The World Energy situation and the Role of Renewable Energy Sources and Advanced Nuclear Technologies, fission and fusion, in Solving the Energy and Environmental Problems

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The World Energy Situation and the Role of Renewable Energy Sources and Advanced Nuclear Technologies, fission and fusion, in Solving the Energy and Environmental Problems

OUTLINE

1. **The World Energy Situation**
   - Need for more energy, impact on the environment, energy-water nexus
2. **Renewable Energy Sources**
   - Solar, wind, geothermal, biomass, hydro, etc.
3. **Nuclear Fission**
   - Existing plants, and contribution to current world energy needs
   - Nuclear renaissance and future outlook
4. **Fusion**
   - What is fusion? And why do we need it?
   - Approaches to fusion and DEMO goal
   - ITER – International fusion project
   - Fusion Nuclear Science and Technology (FNST)
5. **Closing Remarks**

World Energy Situation

Energy Situation

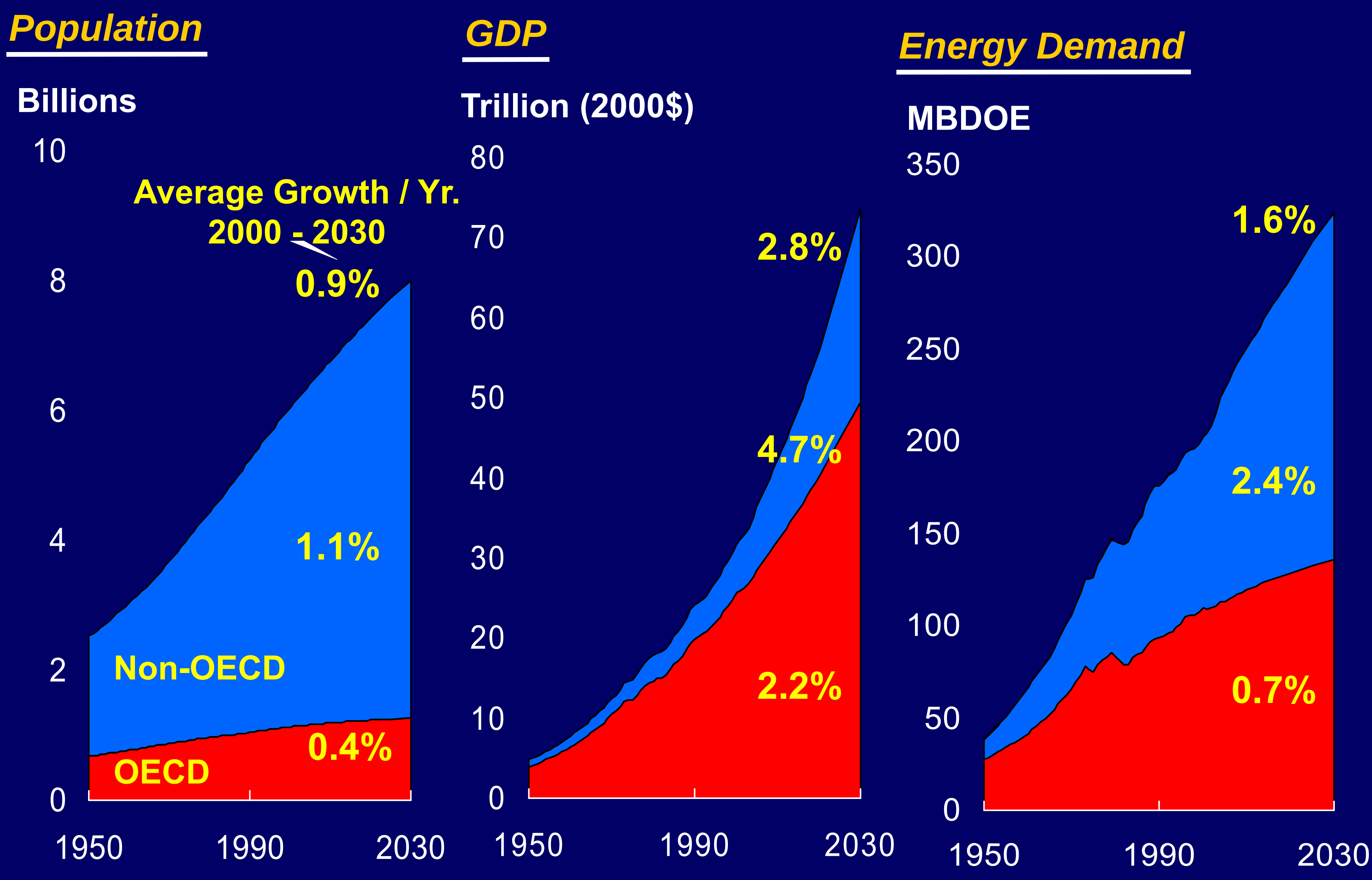
- **The world uses a lot of energy**
  - Average power consumption = 13.6 TW (2.2 KW per person)
  - World energy market ~ $3 trillion / yr (electricity ~ $1 trillion / yr)

- **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
  - CO2 emission is increasing at an alarming rate

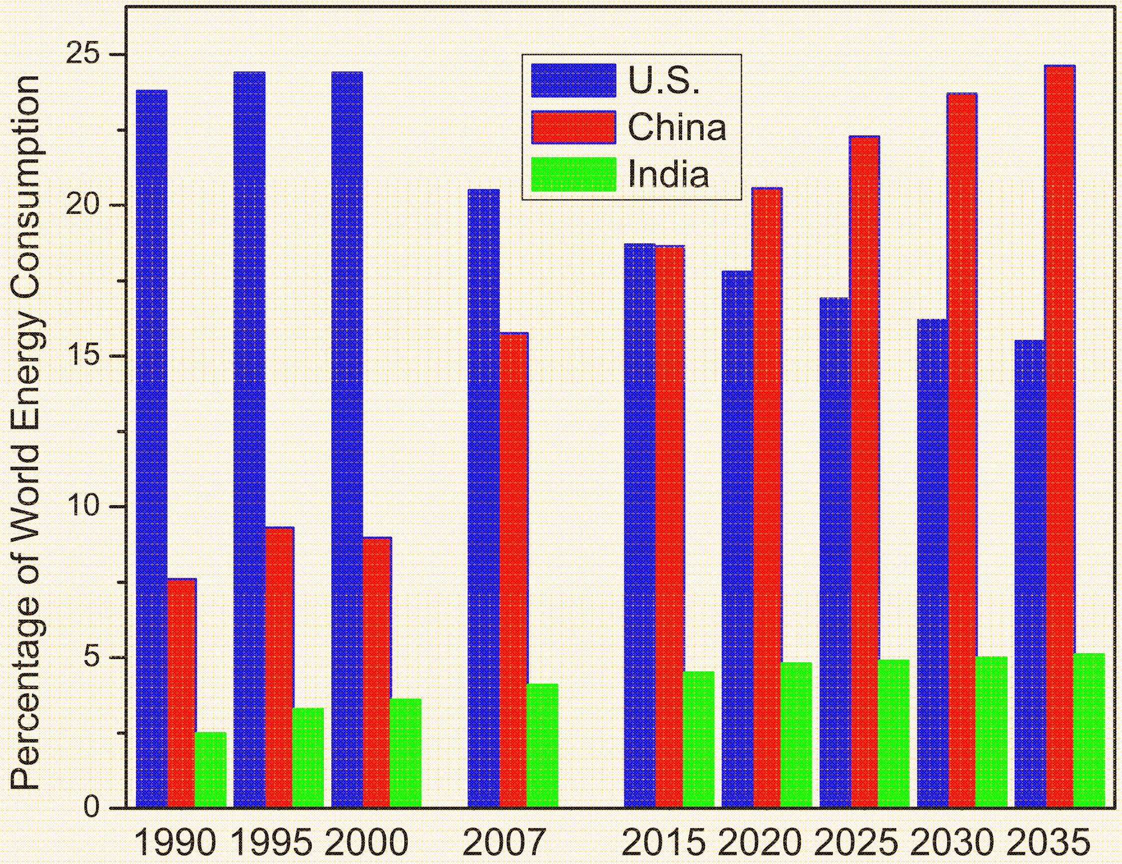
- **Oil supplies are dwindling**
  - Special problem for transportation sector (need alternative fuel)

Global Economics and Energy



Total Projected Energy Use for Selected Countries

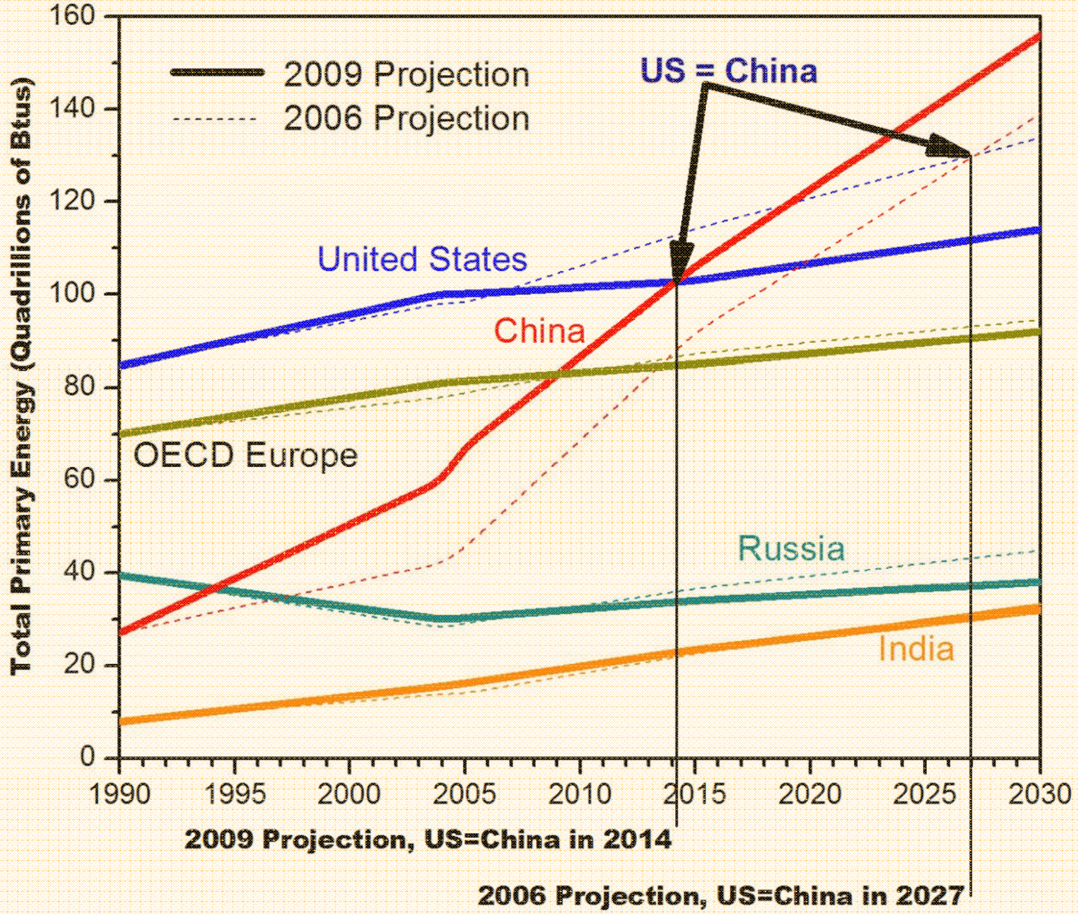
U.S. and China energy use will be the same in 2014



Source: Energy Information Administration, International Energy Outlook 2010

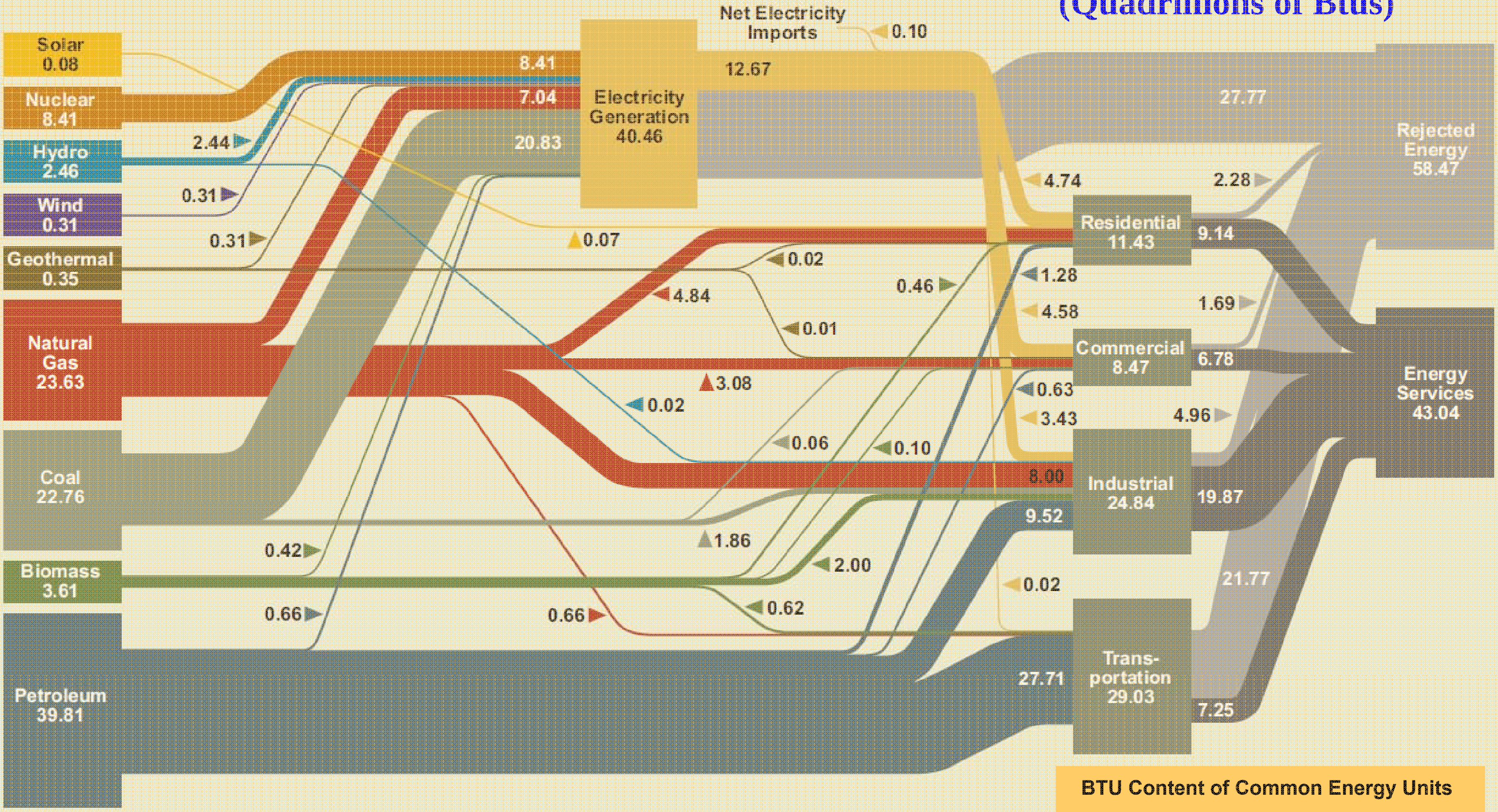
Total Energy Use Projections for Selected Countries: 2006 and 2009 Projections

U.S. and China energy use will be the same in 2014



Source: Energy Information Administration, International Energy Outlook

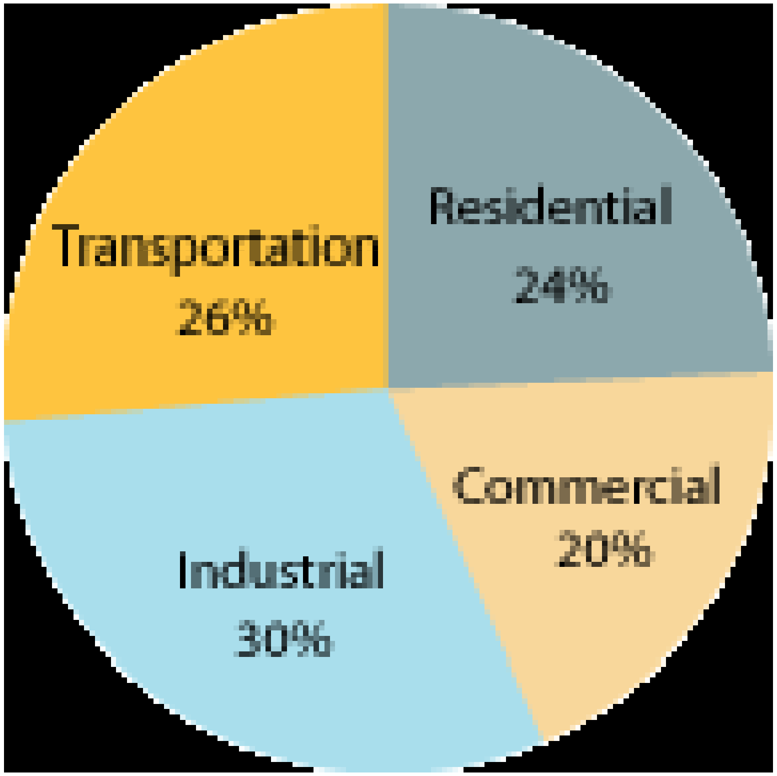
Energy Flows in the U.S. Economy, 2007



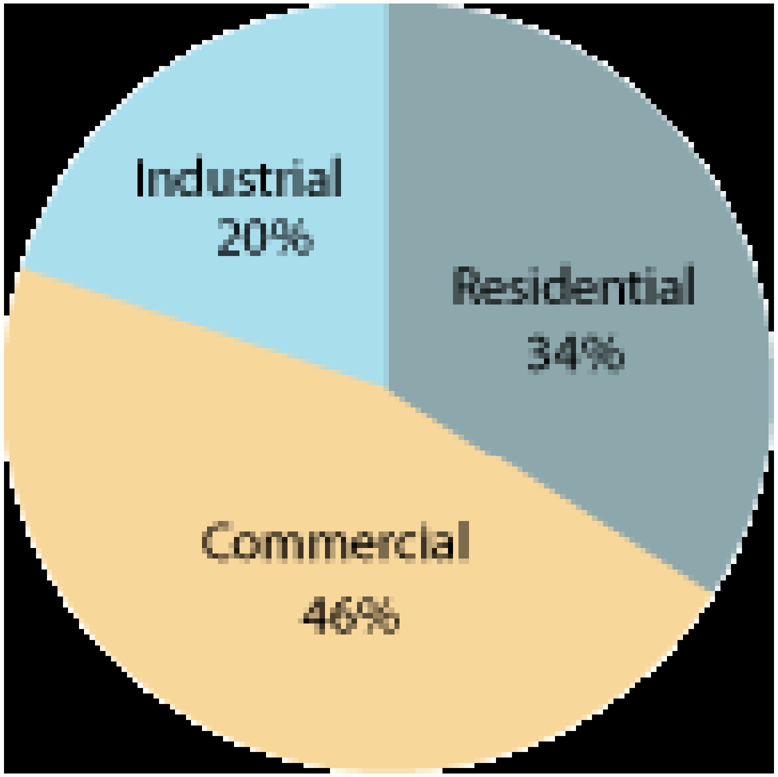
BTU Content of Common Energy Units
1 Quad = 1,000,000,000,000,000 Btu
1 barrel of crude oil = 5,800,000 Btu
1 gallon of gasoline = 124,000 Btu
1 cubic foot of natural gas = 1,028 Btu
1 short ton of coal = 20,169,000 Btu
1 kilowatthour of electricity = 3,412 Btu

Energy Use by Sector (2000)

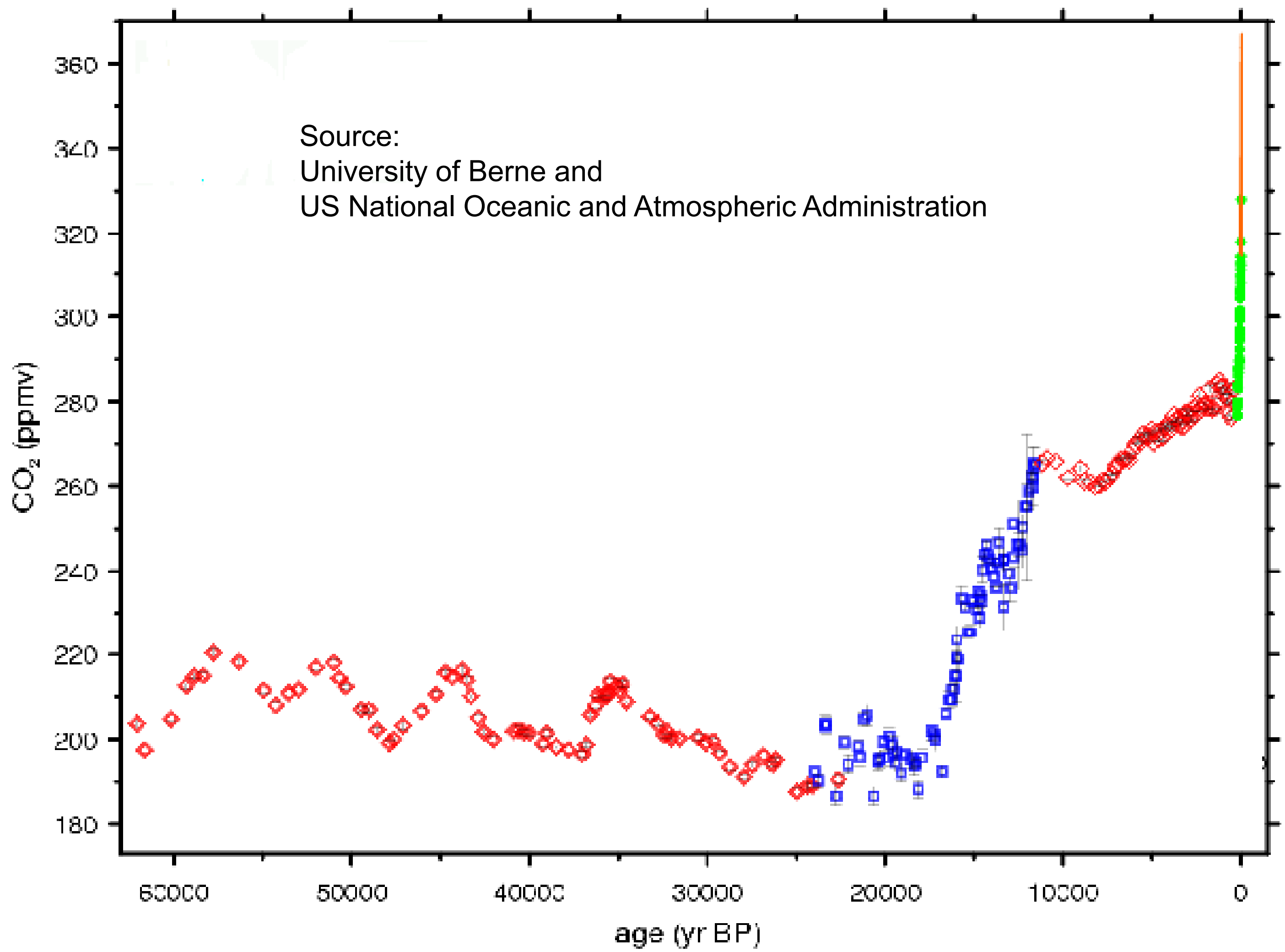
Total Energy



Electricity



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

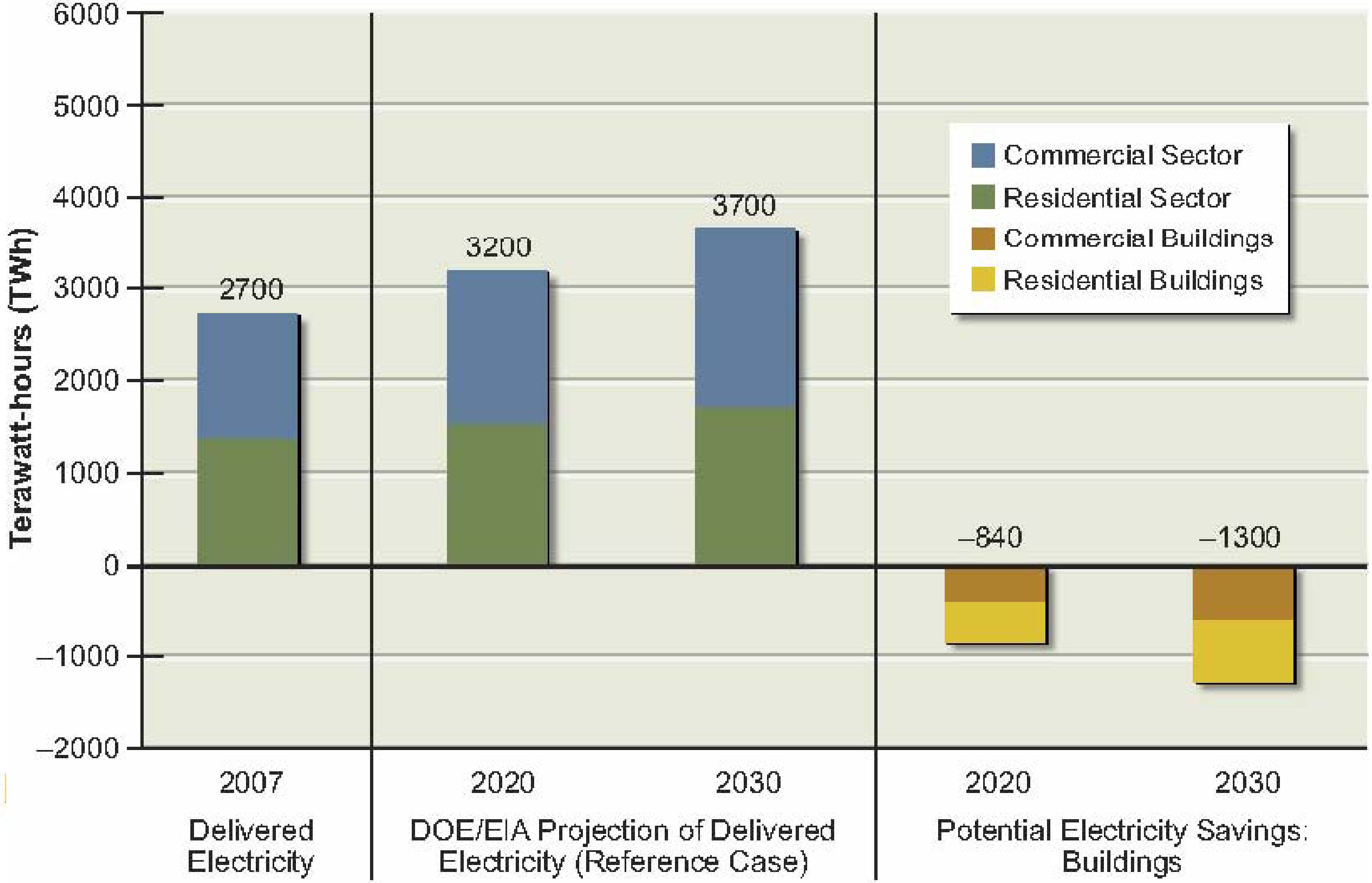


Solving the Energy Problem and Reducing Greenhouse Gas Emission Requires Pursuing a Diversified Portfolio Approach

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

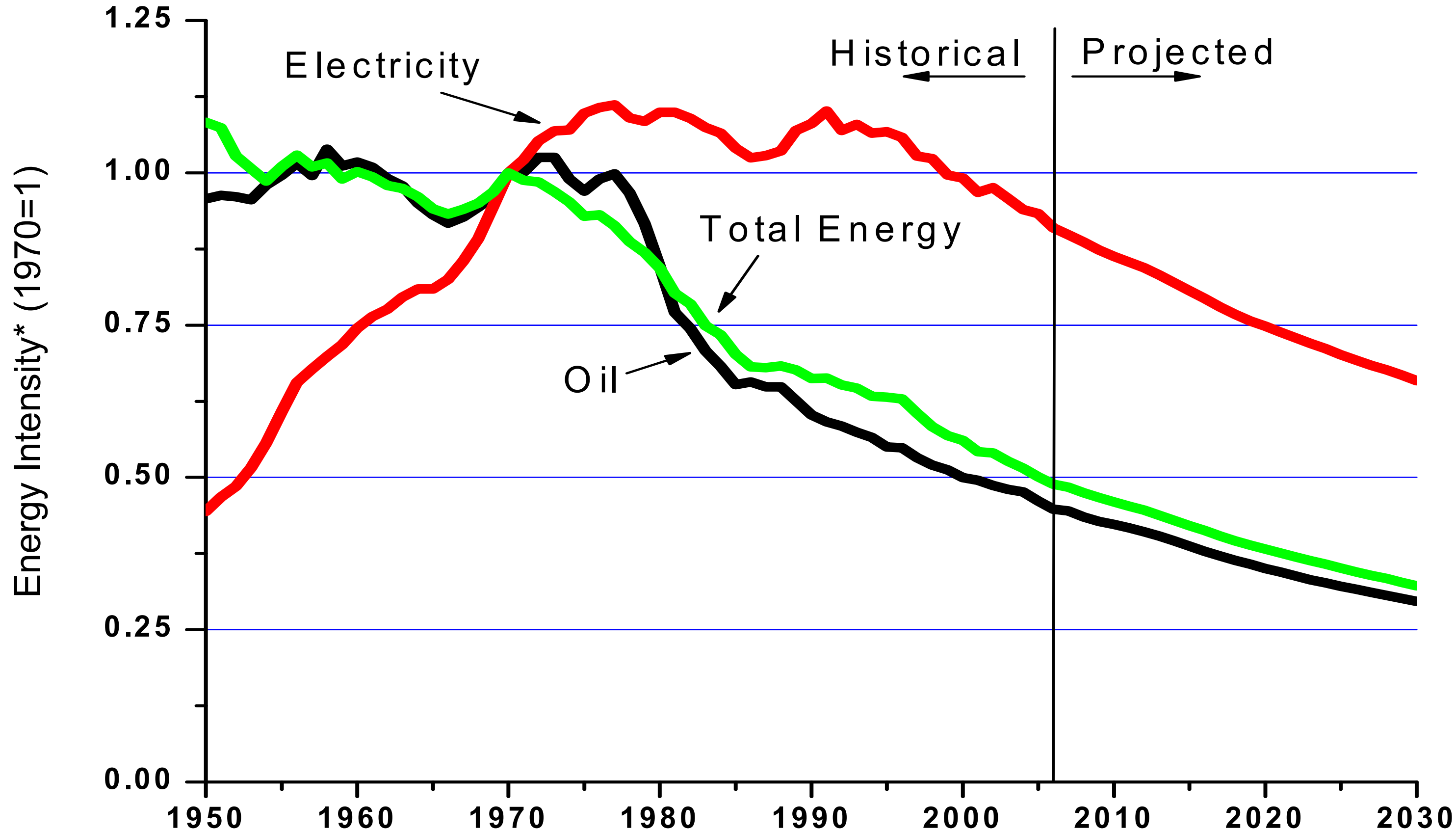
Potential for Increasing Energy Efficiency is Enormous

Potential Electricity Savings in Commercial and Residential Buildings in 2020 and 2030 (currently 73% of electricity used in US – space heating and cooling, water heating, and lighting)



Energy Intensity* (efficiency) of the U.S. Economy Relative to 1970 levels

*Energy consumed per dollar GDP



*Energy consumed per dollar GDP (2000 constant dollars)
Source: Based on EIA, 2006

Renewable Energy Resources

Top Countries with Installed Renewable Electricity by Technology (2009)

Geothermal
1 U.S.
2 Philippines
3 Indonesia
4 Mexico
5 Italy

Wind
1 U.S.
2 China
3 Germany
4 Spain
5 India

Solar PV
1 Germany
2 Spain
3 Japan
4 U.S.
5 Italy

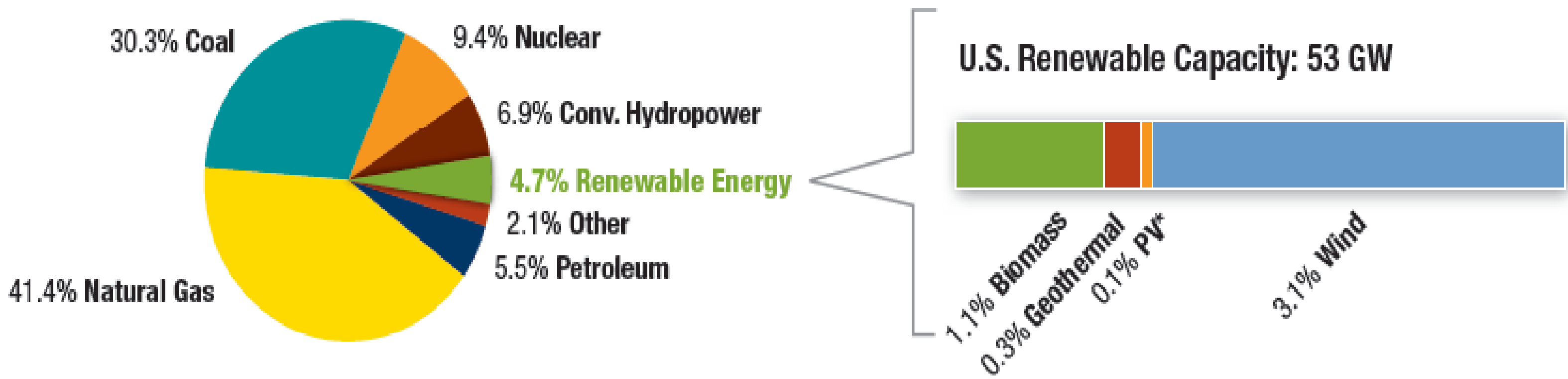
CSP
1 U.S.
2 Spain

Biomass
1 U.S.
2 Brazil
3 Germany
4 China
5 Sweden

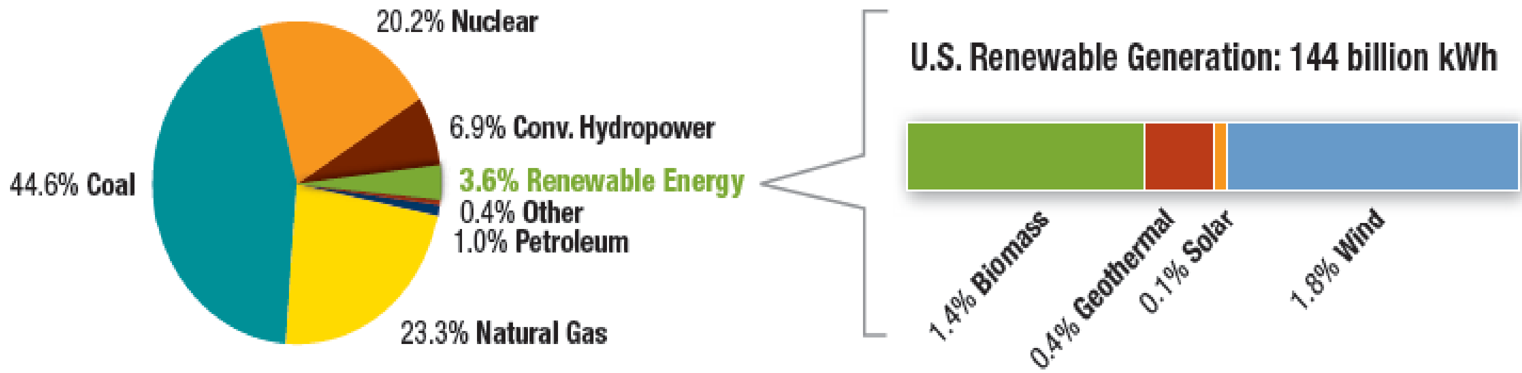
Source: REN21, GWEC, GEA, SEIA

U.S. Nameplate Capacity and Generation (2009)

U.S. Electric Nameplate Capacity (2009): 1,121 GW



U.S. Electric Net Generation (2009): 3,954 billion kWh

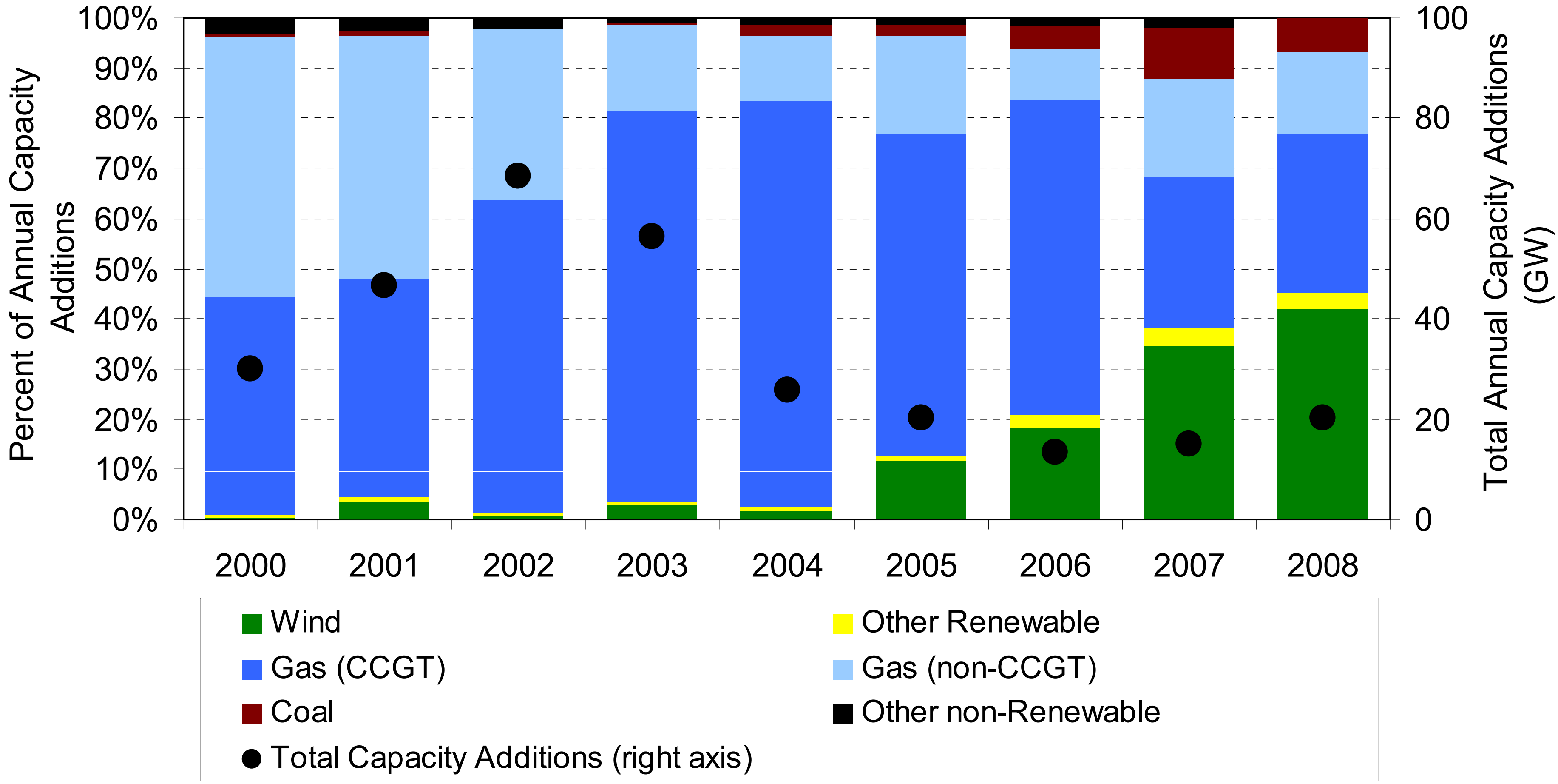


Source: EIA, AWEA, SEIA, GEA

Other includes: pumped storage, batteries, chemicals, hydrogen, pitch, purchased steam, sulfur, tire-derived fuels, and miscellaneous technologies.

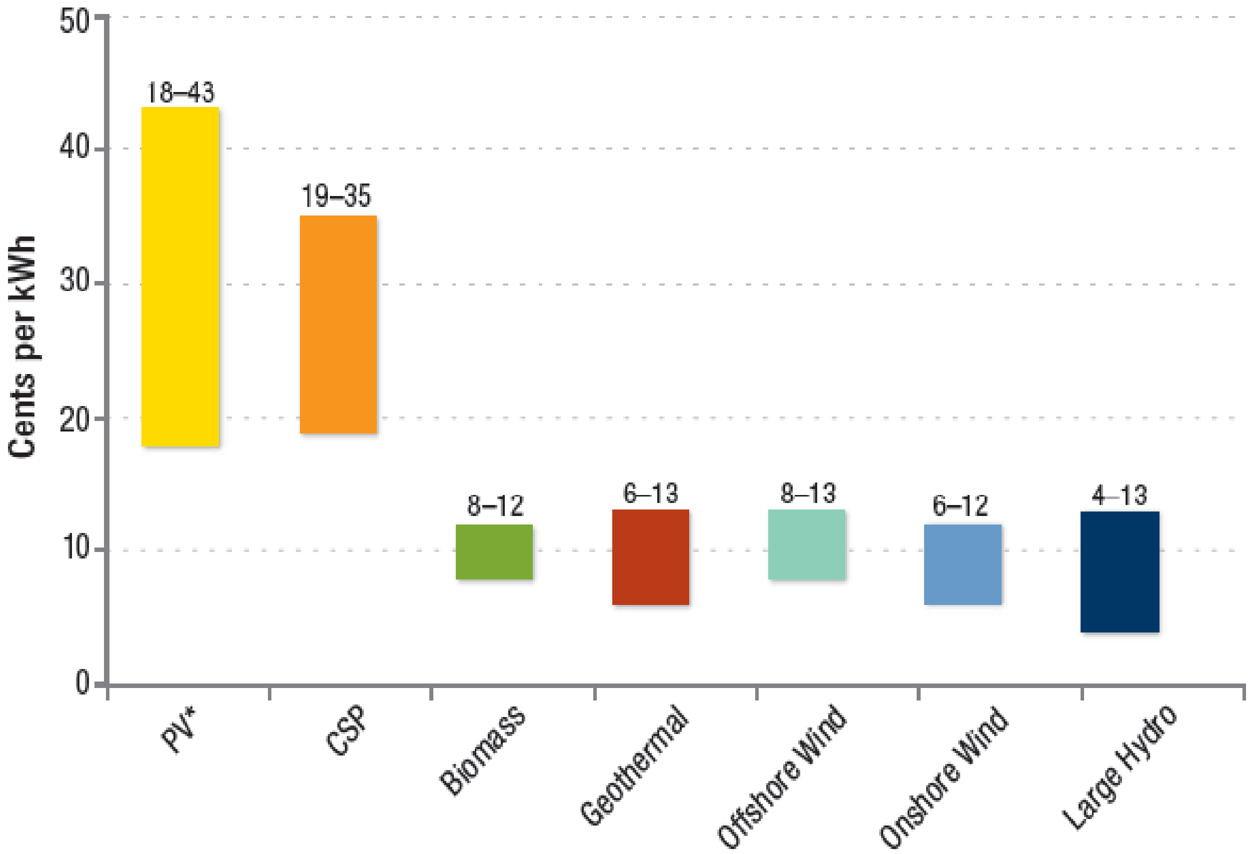
* Includes on- and off-grid capacity.

Status of Renewable Electricity Technologies



Renewable energy has been contributing to a growing portion of U.S. electric capacity additions (45% in 2008)

Levelized Cost of Energy (LCOE) of Renewable Electricity by Technology (2009)



Assumptions

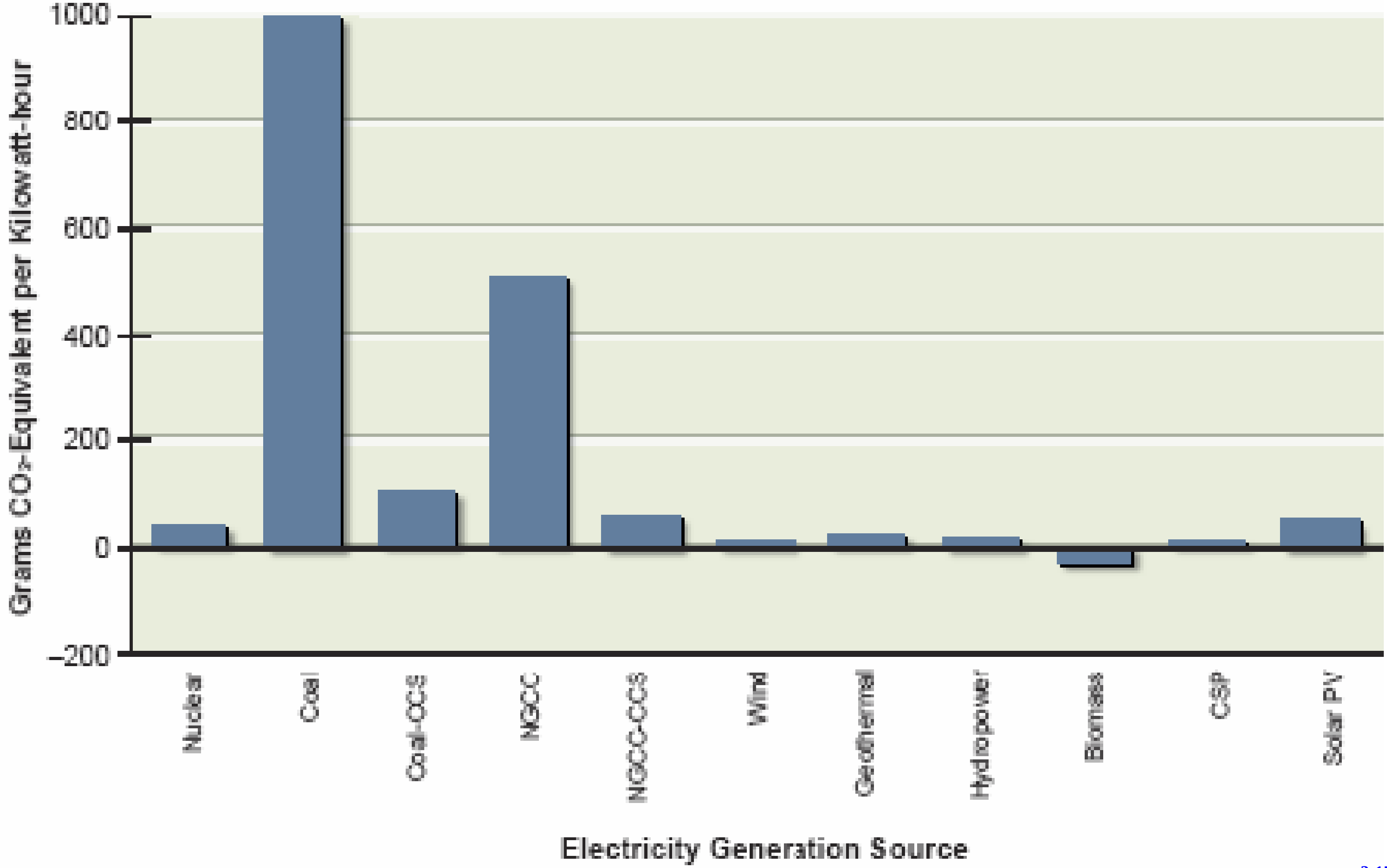
Currency: 2009 US $ (real)
Real Discount Rate: 10.5%
Inflation Rate: 3%
Economic Lifetime: 30 years
Taxes: none
Tax credits: none
Debt/Equity Financing: none
Biomass Fuel Costs: AEO 2009
PV Degradation: none
CSP Technology: no storage
Geothermal Technology: hydrothermal

* Current range of utility scale (greater than 5MW) PV in the U.S.

Sources: AEO, EPA, EPRI, NREL, McGowin, DeMeo et al.

Estimated Greenhouse Gas Emissions from Electricity Generation

Nuclear and Renewable Energy Sources are essential to addressing Climate Change



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Nuclear Fission

Nuclear Renaissance

Internationally, there are ongoing plans for nuclear energy expansion (Nuclear Renaissance)

- 33 countries with nuclear power plants
- **Worldwide**: 366 GWe installed, ~35 GWe currently under construction (~2% / year growth rate)
- **US** has currently 104 nuclear power plants. Incremental improvements enabled these plants to produce more energy than anticipated over their lifetimes. The average plant capacity factor increased from 66% in 1990 to 91.8% in 2007. Other improvements in safety, decreased cost, and reduced generation of high level waste.
- **China** has the most aggressive program

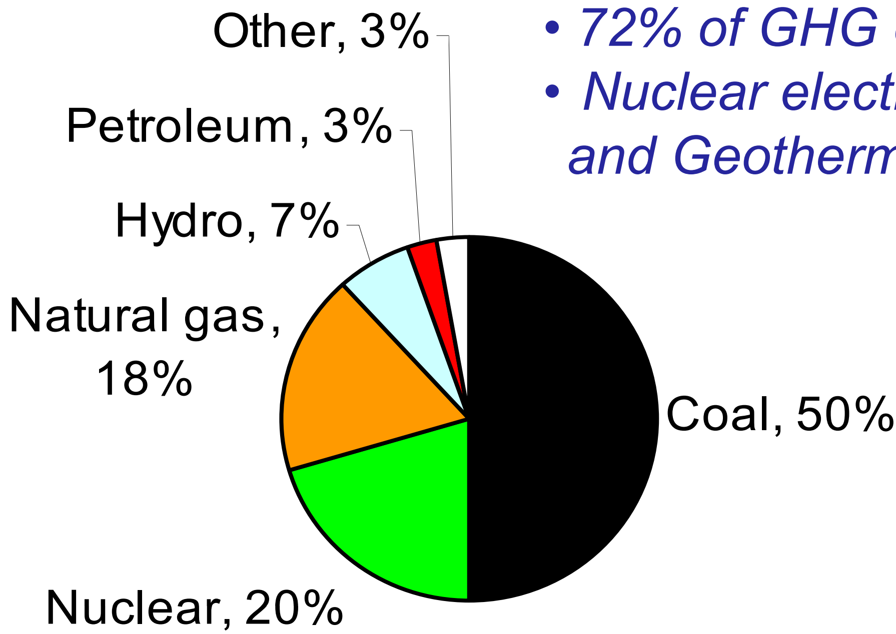
  -- China's nuclear energy plan
  - Present: 6.1 GWe
  - 2020: 32 GWe
  - 2030: 45-50 GWe
  - ~2050: 240 GWe

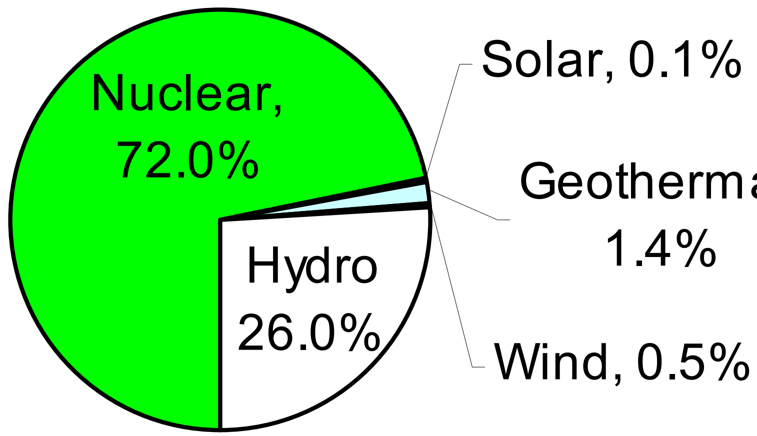
  -- China's fast reactor plans
  - Experimental: 25MWe (2006)
  - Prototype:300-600 MWe(2020)
  - Large: 1000-1500 MWe (2025)
  - Modular: 4-6x300 MWe (2025)

But managing nuclear materials and proliferation is becoming increasingly complex, requiring a modernized international approach.

Nuclear Power Must Remain a KEY Part of Our Energy Portfolio

Nuclear is the second largest source of U.S. electricity
- *20 % of electricity generation*
- *72% of GHG emission-free electricity*
- *Nuclear electricity is10 times more than Solar, Wind and Geothermal combined*





Nuclear energy is the dominant non-fossil energy technology

Evolution of Nuclear Power

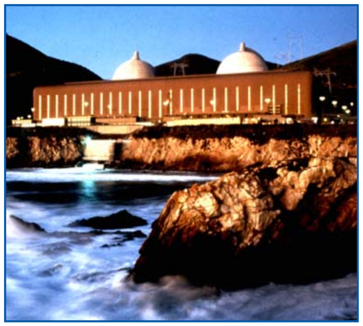
Generation I

Early Prototype Reactors

- Shippingport
- Dresden
- Fermi I
- Magnox

Generation II

Commercial Power Reactors



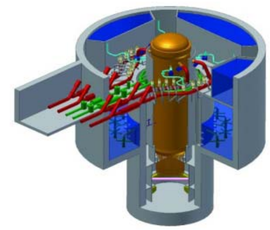
- LWR-PWR, BWR
- CANDU
- VVER/RBMK

Generation III

Advanced LWRs

- ABWR
- System 80+
- AP600
- EPR

Generation III+

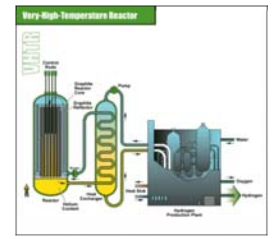


Near-Term Deployment

- AP1000
- PBMR
- SWR-1000
- ABWR-II

Evolutionary Improved Economics

Generation IV



- Highly Economical
- Enhanced Safety
- Minimal Waste
- Proliferation Resistant

Gen I	Gen II	Gen III	Gen III+	Gen IV

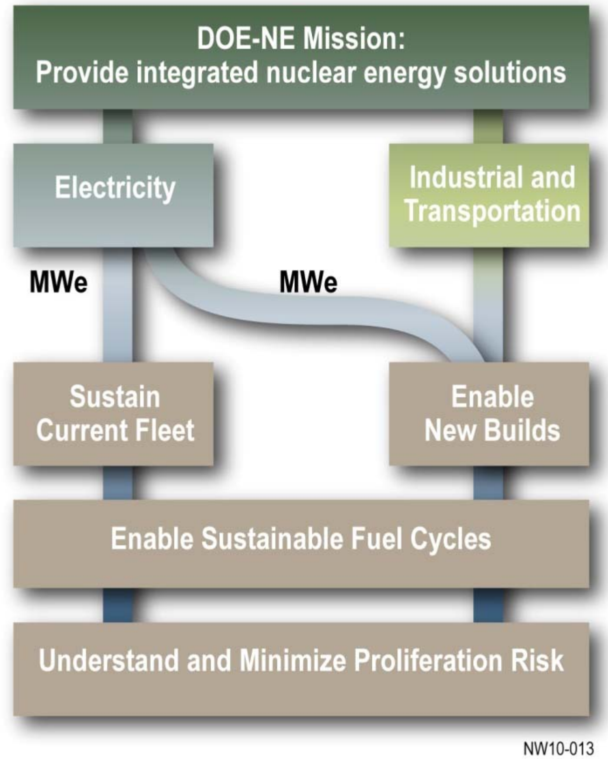
1950 1960 1970 1980 1990 2000 2010 2020 2030

1. U.S. Department of Energy Gen-IV Roadmap Report

U.S. DEPARTMENT OF ENERGY

Current Nuclear Energy Research Objectives

- **Extend life of currently operating plants**
  - **Goal is to extend currently operating LWRs plant life from design life (40 years) to beyond 60 years**
- **Enable new builds for electricity and process heat production and improve the affordability of nuclear energy-**
  - Develop and demonstrate next generation advanced plant concepts and technologies
- **Enable sustainable fuel cycles**
  - high burnup fuel
  - Develop optimized systems that maximize energy production while minimizing waste
- **Understand and minimize proliferation risks**
  - Goal is limiting proliferation and security threats by protecting materials, facilities, sensitive technologies and expertise

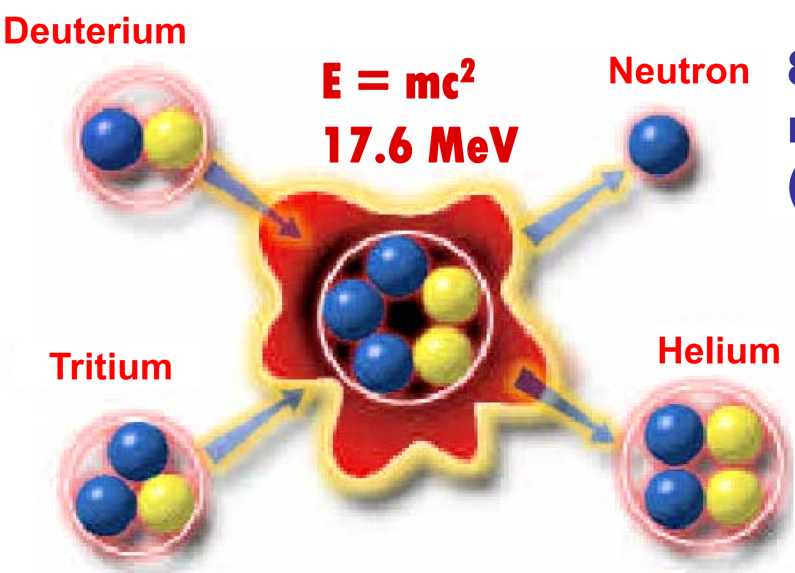


An implementation plan has been developed for each objective

CREATING a Star on Earth
Fusion: The Ultimate Energy Source for Humanity

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**

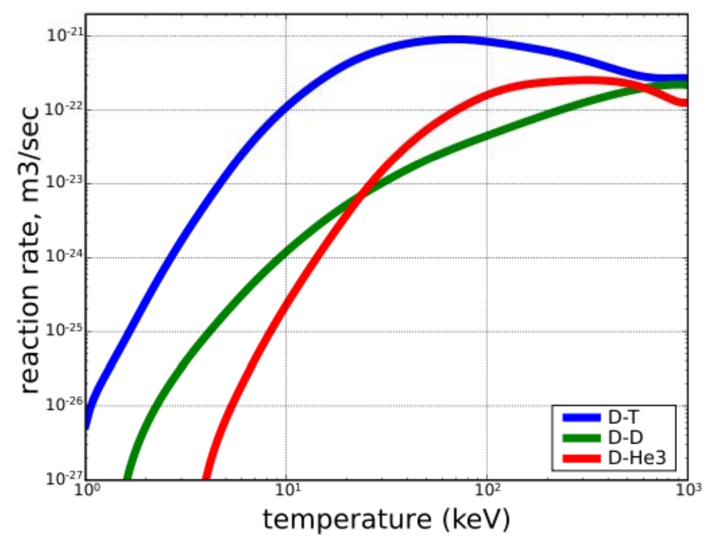
Li + n → T + He

Li in some form must be used in the fusion system

20% of energy release (3.5 MeV)

- **Deuterium and tritium is the easiest: attainable at lower plasma temperature, has the largest reaction rate and high Q value.**

- **The World Program is focused on the D-T Cycle.**



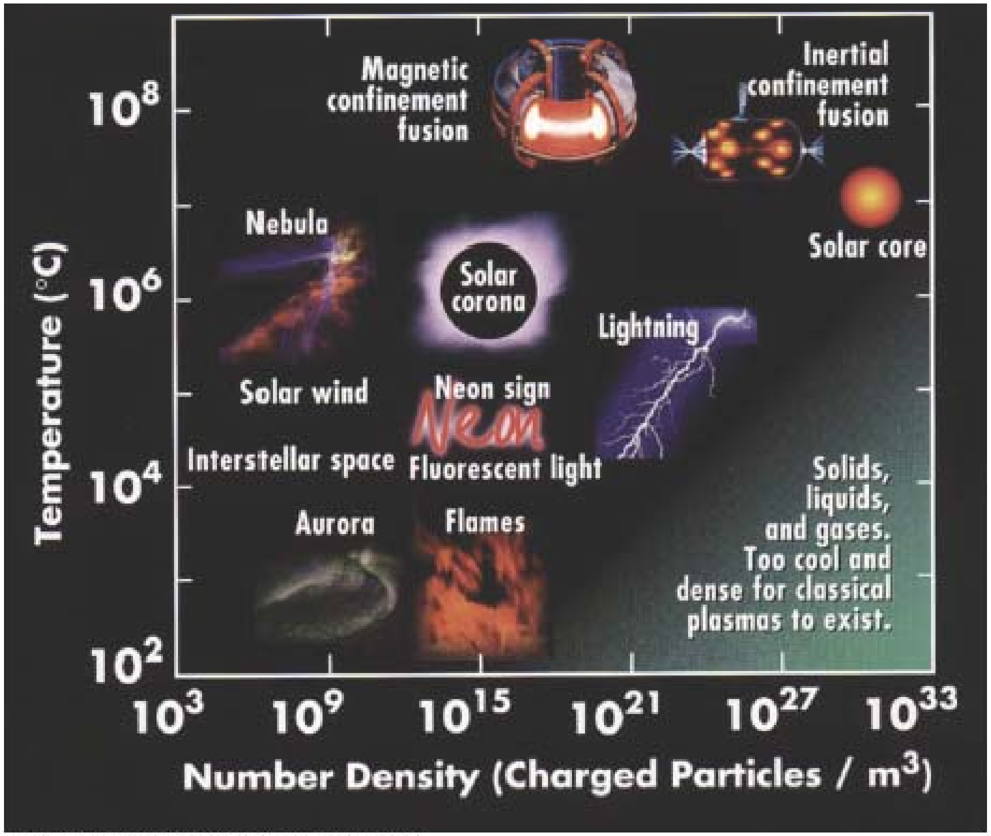
Incentives for Developing Fusion

- 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.

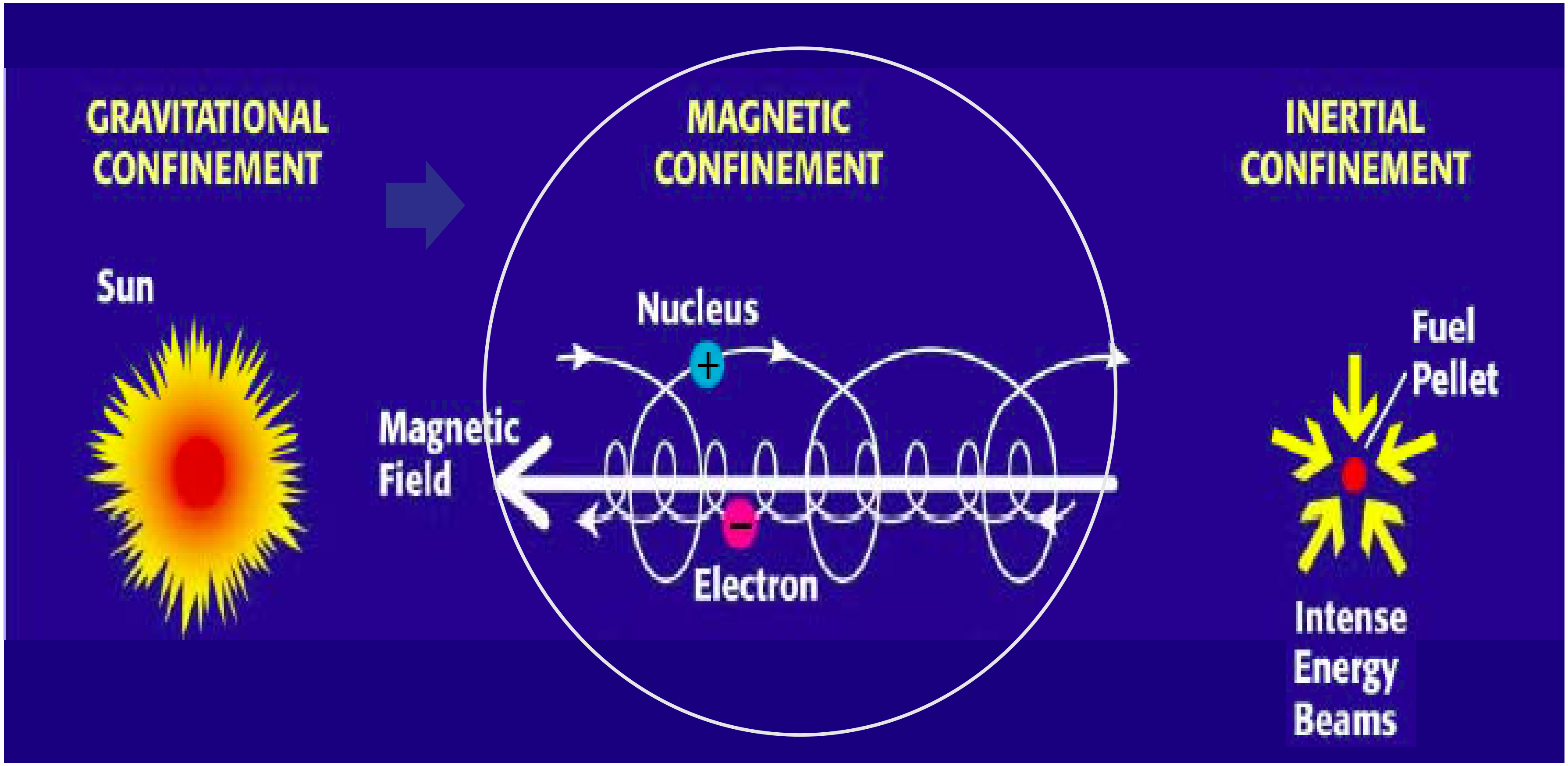
Fusion Reactions Occur in **Hot Plasmas**

- A ***Plasma*** is an ionized gas, a mixture of ***positive ions*** and ***negative electrons*** with overall ***charge neutrality*****.**
- Plasmas constitute the 4th state of matter, the most common state in the universe.
- Obtained at very high temperatures. The temperature of the ***Sun*** is about 15 million °C. On earth we need > 100 million °C.



Contemporary Physics Education Project (CPEP)

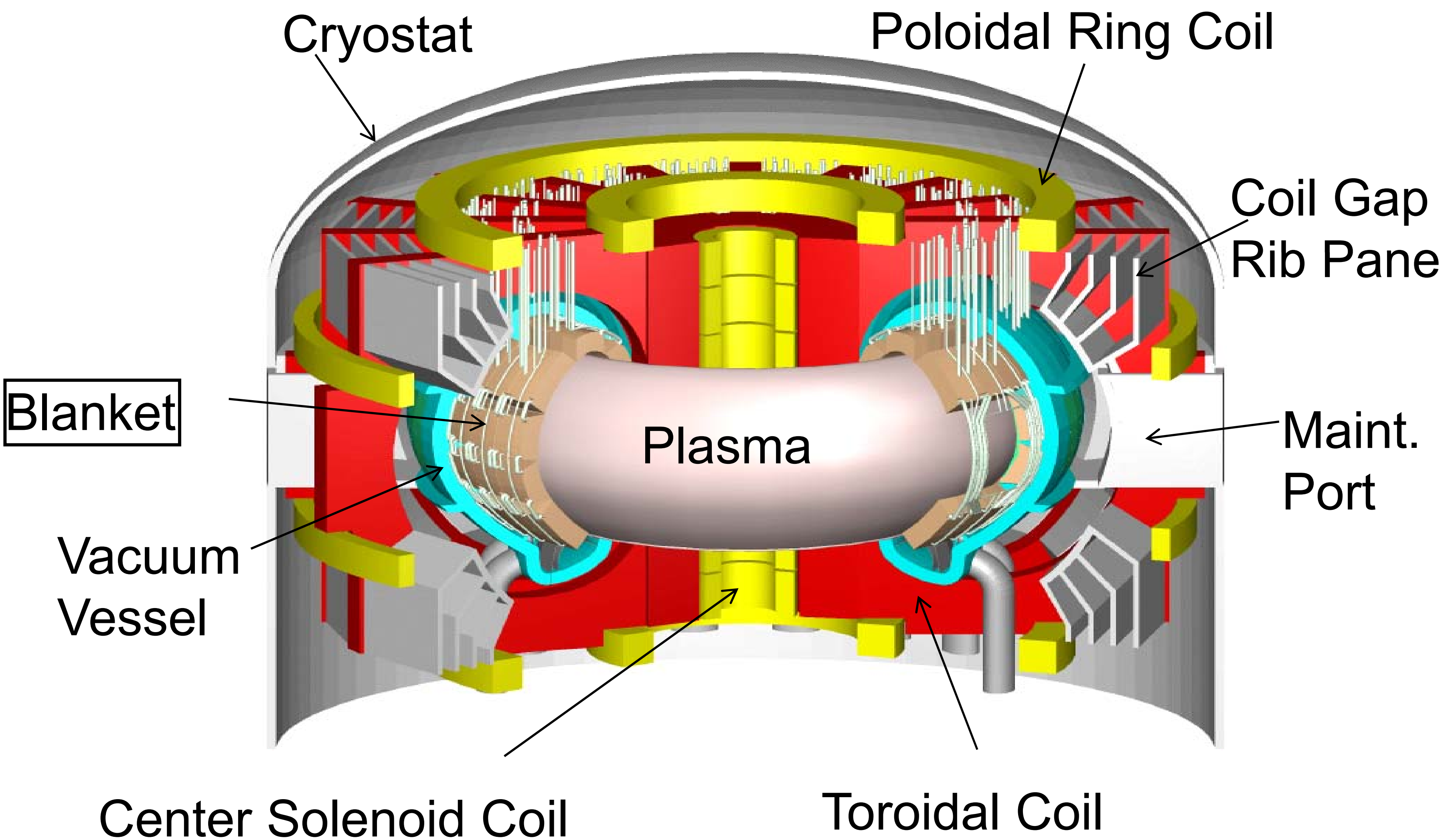
There are several ways to create a self-sustaining fusion plasma



- $m \cdot dv/dt = F_{Lorentz} = q \cdot (v \times B)$ ➡ cyclotron motion with Larmour radius $r_L = mv_{\perp}/|q|B$

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 ~ 2027.**

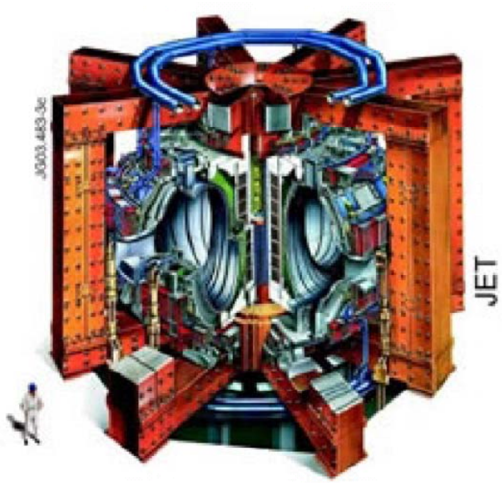
ITER is a reactor-grade tokamak plasma physics experiment - A huge step toward fusion energy

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

By Comparison, JET

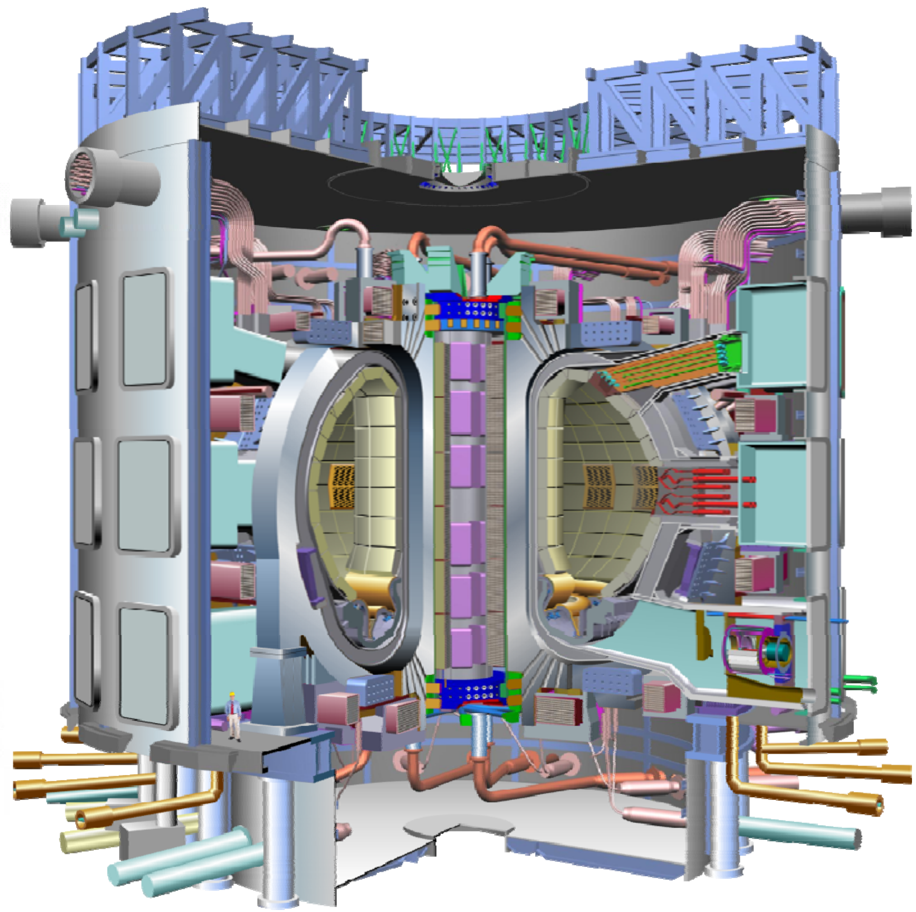
- **~10 MW**
- **~1 sec**
- **Passively Cooled**

~15 m



JET

~29 m



ITER

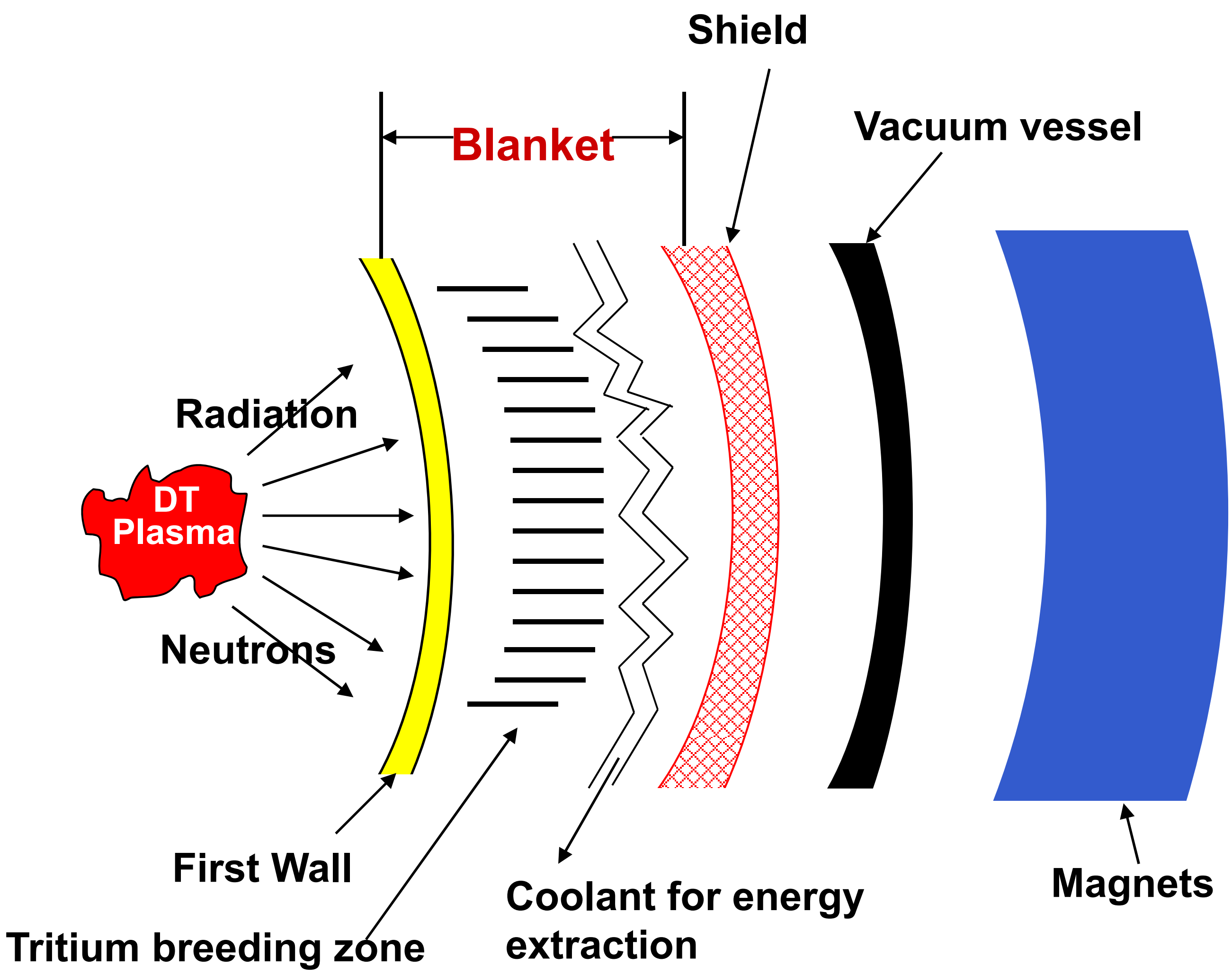
The Deuterium-Tritium (D-T) Cycle

- World Program is focused on the D-T cycle:

$$D + T \rightarrow n + \alpha + 17.58 \text{ MeV}$$

- The fusion energy (17.58 MeV per reaction) appears as kinetic energy of neutrons (14.06 MeV) and alphas (3.52 MeV)
- Tritium does not exist in nature! Decay half-life is 12.3 years
  - Tritium must be generated inside the fusion system to have a sustainable fuel cycle
  - The only possibility to adequately breed tritium is through neutron interactions with lithium. Lithium, in some form, must be used in the fusion system.
- α particles will slow down in the plasma imparting their energy to D and T and keep the plasma heated.
  - *But this "He ash" must be removed from the plasma, eg. via "Divertor"*

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



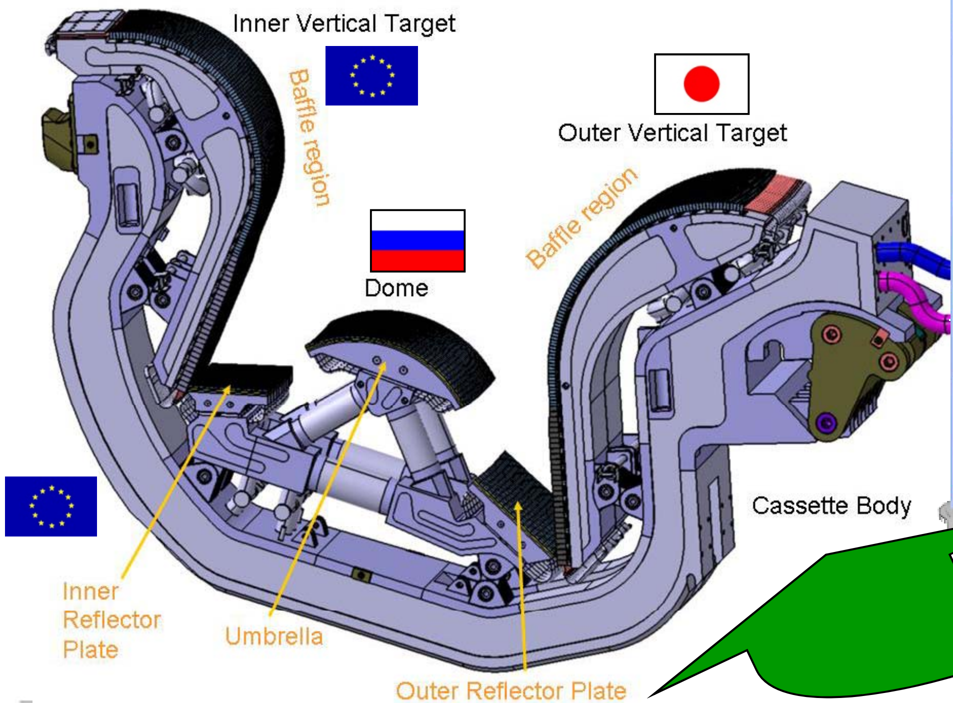
Lithium-containing Liquid metals (Li, PbLi) are strong candidates as breeder/coolant. He-cooled Li ceramics are also candidates.

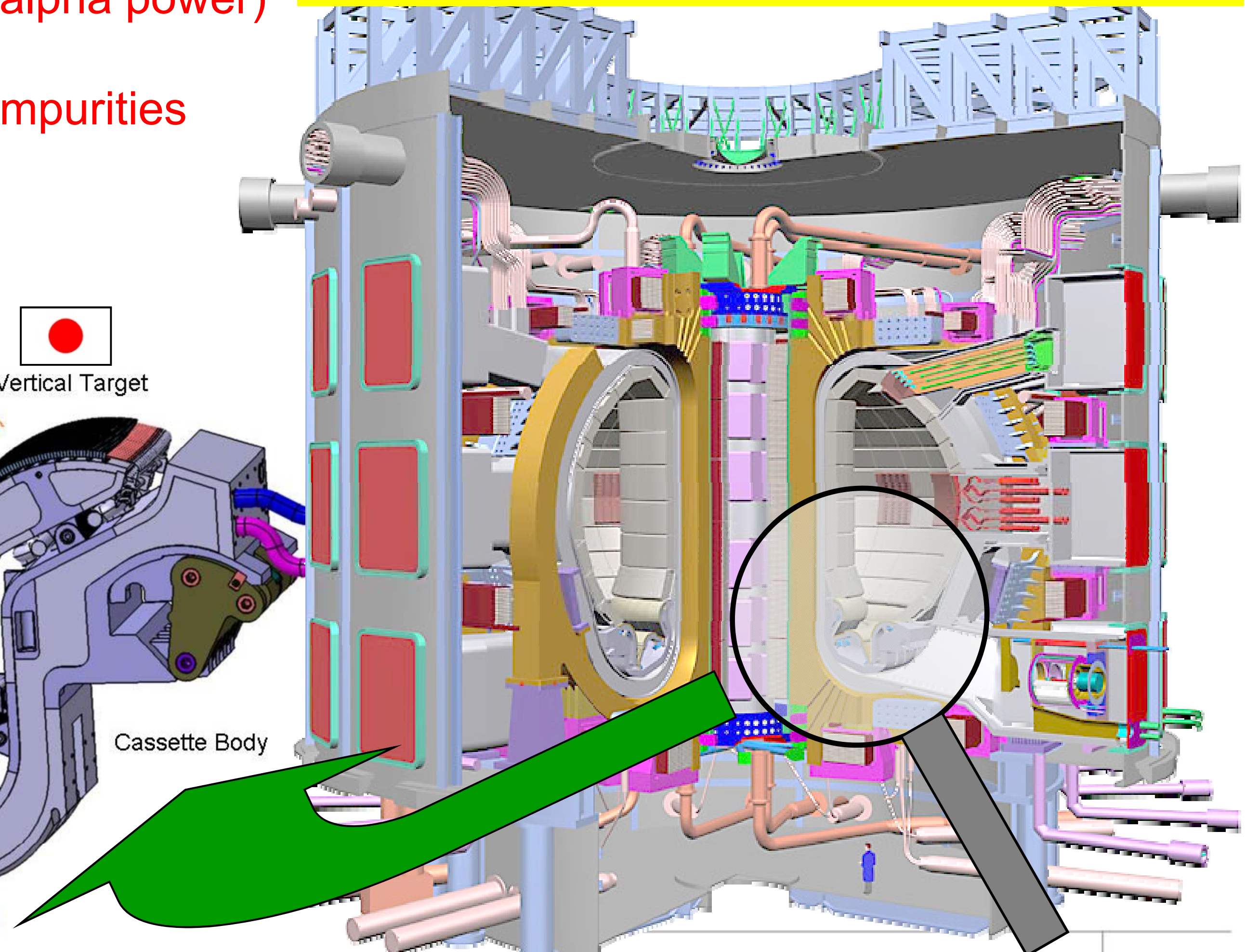
Divertor

Divertor system main functions :

- Exhaust the major part of the plasma thermal power (including alpha power)
- Minimize the helium and impurities content in the plasma

Challenge to develop HHF Componets capable of 20 MW/m²





Fusion Nuclear Science and Technology (FNST)

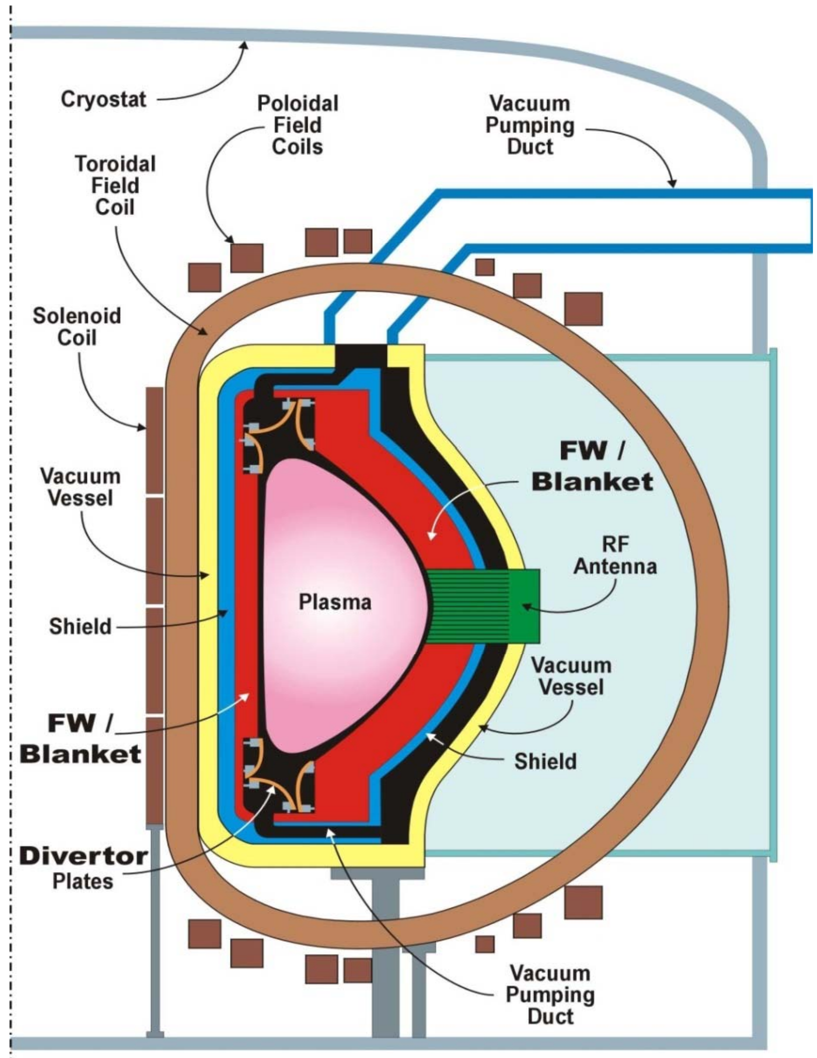
FNST is the **science**, **engineering**, **technology** and **materials** for the fusion nuclear components that generate, control and utilize neutrons, energetic particles & tritium.

Inside the Vacuum Vessel "Reactor Core":

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

Other Systems / Components affected by the Nuclear Environment:

- Tritium Fuel Cycle
- Instrumentation & Control Systems
- Remote Maintenance Components
- Heat Transport & Power Conversion Systems

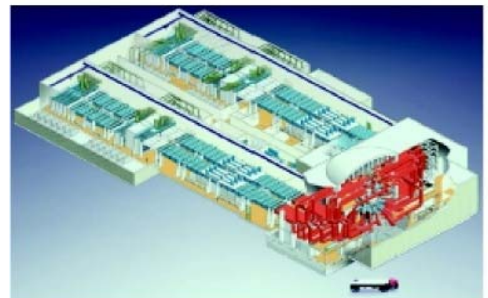


FNST research requires advancing the state-of-the-art, and developing highly integrated predictive capabilities for many cross-cutting scientific and engineering disciplines

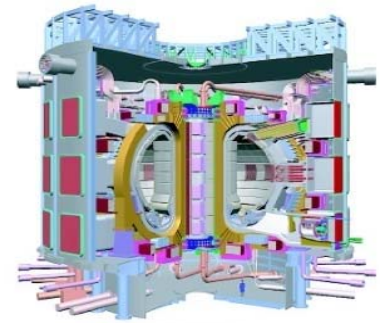
- neutron/photon transport
- neutron-material interactions
- plasma-surface interactions
- heat/mass transfer
- MHD thermofluid physics
- thermal hydraulics
- tritium release, extraction, inventory and control
- tritium processing
- gas/radiation hydrodynamics
- phase change/free surface flow
- structural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

Fusion research requires the talents of many scientists and engineers in many disciplines.
Need to attract and train bright young students and researchers.

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



National Ignition Facility



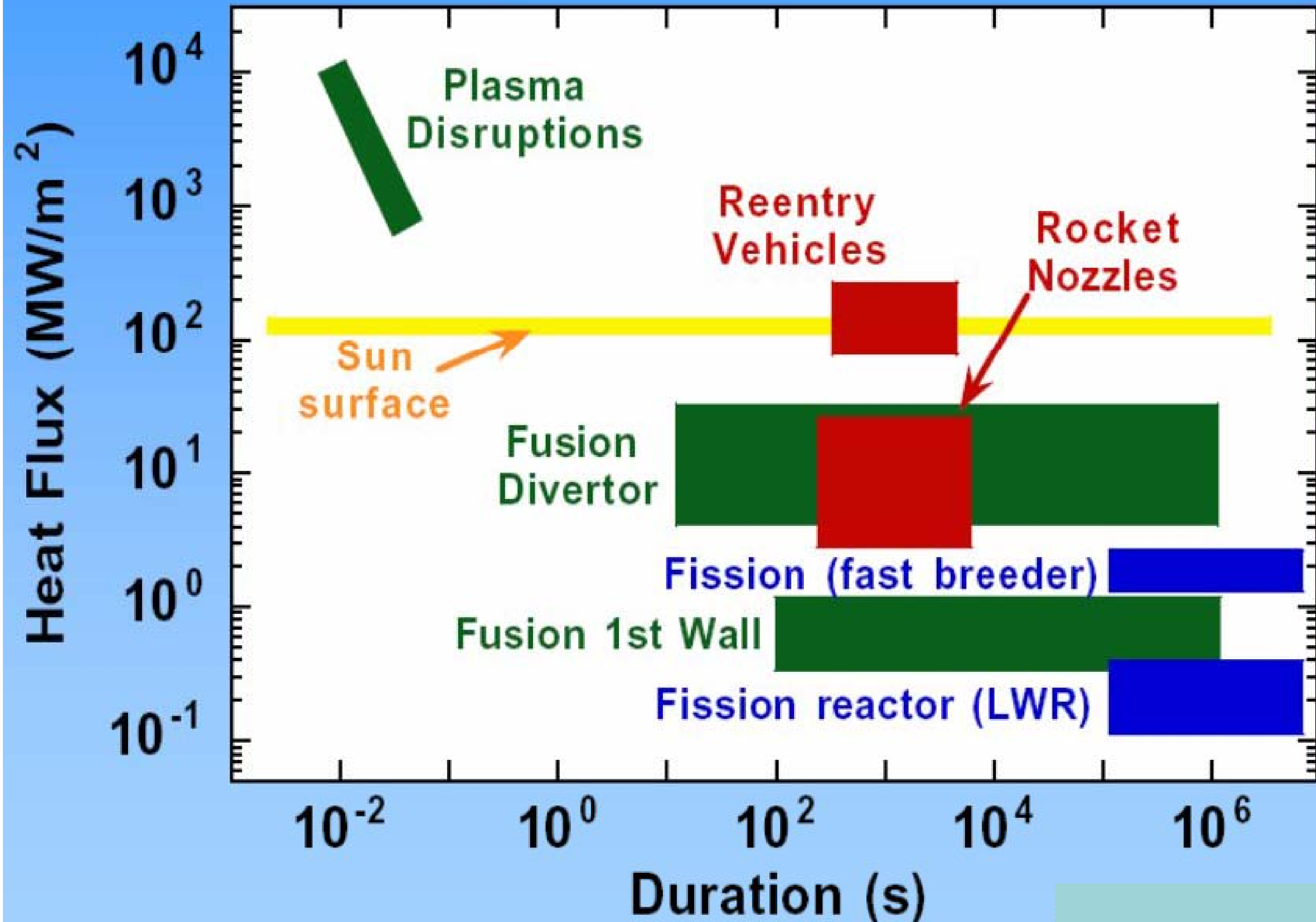
ITER

- **1950-2010**
  - **The Physics of Plasmas**
- **2010-2035**
  - **The Physics of Fusion**
  - **Fusion Plasmas-heated and sustained**
    - **$Q = (E_f / E_{input})$~10**
    - **ITER (MFE) and NIF (inertial fusion)**
- **ITER is a major step forward for fusion research. It will demonstrate:**
  1. **Reactor-grade plasma**
  2. **Plasma-support systems (S.C. magnets, fueling, heating)**

But the most challenging phase of fusion development still lies ahead:
The Development of Fusion Nuclear Science and Technology

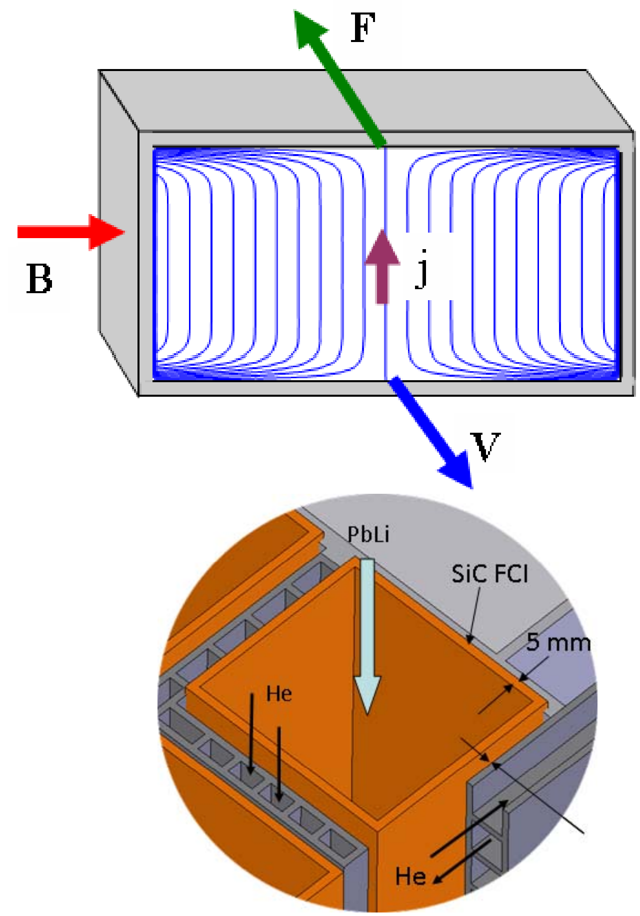
The cost of R&D and the time to DEMO and commercialization of fusion energy will be determined largely by FNST.

Comparison of Heat Fluxes



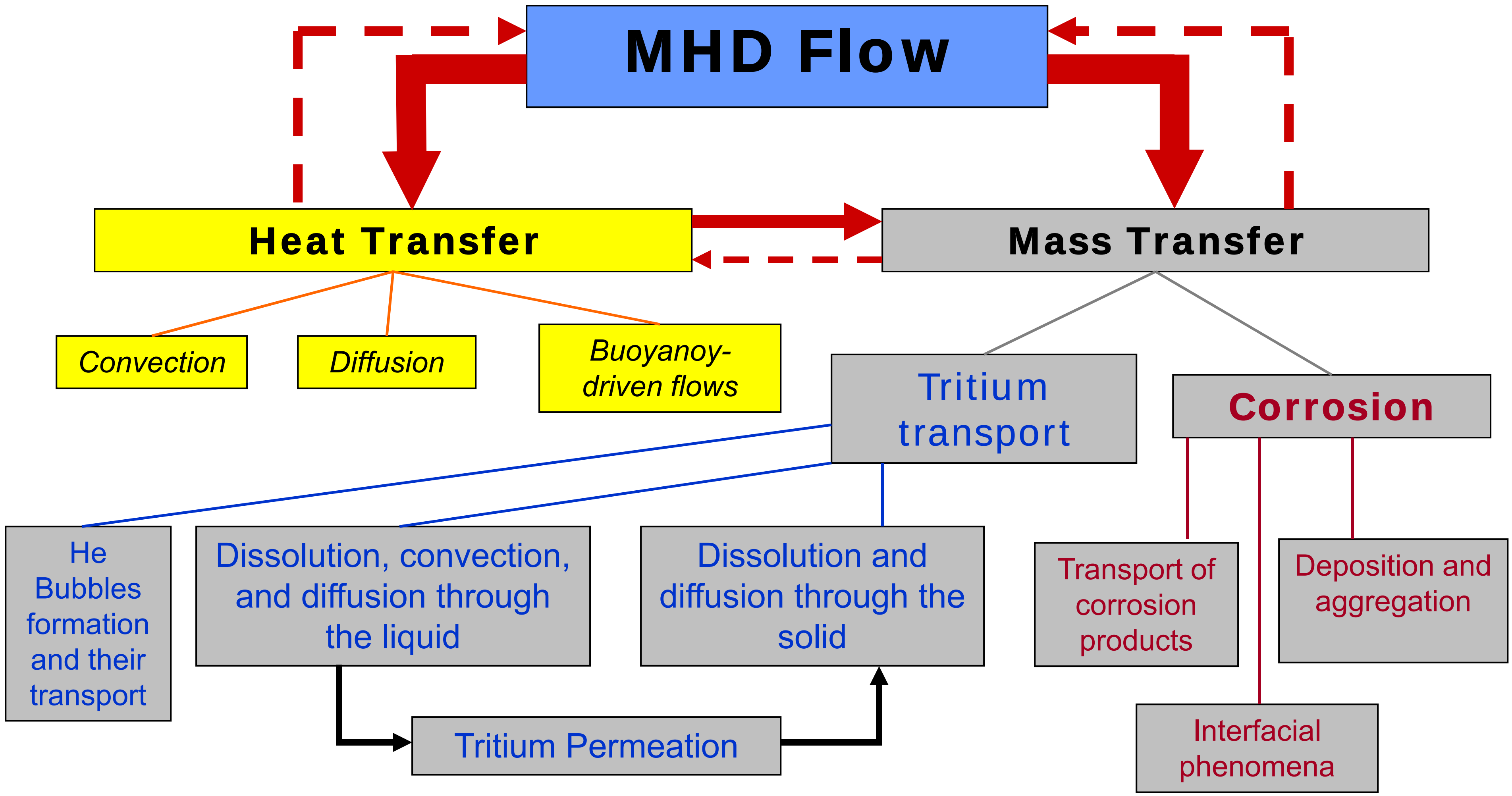
MHD fluid flow and heat/mass transfer issues are primary drivers of liquid metal blanket designs

- The motion of electrically conducting breeder/coolant in strong, plasma-confining, magnetic field induces electric currents, which in turn interact with the magnetic field, resulting in Lorentz forces that modify the original flow in many ways. This is a subject of **magnetohydrodynamics** (***MHD*).**
- MHD forces in fusion blankets are typically 4 to 5 orders of magnitude larger than inertial and viscous forces, changing the fluid dynamics in remarkable ways.
- MHD forces are non-local, flow in one location can be controlled by current closure in boundary layers or structure in another location.
- These unique MHD coolant/breeder flows are non-linearly coupled to other transport phenomena (heat/mass transfer) – blanket performance and design requires an in-depth understanding of all these phenomena.



The electromagnetic *Lorentz force* is orders of magnitude higher than viscous or inertial forces, strongly affecting LM flows in the blanket

Integrated, multi-physics modelling of MHD flow dynamics and heat and mass transfer in blanket flows



Coupling through the source / sink term, boundary conditions, and transport coefficients

Scientific & Technical Challenges for Fusion Materials

- Fusion materials are exposed to a hostile environment that includes combinations of high temperatures, reactive chemicals, large time-dependent thermal-mechanical stresses, and intense damaging radiation.
- Key issues include thermal stress capacity, coolant compatibility, waste disposal, and radiation damage effects.
- The 3 leading structural materials candidates are ferritic/martensitic steel, V alloys and SiC composites (based on safety, waste disposal, and performance considerations).

➢ **The ferritic/martensitic steel is the reference structural material for DEMO**

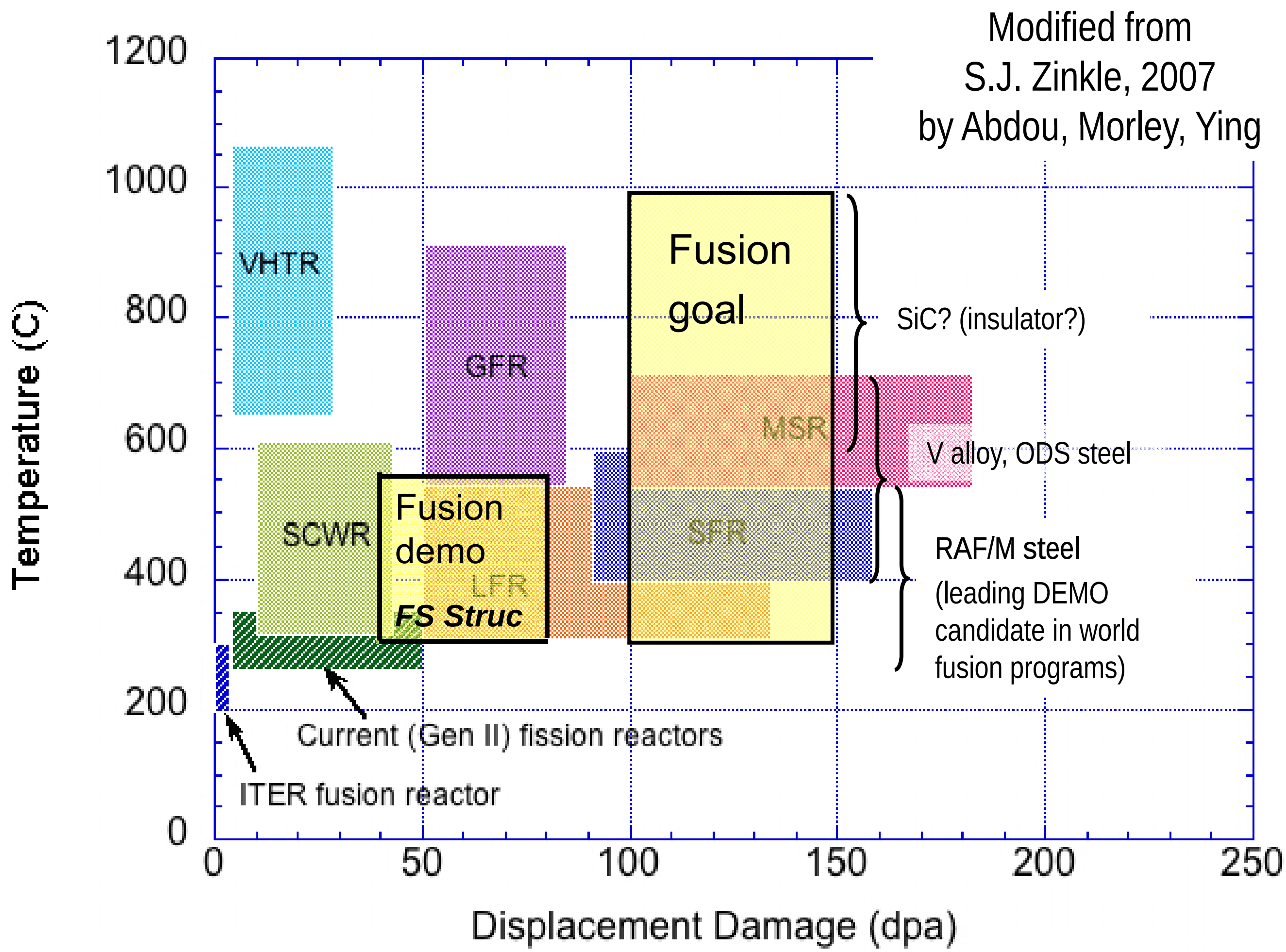
- *Structural materials are most challenging, but many other materials (e.g. breeding, insulating, superconducting, plasma facing and diagnostic) must also be successfully developed.*

Common interest of fission and fusion structural materials: operating temperature and radiation dose (dpa)

(There are many other areas of synergy between fission and fusion technologies)

Notes:

- Fusion values presented here are the maximum at front of the FW/B.
- Dose in fusion structural material has steep radial gradients. Deeper in the blanket:
  - o Damage decreases by ~an order of magnitude
  - o Spectrum is softer and helium production is smaller, similar to fission



GEN IV

VHTR: Very High temperature reactor

SCWR: Super-critical water cooled reactor

GFR: Gas cooled fast reactor

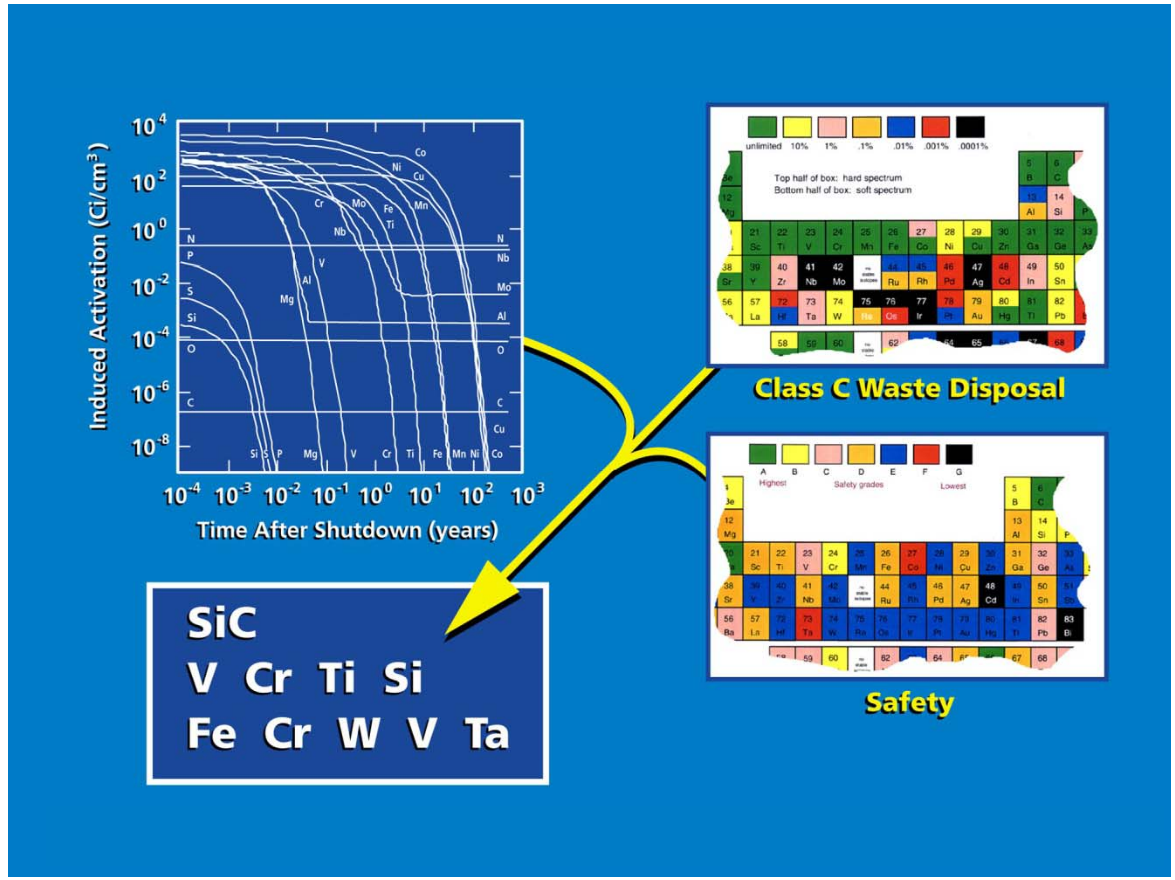
LFR: Lead cooled fast reactor

SFR: Sodium cooled fast reactor

MSR: Molten salt cooled reactor

In fusion, the fusion process does not produce radioactive products. Long-term radioactivity and waste disposal issues can be minimized by careful SELECTION of MATERIALS

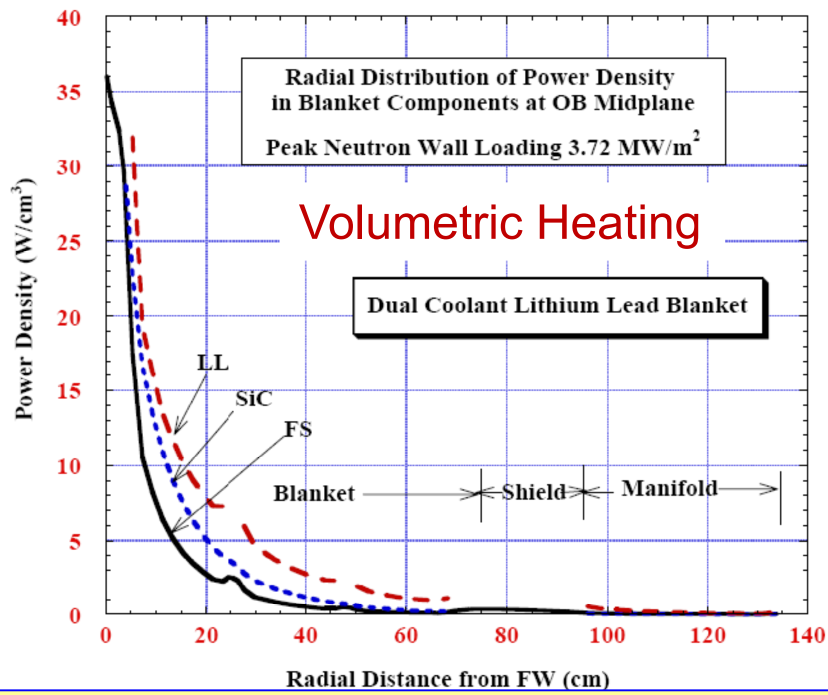
- This is in contrast to fission, where long term radioactivity and waste disposal issues are “intrinsic” because the products of fission are radioactive.
- Based on safety, waste disposal, and performance considerations, the three leading candidates are:
  - RAF/M and NFA steels
  - SiC composites
  - Tungsten alloys (for PFC)

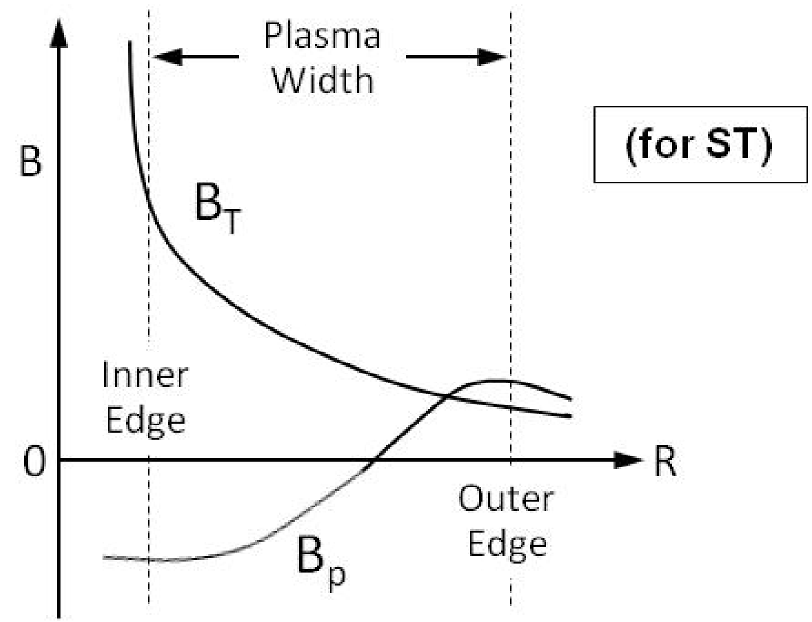


Fusion nuclear environment is unique and complex: multi-component fields with gradients

- •Neutron and Gamma fluxes
- •Particle fluxes
- •Heat sources (magnitude and gradient)
  - – Surface (from plasma radiation)
  - – Bulk (from neutrons and gammas)

- Magnetic Field (3-component)
  - – Steady field
  - – Time varying field
- With gradients in magnitude and direction

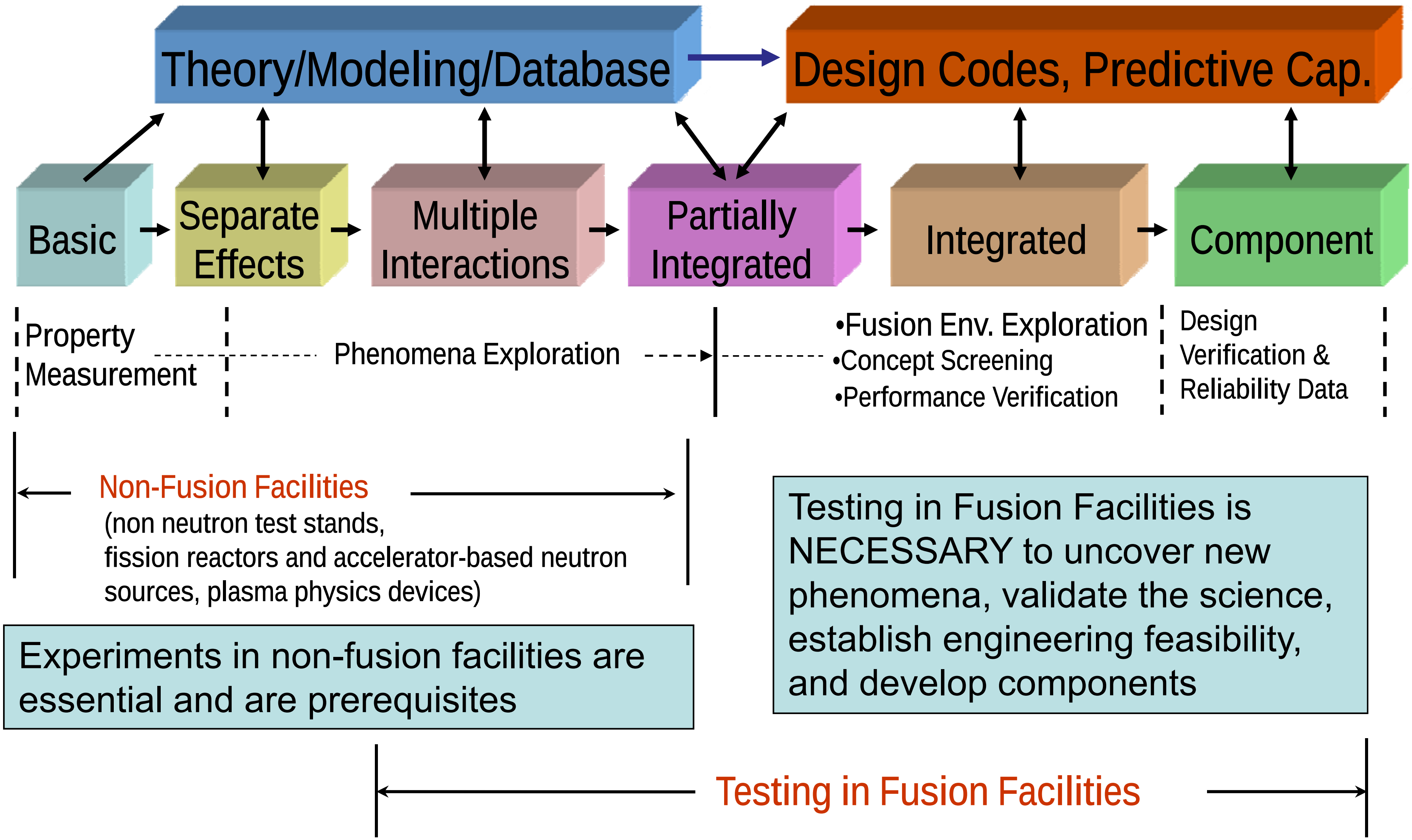




Multi-function blanket/divertor in multi-component field environment leads to:

- *Multi-Physics, Multi-Scale Phenomena* ⇨ *Rich Science to Study*
- **Synergistic effects** that cannot be anticipated from simulations & separate effects tests. Modeling and Experiments are challenging
- Such unique fusion environment and synergistic effects can be reproduced only in plasma-based devices.

Science-Based Framework for FNST R&D involves modeling and experiments in non-fusion and fusion facilities



Stages of FNST Testing in Fusion Facilities Required Prior to DEMO

Stage I	Stage II	Stage III	
Scientific Feasibility	Engineering Feasibility & Performance Verification	Component Engineering Development & Reliability Growth	DEMO
Stage I	Stage II	Stage III	
0.1 - 0.3 MW-y/m²	**1 - 3 MW-y/m²**	**> 4 - 6 MW-y/m²**	
≥ 0.5 MW/m² **burn > 200 s**	**1-2 MW/m²** **steady state or long burn** **COT ~ 1-2 weeks**	**1-2 MW/m²** **steady state or long burn** **COT ~ 1-2 weeks**	
Sub-Modules/Modules	Modules	Modules/Sectors	

Stage I

- Establish scientific feasibility of basic functions under prompt responses and under the impact of rapid property changes in early life

Stage II

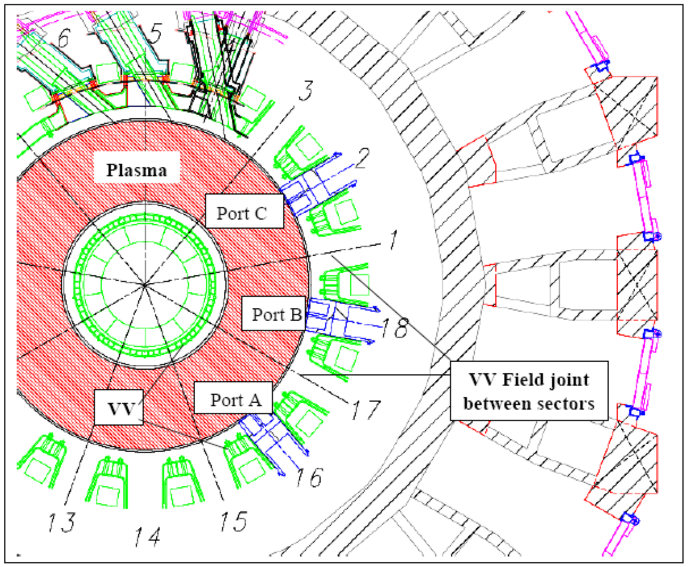
- Establish engineering feasibility of blankets/PFC (satisfy basic functions & performance, up to 10 to 20 % of MTBF and lifetime)

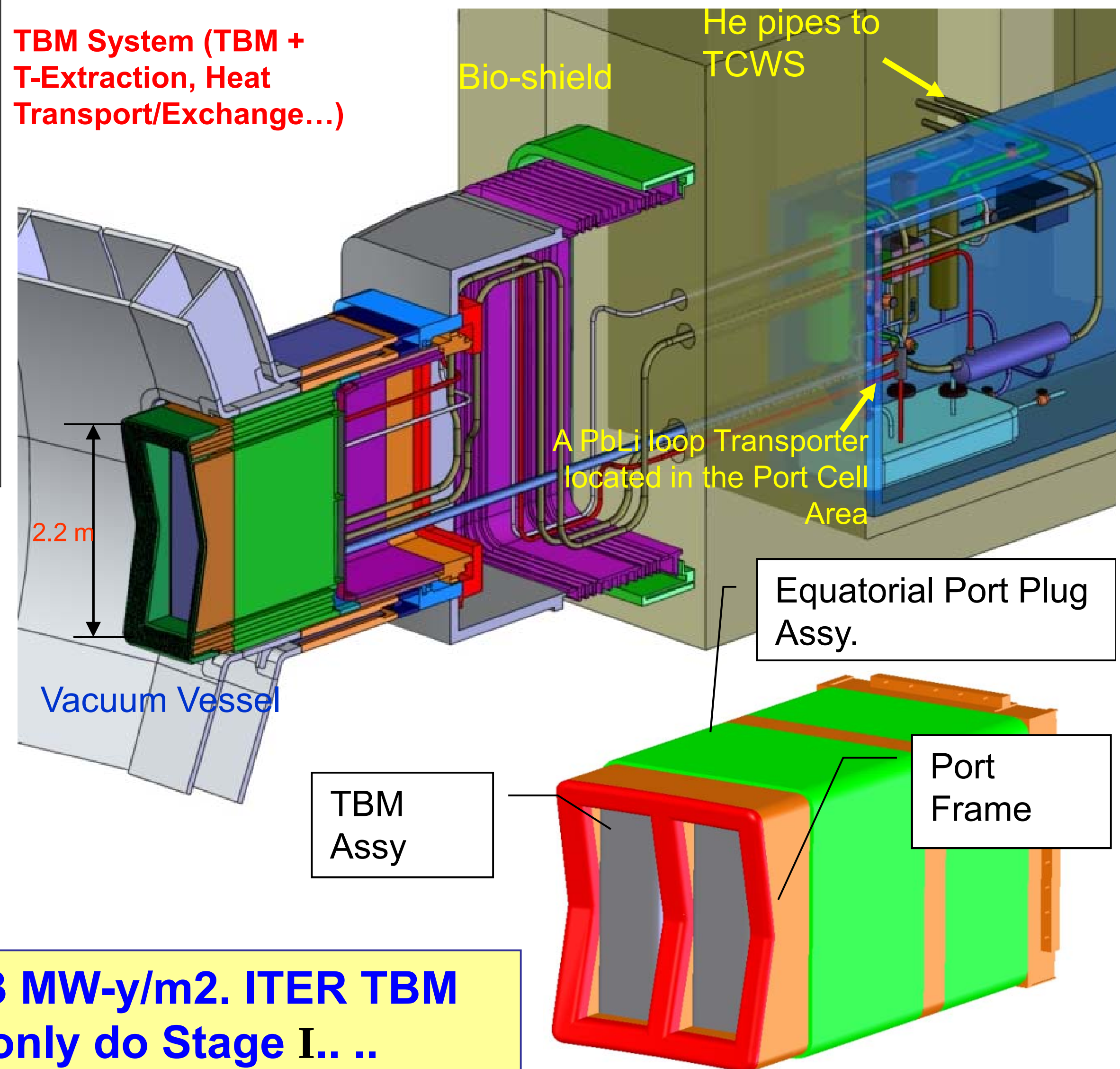
Stage III

- Failure modes, effects, and rates and mean time to replace/fix components (for random failures and planned outage)
- Iterative design / test / fail / analyze / improve programs aimed at reliability growth and safety
- Verify design and predict availability of FNT components in DEMO

Where to do Stages I, II, and III?

ITER Provides Substantial Hardware Capabilities for Testing of Blanket Systems





- ITER has allocated 3 equatorial ports (1.75 x 2.2 m2) for TBM testing
- Each port can accommodate only 2 modules **(i.e. 6 TBMs max)**

Fluence in ITER is limited to 0.3 MW-y/m2. ITER TBM has an important role but can only do Stage I.. .. We need another facility for Stages II & III.

Fusion Nuclear Science Facility (FNSF)

- The idea of FNSF (also called VNS, CTF) is to build a small size, low fusion power DT plasma-based device in which Fusion Nuclear Science and Technology (FNST) experiments can be performed in the relevant fusion environment:

  1- at the smallest possible scale, cost, and risk, and

  2- with practical strategy for solving the tritium consumption and supply issues for FNST development.

  In MFE: small-size, low fusion power can be obtained in a low-Q (driven) plasma device, with normal conducting Cu magnets

  – Equivalent in IFE: reduced target yield (and smaller chamber radius?)

- There are at least TWO classes of Design Options for FNSF:

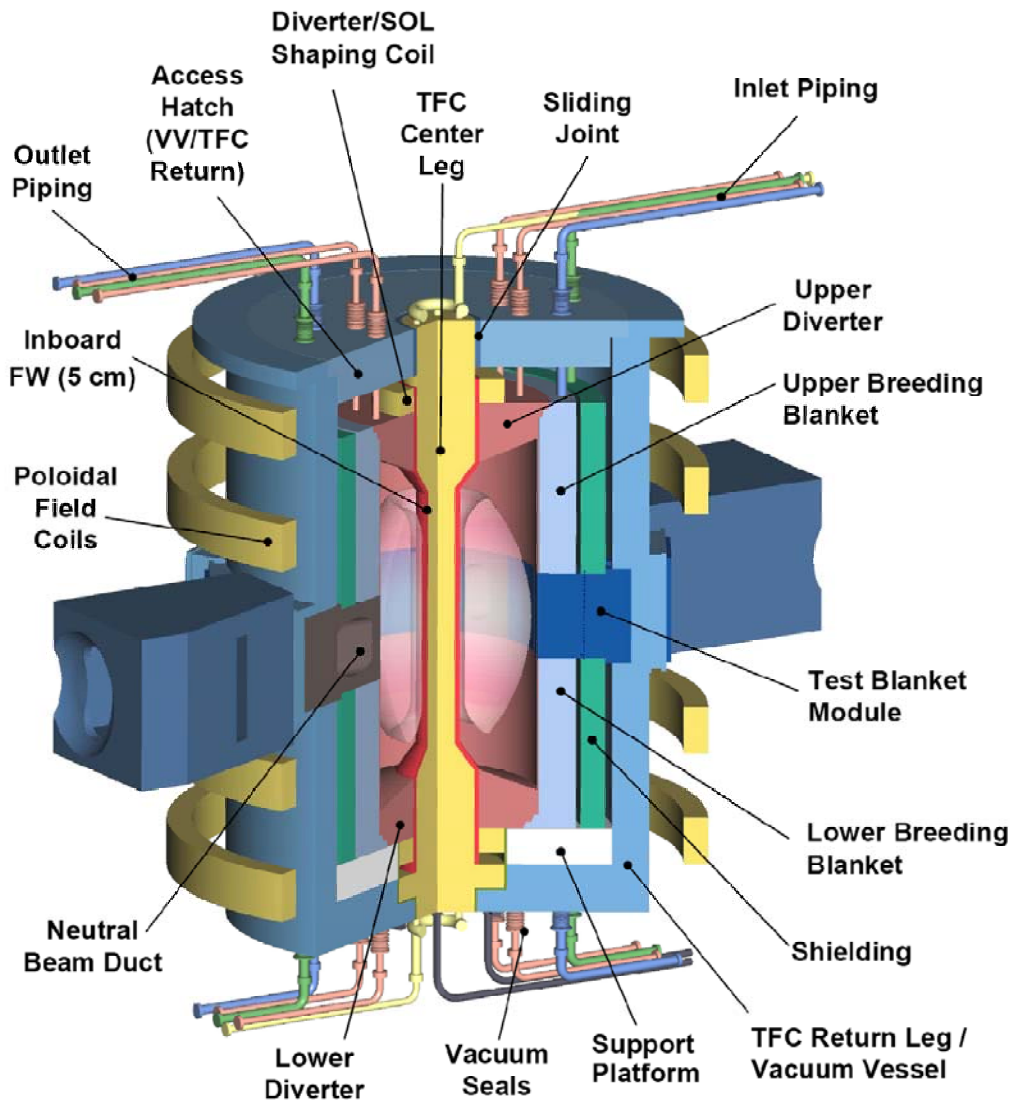
  – Tokamak with Standard Aspect Ratio, A ~ 2.8 – 4

  – ST with Small Aspect Ratio, A ~ 1.5

  Differences are in the physics, configuration, and TF Coil resistive power.

Example Option for FNSF Design: Small Aspect Ratio (ST)
Smallest power and size, Cu TF magnet, Center Post

(Example from Peng et al, ORNL) R=1.2m, A=1.5, Kappa=3, Pfusion=75MW



W_L [MW/m^2]	0.1	1.0	2.0
R0 [m]		1.20	
A		1.50	
Kappa		3.07	
Qcyl	**4.6**	3.7	**3.0**
Bt [T]	**1.13**	2.18	
Ip [MA]	**3.4**	8.2	**10.1**
Beta_N	3.8		**5.9**
Beta_T	**0.14**	0.18	**0.28**
n_e [10^{20}/m^3]	**0.43**	1.05	**1.28**
f_{BS}	**0.58**	0.49	**0.50**
T_{avgi} [keV]	**5.4**	10.3	**13.3**
T_{avge} [keV]	**3.1**	6.8	**8.1**
HH98		1.5	
Q	**0.50**	2.5	**3.5**
P_{aux-CD} [MW]	**15**	31	**43**
E_{NB} [keV]	**100**	239	**294**
P_{Fusion} [MW]	**7.5**	75	**150**
T M height [m]		1.64	
T M area [m^2]		14	
Blanket A [m^2]		66	
$F_{n-capture}$		0.76	

Closing Remarks

- Energy plays a critical role in economic development, economic prosperity, national security, and environmental quality
- Solving the Energy Problem and Reducing Greenhouse Gas Emission Requires Pursuing a Diversified Portfolio Approach
- Key Major Transformations required:
  - Efficient use of energy, e.g., buildings (lighting, heating and cooling), cars and trucks, and industry.
  - New sources of energy for producing electricity that reduce emissions of CO_2—nuclear, coal with CO_2 removed and stored, solar, wind, and geothermal.
  - Transportation fuels that derive from alternatives to petroleum, e.g., liquids from biomass, coal and electricity.

Closing Remarks (cont'd)

- **Fusion is the most promising long-term energy option**
  - Renewable fuel, no emission of greenhouse gases, no long-term radioactive waste, inherent safety
- 7 nations comprising half of the world population are constructing **ITER**
  - The next step in fusion research to demonstrate the scientific and technological feasibility of fusion energy.
  - ITER will have first DT plasma in ~2027
- **The most challenging Phase of Fusion development still lies ahead. It is the development of Fusion Nuclear Science and Technology (FNST)**
  - A Fusion Nuclear Science Facility (FNSF) is required, in parallel to ITER, to develop FNST.
  - FNSF must be small size, small power DT, driven plasma with Cu magnets

Fusion research requires the talents of many scientists and engineers in many disciplines. Need to attract and train bright young students and researchers.

References

For References and Additional Reading:

1. Abdou's presentations and publications on: (http://www.fusion.ucla.edu/abdou/)

2. UCLA Energy Center *(http://cestar.seas.ucla.edu/)*

3. CEREL *(http://ncseonline.org/cerel/)*

4. Additional Information on the America's Energy Future Effort: *(http://www.nationalacademies.org/energy)*

Thank You for Your Attention!