Non-Electric Applications of Fusion

Final Report to FESAC, July 31, 2003

Executive Summary

This report examines the possibility of non-electric applications of fusion. In particular, FESAC was asked to consider "whether the Fusion Energy Sciences program should broaden its scope and activities to include non-electric applications of intermediate-term fusion devices." During this process, FESAC was asked 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 electricity?
- What steps should the program take to incorporate these opportunities into plans for fusion research?
- Are there any possible negative impacts to pursuing these opportunities and are there ways to mitigate these possible impacts?

The panel adopted the following three criteria to evaluate all of the non-electric applications considered:

1. Will the application be viewed as necessary to solve a "national problem" or will the application be viewed as a solution by the funding entity?

2. 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 and is it "on the path" to electricity production?

3. What is the competition for this application, and what is the likelihood that fusion can beat it?

It is the opinion of this panel that the most promising opportunities for non-electric applications of fusion fall into four categories:

1. Near-Term Applications
2. Transmutation
3. Hydrogen Production
4. Space Propulsion

The order that these are presented in is not meant in any way to imply priority. Based on the information available to the panel, and presented in this report, the panel makes the following recommendations. It is important to note that these opportunities should not be pursued at the expense of existing programs, particularly since the fusion program has seen many significant budget cuts, particularly in the area of technology.

NEAR-TERM APPLICATIONS

Findings

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.

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

The DOE-OFES should identify a small, but steady, source of funding to specifically look at near-term 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.

TRANSMUTATION

Findings

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

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. 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.

HYDROGEN PRODUCTION

Findings

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 does not need to be made on which process appears best for fusion until that demonstration has been done. By this time, the development work currently underway on high temperature electrolysis and thermochemical water-splitting under other programs will have provided a firmer basis for comparison and selection.

Recommendations

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 fusion production of hydrogen should not be ignored.

SPACE PROPULSION

Findings

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 antimatter are the only conceivable bases for propulsion systems for heavy payload deep-space or manned missions. Because the fusion confinement concepts that have been approved for advanced space missions are not yet sufficiently developed to allow identification of the detailed technical requirements, the technical challenges of fusion propulsion for space are not known in detail. They may be significantly different such that some technology/physics development areas may be more difficult than those required for terrestrial electrical power production while others may be relaxed.

Recommendations

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.

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I. INTRODUCTION & BACKGROUND

This report examines the possibility of non-electric applications of fusion per the charge to FESAC from James F. Decker, then Acting Director of the Office of Science (see Appendix A). In particular, FESAC was asked to consider "whether the Fusion Energy Sciences program should broaden its scope and activities to include non-electric applications of intermediate-term fusion devices." During this process, FESAC was asked 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 electricity?
- What steps should the program take to incorporate these opportunities into plans for fusion research?
- Are there any possible negative impacts to pursuing these opportunities and are there ways to mitigate these possible impacts?

FESAC assembled a panel to carry out this study, the panel membership is listed in Appendix B. While the panel charge focuses on intermediate-term devices, the panel agreed it was important to expand the focus somewhat, and include nearer-term applications, as well as, applications that may not be economical or feasible until fusion electricity can be produced economically.

Historically, the primary focus of the U.S fusion program has been to address the need for electricity, seeking to develop fusion characteristics that might compete in the future electricity market. The May, 2001 report of the President's National Energy policy Group clearly indicated the need for a comprehensive national energy policy that could address a variety of national energy needs including alternative fuels and improved efficiency as well as electricity. For example, the NEPD Group recommended that the President direct the Secretary of Energy to:

- develop next-generation technology—including hydrogen and fusion
- develop an education campaign that communicates the benefits of alternative forms of energy, including hydrogen and fusion.
- focus research and development efforts on integrating current pro-grams regarding hydrogen, fuel cells, and distributed energy.

Fusion might contribute a non-electric product such as hydrogen fuel directly or indirectly by helping fission produce the same product, such as by using fusion to produce fissile fuel, or by transmuting nuclear waste of fission reactors that produce the product. There are non-energy applications of fusion as well as non-electric energy applications that are valuable to US industry or public health, such as production of valuable radioactive isotopes, for example. In some cases the pursuit of non-electric applications may require the same research for fusion configuration optimization and fusion technology as for electricity production, and in some cases not.

The traditional way of looking at what benefits fusion has to offer beyond electricity has been to point to the "spin-off" from plasma research and technology that has resulted from the construction of complex plasma experiments. Several Government summaries [1,2,3,] individual reviews [4,5,6], and even a recent conference [7] have addressed the indirect benefits of these spin-offs to society that result from funding the fusion program. These benefits are real and impressive. However, essentially all of these commercial products come from non-fusion plasmas or equipment not specifically designed to handle fusion plasmas. The use of plasmas to provide UV to dry printed material, the use of RF generated plasmas to generate light for home use, and the use of RF generated plasmas for etching are only a few examples of commercial products that do not require an actual fusion event, just energetic ions (usually protons) or electrons. It can be convincingly argued that people are happy to accept the benefits that come from this research, but the fusion program is not funded to generate "spin-off", but rather to produce fusion energy in the long run. Therefore, this report will concentrate on only those products that come from fusing plasmas.

Since finite resources for fusion research might result in trade-offs of fusion research between electric and non-electric applications, evaluation of non-electric applications have to include not only feasibility, but also how their pursuit might change the technical direction of the fusion program away from the traditional ones needed for electricity. Such changes to the ongoing fusion program, if required for pursuit of any non-electric applications, would clearly have to be justified in terms of the classical metrics of ***cost, risk, and benefit***. The panel therefore adopted the following three criteria to evaluate all of the non-electric applications considered:

1. Will the application be viewed as necessary to solve a "national problem" or will the application be viewed as a solution by the funding entity?

2. 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 and is it "on the path" to electricity production? For example, what are the requirements for:

- Q
- Power density
- Pulse length/efficient current drive
- Availability/reliability/maintainability
- Tolerable disruption frequency
- Tritium breeding, handling, and processing
- Materials
- Thermal efficiency/high temperature operation
- Economic operation

- Schedule to initial commercial operation

3. What is the competition for this application, and what is the likelihood that fusion can beat it?

The first evaluation criterion is used to judge the magnitude of potential ***benefit*** of the fusion application that could justify the cost of its development by the funding agency-in most cases by DOE, but in some cases, by private industry (e.g., for isotope production). The second criterion is used to judge the technical ***risk*** of developing the non-electric application relative to that of electric production. The third criterion is used to judge the likelihood that the non-electric fusion product will be competitive with other methods of production.

In the following four sections, four categories of non-electric applications are discussed, including comparison to the evaluation criteria. These categories are:

1. Near-Term Applications
2. Transmutation
3. Hydrogen Production
4. Space Propulsion

The panel recommendations are summarized in Section VI.

II. NEAR-TERM APPLICATIONS

The long-range goal of fusion research around the world is to provide safe, clean, and affordable electrical energy for society. However, the estimates for commercial electricity from fusion power are in the middle of the 21st century.[8] What can be done with fusion to benefit society in the near term (next 5 to 10 years), before more fusion energy is produced than invested in the process?

To answer the question posed above, one first has to take stock of what fusion reactions have to offer, that when applied to other raw materials could result in a "value added" product. Furthermore, if one wants to have real commercial products in the next 5-10 years then it is probable that the engineering Q of the fusion device (that is, the net electrical energy out divided by the sum of all electricity invested in the generation of the fusion energy) will be less than one ($Q_{engr}<1$.) One might even go so far as to say that a fusion device capable of delivering a commercial product in the next 5-10 years need not be on the direct path to an economically competitive electric fusion power plant. It is possible that some forms of fusion can benefit society without ever producing electricity.

Still another way to pose the question above is "Can one make a product using fusion reactions that has more economic value than the amortized capital and operating cost of the facility?" Recent research into this question has revealed some positive answers in several areas. The purpose of this chapter is to briefly discuss a few possible near term applications and to suggest a mechanism by which those applications could be brought to the marketplace.

There are at least 5 unique products that we can "sell" from fusion reactions before the fusion community enters the main market for fusion energy (the generation of electricity):

A.) high energy neutrons (2-14 MeV)
B.) thermal neutrons
C.) high energy protons (3-15 MeV)
D.) electromagnetic radiation (microwave to x-rays to γ rays).
E.) high energy electrons coupled with photons to provide ultra high heat fluxes

To gain an appreciation for the amount of particles that can be produced per watt of fusion power, Table 1 lists the conversion values for the 5 most promising fusion reactions. Of course, the exact values depend on the plasma temperature and the confinement method (e. g., a Maxwellian plasma in Tokamaks or a peaked energy distribution in an electrostatic device). Where necessary, the optimum "temperature" (kinetic energy) for various confinement approaches was used to calculate the values in Table 1.

Table 1

The Amount of Fusion Reaction Products Emitted/s Per Watt of Fusion Power

(Including Major Side Reactions)

Reaction	Neutrons (MeV)	Protons (MeV)	^{4}Helium (MeV)
DT	3.6×10^{11}(14.1)	--	3.6×10^{11} (3.52)
DD	8.6×10^{11} (2.45)	p-8.6×10^{11} (3.02) T-8.6×10^{11} (1.01)	^{3}He-8.6×10^{11} (0.82)
D^{3}He	2.3×10^{10} (2.45)	3.5×10^{11} (3.01 and 14.7)	3.6×10^{11} (3.67)
^{3}He^{3}He	--	9.7×10^{11}(≈5.7)	4.9×10^{11} (1.4)
p^{11}B	--	--	2.2×10^{12} (2.9)

High energy neutrons can be very useful for the following processes:

i.) production of radioisotopes (for medical applications and research)
ii.) detection of specific elements or isotopes in complex environments
iii.) radiotherapy
iv.) alteration of the electrical, optical, or mechanical properties of solids
v.) destruction of long-lived radioactive waste

Low energy neutrons can be very useful for the following processes:

i.) production of radioisotopes (for medical applications and research)
ii.) detection of specific elements or isotopes in complex environments
iii.) destruction of long-lived radioactive waste
iv.) production of tritium for military and civilian applications
v.) production of fissile material
vi.) destruction of fissile material for nuclear warheads
vii.) production of radioisotopes for portable □ray sources

High energy protons can be used for the following processes:

i.) production of radioisotopes (for medical applications and research)
ii.) detection of specific elements or isotopes in complex environments
iii.) destruction of long-lived radioactive waste

Electromagnetic Radiation (ER) can be used for:

- i.) food sterilization
- ii.) equipment sterilization
- iii.) pulsed x-ray sources

Ultra high heat fluxes from fusion grade plasmas, sometimes called a "Fusion Torch" [9] can be used for:

- i.) ionizing waste materials and separating elements
    - a.) municipal and medical wastes
    - b.) spent reactor fuel elements
    - c.) chemical weapons
    - d.) extractive metallurgy
- ii.) production of sources of intense radiation to treat industrial, medical, and municipal wastes

The production of RF radiation and x-rays using electricity is quite well established because of the high efficiency with which electricity can be converted into these products. Therefore, if there is an application for fusion in the ER area it would most likely be as a source of gamma rays.

A complete discussion of all of the above applications is beyond the scope of this chapter. Therefore, only a few selected examples will be used here to illustrate the concept of using fusion reaction products for commercial products and the reader is referred to references [10,11,12,13,14] for more information.

DETECTION OF EXPLOSIVES

With the increase in terrorist activity around the world, the continuation of local insurgencies, and all-out warfare in some countries, it has become even more important to have a reliable, efficient, and economical way to detect explosives. The detection of explosive devices aboard airplanes, in subways, and other public transportation vehicles would help to insure the safety of the civilian population. Unfortunately, the low atomic numbers of the elements that make up explosive devices (C, N, O) are not readily detectable by conventional x-ray techniques and more sophisticated means are required. Fortunately, these elements have unique responses to neutrons and the explosives can be detected even though buried in suitcases, packages, or shipping containers. The level of a neutron source required to detect explosives ranges from 5×10^{11} (DD) to 10^{12} (DT) n/s. These neutron sources should be available from <1 Watt of DD fusion power or ≈ 3 Watts of DT fusion power (see Table 1).

Perhaps one of the most humanitarian applications of explosive identification is in the detection of land mines, many of which now contain no metallic components. The magnitude of the problem was illustrated in a paper by Molander[15] that made the following observations:

- Every month, approximately 800 people are killed and 1,000's are injured by land mines
- An estimated 100,000,000 land mines are now buried in 60 countries
- Every year, 2,000,000 new mines (costing ≈ $5 each) are "planted"
- Every year, only 100,000 mines are cleared at an average cost of ≈ $1,000 per mine
- The Red Cross estimates that in Cambodia, 1 person in 235 has had a limb amputated, mostly from mine blasts
- In Afghanistan, nearly 1/4 of the mine casualties are children
- In Libya, 27% of the arable land remains covered by mine-fields dating back to WW II

If small, portable DD or DT fusion neutron devices could be developed with Q values (Energy out/Energy in) of >0.1%, power sources of <1 kW might be used in the field to rid the world of this hazard to the civilian population.

PRODUCTION OF RADIOISOTOPES

Radioisotopes have been used in medicine for over 30 years. Over 30 million critical medical procedures using isotopes are currently carried out every year [16]. Nuclear diagnostics has had an important role in the identification and management of:

- Heart disease,
- Brain disorders,
- Lung and kidney functions, and
- A broad range of cancers.

Within the nuclear diagnostic community, PET (Positron Emission Tomography) has become a major diagnostic of cancers. There are now over 60 PET research and 20 PET distribution centers in the U.S. There are also 180 PET centers worldwide and they represent a $100 M market. The market in 2000 was growing at ≈ 15% per year.

PET analysis has detected unsuspected metastases not seen by Computed Tomography, MRI, and Ultra Sound in 15-30% of patients. In addition, the altered surgical procedures possible because of the PET analyses have produced $5,000-30,000 savings per patient. The demand for PET procedures has recently increased because on January 1, 1998, Medicare in the United States started reimbursing medical organizations for certain PET applications (≈$2,000 for FDG-PET procedures) [17]. Very recently (April 16th, 2003) the Health and Human Services Department (which houses Medicare and Medicaid) has decreed that ^{13}N PET scans for myocardial perfusion will be reimbursed.

Positron Emission Tomography is a 3D method to detect and image abnormalities, such as tumors and cancers inside the body. The PET technique relies on the fact that some abnormalities have an affinity for specific compounds. If those compounds contain a PET isotope, the radioactive isotopes will cluster around the abnormality.

PET analysis uses the fact that when a positron (^{+}e) combines with an electron (^{-}e), they emit two 0.511 MeV gamma rays in opposite directions. Special rotating cameras can spatially and temporally resolve where the gammas originated, thus defining the abnormality.
Currently, the best nuclear imaging agent for PET is ^{18}F-fluorodeoxyglucose (FDG). Cancer cells lose the ability to efficiently convert glucose into energy and they require 20-50 times more glucose than normal cells. Thus cancers become glucose "magnets". The trick is to attach a radioactive isotope (^{18}F with a half life of 110 minutes) to the glucose so that the location of the glucose "magnet" can be identified by the emission of the 0.511 MeV gammas when the positrons from the ^{18}F and background electrons recombine.

The most common method of producing PET isotopes today such as ^{18}F is with accelerators via (p, n) or (p, □) reactions. An example[18] of the ^{18}O(p,n)^{18}F cross-section is shown in Figure 1. It is apparent that proton energies of ≈ 10 MeV or greater are needed to maximize the production of ^{18}F.

Cyclotrons or linacs that produce protons at 10 MeV or greater are large and costly. It would be desirable to have smaller, less expensive high-energy proton generators that could be placed nearer to the patent or in small remote communities where the demand is not enough for a large accelerator.

Quite often physicians would like an even shorter half-life PET isotope than ^{18}F to avoid irradiation of the patent long after the diagnostic procedure is completed (it takes ≈ 10 half lives, or 18 hours for ^{18}F to "disappear"). Half-lives in the 1- to 10-minute range would expose more sensitive patents (pregnant women and children) to less of an "unnecessary" dose. A few of these useful PET isotopes are listed in Table 2.

The drawback with the very short half-life PET isotopes is that it takes time to isolate and transport the isotopes from their production point to the patient. This again points out a need for a portable source of short half-life PET isotopes or an inexpensive, portable source of 10-15 MeV protons to make the isotopes.

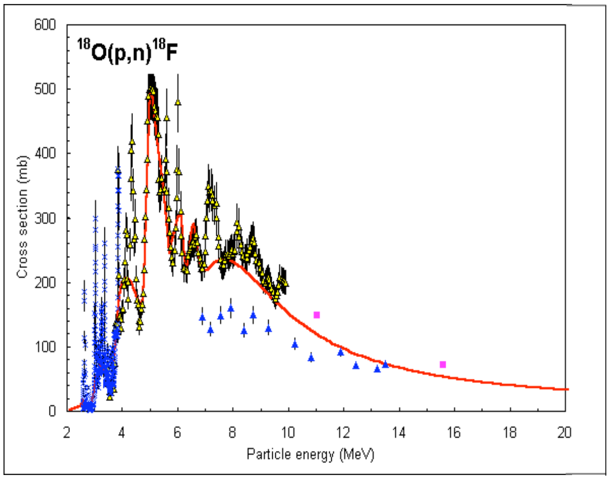


Figure 1. The nuclear cross-section for the production of ^{18}F from ^{18}O requires protons of greater than 10 MeV [13].

Table 2.

There are several potentially useful very short half-life PET isotopes that can be made with energetic protons**.**

Parent Isotope	Production Reaction	PET Isotope	Half-Life Minutes
^{18}O	(p, n)	^{18}F	110
^{94}Mo	(p, n)	^{94m}Tc	52
^{14}N	(p, α)	^{11}C	20
^{16}O ^{13}C	(p, α) (p, n)	^{13}N	10
^{15}N	(p, n)	^{15}O	2

Fortunately, one of the fusion products from a second-generation fusion fuel cycle (D-^{3}He) is a 14.7 MeV proton that can be used to make valuable short-lived PET isotopes. The reaction is listed below:

$$D + {}^{3}He \rightarrow p\ (14.7\ MeV) + {}^{4}He\ (3.7\ MeV) \qquad (1)$$

As can be seen from Figure 1, some PET isotopes are quite easily produced via (p,n) or (p, α) reactions above ≈ 5 MeV. Therefore, what is needed is a device in which controlled D-^{3}He fusion can be produced on a steady-state basis to provide a source of 14.7 MeV protons.

Normally, the D^{3}He reaction is not one that is easily initiated in “conventional” magnetic or inertial confinement devices because of the need for very high, ≈50 keV or more, ion energies. However, this second- generation fuel cycle can be readily produced in an Inertial Electrostatic Confinement (IEC) device of the type currently in operation at several locations in the U. S. and Japan[19,20]. A typical picture of a D^{3}He plasma in the cathode region of the chamber is shown in Figure 2.

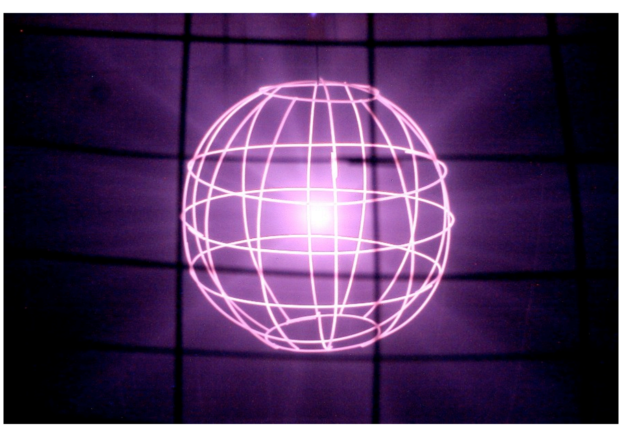


Figure 2. A typical D^{3}He plasma in an IEC fusion chamber. The cathode is 10 cm in diameter

The IEC chambers currently in operation routinely generate steady state DD and D^3He plasmas at approximately the 1 mW level. These devices have already produced small quantities of ^{94m}Tc isotopes by bombarding ^{94}Mo with protons from a D^3He reaction. The PET isotope ^{13}N has also been produced using the D^3He reaction. The current cost estimate of an IEC device designed to just produce PET isotopes is in the $50-100K level.

PRODUCTION OF ^{18}F

At the present time, more than 80% of the PET applications currently use the isotope ^{18}F(1.83 h). It is possible to use either n and p sources to produce ^{18}F. One interesting approach using neutrons has been proposed by Bayless [21] in which a heavy water moderated DT or DD neutron source is used to produce thermal neutron that can react with ^6Li in a Li_2CO_3 compound. The $^6Li(n,^4He)T$ reaction produces an energetic T ion (2.7 MeV) which in turn promotes the $^{16}O(T,n)^{18}F$ reaction. The ^{18}F can be chemically separated out and attached to a "carrier" molecule that transports it to the desired location in the body. Bayless has shown that 4 W DT fusion source can produce ^{18}F at a rate of 1 Ci/hr. The economics of this process must compete with 8-10 MeV proton accelerators that produce ≈ 1 Ci ^{18}F/hr at a capital investment of ≈2 million dollars.

Dawson [22] has proposed injecting certain isotopes into a D^3He plasma to make positron emitters from (p,n) reactions. Protons from the DD reaction (3.02 MeV) have enough energy to make ^{22}Na(2.6 y), ^{18}F(1.83 h), and ^{11}C(20.3 min). In addition, the protons from the $^3He^3He$ reaction (≈5.7 MeV) can make ^{13}N(9.97 min), ^{15}O(122 s), ^{17}F(64.5 s), ^{19}Ne(17.2 s), and ^{26m}Al(6.35 s). Finally, the 14.7 MeV protons from the D^3He reaction can easily make all of the above isotopes and it can be quite easily shielded for use in a populated area. It is found that D^3He power levels of ≈10 W (3.5 x 10^{12} p/s) can make enough isotopes for medical applications. Even Q values of 0.001 would easily allow such a device to be plugged into current medical and industrial electrical wiring systems.

THE PRODUCTION OF ^{99}MO, THE MEDICAL ISOTOPE OF CHOICE IN HOSPITALS

There are ≈38,000 medical diagnostic procedures involving radioisotopes performed each day in the United States and approximately 36,000 daily involve the isotope ^{99m}Tc ($t_{1/2}$ = 6 h) a decay product of ^{99}Mo [23]. By attaching the ^{99m}Tc to a selected carrier agent, it is possible to direct the isotope to a specific location in the body, e. g., the bones, brain, heart, kidneys, liver, lungs, or thyroid gland. By detection of the gamma ray emitted during decay of ^{99m}Tc, doctors can ascertain details about the conditions and functions of the body that could otherwise be obtained only by performing invasive surgery. The isotope of choice for most diagnostic procedures is ^{99m}Tc because its short half-life minimizes the radiation dose to the patient, because its gamma ray (140 keV) is easily detected, and because it can be combined with many different carriers to concentrate in different parts of the body.

The disadvantage of ^{99m}Tc is that its short half life requires a longer life "parent" that can be made elsewhere, transported to the location of the medical investigation, and then the "parent" must decay into the Tc isotope. In the case of ^{99m}Tc, the parent is ^{99}Mo ($t_{1/2}$=66 hr). The relatively short half-lives of the $^{99}Mo/^{99m}Tc$ pair makes these isotopes perishable and requires continuous production to insure a reliable supply.

The U. S. medical community currently uses 60% of the world's supply of $^{99}Mo/^{99m}Tc$ and is entirely dependent on foreign sources. The U. S. supply of ^{99}Mo is currently produced in essentially only one fission reactor in Canada. The ^{99}Mo is separated from the fission products resulting from ^{235}U breakup, stored on a resin column and shipped to hospitals and clinics in the U. S. and around the world. Once at the location where it will be used, the resin column is treated with saline solution to strip off the ^{99m}Tc that is, in turn, attached to a chemical molecule for injection into a patient (the ^{99}Mo itself is not injected into the patient). The ^{99m}Tc is transported to the critical organ and external counters detect the gamma rays emitted during the decay. Sophisticated electronics then can reconstruct the organ and its surroundings to provide the physicians with valuable diagnostic information.

The total U. S. usage of the $^{99}Mo/^{99m}Tc$ generator is ≈ 3,000-6 day Curies per week. A 6d Ci is the amount of ^{99}Mo remaining 6 days after its initial formation and is chosen to account for the time needed to separate the ^{99}Mo from other fission products, package it and send it to its ultimate usage point, e.g., a hospital. To calculate the initial number of Curies produced in an irradiation, the 6-d Ci value must be multiplied by 4.535. Therefore the amount of ^{99}Mo that needs to be made at the production site is ≈ 13,600 Ci/week.

There are at least 4 ways to make ^{99}Mo in nuclear facilities.

1) ^{235}U(n,f), the current Cintichem process
2) ^{238}U(p,f)
3) ^{100}Mo (n, 2n)^{99}Mo, ^{98}Mo(n,□)^{99}Mo
4) ^{100}Mo(p,2n)^{99m}Tc

RESPONSE TO EVALUATION CRITERIA

1. ***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?***

The economic and accurate diagnosis of cancer and other internal abnormalities is a major issue in the medical field. As the population in the U. S. ages, this issue will be of even more interest as Medicaid and Medicare resources are stretched to the limit in order to provide affordable health care service to the population at large. The use of fusion reactions to provide relatively inexpensive PET isotopes in low population density areas could be a big help in keeping health care costs down.

The detection of clandestine materials (explosives, chemical and biological weapons, drugs, etc.) is of vital importance to our national security. Methods that can identify these clandestine materials reliably and economically are needed as internal and external threats have increased over the past few years. The production of neutrons from DD reactions can contribute to Homeland Security especially in circumstances where small portable sources are required.

2. ***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?***

-Q-values of 10^{-4} to 10^{-3} should be sufficient
-Power density-NA
-Pulse/length/efficient current drive-Steady state is required for isotope production and both steady state and pulsed operation are used in the detection mode. Current drive is NA
-Availability/reliability/maintainability-The devices should have availabilities of>90% and they must be easily maintained. Current IEC devices already meet these criteria.
-Tolerable disruption frequency-NA
-Tritium breeding, handling, and processing-NA
-Thermal efficiency/high temperature operation-NA
-Economic operation-Unique aspects could capture a significant fraction of the PET and neutron interrogation markets
-Schedule to commercial operation-Within the next 5 years

*NA= Not Applicable

What R&D is required to meet these requirements and is it on the path to electricity production?

There are two major areas that R&D needs to be performed to allow isotope production from fusion to move into a commercially viable state:

1) Increased research on the D^3He fuel cycle (to produce the 14.5 MeV protons)
2) Increased understanding of low Q operation of IEC devices.

These need not be very expensive programs; equilibrium levels of $2-3 M/y for 5-10 years should be enough to get a definitive answer.

The R&D required for the production of neutrons for clandestine material detection is less than for isotope production. The field is already at the POP level (10^8 DD n's/s steady state which implies a 10^{10} DT n/s production rate). However, further reduction in chamber size is needed to break into an economic competitive environment. This research could involve both plasma physics and technology investigations.

3. What is the competition for this application and what is the likelihood that fusion can beat it?

The main competitor to the production of PET isotopes from fusion is a 10-15 MeV accelerator. These accelerators are costly (≈$2 M each) and bulky, but they currently work and set the price on the PET isotope market. If small, portable IEC devices can be developed at $50-100 k each, then there is a good chance that fusion could capture a large fraction of the market outside of metropolitan areas.

The main competitors to the generation of neutrons from fusion are spontaneous neutron emitters (i. e., ^{242}Cf) and accelerators. The energy needed for the accelerators is less than for the production of protons and therefore the cost advantage for DD IEC devices may be less. However, the portability of small IEC devices may be of great advantage for "field" work. The fact that fusion devices can be turned on and off reduces the shielding requirements compared to spontaneous neutron emitters.

SUMMARY AND RECOMMENDATIONS

There are several applications for small fusing plasmas that could immediately benefit society. The level of power required per device is in the neighborhood of 10's of Watts to 10's of kW. Such low power levels might be achievable in quite different confinement configurations such as inertial electrostatic devices, FRC's, or others not currently considered as lead candidates for power reactors currently because of their low Q characteristics.

Fusion devices need not be expensive (i. e., in the range of 100's of million dollars) to be interesting. Fusing plasmas at the levels quoted here should cost < 1 $M for the first device and when replicated 10 to 100 times, the cost may well fall to the 100 $k level. Positive public reaction could be generated by developing fusion devices to detect explosives, detect chemical pollution, and produce medical isotopes.

If meaningful near term civilian applications can be generated in the next 10-15 years, the community could use the "profits" (both financial and political) to step up to the next phase, i. e., applications of Q=1-5 devices that could compete in specialty niches.

Recommendations:

The DOE-OFES should identify a small, but steady, source of funding to specifically look at near-term 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.

Possible Negative Impacts:

Some of the applications could become classified or be associated with the military. On the one hand, this might be welcomed by the DOD/DOE but fusion might then be associated with defense instead of civilian applications. On the other hand, we have procedures in place to detect such a movement early and the community should be able to make sure that the benefits of this research are interpreted in a the context of public welfare.

III. TRANSMUTATION

There are potential applications of fusion neutron sources to 'drive' sub-critical fission reactors to perform one or more possible 'nuclear' missions. Since only a fraction of the neutrons in these applications would be fusion neutrons, the requirements (e.g. for the transmutation mission-- fusion power $P_{fus} \leq 250$ MW, fusion power density $\beta_N \leq 2.5$, 14 MeV neutron wall load $\Gamma_n < 1$ MW/m^2 and power amplification $Q_p \geq 2$) are modest relative to the requirements for pure fusion electrical power. A sub-critical, source-driven reactor almost certainly would be more expensive and initially would have lower availability than a conventional critical reactor, because of the additional cost and lower initial availability of the fusion or accelerator neutron source. In order to be competitive with a critical reactor for a given mission, a sub-critical reactor must introduce certain advantages that allow the mission to be carried out more efficiently, and there appear to be such advantages. Making use of ITER physics and technology, using ITER as a prototype, and adopting the reactor and processing technology being developed in the nuclear program could lead to a fusion-driven sub-critical reactor for the transmutation of spent nuclear fuel, fissile breeding or disposition of weapons-grade plutonium being on-line by 2040, as compared to the plans for putting critical and accelerator-driven sub-critical reactors on-line for such missions by 2030. All of the R&D needed to develop the fusion neutron source for such a facility is directly on the path to fusion power (in fact is needed for an electric power DEMO); and the operation of a fusion-driven sub-critical reactor could also serve the purposes envisioned for a 'volume neutron source', thus taking the place of such a device in the development path to fusion power.

NUCLEAR MISSIONS

<u>General</u>

There are several possible nuclear missions that could employ fusion neutron sources to drive sub-critical reactors, corresponding to the several scenarios for the future of nuclear energy being discussed within the nuclear community and the government. The transmutation (by neutron fission) of the plutonium and higher actinides in spent nuclear fuel (SNF) to reduce capacity requirements for high-level waste repositories (HLWRs) and, secondarily, to extract the remaining energy content from the SNF and 'dispose of' reactor-grade plutonium is a potential mission in all scenarios for the future of nuclear energy. In scenarios which foresee an increasing use of nuclear energy in the next half-century, the use of reactors fueled with the Pu and higher actinides from SNF for the transmutation (by neutron capture) of fertile U-238 into fissile Pu for fueling light water reactors (LWRs) is foreseen as a necessity. The SNF transmutation mission is less demanding in terms of fusion power (neutron source) level than is the Pu breeding mission, because of the lower multiplication factor of an optimized plutonium breeding reactor, but the other requirements on the fusion neutron source are similar. The 'disposition' of surplus weapons-grade plutonium by using it as reactor fuel provides an additional mission similar to the SNF transmutation mission.

Transmutation Mission[24,25,26,27,28,29]

Because it could be an important national mission under a range of scenarios for the future of nuclear energy in the USA, the transmutation of SNF is chosen as representative of the possible nuclear missions for a sub-critical reactor driven by a fusion neutron source. The SNF inventory is usually given in terms of the metric tonnes of uranium (MTU) that was initially used to fabricate the fresh fuel. In the USA, the SNF inventory is estimated to be 47,000 MTU by the end of 2002, and the current rate of production of the approximately 100 electric power reactors operating in the USA is > 2,000 MTU/year. The Yucca Mountain HLWR has a statutory limit of 70,000 metric tonnes of heavy metal, which includes 63,000 MTU of SNF. If the present level of nuclear power production continues into the near future, which seems likely, a new HLWR of the Yucca Mountain capacity 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 plutonium and the higher actinides. If the HLWR is not sealed for 100 or so years after the SNF is removed from a reactor, the Pu and actinide decay heat will determine the capacity of the HLWR.

Reprocessing of SNF from LWRs to separate: 1) the uranium that can be sent to a low level waste repository; 2) the Pu and higher actinides that can be made into fuel for recycling in 'transmutation' reactors; and 3) the fission products that can be sent to a HLWR would greatly reduce the amount of material sent to the HLWR. In principle, with repeated recycling and reprocessing steps 2 and 3, all of the plutonium and higher actinides can ultimately be fissioned, and only fission products will be sent to the HLWR. However, a practical limit is set by the efficiency with which the Pu and higher actinides can be separated from the fission products that are sent to the HLWR in each processing step. Separation efficiencies well above 99% are projected for both aqueous and pyrometallurgical separation processes, leading to detailed fuel cycle calculations that predict that (with repeated recycling) in excess of 99% of the Pu and higher actinides in SNF can be fissioned, which would reduce HLWR capacity requirements a hundred-fold. Even a 90% separation efficiency would lead to a ten-fold reduction in HLWR capacity requirement; e.g. a new HLWR every 300 years instead of every 30 years at the present level of nuclear power production. Moreover, by repeated recycling of the Pu and higher actinides in transmutation reactors, the energy extracted from the original LWR fuel can be increased by about 30% relative to the energy extracted in the 'once-through' cycle of the original fuel in a LWR.

Fissile Breeding and Plutonium Disposition Missions

The 'fissile breeding' and 'plutonium disposition' missions could be carried out as variants of the recycling/reprocessing scenario described above for the 'transmutation' mission. If the uranium separated from the SNF and the 'depleted' (in fissile U-235) uranium 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 plutonium which can be used as LWR fuel, in which case the 'transmutation' reactor would become a 'breeder' reactor. Of the potential energy content of the original uranium ore, 16.5% remains in the uranium in the discharged SNF and 82.7% remains in the depleted uranium residue from the original fuel enrichment, 0.2% remains in the plutonium and higher actinides in the discharged SNF, and 0.6% has been extracted by fission in one cycle of the fuel in a LWR. Recovering some significant fraction of this remaining potential energy content of the uranium ore is the motivation for the 'fissile breeding' mission.

If weapons-grade plutonium is blended in with the SNF plutonium and higher actinides and recycled repeatedly, the 'plutonium disposition' mission can be carried out as part of the 'transmutation' mission. This mission can also be carried out by blending the weapons-grade plutonium in LWR fuel.

TECHNICAL REQUIREMENTS

Requirements for a Fusion Neutron Source

Since most of the neutrons in a sub-critical transmutation reactor would be created by the fission process in the reactor, and the role of the fusion neutron source would be to provide a modest number of neutrons to maintain the neutron fission chain reaction, the requirements on fusion power level, power density and neutron and thermal wall loads is less demanding than for a pure fusion electric power reactor. Recent studies [30,31,32,33,34,35,36,3738]provide some indication of these requirements.

Tokamak Neutron Source Requirements

A tokamak neutron source for a sub-critical transmutation reactor could be designed using the existing physics and fusion technology databases that were used as the basis of the ITER design [36-38], with a few exceptions. Such a tokamak would be based on the ITER superconducting magnet, first-wall, divertor, heating-current drive, tritium, etc. systems, but would likely use a liquid metal coolant for compatibility with the transmutation reactor and a ferritic steel structural material of the type being developed for nuclear applications. The parameters of such a tokamak recently have been calculated to be about (R = 4.5m, a = 0.9m, □ = 1.8, I = 6 MA, B_o = 7.5 T, $H(y,2)$ = 1.0, $□_N$ □ 2.5, $□_{cd}$ = 0.03-0.04, f_{bs} = 0.2-0.4, $□_{cd}$ = 0.35 Amp/(Wm^2)x10^{-20}, Q_p □ 2, P_{fusion} □ 225 MW, $□_n$ < 1 MW/m^2, q_{FW} < 0.3 MW/m^2). If the superconducting magnet system is replaced by a liquid nitrogen cooled copper magnet system, the major radius and the fusion power are reduced to R □ 3.0 m and P_{fusion} □ 150 MW in a device with the same Q_p, but the electrical power amplification factor drops from $Q_e = 5$ to 1. A recent Russian study of a low aspect ratio tokamak neutron source with copper magnets has the parameters (R = 2m, a = 1m, □ = 1.7, I = 5.85-6.65 MA, Bo = 3.9 T, H(y,2) = 1.4, $□_N$ = 3-3.55, $□□_{cd}$ = 0.05-0.1, f_{bs} = 0.52-0.71, Q_p = 2.4, P_{fusion} = 72-80 MW, $□_n$ = 0.4-0.44 MW/m^2, q_{fw} = 0.31-0.34 MW/m^2). The principal advancement needed in the present physics database to realize such tokamak neutron sources is in the area of non-inductive current drive efficiency and/or bootstrap current enhancement to achieve quasi-steady state operation.

R&D Program for a Tokamak Neutron Source

The ongoing worldwide tokamak program is addressing the current-drive/bootstrap current/steady-state physics issue. Since the physics and technology design bases of a tokamak neutron source would be almost identical to those of ITER, the operation of ITER will provide the prototype test for a tokamak fusion neutron source. Issues related to disruptions and ELMS would be less severe for the neutron source than for ITER and presumably would be resolved by the time of ITER operation. In addition to ITER, a set of technology test facilities will be needed for the high performance testing required to develop the highly reliable components (magnets, first-wall, divertor, heating and current-drive, etc.) needed to obtain high availability operation of a tokamak neutron source; such facilities are also required before the construction of a fusion electric power DEMO. Thus, all of this R&D is directly on the development path for fusion power. Moreover, the operation of a fusion-driven sub-critical reactor could serve most, if not all, the purposes presently envisioned for a 'volume neutron source', thus serving also as one of the facilities presently envisioned to be needed for the development of fusion power.

Other Possible Fusion Neutron Sources

Although the tokamak is the only confinement concept for which the physics database is sufficiently advanced that it can be considered for a neutron source application at the present time, other confinement concepts (e.g. stellarator, spherical torus) are being developed which might have certain advantages relative to the tokamak as a fusion neutron source for the transmutation mission at some point in the future. The absence of disruptions and the natural steady-state operation characteristic of the stellarator and the higher power density and more compact geometry of the spherical torus are features that might ultimately make these concepts superior to the tokamak as a neutron source. However, since in terms of performance these concepts are presently at the stage reached by tokamaks 15-20 years ago, they should be considered as possibilities for a second generation of fusion neutron sources.

Reactor Technologies

In principle, the reactor (nuclear, materials, coolant, separation and processing) technologies that are being developed worldwide for use with critical reactors and with accelerator-driven sub-critical reactors also can be used with fusion-driven sub-critical reactors, with the additional requirement to include a lithium-containing material in or near the reactor for tritium breeding. The transmutation reactor technology that has received the most attention in the US nuclear community is a fast spectrum reactor with metal fuel, liquid metal coolant, ferritic steel structural material and pyrometallurgical separation and processing, although other reactor technologies are now being examined. Recent studies have shown that this technology can be adapted for a sub-critical reactor driven by a fusion neutron source either by including some solid lithium-containing material in the reactor or by using a PbLi coolant in order to breed tritium. The additional development of solid lithium-containing tritium breeding elements and/or of PbLi coolant should be accomplished as part of the ITER program, is directly on the path to the development of fusion power, and is needed before the construction of an electric power DEMO.

The use of molten salt reactor technology with a fusion neutron source also has received recent attention. Molten salt fuel offers the possibility of on-line reprocessing to remove fission products and to recycle 'fresh' actinides, which would reduce or eliminate the decrease in multiplication constant over the fuel cycle found in solid fuel reactors. Experience with an experimental molten salt power reactor was obtained in the 1960s, and R&D has been initiated recently in the nuclear energy and accelerator applications programs for transmutation applications and in the fusion program for fusion electrical power applications. The critical issues with using molten salts are solubility of actinides in the fluoride salts, separation of fission products from actinides, and corrosion control of molten salt with ferritic steels.

The use of long-lived silicon carbide fuel pellets in gas-cooled reactors is another technology that is receiving increased attention.

Fusion Proton Transmutation of Fission Products[39]

Some of the most radiologically troublesome fission products have small neutron cross sections, particularly for fast neutrons, which makes their transmutation into stable isotopes by neutron transmutation more problematical than for the actinides. The possibility of irradiating such fission products with the 15 MeV protons that are produced in D-^{3}He fusion has been investigated. Long-lived isotopes can be transmuted into much shorter lived isotopes by high energy proton capture: e.g. ^{129}I ($t_{1/2} > 10^7$ y) into ^{129}Xe ($t_{1/2} < 10^{-1}$ y); ^{135}Cs ($t_{1/2} > 10^6$ y) into ^{135}Ba ($t_{1/2} < 10^{-2}$ y); ^{93}Zr ($t_{1/2} > 10^6$ y) into ^{93}Nb ($t_{1/2} < 10^2$ y); ^{99}Tc ($t_{1/2} > 10^5$ y) into ^{99}Ru ($t_{1/2} < 10^{-3}$ y). Although the cross sections, hence the transmutation rates, are uncertain, fusion proton transmutation might offer a promising option for disposing of long-lived fission products.

INITIATION AND DURATION OF THE TRANSMUTATION MISSION

The Generation IV nuclear reactor planning activity envisions that the development of the processing technology should be sufficiently advanced by about 2020 that the detailed design of a critical fast transmutation or fissile breeder reactor and the associated processing/separation facility could be started, which would bring the system online in about 2030. The roadmap for developing sub-critical transmutation reactors driven by accelerator-spallation neutron sources also envisions such a reactor coming on line in about 2030. Thus, the implementation of a system of transmutation reactors and processing facilities could be initiated as early as about 2030.

The pacing items in bringing online a tokamak neutron source to drive a sub-critical transmutation reactor are the operation of ITER as a prototype and the operation of a set of technology test facilities required in order to develop component reliability. ITER is scheduled to operate from 2015 to 2035. Component test facilities could be upgraded (existing ITER R&D facilities?) or constructed to operate before and in parallel with ITER, so it would be plausible to begin detailed design of a tokamak neutron source in about 2025. Construction of a sub-critical reactor using the same fast reactor technology and a tokamak fusion neutron source could then begin as early as about 2030, leading to initial operation in about 2040.

The scenario for implementation of a system of transmutation reactors depends on the scenario for the future growth of nuclear power. Enough transmutation reactors would be built to fission the backlog of SNF residing in temporary storage and then to transmute SNF as it is discharged from LWRs. The initial transmutation reactors might be critical, and then sub-critical accelerator- and/or fusion-driven reactors might be phased in a decade or so later. These transmutation reactors also would produce a significant fraction of the electric power coming from the nuclear fleet of LWRs plus transmutation reactors (in a roughly 3/1 ratio). For example, in a recent study of a sub-critical ($k \approx 0.95$) fast reactor driven by the superconducting tokamak neutron source described above, the transmutation reactor produced a net 1800 MWe ($Q_e = 5.0$) and would support (transmute the SNF discharged from) several LWRs producing a total power of 4500 MW_e.

The duration of the transmutation mission will depend on the future of nuclear power. If nuclear power is phased out when the present reactors end their life, which is currently being extended many years by re-licensing, then the transmutation mission would be completed over roughly the last two-thirds of this century. In the more likely case that nuclear power production continues at the present level or increases over the century, the transmutation mission will continue indefinitely, in parallel with the introduction of purely fusion power plants in the latter half of the century.

COMPARISON OF FUSION WITH THE COMPETITION

The competition of fusion-driven sub-critical reactors for the transmutation mission are 1) critical fast spectrum nuclear reactors and 2) accelerator-driven sub-critical fast-spectrum reactors, both of which have been studied extensively for the transmutation mission.

<u>*Inherent Advantages of Sub-Critical Reactors Relative to Critical Reactors*</u>

The fundamental source of any advantage that a sub-critical reactor may have relative to a critical reactor will be associated with its larger reactivity margin of safety. When the neutron multiplication constant, k, exceeds $1+\beta$, where β is the delayed neutron fraction, the neutron population and fission heating will increase exponentially with a period of $T \approx \ell/(k-1-\beta)$, where the neutron lifetime is $\ell \approx 10^{-6}$ s in a fast spectrum reactor, a condition to be avoided or terminated immediately. The reactivity margin relative to this condition is $1+\beta-k_n$, where k_n is the multiplication constant under normal conditions. In a critical reactor ($k_n = 1.000$) the reactivity margin is just β. The necessity to design the reactor so that any off-normal condition does not increase k by more than β for more than a few periods (10-100 microseconds) imposes design constraints (e.g. to insure inherent, instantaneous negative reactivity changes in response to a fuel temperature increase) on the reactor, and these design constraints may in turn penalize the net actinide destruction rate (or Pu breeding rate). Because $\beta \approx 0.0065$ for U-235, 0.0022 for Pu-239, 0.0054 for Pu-241, etc., these design constraints will be more severe for reactors fueled with the Pu and higher actinides in SNF than for uranium fueled reactors.

When a reactor is operated sub-critical, the reactivity margin is much larger. For example, a SNF fueled reactor operating at $k_n = 0.95$ would have an order of magnitude larger reactivity margin of $0.05+\beta$ than the reactivity margin of β for a critical reactor. This larger reactivity margin would allow the use of reactor designs with larger concentrations of Pu and minor actinides (which would have smaller effective β), as well as other design innovations, that would not be advisable in a critical reactor.

Another advantage of sub-critical operation is the ability to compensate the reactivity decrease that occurs with fuel burnup by increasing the neutron source strength over the fuel cycle. This should reduce the excess beginning-of-cycle reactivity necessary to compensate fuel burnup, thus reducing the severity of possible reactivity insertion accidents, and/or allow longer burnup cycles between refueling intervals.

Disadvantages of Sub-Critical Reactors Relative to Critical Reactors

The principal sources of any disadvantages of a sub-critical reactor relative to a critical reactor will be the added cost and power consumption of the neutron source, the added complexity of the reactor configuration needed to accommodate the neutron source, the introduction of thermal and mechanical stress transients in the reactor due to beam trips in accelerators or disruptions in tokamaks, and the initial lower reliability, hence availability, of the neutron source than of the reactor. There may also be secondary disadvantages associated with enhanced power peaking at the reactor-source interface, the more complex dynamics and control of the coupled source-reactor system, etc.

Comparison of Fusion and Accelerator-Spallation Neutron Sources

The geometry of a reactor with an accelerator-spallation neutron source consists of one or more very localized targets and beam ports embedded within a more-or-less conventional cylindrical reactor configuration. The localization of the neutron source will lead to very significant problems of heat removal and neutron damage to materials within the target and to a relatively small volume around the target in which the source neutrons are deposited. This last problem can be mitigated by switching the beam among several targets, but the heat removal and neutron damage problems will remain formidable.

In sharp contrast to the accelerator-spallation neutron source, the fusion neutron source is distributed, and the source neutrons will be deposited over a large volume. Heat removal requirements and radiation damage within the neutron source will be much more modest than for the accelerator-spallation neutron source. On the other hand, the geometry of the fusion neutron source will impose a non-conventional reactor geometry.

RESPONSE TO EVALUATION CRITERIA

1. ***Will the application be viewed as necessary to solve a "national problem" or will the application be viewed as a solution by the funding entity?***

The weapons Pu disposition mission is widely recognized as a national problem and is funded as such by the government, but this can and is being done in critical reactors, and the opportunity for fusion to contribute is small because of the immediate time scale. The transmutation mission, which may be viewed as a reactor grade plutonium disposal mission as well as a high-level waste repository requirements reduction mission, is widely recognized world-wide as solving a "national problem" and there is substantial R&D support for this mission, but the urgency felt by governments to implement a transmutation solution is not so great as for the weapons Pu disposal mission. The transmutation mission is longer term and continuing, and there appear to be some advantages to using sub-critical reactors, which would provide an opening for a fusion contribution. The plutonium breeding mission will become urgent only if the need to rely on nuclear power for expanded electrical power production is recognized as national policy, which is not yet the case.

2. ***What are the technical requirements on fusion imposed by this application with respect to the present state of fusion and to the technical requirements imposed by electricity production?***

The requirements on β, confinement, energy amplification Q_p, and fusion power level are at or below the ITER level, which is much less than the level required for commercial fusion electricity production.

The requirements on availability are more difficult to simply quantify. Availability determines the annual transmutation rate of a given reactor, hence the number of transmutation reactors needed to service the LWR fleet and their total cost. However, the transmutation mission is to destroy long-lived HLW in order to eliminate the need to build a new HLWR repository every 30 years (at present level of nuclear power production) or less (at increased level), which would have a great sociological/psychological impact on the acceptance of expanded use of nuclear power. Given this broader impact, the paramount issue may be technical feasibility, not economic competitiveness.

There is general, but not unanimous, agreement among people who have worked on the problem that sub-critical transmutation reactors will be needed to effectively accomplish the transmutation mission, because of safety constraints imposed on critical transmutation reactors by the small delayed neutron fraction of Pu and the higher actinides and by the absence of U-238 resonance absorption. If the fission reactor people are able to develop solutions to these safety issues that do not significantly penalize the net transmutation rate per unit power, then economic competitiveness (which depends on availability) will be the paramount issue regarding the use of fusion-driven sub-critical transmutation reactors. On the other hand, if it turns out that sub-critical reactors are necessary to effectively accomplish the transmutation mission, then the technical feasibility of a neutron source with good enough availability to eliminate the need for building any further HLWR repositories after Yucca Mountain would be the paramount consideration. Sub-critical reactors driven by tokamak fusion neutron sources based on ITER physics and technology and achieving about 50% availability would accomplish this transmutation mission.

If accelerator-spallation neutron sources are able to overcome the more demanding heat removal and radiation damage challenges and become technically feasible, then the economic competitiveness of fusion with accelerator neutron sources will become an issue for sub-critical reactors.

In summary, there is a possibility that an availability of about 50% may be acceptable for a fusion neutron source for the first generation of sub-critical transmutation reactors. By comparison, electric power producing fusion reactors must compete economically with existing means of producing electricity that have high availability (e.g. nuclear reactors routinely achieve more 90% availability).

Physics Requirements for a Tokamak Neutron Source for Transmutation and for an Economically Competitive Fusion Electric Power Tokamak Reactor

Parameter	Transmutation	Electric Power
Confinement H(y,2)	1.0	1.5-2.0
Beta β_N	< 2.5	> 5.0
Power Amplification Qp	< 2	≥ 50
Bootstrap Current Fraction f_{bs}	0.2-0.4	0.9
Neutron wall load (MW/m^2)	< 1.0	> 4.0
Fusion Power (MW)	$\approx$ 200	3000
Availability (%)	≥ 50	90

What R&D is required to meet these requirements and is it on the path to electricity production?

A tokamak fusion neutron source for the transmutation mission could be designed today using the ITER physics and technology design database, and ITER would serve as a prototype for such a neutron source. Additional physics R&D is required to achieve quasi-steady state operation, and additional technology R&D is required to achieve high component reliability, in order to achieve $\approx$ 50% availability for the first neutron source. Tritium breeding blanket R&D is required. All of this R&D is exactly the same as would be required for an electrical power fusion DEMO.

3. ***What is the competition for this application and what is the likelihood that fusion can beat it?***

The principle competition for the transmutation mission (and all nuclear missions) are critical fission reactors. However, a sub-critical reactor may have some safety-related advantages for the transmutation mission, which provides an opportunity for fusion and accelerator neutron sources to contribute. Because the fusion neutron source is distributed, whereas the accelerator neutron source is highly localized, the fusion neutron source may have some advantages with respect to component failure rates due to radiation damage and heat fluxes that must be handled.

SUMMARY AND RECOMMENDATIONS

The transmutation mission can be carried out with a tokamak fusion neutron source based on physics (H, β_N, Q_p, etc.) similar to or less demanding than that used for the ITER design, so the R&D program supporting ITER and electrical power development will suffice for a transmutation neutron source in most physics areas. However, the transmutation neutron source would need to achieve a higher bootstrap current fraction and/or higher current drive efficiency and to achieve quasi-steady state operation in order to achieve higher availability than ITER. These issues must be addressed prior to the DEMO in the electrical power development path, but would require earlier priority in a physics R&D program for the transmutation mission.

The transmutation fusion neutron source can be constructed with the fusion technology being developed for ITER, for the most part, so the technology R&D supporting ITER will also support the fusion neutron source. However, the fusion neutron source will need to achieve greater availability, hence have greater component reliability, than ITER. The issue of component reliability, which will require various component test facilities, must be addressed prior to the DEMO in the electric power development path, but would require earlier priority in a technology development program to support the transmutation mission.

The reactor technology for the sub-critical reactor driven by the fusion neutron source should logically be adapted from one of the reactor (nuclear, fuel, cooling, processing, materials) technologies being investigated in the nuclear program (e.g. those being considered in the Generation–IV and other such studies), but these technologies must modified to provide for the tritium breeding requirement. A fusion nuclear technology program would have to be re-established with this goal. There is a need to development a long-lived structural material, primarily for the fuel assemblies of the sub-critical reactor but also for the first wall of the fusion neutron source, but it may be possible to build the initial transmutation fusion neutron sources with austenitic stainless steel first walls.

Expansion of the small ongoing systems/conceptual design investigation of the application of fusion to the transmutation (nuclear) mission is a necessary first step for incorporating the possibility of a transmutation (nuclear) mission into the OFES program. Evaluation of the competitiveness of sub-critical reactors driven by fusion neutron sources for the transmutation of SNF and of the required R&D would be the objectives 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 an adaptation of the reactor technology being investigated/developed in the nuclear program.

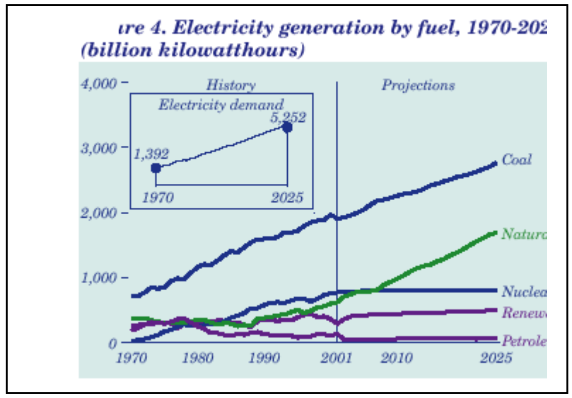
Recommendations:

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. 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.

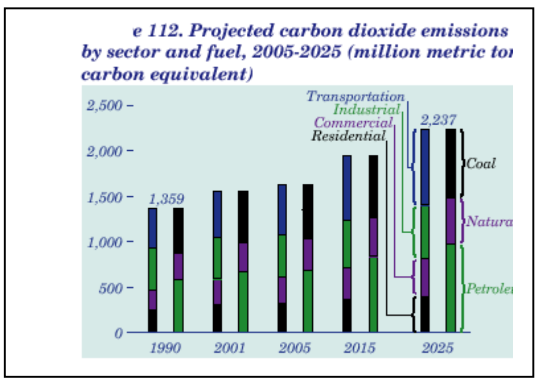
Possible Negative Impacts:

Sub-critical driven reactors driven by accelerators are the primary competition for this application. These systems are generally viewed as extremely expensive, and DOE-NE is exploring whether these systems are necessary. Unless fusion is shown to be less expensive than these systems, there is the possibility that this will contribute to the belief that fusion is an expensive source of energy.

IV. HYDROGEN



The United States is using energy at steady increase. The figure to the right illustrates the expected increasing demand for electricity in the US as predicted by the 2003 Annual Energy Outlook 2003[40]. This predicted increase is expected to be supplied by coal at a steady increase and natural gas at an even higher rate of increase. Nuclear, renewables and petroleum are predicted to have no or little increase. Total energy consumption also is predicted to have a similar increase with coal and natural gas supplying the growing difference. Nuclear and hydro remain at a constant capacity, while non-hydro renewables increase at a low rate. Therefore, the main source of energy will likely remain fossil-based in the near term. Absent any dramatic changes in energy source availability, this situation could continue into the timescale on which fusion energy might be available.



This continued dependence on fossil energy sources highlights the problem of greenhouse gases, primarily production of CO_2 from burning hydrocarbon fuels. The attached figure from Ref 1 shows a predicted steady CO_2 increase of approximately 1-2% annually per sector. In 2001, electricity production accounted for 39% of the carbon dioxide emissions. There are only two solutions. One is to remove the CO_2 from the exhaust stream and sequester it or use it. This can be done, at a cost, at stationary plants, such as electrical generating plants. Capturing the CO_2 is not feasible for transportation system users. The second solution to the CO_2 problem is to convert to a hydrogen economy. Burning H_2 creates only energy and H_2O*. This is feasible for both stationary and mobile users. Today, hydrogen is derived mainly from natural gas; gasification of coal is also used, however it is more expensive than production from natural gas.[41] In fact, it can be expected that fossil fuels will continue to be the major source of hydrogen. However, when the cost of CO_2 sequestration is added to the price, hydrogen produced by other energy sources becomes competitive. Generation with a renewable energy source would be attractive where cheap resources exist. Fission is a good alternative if the public perception and safety issues are resolved as discussed in the fission Generation IV Roadmap[42]. From a very long-

* At combustion temperatures above 4000° Fahrenheit, nitrogen dioxide is also created in small quantities due to the nitrogen content of atmospheric air. This can be avoided by controlling the combustion temperature to be below the 4000°F threshold. There are many standard ways to accomplish this.)

term environmental perspective, fusion would be ideal when the remaining fusion issues are resolved and reasonable plant availability and economics can be validated.

UNIT SIZE

One technical challenge for fusion is the predicted high capital cost for the plant and plant equipment that is reflected in the unit cost of power (electrical or some other form). The unit cost of power is determined directly by the cost (capital and operating) and inversely by the performance factors (fusion power capture, energy conversion efficiency, recirculating power, availability). The present fusion development concentrates on improving the fusion power capture, with little or no effort on the energy conversion efficiency, recirculating power, and availability. The efforts to decrease the costs of a commercial plant are more distant, but the importance is fully appreciated. One global approach that would reduce the capital and operating cost of the plant is to increase the size of the plant. Some plant costs do not scale linearly with the size of the plant, hence as the plant size increases, the unit power costs decrease, reflecting an "economy of scale".

Historically, conceptual electric-producing fusion power plants have been sized in the neighborhood of 1000 MWe or 2000 – 3000 MWth, primarily to compare to existing fission power plants. Also, this size plant (and up to 1400 MWe) is compatible with existing utility systems and grid interfaces. There is a strong desire to decrease the electric plant size down to the several hundred MW size because of the reduced plant capital cost and an unanticipated removal of a smaller production unit from the power grid will have reduced consequences. When the size of a plant is reduced to several hundred MWe, the economy of scale factor significantly increases the unit power cost and the cost of electricity, thus the small fusion plant becomes less attractive.

On the other hand, larger plants benefit from the economy of scale. As the power output increases to larger sizes, the unit cost of power decreases. Certain applications can effectively use the larger size power plants, namely electrical power parks and hydrogen production facilities. Sheffield analyzed the effect of larger plant size in a recent study[43] of the deployment of large fusion power plants. This study concluded that electrical plant sizes up to 3 GWe could be accommodated by larger utilities at a moderate cost and grid impact.

The production of hydrogen is best characterized as a chemical production facility. The plant size can be quite large, 4 GW or larger, depending on the market served. The larger hydrogen production plant size is amenable to capital-intensive fusion plants. The high-quality fusion process heat improves the process efficiency to lower the unit product cost.

Presently, both magnetic fusion energy (MFE) and inertial fusion energy (IFE) are viable candidates for commercial power production. The ARIES (Advanced Reactor Innovation and Evaluation Studies) group is chartered by DOE to *"Perform advanced integrated design studies of the long-term fusion energy embodiments to identify key R&D directions and to provide visions for the fusion program."* This group has and continues to evaluate both MFE and IFE confinement approaches, mainly for electrical generation, as this is the primary DOE research direction. Both confinement approaches have been studied for hydrogen production. The Sheffield study[42] is a recent MFE conceptual design study to produce hydrogen and low cost electricity. Logan[44], et. al., examined hydrogen and low-cost electrical production using multiple IFE target chambers with shared driver and target production facilities. Forsberg and Pickard[45] provide a good summary of hydrogen production with fission, the lessons from which are almost directly applicable to fusion.

One finding from the recent ARIES studies bears directly on the commercial viability of producing either or both electricity or hydrogen. Neither electricity nor hydrogen can be efficiently produced unless the process heat is high quality, that is, at a high temperature of 1000°C or better. The ARIES project has long recognized this factor and, over the past decade, has been steadily designing and evaluating fusion blankets with increasingly higher operating temperatures and thermal conversion efficiencies. The most recent ARIES-AT[6] design uses LiPb heat transfer media with an exit temperature of 1100°C that yields a thermal to electrical conversion efficiency of 59%. For both electricity and hydrogen production, there are stringent requirements on the tritium concentrations on the primary heat transfer flow stream (LiPb or some other suitable media) in conjunction with the use of intermediate heat exchangers to ensure that the tritium can be adequately controlled in the secondary flow stream to the prescribed safety levels. Of course, these conceptual designs have yet to be validated at a prototype level, but these designs and analyses illustrate that such blankets are technically feasible. Ultimately, these high temperature blankets and heat transfer systems will be necessary as a step on the pathway to competitive production of electricity or hydrogen by fusion energy.

HYDROGEN PRODUCTION PROCESS WITH A FUSION POWER PLANT

There are several methods that fusion can use to produce hydrogen or hydrogen-based fuels (synfuels). Generally the process is to generate electricity and use the electricity to produce hydrogen with an electrolyzer process or generate hydrogen directly with a thermochemical process. In the late 1980s, Bourque, Schultz, and the General Atomics staff collected, analyzed, and documented the products that could be produced with fusion. Their Fusion Applications and Market Evaluation (FAME) Study[46] addressed the production of synfuel and hydrogen as one of the potential products. This study provided summary details of several process options for hydrogen or synfuel production, which will be discussed below. The FAME study referenced several other papers [47,48,49.50,51,52,53]that provided process details that are also described below.

<u>*Radiolysis or Photolysis*</u> - Radiolysis uses neutron or secondary gamma ray energy to directly sever the H_2O chemical bonds into H_2 and O (or CO_2 into CO and O). With radiolysis, even the most energy efficient processes use less than 30% of the deposited energy. The reject energy must be utilized in a co-process or co-generation, so it is not a stand-alone process. Also, the reject heat must be in a high quality heat

(high temperature). The radiolysis process could be the decomposition of carbon dioxide into carbon monoxide as one step of a closed two-step thermochemical water splitting cycle, namely,

$$(2CO^2 + \text{Energy} \rightarrow 2CO + O_2, \text{ then } CO + H_2O \rightarrow CO_2 + H_2)$$

This process would produce a byproduct of radioactive ^{14}C. If the reject energy were used for generating additional hydrogen by normal low-temperature electrolysis, the estimated overall efficiency would be around 40%.

Thermal Spike Chemistry – This process uses high-energy neutron energy to create very energetic knock-on atoms to create microscopic regions of very high temperature where non-equilibrium chemical reactions can occur, producing chemical dissociation. These hot spots cool off so quickly that the reverse reactions cannot occur. The problem is that only around 5% of the neutron energy can be captured by the reacting medium.

Thermochemical or Thermochemical/Electrochemical – Several processes show potential to use the thermal energy carried by the neutron. Among these are water-splitting cycles with either pure thermochemical or thermochemical/electrochemical hybrid processes. The technical difficulty is in the complex chemistry and materials compatibility at the extremely high temperatures. GA[47-49], BNL[48], and LLNL[50] studied the high temperature electrolysis[48] and sulfur and iodine[47,49,50] processes to produce hydrogen in that time period. Normally the process operates around 900°C, but operation at elevated temperatures of 1200-1450°C would lead to an improved process efficiency and lower capital cost for a fixed production output. The GA[48] study estimated a process efficiency of 43% using fusion heat at 1250°C for 30% of the energy and at 450°C for the remaining 70%, with a hydrogen production cost 50-60% higher than gasoline or hydrogen from natural gas. LLNL[49] proposed a low temperature (600°C) design using electrical heating (Joule Boosting) for high temperature decomposition and a 900°C design that did not need boosting. Efficiencies were 38% and 43%, respectively. Costs are comparable to the GA approach. Problems identified are thermal material limits, material handling, and chemical processing. The Forsberg reference[44] proposes the I-S thermochemical process coupled with fission power systems, as does the Generation IV[41] for one of its options.

Electrical Generation and Low-Temperature Electrolysis – This process uses a fusion plant (or any other electrical generating plant) to generate electricity and then a conventional low-temperature electrolysis process to generate H_2. The hydrogen production process with low-temperature electrolysis is currently state of the art and is generally 70-85% efficient[42]. Proton Exchange Membrane (PEM) electrolyzers are 80-90% efficient[42]. These processes may become somewhat more efficient in the future. The second part of the efficiency equation is the efficiency of production of electricity by fusion. This value will not be validated until demonstration fusion power plants are operated for long periods of time. The most optimistic efficiency values are in the range of 55-60% per the recent ARIES studies[54]. Combining these two efficiencies, the efficiency of hydrogen production would be in the 44% to 48% range with conventional low-temperature electrolyzers. The FAME study predicted lower overall efficiencies because of the lower fusion plant efficiencies referenced in that time period.

High Temperature Electrolysis (HTE) - A method of increasing the efficiency of the electrolyzer is to raise the temperature of the electrolyte. The energy necessary to separate (electrolyze) water is given by the expression:

$\Delta H = \Delta F + T\Delta S$, where H= enthalpy, F = free energy (electrical input), T = temperature, and S = entropy

Below 100°C, where conventional alkaline and PEM electrolyzers operate, water is in a liquid state (at normal pressures). As the temperature rises, the electricity requirement (ΔF) decreases, but the heat input requirement increases ($T\Delta S$). The voltage required for water splitting at constant temperature without heat exchange is called the "thermoneutral voltage". For electrolyzers operating less than 100°C, this voltage is 1.48 V. Above 100°C, the voltage is 1.3 V. For electrolyzers operating at a voltage above the thermoneutral voltage line, heat is released and the electrolyzer is exothermic. Below the thermoneutral line, heat is added and the system is endothermic. The Sheffield study[42] used an exothermic high temperature electrolyzer operating at 900°C that is 111% efficient. (An efficiency above 100% is possible because efficiency in this case neglects the process heat supplied ($T\Delta S$).) For the exothermic process, low temperature heat is obtained from the helium downstream from the turbine heat the process water to 150°C for the electrolyzer that operates at 900°C. For the endothermic process, high temperature heat is obtained from the helium upstream from the turbine to maintain the electrolyzer energy balance at 900°C. The endothermic efficiency is 136% and the electrolyzer capital cost is higher. Using the process heat degrades the electricity generation thermal conversion cycle efficiency in both cases to differing degrees. These electrolyzers are physically separated from the fusion reactor, which will ease the tritium control.

The BNL study[48], called HYFIRE, used high temperature electrolysis at 1427°C by adapting the STARFIRE reactor design with ZrO_2 HTE blankets inside the fusion reactor. Unique hydrogen production blankets operating at very high temperatures inside the reactor would suggest profound developmental and tritium control problems. The claimed efficiencies were 60% for electrical generation and 70% for hydrogen production at 1800°C

Steam Reforming – Hydrogen is currently produced with steam reforming of natural gas using the reaction:

$CH_4 + 2H_2O \rightarrow CO_2 + 4\,H_2$

This is an endothermic reaction requiring significant supply of energy, typically at 900°C. If higher temperatures are used, the energy input can be reduced. The energy source for steam reforming could be fusion or fission[41]. However, it would be necessary to sequester the CO_2 byproduct.

Summary of Hydrogen Production Processes – Given the goals of large scale, efficient production of hydrogen and no usage of hydrocarbon resources without CO_2 storage, the likely hydrogen production processes for fusion are thermochemical or thermochemical/electrochemical and low or high temperature electrolysis. The thermochemical and thermochemical/electrochemical process is being developed for nuclear applications. This process will use high temperature process heat from a fusion reactor. The low temperature electrolysis process hardware is commercially available, as either as alkaline or proton membrane exchange electrolyzers. This approach will use only electricity from a fusion electrical generation plant. High temperature electrolyzers are being developed and should be available when fusion is ready for hydrogen production. This approach will use both electricity and low or high temperature process heat from a fusion plant.

The common theme is that efficient production of electricity should precede hydrogen production. Efficient electricity production will require high temperature process heat, which is aligned with the requirements for thermochemical or endothermic high temperature electrolyzers. This approach should require little or no research and development funds to adapt the most efficient hydrogen production processes to the fusion energy source.

RESPONSE TO EVALUATION CRITERIA

1. *Will the application be viewed as necessary to solve a "national problem" or will the application be viewed as a solution by the national funding entity?*

Both the public and the national funding entities are beginning to recognize that the hydrocarbon resources are ultimately a limited resource and continued usage of hydrocarbon fuels that generate carbon dioxide will increase our greenhouse gas emissions and despoil our environment. Conversion to a hydrogen (usage) economy is starting to be a national initiative. Methods to produce hydrogen from water are well developed. Production from hydrocarbon fuels should not be considered, as this would further deplete fossil resources and contribute to the CO_2 emissions or abatement. What is needed is an unlimited energy source that is safe and environmentally friendly. Fusion is an ideal candidate for this role.

2. What are the technical requirements on fusion imposed by this application with respect to the present state of fusion and to the technical requirements imposed by electricity production? What R&D is required to meet these requirements and is it on the path to electricity production?

Hydrogen production by fusion using the low temperature electrolysis process requires no additional R&D efforts above and beyond the technical requirements imposed by electricity production. Hydrogen production with electrolysis is completely compatible and supportive of the envisioned fusion electrical production pathway, both for MFE and IFE. This energy application can be demonstrated at any stage of the fusion electrical production development. This electrolysis process in a fusion hydrogen production plant has an additional benefit in that when electricity demand is high, full production of electricity is available and when electricity demand is low, partial or full production can be diverted to hydrogen production for delivery or storage. This approach is akin to a very large pumped storage facility.

Hydrogen production with high temperature electrolysis will leverage electrolyzer developments by other funding agencies. The high temperature electrolyzer will require efficient generation of electricity and may require high temperature process heat from the high temperature blankets developed for efficient electricity production. The development of the basic fusion process will likely be identical to the baseline fusion process for electricity production.

Hydrogen production with thermochemical or thermochemical/electrochemical processes will also require high temperature process heat for efficient hydrogen production. The process heat blankets will probably be identical to those for efficient electricity production and the basic fusion process will likely be identical to the baseline fusion. Electrical production blankets may also be required to support the plant internal electrical needs. Chemical processing systems will have to be developed for the iodine-sulfur thermochemical cycle, and this is being pursued by the DOE Nuclear Energy program. Other than materials and new chemical processes, all other fusion plant parameters (Q, power density, steady state operation, availability, disruption, tritium breeding, efficiency, economics, and schedule to commercial operation) will be similar.

3. What is the competition for this application, and what is the likelihood that fusion can beat it?

Hydrogen production from natural gas (with any energy source) is not desirable because it depletes hydrocarbon resources, diverts hydrocarbon fuels from other end products, and creates carbon dioxide. Hydrogen production from water would be a preferred approach.

Key to the question at hand is the choice of the energy source. It has to be an approach that can supply a national or world economy with a large-scale energy source. Renewable energy sources may be an important source of hydrogen in areas with large wind power, readily available biomass, and if the cost of solar systems is reduced substantially. Production of hydrogen from hydrocarbons is possible for many centuries, but concerns about pollution and the added costs of sequestration, improve the attractiveness of alternatives. Production of hydrogen with fission plants represents the most likely and formidable competitor. Cycle efficiencies and plant availabilities are similar to those predicted for fusion. The main fusion advantages are that fusion is a potentially safer and more environmentally friendly product – no runaway conditions, and low-level (as opposed to high-level) nuclear waste.

If fusion fulfills its promises on safety, low environmental impact, and attractive economics, it will become the energy source of choice for electricity and hydrogen production.

SUMMARY AND RECOMMENDATIONS

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 first task, therefore, is development and demonstration of that fusion plasma core. A decision does not need to be made on which process appears best for fusion does not need to be made until that demonstration has been done. By this time, the development work currently underway on high temperature electrolysis and thermochemical water-splitting under other programs will have provided a firmer basis for comparison and selection.

Recommendations:

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.

Possible Negative Impacts:

Adopting hydrogen production as the second major mission objective runs the risk of diluting the program emphasis on a single goal. On the other hand, it broadens the customer base and the program appeal beyond the single electricity product. It also highlights the environmentally friendly aspects of fusion to provide two non-polluting energy forms, electricity and hydrogen. Further, little effort is needed at this time to establish and maintain hydrogen production as a goal for fusion.

V. SPACE PROPULSION

Compared with all other available energy sources, fusion offers a *unique* potential for advanced space propulsion; that is, to transport large payloads over long distances with acceptable trip times. In particular, many advanced missions involving large robotic platforms and/or human piloted travel to the outer planets of the solar system and beyond are simply impossible for other existing propulsion fuels

Table 3 compares the specific energy yield and ultimate exhaust velocities from various energy sources. Fusion's unique utility lies in the large fraction of mass converted to energy and the fact that this energy is distributed in a reaction mass available for direct thrust thus attaining very high specific jet power.

Table 3. Candidate Fuels for Advanced Space Propulsion

	<u>**Products**</u>	**Specific Energy (J/kg)**	**Converted Mass Fraction**	Maximum Exhaust Velocity (m/s) (Specific Impulse (s))
Chemical (LO_2/LH_2)	H, H_20	1.4×10^{7}	1.5×10^{-10}	<u>***~5×10³***</u> (500)
Nuclear fission	Fission fragments, (n, γ, x,…)	8.2×10^{13}	9.1×10^{-4}	Thermal ~1–5$\times10^{4}$ (a), (b) (1000–5000)
Nuclear fusion – conventional (D-T)	Neutrons, alpha particles (γ, x,…)	3.4×10^{14}	3.8×10^{-3} (20% useable)	1.3×10^{7} (alphas) (1.3×10^{6})
Nuclear fusion – advanced (D-D, D-^{3}He, p-^{11}B,…)	Protons, alpha particles (g, x, n,...)	~similar	~similar (>90% useable)	5.3×10^{7} (protons) (5.3×10^{6})
Matter–antimatter annihilation (c)	Pions, (γ, muons, e^{+}, e^{-},…)	9×10^{16}	1.0 (~40% useable)	2.7×10^{8} (pions) (2.7×10^{7})

(a) Higher values are feasible for fission-electric ion thrusters but at the expense of large masses for power conversion and waste heat rejection (b) ~1.2×10^{7}m/s if fission fragments thrust could be used directly (c) Very speculative; basic feasibility undemonstrated

For propulsion, the objective for the cost of energy is measured in $10's to $100's per kW-hr, rather different from the few cents per kW-hr required for attractive terrestrial electricity generation. Furthermore, by contrast to fission-electric propulsion, it is unnecessary to convert the fusion plasma energy into electricity in that the thermal energy of the fusion plasma can be employed to produce thrust directly. Exhausting of the plasma mass is an integral part of this energy-to-thrust conversion. (For finite-Q, driven fusion systems, it may be required to recirculate a fraction of the fusion power electrically to sustain the fusion reaction; in such cases, there will be a minimum requirement on the plasma-Q. Alternatively, it may be advantageous to provide a separate fission power system for ancillary electric power). Table 4 contrasts the differences in applying fusion to terrestrial electricity production relative to space propulsion.

Table 4. Differences in Applying Fusion to Electric Generation and to Propulsion

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.

HISTORY AND BACKGROUND

A major effort to address the application of fusion in space was undertaken by the former NASA Lewis Research Center (now renamed as the Glen Research Center) between 1958 and 1978[55,56,57,58]. The research, however, was formulated to address the application of fusion to generate electrical power in space, as well as for propulsion. From considerations above, these two applications are somewhat orthogonal, though the underlying plasma and fusion science are similar. The NASA Lewis program was narrowly focused on the simple mirrors and the electric field bumpy torus – both steady-state MFE fusion approaches . The program was cancelled in 1978 for budgetary reasons as NASA was preparing to embark on the shuttle program.

During the same period, several conceptual studies considered the application of ICF to propulsion. Hyde, Wood and Nuckolls at Lawrence Livermore [59,60] and Bond et al. in the U.K. [61]considered laser-driven ICF, whereas Winterberg considered relativistic electron beams driven ICF[62]. In the 1980's and 1990's, a number of propulsion concepts were studied. A modern version of an ICF driven spacecraft was proposed by Orth in 1987[63,64]. Borowski considered the application of the spherical torus (ST) and spheromak to propulsion [65,66] and performed a comparison between fusion and antimatter propulsion. A more elaborate embodiment of the ST concept was later provided by Williams, et. al. in 1998[67]. Both Santarius [68,69,70] and Carpenter [71] studied the use of the tandem mirror in 1988 and 1993 respectively. Teller, et. al. considered the use of the dipole fusion concept in 1992[72]. Nakashima and co-workers considered the use of field reversed configuration in 1994[73]. Kammash [74] in 1995, and later Emrich in 1998, studied the use of the gasdynamic mirrors. Kammash also considered the use of magneto-inertial confinement fusion (MICF) for propulsion[75]. Smith and co-workers studied the use of anti-proton catalyzed fusion [76] and fission-fusion hybrid[77]. Perkins et al. have examined the issues underlying antiproton-driven inertial confinement fusion [78]. Another version of fission-fusion hybrid was considered by Winterberg for propulsion[79]. There were a number of studies made to discuss the engineering issues including the fusion fuels generic to fusion for propulsion and for space power, for example, Hilton[80,81], Roth[82], Wittenberg[83], and Santarius and co-workers[67-69,83]. The reviews by Schulz [57]and by Santarius and Thio [84] updated the arguments on why is it timely for NASA to begin undertaking an aggressive program to develop fusion propulsion.

Most of the above studies involved propulsion units with extremely large powers and with masses typically more than 1000 tonnes. More recently, Thio [85] considered the use of magnetized target fusion driven by plasma jets and a plasma (i.e. non solid) liner. Slough [86] studied the acceleration of FRCs to high velocities; he employed their kinetic energy for self compression through a series of tapering coils and conductors to produce fusion burn and expanded the resultant plasma through a magnetic nozzle. Miley [87] (and earlier, Bussard[88]) assessed the inertial electrostatic confinement fusion approach. These later studies suggested that fusion propulsion units might be achievable with masses below 200 metric tons and with specific jet power exceeding 10 kW/kg. The propulsion systems of Thio and Slough involved pulsed fusion approaches, whereas that of Miley was steady state. The propulsion concept of Thio was later given a more thorough evaluation for a human piloted mission to Callisto, a moon of Jupiter, by NASA in the project HOPE (Human Outer Planet Exploration); this is part of a larger NASA study, RASC (Revolutionary Aerospace System Concepts).

THE RATIONALE FOR FUSION PROPULSION

To send humans and/or heavy robotic equipment (≥20 tonnes) to the outer planets of the solar system and beyond, we will need propulsion technology with much higher performance than can be provided by present-day chemical and nuclear fission propulsion. There are physiological reasons for wanting to limit the length of flight time. Skeletal and muscular atrophy will occur in astronauts after approximately a hundred days in zero gravity. Interactions of cosmic radiation with spacecraft structure result in neutron showers that subject astronauts to high radiation doses. The risk becomes unacceptably high after one year in orbit unless the spacecraft is heavily shielded. Mission cost in general grows with the length of the mission. Ultimately, the length of any mission must be reasonably limited for practical reasons including sustaining public and scientific interest, maintaining social and scientific relevance and, ultimately, obtaining political support. Accordingly, given the enormous distances to the planets, very high cruising speeds are required. Additionally, the ability for an emergency abort to Earth as well as rapid evasive maneuvers to avoid collisions with asteroids or other space objects would be highly desirable.

Consider for example a mission to one of the moons of Jupiter. The orbital separation between Jupiter and the Earth is approximately 650 million kilometers. To complete the outbound trip in 5 months (about 13 million seconds) would require a mean cruising speed of 50 km/s, or a peak velocity increment (Δv) of at least 100 km/s. The round-trip flight time would require approximately ten months. With about two months stay at the destination, the complete mission could be accomplished within a calendar year. Historically this appears to be reasonable for an exploratory expedition to maintain the political attention span.

Exhaust velocities of several hundreds of km/s are required for advanced missions. The propellant exhaust velocity is proportional to the specific impulse of the propellant, defined (in units of seconds) as the thrust imparted to the rocket (in pounds) per mass rate of propellant expended (in pounds/second). Exhaust velocity is a direct measure of the fraction of fuel mass converted to energy. Fusion offers the highest potential in this regard –see Table 1 –other than (very speculative) matter-antimatter annihilation.
Exhaust velocities from chemical propellant are generally limited to less than 5 km/s. Fission heated hydrogen could produce exhaust velocities in the region of about 10 km/s. Advanced gas-core fission reactors could potentially eject gases at a velocity of 20 km/s to 50 km/s. Exhaust velocities from these propulsion devices are far too low to enable efficient human and heavy robotic missions to the outer planets and beyond within reasonable cost and time.

In principle, nuclear fission could be used to generate electricity to accelerate charged particles or plasmas to high exhaust velocities. However, the thermal-to-electric conversion process necessarily produces a large amount of waste heat due to fundamental thermodynamic inefficiencies. Since blackbody radiation (governed by the T^4 law) is the only means of getting rid of waste heat in space, the rejection of the attendant large amount of waste heat at relatively low temperature gives rise to a large amount of thermal mass for the propulsion system. Adding to this is the mass of the power equipment (diodes, transformers, switches, etc.) required to condition the electrical power, i.e., to produce the correct voltage-current characteristic to power the electric thruster. The large mass introduced by the thermal radiators and the power conditioning equipment results in low acceleration for the spacecraft.

Given the exhaust velocity of the propellant, the mean acceleration is limited by the mean jet power per unit mass of the spacecraft, that is the mean specific jet power. For the Jupiter example above, if the spacecraft were to accelerate for one-third of the distance up to a velocity of 100 km/s, coast at constant velocity for the second third of the journey, and decelerate for the last third of the course (a nearly optimum trajectory), the required acceleration is ~0.025 m/s^2. Assuming a reasonable payload fraction (m/m_0) of 0.75 for the outbound trip, the rocket momentum equation dictates a propellant exhaust velocity of 350 km/s. Accordingly, the mean specific jet power of the rocket must exceed 4 kW/kg. Higher values of specific jet power are required for safety, for evasive maneuvers, and for more ambitious mission profile or more distant planets. The specific jet power of nuclear fission powered electric rocket is generally limited to less than 0.1 kW/kg (though claims of higher specific power up to 1 kW/kg have been made occasionally), and is inadequate for meeting the propulsion demands of the high energy space missions considered here.

To attain the very high specific impulses and the very high specific jet power required for advanced missions: (1) nuclear energy is required because of its high specific energy, (2) the nuclear energy should be released in the form of a high-temperature plasma at millions of degrees, and (3) this plasma should be used to generate thrust directly by pushing against a magnetic field, without converting the thermal energy into electricity to power an electric thruster. Thermonuclear fusion is the only near-term physical process that could produce this desirable combination. Only a very small fraction of the fusion energy would be used to generate electricity to provide the auxiliary power required to drive the fusion reactor.

CRITICAL ISSUES FOR FUSION PROPULSION

There are many scientific, technical and operational issues that must be resolved before fusion propulsion can become a reality. Feasibility is a fundamental issue followed closely by projected costs. However, in fusion's favor is the fact that many advanced missions are simply impossible for other propulsion fuels. Moreover, what is considered too costly in one era might not be so in the next. In the foreseeable future, it is thought by many that \$50 B (current worth) is about the maximum that would be tolerated for any human or robotic planetary mission, and that the price tag per mission would need to be considerably lower than this to have any real political support. Budget figures such as \$20 B per mission have been suggested as the "threshold of pain" by NASA senior managers. For reference, in the first conceptual study for a human piloted mission to Mars undertaken under former President Bush's Space Exploration Initiative (SEI) based upon mainly chemical propulsion in 1991, a mission cost estimate of more than \$400 B was cited by the study group. The high mission cost was a major factor that led to the demise of SEI.

Mission cost can be broken down into the cost of propulsion and the cost to achieve mission objectives. The latter includes the cost of the space vehicle excluding the propulsion unit, and other costs such as that for scientific exploration at the destination. Propulsion cost consists of the cost at the initial orbit in space (IOS) – that is, the launch cost and cost of producing the propulsion unit – plus the in-space cost and the cost at destination. At present the launch cost is about \$10K per kg. This might be reduced by an order of magnitude by the 2030's. The projected cost of producing the propulsion unit is much harder to estimate, especially when the technology is not mature. Past experience with the manufacturing of space qualified hardware, however, indicated a range of cost from \$20 K to \$100 K per kg. Clearly, the cost of manufacturing the propulsion unit would dominate the cost at IOS. If we

assume (a) equal distribution of the mission cost between propulsion and the cost to achieve mission objectives, and (b) that the cost of IOS should not exceed half of the budget allocated for propulsion, then the cost at IOS that might be politically sustainable is in the range of $5-10 B. Assuming a mid-range value of $50 K per kg as the rate for manufacturing the propulsion unit, this places a limit of no greater than 500 tons on the propulsion unit. This mass budget would be inclusive of all the auxiliary equipment required by the propulsion unit and the thermal radiators.
Clearly, it will be extremely unlikely that a conventional tokamak or conventional ICF reactor will fit into the above mass envelope. Thus, for practical fusion propulsion, recourse will be necessary to fusion approaches that promise to be more compact and lightweight than the conventional approaches. Such approaches are being investigated in DOE's OFES Innovative Confinement Concepts (ICC) program, and include: the spherical torus, magnetized target fusion, field reversed configurations (FRC), spheromak, levitated dipole, flow stabilized z-pinches, centrifugal confinement, inertial electrostatic confinement, and fast ignition for ICF. Note that some of these approaches have natural divertors. With the exception of the plasma-jet or plasma-liner-driven magnetized target fusion, all these concepts have been formulated for the terrestrial electric program, thus starting with rather different technical objectives and assumptions. So, the fundamental technical issue for future research is to search for and assess confinement concepts that are most appropriate for fusion propulsion.

Because of the severe performance penalty in terms of the thermal management mass, neutrons are in general worse than useless for propulsion unless their kinetic energy can be directly absorbed by the fusing plasma. The latter would have to attain several times solid density; Thio has shown how this might be achieved in some instances[84]. Therefore, fusion schemes and advanced fuels, such as D-He^3 that result in reduced neutron production are favored for propulsion application. In addition, would breeding tritium on-board introduce severe mass penalties, or could appropriate physics and technological pathways be found that would make it feasible to breed at least a small quantity of tritium on-board? The answer to this question would determine to what extent tritium could be part of the fusion fuel. Without a feasible approach for regenerating tritium on-board, for practical and safety reasons in the handling and storage of tritium, only a limited quantity could be brought up from Earth to the propulsion vehicle at IOS. This limited quantity, however, might be sufficient for the tritium to be used as a trigger for advanced fuel ICF targets as studied by Perkins[89] and the plasma-liner driven MTF as studied by Thio[90].

The direct conversion of fusion energy into thrust is a new area of investigation. Though several studies have been made on the subject[89,91,92], relatively very little is known about magnetic nozzles at these power densities, pulsed or steady state. Remote restart capability must be addressed in any propulsion approach; this appears to be a less stringent issue for concepts that use pulsed fusion approaches. Finally, improvements in radiation shielding, nuclear materials and advanced thermal radiators will greatly enhance the performance of the fusion propulsion system.

(We are grateful to Francis Thio for providing the basis for this section)

RESPONSE TO EVALUATION CRITERIA

1. *Will the application be viewed as necessary to solve a "national problem" or will the application be viewed as a solution by the national funding entity?*

Fusion propulsion is recognized by NASA as necessary for human exploration of the outer planets and beyond, and for transporting large robotic payloads in a reasonably short trip time. The bigger issue is when NASA will really embark on this type of mission.

2. What are the technical requirements on fusion imposed by this application with respect to the present state of fusion and to the technical requirements imposed by electricity production? What R&D is required to meet these requirements and is it on the path to 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 differences in mission they may differ significantly from those for terrestrial fusion applications.

3. What is the competition for this application, and what is the likelihood that fusion can beat it?

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

SUMMARY AND RECOMMENDATIONS

Fusion propulsion will almost certainly be necessary for human exploration of the outer planets and beyond, or for large robotic payloads to be sent with reasonable trip times. Such advanced missions are simply impossible for other existing propulsion fuels. Fusion propulsion appears to be relieved of some of the most challenging constraints burdening the terrestrial fusion electric program; this is because: (a) the allowable cost target are much higher, i.e., ~ $10's to $100's per kW-hr, (b) the required operating lifetime is months rather than years, and (c) that fusion has no practical technological competitors for advanced missions. In addition, pulsed fusion approaches may be more readily applicable for propulsion than for terrestrial electric power generation.

However, it is important to note that although confinement concepts have been proposed for advanced space missions, the detailed technical challenges facing fusion for space propulsion are largely unexplored. Because of differences in mission they may differ significantly from those for terrestrial fusion applications. An examination of the subject in a coherent fashion taking advantage of the progress made in the fusion energy program is warranted.

Because the technical priorities are sufficiently different, an independent program directed at researching fusion propulsion separately funded from the terrestrial fusion electric program would be needed to pursue space propulsion. The two programs, however, would have many overlaps in underlying physics and engineering, and would likely involve the same community of researchers. The DOE fusion program should be responsive to any NASA request for support on evaluating (and subsequently developing) space fusion propulsion systems. DOE could provide the management and technical expertise in fusion and plasma sciences, especially in the early phases of the program. As a first step, we recommend that a joint NASA-DOE (with NASA in the lead, and providing funding for anything more than "consultation" type of work) program be undertaken to perform conceptual studies of the potential and the feasibility of fusion for propulsion at the systems level, and to develop a long-range R&D plan for its development. The pursuit of the two synergistic but independent applications will stimulate researchers and management to think "out of the box", with the potential for new discoveries for both approaches. In particular, we suggest that the intellectual challenge of deep space exploration will inspire young scientists to enter fusion and plasma science, thus enriching the future work force for both applications.

Recommendations:

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.

Possible Negative Impacts

If somehow the most promising mission for fusion were to be viewed as space propulsion, then the urgency of fusion research could be decreased even further than it is currently.

VI. FINDINGS & RECOMMENDATIONS

It is the opinion of this panel that the most promising opportunities for non-electric applications of fusion fall into four categories:

5. Near-Term Applications
6. Transmutation
7. Hydrogen Production
8. Space Propulsion

The order that these are presented in is not meant in any way to imply priority. Based on the information available to the panel, and presented in this report, the panel makes the following recommendations. 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.

NEAR-TERM APPLICATIONS

Findings

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.

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

The DOE-OFES should identify a small, but steady, source of funding to specifically look at near-term 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.

TRANSMUTATION

Findings

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

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. 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.

HYDROGEN PRODUCTION

Findings

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

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.

SPACE PROPULSION

Findings

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 heavy payload or manned 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

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.

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Appendix A

Charge Letter

Professor Richard Hazeltine, Chair
Fusion Energy Sciences Advisory Committee
Institute for Fusion Studies
University of Texas at Austin
Austin, TX 78712

Dear Professor Hazeltine:

The long-range vision for the world's fusion research programs is the development of power plants in which the fusion process would be used to produce electricity. It is widely acknowledged that realizing this vision will require a long-term development effort to achieve burning plasmas and technology performance levels that are highly advanced relative to today's capabilities.

However, at various times in the past, the Department's fusion program has also explored ways in which the fusion process might be used to meet other needs that would not require the levels of burning plasma and technological performance needed for economical electricity generation. These explorations have noted that fusion devices on the pathway leading eventually to fusion power plants for electricity generation might be useful for other, nearer term purposes. These non-electric uses of fusion might include the production of hydrogen that could be used as a fuel in the transportation sector, and the production of high-energy neutrons that would have a variety of uses, such as the transmutation of nuclear wastes.

I would like the FESAC to consider whether the Fusion Energy Sciences program should broaden its scope and activities to include non-electric applications of intermediate-term fusion devices. During this consideration, FESAC should answer 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 electricity?
- What steps should the program take to incorporate these opportunities into plans for fusion research?
- Are there any possible negative impacts to pursuing these opportunities and are there ways to mitigate these possible impacts?

I would like FESAC to report its findings to the Office of Science by January 2003.

Sincerely,

James F. Decker
Acting Director
Office of Science

Appendix B

Panel Membership

Dr. Charles Baker, University of California, San Diego
Dr. Edward Cheng, TSI Research, Inc.
Prof. Gerald Kulcinski, University of Wisconsin
Dr. Grant Logan, LBL
Dr. Kathryn McCarthy (Chair), INEEL
Prof. George Miley, University of Illinios
Dr. John Perkins, LLNL
Dr. Dave Petti, INEEL
Dr. John Sheffield, University of Tennessee
Prof. Don Steiner, Rensselaer Polytechnic Institute
Prof. Weston Stacey, Georgia Institute of Technology
Mr. Lester Waganer, Boeing