Exam 3: Wed. Apr. 19
Covers Quantum Physics, Solids, Nuclear Physics

From last time...
- Fission of heavy elements produces energy
- Only works with $^{235}\text{U}$, $^{239}\text{Pu}$
- Fission initiated by neutron absorption.
- Fission products are two lighter nuclei, plus individual neutrons.
- These neutrons cause other fission events: chain reaction

Today: controlled fission and fusion reactions

Global energy production 2000

- New renewables 0.57%
- Traditional 6.4%
- Hydro 6.6%
- Nuclear 6.0%
- Gas 21.1%
- Coal 21.8%
- Oil 37.5%
- Wind 0.04%
- Solar 0.009%
- Geothermal 0.12%
- Biomass 0.4%
- Traditional 6.4%

Unpressurized steam reactor

Controlled Fission Reactors
- The reactor in a nuclear power plant does the same thing that a boiler does in a fossil fuel plant - it produces heat.
- Basic parts of a reactor:
  - Core (contains fissionable material)
  - Moderator (slows neutrons down to enhance capture)
  - Control rods (controllably absorb neutrons)
  - Coolant (carries heat away from core to produce power)
  - Shielding (shields environment from radiation)
- 1,000 megawatt light-water reactor has a core with ~ 75 tons of uranium ~ 200 fuel assemblies.

The Moderator
- Slow neutrons are more likely to cause fission events
- Most neutrons released in the fission process have energies of about 2 MeV
  - In order to sustain the chain reaction, the neutrons must be slowed down
- A moderator surrounds the fuel
  - Collisions with the atoms of the moderator slow the neutrons down as some kinetic energy is transferred
  - Most modern reactors use heavy water as the moderator

Control rods absorb neutrons, taking them out of the reaction.
- Moderator present to slow neutrons for capture.
Nuclear Waste

- What is all the fuss about nuclear waste?
- The gases formed when uranium atoms are split up are usually very radioactive. The “used” fuel rods from a reactor (discarded when about 25% of the uranium has undergone fission) are kept in a cooling pond for months for the more intensely radioactive atoms to decay and release most of their energy. Then they have to be processed to separate “unused” uranium atoms from the remaining fission products that have to be stored safely in barrels, often in underground bunkers (see photo, right).
- Transmutation

Nuclear Fusion

fuel: hydrogen
Temperature: 400 million °C
heat loss

**fuel:** hydrogen

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Fuel</th>
<th>Product</th>
<th>Ignition Temperature (millions of °C)</th>
<th>Output Energy (keV)</th>
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<tbody>
<tr>
<td>H + H</td>
<td>He 4</td>
<td>n + p</td>
<td>45</td>
<td>17,600</td>
</tr>
<tr>
<td>D + T</td>
<td>He 4</td>
<td>n + p</td>
<td>350</td>
<td>18,200</td>
</tr>
<tr>
<td>D + He</td>
<td>He 4</td>
<td>n + p</td>
<td>480</td>
<td>4,000</td>
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<tr>
<td>D + D</td>
<td>He 4</td>
<td>p</td>
<td>490</td>
<td>-4,000</td>
</tr>
</tbody>
</table>

...carrying an incredible amount of energy!
The fusion reaction

\[ D + T \rightarrow \text{He} + n + \text{energy} \]

\[ \text{Li} + n \rightarrow T + \text{He} + \text{energy} \]

Tritium production

In addition, the fusion neutrons react with Lithium producing Tritium. This is re-cycled to be used in the burning fusion plasma.

Terrestrial fusion reactions

- Deuterium = nucleus of (1 proton & 1 neutron)
- Tritium = nucleus of (1 proton & 2 neutrons)

Two basic fusion reactions:
- deuterium + deuterium \( \rightarrow \) \(^{3}\text{He} + n\)
- deuterium + tritium \( \rightarrow \) \(^{4}\text{He} + n\)

Energy is released as result of fusion:
\[ D + T \rightarrow ^{4}\text{He} (3.5 \text{ MeV}) + n (14.1 \text{ MeV}) \]

Energy determined by mass difference

Routes to fusion

- Magnetic confinement in a torus (in this case a tokamak).
- The plasma is ring-shaped and is kept well away from the vessel wall.

Inertial Confinement: National Ignition Facility

Lead/Gold cylinder, 6mmx10mm Cylinder contains plastic fusion capsule.
Fusion capsule lined with a layer of solid deuterium-tritium (DT) fusion fuel kept near absolute zero.
Energy of intense laser beams converted to thermal x-rays.
x-rays heat and cause implosion/fusion of target.
NIF building at Livermore

Fusion Chamber

- Final plan: fuse 1 pellet / second
- Future problems: manufacturing/supplying one pellet /second.
- Extracting energy from the system.

Magnetic Confinement

- Sun confines hot plasma with gravitational forces
- Inertial confinement implodes the material with high pressures to produce high temperatures for a very short time.
- Third alternative uses magnetic fields to confine the plasma.

States of Matter

- SOLID
- LIQUID
- GAS
- PLASMA

oven
hydrogen gas

heating
Problem: wall contact!

Avoid wall contact with magnetic field.
**JET**

JET is a Tokamak with:
- Torus radius 3.1m
- Vacuum vessel 3.96m high x 2.4m wide
- Plasma volume 80m³
- Plasma current up to 5MA
- Main confining field up to 4 Tesla (recently upgraded from 3.4 Tesla)

**JET tokamak test reactor**

- Vacuum inside torus.
- Plasma confined from walls by magnetic field.
- Fusion induced by providing input power.

**Plasma in the JET torus**

**ITER test reactor**

- Superconducting magnet
- Plasma confinement torus
- Proposed ITER fusion test reactor
Site for ITER chosen

- Cadarache, France

A fusion power plant

Possible fusion reactor

Heat from fusion used to drive turbine to produce electricity.

The future of fusion power

<table>
<thead>
<tr>
<th>When</th>
<th>Fusion Power</th>
<th>Typical Pulse duration</th>
<th>Q</th>
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<tbody>
<tr>
<td>1997</td>
<td>16MW</td>
<td>10 second</td>
<td>0.65</td>
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<tr>
<td>2015-2020</td>
<td>500-700MW</td>
<td>30 minutes</td>
<td>10</td>
</tr>
<tr>
<td>2030/40</td>
<td>1.5-2GW</td>
<td>days/steady state</td>
<td>30</td>
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