# FUSION ENERGY SOLUTION TO GLOBAL WARMING AND FOSSIL DEPLETION

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## Energy Supply for Humanity

### Energy Supply Objectives

- Energy resources should be sustainable;
- Energy produced should be socially acceptable;
- Energy supply systems should be environmentally acceptable;
- Releases of pollutants into the environment from energy supply systems should be limited;
- Energy systems should not cause health problems;
- Energy produced should be affordable for promoting sustainable development.

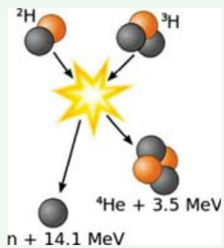
### Energy From Fossil Fuels

- 12 TW are today required for humanity on Earth;
- 80% of energy produced is supplied by fosil fuels;
- 40 $GtCO_2e/yr$ are emitted into the atmosphere;
- Earth's climate system is warming;
- Fossil fuels are severely being depleted.

### Energy From Nuclear Fusion

- High power density (10 $MW/m^2$);
- No long-lived radionuclides are produced;
- No greenhouse gases are produced;
- Fusion fuels are sustainable for millions of years;
- Existing energy distribuion systems can be utilized;
- Controlled fusion is difficult to achieve and will take perseverence.

**Fusion reactions between *deuterium* $D$ ($^2_1H$) and *tritium* $T$ ($^3_1H$) nuclei**



Reactants (r) $a$ and $b$ produce products (p) $c$ and $d$:

$$a+b \rightarrow c+d,\ D+T \rightarrow n+^4_2He+ 17.6\ \text{Mev}$$

Relativistic total energy (rest mass and kinetic) is conserved:

$$\sum_r Mc^2 - \sum_p Mc^2 = \sum_p E_{KE} - \sum_r E_{KE}$$

Binding energy: $B = (Zm_p + (A-Z)m_n - M)c^2$

Q value of nuclear reaction (> 0 for exothermic reaction):

$$Q = \sum_r Mc^2 - \sum_p Mc^2 = \sum_p B - \sum_r B$$

To 1 eV energy corresponds the *plasma* (ionized atoms) temperature of:

$$T_{p1eV} = \frac{1eV}{k_B} = \frac{1.6\times10^{-19}}{1.4\times10^{-23}} = 11,600\ \text{K}$$

Tritium breedig: $n+^6_3Li \rightarrow T+^4_2He + 4.8\ \text{MeV}$

Tritium breedig: $n+^7_3Li \rightarrow T+^4_2He + n - 2.5\ \text{MeV}$

Tritium breeding ratio: TBR=(T production in blanket)/(T destruction in plasma) > 1

## Fusion Energy Harnessing

### Magnetic Confinement Fusion (MCF)

Figure of merit (fusion power produced/external power required to keep plasma hot): $Q_{fus} = \frac{P_{fus}}{P_{aux}}$

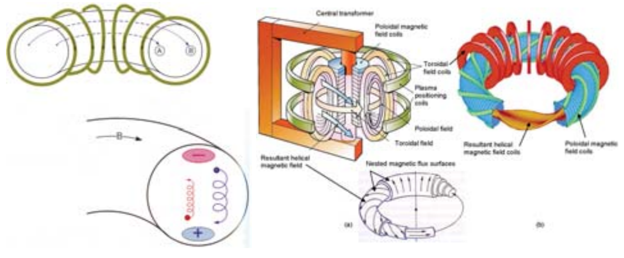
Thermonuclear ignition requires: $Q_{fus} = \infty\ (P_{aux} = 0)$; Fusion power plants require: $Q_{fus} = 30 - 50$

Confinement parameter: $n\tau_E = \frac{3k_BT}{\frac{1}{4}(1/Q_{fus}+\frac{1}{5})Q_{DT}<\sigma v>-C_bT^{0.5}}$

$Q_{DT} = 14.7$ MeV, $Q_{fus} = 1$, $<\sigma v>$ evaluated at $k_BT = 12$ KeV: $n\tau_E > 10^{20}\text{sm}^{-3}$

To confine plasma in a torus a helical magnetic field is required (tokamak and stellarator configurations).
For stable operation, the *safety factor* above 3 is required.

A simple toroidal magnetic field produces ion and elecron drifts that expel the charged particles from plasma (left figure). The avearge number of times a field line goes the short way around a cross-section for each time that it goes the long way around the torus measures the amount of twist and is called the *rotational transform* (inverse of safety factor).



Plasma equilibrium is largely maintained with $\nabla P = \boldsymbol{J} \times \boldsymbol{B}, \boldsymbol{B}\cdot\nabla P = 0, \boldsymbol{J} = \sigma\,(\boldsymbol{E} + \frac{1}{c}\,\boldsymbol{v} \times \boldsymbol{B})$.
$\boldsymbol{J}$ and $P$ are sources of plasma instabilities (kink, interchange, classical and neoclassical diffusion, tearing, sawtooth oscillations, microinstabilities arising from non-uniformity, anisotropy, turbulence, etc.).

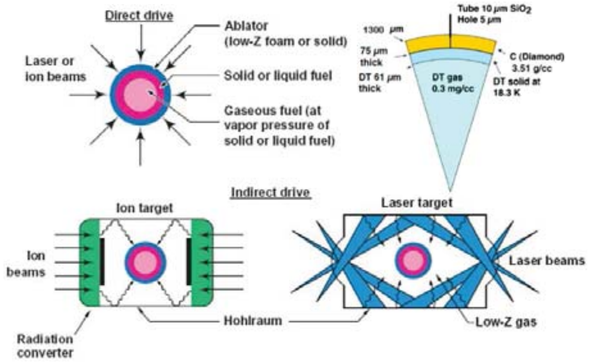
JET (UK) and TFTR (USA) tokamaks produced fusion.

### Inertial Confinement Fusion (ICF)

Target energy gain (fusion energy produced/energy delivered to the target): $G = \frac{E_{fus}}{E_d}$

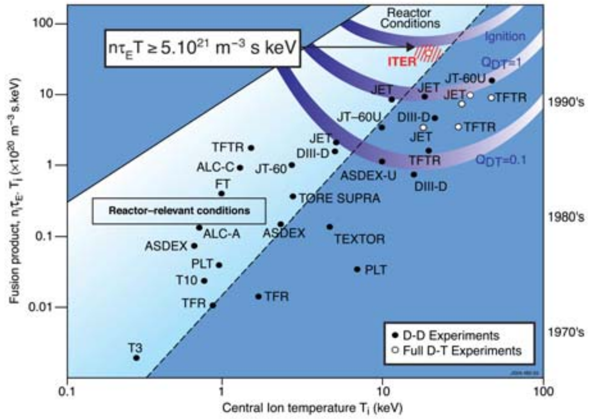
Figure of merit $Q_{fus} = G\eta_d = \frac{1}{\eta_b f}$, where $\eta_d$ is the driver efficiency, $\eta_b$ is the blanket efficiency, $f$ is the recycling power fraction.

$\eta_d = 0.15, \eta_b = 0.4, f = 0.2$: $G = 83$, $Q_{fus} = 12.5$. $E_d = (2-5)$ MJ, $G = 100$: $E_{fus} = (200 - 500)$ MJ per target. Burning 10 targets/s, fusion power release is 2-5 GW.



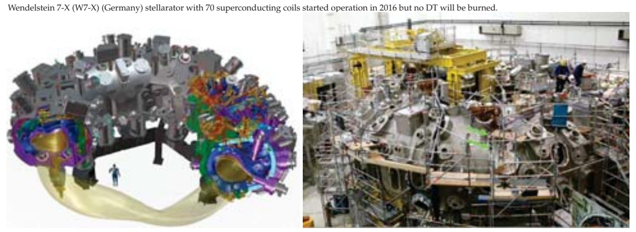
- **Energy supply to fuel targets in 100 ns:** Direct drive, indirect drive (lasers, heavy-ion beams), pulsed power (tens of MA current discharges);
- **Fuel target ignition in 100 ps:** Hot spot, fast, shock, Z-pinch;
- **Instabilities:** Parametric (caused by laser radiation), hydrodynamic (caused by density gradients in fuel during compression);
- **Scientific feasibility of inertial fusion:** Not yet demonstrated, but produced $\alpha$-heating with indirect laser DT targets at LLNL.

## Experimental Machines

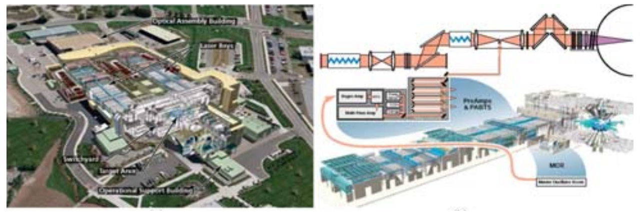


TFTR (USA), JET (UK), JT-60U (Japan) tokamaks. TFTR and JET demonstrated DT fusion.

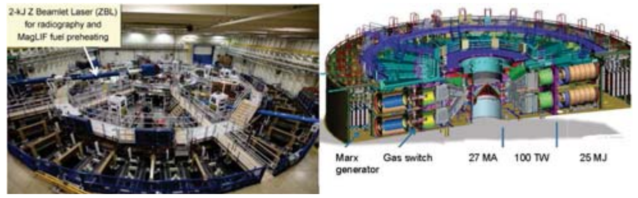
Wendelstein 7-X (W7-X) (Germany) stellarator with 70 superconducting coils started operation in 2016 but no DT will be burned.



National Ignition Facility at Lawrence Livermore National Laboratory with192 laser beams demonstrated $\alpha$-heating but not DT fusion.

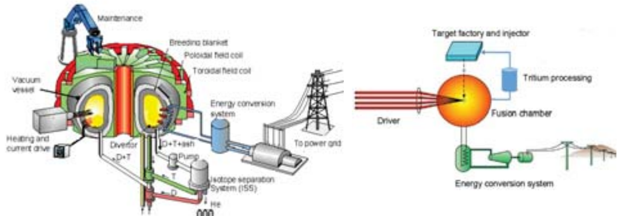


Z-machine at Sandia National Laboratories with Beamlet Laser for preheating fuel targets. Several billion degrees temperature achieved but not plasma ignition.

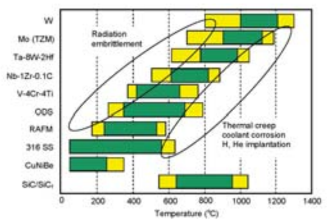


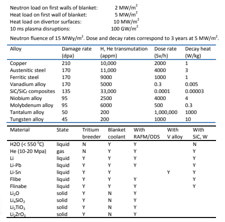
## Fusion Reactor Technology

### ITER & DEMO Fusion Power Reactors



### Materials and Coolants for Fusion Reactors





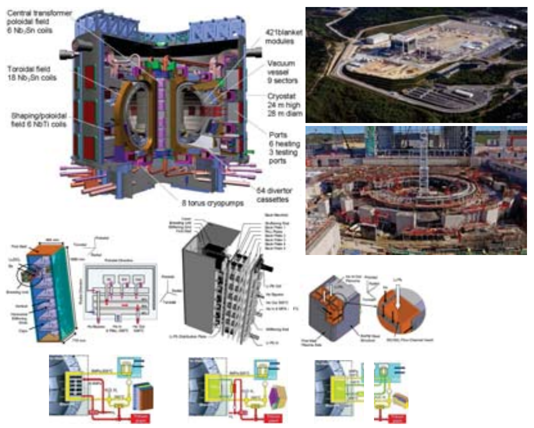
Neutron load on first walls of blanket: 2 MW/m$^2$
Heat load on first wall of blanket: 5 MW/m$^2$
Heat load on divertor surfaces: 10 MW/m$^2$
10 ms plasma disruptions: 100 GW/m$^2$

Neutron fluence of 15 MWy/m$^2$. Dose and decay rates correspond to 3 years at 5 MW/m$^2$.

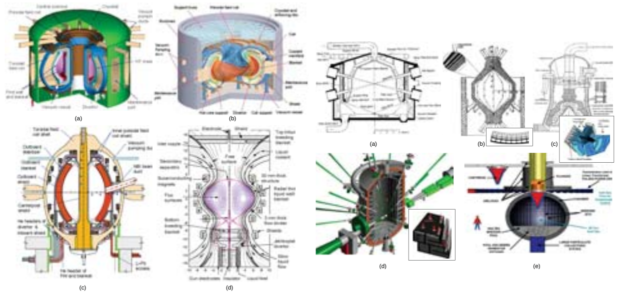
| Alloy | Damage rate (dpa) | H, He transmutation (appm) | Dose rate (Sv/h) | Decay heat (W/kg) |
|---|---|---|---|---|
| Copper | 210 | 10,000 | 2000 | 1 |
| Austenitic steel | 170 | 11,000 | 4000 | 3 |
| Ferritic steel | 170 | 9000 | 1000 | 1 |
| Vanadium alloy | 170 | 5000 | 0.3 | 0.005 |
| SiC/SiC$_f$ composites | 135 | 33,000 | 0.0001 | 0.00003 |
| Niobium alloy | 95 | 2500 | 4000 | 4 |
| Molybdenum alloy | 95 | 6000 | 500 | 0.3 |
| Tantalum alloy | 50 | 200 | 1,000,000 | 1000 |
| Tungsten alloy | 45 | 200 | 1000 | 10 |

| Material | State | Tritium breeder | Blanket coolant | With RAFM/ODS | With V alloy | With SiC, W |
|---|---|---|---|---|---|---|
| H2O (< 550 °C) | liquid | N | Y | Y |  | N |
| He (10-20 Mpa) | gas | N | Y | Y |  | Y |
| Li | liquid | Y | Y | Y |  | Y |
| Li-Pb | liquid | Y | Y | Y |  | Y |
| Li-Sn | liquid | Y | Y |  | Y | Y |
| Flibe | liquid | Y | Y | Y |  | Y |
| Flinabe | liquid | Y | Y | Y |  | Y |
| $Li_2O$ | solid | Y | N | Y |  |  |
| $Li_4SiO_2$ | solid | Y | N | Y |  |  |
| $Li_2TiO_3$ | solid | Y | N | Y |  |  |
| $Li_2ZrO_3$ | solid | Y | N | Y |  |  |

### ITER DT Fusion by 2035 and TBMs for DEMOs



### MCF and ICF DEMO Fusion Reactors by 2050



## Sustainability of Fusion Energy

### Prospects for Achieving Fusion Ignition

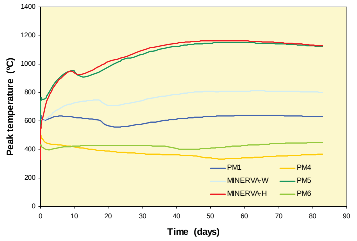
- DT fusion in JET and TFTR tokamks has been achived for several seconds only;
- LHD, W7-X, and ITER will help build MCF DEMOs;
- ICF laser and ion beam advances show great promise.

### Sustainability of DT Fusion Materials

- D resources: 1 part of $D_2O$/6400 parts of $H_2O$;
- T can be produced from Li and neutron multiplying materials Be and Pb. Resources: Li 230 Gt ($10^6$ yrs), Be 80 kt, Pb 1.5 Gt;
- He is used in superconducting coils ($Nb_3Sn$ and NbTi) and to cool blankets. Resources: He 10 Mt, Nb 4 Mt;
- Issues with Li (if also used in batteries), Be, He, Nb;
- Advanced fusion fuels: $p+^{11}B \rightarrow 3\alpha$. Resources: B 210 Gt.

### Safety and Environmental Issues

- Only tritium and neutron-activated materials are produced in fusion reactors. No high-level radioactive waste is produced;
- No long-term isolation of activated materials is required. Once removed, materials can be safely handled after 50-100 years;
- Fusion reactor contains a small amount of fuel inventory and low power density. Reactions are terminated after 1 minute.;
- No active cooling of fusion reactor is required after an accident;
- Worst possible accident does not constitute a major hazard to populations outside the plant (< 4 mSv/y background).



## Conclusions

- Sustainability of fusion energy requires:
  Sustained ignition, long-term supply of fusion fuels, low-activation materials, high efficiency energy conversion systems, safe operations of plants;
- Fusion will become (with perseverence) a sustainable energy source.