The Energy Challenge

Scale:
1 EJ = 10^{18} J = 24 Mtoe
1 TW = 31.5 EJ/year
World energy use ~ 450 EJ/year
    ~ 14 TW
With industrialization of emerging nations, energy use is expected to grow ~ 4 fold in this century (average 1.6% annual growth rate)

Data from IEA World Energy Outlook 2006 (Chart from Steve Koonin, BP)
Quality of Life is strongly correlated to energy use.

**HDI:** (index reflecting life expectancy at birth + adult literacy & school enrolment + GNP (PPP) per capita)

- **Typical goals:** HDI of 0.9 at 3 toe per capita for developing countries.
- For all developing countries to reach this point, would need world energy use to double with today’s population, or increase 2.6 fold with the 8.1 billion expected in 2030.
World Primary Energy Demand is expected to grow substantially.

- Data from IAE World Energy Outlook 2006 Reference (Red) and Alternative (Blue) scenarios.
- World population is projected to grow from 6.4B (2004) to 8.1B (2030).
- Scenarios are very sensitive to assumption about China.
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
CO₂ concentration in the atmosphere is rising due to fossil fuel use

- 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 IEA Reference 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 four fold increase of energy demand in the next 100 years

Reducing emissions is an enormous, complex challenge; technology development must play the central role.
Technologies to meet the energy challenge do not exist

- Improved efficiency and lower demand
  - Huge scope but demand has always risen faster due to long turn-over time.

- Renewables
  - Intermittency, cost, environmental impact.

- Carbon sequestration
  - Requires handling large amounts of C (Emissions to 2050 =2000Gt CO₂)

- Fission
  - Fuel cycle and waste disposal

- Fusion
  - Probably a large contributor in the 2nd half of the century 😊
There is a growing acceptance that nuclear power should play a major role in emissions and energy. 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.
Energy Challenge: A Summary

- Large increases in energy use is expected.
- IEA world Energy Outlook indicate that it will require increased use of fossil fuels
  - Air pollution & Global Warming
  - Will run out sooner or later
- Limiting CO₂ to 550ppm by 2050 is an ambitious goal.
  - USDOE: “The technology to generate this amount of emission-free power does not exist.”
  - IEA report: “Achieving a truly sustainable energy system will call for radical breakthroughs that alter how we produce and use energy.”
- Public funding of energy research is down 50% since 1980 (in real term). World energy R&D expenditure is 0.25% of energy market of $4.5 trillion.
Most of public energy expenditures is in the form of subsidies.

Energy Subsidies (€28B) and R&D (€2B) in the EU

- Coal: 44.5%
- Oil and gas: 30%
- Renewables: 18%
- Fusion: 1.5%
- Fission: 6%


Slide from C. Llewellyn Smith, UKAEA
Fission (seeking a significant fraction of World Energy Consumption of 14TW)
Nuclear power is already a large contributor to world energy supply

- Nuclear power provide 8% of world total energy demand (20% of US electricity)
- Operating reactors in 31 countries
  - 438 nuclear plants generating 353 GWe
  - Half of reactors in US, Japan, and France
  - 104 reactor is US, 69 in France
- 30 New plants in 12 countries under construction

- No new plant in US for more than two decades
- Increased production due to higher availability
  - 30% of US electricity growth
  - Equivalent to 25 1GW plants
  - Extended license for many plants
Evolution of Fission Reactors

**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+

**Generation III +**
- Evolutionary Designs Offering Improved Economics for Near-Term Deployment

**Generation IV**
- Highly Economical
- Enhanced Safety
- Minimal Waste
- Proliferation Resistant

Timeline:
- 1950
- 1960
- 1970
- 1980
- 1990
- 2000
- 2010
- 2020
- 2030
Challenges to Long-term viability of fission

- **Economics:**
  - Reduced costs
  - Reduced financial risk (especially licensing/construction time)

- **Safety**
  - Protection from core damage (reduce likelihood)
  - Eliminate offsite radioactive release potential

- **Sustainability**
  - Efficient fuel utilization
  - Waste minimization and management
  - Non-proliferation

- Reprocessing and Transmutation
- Gen IV Reactors
Uranium Resources

- 120 years at IEA expected 2030 use, 40 years if nuclear displaces 50% of fossil fuels.
- Unless U can be extracted from sea water cheaply, breeders are necessary within this century.

Note: COE is insensitive to U cost (+$100/kg U → 0.25 c/kWh)
Large Expansion of Nuclear Power Requires Reprocessing of Waste

Gen IV International Forum (10 parties) has endorsed Six Gen IV Concepts for R&D

- Very high-temperature gas-cooled reactor (safety, hydrogen production)
- Lead-cooled Fast Reactor (sustainability, safety)
- Gas-Cooled Fast Reactor (sustainability, economics)
- Supercritical-water-cooled reactor (economics)
- Molten Salt reactor (sustainability)
- Sodium-cooled fast reactor (sustainability)

- Most use closed-cycle fast-spectrum to reduced waste heat and radiotoxicity (to extend repository capacity) and to breed fuel.
Two High-Temperature Helium-Cooled Reactors Are Currently Operating in Asia

**Prismatic-Block HTTR in Japan**

**Pebble-Bed HTR-10 in China**

HTTR reached outlet temperature of 950°C at 30 MW on April 19, 2004.
Fusion: Looking into the future
ITER will demonstrate the technical feasibility of fusion energy

- Power-plant scale device. Baseline design:
  - 500 MW of fusion power for 300s
  - Does not include breeding blanket or power recovery systems.

- ITER agreement was signed in Nov. 2006 by 7 international partners (US, EU, Japan, Russia, China, Korea, and India)

- Construction will begin in 2008.
ARIES-AT is an attractive vision for fusion with a reasonable extrapolation in physics & technology

- Competitive cost of electricity (5c/kWh);
- Steady-state operation;
- Low level waste;
- Public & worker safety;
- High availability.
ITER and satellite tokamaks will provide the necessary data for a fusion power plant

<table>
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<tr>
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<th>DIII-D Simultaneous</th>
<th>DIII-D Max</th>
<th>ITER Baseline</th>
<th>ARIES-I’</th>
<th>ARIES-AT</th>
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<td>Major toroidal radius (m)</td>
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<td>1.7</td>
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<td>Plasma Current (MA)</td>
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<td>Electron temperature (keV)</td>
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<td>8.9**</td>
<td>15**</td>
<td>18**</td>
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<td>Density ($10^{20}$ m$^{-3}$)</td>
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<td>Confinement time (s)</td>
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<td>$\beta$ (plasma/magnetic pressure)</td>
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<td>1.8</td>
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<td>Fusion Power (MW)</td>
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<td>Pulse length</td>
<td>300</td>
<td>S.S.</td>
<td>S.S.</td>
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</table>

* Peak value,  **Average Value
The ARIES-AT utilizes an efficient superconducting magnet design

- On-axis toroidal field: 6 T
- Peak field at TF coil: 11.4 T
- TF Structure: Caps and straps support loads without inter-coil structure;

Superconducting Material
- Either LTC superconductor (Nb₃Sn and NbTi) or HTC
- Structural Plates with grooves for winding only the conductor.
Use of High-Temperature Superconductors Simplifies the Magnet Systems

- HTS does offer *operational advantages*:
  - Higher temperature operation (even 77K), or dry magnets
  - Wide tapes deposited directly on the structure (less chance of energy dissipating events)
  - Reduced magnet protection concerns

**Epitaxial YBCO**

Inexpensive manufacture would consist on layering HTS on structural shells with minimal winding!

- YBCO Superconductor Strip Packs (20 layers each)
- CeO$_2$ + YSZ insulating coating (on slot & between YBCO layers)
- Inconel strip
- 8.5 mm
- 430 mm
DT Fusion requires a T breeding blanket

- Requirement: Plasma should be surrounded by a blanket containing Li
  \[
  D + T \rightarrow He + n \\
  n + 6Li \rightarrow T + He
  \]
- Through careful design, only a small fraction of neutrons are absorbed in structure and induce radioactivity
  - Rad-waste depends on the choice of material: Low-activation material
  - Rad-waste generated in DT fusion is similar to advanced fuels (D-3He)
  - For liquid coolant/breeders (e.g., Li, LiPb), most of fusion energy (carried by neutrons) is directly deposited in the coolant simplifying energy recovery
- Issue: Large flux of neutrons through the first wall and blanket:
  - Need to develop radiation-resistant, low-activation material:
  - Ferritic steels, Vanadium alloys, SiC composites
Radioactivity levels in fusion power plants are very low and decay rapidly after shutdown.

- SiC composites lead to a very low activation and afterheat.
- All components of ARIES-AT qualify for Class-C disposal under NRC and Fetter Limits. 90% of components qualify for Class-A waste.

After 100 years, only 10,000 Curies of radioactivity remain in the 585 tonne ARIES-RS fusion core.
ARIES-AT features a high-performance blanket

- Simple, low pressure design with SiC structure and LiPb coolant and breeder.
- Innovative design leads to high LiPb outlet temperature (~1,100°C) while keeping SiC structure temperature below 1,000°C leading to a high thermal efficiency of ~ 60%.
- Simple manufacturing technique.
- Very low afterheat.
- Class C waste by a wide margin.
Modular sector maintenance enables high availability

- Full sectors removed horizontally on rails
- Transport through maintenance corridors to hot cells
- Estimated maintenance time < 4 weeks
Advances in fusion science & technology has dramatically improved our vision of fusion power plants.

Major radius (m)

- Mid 80's Pulsar
- Early 90's ARIES-I
- Late 90's ARIES-RS
- 2000 ARIES-AT

Estimated Cost of Electricity (c/kWh)

- Mid 80's Physics
- Early 90's Physics
- Late 90's Physics
- Advanced Technology
Fusion Core Is Segmented to Minimize the Rad-Waste

- Only “blanket-1” and divertors are replaced every 5 years
Waste volume is not large

- 1270 m³ of Waste is generated after 40 full-power year (FPY) of operation.
  - Coolant is reused in other power plants
  - 29 m³ every 4 years (component replacement), 993 m³ at end of service
- Equivalent to ~ 30 m³ of waste per FPY
  - Effective annual waste can be reduced by increasing plant service life.

- 90% of waste qualifies for Class A disposal
In Summary, ...
In a CO$_2$ constrained world uncertainty abounds

- No carbon-neutral commercial energy technology is available today.
  - Carbon sequestration is the determining factor for fossil fuel electric generation.
  - A large investment in energy R&D is needed.
  - A shift to a hydrogen economy or carbon-neutral syn-fuels is also needed to allow continued use of liquid fuels for transportation.

- Problem cannot be solved by legislation or subsidy. We need technical solutions.
  - Technical Communities should be involved or considerable public resources would be wasted.

- The size of energy market ($1T annual sale, TW of power) is huge. Solutions should fit this size market
  - 100 Nuclear plants = 20% of electricity production
  - $50B annual R&D represents 5% of energy sale
Status of fusion power

- Over 15 MW of fusion power is generated (JET, 1997) establishing “scientific feasibility” of fusion power
  - Although fusion power < input power.
- ITER will demonstrate “technical feasibility” of fusion power by generating copious amount of fusion power (500MW for 300s) with fusion power > 10 input power.
- Tremendous progress in understanding plasmas has helped optimize plasma performance considerably. Vision of attractive fusion power plants exists.
- Transformation of fusion into a power plant requires considerable R&D in material and fusion nuclear technologies (largely ignored or under-funded to date).
  - This step, however, can be done in parallel with ITER
- Large synergy between fusion nuclear technology R&D and Gen-IV.
Thank you!
Any Questions?