Perspective on Fusion Energy

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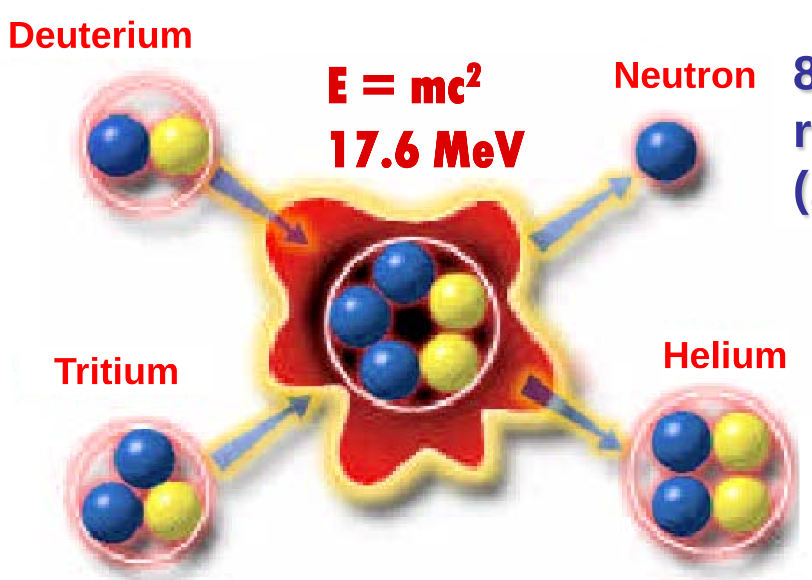
What is fusion?

- **Two light nuclei combining to form a heavier nuclei (the opposite of nuclear fission). Fusion powers the Sun and Stars.**



80% of energy release (14.1 MeV)

Used to breed tritium and close the DT fuel cycle

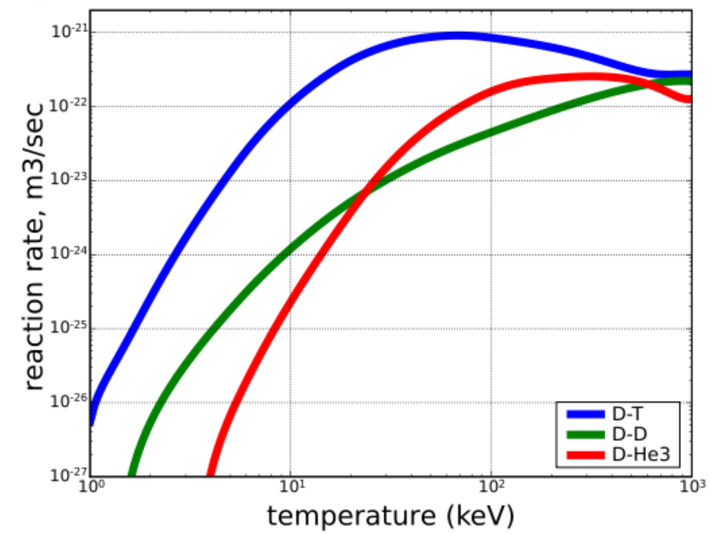
Li + n → T + He

Li in some form must be used in the fusion system

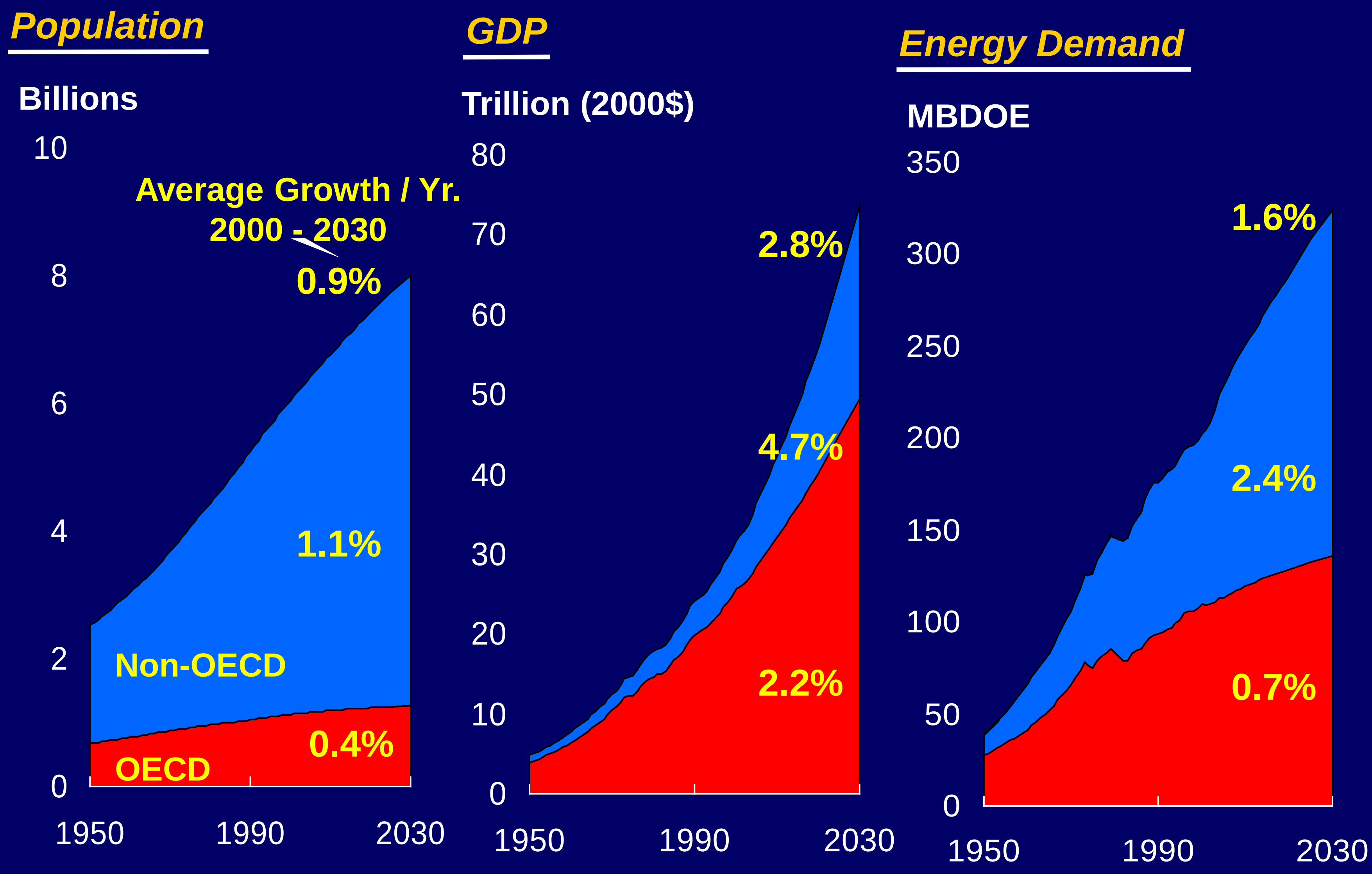
20% of energy release (3.5 MeV)

Illustration from DOE brochure

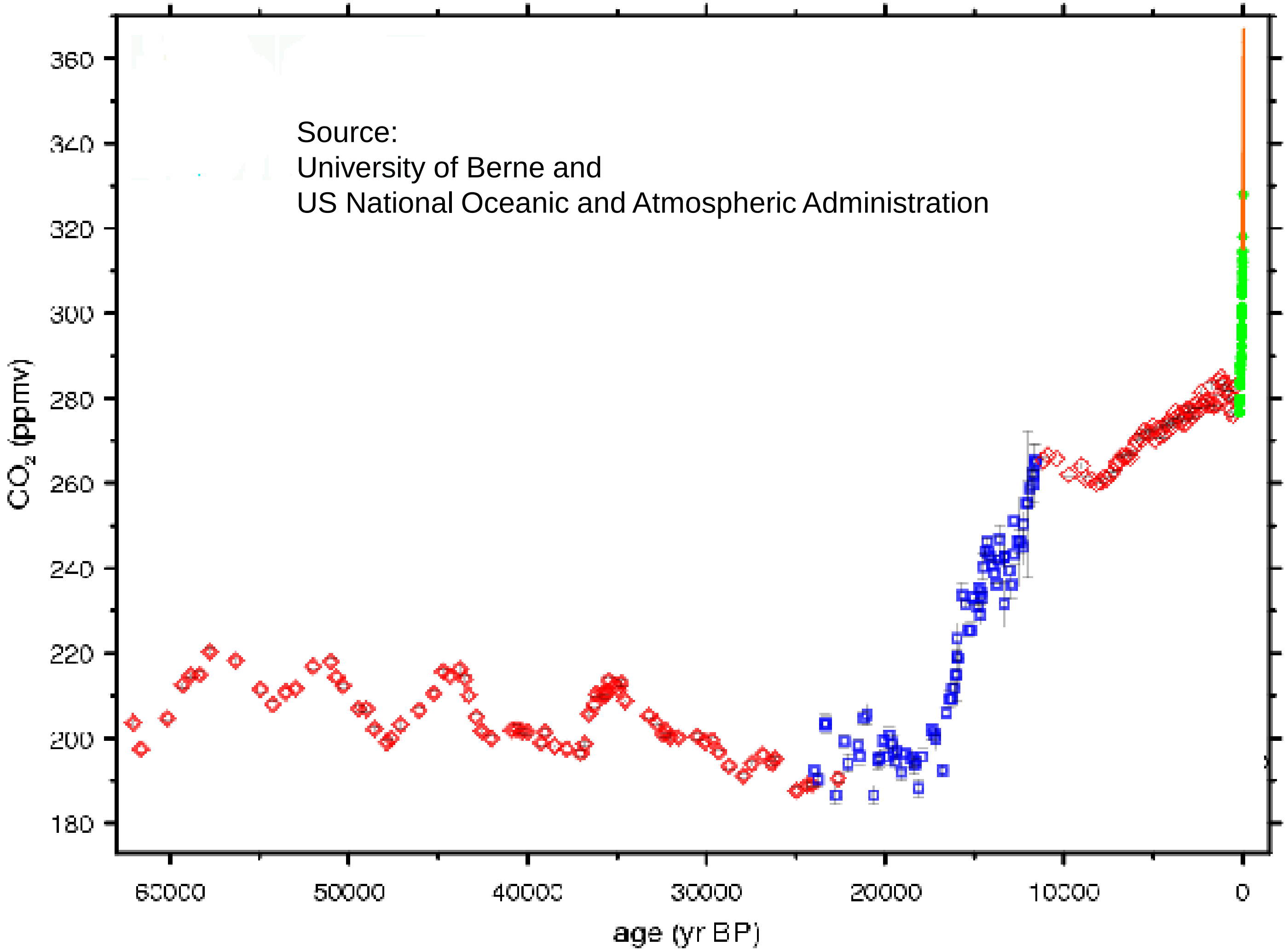
- **Deuterium and tritium is the easiest, attainable at lower plasma temperature, because it has the largest reaction rate and high Q value.**
- **The World Program is focused on the D-T Cycle.**



Global Economics and Energy



Carbon dioxide levels over the last 60,000 years - we are provoking the atmosphere!



Energy Situation

- **The world uses a lot of energy**
  - Average power consumption = 13.6 TW (2.2 KW per person)
  - World energy market ~ $3 trillion / yr (electricity ~ $1 trillion / yr)

- **The world energy use is growing**
  - to lift people out of poverty, to improve standard of living, and to meet population growth

- **Climate change and debilitating pollution Concerns are on the rise**
  - 80% of energy is generated by fossil fuels
  - CO_2 emission is increasing at an alarming rate

- **Oil supplies are dwindling**
  - Special problem for transportation sector (need alternative fuel)

Solving the Energy Problem Requires a Diversified Portfolio and Pursuing Several Approaches

- Develop major new (clean) energy sources (e.g. fusion)
- Expand use of existing “clean” energy sources (e.g. nuclear, solar, wind)
- Develop technologies to reduce impact of fossil fuels use (e.g. carbon capture and sequestration)
- Improve energy efficiency
- Develop alternate (synthetic) fuels for transportation

Incentives for Developing Fusion

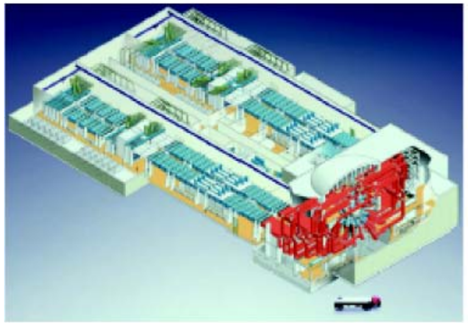
- Sustainable energy source

  (for DT cycle: provided that Breeding Blankets are successfully developed and tritium self-sufficiency conditions are satisfied)

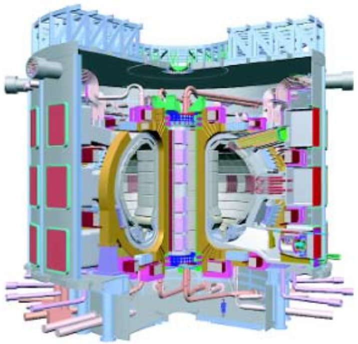
- No emission of Greenhouse or other polluting gases
- No risk of a severe accident
- No long-lived radioactive waste

Fusion energy can be used to produce electricity and hydrogen, and for desalination.

Fusion Research is about to transition from Plasma Physics to Fusion Science and Engineering



National Ignition Facility

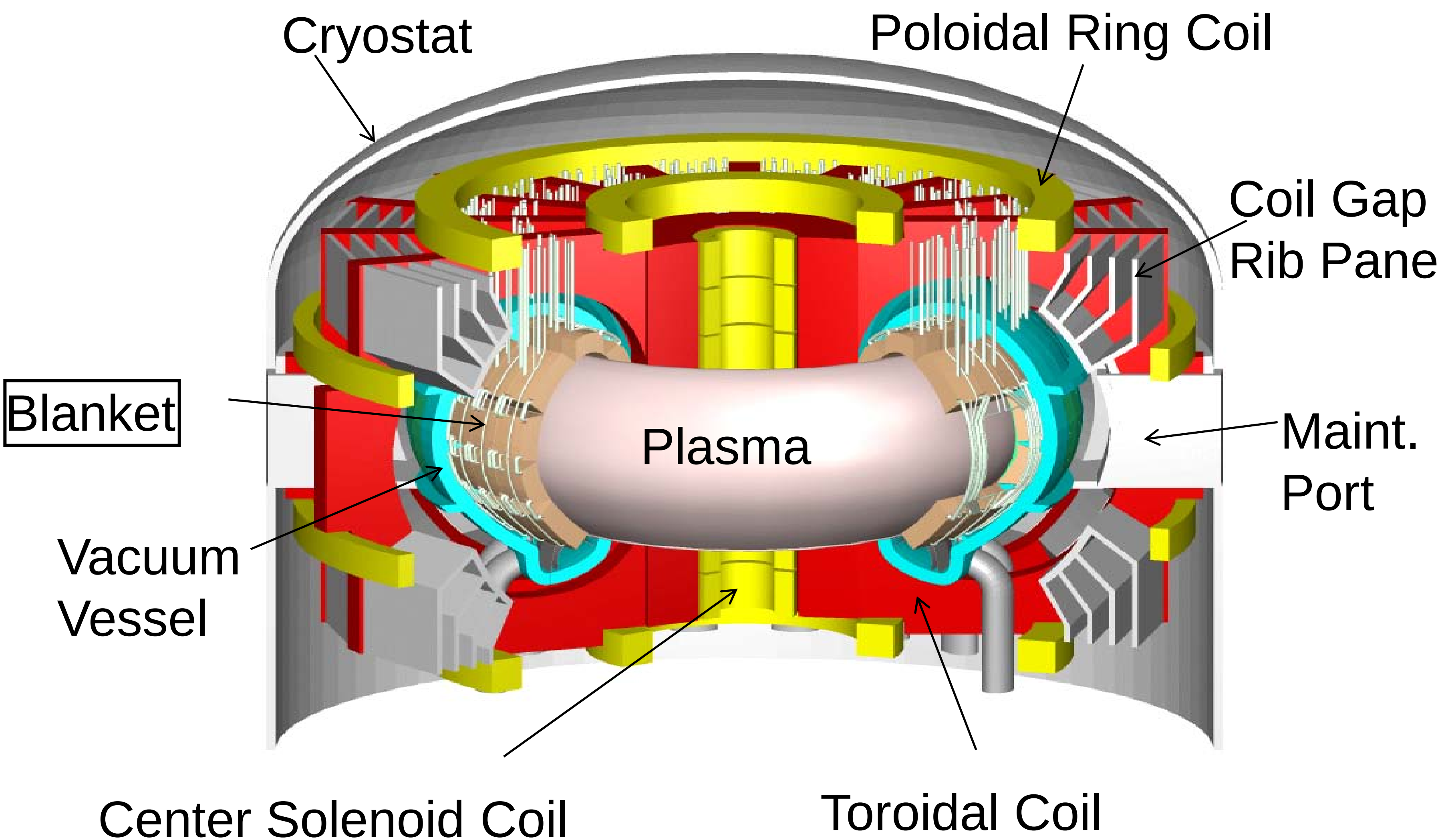


ITER

- **1950-2010**
  - **The Physics of Plasmas**
- **2010-2035**
  - **The Physics of Fusion**
  - **Fusion Plasmas-heated and sustained**
    - **$Q = (E_f / E_{input})$~10**
    - **ITER (magnetic fusion) and NIF (inertial fusion)**
- **2010-2040 ?**
  - **Fusion Nuclear Science and Technology for Fusion**
- **> 2050 ?**
  - **DEMO by 2050?**
  - Large scale deployment > 2050!

The World Fusion Program has a Goal for a Demonstration Power Plant (DEMO) by ~2040(?)

Plans for DEMO are based on Tokamaks



(Illustration is from JAEA DEMO Design)

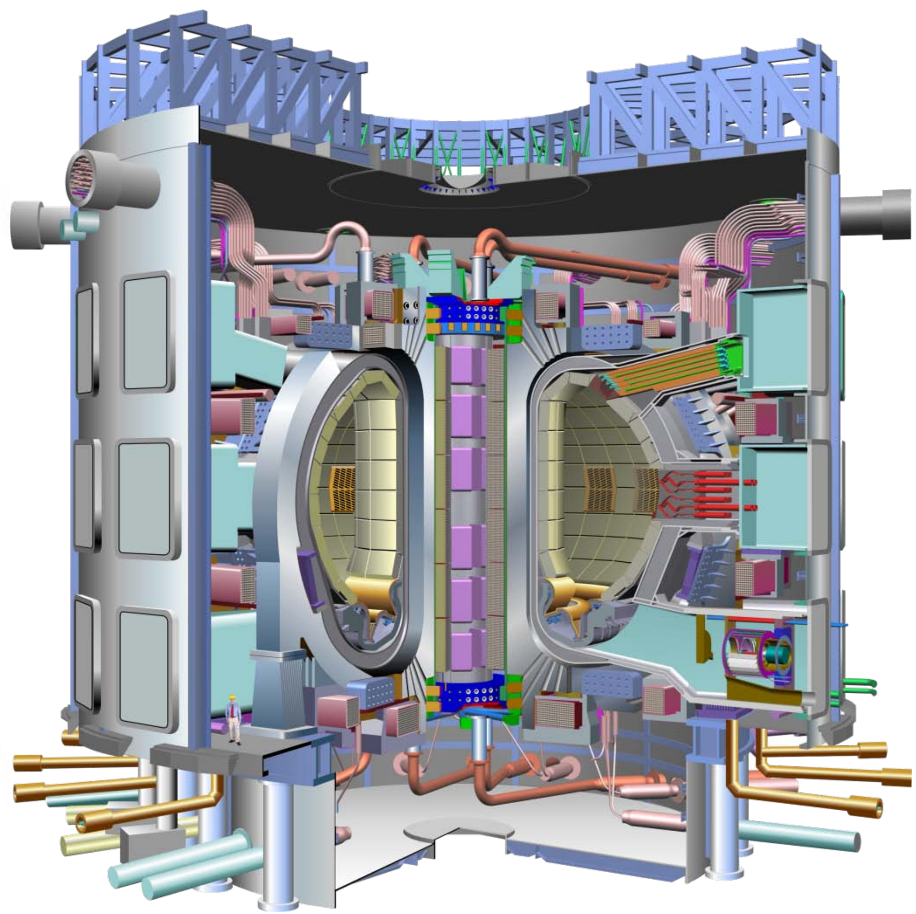
ITER

- The World has started construction of the **next step** in fusion development, a device called ITER.
- ITER will demonstrate the **scientific and technological feasibility** of fusion energy for peaceful purposes.
- ITER will produce **500 MW** of fusion power.
- Cost, including R&D, is ~15 billion dollars.
- **ITER is a collaborative effort among Europe, Japan, US, Russia, China, South Korea, and India. ITER construction site is Cadarache, France.**
- ITER will begin operation in hydrogen in ~2019. **First D-T Burning Plasma in ITER in ~ 2026.**

ITER is a reactor-grade tokamak plasma physics experiment - A huge step toward fusion energy

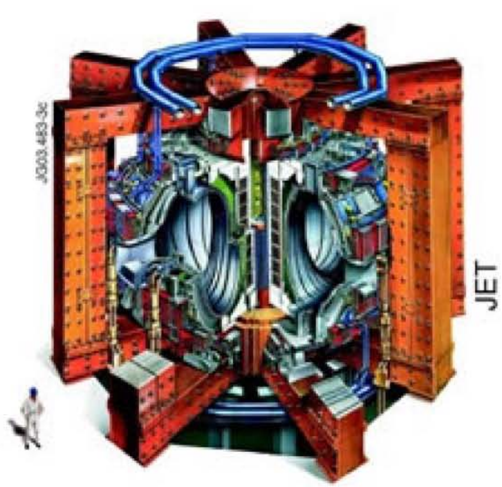
- **Will use D-T and produce neutrons**
- **500MW fusion power, Q=10**
- **Burn times of 400s**
- **Reactor scale dimensions**
- **Actively cooled PFCs**
- **Superconducting magnets**

~29 m



By Comparison, JET
- **~10 MW**
- **~1 sec**
- **Passively Cooled**

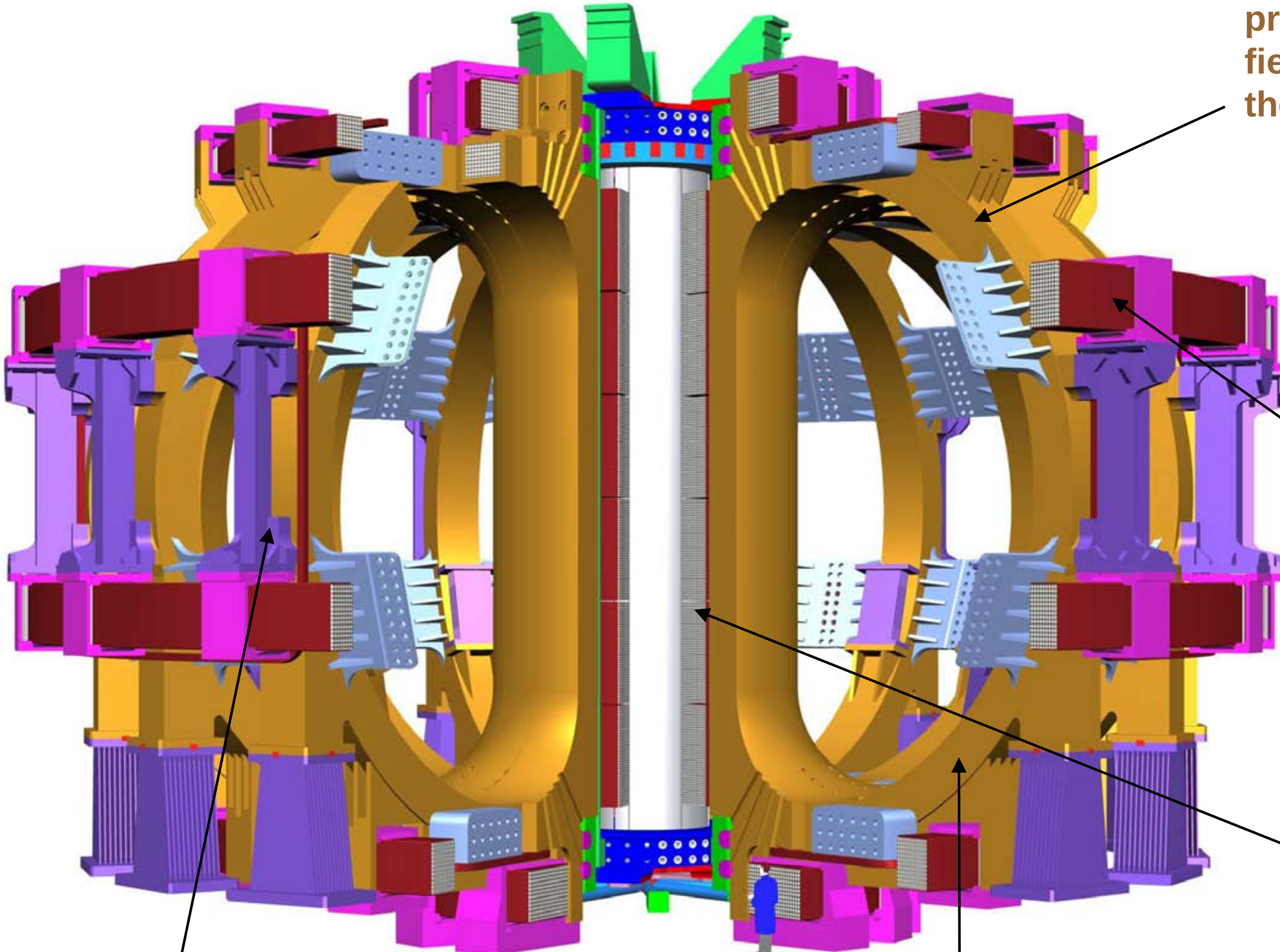
~15 m



JET

ITER

Magnet System in Tokamak (e.g. ITER) has 4 sets of coils



- 18 Toroidal Field (TF) coils produce the toroidal magnetic field to confine and stabilize the plasma
  - Superconducting, Nb_3Sn/Cu/SS
  - Max. field: 11.8T

- 6 Poloidal Field (PF) coils position and shape the plasma
  - Superconducting, NbTi/Cu/SS
  - Max. field: 6T

- Central Solenoid (CS) coil induces current in the plasma
  - Superconducting, Nb_3Sn/Cu/alloy908
  - Max. field: 13.5T

- 18 Correction coils correct error fields
  - Superconducting, NbTi/Cu/SS
  - Max. field < 6T

TF coil case provides main structure of the magnet system and machine core

Stored energy in ITER magnetic field is large ~ 1200 MJ

Equivalent to a fully loaded 747 moving at take off speed 265 km/h

New Long-Pulse Confinement and Other Facilities Worldwide will Complement ITER

China

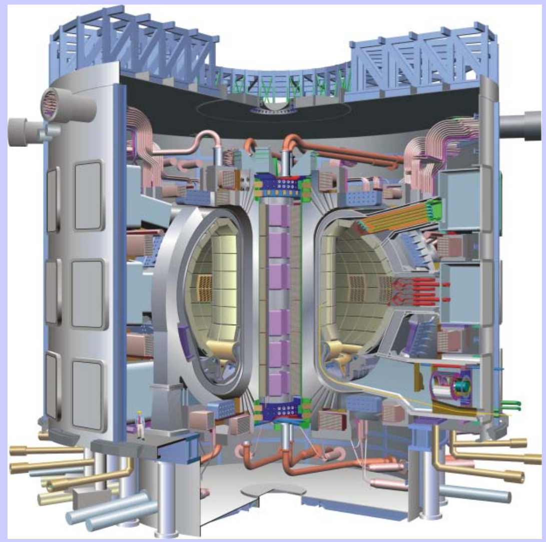
EAST

Europe

W7-X (also JT-60SA)

India

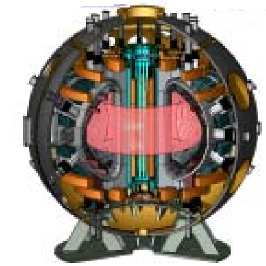
SST-1



ITER Operations:

34%	Europe
13%	Japan
13%	U.S.
10%	China
10%	India
10%	Russia
10%	S. Korea

Japan (w/EU)



JT-60SA (also LHD)

South Korea

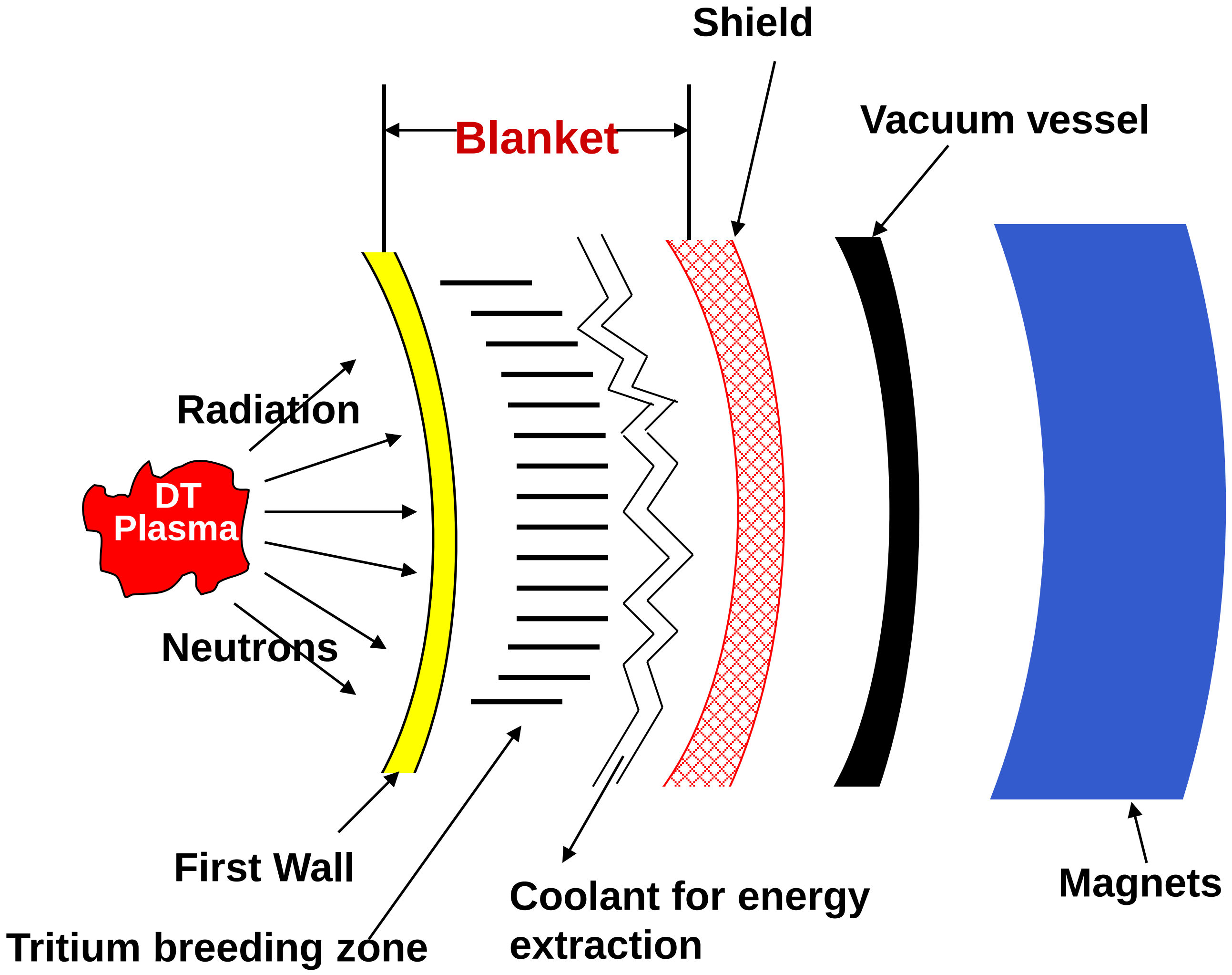
KSTAR

U.S.

Being planned

Fusion Nuclear Science &Technology Testing Facility (FNSF/CTF/VNS)

The primary functions of the blanket are to provide for: Power Extraction & Tritium Breeding



Lithium-containing Liquid metals (Li, PbLi) are strong candidates as breeder/coolant.

Fusion Nuclear Science and Technology (FNST)

FNST is the *science*, *engineering*, *technology*, and *materials* for the fusion nuclear components that generate, control and utilize neutrons, energetic particles & tritium

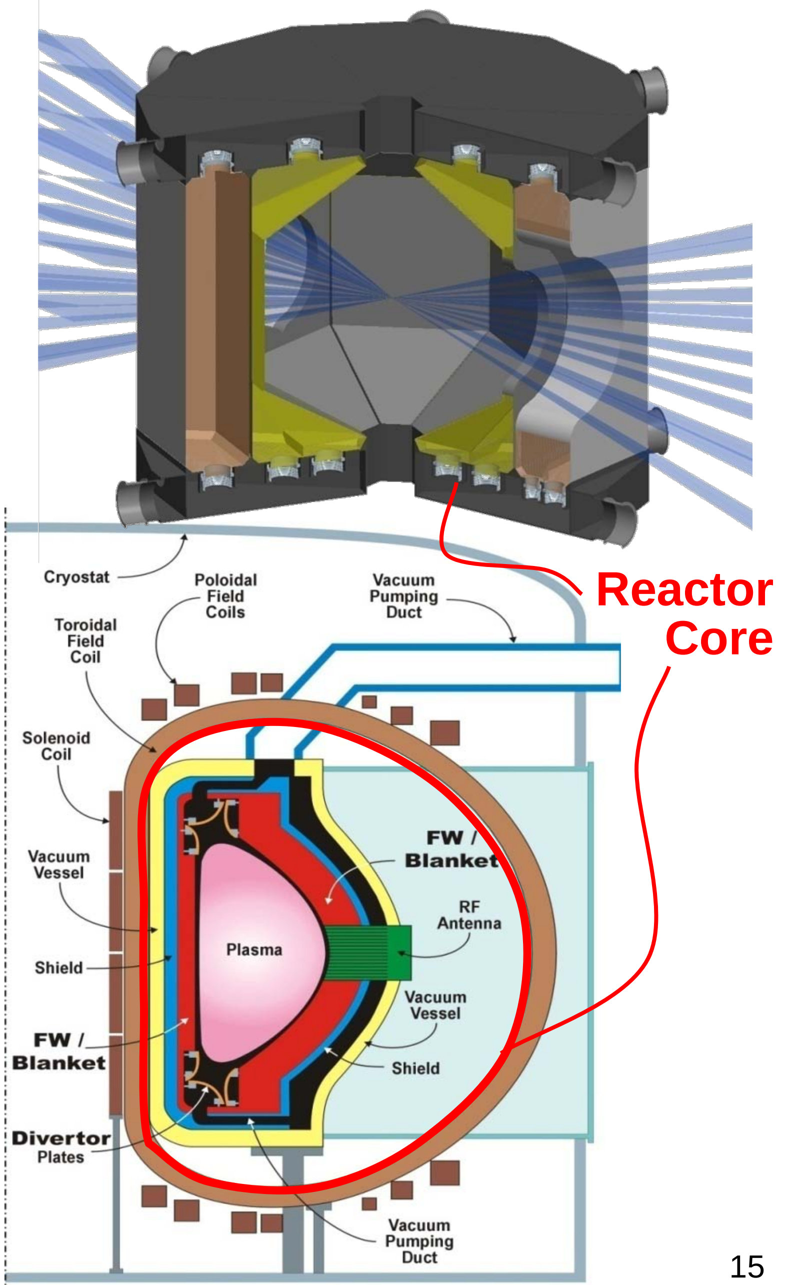
(For both MFE and IFE)

Inside the Vacuum Vessel "Reactor Core":

- Plasma Facing Components
  divertor, limiter and nuclear aspects of plasma heating/fueling and IFE final optics
- Blanket (with first wall)
- Vacuum Vessel & Shield

Other Systems / Components affected by the Nuclear Environment:

- Tritium Processing and Target Factory Systems
- Instrumentation & Control Systems
- Remote Maintenance Components
- Heat Transport & Power Conversion Systems



FNST research requires advancing the state-of-the-art, and developing highly integrated predictive capabilities for many cross-cutting scientific and engineering disciplines

- neutron/photon transport
- neutron-material interactions
- plasma-surface interactions
- heat/mass transfer
- MHD thermofluid physics
- thermal hydraulics
- tritium release, extraction, inventory and control
- tritium processing
- gas/radiation hydrodynamics
- phase change/free surface flow
- structural mechanics
- radiation effects
- thermomechanics
- chemistry
- radioactivity/decay heat
- safety analysis methods and codes
- engineering scaling
- failure modes/effects and RAMI analysis methods
- design codes

These capabilities are needed by any MFE/IFE fusion energy program

Fusion nuclear environment: multi-field, harsh, unique

Neutrons ***(fluence, spectrum, gradients)***

- **Radiation Effects**
- **Tritium Production**
- Bulk Heating
- **Activation and Decay Heat**

Heat Sources ***(thermal gradients)***

- **Bulk (neutrons)**
- **Surface (particles, radiation)**

Particle, X-ray Fluxes ***(energy, density, gradients)***

Magnetic Fields ***(3-components, gradients)***

- **Steady and Time-Varying Field**

Mechanical Forces

- **Steady, Cyclic, Transient/Pulsed, Failure-caused**

Fusion nuclear environment: complex effects, interactions, and science

Neutrons *(fluence, spectrum, gradients)*

- Radiation Effects
- Tritium Production
- Bulk Heating
- Activation and Decay Heat

Heat Sources *(thermal gradients)*

- Bulk (neutrons)
- Surface (particles, radiation)

Particle, X-ray Fluxes *(energy, density, gradients)*

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Mechanical Forces

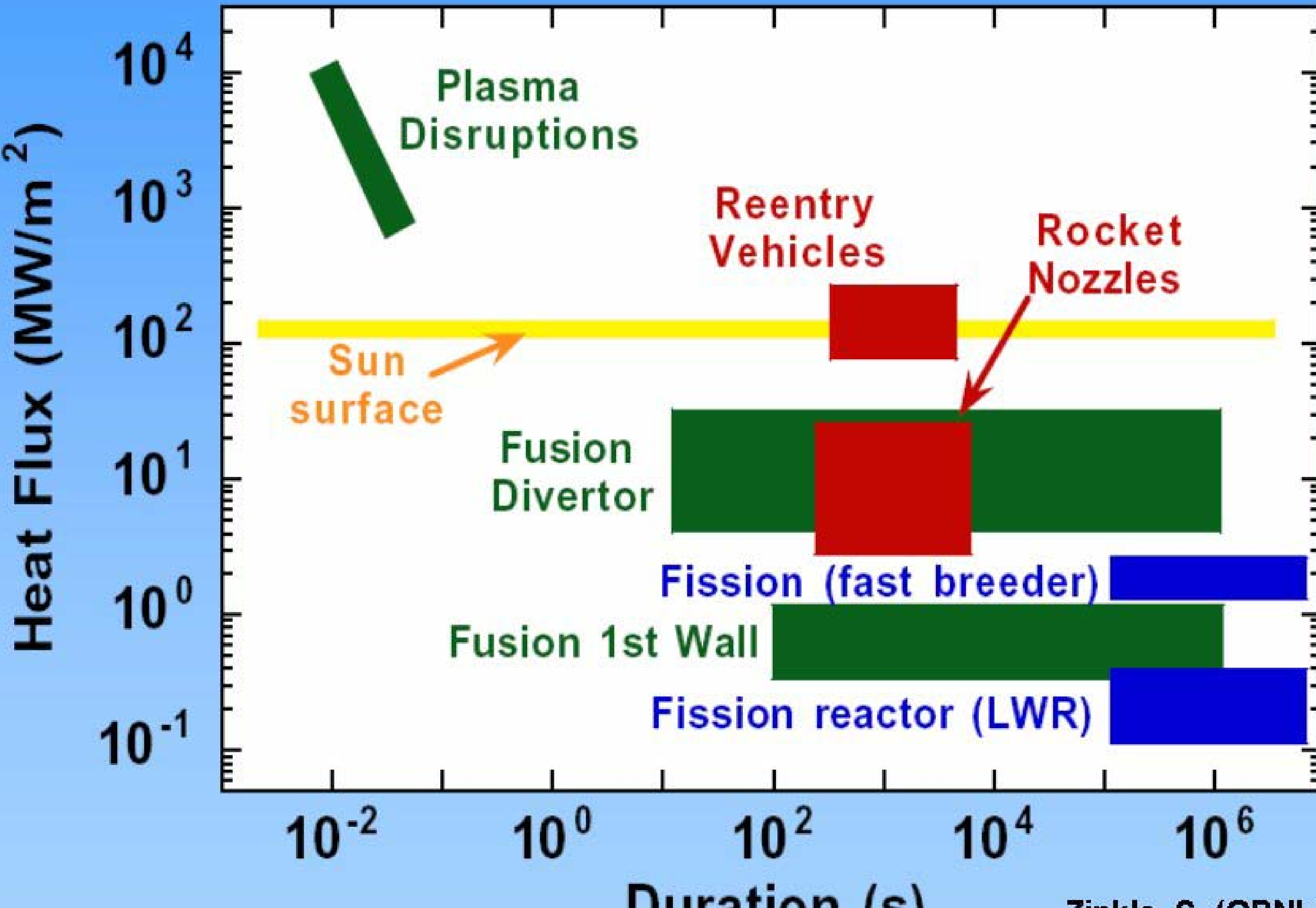
- Steady, Cyclic, Transient/Pulsed, Failure-caused

Combined Loads, Multiple Environmental Effects

- Thermal-Chemical-mechanical-electrical-magnetic-nuclear interactions and synergistic effects
- Interactions among physical elements of components

Highly Constrained Multi-Function Components

Comparison of Heat Fluxes



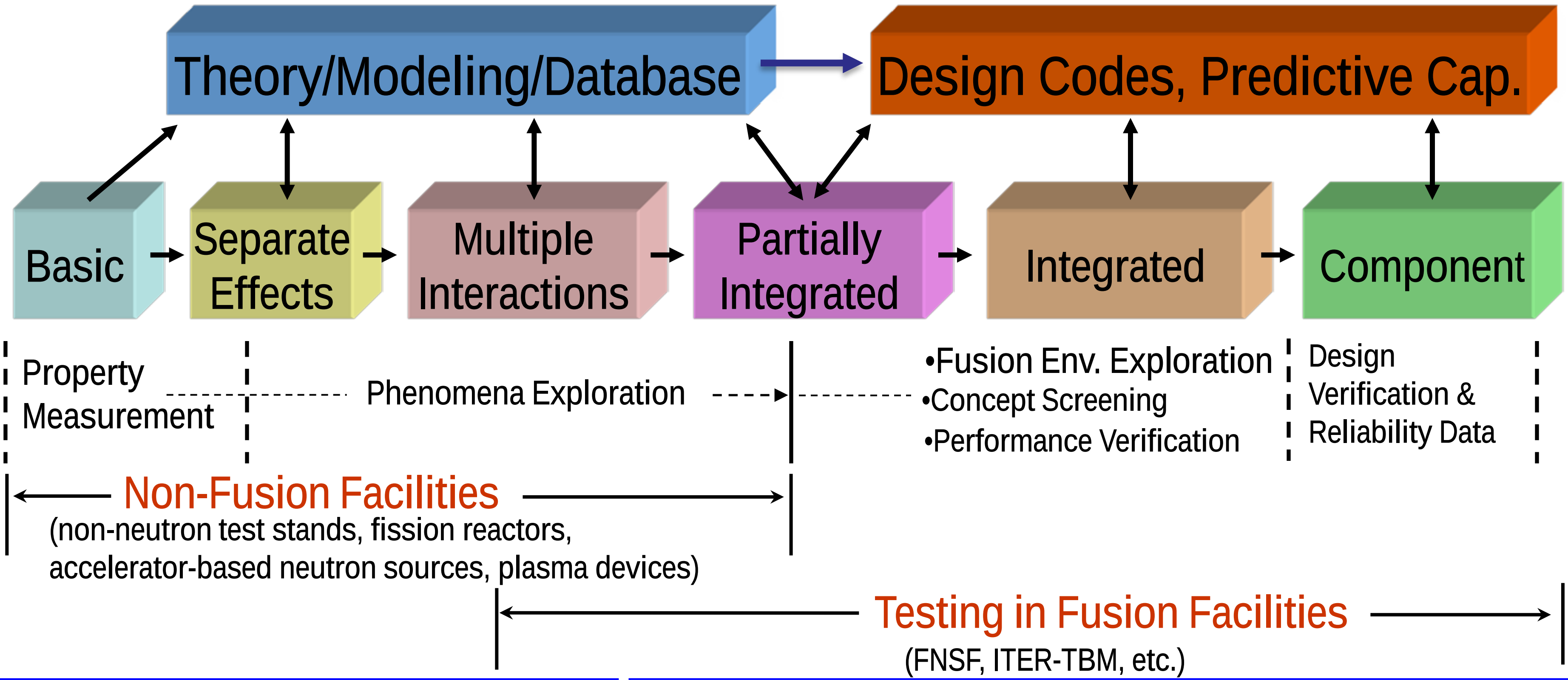
Zinkle, S. (ORNL)

Challenging
Fusion Nuclear Science & Technology Issues

1. Tritium Supply &
   Tritium Self-Sufficiency
2. High Power Density
3. High Temperature
4. MHD for Liquid Breeders / Coolants
5. Tritium Control (Extraction and Permeation)
6. Reliability / Maintainability / Availability
7. Testing in Fusion Facilities

Science-Based Framework for FNST R&D

(Developed by FNST community and Supported by ReNeW)



Experiments in non-fusion facilities are essential and are prerequisites

Testing in Fusion Facilities is NECESSARY to uncover new phenomena, validate the science, establish engineering feasibility, develop reliable components

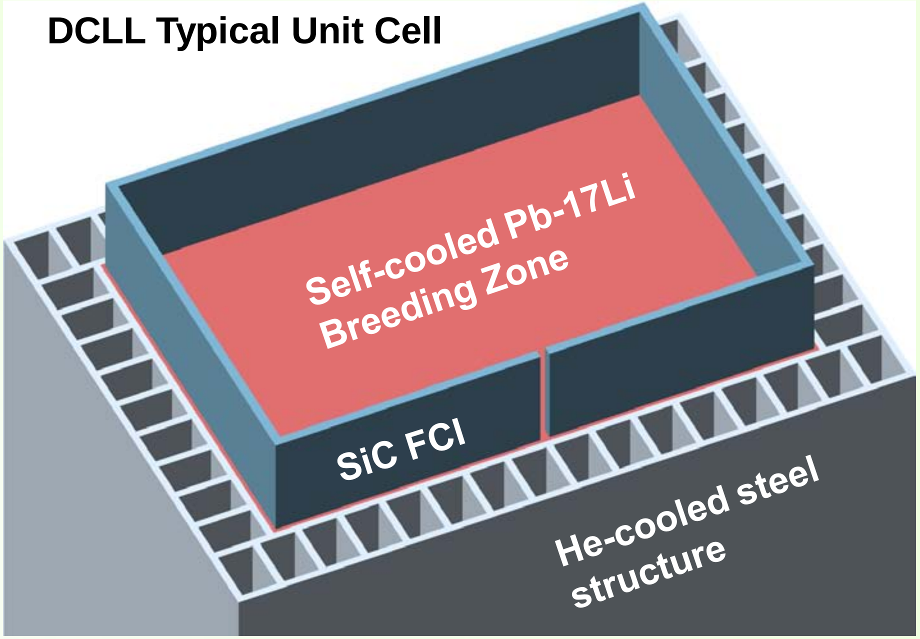
What we need now:

- A strong program of modeling and laboratory experiments in new & existing non-fusion facilities
- Plan for ITER TBM and initiate a study to define and select a DT Fusion Nuclear Science Facility (FNSF) dedicated to FNST R&D in the integrated fusion environment

Pathway Toward Higher Temperature through Innovative Designs with Current Structural Material (Ferritic Steel): *Dual Coolant Lead-Lithium (DCLL) FW/Blanket Concept*

- **First wall and ferritic steel structure cooled with helium**
- **Breeding zone is self-cooled**
- **Structure and Breeding zone are separated by SiCf/SiC composite *flow channel inserts (FCIs)* that:**
  - **Provide thermal insulation to decouple PbLi bulk flow temperature from ferritic steel wall**
  - **Provide electrical insulation to reduce MHD pressure drop in the flowing breeding zone**

FCI does not serve structural function



Pb-17Li exit temperature can be significantly higher than the operating temperature of the steel structure ⇒ High Efficiency

Lessons learned: The most challenging problems in FNST are at the *INTERFACES*

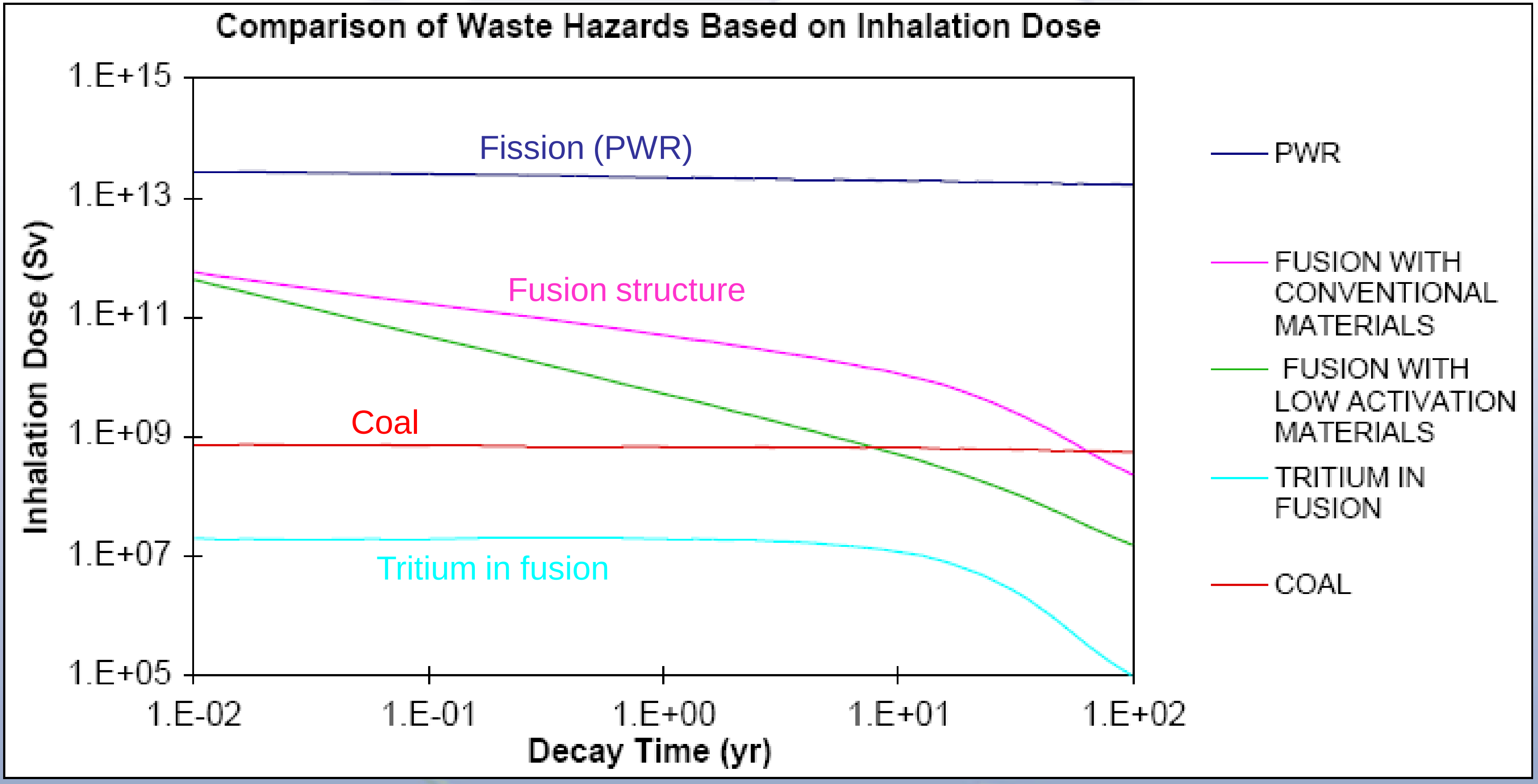
- Examples:
  - **MHD insulators**
  - **Thermal insulators**
  - **Corrosion** (liquid/structure interface temperature limit)
  - **Tritium permeation**

- Research on these interfaces **must integrate the many technical disciplines of fluid dynamics, heat transfer, mass transfer, thermodynamics and material properties in the presence of the multi-component fusion environment.**

- Modeling and Experiments should progress from single effects to multiple effects in laboratory facilities and then to integrated tests in the fusion environment.

  Research **must be done jointly by blanket and materials researchers.**

Radiotoxicity (inhalation) of waste from fusion is less than fission and similar to that from coal at 100 years.



- From “A Study of the Environmental Impact of Fusion” (AERE R 13708).
- Coal radiotoxicity is based on Radon, Uranium, Thorium, and Polonium in coal ash
- Inhalation represents major pathways for uptake of material by the human body
- Dose hazard used here is a relative measure of radiotoxicity of material

Summary

- Fusion is the most promising long-term energy option.
  - renewable fuel, no emission of greenhouse gases, inherent safety
- 7 nations started construction of **ITER** to demonstrate the scientific and technological feasibility of fusion energy.
  - ITER will have first DT plasma in ~2026
- **The most challenging Phase of Fusion development still lies ahead. It is the development of Fusion Nuclear Science and Technology (FNST).**
  - ITER, limited fluence, addresses only initial Stage of FNST testing
  - A Fusion Nuclear Science Facility (FNSF) is required to develop FNST.
  - FNSF must be small size, small power DT, driven plasma with Cu magnets
- **Magnets and magnetic field interactions are a major part of the magnetic fusion energy system**
  - Superconducting magnets are used in ITER and essential for Power Reactors, but Normal Cu magnets with special joints and features are needed for FNSF.
  - **LM Blankets are most promising**, but their potential is limited by MHD effects. Innovative concepts must continue to be proposed and investigated.