Final Report from Non-Electric Applications Panel

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FESAC Meeting
July 31 - August 1, 2003
Gaithersburg, Maryland

This charge asked FESAC to consider the following questions

- What are the most promising opportunities for using intermediate-term fusion devices to contribute to the Department of Energy missions beyond the production of energy?
- What steps should the program take to incorporate these opportunities into plans for fusion research?
- Are there any negative possible impacts to pursuing these opportunities and are there ways to mitigate these possible impacts?

Panel Members

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Process for Fulfilling Charge

- Exhaustive list of potential applications was compiled
- A set of criteria for evaluating each application was developed
- A speaker for each application or group of applications spoke to the panel
- Panel members assembled/modified/approved the report

Evaluation Criteria

- Will the application be viewed as necessary to solve a "national problem" or will the application be viewed as a solution by the funding agency?
- What are the technical requirements on fusion imposed by this application with respect to the present state of fusion and the technical requirements imposed by electricity production?
  - What R&D is required to meet these requirements?
  - Is it on the path to electricity production?
- What is the competition for this application, and what is the likelihood that fusion can beat it?

The panel took a somewhat broader view of the charge

- It became clear early in the panel deliberations that there were extremely few, if any, applications that really met the restrictive words of the charge
- The panel agreed to consider all potential non-electric applications rather than just those that focused on intermediate-term devices

The Most Promising Opportunities for Non-Electric Applications of Fusion Fall into Four Categories

- Near Term Applications
- Transmutation
- Hydrogen Production
- Space Propulsion

Near-term applications focus on products that could be available in the next 5-10 years

- To meet this time scale, it is likely that the engineering Q of the fusion device will be less than one
- Some of these devices may not be "on the path to fusion electricity"

There are at least five products that fusion can sell

- High energy neutrons (2-14 MeV)
- Thermal neutrons
- High energy protrons (3-15 MeV)
- Electromagnetic radiation (microwave to x-rays to γ rays)
- High energy electrons coupled with photons to provide ultra high heat fluxes

Uses for these products include

- Production of radioisotopes (for medical applications and research)
- Detection of specific elements or isotopes in complex environments
- Radiotherapy
- Alteration of the electrical, optical, or mechanical properties of solids
- Destruction of long-lived radioactive waste
- Production of tritium for military and civilian applications
- Production of fissile material
- Destruction of fissile material for nuclear warheads
- Food and equipment sterilization
- Pulsed x-ray sources

Detection of explosives

- The low atomic numbers of elements that make up explosive devices (C, N, O) are not readily detectable by conventional x-ray techniques
- These elements have unique responses to neutrons and the explosives can be detected even though buried in suitcases, packages, or shipping containers
- Fusion neutrons sources from < 1 watt of DD fusion or ~ 3 watts of DT fusion power would provide the neutron source required for detection
- Portable DD or DT fusion sources with Q > 0.1% could be used for explosives detection

Production of Radioisotopes

- PET (Positron Emission Tomography) is a major diagnostic of cancers, ^{18}F is typically used, even shorter half-lived isotopes are often desired
- A portable source of short half-life PET isotopes, or an inexpensive, portable source of 10-15 MeV protons to make the isotopes is needed
- The Inertial Electrostatic Confinement (IEC) device using D^3He is an option

Will the products of these near-term applications be viewed as necessary?

- The economic and accurate diagnosis of cancer and other internal abnormalities is a major issue in the medical field
- The detection of clandestine materials (explosives, chemical and biological weapons, drugs, etc.) is of vital importance to our national security

Technical requirements for these applications compared with electricity production

- Q values of 10^{-4} to 10^{-3} are likely sufficient
- IEC devices already meet availabilities of >90%, and are easily maintained
- This application could begin commercial operation within the next 5 years
- Two major areas of R&D needs:
  - Increased research on the D^3He fuel cycle
  - Increased understanding of low Q operation of IEC devices
  - Cost is on the order of $2-3M/year for 5-10 years

Competition comes from accelerators and spontaneous neutron emitters

- The main competitor for production of PET isotopes is a 10-15 MeV accelerators
  - Cost is ~$2M each and they are bulky
  - Small portable IEC devices (~$50-100K) each, could be competitive
- The main competitors to the generation of neutrons are spontaneous neutron emitters (e.g., ^{242}Cf) and accelerators
  - Less energy is needed for the production of neutrons than protons, so the cost advantage for DD IEC devices may be less
  - Portability of small IEC devices may be great advantage for "field" work

Transmutation

- There are potential applications of fusion neutron sources to “drive” sub-critical fission reactors to perform one more more possible “nuclear” missions
  - Transmutation (by neutron fission) of the plutonium and higher actinides in spent nuclear fuel (SNF) to reduce capacity requirements for high-level waste repositories (disposition of surplus weapons-grade plutonium is a related mission)
  - Transmutation (by neutron capture) of fertile U-238 into fissile plutonium for fueling light water reactors

The transmutation of SNF is representative of the possible nuclear missions for a sub-critical reactor driven by a fusion neutron source

- The SNF inventory in the US was estimated to be ~47,000 MTU at the end of 2002
- Current rate of production of SNF is about 2,000 MTU/year
- The Yucca Mountain High Level Waste Repository (HLWR) has a statutory limit of 70,000 MT of heavy metal, which includes 63,000 MTU of SNF
- At the present rate of nuclear power production, a new Yucca Mountain will be needed in 8 years, and every 30 years thereafter

The capacity of a HLWR is set by the decay heat removal capability

- During the first 100 or so years after irradiation, the decay heat of SNF is dominated by fission products, after which it is dominated by the decay of Pu and the higher actinides
- If the HLWR is not sealed for 100 years or so after the SNF is removed from a reactor, the Pu and actinide decay heat will determine the capacity of the HLWR

Reprocessing SNF and subsequent transmutation can delay the need for additional HLWRs

- Separate the uranium that can be sent to a low level waste repository
- Separate the Pu and higher actinides that can be made into fuel for recycling in “transmutation” reactors
- The small amount of fission products that remain can be sent to a HLWR
- Even a 90% separation efficiency (current estimates, yet unproven, are in excess of 99%) would mean a new HLWR every 300 years instead of every 30

Fissile breeding and plutonium disposition missions

- These are a variant of the recycling/reprocessing scenario for the transmutation mission
- The U separated from the SNF and the depleted U from the depleted (in fissile U-235) U from the original fuel enrichment are recycled back as part of the transmutation reactor fuel
- The transmutation of U-238 by neutron capture will produce fissile P which can be used as LWR fuel (the transmutation reactor becomes a breeder reactor)
- Weapons grade Pu can be blended in with the SNF Pu and higher actinides

Technical requirements for the fusion neutron mission

- Most of the neutrons in a sub-critical transmutation reactor would be created by the fission process in the reactor
- The role of the fusion neutron source would be to provide a modest number of neutrons to maintain the neutron fission chain reaction
- Therefore the requirements on fusion power level, power density, and neutron and thermal wall loads is less demanding than for fusion electric power

Will transmutation be viewed as necessary?

- The weapons Pu disposition mission is widely recognized as a national problem and is currently funded by the government
- The transmutation mission is recognized as a national need and has significant funding (~$60M in FY-03 to support separations/transmutation/ systems etc.), but there may be less urgency felt by the government for this mission

Technical requirements for transmutation compared with electricity production

- The requirements on β, confinement, energy amplification (Q_p), and fusion power are at or below the ITER level; additional physics R&D is required to achieve quasi-steady state operation
- Availability requirements based only on SNF needing recycling (to avoid a second HLWR every 30 years) are modest (~50%)
- However, economic competitiveness could result in must stricter availability requirements

Fission reactors are the primary competition for the transmutation mission

- Critical fission reactors are the primary competition for the transmutation mission
- A sub-critical reactor may have some safety advantages, providing an opportunity for fusion and accelerator neutron sources to contribute
  - The fusion neutron source is distributed whereas the accelerator neutron source is highly localized; this could provide some advantage to the fusion neutron source

Hydrogen Production

- Converting to a hydrogen economy is seen as a possible solution to the CO_2 problem
- Today, hydrogen is derived primarily from natural gas
- When the cost of CO_2 sequestration is added to the price of producing hydrogen from fossil fuels, hydrogen produced by other energy sources becomes competitive

Fusion production of hydrogen

- Hydrogen plant sizes can be quite large (4 GW or larger), depending on the market served; this is amenable to capital-intensive fusion plants (which benefit from economy of scale)
- Both MFE and IFE have been studied for hydrogen production
- High temperature blankets and heat transfer systems benefit hydrogen production as well as electricity production

Several methods can be used to produce hydrogen; three of these are most likely to be used for fusion

- Thermochemical or thermochemical/electrochemical
  - Uses thermal energy carried by the neutron
  - Currently under development for nuclear applications
- Low-temperature electrolysis
  - Process hardware is commercially available
- High-temperature electrolysis
  - Currently under development

Will hydrogen production be viewed as necessary?

- Both the public and the national funding entities are beginning to recognize that the hydrocarbon resources are ultimately a limited resource and that continued usage of hydrocarbon fuels that generate CO_2 will increase our greenhouse gas emissions and despoil our environment
- Conversion to a hydrogen economy is starting to be a national initiative

Technical requirements for hydrogen production compared with electricity production

- Efficient production of electricity should precede hydrogen production (requirements for hydrogen production are no less than those for electricity production)
- Hydrogen production using low-temperature electrolysis requires no R&D beyond requirements imposed by electricity production
- Hydrogen production with high temperature electrolysis will leverage electrolyzer developments by other funding agencies
- Hydrogen production with thermochemical or thermochemical/electrochemical processes will be similar with the exception of materials and chemical processes needs

Competition for hydrogen produced by fusion

- Hydrogen production from natural gas is not desirable because it depletes hydrocarbon resources, diverts hydrocarbon fuels from other end products, and creates CO_2
- Renewable energy sources may be an important source in areas with large wind power, readily available biomass, and if the cost of solar systems is reduced substantially
- Production of hydrogen with fission plants represents the most likely and formidable competitor

Space propulsion

- Fusion offers a unique potential for advanced space propulsion
  - Ability to transport large payloads over long distances with acceptable trip times
  - Missions to the outer planets of the solar system and beyond involving human piloted travel and/or large robotic platforms are impossible for existing propulsion fuels

Fusion applied to space propulsion is quite different from fusion applied to electricity generation

Terrestrial Electric Power	**Space Propulsion**
Fusion energy valued for a few cents per kW-hr	Fusion energy valued for $10's to $100's per kW-hr
Conversion to electricity mandatory	Conversion to thrust directly.
Cost of electricity is a physics driver	Specific jet power is a physics driver
Neutrons cherished for their energy, but accentuate reactor material engineering challenge	Neutrons are worse than useless and are vented out freely to space, alleviating the reactor material problems
Years of low-maintenance operation – inherently favors steady-state fusion approaches	Months of operating duty cycle between major overhauls – open the doors for pulsed fusion approaches
Terrestrial environment where creating a clean, high vacuum is a non-trivial engineering burden	Space environment where a near perfect clean vacuum is readily available.

Will fusion propulsion be viewed as necessary?

- Fusion propulsion is already recognized by NASA as necessary for certain types of missions; the bigger issue is when the nation will be ready to embark on such missions

Technical requirements for space propulsion compared with electricity production

- Although confinement concepts have been proposed for advanced space missions, the detailed technical challenges facing fusion for space propulsion are largely unexplored in a systematic manner
- Because of the differences in mission, they may differ significantly from those for terrestrial fusion applications

Competition for space propulsion produced by fusion

- Compared with all other available energy sources, fusion offers a unique potential for advanced space propulsion

Panel Recommendations

- The most promising opportunities identified:
  - Near-Term applications
  - Transmutation
  - Hydrogen production
  - Space propulsion
- It is important to note that these opportunities should not be pursued at the expense of existing programs, in light of the many significant budget cuts the fusion program has seen lately, particularly in the area of technology

Findings: Near-Term Applications

The use of fusion reactions to provide relatively inexpensive PET isotopes in low population density areas for the diagnosis of cancers and other abnormalities can be a big help in keeping related Medicaid and Medicare health care costs down. Small quantities of PET isotopes have already been produced in low Q fusion devices and future scale up of existing facilities could have impact in a 5-10 year time frame. A modest plasma physics effort will be required to increase the current PET isotope production rate to a commercially competitive level.

Findings: Near-Term Applications (con't)

The production of neutrons from DD reactions in small portable fusion devices can contribute to the nation's Homeland Security mission. The detection of clandestine materials (explosives, chemical and biological weapons, drugs, etc.) is of vital importance to our national security and is an area where existing low Q fusion devices are already at the proof of principle stage. Scale up and miniaturization could be achieved by modest investments in plasma physics research.

Recommendations: Near-Term Applications

The DOE-OFES should identify a small, but steady, source of funding to specifically look at applications that are not related to electricity production. This should not be done at the expense of existing programs, but rather could be accomplished by an SBIR-like process that includes opportunities for universities, industry, and national laboratories.

Findings: Transmutation

There are a number of important neutron transmutation missions (destruction of long-lived radioisotopes in spent nuclear fuel, ‘disposal’ of surplus weapons grade plutonium, ‘breeding’ of fissile nuclear fuel) that perhaps can be best performed in sub-critical nuclear reactors driven by a neutron source. The physics requirements on a fusion neutron source for such transmutation missions are less demanding than for commercial electrical power production. A tokamak fusion neutron source based on the current physics and technology database (ITER design base) would meet most of the needs of the transmutation mission; however, achieving the availability needs would require advances in component reliability and quasi steady-state physics operation.

Recommendations: Transmutation

DOE-NE currently has a program to look at spent fuel recycling, including transmutation with fission reactors. DOE-OFES should establish a 'watching brief' of these fuel cycle activities to guide any future expansion of the existing fusion transmutation of waste program. Such an expansion of the small ongoing systems/conceptual design investigation of the application of fusion to the transmutation mission is a necessary first step for evaluating the possibility of incorporating a transmutation mission into the OFES program.

Recommendations: Transmutation (con't)

Evaluation of the competitiveness of sub-critical reactors driven by fusion neutron sources for the destruction of long-lived radioisotopes in spent nuclear fuel and identification of the required R&D would be the first objective of these studies. These investigations should initially be based on the most developed tokamak confinement concept (using the ITER physics and technology databases) and on adaptation of the reactor technology being investigated/developed in the nuclear program.

Findings: Hydrogen Production

From the design and evaluation studies done over the past 30 years, fusion could provide a long-term source of hydrogen by low temperature electrolysis, high temperature electrolysis or thermochemical water-splitting. Hydrogen production by low temperature electrolysis would have no impact on the fusion power plant, and in fact, could be done remotely for distributed production of hydrogen where it is needed. The requirements on the fusion power plant are essentially identical with the requirements for commercial electric power production. A decision on which hydrogen process is best for fusion does not need to be made until that demonstration has been done. By that time, the development work currently underway on high temperature electrolysis and thermochemical water-splitting funded under other programs will have provided a firmer basis for comparison and selection.

Recommendations: Hydrogen Production

The immediate need is to include production of hydrogen as a goal of the Fusion Program, and as an element in the fusion research planning. The Fusion Program should immediately become an active participant in the U.S. Interagency Hydrogen Research and Development Task Force. A small task should be established to review hydrogen production techniques and recommend technical areas, such as tritium control, that may need additional study. The progress on development of hydrogen production technologies in other programs should be monitored and the results incorporated into the understanding of and directions for fusion production of hydrogen. As in all aspects of fusion energy, the possibility of new discoveries for production of hydrogen with fusion should not be ignored.

Findings: Space Propulsion

Manned interplanetary space travel is one of the great uplifting dreams that enriches the spirit of humanity. It appears, from mass-thrust considerations, that fusion and anti-matter are the only conceivable bases for propulsion systems for manned or heavy payload deep-space missions. Because no confinement concept has yet been identified that could conceivably satisfy the requirements of such deep-space missions, the technical requirements are unknown, but they may be significantly different such that some technology/physics development areas may be more difficult than the required for terrestrial electrical power production while others may be relaxed.

Recommendations: Space Propulsion

The OFES program should be responsive to any NASA request for support in evaluating (and subsequently developing) space fusion propulsion systems. As a first step, we recommend that DOE contact NASA about establishing a joint task force (led by NASA) to evaluate at the conceptual level the feasibility of fusion for space propulsion.