# ENERGY ISSUES WORKING GROUP ON LONG-TERM VISIONS FOR FUSION POWER

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The Energy Issues Working Group on Long-Term Visions for Fusion Power considered the following four questions:

1. What is the projected market for electrical energy production in the next century?

2. What is fusion's potential for penetrating the energy market in the next century?

3. Is there a potential role for advanced fusion fuels?

4. What is fusion's potential for applications other than conventional power plants?

The first two questions were considered together in one session. Questions 3 and 4 were each considered in separate sessions. The following sections summarize the context, session format, and major conclusions emerging from each session.

## 1.0 THE PROJECTED MARKET FOR ELECTRICAL ENERGY PRODUCTION IN THE NEXT CENTURY AND FUSION'S POTENTIAL FOR PENETRATING THIS ENERGY MARKET.

### 1.1 Introduction

Projections of energy needs for the next century have been performed by several groups. These projections provide a benchmark for evaluating fusion's potential role. In addition, design studies of the anticipated economic and environmental characteristics of future fusion energy systems provide a context for assessing directions for fusion energy development. Thus, the technical bases for the discussions in this session were provided by the results of energy projections and fusion energy design studies.

### 1.2 Session Format

The format for the discussions in this session consisted of panel discussions on selected topics followed by open discussions involving the panelists and the audience.

### 1.3 Summary of Discussions

The key issues and conclusions emerging from this session are summarized below.

## Introduction of Fusion into the Energy Market

Almost all studies of projected energy requirements in the upcoming century indicate the need for a large number of new power plants, particularly after the year 2050. Typical projections suggest that on the order of 1000 new 1 GW plants will be required worldwide by the year 2100. The conclusion is that there is indeed an opportunity for fusion power in the second half of the century, but only if fusion power plants are economical, reliable, and environmentally friendly. An issue for the current fusion energy program is to determine whether, and if so how, this long time scale should be incorporated into its planning strategy.

On a related issue it was pointed out at the Conference that at any given time, the financial health of the fusion program is strongly influenced by external events out of the control of the community. Such events include oil embargoes, new discoveries of fossil fuel resources, global warming, etc. The question then arose as to whether or not the community should account for these unpredictable external events in its R&D planning, and if so how? For instance, such considerations might lead to a different balance between the various components in the program (e.g. plasma physics, technology, non-fusion applications, etc.)

## Requirements for an Attractive Fusion Power Plant

The current cost of electricity (COE) for new combined cycle gas fueled power plants is approximately 3 c/kWh. In the future there is a plausible expectation that this cost may rise. Depletion of fossil fuel reserves and the costs associated with carbon sequestration are two reasons for this rise. Electricity from alternate energy sources is also expected to cost more than 3 c/kWh – fission because of its complexity and renewable because of their low power density. In trying to estimate these effects, energy planners suggest that during the next century, the COE will be in the range of 4–6 c/kWh.

For fusion to be a competitive future source of electricity, its COE must be lie in this range. There is general agreement that the capital cost of a fusion power plant will always be relatively high because of the complexity of the system: magnets, a large support structure, external plasma heating supplies, a large vacuum system, etc. This disadvantage, which is reasonably well quantifiable, clearly contributes to a higher COE. To offset this disadvantage, fusion offers potential advantages in safety, environment, fuel supply, waste and proliferation. These advantages are somewhat more difficult to quantify. Even so, it is an important challenge for the fusion community to attempt this quantification, not only for fusion, but for its competitors as well. Only when this is accomplished can we actually make a fair comparison between fusion and other energy sources.

## The Cost of Electricity (COE) as a Metric

The cost of electricity is obviously an important parameter to determine the attractiveness of a future fusion reactor. The COE can and should be used to identify key

R&D directions within the program. It can and should be used to compare different concepts within the fusion program. Finally, it can and should be used to compare fusion with non-fusion competitors.

In spite of its importance, however, difficulties arise because of uncertainties associated with the early stage of fusion development. This lack of real world experience for fusion as an energy producer makes it somewhat difficult to obtain a reliable COE; that is, the error estimates in COE are substantial. The challenge facing the fusion community is to determine how to address these uncertainties. If COE is treated as a critical metric, this would have an important impact on the allocation of resources, in particular on which concepts are emphasized. If its importance is reduced, a different resource allocation would likely follow.

### Balance Between Power Plant Attractiveness and Technical Risk

At the conference, there was general consensus that an advanced tokamak might lead to an attractive power plant, although this was far from a certainty. Problems associated with high capital cost, achievement of steady state operation, and plasma disruptions must be overcome. While plausible solutions for the latter two problems have been proposed, they have yet to be fully demonstrated experimentally.

It was also pointed out that mature alternates such as the stellarator and RFP, or new Proof-of-Principle concepts such as the Spherical Torus have the potential for an even more attractive reactor vision but at this time are behind in demonstrated experimental performance. Furthermore, several of the emerging concepts have even more potential in terms of reactor vision, but are even further behind in demonstrated experimental performance.

The issue facing the community is to determine the appropriate metrics and how they should be applied to make programmatic decisions concerning the allocation of resources for different concepts. This must be accomplished in accordance with the recent restructuring of the fusion program into one emphasizing plasma science. There is a general feeling in the community that a promising reactor vision is not sufficient reason by itself to fund a particular concept. The physics vision must also be promising.

## 2.0 Potential Role for Advanced Fusion Fuels

### 2.1 Introduction

The great majority of fusion reactor studies are based on the deuterium/tritium (D-T) fuel cycle through the reaction t(d,n)$\alpha$. This reaction is chosen because it has the largest fusion cross-section (peaking at about 5 barns) and reaches this maximum cross-section at the lowest energy (~65 keV in the center-of-mass) of any potential fusion fuel. This large cross-section and low center-of-mass energy lead to the lowest confinement requirement for ignition (ignition in D-T requires a confinement triple-product $n_e\tau_E T=3\times10^{21}$ keV-s/m$^{-3}$ in the presence of a plausible impurity mix) and the highest fusion power density at fixed plasma pressure. The D-T fuel cycle also presents unique challenges to reactor designers. Two particular issues are the 14 MeV neutrons produced in the t(d,n)$\alpha$ reaction, and the presence of tritium in the fuel cycle. The 14 MeV neutrons damage reactor components (principally the structure of the blanket and shield) thereby limiting their useful lifetime; and activate materials, thereby opening the possibility that D-T fusion reactors will produce large volumes or high levels of radioactive wastes. Tritium does not occur in nature, but must be bred through neutron reactions with lithium in a breeding blanket which surrounds the plasma. This tritium breeding blanket complicates fusion reactor design. In addition, in situ breeding of tritium can result in large on-site tritium inventories (principally in the blanket and tritium recovery system) raising safety concerns.

Alternative ("advanced") fuel cycles have also been under investigation for many years. Three considerations have motivated these investigations:

(i) Eliminating (or greatly reducing) neutron production in fusion reactors as a means of avoiding (or greatly ameliorating) neutron damage to, and activation of fusion reactor components.
(ii) Removing tritium from the fuel cycle in order to simplify the fuel cycle (no tritium breeding), and expand the available fuel supply (the earth's lithium supply limits the ultimate amount of tritium which might be produced by breeding blankets).
(iii) Increasing the charged-particle power fraction, in order to utilize potentially high-efficiency direct conversion of fusion energy to electricity.

The three most studied advanced fuel cycles are D-$^3$He [which features the reaction $^3$He(d,p)$\alpha$], "catalyzed DD" [that is, a primary cycle involving the two reactions d(d,n)$^3$He and d(d,p)t together with the secondary reactions t(d,n)$\alpha$ and $^3$He(d,p)$\alpha$ to consume all t and $^3$He produced by the primary reactions], and p-$^{11}$B [which features the reaction $^{11}$B(p,$\alpha$)2$\alpha$]

The D-$^3$He fuel cycle has the advantage that it produces only 1–5% of the fusion power (12% in number) in neutrons compared to the D-T fuel cycle. While the principle reaction $^3$He(d,p)$\alpha$ is aneutronic, neutron production via the side reaction d(d,n)$^3$He and the secondary reaction d(t,n)$\alpha$ is unavoidable. The neutrons produced mainly have lower energy [2.45 MeV neutrons from d(d,n)$^3$He reactions as opposed to 14 MeV neutrons from d(t,n)$\alpha$ reactions] so that material damage is reduced relative to the DT fuel cycle. Reactor studies show that the D-$^3$He fuel cycle largely solves the reactor component lifetime issues associated with neutron damage, while neutron activation and the associated production of radioactive waste remains a concern. The D-$^3$He fuel cycle avoids tritium breeding, but does this by replacing tritium with another exotic isotope, $^3$He. $^3$He does not occur on earth in sufficient quantities to support a fusion power industry. However, Apollo program lunar samples were found to contain $^3$He, and proponents of the D-$^3$He fuel cycle have suggested that it may be economic to mine $^3$He on the moon and transport it to earth to fuel a fusion power industry. The D-$^3$He fuel cycle has a higher confinement requirement for ignition (ignition in D-$^3$He requires a confinement triple-product $n_e\tau_E T{\sim}1\times10^{23}$ keV-s/m$^{-3}$ in the presence of a plausible impurity mix), and a lower fusion power density at fixed plasma pressure.

The Catalyzed D-D fuel cycle avoids tritium breeding without introducing any exotic isotopes, and thereby holds out the promise of an essentially unlimited supply of fuel for fusion power generation. The catalyzed D-D cycle actually produces more neutrons per unit of fusion power than does the D-T cycle so that this fuel cycle does not address materials damage and activation concerns. The catalyzed D-D fuel cycle has a higher confinement requirement for ignition—ignition in catalyzed D-D requires a confinement triple-product $n_e\tau_E T{\sim}2\times10^{23}$ keV-s/m$^{-3}$ in the absence of impurities, while ignition in catalyzed DD cannot be achieved at impurity levels characteristic of present magnetic confinement experiments. The catalyzed D-D fuel cycle also has a lower fusion power density at fixed plasma pressure.

The p$^{11}$B fuel cycle avoids exotic isotopes, so that no breeding of fuel is required and the potential fuel supply is essentially unlimited. It is also nearly aneutronic, thus addressing materials damage and much of the materials activation concern. However, there are residual activation issues associated with high energy $\gamma$-rays produced via the reaction $^{11}$B(p,$\gamma$)$^{12}$C, and with neutron production from the reactions $^{11}$B($\alpha$,n)$^{14}$N and $^{11}$B(p,n)$^{11}$C; and safety concerns associated with possible equilibrium inventories of MCi/GW of $^{11}$C. More fundamentally, there is the problem that the p-$^{11}$B fusion reactivity appears to be too low to compete with bremsstrahlung radiation losses, so that ignition (or even high fusion gain) cannot be achieved with this fuel.

## 2.2 Session Format

The session format consisted of presentations by proponents followed by open discussion.

## 2.3 Summary of Discussion

The discussions of advanced fuels in the energy working group at Snowmass centered on the prospects for aneutronic fusion and the D-$^3$He fuel cycle. Critical issues associated with burning D-$^3$He are summarized in Table 2.1. The comments on the Table are further elaborated below.

**<u>Energy Confinement</u>**. Our metric for energy confinement is the confinement triple product, $n_e\tau_E T$. Zero-dimensional analysis indicates that, with a reasonable impurity mix (e.g., 2% Be and 0.01% Mo, which would yield a $Z_{eff}{\sim}1.5$ in a hydrogen plasma; and an $\alpha$-ash pumping efficiency $\tau_p^*/\tau_E{\sim}3$) a confinement triple-product $n_e\tau_E T \sim 10^{23}$ keV-s/m$^3$ will be required to achieve ignition in D-$^3$He. The current state-of-the-art (for volume-averaged quantities) is ~ few $\times10^{20}$ keV-s/m$^3$, produced in tokamaks. Substantial advances must be made in energy transport, particularly in high-$\beta$ or high B-field magnetic confinement systems before we can construct devices with such confinement triple-products of an affordable size and cost.

**Table 2.1 Summary of Assessment, Issues, & Opportunities for D-$^3$He**

| **Issue** | **Metric** | **Goal** | **Opportunities for Next Decade** |
|---|---|---|---|
| Energy confinement | $n_e\tau_E T$ | $\sim 10^{23-}$ keV-s/m$^3$ | To be addressed by physics program |
| $\alpha$/p –ash | $\tau_p^*/\tau_E$ | ~3 | " |
| Power density | $\beta B^2$ | >12 T$^2$ | " |
| Synchrotron radiation | Power loss fraction | << fusion power | Develop tools for accurate calculation |
| Safety & environment | Activation | Reduced waste volume | Build on ongoing engineering efforts |
| Radiation damage | Radiation lifetime | Plant lifetime | " |
| Direct conversion | Efficiency | 60%–70% | Small-scale tests |
| $^3$He fuel supply | Accessibility<br>& cost | \$500/g<br>(< 10 mill/kW-hr) | • Lunar mining<br>• Breeding |

**a/p –ash Exhaust**. We expect that the confinement time of the proton and helium ash produced in $^3$He(d,p)$\alpha$ reactions will scale with that for the confinement of thermal energy because the same processes (microturbulence or, more optimistically, neoclassical effects) are responsible for both the transport of particles and thermal energy. Hence, an appropriate figure-of-merit for the removal of proton and helium ash is the ratio of the ash confinement time (including recycling from the walls) to the thermal energy confinement time, $\tau_p^*/\tau_E$. Zero dimensional calculations indicate that $\tau_p^*/\tau_E \sim 3$ is required to achieve D-$^3$He ignition at $n_e\tau_E T \sim 1\times10^{23}$ keV-s/m$^3$ in the presence of trace impurities (e.g., 2% Be and 0.01% Mo). Tokamaks with high-recycling divertors operate at $\tau_p^*/\tau_E \sim 5$. Improved ash exhaust would require low-recycling divertor operation in toroidal configurations or the use of configurations (like FRC's, spheromaks, or magnetic mirrors) in which the plasma is not surrounded by toroidal field coils.

**Power Density**. At fixed plasma pressure, and accounting for the greater $\alpha$/p –ash fraction expected at similar ash pumping efficiencies (i.e., similar $\tau_p^*/\tau_E$) in a D-$^3$He burn, the fusion power density in D-$^3$He is about 100 times less than that of D-T. Hence, a factor of ~10 increase in the plasma pressure is required to achieve fusion power densities in D-$^3$He similar to that anticipated for the D-T fuel cycle. Interesting fusion power densities in D-$^3$He can be achieved by increasing the product $\beta B^2$ (where $\beta \equiv 2\mu_o p/B^2$ is the ratio of the plasma pressure to the magnetic pressure) to 12 (Tesla)$^2$. Tokamaks at $\beta$=2 to 5%, typical of recent power-plant conceptual designs, would thus require B=15 to 24 T in the plasma to burn D-$^3$He. An FRC power plant, at $\beta \approx 80\%$, would require B=4T.

**Synchrotron Radiation.** At the higher temperatures required for a D-$^3$He burn synchrotron radiation can be important both as a direct loss mechanism, and as a mechanism for transporting energy from electrons in the plasma core to electrons at the plasma edge. Present estimates of these effects range from negligible losses to power losses comparable to, or even greater than the fusion power density. Effective tools for estimating the synchrotron losses (both direct losses and the contribution of synchrotron radiation to electron conduction losses) need to be developed and widely applied in studies of D-$^3$He reactors.

**Safety and Environment.** D-$^3$He plasmas typically produce ~12% of the number of neutrons of D-T plasmas for the same total fusion power. The precise value depends on the ion temperature, $^3$He-to-D density ratio, and fraction of D-D tritium burned in D-T reactions. Higher $^3$He-to-D ratios reduce the neutron production at the expense of fusion power density. The lower neutron production reduces the rate of activation of materials, and conceptual power-plant studies have taken this engineering benefit, reducing the radioactive waste volume by about a factor of ten compared to D-T.[3] The resulting D-$^3$He waste material would qualify as Class A—analogous to hospital low-level radioactive waste if a low-activation steel structure is used for the lifetime of the plant. Alternatively, change-out of the relevant structures could be done on a D-T-like schedule of approximately every three years, increasing the volume of waste, but decreasing its radioactivity. Near-term research could usefully address the tradeoff of hazard versus volume plus quantify in more depth the activation of relevant alloys, including the critical levels of the impurities in the structure, which often dominate activation calculations.

**Radiation Damage.** Neutron damage depends on the fraction of the fusion power produced as neutrons, typically 1-5% for D-$^3$He compared to D-T. Perhaps the largest engineering advantage of D-$^3$He fuel over D-T fuel lies in the full-lifetime first wall and shield of a D-$^3$He fusion core. D-T power plants must schedule substantial down time for replacement of blanket modules. Quantification of the D-$^3$He structural lifetime and maintenance issues would valuably complement ongoing efforts related to D-T power plant conceptual design.

**Direct Conversion.** The increased efficiency due to directly converting fusion power to electricity compared to utilizing Carnot-limited thermal conversion has long been considered a key advantage of advanced fuel cycles. Predicted efficiencies for these systems range from 60 to 80%, and a conversion efficiency of 87±6 % has been demonstrated in mono-energetic beam direct energy conversion experiments. Techniques presently under investigation include electrostatic, traveling-wave, Peniotron-type and synchrotron-radiation direct conversion. Conceptual designs and small-scale tests could be done in the near term and would help quantify this issue.

**$^3$He Fuel Supply.** The terrestrial $^3$He supply of approximately 500 kg (about 10,000 MW-a of fusion power) would suffice for an engineering test program but could not support commercial fusion power. To be economic, the proposed lunar $^3$He source[5] requires two key types of technology to be demonstrated. First, heavy-lift launch vehicles capable of transporting mining equipment economically from Earth to the Moon must be developed. Second, $^3$He acquisition technologies, primarily bucket-wheel excavators, conveyor belts, solar reflectors, and heat-pipe recuperators, although common on Earth, must be shown to work reliably on the Moon. Demonstrating a modest-scale lunar miner could conceivably be accomplished during the coming decade. Alternatively, research on concepts for $^3$He breeding might produce a viable terrestrial technique for supplying this fuel.

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## 3.0 ALTERNATE APPLICATIONS OF FUSION ENERGY SYSTEMS

### 3.1 Introduction

Alternate applications of fusion plasmas have been considered since the earliest days of the fusion program and have focused primarily on fusion energy systems as neutron sources. Initial considerations have included: (1) hybrids for fissile fuel breeding, that is, in an energy-suppressed mode of operation, and also hybrids for energy production, that is, in a mode in which the fusion neutrons drive a subcritical fission blanket; (2) the use of fusion neutrons for the transmutation of radioactive waste from fission reactors; and (3) the application of a fusion based neutron source for fusion materials and engineering testing. The neutron source strengths for these applications were in the range of about $10^{19}$ to $10^{21}$ neutrons per second (n/s). Plasmas for these applications were based on mirror and tokamak physics.

More recent studies have added to the repertoire applications such as tritium production, the burning of plutonium from dismantled weapons, radioisotope production, medical radiotherapy, hydrogen production, and the detection of explosives. A unique characteristic of the more recent studies is the consideration of applications allowing a range of neutron source strengths from about $10^{11}$ to $10^{13}$ n/s on the low-end, up to about $10^{19}$ to $10^{21}$ n/s on the high-end. The high end studies have considered plasmas based on ITER physics, advanced mode tokamak operation, and the spherical torus. The low-end studies have focused on inertial electrostatic confinement concepts. Clearly, IFE systems could also be the basis for all of these applications.

Most studies have considered the D-T fuel cycle but a few have examined the D-D-T fuel cycle. Although less reactive than the D-T fuel cycle, the D-D-T fuel cycle has the advantages of (1) eliminating the need for tritium breeding, and (2) providing a much greater neutron excess per unit of fusion energy release than the D-T fuel cycle.

For the most part existing fusion neutron source studies have been at the conceptual level. As yet there have been no detailed, self-consistent studies which consider engineering, economics and environmental issues, as well as development needs and timeframe.

In addition to neutron source applications, other alternate applications have included high-temperature heat sources for hydrogen production, and fusion plasmas for space propulsion.

### 3.2 Session Format

The session format for this topic consisted of presentations by proponents of various applications. After describing the particular application, each proponent was asked to address the following six assessment questions:

(1) What is the market potential of the proposed application?

(2) What are fusion's competitors for this application and what are fusion's advantages/disadvantages relative to the competition?

(3) What are the major environmental, safety or licensing issues associated with the application?

(4) Will the application shorten the time scale for realizing commercial fusion energy systems?

(5) What are the key technical issues and development needs associated with the application?

(6) What are the opportunities for addressing the issues and development needs of the particular application.

Following the presentation there was open discussion and an attempt to reach consensus on the responses to the assessment questions.

### 3.3 Summary of Discussions

During the first week of discussions the proposed alternate applications fell into two general categories: (1) neutron sources for fusion-fission applications; and (2) fusion systems for deep space propulsion. During the second week there was a brief discussion of the use of fusion systems for cogeneration, e.g., electricity generation plus hydrogen production. However, there were no detailed presentations on this particular application.

The specific fusion-fission applications proposed included the breeding of uranium-233, the burning of plutonium and other actinides, and the burning of depleted uranium. The fusion embodiment for these applications involved a low Q device ($Q \sim 1$-$5$) with either steady-state or high duty factor operation. The engineering and technology requirements for these applications approached those necessary for power plants. The fusion concepts proposed for the applications included the tokamak and the spherical torus, although in some peripheral discussions there was mention of using a gas dynamic trap for these applications. Some of the metrics proposed to evaluate these applications included: (1) the cost of neutrons; (2) the effectiveness of the neutrons spectrum; (3) the cost of product; and (4) $k_{eff}$ (the effective neutron multiplication factor).

With regard to deep-space propulsion applications, the fusion embodiments generally involved large-output power systems (1-8 GW) and advanced fuel cycles, primarily the D-$^3$He fuel cycle. The physics embodiments included the ST, FRC and other emerging concepts. The metrics for evaluating these applications included: (1) specific impulse; (2) exhaust velocity; (3) specific power; and (4) mission cost.

Although there were no detailed presentations on the cogeneration application, it was mentioned that such applications would involve large output power, 3-5 GW.

Table 3.1 summarizes the responses to the assessment questions for the neutron-source and the space-propulsion applications. The comments on the table are further elaborated below.

**Table 3.1 Summary of Responses to Assessment Questions**

| **Item** | **Neutron Source** | **Space Propulsion** |
|---|---|---|
| **Market Penetration & Customer** | ● Nuclear power industry<br>● DOE/Waste Disposal | ● NASA |
| **Competition** | ● Fission<br>● Accelerators<br>● Burial | ● One of the few options for deep-space missions |
| **Environment, Safety, & Licensing** | ● Applications look more like fission than fusion | ● Safety implications not yet assessed |
| **Impact on Time-scale** | ● Could provide an intermediate mission prior to pure fusion systems | ● NASA interest provides outside advocate for fusion development |
| **Key Issues** | ● Must establish a market niche<br>● Impact on fusion image<br>● Impact on pure fusion development plan<br>● Technology, reliability, & availability implications | ● Technical basis must be established |
| **Opportunities** | ● System studies<br>● NSO program | ● NASA/DOE cooperation |

## Neutron-Source Applications

Potential customers for the neutron-source applications include the nuclear power industry and the Department of Energy, Office of Waste Disposal. Fusion's competitors for these applications include fission reactors, accelerators, and burial in the case of waste disposal and Pu disposition. Compared to fission reactors, fusion systems have the advantage of a higher neutron yield per unit of energy liberated and the capability of operating in a subcritical mode. The disadvantage of fusion is that fusion technology is much less developed than fission technology. With regard to accelerators, fusion has the potential of being more energy efficient and therefore, being able to operate with a lower $k_{eff}$, i.e., a higher degree of subscriticality. The disadvantage of fusion is the perception that the accelerator technology is much further ahead, however, there was some debate on this issue. With regard to burial, fusion had the advantage (as do the accelerator and fission systems) of deriving energy from waste and Pu sources. Burial has the advantage of being a relatively simple technology, however, the burial of high-level radioactive waste and plutonium has not yet been approved in the United States. The environment, safety, and licensing aspects of the various fusion-fission applications appear to be characteristic of fission systems rather than pure fusion systems.

It appears that the neutron source application could provide an intermediate mission prior to the introduction of pure fusion systems and therefore, might represent a positive impact on the time scale for fusion development. There are several key issues associated with implementing the neutron source applications. First is the necessity to establish a market need, that is, to find a customer who advocates fusion for these applications. Second is the requirement to assess the impact such a thrust might have on the image of fusion as being relatively clean compared to fission. Third is the need to assess the impact of such a direction on the overall fusion development plan. The fourth issue relates to the technology, reliability and availability implications of fusion-fission applications relative to those of pure fusion systems. The opportunities for addressing the key issues in the near term are represented by systems studies such as the current ARIES study which is assessing the potential of fusion neutron-source applications. If the ARIES study yields positive results, then a detailed design could be pursued. It was also suggested that fusion-fission applications be considered in the Next Step Options (NSO) activity.

## Space Propulsion Applications

NASA is currently funding several studies of fusion systems for deep-space missions. Therefore, at the study level, there is currently a customer for this application. With regard to competition, fusion seems to be one of only a few options for deep-space missions. Other options such as matter-antimatter reactions and light sails represent more advanced technologies than fusion. The environmental, safety and licensing issues associated with fusion space propulsion applications have not yet been addressed. The NASA interest does provide an outside advocate for fusion development and, therefore, could have a positive impact on the fusion development time scale. The key fusion-based issues relating to this application are the same as those noted in the advanced fusion fuels discussion. Finally, opportunities associated with this application center around efforts to further pursue a NASA/DOE cooperation, which could enhance outside advocacy, and support for fusion development.

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## 4.0 SUMMARY

The answers to the four general questions considered by the Working Group can be summarized as follows:

1. What is the projected market for electrical energy production in the next century?

**The demand for non-polluting technologies will be enormous in the next century.**

2. What is fusion's potential for penetrating the energy market in the next century?

**It depends on the pace of technical progress and demonstrating fusion's environmental potential.**

3. Is there a potential role for advanced fusion fuels?

**The proposed physics embodiments required for advanced fuels need to be demonstrated.**

4. What is fusion's potential for applications other than conventional power plants?

**Several applications have been identified**.