Non-Electric Applications of Fusion Energy – An Important Precursor to Commercial Electric Power

G.L. Kulcinski

June 1998

UWFDM-1087

Presented at the 13th Topical Meeting on the Technology of Fusion Energy, June 7–11, 1998, Nashville TN

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

NON-ELECTRIC APPLICATIONS OF FUSION ENERGY-- AN IMPORTANT PRECURSOR TO COMMERCIAL ELECTRIC POWER

G. L. Kulcinski
University of Wisconsin-Madison, Fusion Technology Institute
1500 Engineering Drive
Madison, Wisconsin 53706-1687 USA
(608) 263-2308

ABSTRACT

A significant departure from the traditional approach to large DT tokamak fusion power plants is suggested. The new approach recognizes that near-term commercial applications for fusion energy may be needed to sustain another 40-50 years of public and private funding. Such funding is necessary to reach the ultimate potential of fusion energy, the production of safe, clean and economic electrical energy. 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 appear to be quite advantageous to this stage of fusion research.

I. INTRODUCTION

In the 1970's and 1980's, the U. S. magnetic fusion community was almost exclusively focused on building a proof of principle (POP) tokamak device. The plan was then to move on to an experimental power reactor (EPR), then to a demonstration power reactor (DPR), and finally to a commercial power reactor (CPR). However, a combination of budget cuts and the realization that the DT tokamak, as currently envisioned, may not be commercially viable has forced a drastic reconsideration of that philosophy.

There are currently suggestions to replace the DT tokamak POP, EPR, DPR, and CPR approach with one in which the confinement concept can attain POP at more modest sizes (costs).[1,2] Still, this latter approach will require decades before economic electricity can be produced from fusion. This long time period has clearly frustrated the taxpayers who have already funded magnetic fusion research for over 40 years to the tune of $13 billion (in 1998$). Furthermore, there is little electric utility or private industry financial support of a program that appears to be at least 50 years away from producing a commercially acceptable product.

Another way to eventually realize the long-range potential of fusion energy while at the same time retaining the interest of the financial community, is to recognize that fusion has a great deal to contribute to society *before* it makes electricity.[3,4] The use of fusion fuels (such as those listed in Table 1) in low Q (where Q is defined as output energy/input energy) devices can produce copious amounts of high energy neutrons, protons, and alpha particles as well as high intensities of electrons, x-rays, and gamma rays. Some of these particles are relatively unique (e.g., 14 MeV neutrons, 15 MeV protons, etc.) and they can be used to make commercial products for today's marketplace.

Table 1. Selected Fusion Reactions That Could Be Used to Produce High Energy Nuclear Particles for Near-Term Applications

D + T --> n(14.07 MeV) + ^{4}He (3.52 MeV)
D + ^{3}He --> p(14.68 MeV) + ^{4}He (3.67 MeV)
D + D ---50%---> n(2.45 MeV) + ^{3}He(0.82 MeV) ---50%---> p(3.02 MeV) + T(1.01MeV)

A short list of the products or applications includes:[4,5,21]

1. Production of radioisotopes for medical and industrial applications
2. Detection of contraband materials
3. "Burning" of radioactive waste
4. Destruction of hazardous materials

An example of how a restructured fusion program would appear if it concentrated on near term products (while keeping in mind the long-range goal of electricity production) is shown schematically in Figure 1. The main difference between the "commercial products" approach and the "traditional" approach is that one would start with small, inexpensive devices with Q << 1. It would also be helpful if such devices were well suited to burning the advanced fusion fuel, D^3He, in addition to DT. As we shall see, the D^3He cycle is critical to the commercial

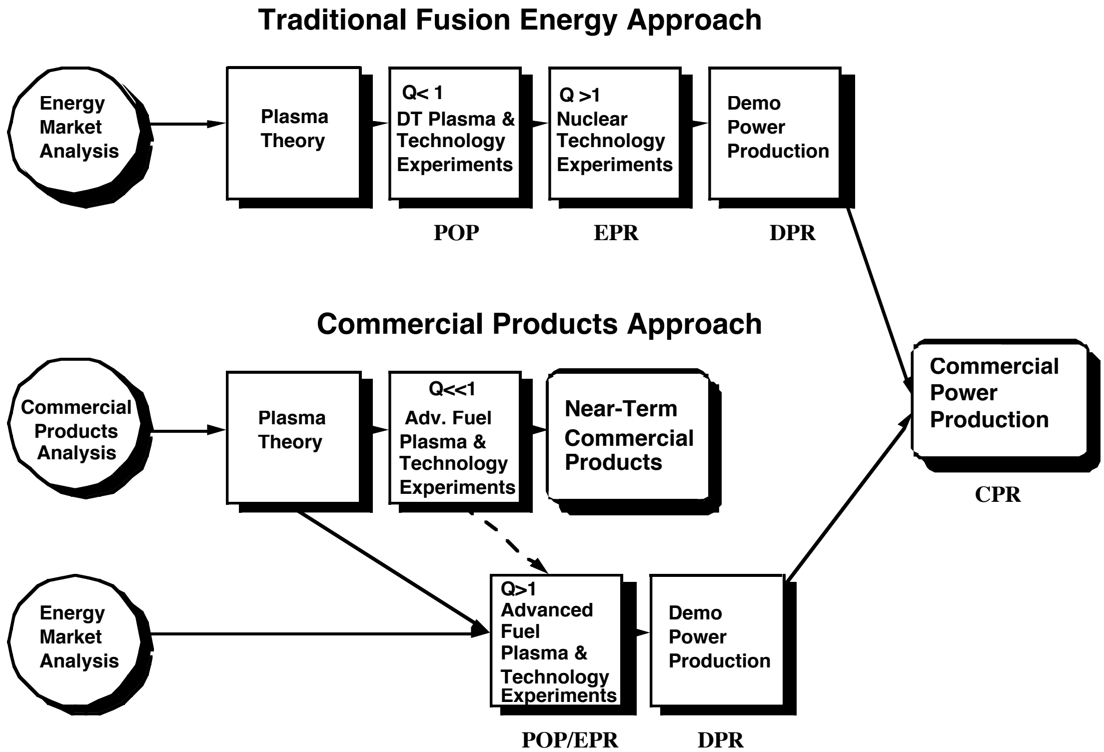

Figure 1. One possible approach to a more attractive fusion program.

product scenario because of its ≈15 MeV proton reaction product. If the public and financial institutions were "rewarded" with useful commercial products from fusion at an early stage, they then might be more willing to make the long-range investment in a cleaner and safer form of energy. Meanwhile, as researchers build large numbers of Q<1 devices, they should be able to understand more of the physics issues and, therefore, build improved units in the future. If the advanced fusion fuel cycles are used, there are then fewer technology problems to solve because of the low neutron production, and the POP and EPR might then be combined into a single unit built at a later time. This "bootstrap" approach may cost considerably less annually (and in total) than the "traditional" POP->EPR->DPR->CPR approach to multi-GWe units. The lower costs could be realized because the larger units will have to be designed very conservatively, pushing the total developmental costs up as well. If a given low Q concept used to make products does not appear feasible for Q>>1 operation, then very little net cost will accrue to the public.

An example of one class of commercial products that can be made in fusion devices for near-term markets is the production of radioisotopes. For the remainder of this paper, the isotope production potential of fusing plasmas will be explored (see reference 4 for other applications).

II. MARKET FOR RADIOISOTOPES

The worldwide market for radioisotopes can be separated into three areas: medical, industrial, and research. The A. D. Andersen Corporation, in a 1994 report[6], estimated the annual level of worldwide demand for radioisotopes to be ≈ $102 million, with ≈$59 million for medical isotopes, ≈$39 million for industrial isotopes, and ≈$4 million for research isotopes. Commercial sales account for 96% of all revenue.

In the U. S. alone, over 12 million nuclear medical procedures are conducted annually and the total value of these procedures is estimated to be $7-10 billion per year.[7,8] Unfortunately, the major supply of these radioisotopes currently comes from aging and/or non-U. S. sources, and there is a great deal of uneasiness in the domestic market. There are also many cases where the cost of certain radioisotopes are too high for their introduction on a commercial scale even though the isotopes might have great benefits for society. All of this evidence points to a situation where new domestic sources are sorely needed. Obviously, low Q fusion devices could be one of the new domestic sources.

A more detailed analysis of the specific radioisotopes currently in demand is given in Table 2. It is especially important to note that while there are dozens of isotopes used in the commercial world, two of them – ^{99}Mo and

^{60}Co – comprise ≈75% of the market. All the rest of the radioisotopes account for less than a few percent of the market each. The long half-life of ^{60}Co and the ease with which it can be made in fission reactors make it a less attractive target for fusion devices than ^{99}Mo.

Table 2. The 1994 World Demand for Radioisotopes[6,7]

Isotope	Half Life	Market-$ Millions	Est. Growth Rate-%
Medicine			
Mo-99	2.7 d	43	5-10
I-125	59.4 d	2.9	3-4
Xe-133	5.2 d	2.3	3-4
I-131	8.0 d	2.0	5-6
Cs-137	30.1 y	1.7	5-6
Co-60 (med.)	5.3 y	1.5	10-20
Sr-82	25.6 d	1.4	50-100
Others		4.2	4-5
Total Medicine		59	≈5
Industry			
Co-60 (indust.)	5.3 y	30	3-4
Ir-192	73.8 d	4.5	5-6
Cf-252	2.6 y	1.6	5-6
H-3	12.3 y	1.0	3-4
Ge-68	270.8 d	0.5	3-4
Others		1.7	4-5
Total Industry		39.3	≈4
Research			
H-3	12.3 y	1.1	2-3
Y-90	2.7 d	0.5	5-6
Others		2.1	2-3
Total Research		3.7	≈3
Total Market		102	≈5

A. Molybdenum-99 Production

The special case of the $^{99}Mo/^{99m}Tc$ generator is worthy of further analysis. First of all, the ^{99}Mo parent has a 65.9 h half-life and the daughter, ^{99m}Tc, which is extracted from the parent at the site of use, has a 6.01 h half-life and emits a 140 keV photon. This latter isotope is the most widely used radionuclide in clinical nuclear medicine, with approximately 38,000 imaging procedures[10] conducted every day! The ^{99m}Tc is used to label carrier agents that are deposited in specific areas of the body that will then produce images of various organs and bone structures.

The worldwide market for ^{99}Mo is ≈ 5,700 curies (6 day)/week. A 6-day curie is defined as the amount of product, in curies, remaining 6 days after the product is delivered to the radiopharmaceutical company. In spite of the fact that the U. S. demand accounts for approximately half of that number,[9] there is currently no domestic supplier. Most of the domestic supply comes from the 40-year-old National Research Universal (NDU) reactor in Chalk River, Canada. Because of the short half-life of the ^{99}Mo, the U. S. is literally within weeks of a complete loss of this critical isotope should the NDU reactor be shut down because of a variety of possible failure modes. To counter this problem, the U. S. has recently proposed using a small facility at Sandia National Laboratory to provide 10-30% of the U.S. needs.[9]

Essentially all the current ^{99}Mo is produced as a by-product of ^{235}U fission. The ^{99}Mo is separated from the fission products and shipped to the site of application where the ^{99m}Tc is "milked" from the molybdenum substrate. There have been proposals to produce ^{99}Mo in proton accelerators via the $^{100}Mo(p, pn)^{99}Mo$ reaction or to produce the ^{99m}Tc directly from the $^{100}Mo(p, 2n)^{99m}Tc$ reaction[10-11] (see Figure 2 for the $^{100}Mo(p, 2n)\,^{99m}Tc$ cross section[12]). This latter reaction is particularly well suited to advanced fusion fuels as the peak of the direct ^{99m}Tc production cross section occurs at 15 MeV, exactly at the energy of protons emitted from a D^3He fusion reaction. Even though there is no ^{99}Mo or ^{99m}Tc currently on the market that has been produced in an accelerator, the possibility of using a 300-watt D^3He device for commercial products warrants further investigation[4].

B. Positron Emission Tomography Isotopes

One of the most popular isotopes used in Positron Emission Tomography (PET) is ^{18}F. It is used for a large number of diagnostic procedures and is particularly good for brain scans. The ^{18}F isotope can be produced by bombarding Li_2CO_3 (enriched in ^6Li) with thermal neutrons (Figure 3) or by proton bombardment of ^{18}O or ^{21}Ne. Either bombarding particle can be produced by fusing plasmas and, if the fusion device were small enough, it could produce the desired quantities on site for "just-in-time" applications.

Because of the 1.8-h half-life of ^{18}F and the exposure received by the patient after the test, this isotope is currently not used in pregnant women and children. On the other hand, if a much shorter half-life isotope were available, the residual dose following the diagnostic procedure would be less. One isotope that fills this requirement is ^{15}O (half-life ≈2 min). The problem with this isotope is that its half-life is so short that it is impossible to manufacture ^{15}O at a location very far from

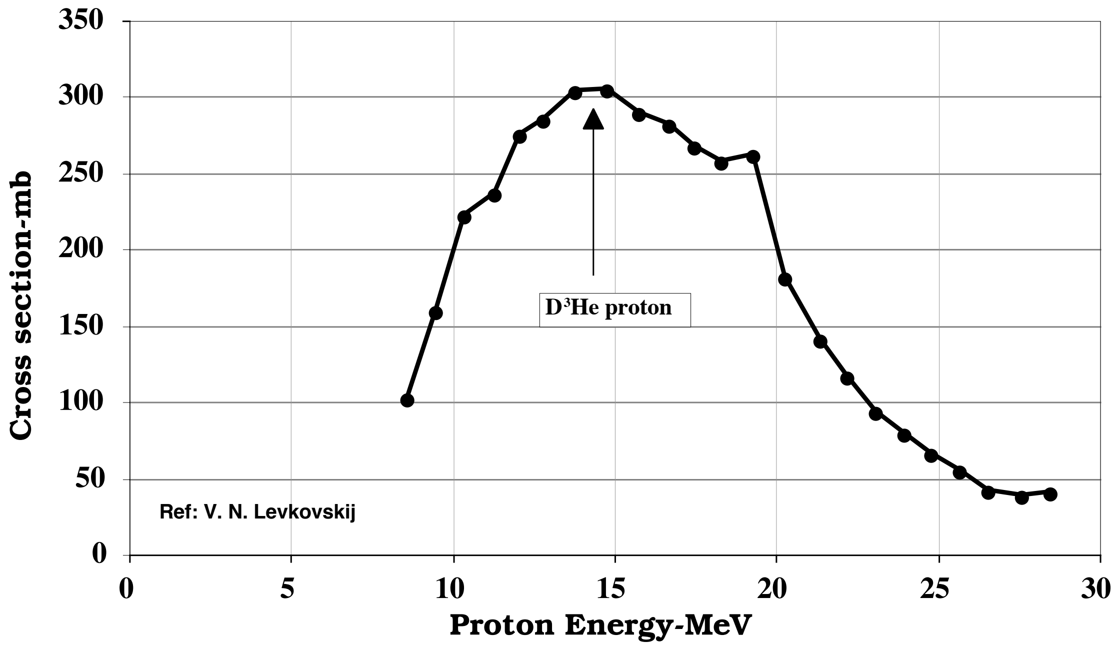

Figure 2. The direct production of ^{99m}Tc from ^{100}Mo by energetic neutrons peaks at the D^{3}He proton energy.

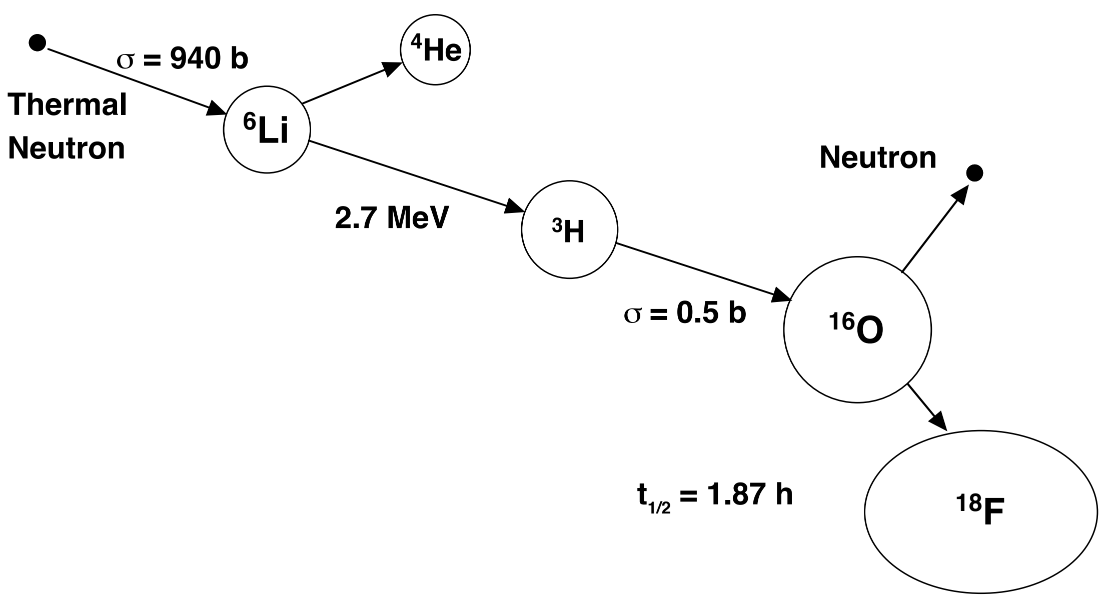

Figure 3. The ^{18}F isotope can be produced by thermal neutron bombardment of Li_2CO_3 enriched with ^{6}Li (after Bayless).

the actual point where it will be used. A small (1-watt) D^{3}He source could produce ≈1 Ci (steady state) of ^{15}O from the (p, n) reaction with ^{15}N (see Figure 4 for the ^{15}N [p, n] ^{15}O cross section). Such a fusion source could be used in close proximity to a patient because of the limited shielding required by this fusion reaction. In this case, even a Q = 10^{-3} source would require a power supply of only 1 kW. It could literally be a "coffee cart" source of radioisotopes that is needed to compete with larger cyclotrons that are, of course, not mobile.

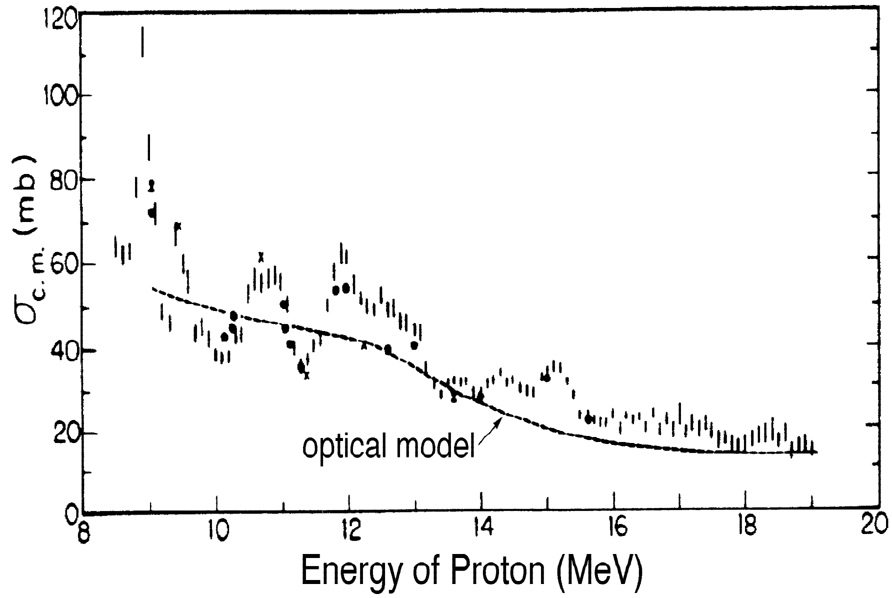

Figure 4. The measured and calculated cross section for production of ^{15}O with high energy protons (after Byrd et al.[13])

C. Other Isotopes Which May Be Produced In Fusion Facilities

There are at least three classes of isotopes that can be considered for production in fusion devices that do not include fissile material (see references 7-9 for further discussion).

Those isotopes currently in use:

- ^{125}I-Prostate cancer treatment
- ^{133}Xe-To measure blood flow and lung functions
- ^{192}Ir-Cancer therapy and nondestructive testing of welds
- ^{32}P-Pain relief for bone, breast, and prostate cancers
- ^{89}Sr-Pain relief from bone cancers
- ^{201}Tl-Heart muscle analysis

Those isotopes that would be used more if they were less expensive:

- ^{111}In-Imaging and radioimmunotherapy
- ^{127}Xe-Analysis of lung ventilation
- ^{81m}Kr-Analysis of lung ventilation
- PET isotopes-^{11}C, ^{13}N

Those isotopes that are new and show promise but need an economical and reliable production process:

- PET isotopes-^{68}Ga, ^{62}Cu, ^{52m}Mn, ^{72}As, ^{87m}Sr, ^{124}I, and ^{134}La.
- SPECT isotopes-^{97}Ru, ^{203}Pb for heart diagnosis
- ^{67}Ga-Tumor and cancer imaging

A summary of those fusion fuel cycles particularly suited for producing the isotopes listed above is given in Table 3.

Table 3. Radioisotopes That Can Be Produced By Near-Term Fusion Fuel Cycles (Without Using Fissile Material)

	DT or DD (n, γ), (n, p), (n, α), (n, 2n)	D^3He (p, n), (p, pn), (p, 2n), (p, α)
High Market Volume	^{99}Mo, ^{60}Co	^{99}Mo, ^{99m}Tc
Potential for Growth	^{18}F, ^{32}P, ^{68}Ga, ^{81m}Kr, ^{89}Sr, ^{97}Ru, ^{127}Xe, ^{133}Xe, ^{192}Ir, ^{203}Pb	^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{67}Ga, ^{68}Ga, ^{81m}Kr, ^{87}Y, ^{111}In, ^{124}I, ^{125}I, ^{127}Xe, ^{192}Ir, ^{201}Tl, ^{203}Pb

III. WHAT KIND OF FUSION DEVICES WOULD BE BEST SUITED FOR ISOTOPE PRODUCTION?

As can be gathered from the previous discussion, small (1 to a few 100 watts) fusion facilities that are portable and affordable. In addition, those devices that can burn the advanced fusion fuel cycle D^3He also would be favored. Since there is no initial requirement to achieve Q>1, Q values as low as $\approx 10^{-3}$ might be acceptable. These criteria are consistent with the Inertial Electrostatic Confinement (IEC) devices that have been discussed in the literature by several authors.[3,4,14-19] Thus far, steady-state IEC fusion plasmas have produced 10^{10} n/s ($\approx$30 milliwatt) from the DT reaction,[19] and recent experiments[20] have produced 10^7 n/s from the DD cycle (equivalent to ≈10^9 n/s from DT). Experiments are now underway to burn D^3He in an IEC device at the University of Wisconsin[20] at the few milliwatt level. Since current IEC devices cost ≈$60,000, development of improved models can be done rather inexpensively[18].

Devices that may be able to produce kilowatts of fusion power (particle strengths of 10^{14}/s) include the Field Reversed Configuration (FRC) or even a small Spherical Torus (ST). Since both of these devices have high beta (plasma pressure/magnetic pressure) characteristics, they are also well suited to burn the advanced fuels. The cost for Q<1 FRC or ST devices can only be estimated at this time but they are likely to run in the tens of millions of dollars and the configurations, as currently understood, are not particularly small or mobile.

IV. CONCLUSIONS

It has become clear that the scientific community must address three very troublesome issues if fusion is ever to produce commercial electric power. These issues are:

- Developing fusion concepts that require smaller prototypes than the DT tokamak
- Designing an economical fusion power plant
- Developing near-term commercial products

With regard to the latter issue, the most promising near-term commercial applications appear to be the production of medical isotopes. The production of ^{99}Mo or ^{99m}Tc appears to have the greatest financial attractiveness while the production of PET isotopes may produce the largest growth.

A promising fusion concept that satisfies the need for small and inexpensive units, as well as possessing the ability to burn the advanced fuels, particularly D^3He, is the Inertial Electric Confinement concept. If successful, this concept could effectively compete with fission reactors and cyclotrons in the production of medical and industrial radioisotopes.

ACKNOWLEDGMENTS

Funding for this work was provided by the Grainger Foundation and the University of Wisconsin.

REFERENCES

1. A. Lawler and J. Glanz, "Competition Heats Up on the Road to Fusion", Science, **281**, 26 (1998).

2. Robert L. Hirsch, Gerald L. Kulcinski, and Ramy Shanny, "Fusion Research With a Future", Issues in Science and Technology, Vol. XIII, 4(60) (Summer 1997).

3. G. L. Kulcinski and J. F. Santarius, "Reducing the Barriers to Fusion Electric Power", to be published in J. Fusion Technology (1998).

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

5. G. L. Kulcinski, J. F. Santarius, and H. Y. Khater, "Overview of Neutron/Proton Source Applications from IEC Fusion Devices", Trans. Am. Nucl. Soc., **77**, 507 (1997).

6. A. Andersen, "Worldwide Isotope Market Update: U.S. Dept. of Energy, Isotope Production and Distribution Program" (1993).

7. K. M. Spicer, et al., "Evaluation of the Medical Radionuclide Production with the Accelerator Production of Tritium (APT) Facility", University of South Carolina (1997).

8. S. J. Adelstein and F. J. Manning, eds., Isotopes for Medicine and the Life Sciences, National Academy Press, Washington D.C. (1995).

9. U. S. Department of Energy, "Medical Isotopes Production Project: Molybdenum-99 and Related Isotopes. Environmental Impact Statement", U. S. Dept. of Energy, Office of Nuclear Energy, Science and Technology, Washington D. C. (1996).

10. M. P. Iturralde, "Molybdenum-99 Production in South Africa", Euro. J. Nucl. Med., **23(12)**, 1681 (1996).

11. M. C. Lagunas-Solar et al., "Cyclotron Production of NCA ^{99m}Tc and ^{99}Mo. An Alternative Non-Reactor Supply Source of Instant ^{99m}Tc and ^{99}Mo->^{99m}Tc Generators", Int. J. Radiat. Appl. Instrum. Part A, **42(7)**, 643 (1991).

12. V. N. Levkovskij in the National Nuclear Data Center File-CSISRS, "Experimental Data on Neutron, Photon, And Charged Particle Reactions" (1981).

13. R. C. Byrd et al., "Measurement and Lane-Model Analysis of Cross Sections for the ^{13}C(p, n)^{13}N and ^{15}N(p, n)^{15}O Reactions", Nuclear Physics, **A351**, 189 (1981)

14. G. L. Kulcinski, J. F. Santarius, and H. Y. Khater, "Overview of Neutron/Proton Source Applications From IEC Fusion Devices", Trans. Am. Nucl. Soc., **77**, 504 (1997).

15. G. H. Miley et al., "An Intense Electrostatic Confinement Neutron/Proton Source", *Dense Z-Pinches*, 675.

16. M. Haines and A. Knight, eds., AIP Conf. Series 299, AIP Press (1994).

17. R. Nieble, Los Alamos National Laboratory, to be published.

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

19. R. L. Hirsch, "Inertial-Electrostatic Confinement of Ionized Fusion Gases," J. of Applied Physics, **38**(11), 45-22 (October 1997).

20. T. A. Thorson, R. D. Durst, R. J. Fonck, and L. P. Wainwright, "Convergence, Electric Potential, And Density Measurements In A Spherically Convergent Ion Focus", Phys. Plasmas, **4** (1), 4 (1997).

21. L.M. Waganer, "Assessment of Markets and Customers of Fusion Applications," 17th IEEE/NPSS Symposium on Fusion Engineering, San Diego, CA, October 6-10, 1998, p. 1039.