Environmentally Responsible Energy Security Future Requires Diversified Portfolio Approach

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Humble Administrator's Garden, Suzhou

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OUTLINE

1. **The World Energy Situation**
   - Need for more energy, dominance of fossil fuels, 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 future outlook
4. **Fusion**
   - Incentives to fusion
   - Approaches to fusion and DEMO goal
   - Current Progress AND when can we have fusion?
5. **Closing Remarks**

World Energy Situation

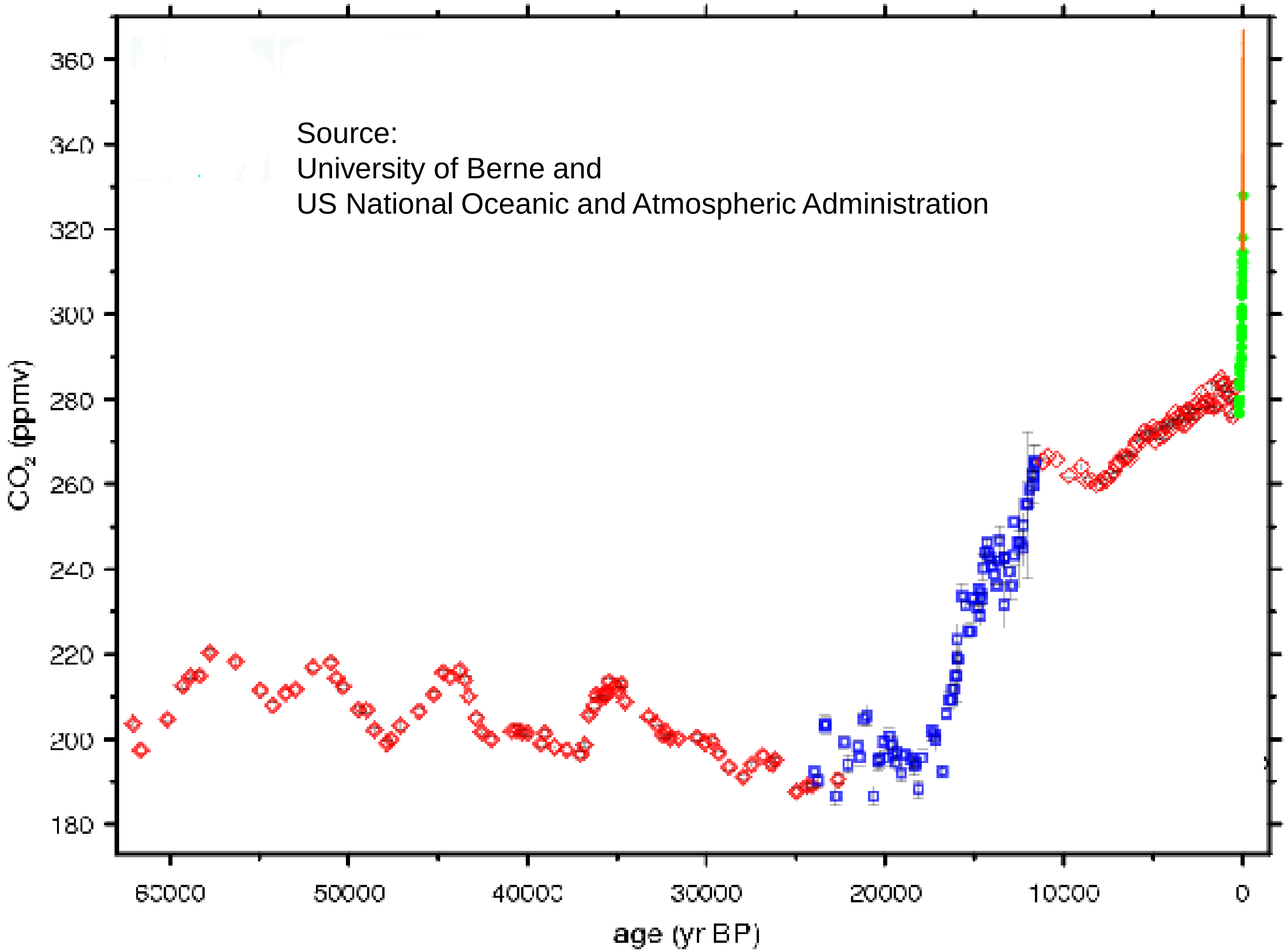
- **The world uses a lot of energy**
  - **Average power consumption = 17.7 TW** (2.5 KW per person)
  - **World energy market ~ $3 trillion / yr** (electricity ~ $1 trillion / yr)

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

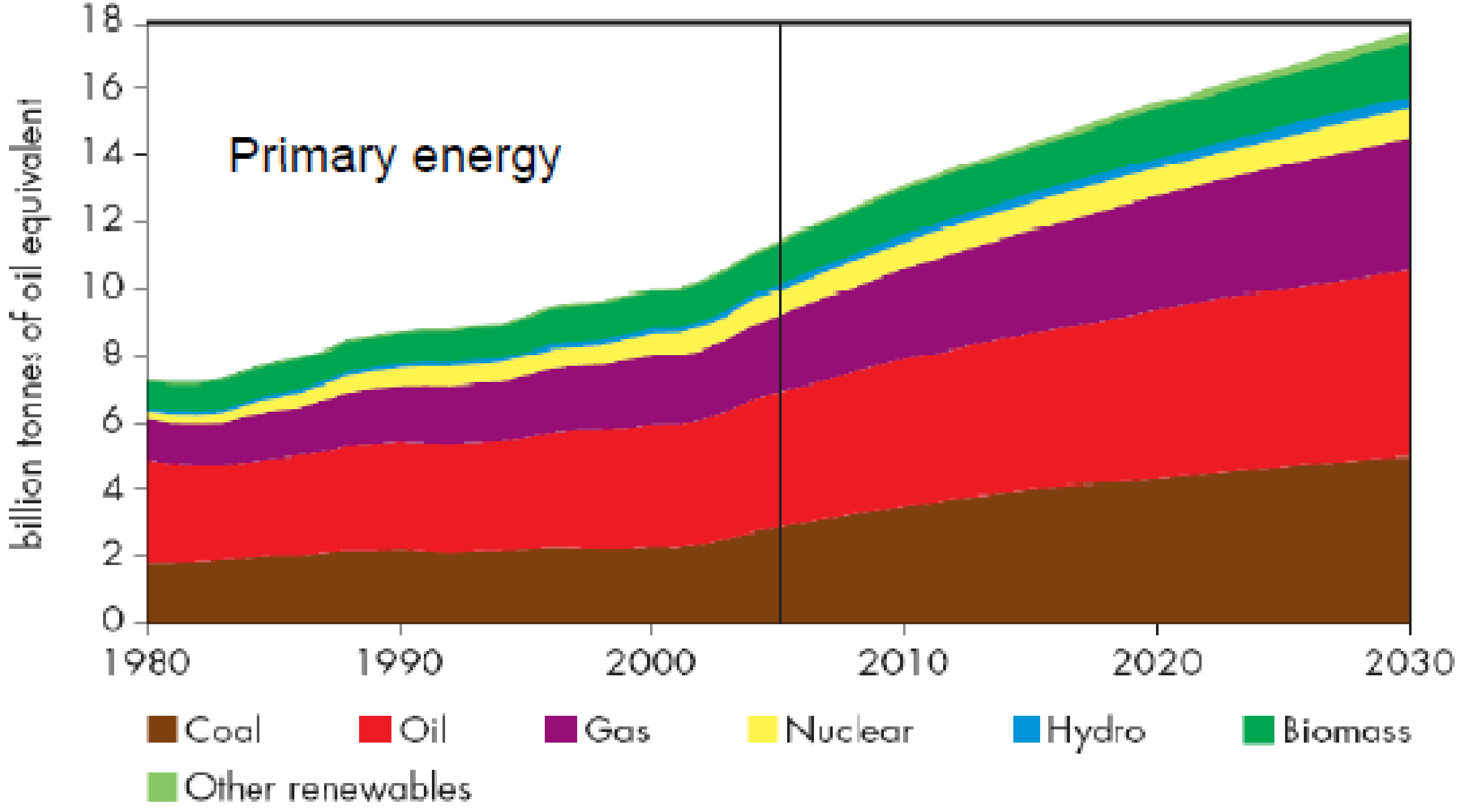
- **Climate change and debilitating pollution concerns are on the rise**
  - **80% of energy is generated by fossil fuels**
  - **CO_2 emission is increasing at an alarming rate**

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

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



Where we're headed under BAU: by 2030, energy +60%, electricity +75%, continued fossil dominance



WEO 2007

What is problematic about this future ?

The problem is <u>not</u> "running out" of energy

Some mid-range estimates of world energy resources. Units are terawatt-years (TWy). Current world energy use is ~17.7 TWy/year.

OIL & GAS, CONVENTIONAL	**1,000**
UNCONVENTIONAL OIL & GAS (excluding clathrates)	**2,000**
COAL	**5,000**
METHANE CLATHRATES	**20,000**
OIL SHALE	**30,000**
URANIUM in conventional reactors	**2,000**
…in breeder reactors	**2,000,000**
FUSION (if the technology succeeds)	**250,000,000,000**
RENEWABLE ENERGY (available energy <u>per year</u>)	
Sunlight on land	**30,000**
Energy in the wind	**2,000**
Energy captured by photosynthesis	**120**

From J. Holdren, OSTP

Real problems: the economic, environmental, and security risks of fossil-fuel dependence

- Coal burning for electricity & industry and oil burning in vehicles are main sources of severe urban and regional **air pollution** – SO_x, NO_x, hydrocarbons, soot – with big impacts on public health, acid precipitation.

- Emissions of CO_2 from *all* fossil-fuel burning are largest driver of **global climate disruption**, already associated with increasing harm to human well-being and rapidly becoming more severe.

- Increasing dependence on imported oil & natural gas means economic vulnerability, as well as international tensions and potential for conflict over access & terms.

Real problems: Alternatives to conventional fossil fuels all have liabilities & limitations

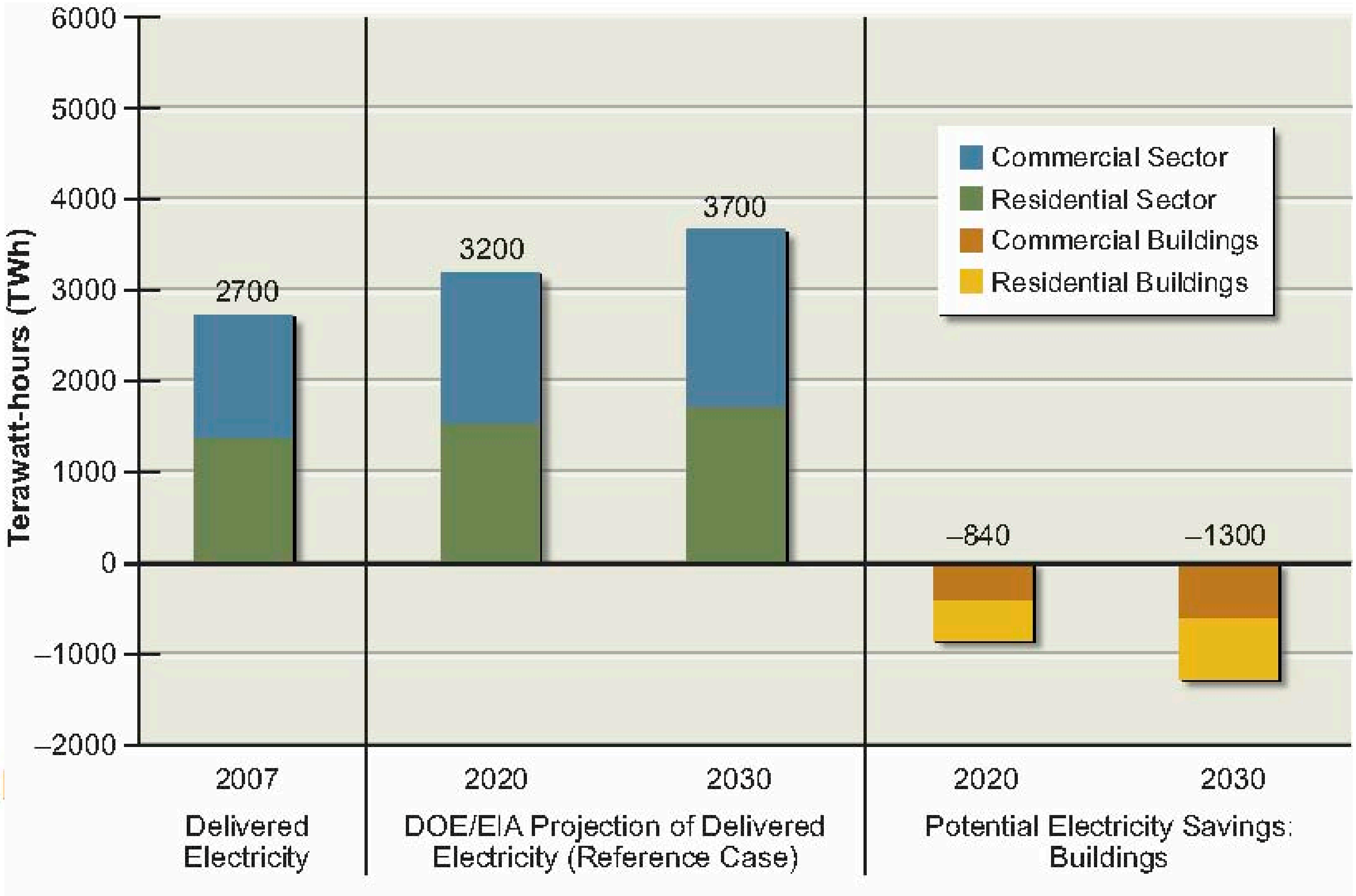
- Traditional biofuels (fuelwood, charcoal, crop wastes, dung) create huge indoor air-pollution hazard
- Industrial biofuels (ethanol, biodiesel) can take land from forests & food production, increase food prices
- Hydropower and wind are limited by availability of suitable locations, conflicts over siting
- Solar energy is costly and intermittent
- Nuclear fission has large requirements for capital & highly trained personnel, currently lacks agreed solutions for radioactive waste & links to nuclear weaponry
- Nuclear fusion doesn't work yet
- Coal-to-gas and coal-to-liquids to reduce oil & gas imports doubles CO_2 emissions per GJ of delivered fuel
- Increasing end-use efficiency needs consumer education

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

Currently, 73% of electricity used in the US is for Commercial & Residential Buildings. Studies show that 25-30% can be saved by using more efficient technologies for space heating and cooling, water heating, and lighting.



Renewable Energy (Solar, Wind, Geothermal, Biomass, hydropower)

- **Renewable energy technologies are a critical element of the low-carbon pillars of global energy supply. Renewables are rapidly gaining ground, helped by global subsidies (amounting to $120 billion in 2013).**
- **Renewables accounted for a record 6.0% of global power generation in 2014. The strong growth of renewables in many countries raises their expected share in global power generation to ~ 30% by 2040.**
- **Cost and efficient energy storage remain as issues requiring innovative solutions.** For example, the high cost of solar plus being intermittent source is not helping solar in some countries such as the US.
- **Renewables alone cannot meet the booming global population's insatiable appetite for energy in the long term. The World needs Other Clean Energy Sources (e.g. nuclear fission and fusion) to meet growing energy demands and make the transition to a cleaner world by 2050.**

Nuclear Fission

Current Contributions and Future Outlook

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

- **Worldwide Currently Operating**: 436 fission power reactors totaling 392 GWe of capacity in 31 countries (11% of world's electricity). Additionally, 67 more reactors with ~70 GWe currently under construction.

  - *357 of the 436 reactors are light-water reactors (LWRs). The rest are heavy-water reactors, gas cooled reactors, and graphite-moderated light-water reactors*.

- **US** has currently 99 nuclear power plants. As of October 2015:

  5 under construction

- **China has the most aggressive nuclear energy plan**
  - **Present: 23.1 GWe**
  - **2020: 58 GWe**
  - **2030: 150 Gwe**

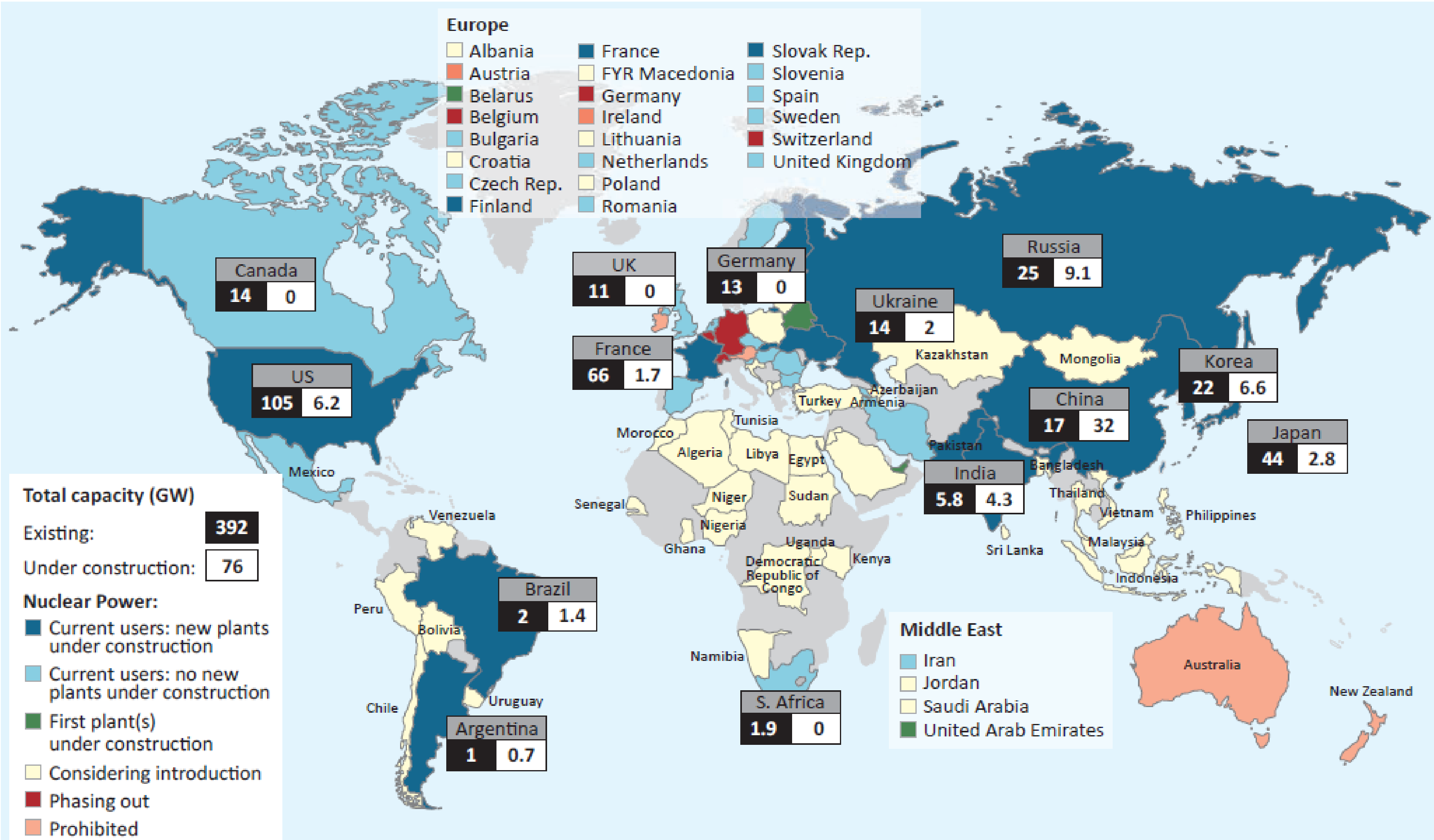
-- China's fast reactor plans

- Experimental: 20 MWe (2010)
- Large: BN-800 (2018,suspended) and CDFR-1000 MWe (2023)

Source: world-nuclear.org

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

There is a marked variation between national policies in views toward nuclear power. This is reflected in the Global Status of Nuclear Power Plants



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

WEO-2014

There has been Impressive Improvements in the Economics of Nuclear Power in Existing Fission Power Plants in the past 20 years
Also, Major Improvements in Safety and Reduced Generation of High Level Waste in New Designs

- Incremental improvements enabled currently operating fission power plants to produce more energy than anticipated over their lifetimes. **The U.S. average plant capacity factor increased from 66% in 1990 to 91.7% in 2014**. Source: Nuclear Energy Institute

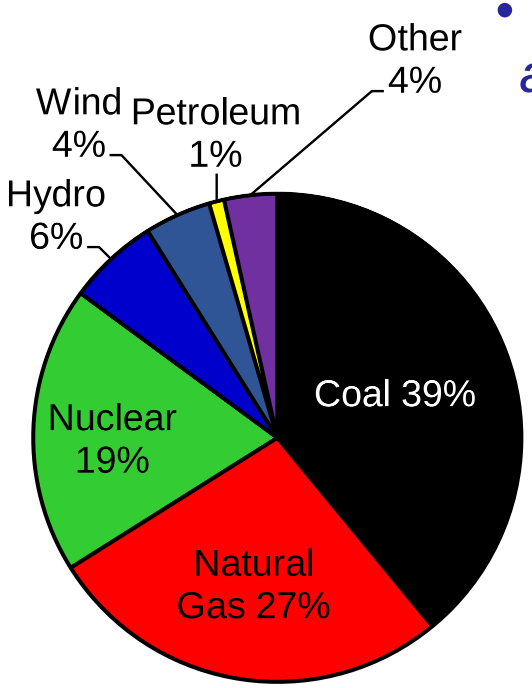
- From Australian National Affairs Article:

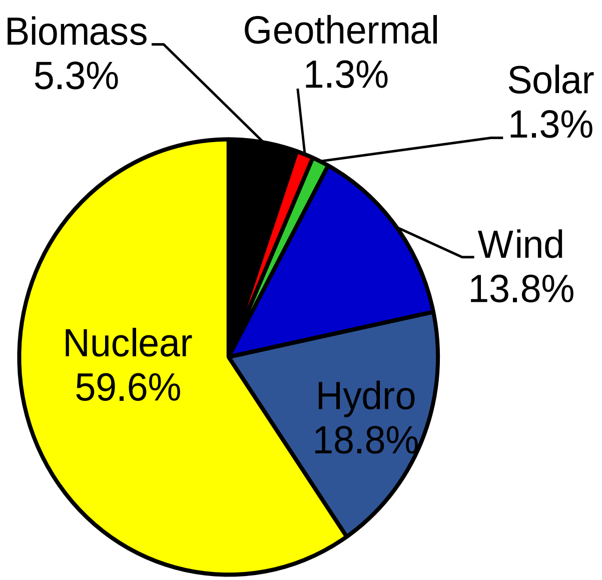
The standout technology, from a cost perspective, is nuclear power. From the eight nuclear cost studies we reviewed (all published in the past decade, and adjusted to 2009 dollars), the median cost of electricity from current technology nuclear plants was just above new coal plants with no carbon price. Having the lowest carbon emissions of all the fit-for-service technologies, **nuclear remains the cheapest solution at any carbon price. Importantly, it is the only fit-for-service baseload technology that can deliver the 2050 emission reduction targets…………………………**

Nuclear Power Must Remain a KEY Part of Our Energy Portfolio

- Nuclear is the third largest source of U.S. electricity

- *19 % of electricity generation*
- *59 % of GHG emission-free electricity*
- *Nuclear electricity is 3 times more than Solar, Wind and Geothermal combined*





No GHG Electricity

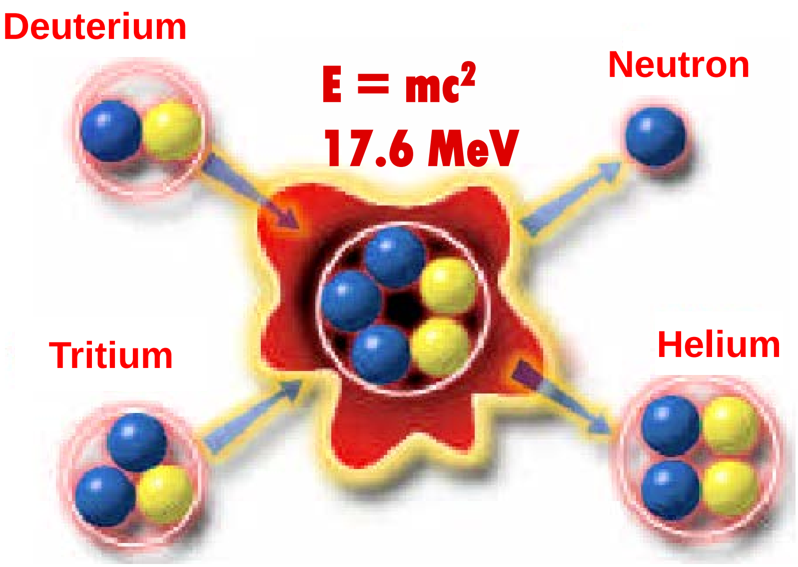
Nuclear energy is the dominant non-fossil energy technology

US. Energy Information Administration, 2014

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

What is fusion?

- **Fusion powers the sun and stars:** Fusion is the energy-producing process taking place in the core of the sun and stars. Fusion research is akin to "creating a star on earth"
- **Two light nuclei combine to form a heavier nuclei, converting mass to energy** - the opposite of nuclear fission where heavy nuclei split



80% of energy release (14.1 MeV) → Used to breed tritium and close the DT fuel cycle

$Li + n \rightarrow T + He$

Li in some form must be used in the fusion system

20% of energy release (3.5 MeV)

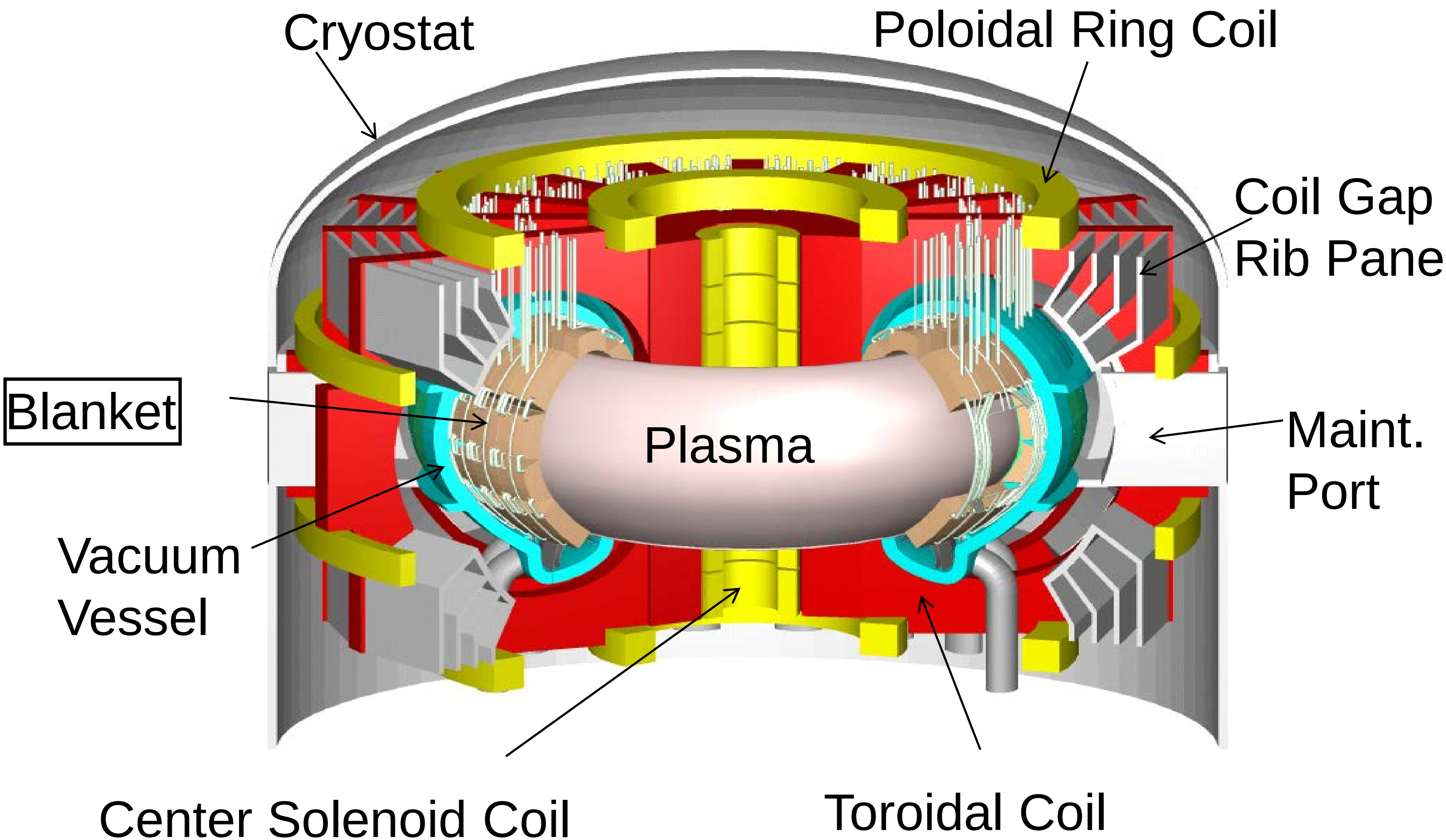
Incentives for Developing Fusion

- 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.

The World Fusion Program has a Goal for a Demonstration Power Plant (DEMO) by ~2050(?)

Plans for DEMO are based on Tokamaks

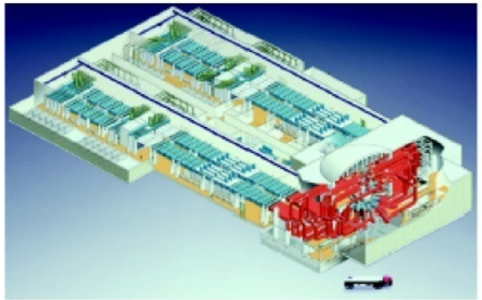


(Illustration is from JAEA DEMO Design)

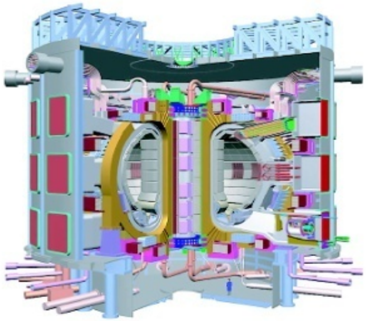
ITER

- 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
- ITER will produce **500 MW** of fusion power.
- Cost is ~20 billion dollars.
- **ITER is a collaborative effort among Europe, Japan, US, Russia, China, South Korea, and India. – represent half the world's population**
- ITER construction site is Cadarache, France
- ITER will begin operation (first plasma) ~ 2025
- **ITER will open the way for commercial reactors**

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



National Ignition Facility



ITER

- **1950-2017**
  - **The Physics of Plasmas**

- **2017-2035**
  - **The Physics of Fusion**
  - **Fusion Plasmas-heated and sustained**
    - **$Q = (E_f / E_{input})$~10**
    - **ITER (MFE) and NIF (inertial fusion)**

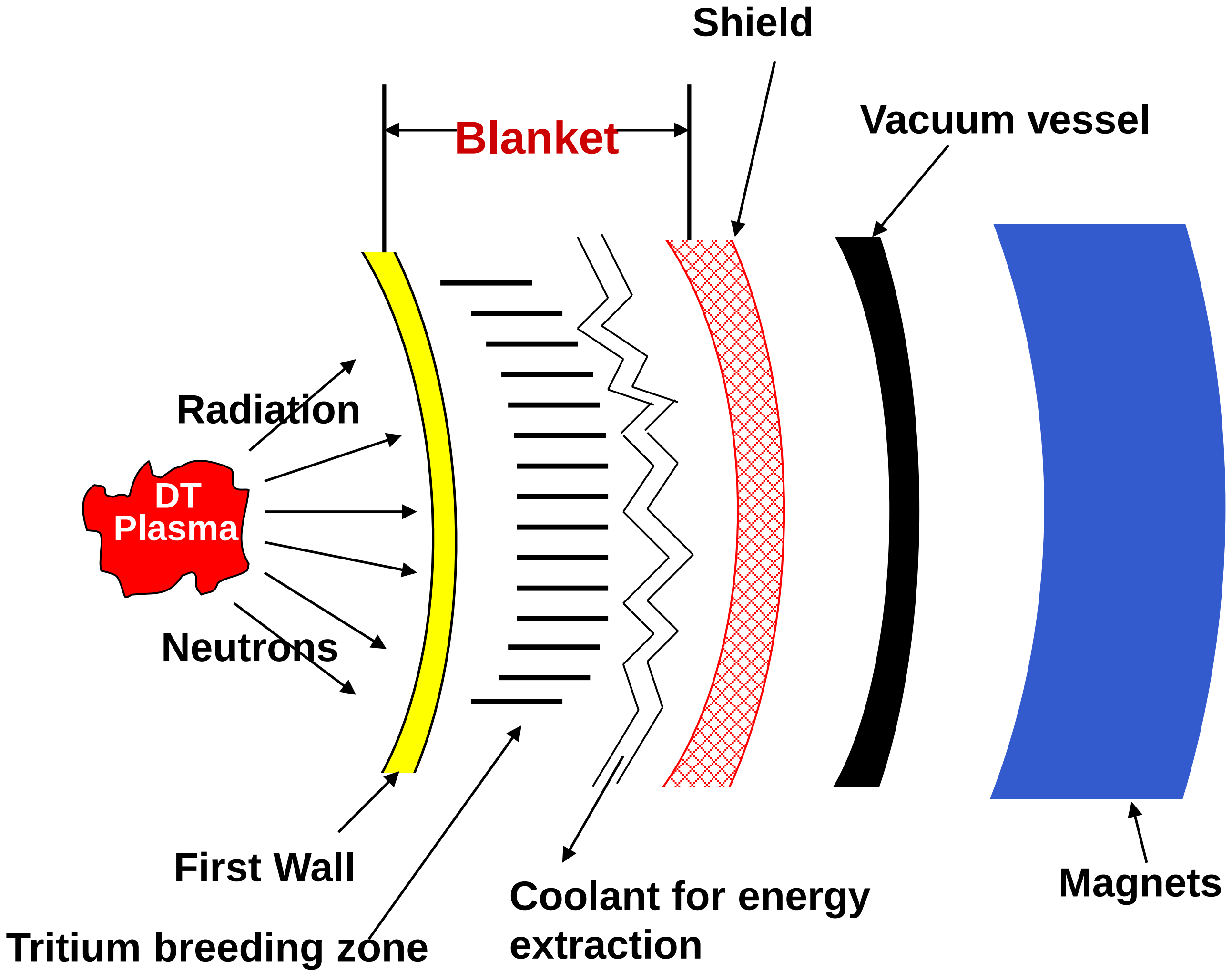
- **ITER is a major step forward for fusion research. It will demonstrate:**
  1. **Reactor-grade plasma**
  2. **Plasma-support systems (S.C. magnets, fueling, heating)**

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.

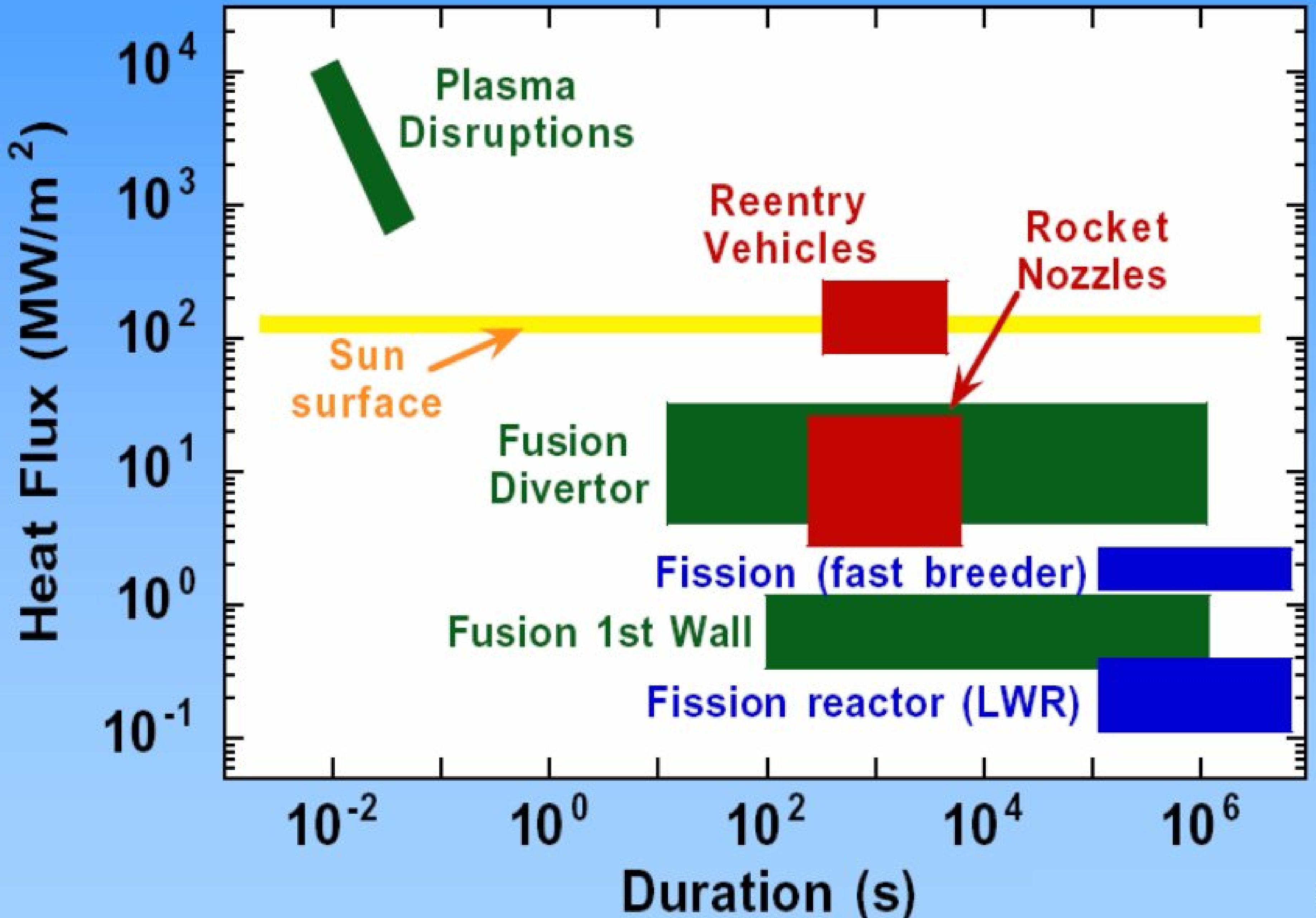
A Key FNST Component is the Blanket

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



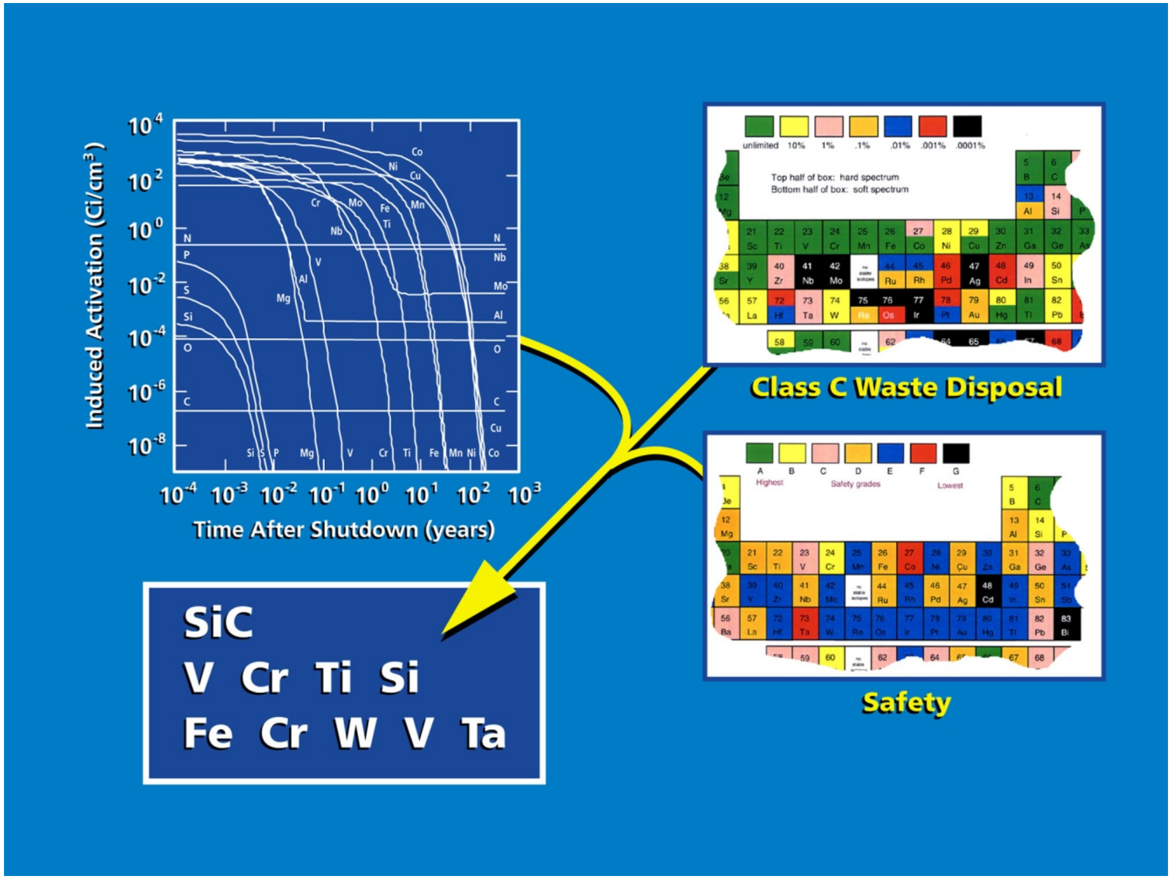
Lithium-containing Liquid metals (Li, PbLi) are strong candidates as breeder/coolant. Li ceramics are also candidates as breeder – with He-cooling

Comparison of Heat Fluxes



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

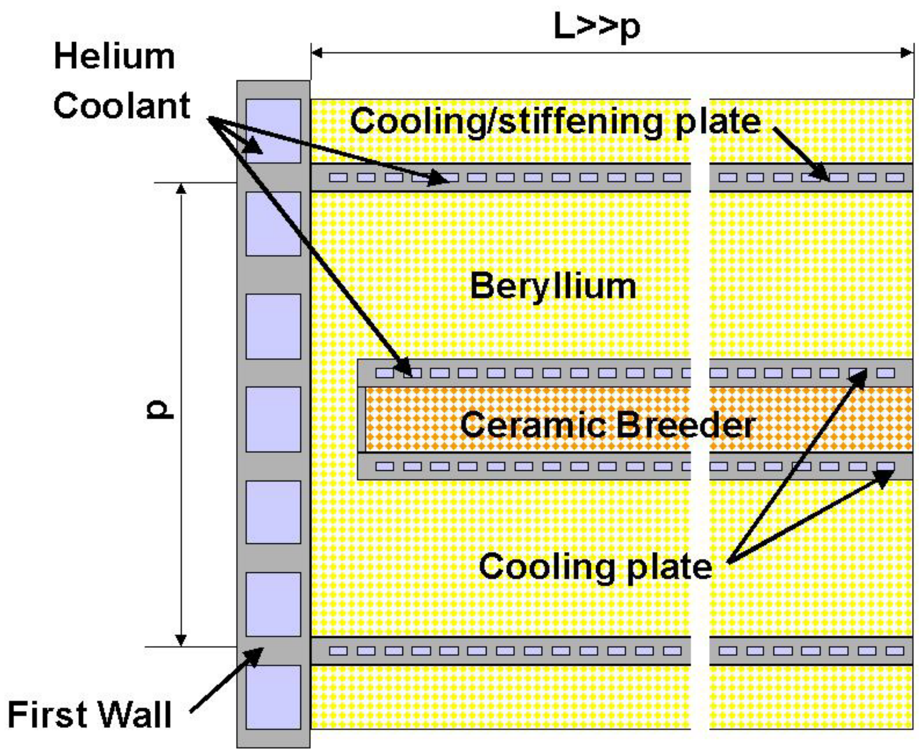
- This is in contrast to fission, where long term radioactivity and waste disposal issues are "intrinsic" because the products of fission are radioactive.
- Based on safety, waste disposal and performance considerations, the three leading candidates are:
  - RAFM and NFA steels
  - SiC composites
  -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

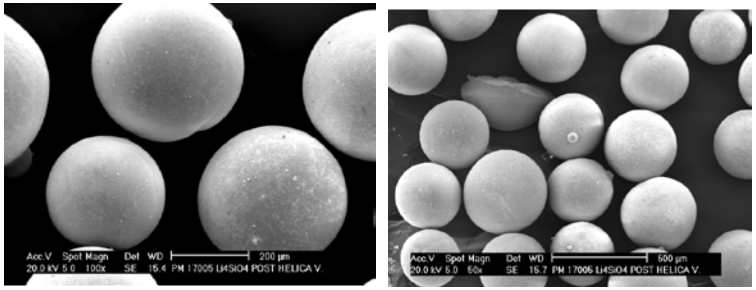


Solid breeder blankets utilize immobile lithium ceramic breeder and Be multiplier

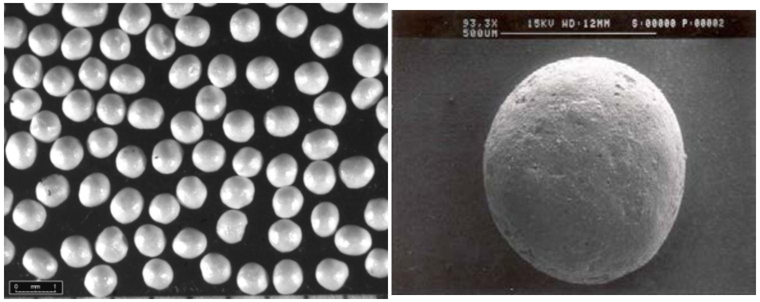
Material Functions

- **Beryllium** (pebble bed) for neutron multiplication
- **Ceramic breeder** (Li_4SiO_4, Li_2TiO_3, Li_2O, etc.) for tritium breeding
- **Helium purge** to remove tritium through the "interconnected porosity" in ceramic breeder
- **High pressure Helium** cooling in structure (advanced ferritic)

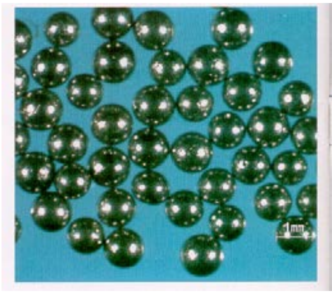




0.2- 0.4 mm Li_4SiO_4 pebbles (FZK)



0.6 – 0.8 mm Li_2TiO_3 pebbles (CEA)



NGK Be-pebble

Flows of electrically conducting coolants will experience complicated **MHD** effects in the magnetic fusion environment 3-component magnetic field and complex geometry

- Motion of a conductor in a magnetic field produces an EMF that can induce current in the liquid. This must be added to Ohm's law:

$$\mathbf{j} = \sigma(\mathbf{E} + \mathbf{V} \times \mathbf{B})$$

- Any induced current in the liquid results in an additional body force in the liquid that usually opposes the motion. This body force must be included in the Navier-Stokes equation of motion:

$$\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V} \cdot \nabla)\mathbf{V} = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{V} + \mathbf{g} + \frac{1}{\rho}\mathbf{j} \times \mathbf{B}$$

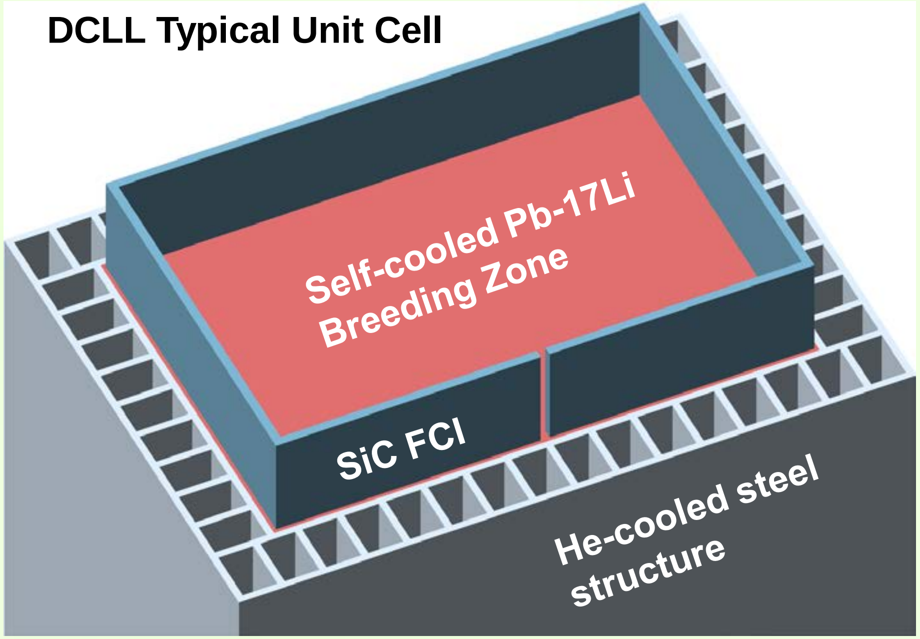
- For liquid metal coolant, this body force can have dramatic impact on the flow: e.g. enormous MHD drag, highly distorted velocity profiles, non-uniform flow distribution, modified or suppressed turbulent fluctuations.

Dominant impact on LM design.
Challenging Numerical/Computational/Experimental Issues

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



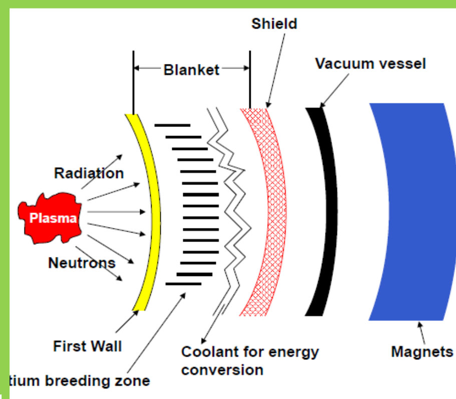
Pb-17Li exit temperature can be significantly higher than the operating temperature of the steel structure ⇒ High Efficiency

Key Technical Challenges beyond ITER

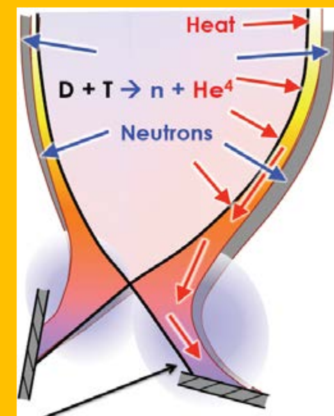
FNST: Fusion Nuclear Components (In-Vessel Components: Blanket/FW, Exhaust/Divertor) and associated technical disciplines (Materials, RAMI, Tritium)

Blanket / FW

- Most important/challenging part of DEMO
- Strict conditions for T self-sufficiency with many physics & technology requirements
- Multiple field environment, multiple functions, many interfaces
- Serious challenges in defining facilities and pathway for R&D
- T supply major issue



Exhaust / Divertor



- High heat and particle fluxes and technological limits: challenge to define a practical solution
- Both solid and liquid walls have issues
- Huge T inventory in Exhaust for low T burn fraction

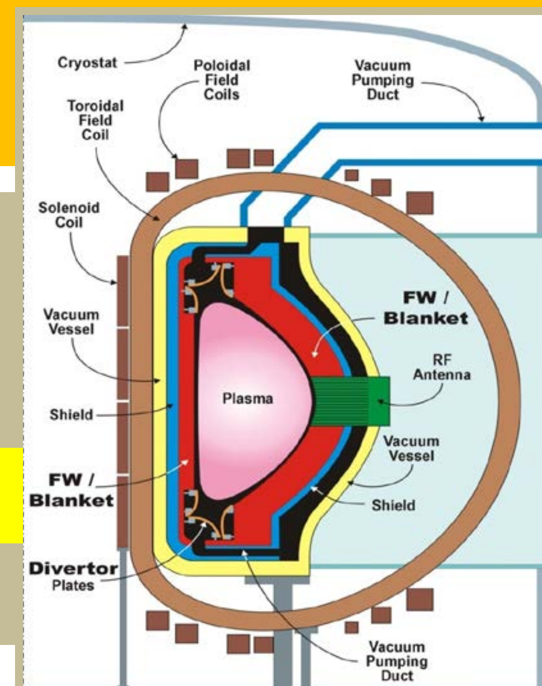
Materials

- Structural, breeding, multiplier, coolant, insulator, T barrier Exposed to steep gradients of heating, temperature, stresses
- Many material interfaces e.g. liquid/structure
- Many joints, welds where failures occur, irradiation

Reliability / Availability / Maintainability / Inspect. (RAMI)

- FNCs inside vacuum vessel in complex configuration lead to fault intolerance and complex lengthy remote maintenance
- Estimated MTBF << required MTBF
- Estimated MTTR >> required MTTR
- No practical solutions yet
- How to do RAMI R&D?

Low avail.



- **Serious Challenges that require aggressive FNST R&D and a well thought out technically Credible Pathway to DEMO**

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, fusion, 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
- But the problem is that fusion is not being developed fast enough. **"The Time to Fusion seems to be always 40 years away". Need more funding, more ingenuity, and focus on the most difficult remaining challenge : Fusion Nuclear Science and Technology (FNST)**

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

Thank You!