Non-Electrical Power, Near-Term Applications of Fusion Energy

G.L. Kulcinski

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FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

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Gerald L. Kulcinski
Fusion Technology Institute, University of Wisconsin-Madison, Madison WI 53706

Abstract-A significant departure from the traditional approach of generating electricity from DT fusion power plants is suggested. This different approach recognizes that near-term commercial applications for fusion energy may be needed to sustain long-term public and private funding for fusion research. Fortunately, there are opportunities for using the fusion process to make useful products other than electricity. In the past, these applications were associated with "by-products" from large thermonuclear plasmas such as fissile material, synfuels, hydrogen, process heat, etc. Such uses require the construction of full-scale, multi-GW_{th} reactors and therefore have essentially the same timeline as commercial fusion electricity plants. More recent investigations of alternative approaches to fusion with a wide variety of fuels have revealed that there is another class of small (a few watts to < 10 kW) devices which can have immediate commercial applications even when the overall Q value (energy out/energy in) is < 1. If the production of small, sometimes portable sources of high-energy particles (neutrons, protons, and alpha particles) is cheap enough, they then can compete with other more conventional sources of radiation (accelerators and small fission reactors). Possible near-term applications are discussed with a focus on the production of medical isotopes. The use of small devices that can burn advanced fusion fuels such as D^3He also appear to be quite advantageous to this stage of fusion research.

INTRODUCTION

Presently, there is a great concern in the fusion community about the receding date of the first commercial fusion electrical power plant. Reviews of the fusion program in the U.S. by outside experts [1, 2] and by the fusion community itself [3] put that important date no sooner than 2050. In addition, even the most optimistic fusion supporters concede that it will take at least $20 billion to develop the first commercial power plant. These conclusions, coupled with the fact that keeping the American taxpayers' attention on a multibillion-dollar project for four to five decades, indicate that it will be difficult to maintain a viable fusion program to generate electricity alone.

In analyzing this situation, it is possible that at least part of the problem in the past has come from an almost exclusive focus on producing electricity with fusion energy [4-10]. All of this prompts the serious question:

"What else can be done to demonstrate tangible benefits from fusing plasmas on a much shorter time frame, say in about 5-10 years, for investments that the American taxpayer is willing to make?"

In asking such a question, one has to be careful to point out that this does not imply that the ultimate goal of producing electrical energy should be abandoned. It should not! The thesis of this paper is that developing commercial products from fusion can act as a bridge from today's science-based research program to the ultimate energy goal of generating electricity.

WHAT DOES THE FUSION PROGRAM HAVE TO SELL THAT IS UNIQUE?

In the near term, there are basically three things that can be "sold." Spin-off technologies that can happen and has occurred everyday from a large program such as fusion are excluded. Spin-offs are not something that can be scheduled nor do they justify a $200-300 million budget.

The three unique things that can be sold are (even when Q <<1):

1) a portable source of neutrons
2) a portable source of protons, and
3) a portable source of electromagnetic radiation.

Why is the word "portable" emphasized? There are plenty of "stationary" sources of neutrons in test or commercial fission reactors and the physics community has been making high-energy protons with "fixed" accelerators for over half of the 20th century. What is really meant here is the kind of radiation producing facility that can be carried around either by a person or at the most on a small truck or van.

The advantages of producing neutrons from a small (few watts) fusion source, compared to a fission reactor, include:

1) avoiding the production of fission products,
2) using a power level so low that it would not be considered a proliferating technology, and
3) producing a wide spectrum of neutron energies ranging from thermal to 15 MeV.

Similarly, the potential advantages of producing protons from a few watts of fusion power (compared to much larger accelerators or cyclotrons) include:

1) producing little auxiliary radioactivity
2) production of 3-15 MeV energetic protons, and
3) potential for much lower capital costs.

The level of particle production that can be obtained with a 1 watt fusion power device is summarized in Table 1.

Table 1. Particle production rates from selected fusion reactions

	Particles/s per Watt of Fusion Power		
	Neutrons (MeV)	Protons (MeV)	He Atoms (MeV)
DT	3.6×10^{11} (14.1)	--	3.6×10^{11} (3.52)
DD	8.6×10^{11} (2.45)	3.6×10^{11} (3.01)	--
D^3He (100 keV)	2.3×10^{10} (2.45)	3.5×10^{11} (3.01 & 14.7)	3.6×10^{11} (3.67)
$^3He^3He$	--	9.7×10^{11} (≈ 5.7)	4.9×10^{11} (1.4)
$p^{11}B$	--	--	2.2×10^{12} (2.9)

An examination of Table 1 reveals that one can obtain, from a wide variety of fusion reactions, particle production rates of 10^{10} to 10^{12} per second of both neutrons and protons in the energy range of 2.5 to 15 MeV.

The next obvious question is, what can these particles be used for?

GENERAL APPLICATIONS OF ENERGETIC FUSION NEUTRON AND PROTON SOURCES

At this point, it is convenient to classify the applications in terms of the relevant time frame (near-term and intermediate-term) mainly on the basis of the power level required. Table 2 gives a summary of the most important opportunities in each category.

Table 2. Potential non-electric commercial opportunities from fusion

	Near-term	Intermediate Term
Medical	- Isotope Production (local) - Cancer Therapy	- Isotope Production (national)
Civilian Commercial	- Proton Activation Analysis - Gemstone Enhancement - Neutron Radiography	- Production of Hydrogen - Desalinization - Neutron Irradiation Facility
Environment	- Detection of Chemical Spills	- Destruction of Fission Products
Defense	- Detection of Explosives - Detection of Chemical & Biological Weapons	- Destruction of HEU & Pu - Production of Tritium

In the near term (next 5-10 years), fusion systems that produce only a few watts steady state are considered. This means that even if the Q values are very low, e.g., 0.001, then the input power is in the kW electrical range. Obviously the applications that produce tritium, hydrogen, or burn fissile fuel or fission products [7-9] require 10's to 100's of MW and the Q values will have to be much closer to 1 if not exceeding 1.

Only a few of the potential applications are listed in Table 2 just to point out the range of medical, civilian, commercial, environmental, and defense markets that could be commercially attractive. The intermediate applications have been discussed by Waganer [7-9] and will not be discussed further in this short paper. The rest of this paper will focus on near-term applications such as those listed in Table 3.

Table 3. Selected near-term applications of portable neutron and proton sources

Neutron Applications	-Detection of Clandestine Materials -Detection of Trace Elements	-PET Isotopes ^{18}F	-Radioisotopes ^{99}Mo
Proton Applications	-PET Isotopes ^{15}O, ^{11}C, ^{13}N	-PET Isotopes ^{18}F	-Radioisotopes ^{99m}Tc
Fusion Power Level	1-10 watts	10-1,000 watts	1-100 kW
	← Nearer Term		

It is evident from Table 3 that there are at least two markets where the fusion community might have a chance to have a real near-term impact:

1) Detection of clandestine materials, and
2) Production of PET (positron emission tomography) isotopes.

In particular, the production of PET isotopes that have very short half-lives (e.g., < 20 minutes) is especially attractive.

Why is fusion uniquely suited to make these isotopes? The answer lies in the way they are produced, namely by 10-20 MeV protons. It was already shown in Table 1 that one watt of $D\text{-}^3He$ fusion power will produce 3.5×10^{11} (14.7 MeV) protons per second. The high-energy protons can produce short-lived PET isotopes via the (p,n) reaction. The cross section for such reactions in $^{15}N(p, n)^{15}O$ ($t_{1/2}$ =2.03 min) is shown in Figure 1.

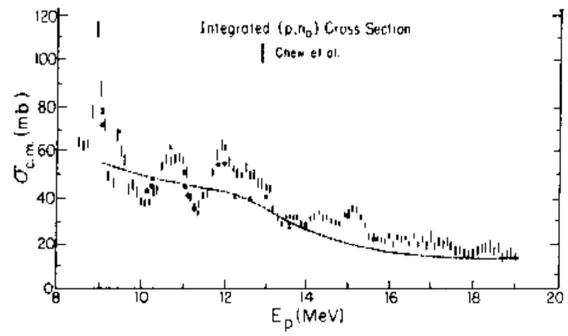

Figure 1. The cross section for producing ^{15}O from ^{15}N. After R. C. Byrd et al. [11].

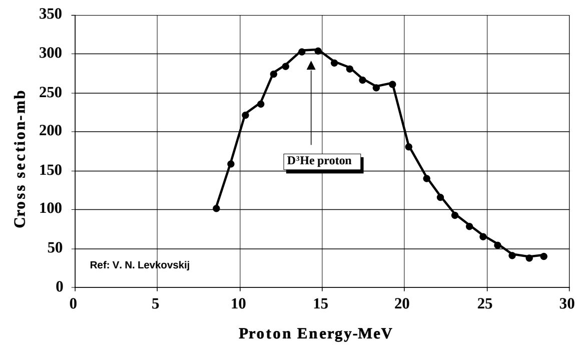

Figure 3. The $^{100}Mo(p, 2n)^{99m}Tc$ cross section. After V. N. Levkovskij [13].

Presently, the PET isotope (^{18}F) in the form of fluorodeoxyglucose (FDG) is extensively used for brain scans. However, even with a 1.8 h half-life, the exposure after the scan is made precludes the repeated use of FDG in young children and pregnant women. A much more suitable isotope would be ^{15}O with its two-minute half-life. The problem is that if the production of ^{15}O is not done right next to the patient, most of the isotope would be gone by the time it gets to the place it is needed. Therefore, if a small (≈1 watt) D-^{3}He plasma could be made and operated near the patient, one might be able to make wider use of this isotope and open up the beneficial effects of PET to a whole new class of patients. A one-watt steady state D-^{3}He source can make ≈ 8 mCi of ^{15}O, which is enough to treat several patients at a time.

Similarly, the production of ^{18}F via the $^{18}O(p, n)^{18}F$ reaction is shown in Figure 2. Note that this cross section peaks between 5-6 MeV making it a suitable candidate for the protons from the D-^{3}He reaction.

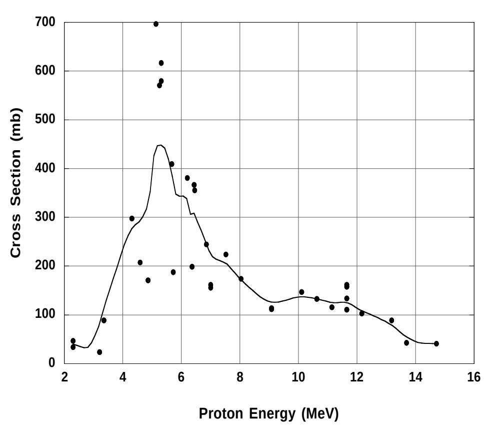

Figure 2. The (p,n) cross section for ^{18}F production peaks at 5-6 MeV [12].

Similarly, the $^{100}Mo(p, 2n)^{99m}Tc$ cross section peaks at the energy of the D-^{3}He proton. The main difference between this method of making ^{99M}Tc and the "normal" method (via fission products) is that no ^{99}Mo carrier is employed and the 6 h half-life ^{99m}Tc must be used directly.

A summary of the production and application rates of these isotopes is shown in Table 4.

Table 4. Radioisotopes particularly suited for production with protons from D-^{3}He fusion

Isotope	$t_{1/2}$	Parent Isotope	Max. Steady State Prod. @ Equilibrium (mCi per Watt)	Useful Dose (mCi)
^{15}O	2.03 min	^{15}N	8	≈ 1
^{18}F	1.83 h	^{18}O	14	1-10
^{99m}Tc	6.01 h	^{100}Mo	4	1-25

An interesting point of this table is that even with a 1 watt fusion power source, one could make the equivalent of 1-10 useful doses for the diagnosis of a wide range of cancers. If a device to do this could be manufactured for less than ≈$500,000, then it could compete directly with the accelerator network now in nearly 20 locations in the U.S. today [14].

Several research facilities in the world (U.S., Germany, and Japan) are now investigating the use of the Inertial Electrostatic Confinement (IEC) concept to produce neutrons and/or protons for the applications discussed above. One such device is currently operating at the University of Wisconsin in Madison. This facility has recently produced protons from a steady state D-^{3}He plasma at the rate of ≈ 2 x 10^5 per second [15]. The same device has also routinely produced steady state neutrons from a DD plasma at ≈ 2 x 10^7 per second. While these rates are not yet at the level that could produce commercial quantities of radioisotopes, they do serve as proof of principle demonstrations of the concept.

CONCLUSIONS

So what should one conclude from all of this? First of all, the fusion program could have a very positive, near-term impact on the production of very short half-life PET radioisotopes for diagnostic applications in hospitals.

Secondly, research into advanced fuel, very low Q devices, is relatively inexpensive as demonstrated by the University of Wisconsin IEC device [15]. The UW-IEC device is already at a proof-of-principle size and the path to milliwatt sources appears to be straightforward. An important side benefit of this work is that it will also contribute to our understanding of the long-range potential of these "second generation" fuels.

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