Role of Fusion Energy in the 21st Century

Farrokh Najmabadi
Prof. of Electrical Engineering
Director of Center for Energy Research
UC San Diego

UCLA
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Dr. Steve Koonin, BP, for energy data.
The Energy Challenge
Facts and Fiction
With industrialization of emerging nations, energy use is expected to grow by ~ 4 fold in this century (average 1.6% annual growth rate).
Energy supply will be dominated by fossil fuels for the foreseeable future.

Source: IEA World Energy Outlook 2006 (Reference Case), Business as Usual (BAU) case
We are NOT running out of fossil fuels

The issue is the distribution of fossil fuels, i.e., Energy Security.
CO₂ concentration in the atmosphere is rising due to fossil fuel use. 

The global temperature is increasing. 
There is a plausible causal connection between CO₂ concentration and global temperature (global warming).

- But this is a ~1% effect in a complex, noisy system
- Scientific case is complicated by natural variability, ill-understood non-linear behavior, etc.
**CO₂ concentration will grow geometrically!**

- The earth absorbs anthropogenic CO₂ at a limited rate
  - The lifetime of CO₂ in the atmosphere is ~1000 years
  - The atmosphere will accumulate emissions during the 21st Century
- Impact of higher CO₂ concentrations is uncertain
  - ~2X pre-industrial is a widely discussed stabilization target (550 ppm)
  - Reached by 2050 under BAU Scenario shown.
- To stabilize CO₂ concentration at 550 ppm, emissions would have to drop to about half of their current value by the end of this century
  - This in the face of a five fold increase in energy demand in the next 100 years (1.6% per year emissions growth)
  - Modest emissions reductions only delay the growth of concentration (20% emissions reduction buys 15 years).

- Reducing emissions is an enormous, complex challenge; technology development must play the central role.
Many sources contribute to the emission of greenhouse gases.

**Energy Emissions**
- Power (24%)
- Transport (14%)
- Buildings (8%)
- Industry (14%)
- Other energy related (5%)
- Waste (3%)

**Non-Energy Emissions**
- Agriculture (14%)
- Land use (18%)

Total emissions in 2000: 42 GtCO2e.

Energy emissions are mostly CO₂ (some non-CO₂ in industry and other energy related). Non-energy emissions are CO₂ (land use) and non-CO₂ (agriculture and waste).
There is a growing acceptance that nuclear power should play a major role in reducing CO2 emissions and meeting energy needs.

Large expansion of nuclear power, however, requires rethinking of the fuel cycle and waste disposal, e.g., Reprocessing, deep burn of actinides, Gen IV reactors.
Need a few good engineers!

- Energy debate is dominated by activists and lobbyists.
  - Left: “Energy challenge can be readily met by conservation and renewables alone.”
  - Right: “Limiting greenhouse emissions are so costly that it will wreck the economy.” or “Uncertainty in the CO₂ impact justifies inaction.”

- Scientists and engineers are NOT involved in the debate
  - Most proposals by activist and hyped by popular media either violate physical laws, or are beyond current technology, or would not make any sizeable impact.

- No carbon-neutral commercial energy technology is available today.
  - Solution CANNOT be legislated. Subsidies do not work!
  - Energy market is huge (T$ annual sale, TW of power).

Get Involved and Educate!
We Should Be Ready to Accelerate Fusion Development!

- With the industrialization of the emerging nations, the demand for energy will increase by many folds.

- Few options available:
  - Energy Efficiency: Only has reduced the growth rate
  - Fossil fuels: CO₂ and Climate Change
  - Renewable: Intermittency, high cost, environmental impact
  - Nuclear (fission): Waste disposal, proliferation

- There would be a large increase in energy R&D in the next 5-10 years.

- We need to be prepared to put fusion option on the table.
Fusion Option: How to get from ITER to an attractive final product?
Integration of fusion plasma with fusion technologies

"Fusion Power: Research and Development Requirements." Division of Controlled Thermonuclear Research (AEC).
MFE Program

Integration of fusion plasma with fusion technologies?

Advanced Tokamaks
Spherical Torus
Compact Stellarator
Reverse-field Pinches

Advanced driver & Target R&D;
Blankets;
Divertors;
Tritium Systems;
Remote handling

Theory, Simulation and Basic Plasma Science

Configuration Optimization

Concept Exploration/Proof of Principle

MFE PE(s)

Burning Plasma

Complete ITER Ops Phase 1

MFE ITER (or FIRE)

Materials Testing

Materials Science/Development

Complete IFMIF Ops 80 dpa

Prelim. IFMIF Ops 150 dpa

MFE IFMIF

Component Testing

Engineering Science/Technology Development

MFE CTF

Demonstration

Design Studies

US Demo
We need to develop a 5,000 ft view of fusion development
What do we need to bridge the gap between ITER and attractive power plants?

- Do we have a detailed map for fusion power development?
- How do we optimize such a development path?
  - Metrics will be needed for cost/benefit/risk tradeoffs
  - What can we do in simulation facilities and what requires new fusion devices?
- How can we utilize existing devices to resolve some of these issues?
  - Preparation for launching new facilities.
  - Resolving issues that can make a difference in any new facilities.

- Serious money requires a plan with an attractive product with a reasonable time frame and clear milestones!
  - We need to overcome the perception that fusion is always 30 years away and it is NOT really an energy program.
  - Judge is the energy industry not other scientists!
A holistic/integrated optimization approach should drive the development path.

Traditional Approach: Ask each scientific area (e.g., plasma, blanket)
- What are the remaining major R&D areas?
- Which of the remaining major R&D areas can be explored in existing devices or simulation facilities (e.g., fission reactors)? What other major facilities are needed?

Holistic/Integrated Approach: Fusion energy development should be guided by the requirements for an attractive fusion energy source
- What are the remaining major R&D areas?
  - What is the impact of this R&D on the attractiveness of the final product.
- Which of the remaining major R&D areas can be explored in existing devices or simulation facilities (i.e., fission reactors)? What other major facilities are needed?
  - Should we attempt to replicate power plant conditions in a scaled device or Optimize facility performance relative to scaled objectives?
Elements of the case for fusion power were developed through interaction with representatives of U.S. Electric utilities and energy industry.

- **Have an economically competitive life-cycle cost of electricity**

- **Gain Public acceptance by having excellent safety and environmental characteristics**
  - No disturbance of public’s day-to-day activities
  - No local or global atmospheric impact
  - No need for evacuation plan
  - No high-level waste
  - Ease of licensing

- **Reliable, available, and stable as an electrical power source**
  - Have operational reliability and high availability
  - Closed, on-site fuel cycle
  - High fuel availability
  - Capable of partial load operation
  - Available in a range of unit sizes

- Low-activation material
Existing facilities fail to address essential features of a fusion energy source

**Metric**

<table>
<thead>
<tr>
<th>Metric</th>
<th>ITER</th>
<th>D3/JET</th>
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<tbody>
<tr>
<td>waste</td>
<td>3 need to deal with it, but wrong materials, little fluence</td>
<td>0 little relevance</td>
</tr>
<tr>
<td>reliability</td>
<td>3 some machine operation, little fluence</td>
<td>1 some machine operation, no fluence</td>
</tr>
<tr>
<td>maintenance</td>
<td>5 unprototypic construction, modules replaced</td>
<td>1 experience moving tokamak equipment</td>
</tr>
<tr>
<td>fuel</td>
<td>3 tritium handling, but no breeding, no fuel cycle</td>
<td>1 Some tritium handling, no breeding, no fuel cycle</td>
</tr>
<tr>
<td>safety</td>
<td>6 hazards are lower, operations different</td>
<td>2 hazards much lower, operations much different</td>
</tr>
<tr>
<td>partial power</td>
<td>4 experience with operating modes</td>
<td>2 experience with operating modes</td>
</tr>
<tr>
<td>thermal efficiency</td>
<td>0 no power production, low temperature, wrong materials</td>
<td>0 no power conversion</td>
</tr>
<tr>
<td>power density</td>
<td>5 low average power density, local regions of HHF</td>
<td>1 low power handling required, some divertor heating</td>
</tr>
<tr>
<td>cost</td>
<td>5 1st of a kind reactor costs, cost reduction needed</td>
<td>1 not relevant to a power plant</td>
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ITER is a major step forward but there is a long road ahead.
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ARIES studies emphasize holistic R&D needs and their design implications

<table>
<thead>
<tr>
<th>Traditional approach</th>
<th>Concurrent engineering/physics</th>
</tr>
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<tbody>
<tr>
<td>Plasma</td>
<td>Power control</td>
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<tr>
<td>Blankets</td>
<td>Power and particle management</td>
</tr>
<tr>
<td>Divertors</td>
<td>Fuel management</td>
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<td>Magnets</td>
<td>Maintenance</td>
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<td>Vacuum vessel</td>
<td>Safety</td>
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<td></td>
<td>Waste</td>
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<td></td>
<td>Cost</td>
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Examples of holistic issues for Fusion Power

- **Power management**: Demonstrate extraction of power core high-grade heat, divertor power handling, nuclear performance of ancillary equipment.

- **Fuel management**: Demonstrate “birth to death” tritium management in a closed loop with self-sufficient breeding and full accountability of tritium inventory.

- **Safety**: Demonstrate public and worker safety of the integral facility, capturing system to system interactions.

- **Plant operations**: Establish the operability of a fusion energy facility, including plasma control, reliability of components, inspectability and maintainability of a power plant relevant tokamak.
Flow Diagram of Power Management

- $P_{\text{fusion}}$
- $P_{\alpha}$
- $P_{\text{injected}}$
- $P_{\text{neutron}}$
- $P_{\text{rad}}$
- $P_{\text{cond}}$
- In-vessel: rf antennas, magnets, diagnostics, etc.
- Blanket
- PFC’s
- First wall
- Divertor

Core power: $P_{\text{cond}}$

Edge power: $P_{\text{rad}}$
The integrated approach leads to important choices in R&D.

- Interaction between components and disciplines often dictate the optimized solution. For example,
  - Improved plasma performance (e.g., increased power density) should be balanced against constraints such as divertor power handling.
  - First wall, divertor, and in-vessel components should not impede a high-performance plasma operation (e.g., material choices).
  - R&D requires integrated testing of power technologies in the presence of a fusion plasma with prototypical edge plasma conditions.
  - Does not allow problem to be solved by transferring to another system: A 100% radiating plasma transfers the problem from divertor to the first wall.
  - Allows Prioritization of R&D. For example, is it better to develop a high $\beta$ plasma or a high efficiency blanket?
  - Most technologies for current experiments & ITER are NOT transferable to a power plant. Is this an optimum approach?
Integration of a fusion plasma and fusion technologies is essential

- Fusion roadmap and R&D prioritization should be driven by integrated response of the system.
- Fusion development requires an experimental device to perform integrated testing of a fusion plasma and fusion technologies in order to provide the data base necessary to convince utilities to proceed with the Demo and for the licensing authorities to license that device.
  - This is the primary mission of CTF
Further Thoughts
We should focus on an aggressive plan for accelerated fusion development

- We will not be able to compete with Asian Superconducting tokamaks and ITER in a timely manner.
- However, we can leap-frog the rest of the world by focusing on the pace-setting issues – Plasma and fusion technologies. This can be done in parallel with ITER!

- We can aim at a Fusion Pilot Plant: A steady-state demonstration device with the capability to produce copious amount (> 100 MW) of fusion power and provide an integrated test bed for all aspect of a fusion power plant.
  - This device does NOT have to be a net energy producer! (Q =1-2 is enough!)
  - It would resolve the remaining issues of fusion plasma physics.
  - It would set the necessary technical/regulatory data base for moving towards a fusion power plant.
Are we ready to accelerate fusion development?

- We probably have the plasma basis to proceed with such a device (a physics basis is needed).
- We do NOT have the Engineering Sciences basis to move forward.
- We do NOT have the people! (Very few students in fusion technology area, very few universities involved.)

**Proposal:** A Concept Exploration Program for Fusion Engineering Sciences:

- Small Grants, involve as many universities as possible.
- Clear goals and milestones, reward performers and drop non-performers.
- This will allow a new generation of fusion scientists to come forward to take the leadership of this area.
In Summary, ...
A CO₂ constrained world provides a major opportunity for fusion development

- Serious money requires a plan with an attractive product with a reasonable time frame and clear milestones!
  - We need to overcome the perception that fusion is always 30 years away and it is NOT really an energy program.
  - Judge is the energy industry not other scientists!
- A detailed development plan for fusion is needed which provides all of data base necessary to proceed with the Demo.
- An integrated approach would result in an optimized R&D program
- An aggressive fusion development is possible. We can leap-frog the rest of the world by focusing on the pace-setting issues – integration of a fusion plasma with fusion technologies. This can be done in parallel with ITER!
- We need to initiate a “concept development”-type program aiming at increasing involvement of universities in fusion technologies.
Thank you!
Any Questions?
Development of fusion has been constrained by funding!

~ 1 week of world energy sale