The Significance of Helium-3 Fusion

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Lecture 25
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How do We Make Atoms Fuse?

• Placing them under very high pressures at high temperature.
  – Gravity
  – Inertial confinement

• Heating them to very high temperatures (i.e., high velocities) and running them into each other.
  – Containment with high magnetic fields

• Acceleration into each other at high velocities.
  – Electrostatic confinement
Reactivities ($\Sigma E_{\text{fus}}\sigma v$) versus IEF Well Depth
There Are 2 Basic Approaches to IEF

Purely Electrostatic

Virtual Cathodes (Established by Excess Electrons)

Ion/Grid Collision Losses

Ion Accelerating Well

Cusp Electron Losses

Magnet Coils

Cusp B Fields

Injection At Low E_i

Injection At High E_e

i-Gun

e-Gun

Grids
Fusion Power from a Maxwellian Plasma Comes Mainly from the High-Energy Tail in the Distribution

- The reaction cross-section is high only at temperatures above the peak in the distribution function.

- Considerable energy is invested in filling the Maxwellian with ions which do not contribute to the fusion rate.
Why is IEF Different from Fusion in a Tokamak?

- When containing a collection of plasma particles at high temperatures with a magnetic field, the particles equilibrate in a Maxwellian distribution.

- Considerable energy is invested in filling the Maxwellian with ions which do not contribute much to the fusion rate.
Why is IEF Different from Fusion in a Tokamak?

- In IEF, energy can be invested in only those ions which have a high chance of fusion.
Spherically Convergent Ion Focus Experiment

Converged Core
H$_\alpha$ filtered

18 kV bias
P$_H$ $\approx$ 2 x 10$^{-4}$ torr
Source Plasma ON

$R_{\text{core grid}}$ = 5 cm
$R_{\text{source grid}}$ = 25 cm

NEEP
UW-Madison

Midplane Intensity Profile:

HWHM $\approx$ 0.9 cm
Steady State $D^3He$ Reaction Rate Achieved in Wisconsin IEC Device

cathode voltage=55 kV
cathode current=60 mA
pressure=1 mtorr

Voltage
-50 keV (typical)

reaction products

electric potential well

ion density

Diagram showing reaction products, electric potential well, and ion density.

Picture of a Wisconsin IEC Device with cathode voltage and current details.
Why Are We Interested in $^3$He Fusion if DT Fusion is Easier?
The Public Developed a Resistance to Nuclear Power in the Late 20th Century

The resistance seems to be largely based on:

1) Fear of radioactivity releases
2) Uneasiness with long-term nuclear waste storage
3) Fear of proliferation of nuclear weapons grade material

All of the above problems stem from the nuclear reaction:

1) Radioactive fuel
2) Radioactive reaction products
3) Neutrons
Can the Use of Fusion Fuels Alleviate the Public’s Fear About Radioactivity?
**Fusion Can be Conveniently Divided into Three Eras**

<table>
<thead>
<tr>
<th>Generation</th>
<th>Reaction</th>
<th>Products</th>
<th>Energies</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1st Generation</strong></td>
<td>D + T $\rightarrow$ n (14.07 MeV) + $^4$He (3.52 MeV)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>D + D $\rightarrow$ n (2.45 MeV) + $^3$He (0.82 MeV)  {50%}</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\rightarrow$ p (3.02 MeV) + T (1.01 MeV)  {50%}</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>2nd Generation</strong></td>
<td>D + $^3$He $\rightarrow$ p (14.68 MeV) + $^4$He (3.67 MeV)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>3rd Generation</strong></td>
<td>$^3$He + $^3$He $\rightarrow$ 2p + $^4$He               (12.9 MeV)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The Form of Energy Released Depends on the Fuel Cycle

- DT
- DD
- D3He
- 3He3He
Some Fusion Fuels Have More Radioactivity Associated With Them Than Others

<table>
<thead>
<tr>
<th>Fuel Cycle</th>
<th>Radioactive Fuel</th>
<th>Direct Radioactivity</th>
<th>Indirect Radioactivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>DD</td>
<td>--</td>
<td>n</td>
<td>T</td>
</tr>
<tr>
<td>DT</td>
<td>T</td>
<td>n</td>
<td>--</td>
</tr>
<tr>
<td>D³He</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>³He³He</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>p⁶Li</td>
<td>--</td>
<td>--</td>
<td>n</td>
</tr>
<tr>
<td>p¹¹B</td>
<td>--</td>
<td>--</td>
<td>n</td>
</tr>
</tbody>
</table>

Half Life: \( T = 12.3 \text{ y}, \quad ^{7}\text{Be} = 52 \text{ d}, \quad ^{11}\text{C} = 0.33 \text{ h}, \quad ^{14}\text{C} = 5,600 \text{ y} \)
The Number of Neutrons Generated by Helium-3
Fusion Fuels is Very Small

<table>
<thead>
<tr>
<th>Fusion</th>
<th>Rel. n/MeV Released in Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fission</td>
<td>1</td>
</tr>
<tr>
<td>DT</td>
<td>5</td>
</tr>
<tr>
<td>DD</td>
<td>11</td>
</tr>
<tr>
<td>D(^3)He</td>
<td>0.04–0.2</td>
</tr>
<tr>
<td>(^3)He-(^3)He</td>
<td>0</td>
</tr>
</tbody>
</table>

*burn half of T bred*
The Amount and Form of Energy Release Depends on the Fusion Fuel Cycle Used

Normalized to DT

- DT
- DD
- D3He
- 3He3He

Relative # of Fusion Reactions Needed to Produce the Same Power Level

- Neutrons
- Transport
- Synchrotron
- Bremsstrahlung
The Low Radiation Damage in D³He Reactors Allows Permanent First Walls to be Designed

"Permanent" Life Regime for Steel

Maximum Structural Temperature, °C

Maximum dpa per 30 Full Power Years

UWMAK-III (Mo)
UWMAK-II (AS)
HSR (AS)
ARIES-III
ARIES-II (Y)
ARIES-IV (SiC)
Aries-I (SiC)
Aries-RS (Y)
MARS (FS)
STARFIRE (AS)
ASBA-6C (AS)
UWMAK-I (AS)
MINIMARS (FS)
UWTOR-M (FS)
TITAN (Y)
NUWMAK (Ti)

DT Fuel
D³He Fuel
The Use of 2nd and 3rd Generation Fusion Fuels Can Greatly Reduce or Even Eliminate Radioactive Waste Storage Problems

<table>
<thead>
<tr>
<th>Class of Waste</th>
<th>Relative Cost of Disposal</th>
<th>LWR Fission (Once Through)</th>
<th>DT (SiC)</th>
<th>D³He (SiC)</th>
<th>³He²He (any material)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class A</td>
<td>1</td>
<td>several times Class C amount</td>
<td>several times Class C amount</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class C</td>
<td>≈10</td>
<td>55</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep Geological (Yucca Mtn.)</td>
<td>≈1000</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Nuclear Energy Conversion Efficiencies

Electrical Conversion Efficiencies

- D-3He/3He-3He: 60-70%
- DD: 50%
- DT: 45%
- LMFBR: 40%
- LWR: 33%
Direct Conversion of Plasma Energy to Electricity at High Efficiency Has Been Demonstrated

- Experiment and theory agreed to within 2% for the LLNL direct converter experiments.
The 20th Century Approach to Fusion Only Partly Alleviates Public Concerns About Nuclear Power

<table>
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<tr>
<th>Public Concern</th>
<th>How DT Fusion Addresses Concern</th>
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<tr>
<td><em>Radioactive Releases</em></td>
<td>Avoid runaway reactions and &quot;meltdown&quot; scenarios</td>
</tr>
<tr>
<td></td>
<td>However, still have gigacuries in reactor in the event of an accident</td>
</tr>
<tr>
<td><em>Long Term Radioactive Waste Storage</em></td>
<td>Choice of fuel and structural material can reduce effective half life to $&lt; 100\text{'}s$ years</td>
</tr>
<tr>
<td></td>
<td>However, radiation damage and replacement of components can produce large volumes of radioactive waste</td>
</tr>
<tr>
<td><em>Proliferation</em></td>
<td>Reactor does not require fissile or fertile material</td>
</tr>
<tr>
<td></td>
<td>However, excess neutrons can be used to breed fissile fuel</td>
</tr>
</tbody>
</table>
Characteristics of D $^3$He Fusion Power Plants

- No Greenhouse or Acid Gas Emissions During Operation
- Very High Efficiencies (>70%)
- Greatly Reduced Radiological Hazard Potential Compared to Fission Reactors (<1/10,000)
- Low Level Waste Disposal After 30 y
- No Possible Offsite Nuclear Fatalities in the Event of Worst Possible Accident
Characteristics of $^3\text{He}$ Fusion Power Plants

- No Greenhouse or Acid Gas Emissions During Operation
- Very High Efficiencies Possible (>70%)
- No Residual Radioactivity After 30 Years of Operation (No Radioactive Waste or Nuclear Safety Hazard).

Nuclear Energy Without Nuclear Waste !!
# Major Societal and Technical Concerns of Nuclear Energy Options

<table>
<thead>
<tr>
<th>Major Societal and Technical Concerns</th>
<th>Fission</th>
<th>Fusion Generation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DT</td>
<td>DD</td>
</tr>
<tr>
<td>Proliferation</td>
<td>Red</td>
<td>Yellow</td>
</tr>
<tr>
<td>Radiation Damage</td>
<td>Red</td>
<td>Yellow</td>
</tr>
<tr>
<td>Nuclear Waste</td>
<td>Red</td>
<td>Yellow</td>
</tr>
<tr>
<td>Radiological Hazard</td>
<td>Red</td>
<td>Yellow</td>
</tr>
<tr>
<td>Tritium</td>
<td>Red</td>
<td>Yellow</td>
</tr>
<tr>
<td>Physics Req't.</td>
<td>Green</td>
<td>Yellow</td>
</tr>
</tbody>
</table>

*Hardest - Major Problem, Easiest - Minor Problem*
Why Consider the Advanced Fuels for Power Production?

**Major Advantages**

- Significant Reduction in Radiation Damage  
  – (permanent 1st wall)
- Greatly reduced (or no) radioactivity
- Potential for Direct Conversion  
  – (higher efficiency & lower waste heat)

**Major Disadvantages**

- Higher operating temperature  
  – (higher $n\tau$ values)
- Lower plasma power density or yield  
  – (requires higher beta or $\rho r$)
- Fuel source - $^3$He  
  – (requires NASA collaboration)
The Steady State D-³He Fusion Rate in the UW IEC Device is Now $1.5 \times 10^8$ p/s
(115 kV, 60 mA)

Run 265
90kV, 30mA
Significant Progress Has Been Made in Producing High Energy Protons from the D\(^3\)He Reaction

Steady State Reactions/Second

Date Experiments Conducted in Wisconsin IEC Device
Significance of Lunar Helium-3

- 1 tonne of He-3 can produce 10,000 MWe-y of electrical energy.

- 40 tonnes of He-3 will provide for the entire U.S. electricity consumption in 2000.
At 1 Billion Dollars a Tonne the Energy Cost of Helium-3 is Equivalent to Oil at $7 per Barrel
There is 10 Times More Energy in the Helium-3 on the Moon Than in All the Economically Recoverable Coal, Oil and Natural Gas on the Earth.
The Development of the 2nd and 3rd Generation Fusion Fuels in the 21st Century Could Lead to Near Term, as Well as Long-Term Benefits to Society

**Phase 1**
- Near Term Spinoff from a Q < 1 Device
  - Medical Treatment
  - Civilian Commercial Markets
  - Environmental Restoration
  - Defense

**Phase 2**
- Intermediate Term Spinoff from a Q = 1–5 Device
  - All of Phase 1
  - Destruction of Toxic Materials
  - Space Power
  - Propulsion Technologies
  - Remote Electricity Stations

**Phase 3**
- Long Range Benefits of a Q>10 IEC Device
  - All of Phase 1
  - All of Phase 2
  - Small, Safe, Clean and Economical Electrical Power Plants

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- Medical Treatment
- Civilian Commercial Markets
- Environmental Restoration
- Defense

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- All of Phase 1
- All of Phase 2
- Small, Safe, Clean and Economical Electrical Power Plants
### Applications

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<th>Near Term</th>
<th>Long Range</th>
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</thead>
<tbody>
<tr>
<td>• Medical Isotope Production</td>
<td>• Small (50-100 MWe) Electrical Power Plants</td>
</tr>
<tr>
<td>• Cancer Therapy</td>
<td>• Use of Advanced Fuels (Helium-3)</td>
</tr>
<tr>
<td>• Detection of Explosives</td>
<td>• Space Propulsion</td>
</tr>
<tr>
<td>• Detection of Chemical Wastes</td>
<td>• Base Load Electrical Power Plants</td>
</tr>
<tr>
<td><strong>Mid-Term</strong></td>
<td><strong>Long Range</strong></td>
</tr>
<tr>
<td>• Destruction of Fissile Material</td>
<td>• Hydrogen Production</td>
</tr>
<tr>
<td>• Destruction of Radioactive Wastes</td>
<td>• Synthetic Fuel Production</td>
</tr>
</tbody>
</table>
Conclusions

The use of second and third generation fusion fuels could revolutionize the Public's view of fusion power by:

1) eliminating one of the greatest barriers to public acceptance of nuclear power – the concern over radioactive waste, radioactivity releases, and proliferation of weapons grade

2) allowing off-the-shelf structural materials to be used, thus eliminating expensive neutron test facilities & long development times.

3) allowing high efficiency operation and in-city siting of electrical power plants
They Said It Couldn’t Be Done

"Man will not fly for fifty years." – Wilbur Wright, 1901

"Heavier-than-air flying machines are impossible." – Lord Kelvin, president, Royal Society, 1895

"There is not the slightest indication that [nuclear energy] will ever be obtainable. It would mean that the atom would have to be shattered at will." – Albert Einstein, 1932

"Anyone who looks for a source of power in the transformation of the [nucleus of the] atom is talking moonshine." – Ernest Rutherford, 1933

"Space travel is utter bilge." – Dr. Richard Wooley, Astronomer Royal, space advisor to the British government, 1956

"Airplanes are interesting toys but of no military value." – Marshall Foch, future WWI French commander-in-chief, 1911