Materials Challenges for Fusion Energy

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Materials-The Opportunity

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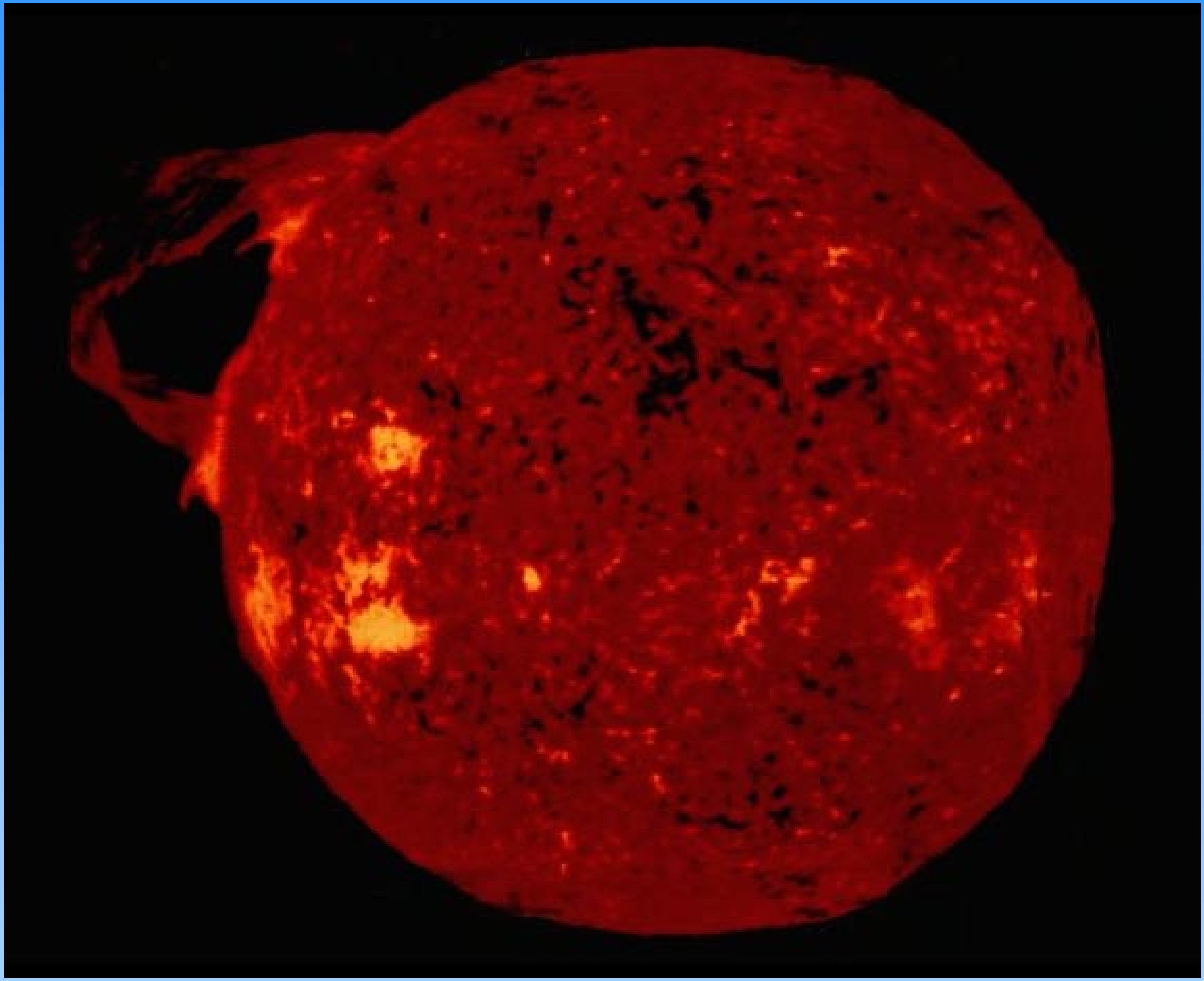
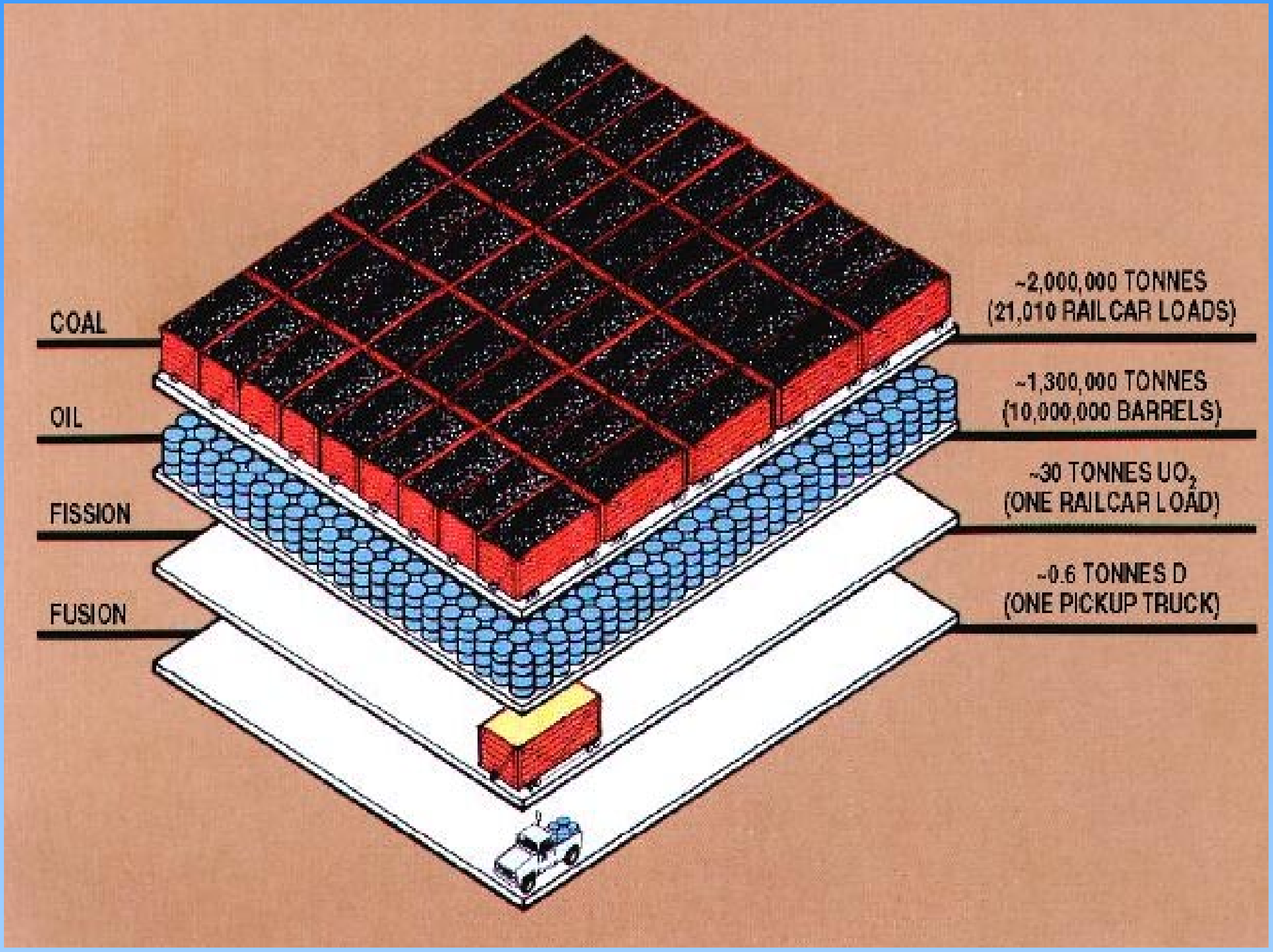


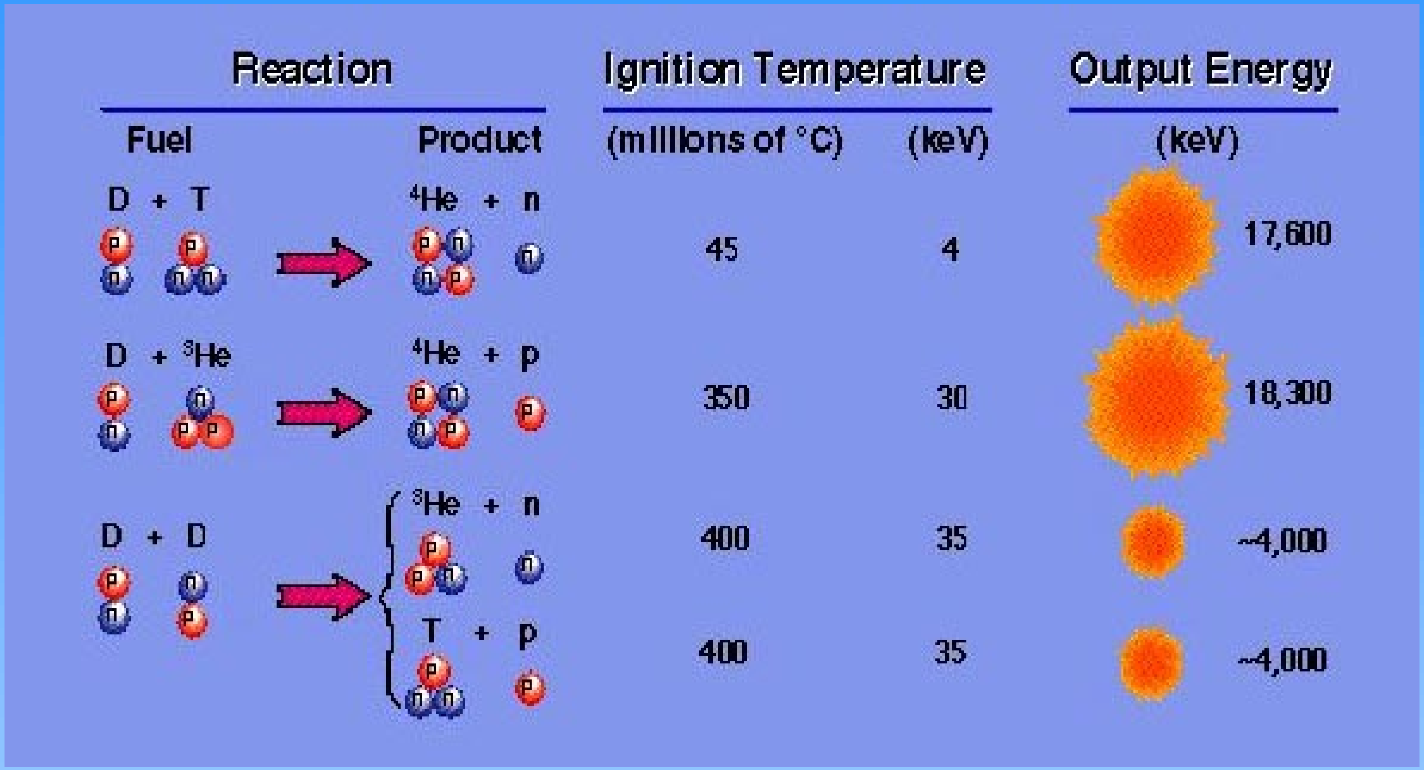
“I remain dedicated to the concept of fusion power, as a citizen, and I wish I was in a position to do more about it.” Ansel Adams, July 1983

Annual Fuel Requirements for a 700 MW_e Power Plant



One cup of water (D-D reaction) = 20 gallons of oil

Partial List of Fusion Reactions



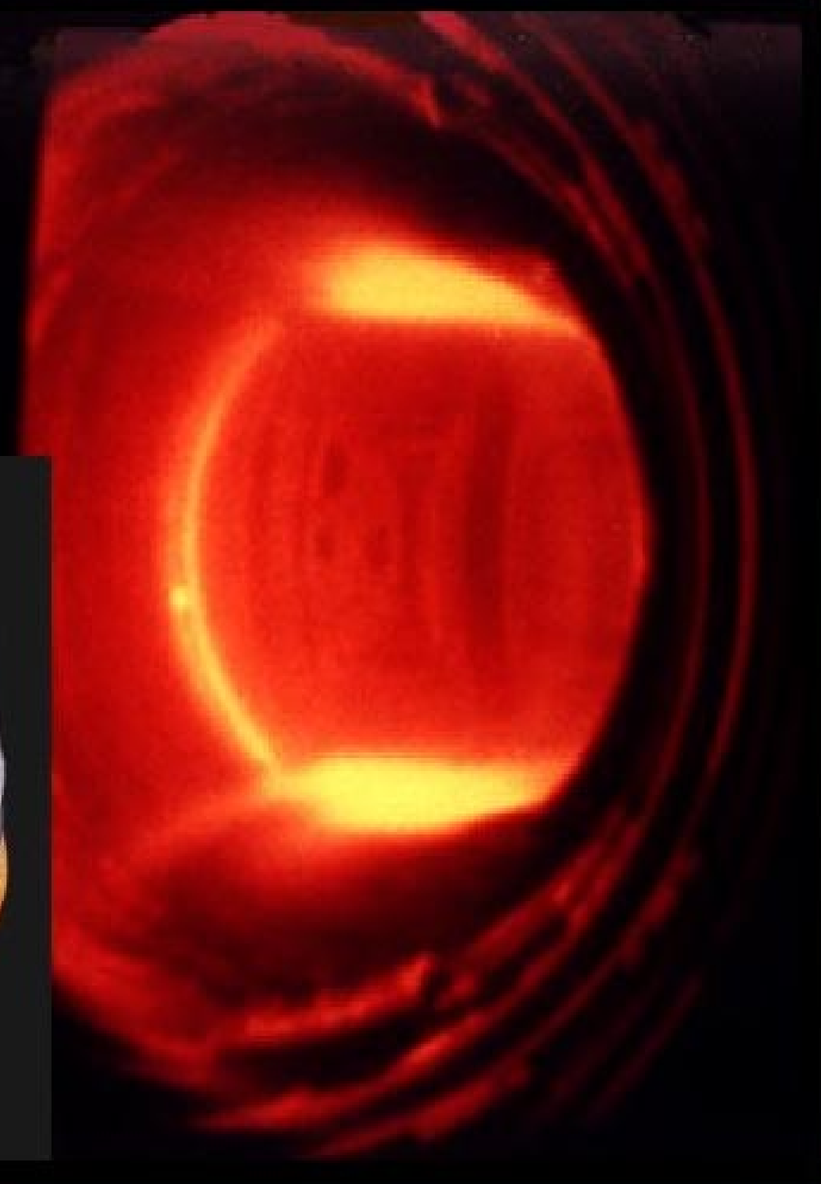
Tritium can be made from lithium (n + Li –> T + He)

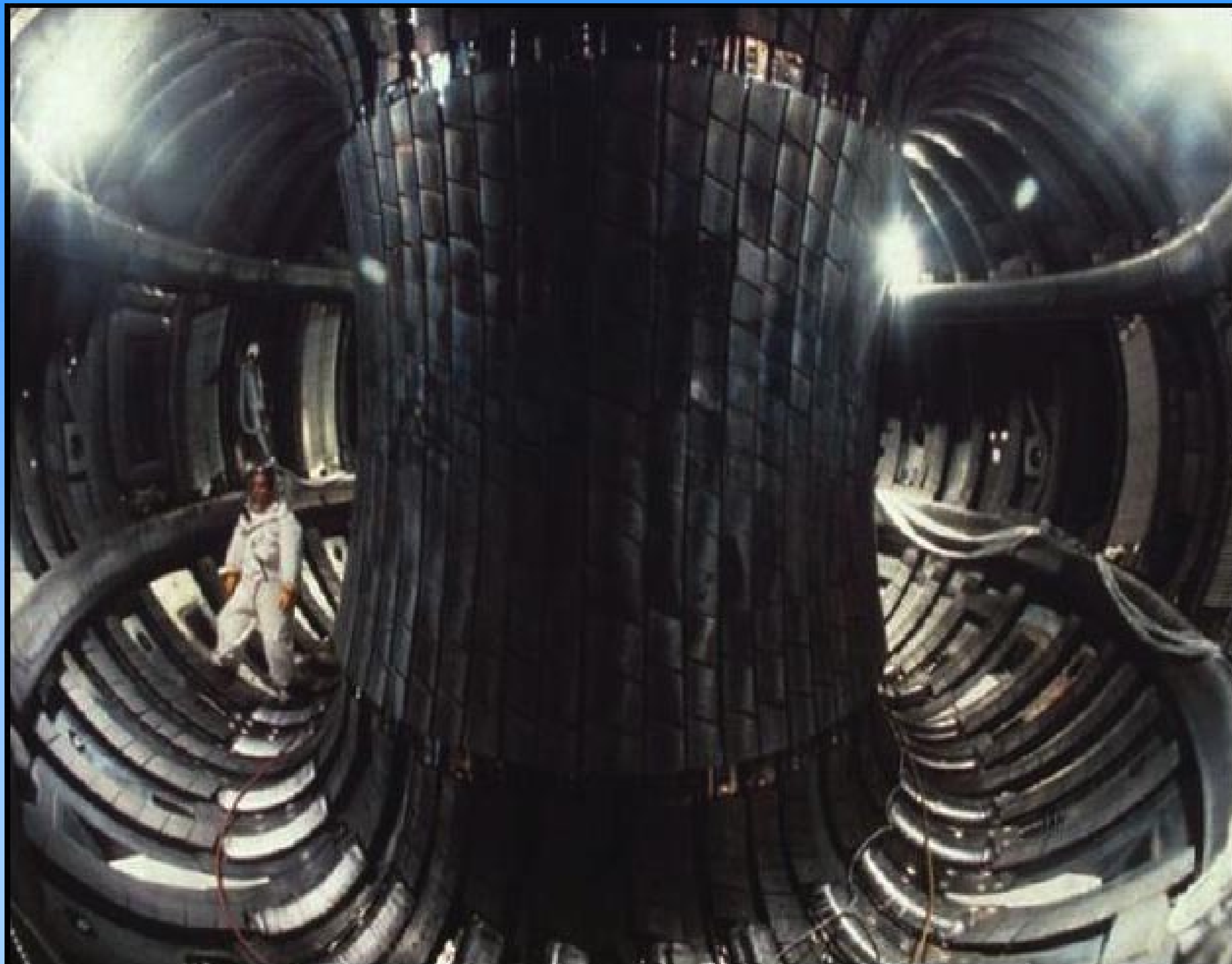
• **Neutrons produce radiation damage and bulk heating in structure**

Properties of Typical Plasmas

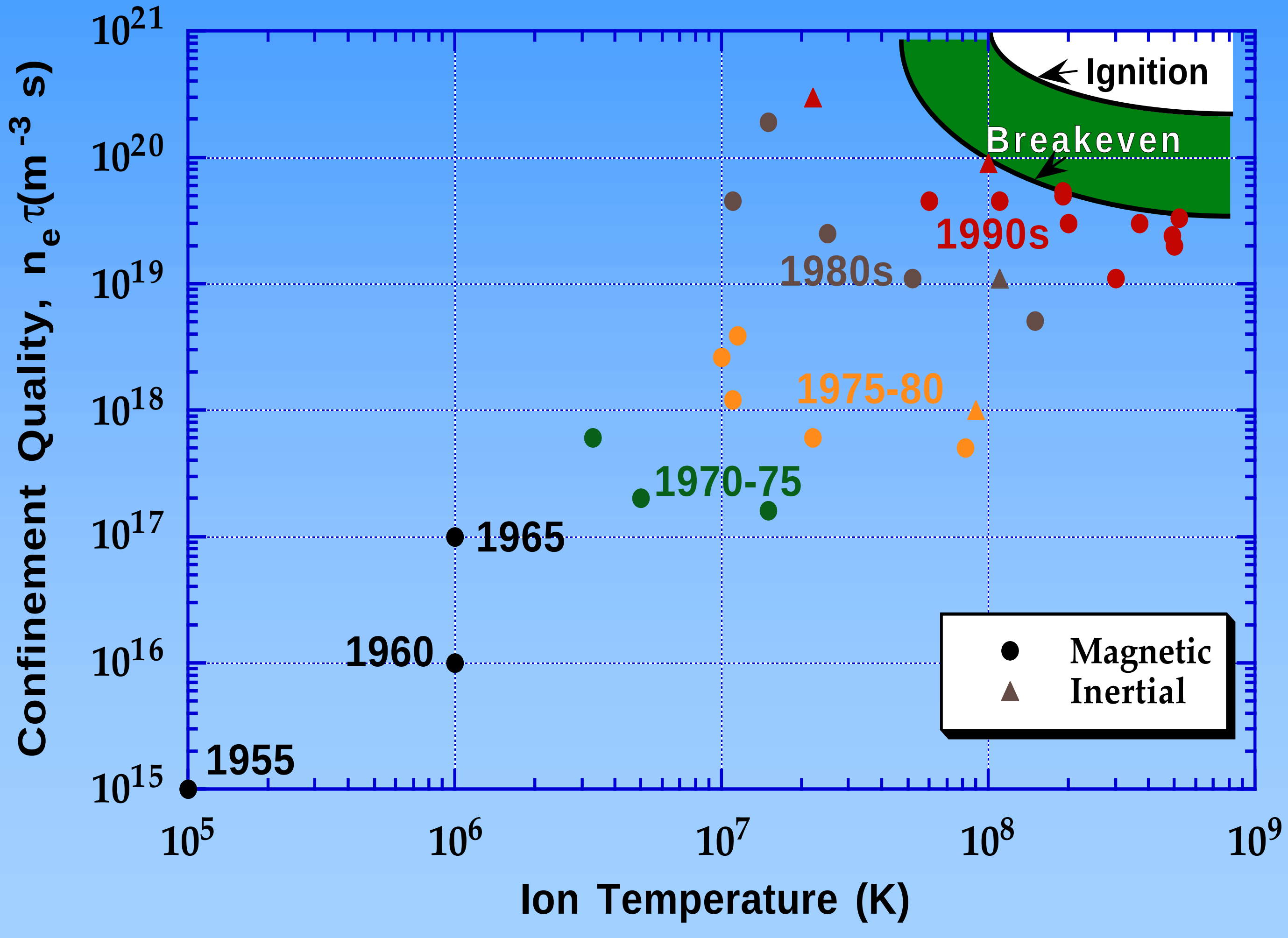
	Density	Temperature	
	N_e (m^{-3})	T_e (eV)	Kelvin
Interstellar	10^6	1	10^4
Solar Corona	10^{12}	10^2	10^6
Fluorescent lamp	10^{18}	10	10^5
Magnetic fusion	10^{20}	10^4	10^8
Inertial fusion	10^{26}	10^2	10^6
Air density	10^{25}	0.025	293

Toroidal Magnetic Confinement of Plasma

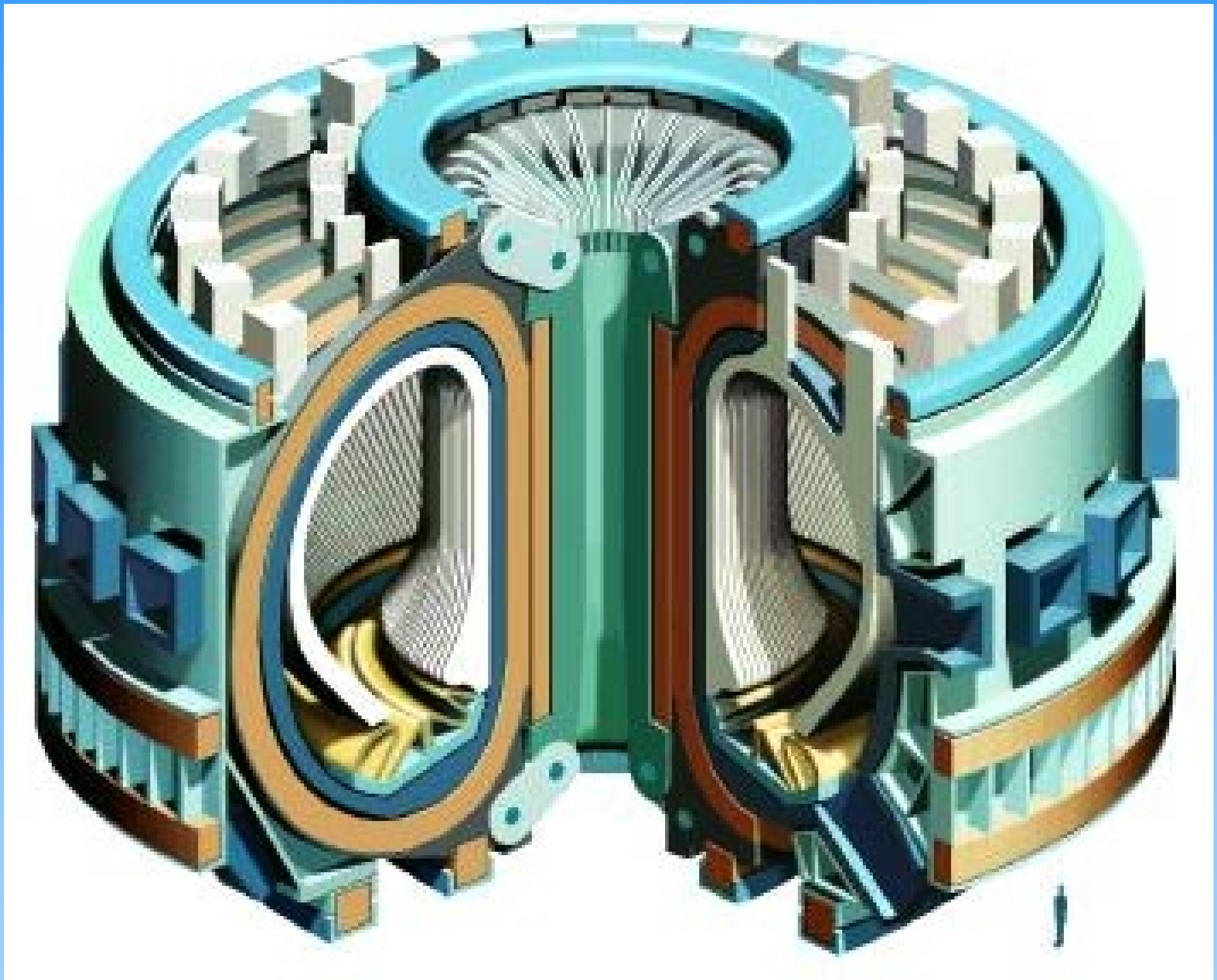




Steady Progress has led to Achievement of Breakeven Condition



ITER (International Thermonuclear Experimental Reactor)



30 meters diameter by 30 meters tall

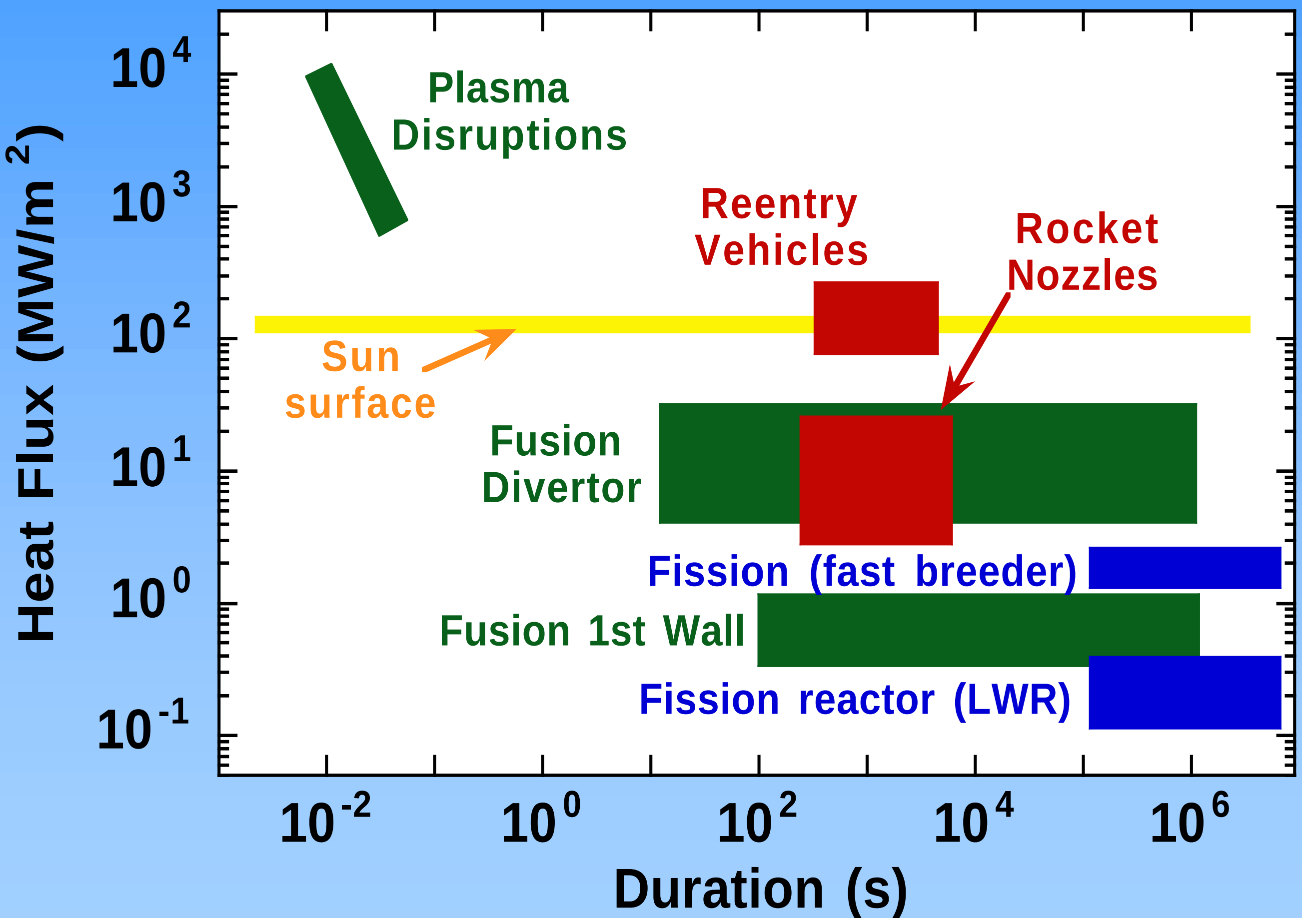
Fusion Energy R&D is at a Crossroad

- Concept feasibility, proof of performance have been demonstrated
- Pathway for most attractive commercial power plant is uncertain
  - Magnetic vs. inertial confinement
  - Tokamak vs. spherical torus, stellarator, etc.
- Materials technology will play a major role in determining the most viable path to commercialization

Three Examples where Materials Impact the Fusion Reactor Design

- Plasma facing (high heat flux) components
- Plasma diagnostic, heating and magnet systems
- First wall/blanket structural materials

Comparison of Heat Fluxes



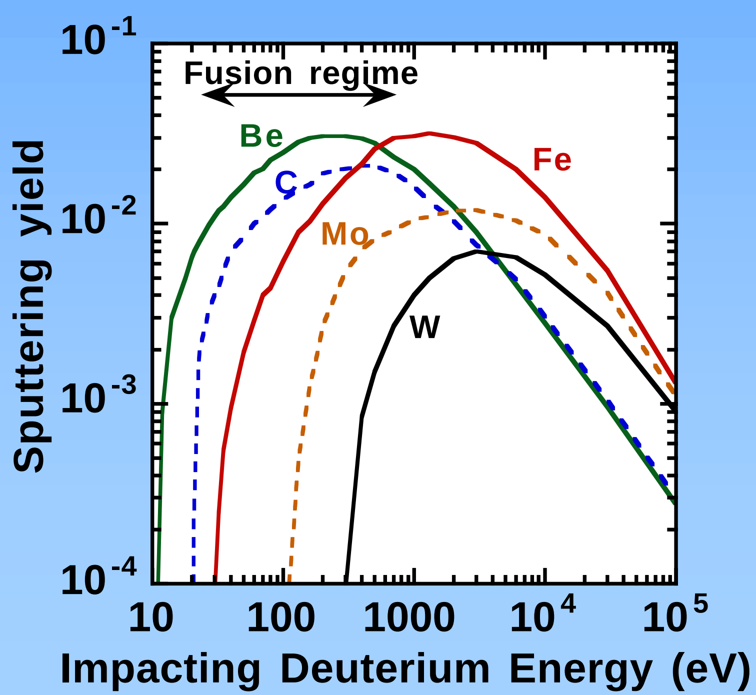
Plasma facing (high heat flux) components

- Capital costs can be reduced by increasing the fusion reactor power density
- Steady-state heat flux limit for structural materials is ~0.5 to 2 MW/m^2 for 5 mm walls in a fusion reactor
  - Capacity to withstand steady state heat fluxes of >35 MW/m^2 has been demonstrated (He-cooled Cu divertor)
- Carbon/carbon composites do not appear to be suitable for fusion reactors due to radiation induced thermal conductivity degradation
- Plasma-facing liquid coolants can provide high steady state heat flux removal capability (>2 MW/m^2)
  - Considerable technological challenges exist for application to toroidal geometry (plasma shaping, coolant vaporization, metal/coolant corrosion)

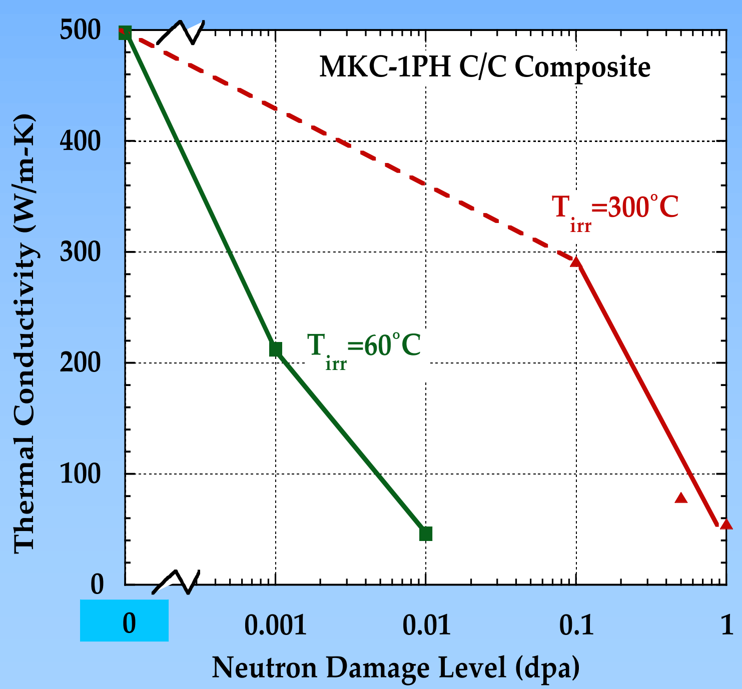
Key Factors for Plasma-Facing Materials

- A tradeoff exists between the amount of erosion (N) and the atomic number (Z) of the sputtered plasma-facing material
  - Plasma power loss is proportional to $N_i Z_i$

- Be, C and W are the leading plasma-facing candidates

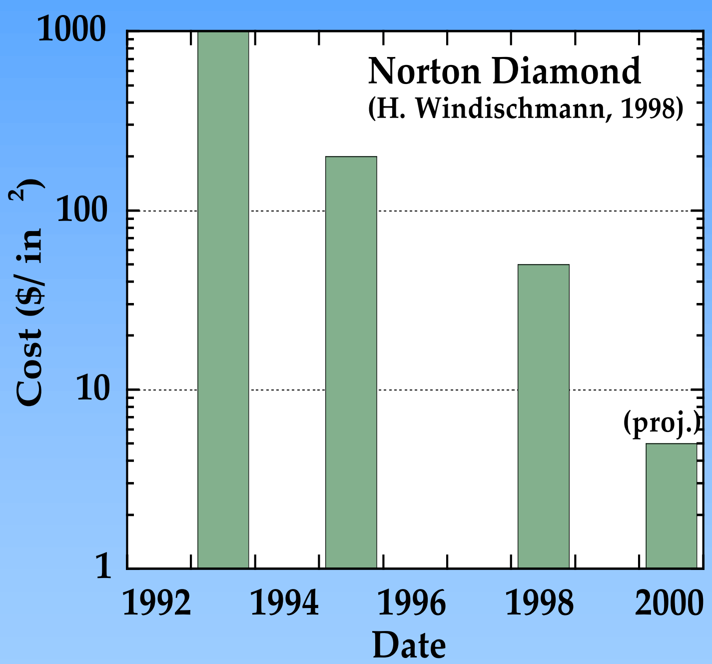


- Neutron irradiation causes a large decrease in C/C conductivity

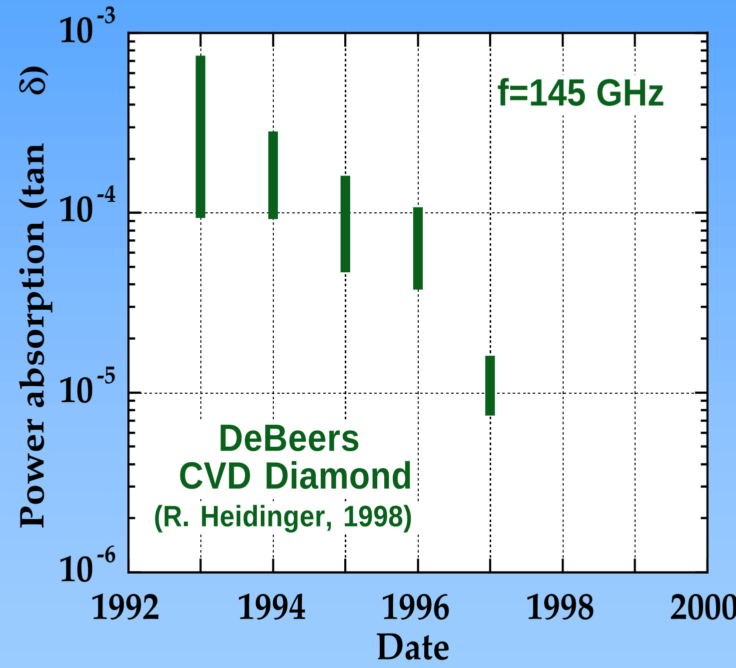


Recent Advances in CVD Diamond Fabrication now allow High-power (~1 MW) Gyrotrons to be used for Plasma Heating

- CVD diamond production costs have decreased rapidly



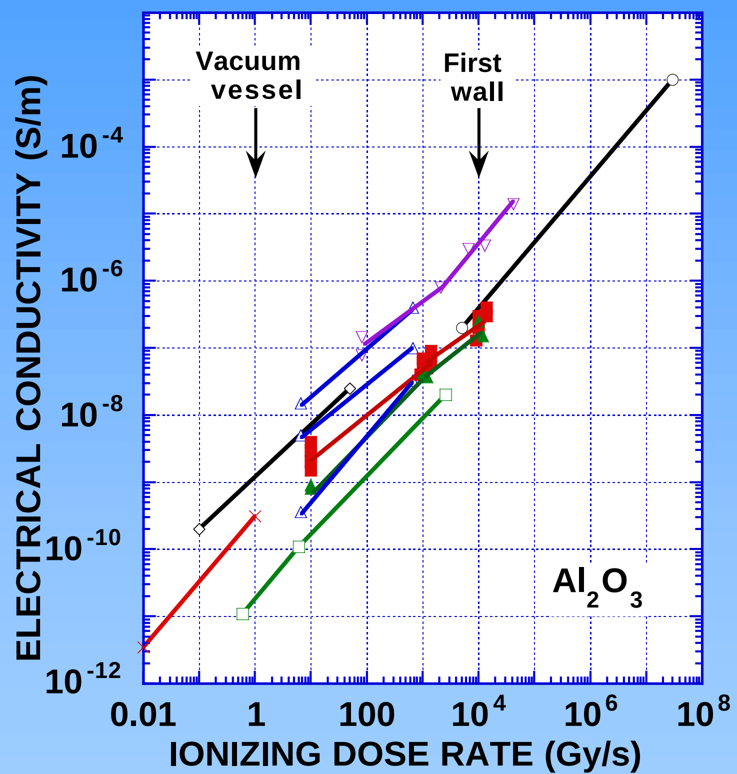
- High-quality CVD diamond (low RF power absorption) is now available



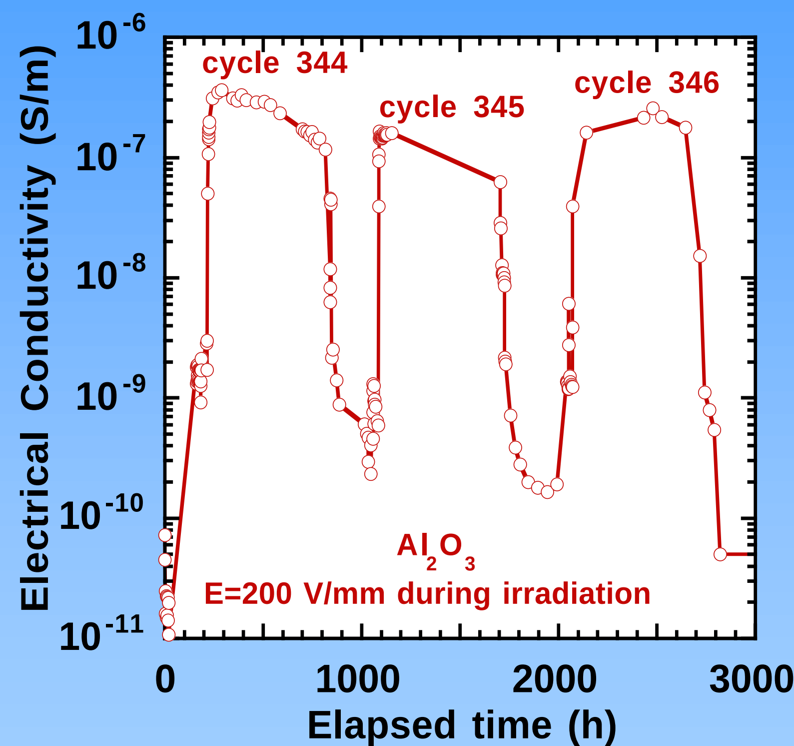
- **Low power absorption is maintained in CVD diamond after irradiation to moderate neutron doses (10^{-3} dpa)**

Ionizing Radiation Causes Large Prompt Changes in Electrical Conductivity of Insulators

- The electrical conductivity is proportional to dose rate



- No permanent degradation occurs after neutron irradiation

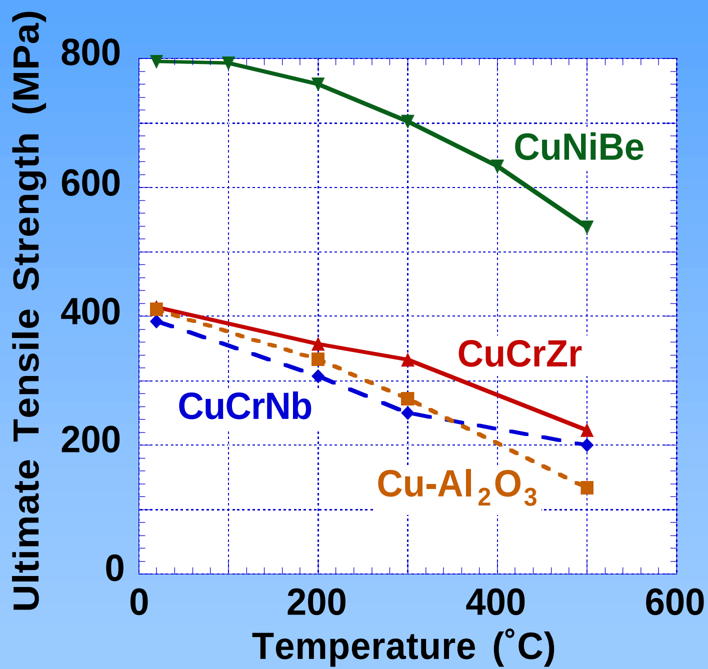


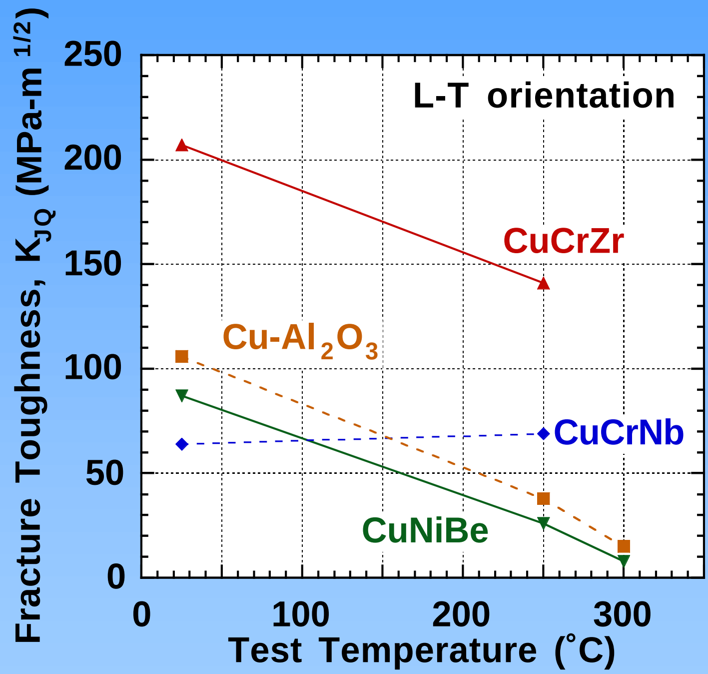
- **Suitable insulators are available for fusion reactor applications**

Structural Materials will Strongly Impact the Economics of Fusion Energy

- Key issues include thermal stress capacity, coolant compatibility, safety, waste disposal, and radiation damage effects
- The 3 leading candidates are ferritic/ martensitic steel, V alloys, and SiC/SiC
  - Ti alloys have high hydrogen (tritium) solubility and permeability, and low thermal stress capacity
  - Ni base superalloys have poor radiation stability (grain boundary embrittlement)
  - Refractory alloys (Ta, Mo, W) must be operated at very high temperature (>650˚C) to avoid radiation embrittlement

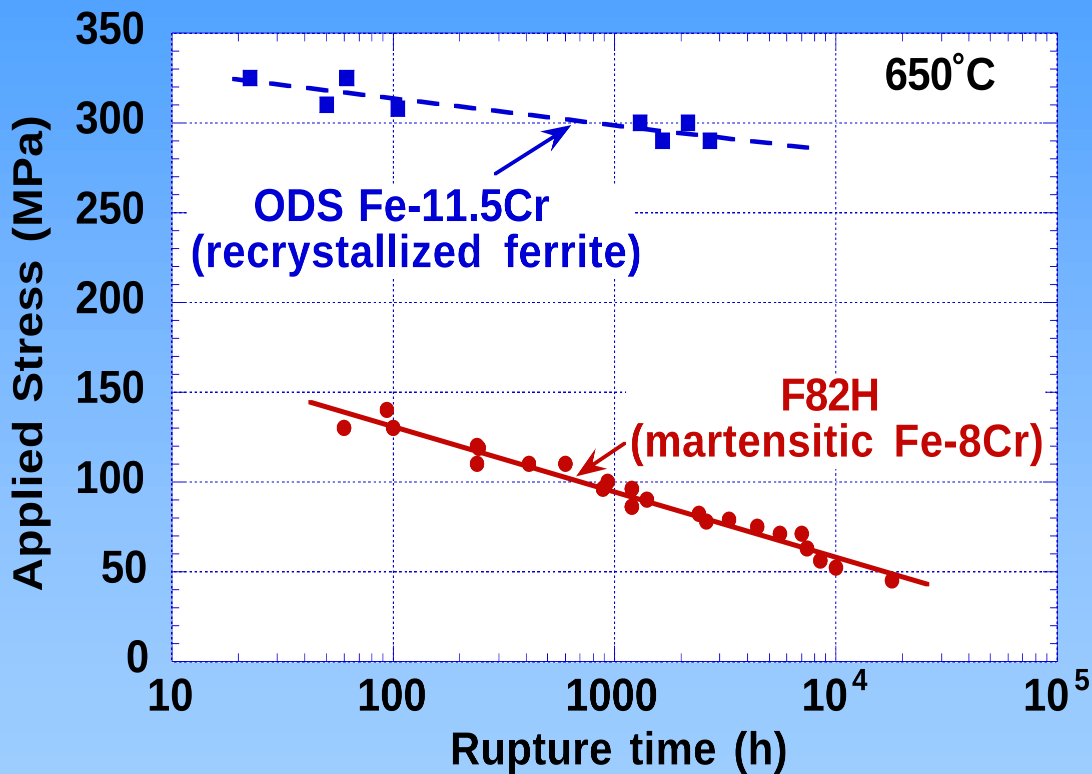
Copper Alloys have High Thermal Stress Capacity at Low Temperatures, but Poor Elevated Temperature (>300˚C) Mechanical Properties





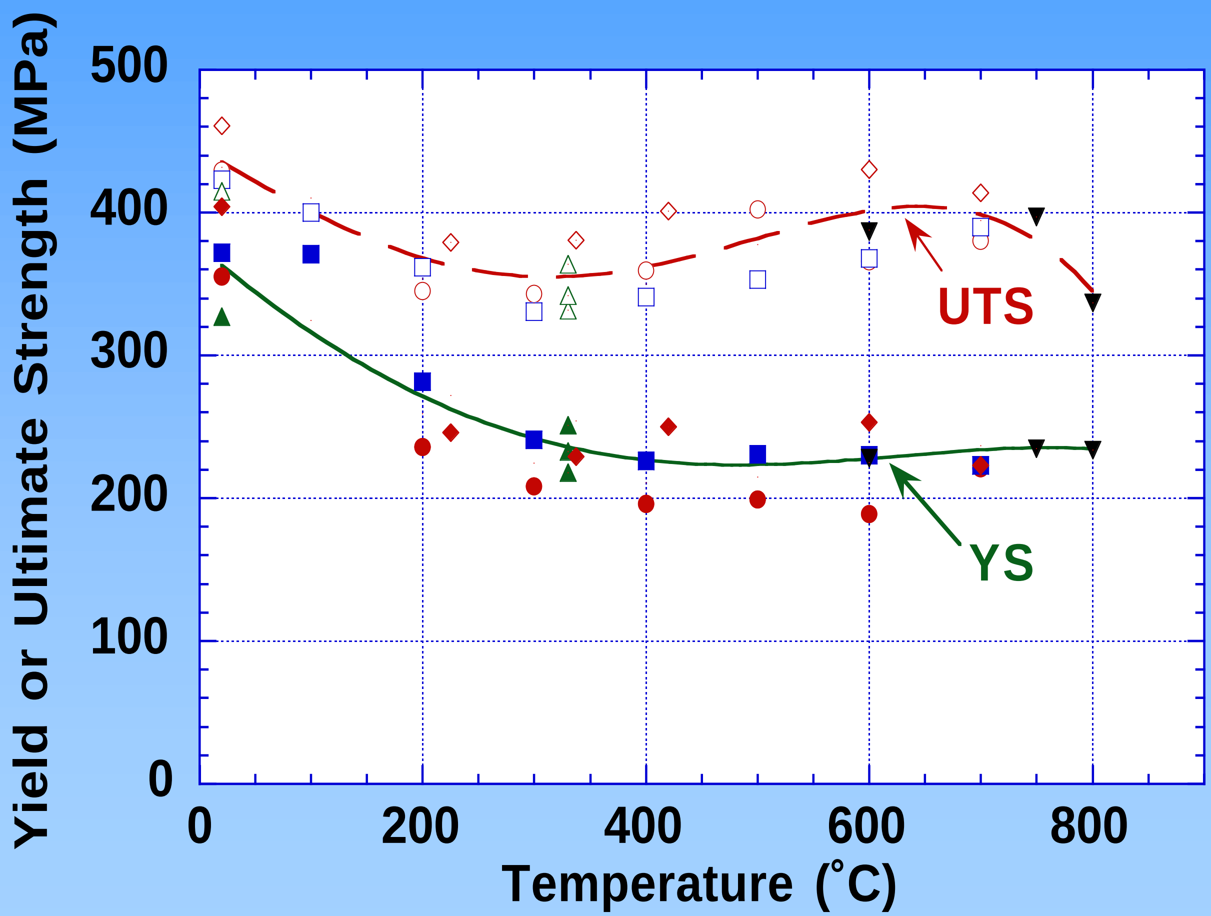
• Copper alloys are not attractive candidates for 1st wall/ blanket structural applications (low thermodynamic efficiency)

Recently Developed Isotropic Oxide Dispersion Strengthened Steels Offer Potential for Improved Performance



- **Thermal creep temperature limit for martensitic Fe-8Cr steel is ~550˚C (vs. >650˚C for ODS steel)**

V-4Cr-4Ti has an attractive combination of strength, liquid metal compatibility, and high temperature radiation resistance



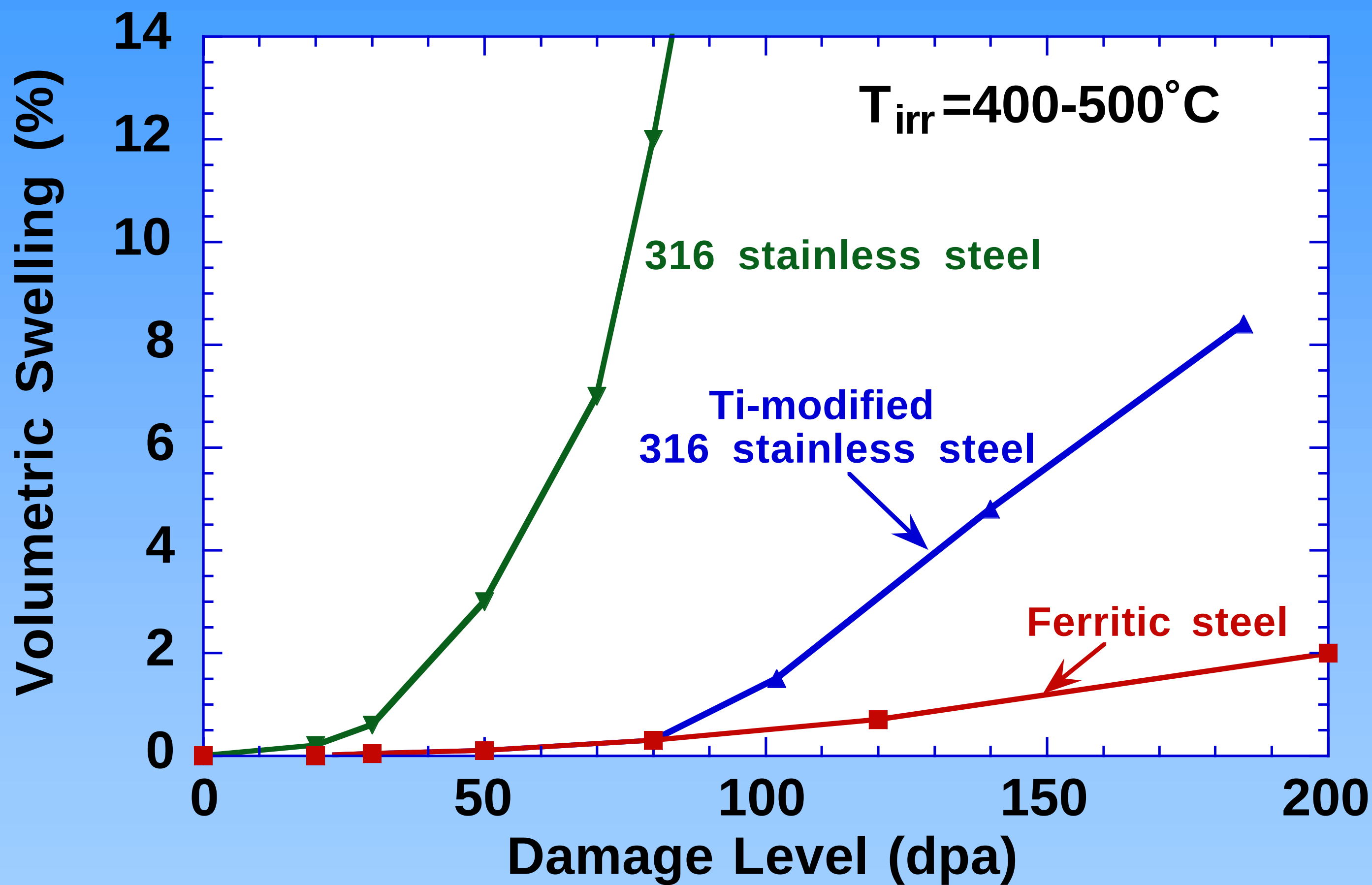
Radiation Damage can Produce Large Changes in Structural Materials

- Radiation hardening and embrittlement (<0.4 T_M)
- Irradiation creep (<0.45 T_M)
- Volumetric swelling from void formation (0.3-0.6 T_M)
- High temperature He embrittlement (>0.5 T_M)

In addition…

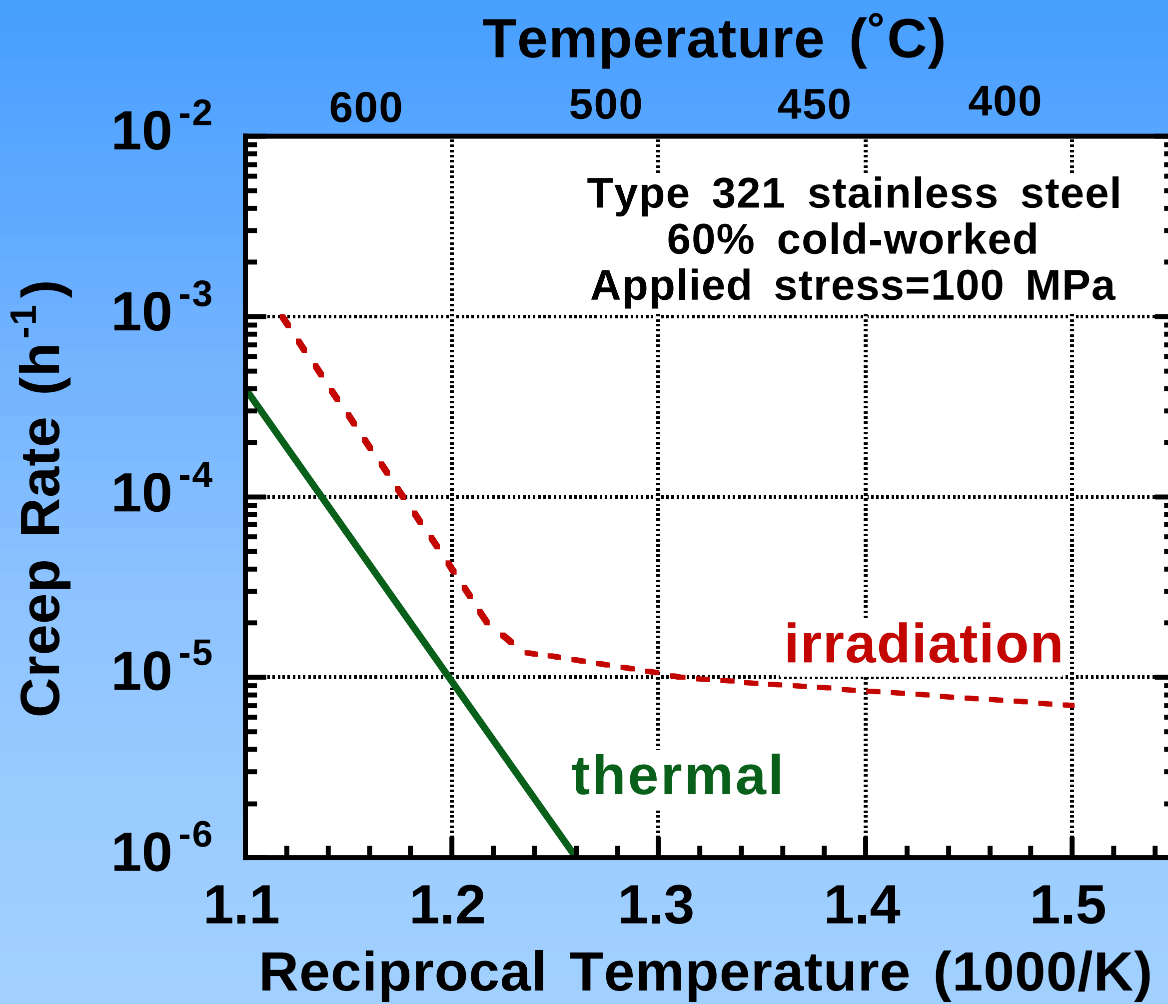
- The irradiation environment associated with a D-T fusion reactor is more severe than in fission reactors
  - Higher lifetime dose requirements for structure
  - Higher He generation rates (promotes He embrittlement of grain boundaries, void swelling)

Swelling resistant alloys have been developed via international collaborations

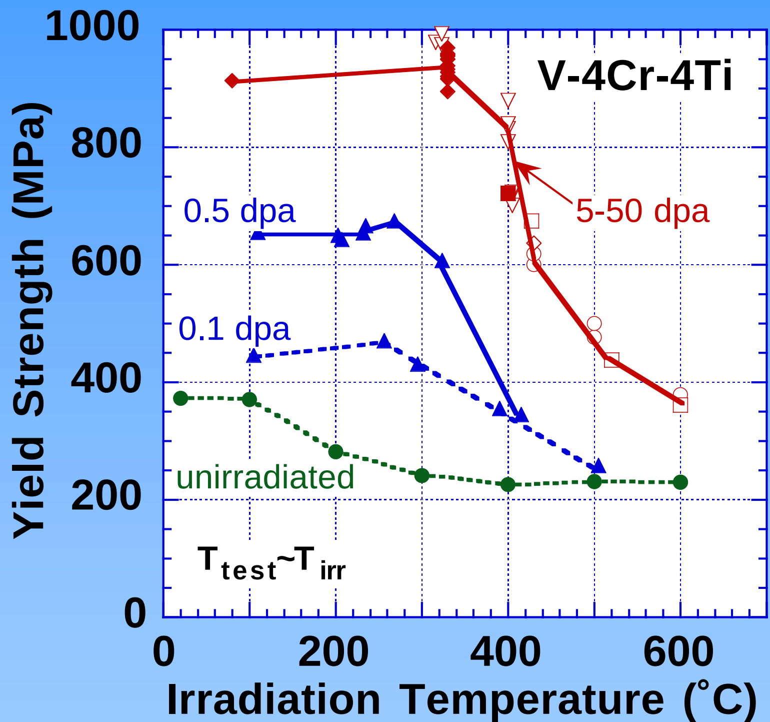


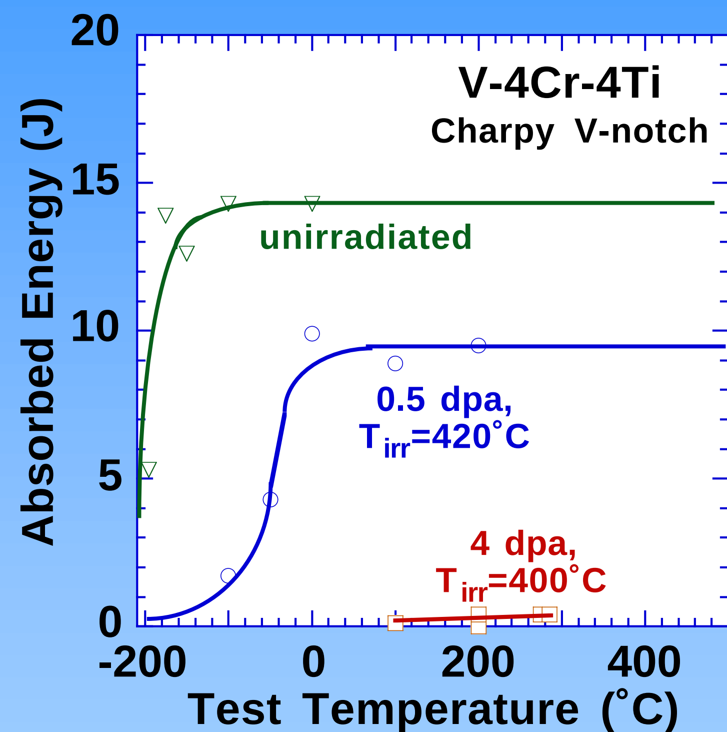
- **Lowest swelling is observed in body-centered cubic alloys (V alloys, ferritic steel)**

Irradiation Creep Dominates over Thermal Creep below 500°C in Austenitic Steel



Low Temperature Irradiation causes Hardening and Loss of Ductility in Metals





- **Matrix hardening produces an increase in the ductile-to-brittle transition temperature in body-centered-cubic alloys (ferritic steels, V alloys)**

Summary

- Impressive physics advances have been achieved from a relatively modest investment
  - 1950-1995 fusion R&D funding ~5% of annual gasoline expenditure by US consumers
- Several key questions still remain
  - What is the optimal path for development of a commercially viable power plant (magnetic vs. inertial confinement, etc.)?
  - Can fusion be cost-competitive with coal, fission?
- Materials will play a major role in determining the fate of fusion energy
  - Fusion energy economics may require new high heat flux, radiation resistant materials