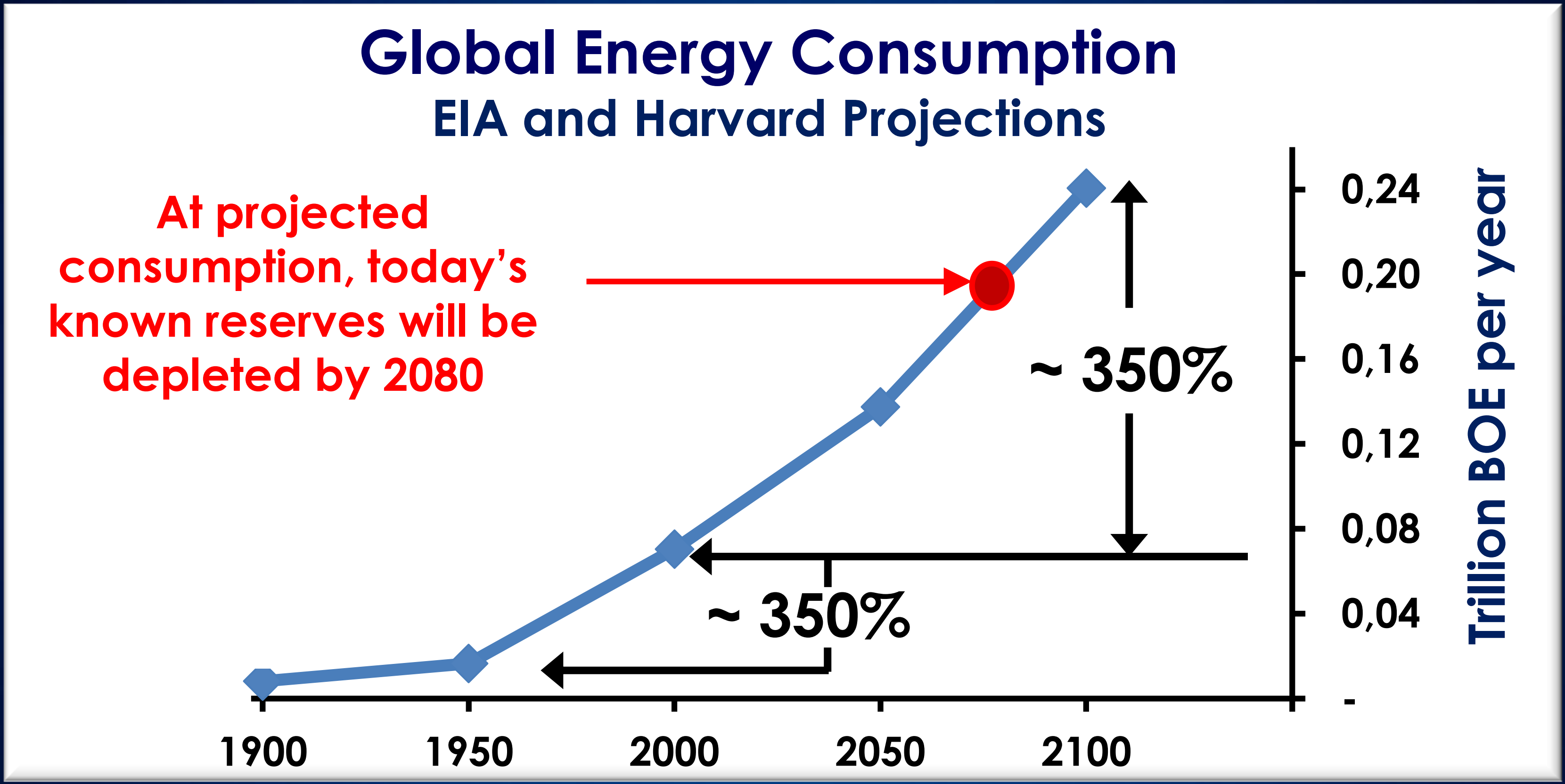
Future Energy Security for the World

By
John Parmentola
Senior Vice President
Energy and Advanced Concepts

Presented at
The Monaco ITER International Fusion Energy Days 2013

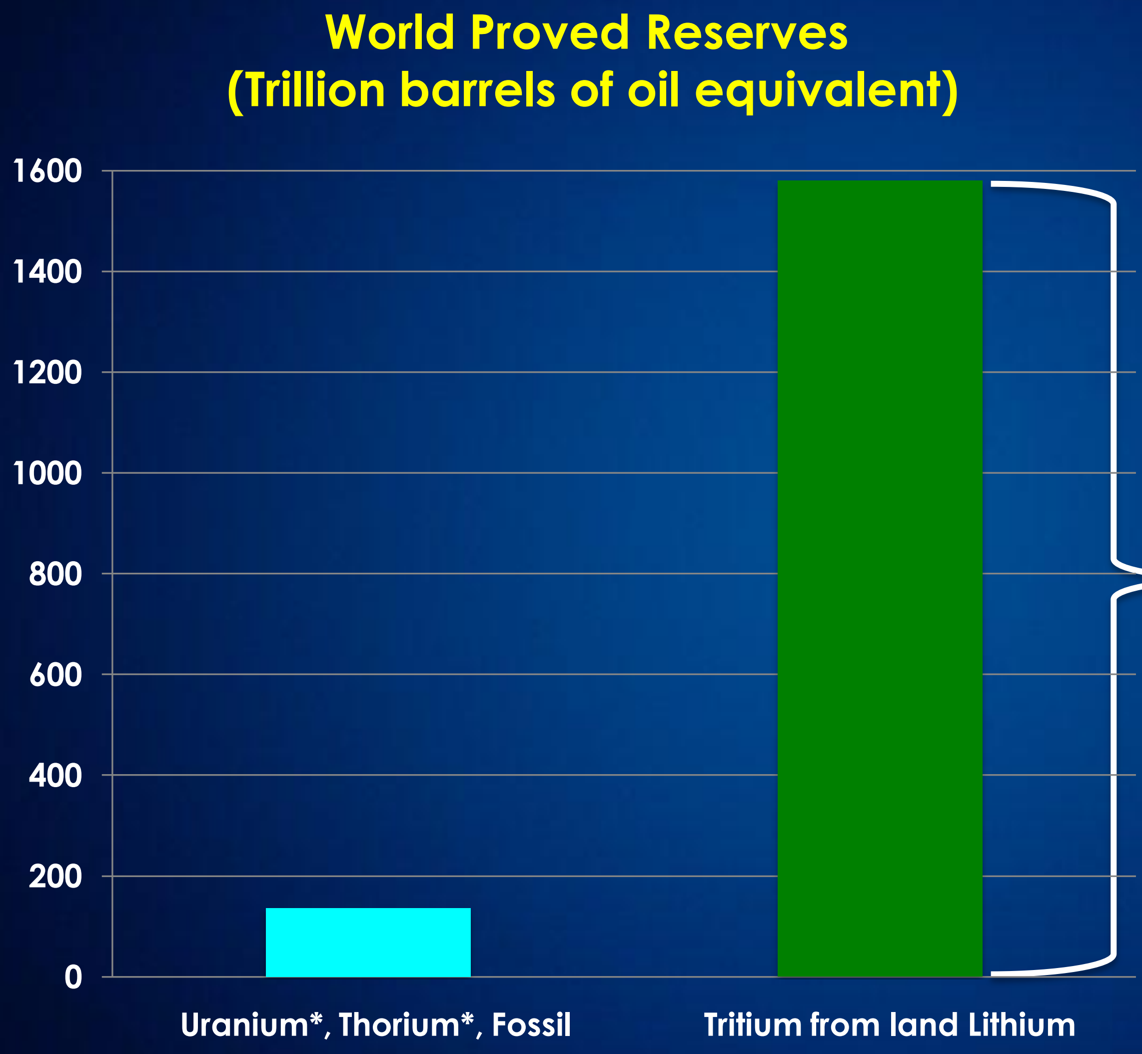
December 3, 2013

World Energy Requirements Present Major Challenges and Large Opportunities



Fusion can be a major clean-energy factor in supporting this growth

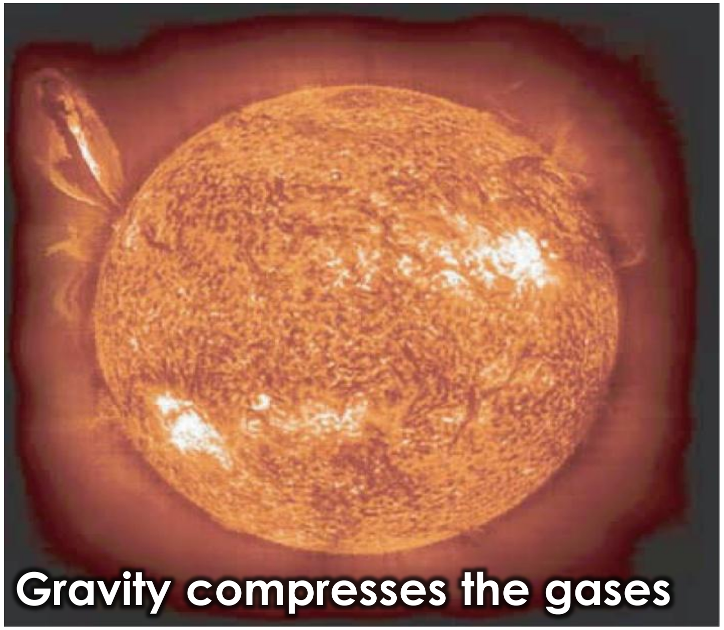
World's Lithium Reserves Hold 12X More Energy than ALL Uranium*, Thorium*, Coal, Oil and Natural Gas Supplies



Can meet Global energy needs for ***over 16,000 years*** at current rates of consumption

* When used in a fast closed cycle reactor

Fusion – Energy for the Future of Mankind



High temperature and pressure

DIII-D: Largest tokamak in the U.S.
Magnetic fields confine the gases

- **Fusion is an attractive source of electricity**
  - Inherently safe clean energy
  - No long-term waste
  - Can produce its own fuel
  - Proliferation resistant

Perspectives in Fission and Fusion

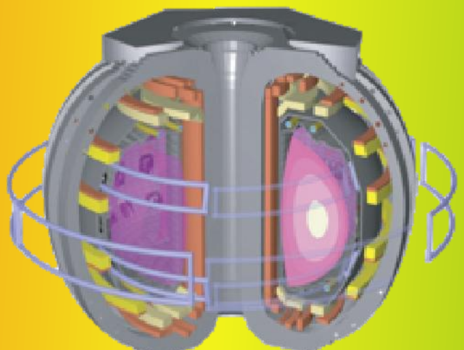
Imaginable → **Plausible** → **Feasible**

Imaginable

- Understanding to solve unique problems
- Speculative application; no proof or detailed analysis
- Scientific research begins translation into applied R&D

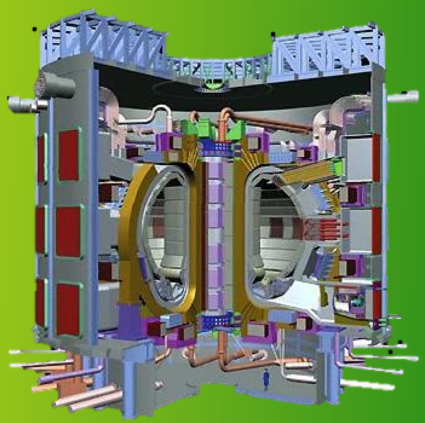
Plausible

- Analytical & lab studies to validate predictions of separate technology elements
- Technology integration to establish pieces will work together at low fidelity

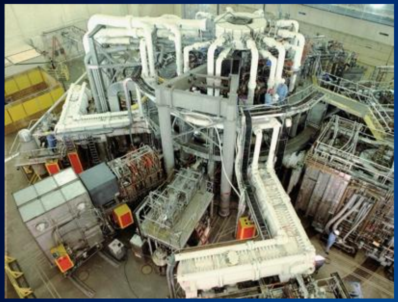


Feasible

- Increased fidelity of breadboard technology; tests in simulated environment
- Representative model or prototype tested in relevant environment



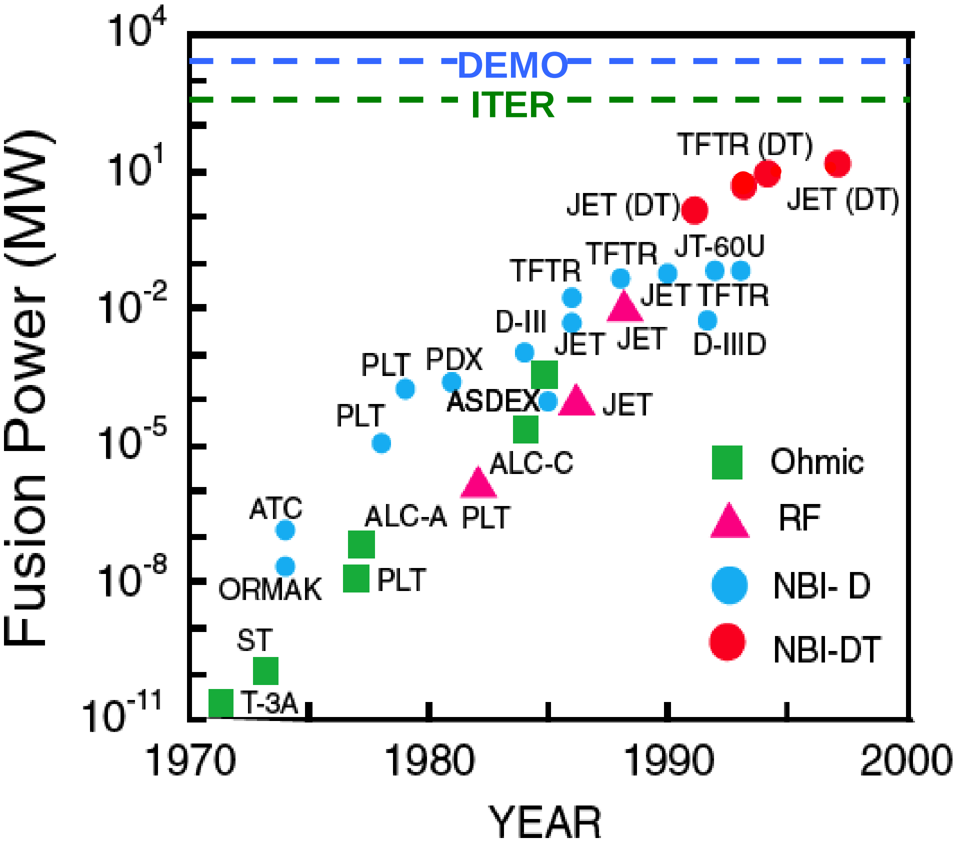
Worldwide Research has Advanced Fusion to the Goal of Sustained Ignition


TFTR

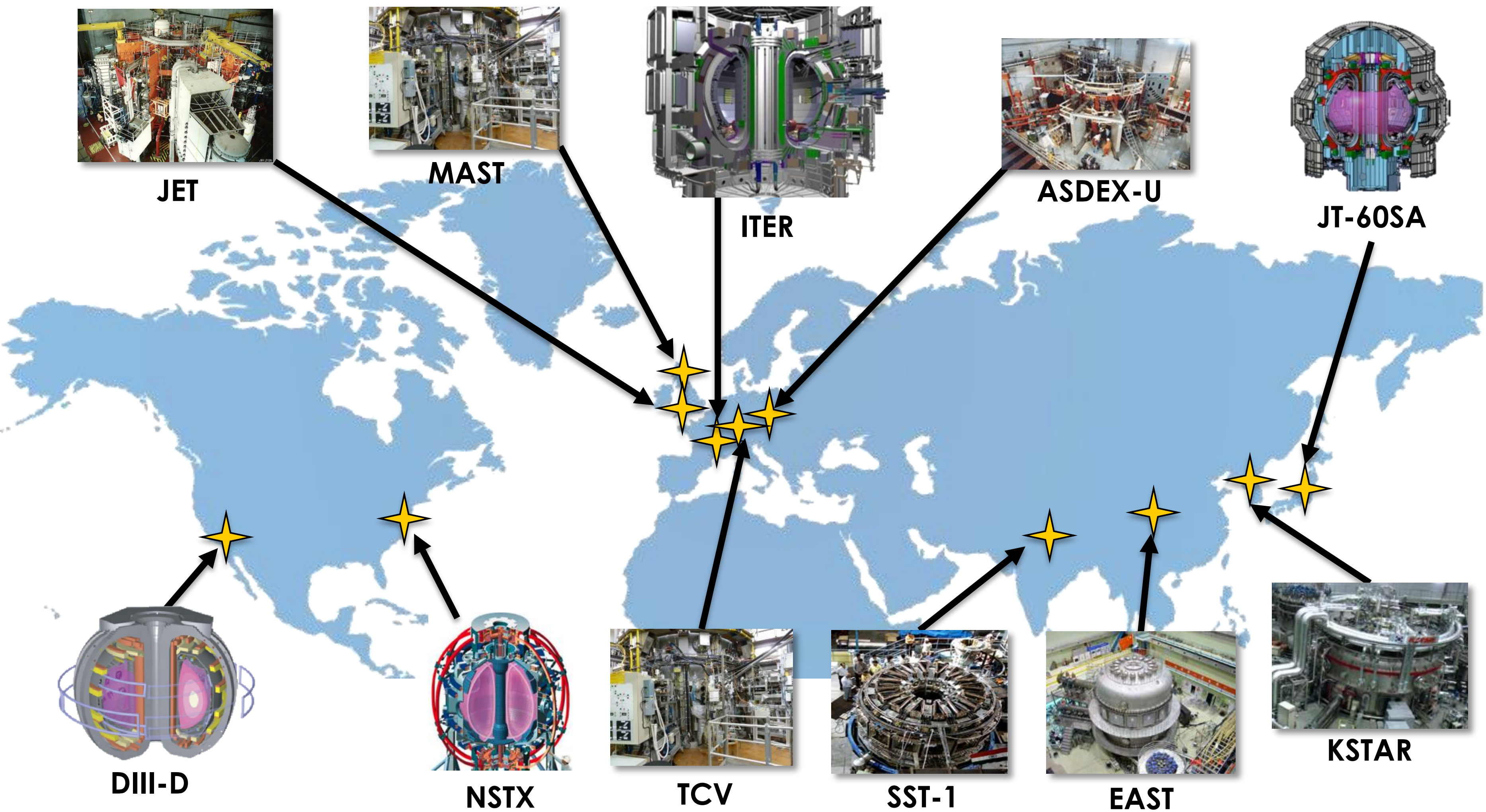

JET

- Significant fusion power (>10 MW) already demonstrated
- Many orders of magnitude (a factor of one trillion) improvement have been achieved over 40 years

ITER will demonstrate a 500 MW sustained fusion plasma



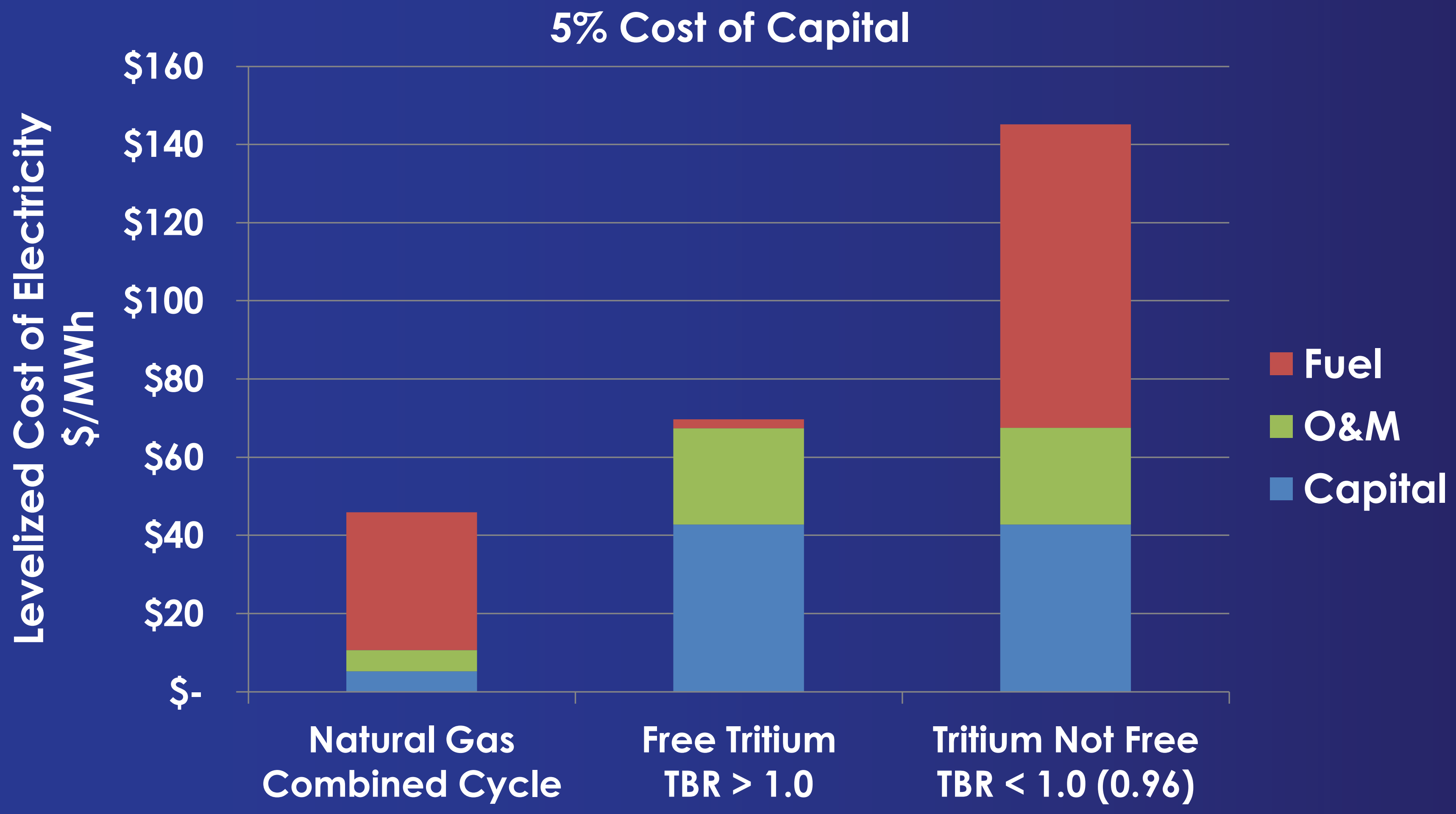
The World Tokamak Programs Are Working Together to Prepare for ITER



Gifted and talented work force is required to support & exploit ITER

Levelized Cost of Electricity

1,000 MWe Fusion NOAK Plant

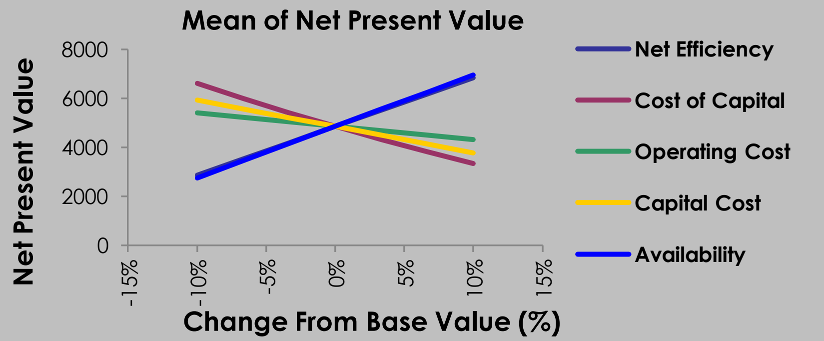


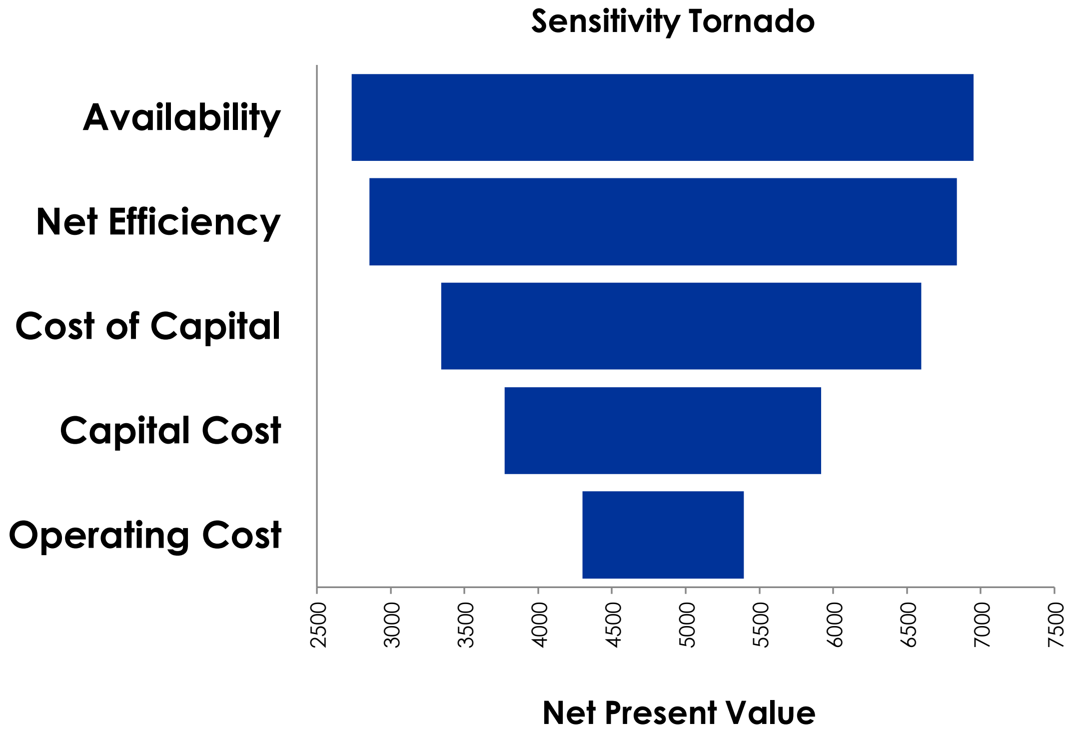
Current Cost of Tritium is ~$100M/kg

Sensitivity Analysis

1,000 MWe Fusion NOAK Plant

Cost of Capital = 5%
Electricity Sales Price = $0.09/kWh



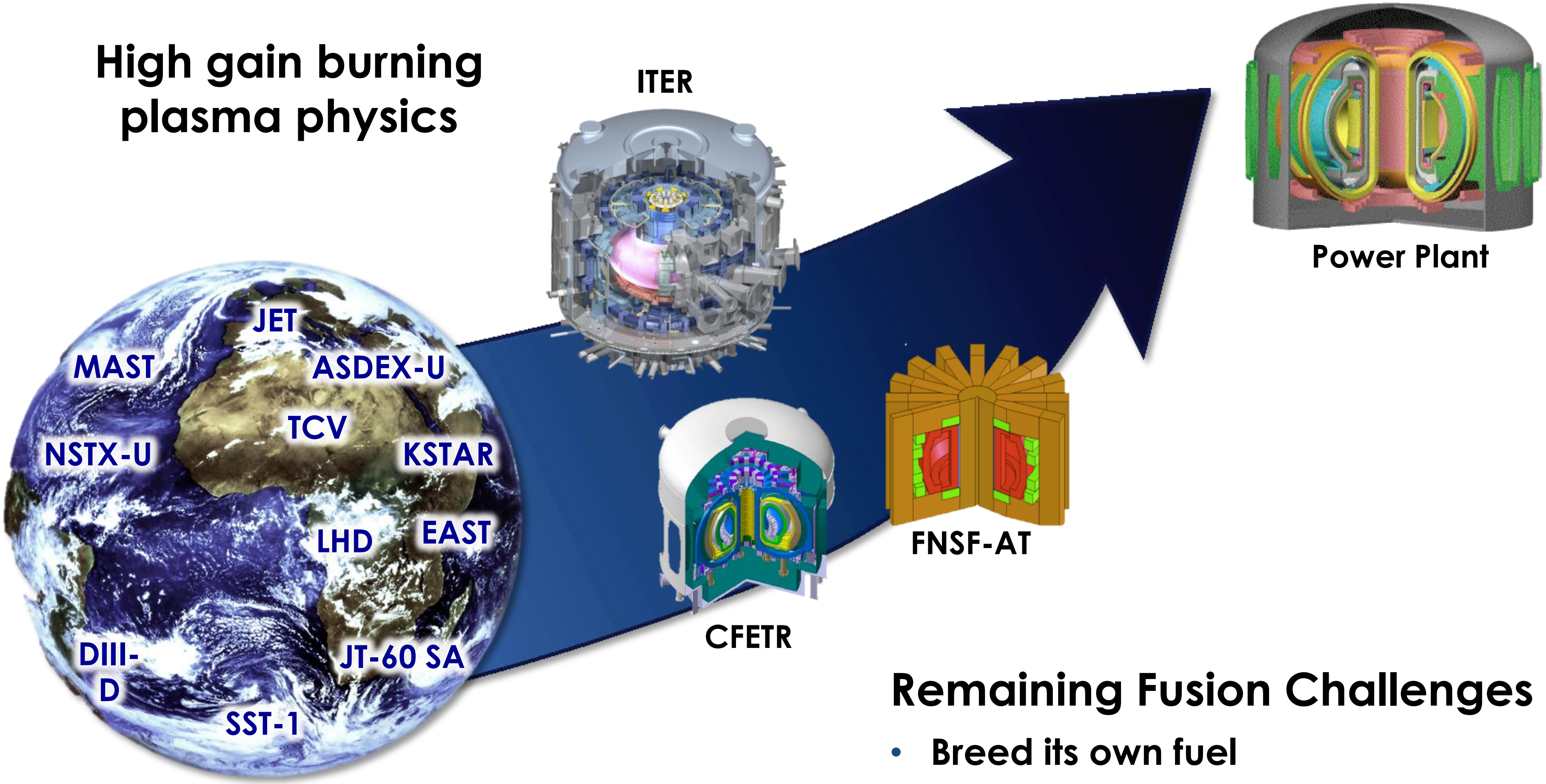


- Steady State vs. Pulsed Operation, Maintenance
- Thermal Conversion Efficiency, Recirculating Power
- Expected Rate of Return, Financing Costs
- Magnet Cost, Turbine Plant System Cost
- FW/Blanket and Divertor Capital Replacement

GENERAL ATOMICS

Path to Net Electricity and New Facilities

High gain burning plasma physics



Fusion Facilities of the World

Remaining Fusion Challenges

- Breed its own fuel
- Materials in extreme conditions
- High performance, steady-state

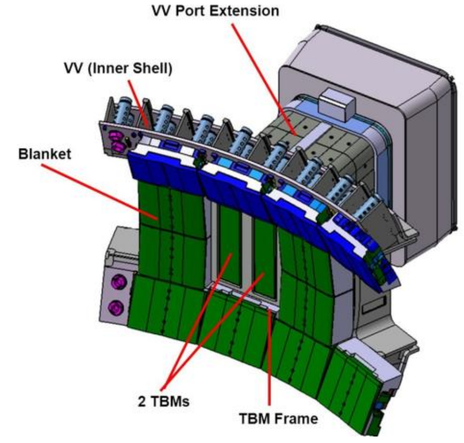
Tritium Self-Sufficiency is a Critical Issue for Fusion Energy

- **Cost of tritium from present sources is prohibitive and supply is limited**
  - Tritium cost is approximately $100 M/kg
  - 1GW electric for 1 day requires ~ ½ kg of Tritium
  - → 10 % short-fall = $0.2/kW-hr

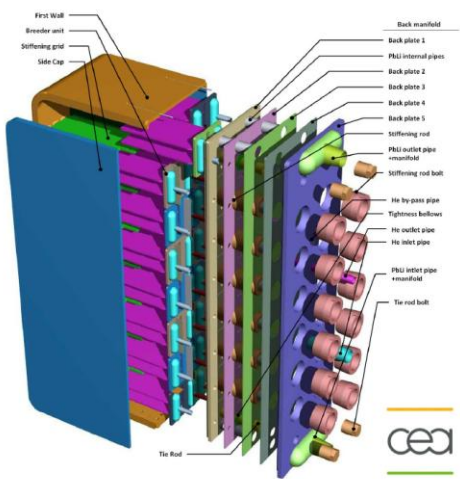
- **Test Blanket Module program on ITER will address tritium breeding – 6 modules**
  - Two from Europe, one each from Japan, China, Korea, and India

- **Challenges remain in development of blankets for power plants**
  - Produce sufficient tritium for the plant
  - Produce high quality heat
  - Survive in harsh environment: neutron fluence, temperature, & magnetic loads

ITER Test Blanket Module Port



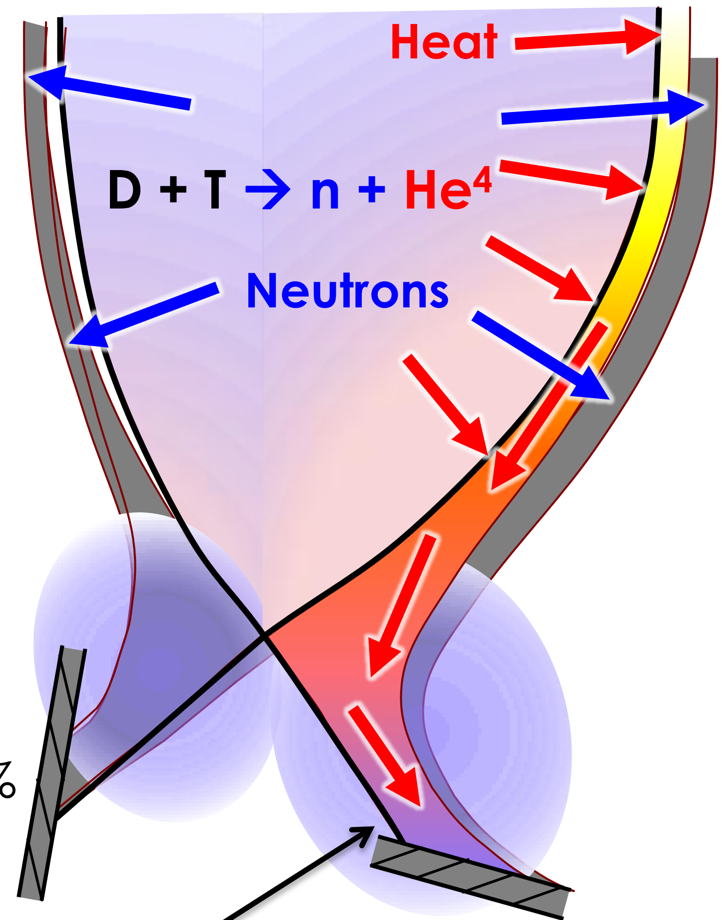
Europe Helium Cooled Lead Lithium



GENERAL ATOMICS

Fusion Reactor Creates Unique Challenge for Materials Due to Extreme Heat and Neutron Fluxes

- **D-T reaction produces high energy neutron (14.1 MeV) and alpha particle (3.5 MeV)**
- **Neutron penetrates deeply into chamber walls and has distinct effect on economics**
  - 2-3 GW volumetric heat source – 80%
  - Enables tritium breeding
  - Reduced lifetime $N_{lifetime}$ of walls due to high dpa (100 dpa → $N_{lifetime}$ ~ 5 years)
    - Replacement cost ~ \$0.05/kW-h /$N_{lifetime}$
- **Surface heating of the divertor from plasma power flow can also limit lifetime**
  - Heat source is largely alpha particles – 20%
  - Peak heat fluxes near or above material limits for melting (~ 10 MW/m²)
  - Could be mitigated by plasma/divertor design



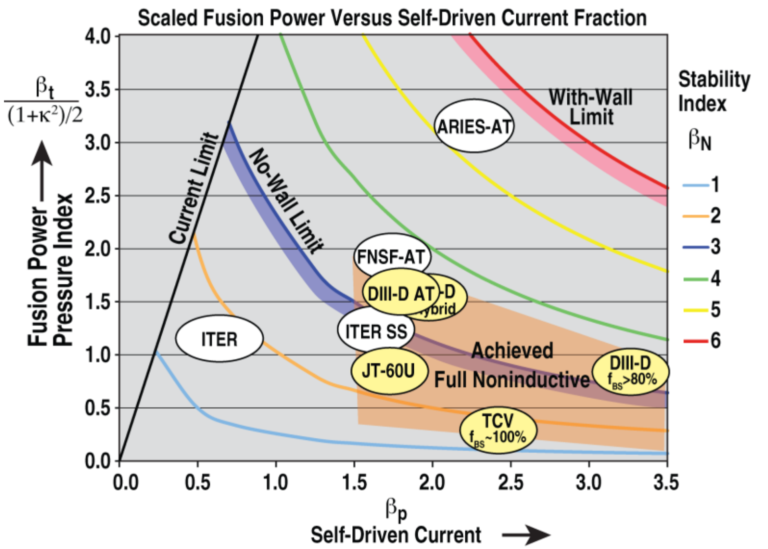
Exhaust heat can be captured

Economical Tokamak Solutions Depend on Choice of Current Generation

- **Fusion power density increases with the square of the plasma pressure**
  - $P_F \approx p^2 \approx \beta^2 B^4 \approx (\beta_N \; I_P \; B)^2$
- **Limits**
  - β limited by plasma stability
  - B limited by mechanical forces
  - I_P generated by central solenoid action or external current drive
- **Central solenoid → inherently pulsed**
  - Most efficient current drive: low recirculating power, I_P large → High P_F
  - Pulsed operation reduces duty cycle and increases thermal and mechanical stresses
- **Steady state → external current drive**
  - Requires increased recirculating power
  - Takes advantage of higher self-driven current
  - Reduced cyclic stresses

$$\beta = \frac{\text{Kinetic Pressure}}{\text{Magnetic Pressure}}$$

I_P = Plasma Current
B = Toroidal Field



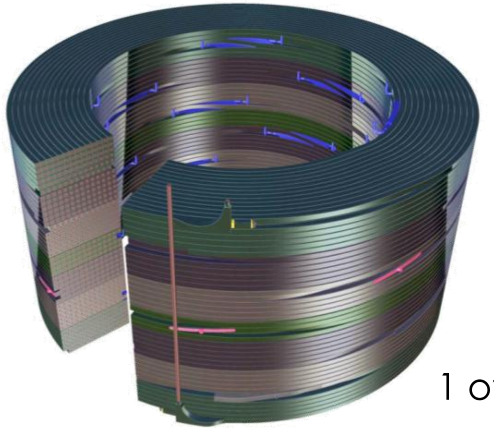
An ITER objective: "Aim at non-inductive steady-state at Q >5"

Promise of Fusion is Near – ITER Being Built Now

ITER Mission

"To demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes."

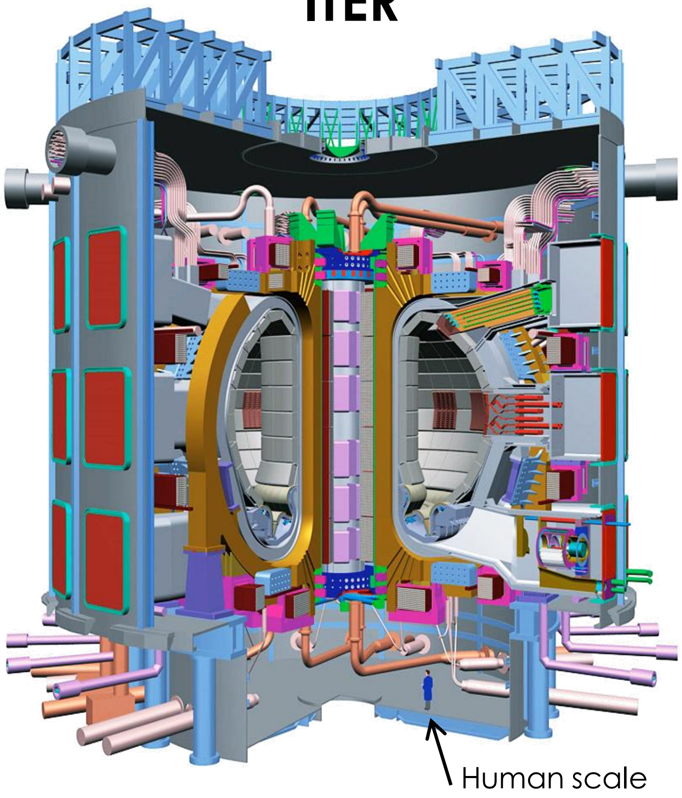
General Atomics is manufacturing the most critical technology for ITER



1 of 7

220,000 pounds, 4 miles of conductor

ITER



Partnership between U.S., EU, Japan, Russia, China, Korea and India

Summary

- **Fusion is by far the most abundant energy source available to satisfy the world's energy needs for many centuries**
- **We have an interesting and promising approach to fusion within our reach**
- **We can envision the end-point and the paths to realizing fusion energy, however, significant technical challenges remain**

Pooling of world talent and resources will be required to overcome the remaining technical challenges