Alternate Applications of Fusion–Production of Radioisotopes


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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/He 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. 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<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. 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 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. 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. 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).\textsuperscript{7}

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 \textsuperscript{18}F to avoid irradiation of the patient long after the diagnostic procedure is completed (it takes \(\approx\) 10 half lives, or 18 hours for \textsuperscript{18}F to “disappear”). Half lives in the 1- to 10-minute range would expose more sensitive patients (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

<table>
<thead>
<tr>
<th>Parent Isotope</th>
<th>Production Reaction</th>
<th>PET Isotope</th>
<th>HalfLife Minutes</th>
</tr>
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<tbody>
<tr>
<td>\textsuperscript{17}O</td>
<td>(p, n)</td>
<td>\textsuperscript{18}F</td>
<td>110</td>
</tr>
<tr>
<td>\textsuperscript{94}Mo</td>
<td>(p, n)</td>
<td>\textsuperscript{94m}Tc</td>
<td>52</td>
</tr>
<tr>
<td>\textsuperscript{14}N</td>
<td>(p, \alpha)</td>
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<td>20</td>
</tr>
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<td>(p, n)</td>
<td>\textsuperscript{13}N</td>
<td>10</td>
</tr>
<tr>
<td>\textsuperscript{15}O</td>
<td>(p, n)</td>
<td>\textsuperscript{15}O</td>
<td>2</td>
</tr>
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</table>

The most common method of producing PET isotopes today such as \textsuperscript{18}F is with accelerators via (p, n) or (p, \alpha) reactions. An example of the \textsuperscript{16}O(p, n)\textsuperscript{18}F cross-section is shown in Figure 1. It is apparent that proton energies of \(\approx\) 10 MeV or greater are needed to maximize the production of \textsuperscript{18}F.

![Figure 1](image1.png)

Figure 1. The nuclear cross section for the production of \textsuperscript{18}F from \textsuperscript{16}O requires protons of greater than 10 MeV.\textsuperscript{8}

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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-^3He) is a 14.7 MeV proton that can be used to make valuable short-lived PET isotopes. The reaction is listed below:

\[
D + ^3He \rightarrow p \ (14.7 \text{ MeV}) + ^4He \ (3.7 \text{ MeV}). \quad (1)
\]

As can be seen from Figures 1-4, some PET isotopes are quite easily produced via (p, n) or (p, α) reactions above \(\approx 5 \text{ MeV}\). Therefore, what is needed is a device in which controlled D-^3He fusion can be produced on a steady-state basis.

Normally, the D-^3He reaction is not one that is easily initiated in “conventional” magnetic or inertial confinement devices because of the need for very high, \(\approx 50 \text{ keV}\) 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). 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.
The aluminum UW-IEC chamber currently in operation routinely generates steady-state DD and D³He plasmas at approximately the 1 mW level ($\approx 3 \times 10^8$ reactions/second). This device has already produced small quantities of $^{94m}$Tc isotopes by bombarding $^{94}$Mo with protons from a D³He reaction as a proof of principle. Weidner et al. have constructed a water target, consisting of 100 micron thick Al tubes, capable of using the D³He 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.

One can estimate the amount of radioisotopes that can be produced in a D³He 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 $\approx 11$ MeV.

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

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

A typical amount of PET isotope used per procedure is $\approx 0.1$ to 1 mCi. This implies that $\approx 1$ steady-state microamp ($6 \times 10^{12} /s$) of protons is needed to produce one dose. Depending on the spatial origin of the D³He 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 $^3$He$^+$
- 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 D³He 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

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REFERENCES


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