Fusion Fuel Cycles

\[ \text{Deuterium} + \text{Tritium} \rightarrow \text{Neutron} + \text{Helium-4} \] 17.6 MeV

\[ \frac{1}{2} \text{Deuterium} + \frac{1}{2} \text{Deuterium} \xrightarrow{50\%} \text{Neutron} + \text{Hydrogen} + \frac{1}{2} \text{Helium-3} \] 3.3 MeV

\[ \frac{1}{2} \text{Deuterium} + \frac{1}{2} \text{Helium-3} \rightarrow \text{Hydrogen} + \text{Helium-4} \] 18.4 MeV

\[ \text{Helium-3} + \text{Helium-3} \rightarrow \text{Hydrogen} + \text{Hydrogen} + \text{Helium-4} \] 12.9 MeV
The Tokamak is the leading magnetic fusion concept for the DT fuel cycle.

\[ D + T \rightarrow n \text{(14 MeV)} + ^4\text{He} \text{(3.5 MeV)} \]

Schematic of a Tokamak

Joint European Torus – JET

~ 40 MW
Inertial fusion energy (IFE) power plants of the future will consist of four parts:

**Target factory**
To produce low-cost targets rapidly
- \(1-2 \times 10^8\) yr
- Cost < 30¢/target
- Survivable targets

**Driver**
To heat and compress the target to fusion ignition
- Many beams
- 5–10 Hz operation
- \(\eta > 5\%\) (depends on target gain)
- > 500 TW total peak power
- Brightness sufficient to illuminate target at > 5 m standoff

**Focusing element**
- Optics survive > 1 yr
- Protected from x-rays and debris

**Fusion chamber**
To recover the fusion energy pulses from the targets
- High rep-rate operation (5–10 Hz)
- Protected first wall
- High availability (> 95%)

**Steam plant**
To convert fusion heat into electricity
- Conversion efficiency 40–50%

An IFE power-plant would ignite five to ten targets per second to produce as much electricity as today’s one gigawatt power plant.
There Are Four Different ICF Target Designs

Direct Drive Lasers

Indirect Drive Lasers

(Fast Ignitor Variation)

Indirect Drive Heavy Ions

Indirect Drive Light Ions
There are 4 Current ICF Drivers

**Laser**

**Heavy Ion Beam**

**Light Ion Beam**

**Z-Pinch** – Energy application depends on finding a credible rep-rate concept

Light ion development currently on hold due to inability to focus adequately
The Form of Energy Release is Quite Different in DT, DD, D³He and ³He-³He Fuel Cycles

Fraction of Total Energy Released

- ARIES-I (DT)
- WILDCAT (DD)
- Apollo-L3 (D³He)
- POLYWELL™ (³He-³He)

- Bremsstrahlung
- Synchrotron
- Transport
- Neutrons

Graph showing the fraction of total energy released in different fuel cycles.
The Amount and Form of Energy Required to Make Fusion Power is Quite Dependent on the Fusion Fuel Cycle

Relative Amount of Fusion Reactions to Make the Same Electrical Power
Maxwellian Fusion Reaction Rates

- DT
- $D^3He$
- DD
- $p^{11}B$
- $^{3}He^{3}He$

Reaction Rate ($m^3/s$)

Ion Temperature (keV)
Magnetic Fusion Has Made Outstanding Progress During the Past 15 Years

- Computer Chip Memory (Bytes)
- Fusion Power (Watts)

- Achieved (DHe3)
- Achieved (DD)
- Achieved (DT)
- Projected (DT)

Year:
- 1970
- 1975
- 1980
- 1985
- 1990
- 1995
- 2000
- 2005
- 2010
There Are 2 Basic Approaches to IEF

Purely Electrostatic

Virtual Cathodes (Established by Excess Electrons)

- Grids
- Magnet Coils
- i^+ Gun
- Injection At Low $E_i$
- Ion Accelerating Well

- Cusp B Fields
- e^- Gun
- Injection At High $E_e$
- Cusp Electron Losses

Ion/Grid Collision Losses
**Spherically Convergent Ion Focus Experiment**

- Converged Core
- $H_\alpha$ filtered

- $18 \text{kV bias}$
- $P_H \approx 2 \times 10^{-4} \text{ torr}$
- Source Plasma ON

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

**Midplane Intensity Profile:**

- HWHM $\approx 0.9 \text{ cm}$
Reactivities ($\Sigma E_{\text{fus}}$) versus IEF Well Depth

![Graph showing reactivities versus IEF Well Depth. The x-axis represents IEF Well Depth (kV) ranging from 1 to 500. The y-axis represents Reactivity (MeV-m$^3$/s) ranging from $10^{-24}$ to $10^{-19}$.

- DT
- D$^3$He
- DD
- $^3$He-$^3$He
- p-$^{11}$B]
Blanket and Shield Design

Objective: To convert TN heat into useful energy, i.e.,

- **Steam**
- **Fissile Fuel**
- **Synthetic Fuel**
- **Electricity (directly)**

---

**Fusion**

- Neutrons
- Photons
- Ions
- Neutrals

**1st Wall**

- **Blanket**
  - 1 cm
  - = 50 cm

- **Moderator**
  - = 20 cm

- **Reflector**
  - = 50 - 100 cm

**Surface flux**

- Slow Down n's & Breed Tritium
- Reflect Neutrons
- Absorb Neutrons
Chamber Pressure

Magnetic ≈ 10^{-5} \text{ torr}

Laser ≈ 1 \text{ torr}

HIB ≈ 10^{-4} \text{ torr}

LIB ≈ 1-100 \text{ torr}

What Kind of Materials are in Fusion Reactors?

**Chamber Gas**  He, Ne, Xe

**Blankets**
- Structure  Steel, V, SiC, C, Ti Alloys
- Breeder  Li, Li_2O, LiAlO_2, Pb-Li, H_2O +LiOH

**Coolants**  H_2O, Li, He, Pb-Li, Li_2O

**n Multipilier**  Be, Pb, Zr

**Moderator/ Reflector**  Steel, C

**Shield**  Steel, B, Pb, W, Concrete
The DT Fusion Cycle Uses D and Li Fuels

\[ ^2\text{H} + ^3\text{H} \rightarrow ^4\text{He} \]

\[ ^7\text{Li} \rightarrow ^4\text{He} + ^3\text{H} \]

\[ ^6\text{Li} \rightarrow ^4\text{He} + ^3\text{H} \]

\[ \text{n (14.1 MeV)} \]

92.5% \[ ^7\text{Li} \]

7.5% \[ ^6\text{Li} \]
Potential Lithium Containing Materials That Could Be Used to Breed Tritium

Li atoms/cm³ x 10²²

Non-Metallic
Metallic

Li (liq.)
Li₂BeF₄ (liq.)
LiBi₅Pb₄ (liq.)
LiH
LiF
LiOH
Li₂C₂
LiAl
Li₃N
Li₃Bi
Li₄SiO₄
LiAlO₂

T_melt (°C)

0 500 1000 1500 2000
# Information Summary of Candidate Breeder Materials

<table>
<thead>
<tr>
<th></th>
<th>Li(liquid)</th>
<th>LiPb₄ (liq)</th>
<th>LiBi₅Pb₄ (liq)</th>
<th>Li₇Pb₂(s)</th>
<th>LiAl(s)</th>
<th>Li₂O(s)</th>
<th>LiAlO₂(s)</th>
<th>LiOH( liq)</th>
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<td>Materials Data Base</td>
<td>Good</td>
<td>Poor</td>
<td>Zero</td>
<td>Fair</td>
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<td>MP °C</td>
<td>180</td>
<td>235</td>
<td>125</td>
<td>726</td>
<td>700</td>
<td>1440</td>
<td>1600</td>
<td>0</td>
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<tr>
<td>Tmin °C</td>
<td>230</td>
<td>285</td>
<td>175</td>
<td>270</td>
<td>250</td>
<td>500</td>
<td>450</td>
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<td>Tmax °C</td>
<td>400</td>
<td>550</td>
<td>400</td>
<td>330</td>
<td>310</td>
<td>800</td>
<td>850</td>
<td>200</td>
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<td>Reason for Tmax</td>
<td>Corrosion</td>
<td>Corrosion</td>
<td>Corrosion</td>
<td>&lt;---------Sintering-------------&gt;</td>
<td>Corrosion</td>
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<tr>
<td>Breeding Capability</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Excellent</td>
<td>Poor</td>
<td>Good</td>
<td>Poor</td>
<td>Good</td>
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<tr>
<td>Steady Tritum</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
<td>Fair</td>
<td>Excellent</td>
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<tr>
<td>recovery</td>
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<td></td>
<td></td>
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<tr>
<td>Reactor Relevant</td>
<td>Very Good</td>
<td>Very Good</td>
<td>Very Good</td>
<td>poor</td>
<td>Poor</td>
<td>?</td>
<td>?</td>
<td>Poor</td>
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<tr>
<td>Chemical Reactivity</td>
<td>Bad</td>
<td>Fair</td>
<td>Fair</td>
<td>Poor</td>
<td>Poor</td>
<td>Hygroscopic</td>
<td>Best</td>
<td>Best</td>
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</tbody>
</table>
Structure: TZM
Breeder: Li
Coolant: Li
Reflector: C
BLANKET SECTION FOR UWMAK-II

HELIUM SUPPLY HEADERS

HELIUM RETURN HEADERS

11 cm

3 cm

48 cm

89 cm

27 cm

23.1 cm

VERTICAL STRUCTURE SECTION

STAINLESS STEEL CANS

GRAPHITE S.S. CLAD

TRITIUM COLLECTION MANIFOLDS

SEAL BETWEEN CELLS

ATTACHMENT POINT

Li Al O₂

Be

Li Al O₂

COOLANT CHANNELS

SECTION A-A

REMOVABLE FRONT WALL SECTION

PLASMA
Tritium Decay

\[ ^3\text{H} \rightarrow \text{Beta (5.7 keV)} + ^3\text{He} \]

\[ t_{1/2} = 12.35 \text{ y} \quad 5.6\% \text{ y}^{-1} \]

Tritium Costs

Activity = 10,000 Ci/g
Cost \approx \$30,000/g \quad 30\$B/tonne

Biological Effects

- Biological half life \approx 10 \text{ days}
- Ingested Dose \quad 1 \text{ Ci} \approx 70 \text{ mrem}
- Maximum Permissible Body Burden \approx 1 \text{ mCi}
- Oxide forms (HTO, \text{T}_2\text{O}) greater hazard than gaseous forms
Figure 1. Hydrogen permeability curves for selected metals and alloys.
<table>
<thead>
<tr>
<th></th>
<th>Units</th>
<th>Plutonium</th>
<th>Tritium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inv. Outside Blanket</td>
<td>kg</td>
<td>900</td>
<td>25</td>
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<tr>
<td>Annual Flow Outside Blk.</td>
<td>kg/y</td>
<td>1600</td>
<td>32 (BR=1.25)</td>
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<tr>
<td>MPC (air)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insoluble $^{239}$Pu, HT or T$_2$ gas</td>
<td>Ci/km$^3$</td>
<td>0.001</td>
<td>40,000</td>
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<tr>
<td>Sol. $^{239}$Pu, HTO vapor</td>
<td>Ci/km$^3$</td>
<td>0.0006</td>
<td>200</td>
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<tr>
<td>BHP (air)</td>
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<td></td>
<td></td>
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<tr>
<td>Pure $^{239}$Pu, T$_2$</td>
<td>km$^3$/g</td>
<td>63 to 1,000</td>
<td>0.25</td>
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<tr>
<td>Reactor Pu*, T in HTO</td>
<td>km$^3$/g</td>
<td>300 to 5,000</td>
<td>50</td>
</tr>
<tr>
<td>BHP (air)/GWe•y</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insoluble Pu, T$_2$</td>
<td>million km$^3$/y</td>
<td>450</td>
<td>0.008</td>
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<tr>
<td>Soluble Pu, HTO</td>
<td>million km$^3$/y</td>
<td>7,500</td>
<td>1.6</td>
</tr>
<tr>
<td>BHP (air)/GWe</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insoluble Pu, T$_2$</td>
<td>million km$^3$</td>
<td>270</td>
<td>0.006</td>
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<tr>
<td>Soluble Pu, HTO</td>
<td>million km$^3$</td>
<td>4,500</td>
<td>1.25</td>
</tr>
<tr>
<td>MPC (water)</td>
<td>Ci/km$^3$</td>
<td>5,000</td>
<td>3,000,000</td>
</tr>
<tr>
<td>BHP (water)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pure $^{239}$Pu in Soluble Compound</td>
<td>m$^3$/g</td>
<td>12,500</td>
<td></td>
</tr>
<tr>
<td>Reactor Pu* in Soluble Compound</td>
<td>m$^3$/g</td>
<td>62,500</td>
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</tr>
<tr>
<td>Pure Tritium in HTO</td>
<td>m$^3$/g</td>
<td>3,300,000</td>
<td></td>
</tr>
<tr>
<td>BHP/GWe•y</td>
<td>km$^3$/water/ y</td>
<td>94</td>
<td>110</td>
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<tr>
<td>BHP/GWe</td>
<td>km$^3$/water</td>
<td>56</td>
<td>83</td>
</tr>
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</table>

* $^{238}$Pu, $^{239}$Pu, $^{240}$Pu, $^{241}$Pu, $^{242}$Pu