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

Unpressurized steam reactor

- Nuclear fuel rods
- 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)

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

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.
Nuclear Waste

- "used" reactor fuel rods (~25% of the uranium fissioned) are still radioactive.
- Kept in a cooling pond for months—highly radioactive atoms to decay.
- Processed to separate "unused" uranium atoms from the remaining fission products—stored in barrels.
- Transmutation

Nuclear Fusion

fuel: hydrogen

Temperature: 400 million °C

Result: intense heat

<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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</thead>
<tbody>
<tr>
<td>D + T</td>
<td>45</td>
<td>He + n</td>
<td>4</td>
<td>17,600</td>
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<tr>
<td>D + He</td>
<td>330</td>
<td>He + p</td>
<td>30</td>
<td>18,200</td>
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<tr>
<td>D + D</td>
<td>400</td>
<td>He + n</td>
<td>35</td>
<td>-6,000</td>
</tr>
<tr>
<td>D + T</td>
<td>400</td>
<td>He + p</td>
<td>35</td>
<td>-6,000</td>
</tr>
</tbody>
</table>

fuel: hydrogen

deuterium tritium helium neutron

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

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

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 \( \rightarrow \) \( ^3\text{He} + \text{n} \)
  - deuterium + tritium \( \rightarrow \) \( ^4\text{He} + \text{n} \)

Energy is released as result of fusion:

\[ \text{D} + \text{T} \rightarrow ^4\text{He} (3.5\text{ MeV}) + \text{n} (14.1\text{ MeV}) \]

Energy determined by mass difference

Fusion bombs

Fission bombs worked, but they weren’t very efficient.

- Fusion bombs, have higher kiloton yields and efficiencies,
  - But design complications
- Deuterium and tritium both gases, which are hard to store.
- Tritium is in short supply and has a short half-life,
- Deuterium or tritium has to be highly compressed at high temperature to initiate the fusion reaction.

Solution:

- Use fission bomb to ignite fusion reaction.

Nuclear Fusion

- ‘Opposite’ process also occurs, where nuclei are fused to produce a heavier nucleus, but requires large initial energy input.
- Called nuclear fusion.

The Origin of Solar Energy
Routes to controlled fusion

- Laser beams compress and heat the target; after implosion, the explosion carries the energy towards the wall.

- 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, 6mm x 10mm
- 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.

problem: wall contact!

avoid wall contact with magnetic field
**avoid wall contact with**

**hot hydrogen plasma**

**magnetic field**

**heating**

**HIGH**

**problem: end losses**

**hot hydrogen plasma**

**avoid end losses: torus!**

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**JET (Joint European Torus)**

**JET** is a **Tokamak** with:
- Torus radius 3.1m
- Vacuum vessel 3.96m high x 2.4m wide
- Plasma volume 86m$^3$
- Plasma current up to 5MA
- Main confining field up to 4 Tesla (recently upgraded from 3.4 Tesla)

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**JET tokamak test reactor**

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

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Plasma in the JET torus

Madison Symmetric Torus

ITER 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>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td>16MW</td>
<td>10 second</td>
<td>0.65</td>
</tr>
<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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