Alternate Applications of Fusion– Production of Radioisotopes

G.L. Kulcinski, J. Weidner, B. Cipiti, R.P. Ashley,
J.F. Santarius, S.K. Murali, G. Piefer, R. Radel

November 2002

UWFDM-1216

Presented at the 15th ANS Topical Meeting on the Technology of Fusion Energy, 17-21 November 2002, Washington, DC; published in *Fusion Science and Technology* 44, 559 (2003).

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

Alternate Applications of Fusion–Production of Radioisotopes

G. L. Kulcinski, J. Weidner, B. Cipiti,
R. P. Ashley, J. F. Santarius, S. K. Murali, G.
Piefer, and R. Radel

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

November 2002

UWFDM-1216

Presented at the 15th ANS Topical Meeting on the Technology of Fusion Energy, 17-21 November 2002, Washington, DC; published in *Fusion Science and Technology* 44, 559 (2003).

Alternate Applications of Fusion - *Production of Radioisotopes*

G. L. Kulcinski, J. Weidner, B. Cipiti, R. P. Ashley, J. F. Santarius, S. K. Murali, G. Piefer, and R. Radel
University of Wisconsin-Madison, Fusion Technology Institute
1500 Engineering Drive
Madison, WI 53706
(608) 263-2308, kulcinski@engr.wisc.edu

ABSTRACT

A major effort to find near-term, non-electric applications of fusion energy has shown that the production of radioisotopes is attractive. The use of the D^3He fusion reaction to produce Positron Emission Tomography (PET) isotopes is described. An Inertial Electrostatic Confinement (IEC) device is particularly well suited to produce low levels of high-energy (14.7 MeV) protons, which in turn, can produce short-lived PET isotopes. The IEC device at the University of Wisconsin has been modified to investigate the potential of this process to be commercially attractive.

I. INTRODUCTION

The long-range goal of fusion research around the world is clearly to provide safe, clean, and affordable electrical energy for society. However, the slowing growth rate of electricity consumption in the developed nations, the increased availability of natural gas in the short run, and difficulties in finding a suitable fusion concept and fusion fuel cycle have pushed estimates for commercially available fusion power out to the middle of the 21st century.[1] What can be done with fusion to benefit society on a more near term timeframe (next 5 to 10 years), well before breakeven (Q> 1) is achieved?

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 with more economic value than the amortized cost of the facility plus the operating cost to run the facility?" Recent research into this question has revealed some positive answers in several areas.[2,3,4] The purpose of this paper is to concentrate on one of those areas, namely, the possibilities of using fusion reactions to make medical diagnostic radioisotopes. There are certainly other potential near-term applications of fusion devices such as the production of neutrons for detection of land mines, detection of explosive devices hidden in suitcases, transmutation of long lived radioisotopes into short-lived, or even stable isotopes, etc. These applications have been discussed previously[5] and will not be repeated here.

II. NEED FOR 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.[6] 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 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.[6]

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.[6] 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).[7]

What is Positron Emission Tomography? It 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, α) reactions. An example 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.

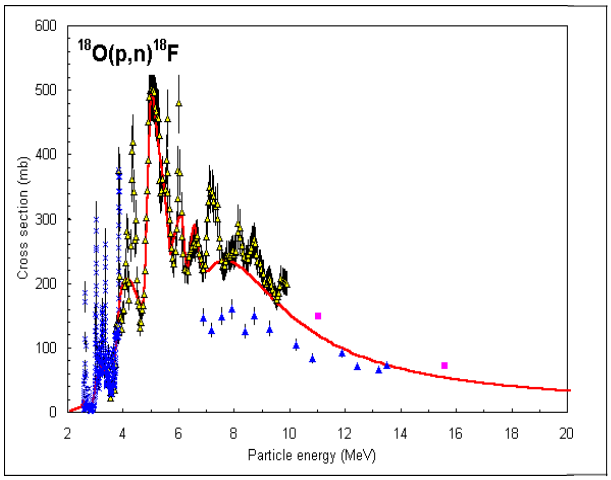

Figure 1. The nuclear cross section for the production of ^{18}F from ^{18}O requires protons of greater than 10 MeV.[8]

Unfortunately, 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 patient 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 1 and their production cross sections are shown in Figures 2-4.

Table 1. There are several potentially useful very short half-life PET isotopes that can be made with energetic protons

Parent Isotope	Production Reaction	PET Isotope	HalfLife 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

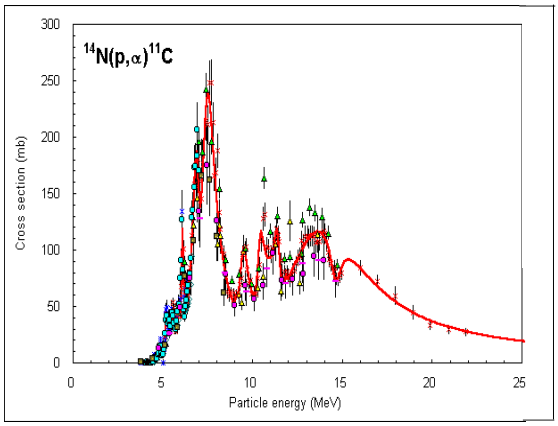

Figure 2. The nuclear cross section for the production of ^{11}C from ^{14}N requires protons of greater than 10 MeV.[9]

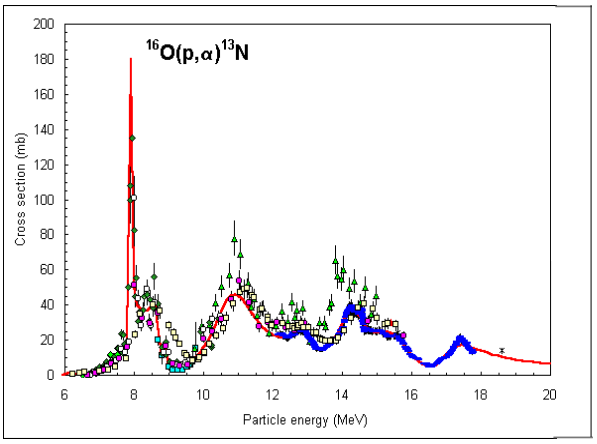

Figure 3. The nuclear cross section for the production of ^{13}N from ^{16}O requires protons of greater than 10 MeV.[9]

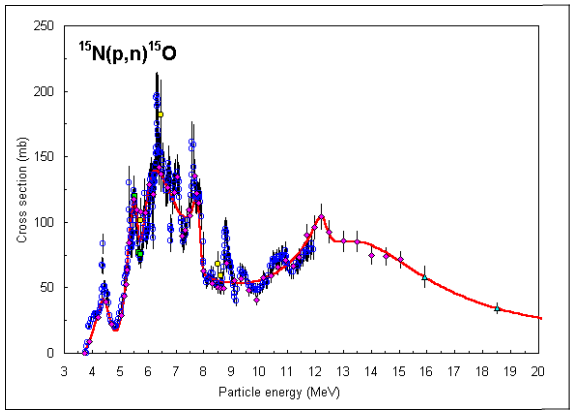

Figure 4. The nuclear cross section for the production of ^{15}O from ^{15}N requires protons of greater than 10 MeV.[9]

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.

III. THE FUSION CONNECTION

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:

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

As can be seen from Figures 1-4, 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.

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. Fortunately, this second-generation fuel cycle can be readily produced in an Inertial Electrostatic Confinement (IEC) device of the type currently in operation at the University of Wisconsin (UW).[9,10,11] Figure 5 shows the most recent IEC chamber to be put into operation at Wisconsin. It is a double-walled, water-cooled stainless steel device with special construction to accommodate ion injection guns. A typical picture of a plasma in the cathode of the chamber is shown in Figure 6.

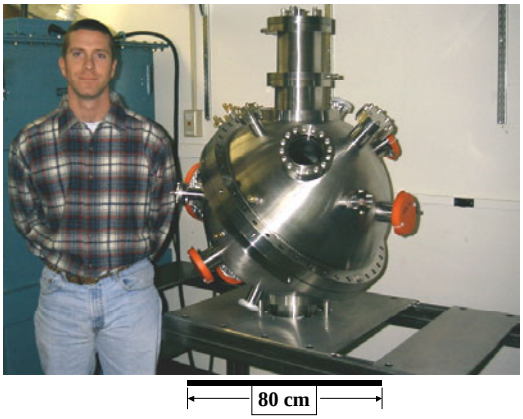

Figure 5. The water-cooled, double-walled, stainless steel chamber at the University of Wisconsin is capable of producing a steady state flux of D^{3}He fusion protons at 14.7 MeV.

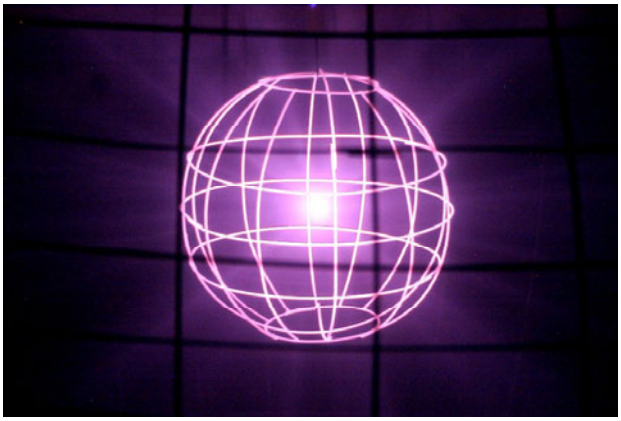

Figure 6. A typical plasma in the University of Wisconsin IEC fusion chamber. The cathode is 10 cm in diameter.

The aluminum UW-IEC chamber currently in operation routinely generates steady-state DD and D^3He plasmas at approximately the 1 mW level (≈ 3 x 10^8 reactions/second). This device has already produced small quantities of ^{94m}Tc isotopes[12] by bombarding ^{94}Mo with protons from a D^3He reaction as a proof of principle. Weidner et al.[13] have constructed a water target, consisting of 100 micron thick Al tubes, capable of using the D^3He protons to produce ^{13}N (see Figure 3 for the cross section of the $^{16}O(p, \alpha)^{13}N$ reaction). The current estimate of an IEC device designed to just produce PET isotopes is in the $50-100k level.[14]

One can estimate the amount of radioisotopes that can be produced in a D^3He fusion device from the thick target yields measured with an accelerator (see Table 2). Note that a 14.7 MeV proton will lose 2-3 MeV in passing through a 100-micron thick Al tube containing the target material and therefore the proton incident on the target isotopes will be on the order of ≈ 11 MeV.

Table 2. Experimental Production Rate of Thick Target Positron Emitting Isotopes at the University of Wisconsin[15]

PET Isotope	Half Life minutes	Production Reaction	Experimental Measurements @ 11 MeV and Saturation, mCi/ A
^{18}F	110	$^{18}O(p, n)$	120
^{94m}Tc	52	$^{94}Mo(p, n)$	TBD
^{11}C	20	$^{14}N(p, \alpha)$	80
^{13}N	10	$^{16}O(p, \alpha)$ $^{13}C(p, n)$	7 (water) 133 (Solid C)
^{15}O	2	$^{15}N(p, n)$	70

A typical amount of PET isotope used per procedure is ≈ 0.1 to 1 mCi. This implies that ≈ 1 steady-state microamp (6 x 10^{12} /s) of protons is needed to produce one dose. Depending on the spatial origin of the D^3He reactions (e.g., converged core, charge exchange or embedded fusion), such fluxes of protons will require increased reaction rates by 4 orders of magnitude over the present values. These higher levels of performance could be obtained through a combination of effects in IEC devices such as:

- increasing the cathode voltage,
- increasing the fraction of $^3He^{++}$
- increasing the ion current,
- increasing the background pressure.

All of these possibilities will be the focus of future work.

VI. CONCLUSIONS

It is possible to produce proof of principle levels of PET isotopes in an IEC device using the 14.7 MeV protons from the D^3He fusion reaction. The advantage of this method of producing PET isotopes is that smaller and less expensive facilities (as compared to accelerators) would be possible for use in small towns or remote locations. This approach may be particularly attractive when individual doses are needed, but it will be difficult to serve large, high-demand markets with IEC devices as presently envisioned.

ACKNOWLEDGEMENT

The work was performed with funding from the Grainger Foundation, the Wilson Greatbatch Foundation, and the University of Wisconsin.

REFERENCES

1. "Critical Negotiations Set for Fusion's Future", Nuclear News, American Nuclear Society, October 2002, pp. 60-61.

2. G. L. Kulcinski, "Near Term Commercial Opportunities from Long Range Fusion Research", Fusion Technology, 30(3), 411 (1996).

3. G. L. Kulcinski, "Non-Electric Applications of Fusion Energy – An Important Precursor to Commercial Electric Power", Fusion Technology, 34, 477 (1998).

4. G. L. Kulcinski, "Non-Electrical Power, Near Term Applications of Fusion Energy", IEEE Publication 99CH37050, pg. 5-13, 18th Symposium on Fusion Engineering, October 1999.

5. G. L. Kulcinski and J. F. Santarius, "New Opportunities for Fusion in the 21st Century-Advanced Fuels", Fusion Technology, Vol. 39, p. 480 (2001).

6. "Beneficial Uses and Production of Isotopes-2000 Update," OECD Nuclear Energy Agency, Paris, 2000.

7. FDA Reform Bill Passed by the United States Congress in 1997 (also see Department of Health and Human Services "Medicare Coverage Issues Manual", Change Requests 860 and 861, April 1999).

8. "Charged-Particle Cross Section Database for Medical Radioisotope Production", IAEA-TECDOC-1221 (May 2001).

9. R. P. Ashley, G. L. Kulcinski, J. F. Santarius, S. Krupakar Murali, G. Piefer, and R. Radel, "D-^{3}He Fusion in an Inertial Electrostatic Confinement Device", p. 35 in the 18th IEEE/NPSS Symposium on Fusion Engineering, Oct. 1999, Published by IEEE, 99CH37050.

10 .R. P. Ashley, G. L. Kulcinski, J. F. Santarius, S. Krupakar Murali, G. Piefer, and R. Radel "Steady State D^{3}He Proton Production in an IEC Fusion Device", Fusion Technology, Vol. 39, p. 546 (2001).

11. R. P. Ashley, et. al., this conference.

12. B Cipiti, et. al., this conference.

13. J. Weidner et. al., this conference.

14. J. Sved, "The Commercial IEC Portable Neutron Source", Trans. Am. Nucl. Soc., **77**, 504 (1997).

15. R. J. Nickles, "Production of a Broad Range of Radionuclides with an 11 MeV Proton Cyclotron", J Label Comp Radiopharm. 30:120-122 (1991).