for fuel manufacture
- Typical fuel pellets are UO$_2$
- Yellowcake peaked at $\$300$/kg and then dropped to $\sim$ $\$60$/kg
- Based on current production rates, it is estimated that reserves will last for about a century

Image credits: Wikipedia - Figures are from 2007
Uranium from seawater?

- Low concentrations 3.3mg/m³, but practically limitless reserves
- There is technology with which it could be extracted at $240/kg
Public perception
Radiation, explosions, and nuclear waste
Radiation

• Definitions:
  – **Radiation** - energy traveling in the form of particles or waves, for example: microwaves, radio waves, light, medical X-rays, alpha, beta, gamma radiation
  – **Radioactivity** - a natural process through which unstable atoms of an element radiate excess energy in the form of particles or waves
  – **Radioactive material** - material that emits radiation
  – **Radioactive contamination** - radioactive material in unwanted places

• Important facts:
  – Radiation is commonplace
  – A person exposed to radiation does not become contaminated
  – Contamination is the result of direct contact with removable radioactive material
  – The distinction between harmful and safe depends on *quantity*. This is true about everything from paracetamol to arsenic
  – Dose is important
Bananas are a natural source of radioactive isotopes.

Eating one banana = 1 BED = 0.1 μSv = 0.01 mrem

<table>
<thead>
<tr>
<th>Number of bananas</th>
<th>Equivalent exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>100,000,000</td>
<td>Fatal dose (death within 2 weeks)</td>
</tr>
<tr>
<td>20,000,000</td>
<td>Typical targeted dose used in radiotherapy (one session)</td>
</tr>
<tr>
<td>70,000</td>
<td>Chest CT scan</td>
</tr>
<tr>
<td>20,000</td>
<td>Mammogram (single exposure)</td>
</tr>
<tr>
<td>1000</td>
<td>Chest X-ray</td>
</tr>
<tr>
<td>700</td>
<td>Living in a stone, brick or concrete building for one year</td>
</tr>
<tr>
<td>400</td>
<td>Flight from London to New York</td>
</tr>
<tr>
<td>100</td>
<td>Average daily background dose</td>
</tr>
<tr>
<td>50</td>
<td>Dental X-ray</td>
</tr>
<tr>
<td>1 - 100</td>
<td>Yearly dose from living near a nuclear power station</td>
</tr>
<tr>
<td>3</td>
<td>Same near a coal-fired power plant</td>
</tr>
</tbody>
</table>
**Nuclear waste**

**Common concerns:**
- Nuclear waste (spent fuel) is an unresolved problem
- The nuclear industry produces horrific wastes that will be an enduring nightmare for our descendants
- Nuclear reactors are unsafe, the Fukushima accident just proved it

**Facts:**
- The nuclear industry is the only energy-producing industry that fully manages its wastes, and bears the costs
- In all countries producing nuclear energy there are well established procedures for the management, transportation and storage of nuclear waste
- Nuclear waste is always contained, never deliberately released
- The nuclear industry has an outstanding safety record with more than 14,000 reactor years of operation over 5 decades
Waste management

• **Low level (operational) waste**
  – short-lived radioactive products: tools, filters, clothing, rags
  – 90% of the waste volume, but containing only 1% of radioactivity
  – incinerated in closed containers, then buried in shallow landfill sites

• **Intermediate level waste**
  – materials that require shielding when handled: control rods, internal components, cladding
  – short-lived radioactive products can be disposed with LLW
  – long-lived go with HLW into geological storage
  – incorporated into cement or an organic solid (bitumen or resin), placed in shielding containers and buried

• **High level waste**
  – fission products and spent fuel, approximately 4% of waste volume
  – vitrified and/or enclosed in copper or stainless steel containers
  – 50 years in interim storage in purpose-built enclosures
  – no deep geological disposal facilities needed yet

Quantities:

1GWe reactor produces yearly

100m³ of LLW

3.5m³ of ILW per year per GWe or

70m³ of ILW per year per GWe if one includes decommissioning

5t of vitrified glass, or ≈12 canisters 0.4m in diameter and 1.3m height per year per GWe
Nuclear explosion vs. explosion at a nuclear plant

Hiroshima Nuclear Explosion
Energy released: 64TJ

Chernobyl Nuclear Excursion
Energy released: 40GJ

\[ \frac{E_B}{E_A} = 1600 - 5,000,000 \]

Original images: Wikimedia Commons
<table>
<thead>
<tr>
<th>Event</th>
<th>Type</th>
<th>TNT Equivalent</th>
<th>Energy released</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tsar Bomba</td>
<td>3-stage Teller-Ulam design Thermonuclear test bomb</td>
<td>50 MT</td>
<td>210,000,000 GJ</td>
</tr>
<tr>
<td>Castle Romeo</td>
<td>Thermonuclear test bomb</td>
<td>15 MT</td>
<td>63,000,000 GJ</td>
</tr>
<tr>
<td>Chernobyl (one unit) during one year</td>
<td>RBMK-1000 reactor 1 GWe (3.2 GWt)</td>
<td>15 MT</td>
<td>30,000,000 GJ</td>
</tr>
<tr>
<td>Three Mile Island Unit 1 operated one year</td>
<td>PWR reactor 800 MWe</td>
<td></td>
<td>24,000,000 GJ</td>
</tr>
<tr>
<td>Fukushima Unit 1 operated one year</td>
<td>BWR3 reactor (GE) 439 MWe</td>
<td></td>
<td>14,000,000 GJ</td>
</tr>
<tr>
<td>Peacekeeper</td>
<td>ICBM weapon</td>
<td>10 x 300 kT</td>
<td>12,500,000 GJ</td>
</tr>
<tr>
<td>Fat Man (Nagasaki)</td>
<td>$^{239}$Pu implosion-type bomb</td>
<td>21 kT</td>
<td>88,000 GJ</td>
</tr>
<tr>
<td>Little Boy (Hiroshima)</td>
<td>$^{235}$U gun-type bomb</td>
<td>15 kT</td>
<td>64,000 GJ</td>
</tr>
<tr>
<td>Chernobyl</td>
<td>Nuclear excursion accident</td>
<td></td>
<td>40 GJ</td>
</tr>
<tr>
<td>Steam explosion at nuclear power plant</td>
<td>Accident</td>
<td></td>
<td>0.1 GJ</td>
</tr>
</tbody>
</table>
Three Mile Island - 28 March 1979, Harrisburg PA, USA

- INES Level 5 accident at Unit 2
- Accident type: core meltdown
- Deaths: none

Sequence of events:
- 4 AM: For unknown reasons, secondary water circuit pumps stop
- Steam generators stop automatically and reactor performs emergency shutdown (SCRAM)
- Control rods are inserted but core temperature continues to rise due to residual heat
- Auxiliary pumps activate but valves were closed for maintenance
- Core temperature and pressure rise

- Causes: human error combined with minor equipment failures
TMI accident: sequence of events (cont’d)

• Relief valve on the pressuriser tank opens automatically to vent the steam, but fails to close afterwards due to mechanical failure

• Operators are convinced that the valve is shut, because of a design fault of the indicator lamp

• Water in the core vessel starts to boil

• Operators are convinced that the core vessel is overfilled and turn off the emergency cooling pumps

• Around 6 AM, the top of the reactor core is exposed and cladding starts to melt

• The 6 AM shift correctly identifies the situation and takes steps to control it. Emergency is declared at 6:58 AM

• Roughly 16 hours later, the primary loop pumps were turned on again, and the core temperature began to fall

• Years later investigators will find that at about 8 AM, roughly half of the uranium fuel had already melted
Impact of the TMI accident

- Worst nuclear disaster in the USA
- 40,000 gallons of radioactive waste water was released in the nearby river (an Olympic sized pool contains ≈ 500,000 gallons of water)
- No significant level of radiation was released outside the TMI-2 facility
- Population in the TMI area (≈ 2 million people) were exposed to 1 mrem (a chest X-ray is 10 mrem)
- Ulterior studies found no perceptible effect on cancer incidence; no measurable health effects
- Media coverage was strongly influenced by ‘The China Syndrome’, a thriller released just 12 days earlier
- The event crystallised anti-nuclear safety concerns among activists and general public
- New regulations were introduced
- The accident contributed to a decline of new reactor construction
Chernobyl - 26 April 1986, Prypiat, Ukraine (USSR)

- INES Level 7 accident at Unit 4
- Accident type: steam explosion, nuclear excursion
- Cause: human error, design flaws

Death toll varies widely:
- UNSCEAR 64 (31 directly attributable)
- WHO 4000

Sequence of events:
- A test aimed to improve safety in case of a power grid failure is scheduled
- Plan is to reduce power from 3.2 GWt to between 0.7 and 0.8 GWt
- Power decreases to 0.5 due to reactor poisoning, and due to operator error drops further, to 0.03
- Operators struggle to increase and stabilise the power, retracting all control rods in the process
The result of all this is that the reactor operates now in a regime very far from its safe design configuration; it is now primed for a *positive feedback* loop.

The planned test is started at 1:23 AM. All along, the automatic control system maintains stability by continuously inserting control rods.

Less than a minute later, the test is finished and - for reasons still unknown - a SCRAM is initiated: all controls rods start to be inserted.

Due to a design flaw of the graphite-tipped control rods, the reactivity in the lower half of the core increases and the power output spikes to about 30 GWt.

A steam explosion occurs, tearing off and lifting the 2,000-ton upper plate.

Fuel rods fracture, control rods are jammed at one-third insertion.

Few seconds later, a second explosion resulting from a *nuclear excursion* dispersed the core and effectively terminated the nuclear chain reaction (other hypotheses: steam explosion or hydrogen explosion).

A graphite fire starts; large quantities of radioactive contaminants are dispersed.

In some areas, unprotected workers received fatal doses within minutes.
Impact of the Chernobyl accident

- Worst nuclear power plant accident in history
- 130,000 people were evacuated, a 30km radius Exclusion Zone is still in effect
- 237 people with acute radiation sickness (ARS), of whom 31 died within months
- 400 times more radioactive material than the Hiroshima bomb, but less than 1% of the radioactive material released by the weapon tests of the 1950s and ‘60s
- 100,000 km² of land was contaminated with fallout, the worst hit regions were in Belarus, Ukraine and Russia, but half of it fell outside the USSR (Sweden, Norway)
- Most dangerous isotopes released were $^{131}$I, $^{90}$Sr and $^{137}$Cs
- 15 deaths from Thyroid cancer were recorded since
- No scientifically significant mutations in animals were documented
- No increase in the rate of birth defects or abnormalities, or solid cancers (IAEA)
- Debate about health effects is still ongoing, many studies done
- Economic cost over the last 30 years estimated at £150 billion