Near Term Commercial Opportunities from Long Range Fusion Research

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NEAR TERM COMMERCIAL OPPORTUNITIES FROM LONG RANGE FUSION RESEARCH

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ABSTRACT

An alternate approach to the development of safe, clean, and economical fusion energy for the 21st Century is presented. Instead of continuing exclusively on the path of larger and more costly magnetic confinement fusion reactors based on the DT cycle, it is proposed that near term commercial opportunities using fusion plasmas be identified and pursued. Specific examples of such opportunities are given in the areas of the detection of explosives, the production of medical isotopes, and the destruction of long lived fission product isotopes. It is also suggested that a more profitable path to the goal of fusion electricity might be to concentrate on small, simple devices that eventually can burn the more advanced fusion fuels that emit few if any neutrons. Such devices could gain back the public confidence and counter the "fusion is always 50 years away" syndrome.

I. INTRODUCTION

The fusion community now finds itself in a very precarious position. It is trying to develop a safe, clean, and economical energy source to replace fossil and fission fuels in the middle of the 21st Century while a growing fraction of society sees no urgency for such a program in the 1990's. It also appears that a large number of legislators in the U. S. are also growing weary of the financial cost.[1−4]

The quest for this energy source began nearly 50 years ago and after spending over 12 billion dollars (1995$) on the magnetic confinement[5] approach (mainly on tokamaks), and another 6 billion dollars (1995$) on the inertial confinement[5] approach, we still have not collected more energy than we have invested to produce the fusion reactions in the first place. Furthermore, the international magnetic fusion community is on the verge of requesting another 10 billion dollars to build a DT fueled tokamak (called ITER[6]) which, when completed, still will not have produced a single watt of electricity by $\approx$ 2010. There is considerable doubt whether the United States will be a major partner in such a project.[7] A further disconcerting note is that some representatives of the "customer" for fusion electricity, the electric utility industry, have recently expressed reservations about ever buying a DT tokamak for their grids.[8−9] While most fusion scientists and engineers believe that an attractive confinement/fuel concept can be developed, the present budget cutting climate and the commitment to ever larger and larger facilities have almost completely eliminated work on truly innovative fusion ideas in the U.S.

United States history includes many examples of large scale science/energy projects, such as the Superconducting Super-Collider[10] (SSC), the Liquid Metal Fast Breeder[11] (LMFBR), and the Synthetic Fuels[12] program (SF) which have had similar difficulties. Each of these projects had lofty goals, each had their costs escalate into the multi-billion dollar range, and each was canceled within the past 15 years. While the conditions for canceling each of the projects were different, the proponents of these programs all misjudged what the public (through the Congress) was willing to support with tax dollars. Similarly, industrial managers did not view these projects as worthy of substantial financial support with their own funds and the programs have essentially disappeared.

Is there another way that we can develop new energy sources for the future without suffering the same consequences as the SSC, LMFBR, and SF projects?

The purpose of this paper is to suggest a different approach to achieve the same goal, i.e., safe, clean, and economical energy in the 21st Century. That approach, described in the rest of the paper, capitalizes on near term commercial opportunities using fusing plasmas in smaller and simpler devices than now produced in current and projected DT tokamaks. The way to implement this approach will require some thinking "outside the box" which may not be initially pleasant to those of us who are long time fusion advocates. However, if the present course of action is continued, fusion advocates may in fact join those SSC, LMFBR, and SF advocates in retirement or in pursuit of other jobs as we try to analyze what went wrong in the 90's with our plans to commercialize fusion.

II. WHY IS THE PRESENT MAGNETIC FUSION PROGRAM NOT WORKING?

Consumers have generally accepted that electricity is a useful and desirable form of energy that can, in its own right, be safe, clean, and for the time being, economical. The fact that the fraction of world energy consumption used for the generation of electricity has been steadily increasing from 20% in 1950 to 38% in 1995,[13] is evidence of that acceptance. Furthermore, it is anticipated that the fraction of energy devoted to produce electricity will approach 50% early in the 21st Century as a transition from liquid fueled automobiles to electric vehicles is made and the trend to more electronic intensive businesses continues.

The need for much more electricity in the future is not really questioned among most energy experts. However, the *way* the electricity is made *is* under serious debate. Questions about greenhouse gas emissions, depletion of fossil fuel resources, storage of nuclear wastes, minimum power plant size, and energy independence have all been raised.

While fusion energy can easily show significant advantages over fossil fuels in the area of atmospheric pollution (CO_2, SO_x, NO_x, particulates, etc.) as well as preserving fossil fuels for future generations, it has not yet put enough distance between itself and fission reactors with respect to radioactive wastes and hazards. By any reasonable standard, the fusion community has not yet demonstrated that there will be significantly smaller routine operational releases of radioactivity from operating fusion power plants than from present operating fission reactors. The simple reason is that we have not yet built a fusion reactor and our present designs appear to be too complicated to realistically claim highly reliable operation with billions of curies of radioisotopes contained in structures that have never been tested at the temperatures and radiation damage levels expected in the mainline approach–DT fueled tokamaks! The question of the consequences of severe accidents also has yet to be resolved. Even though the proponents of fusion power can point to several favorable paper analyses which use untested exotic materials (i.e., SiC, V,... tested under radiation damage conditions to be found in fusion power plants) that can be shielded from the atmosphere in the event of an accident, the fusion community has not yet tried to publicly defend the validity of such assumptions in front of highly critical opponents of nuclear power.

The question of the cost and timetable for the development of fusion power is also connected with the minimum size that is required to demonstrate a commercial unit. Fossil fuel plants which use oil or natural gas can be demonstrated at the 10–50 MWe level while many of the early fission plants were built at the 50 to 100 MWe levels.[14] Even though the economies of scale have pushed the size of the fission plants to ≈1,000 MWe now, the fact that the feasibility of nuclear power was demonstrated by the smaller plants is an important lesson for the fusion community. Unfortunately, it appears that the present mainline approach, the DT tokamak, is not suited for small (< 100 MWe) power plants and since its confinement properties scale with size, minimum power levels of 1,000 MWe may be necessary. Present studies of DT tokamaks[15] show that even at the 1,000 MWe level, the projected cost of electricity is more than twice the cost of current power plants and it may be necessary to go to even higher power levels to demonstrate economic feasibility. The total capital cost of such a 1,000 MWe reactor is already in the neighborhood of 5 billion dollars (1995$), clearly an impediment to rapid development.

Finally, we have not yet demonstrated any major non-electric power applications for much smaller, and cheaper, fusion units on the way to the ultimate commercial market, the production of electricity. There are many commercial applications of plasmas generated by RF (radio frequency) sources[16] or energetic ions[17] produced by accelerators. However, there are currently no known commercial products that use the output from an actual thermonuclear fusion reaction (i.e., from a reaction in which energetic ions are produced in a manner similar to that used in an electrical power production facility). This probably means that there will be very little, private money invested in fusion research for the foreseeable future (i.e., the next

20 years) and the fusion community will have to rely mainly on Federal tax money.

In summary, the problems that the fusion community is presently struggling with seem to lie in 4 areas:

- A fuel cycle that produces copious neutrons which damage and activate the structure of the reactor.
- The acceptability of the tokamak as a reliable power reactor (i.e., 70-80% availability) in a utility grid system.
- The minimum size power plant that is required for commercial demonstrations.
- The lack of near term commercial applications from fusion reactions produced in the same way that they would be in a power plant.

A different approach to developing fusion energy systems would be to build small, less complicated fusion systems, capable of operating on advanced fuel cycles that produce fewer, or even no neutrons. Such units could attract commercial funding, even if those units were not net energy producers. In that way, one might be able to attract enough capital to do more research on the concept, build bigger units, and eventually jump to the ultimate goal of fusion researchers: to provide that safe, clean, and economical energy source for future generations.

III. WHAT DO WE HAVE TO SELL?

The traditional way of answering this question has been to point to the "spin-off" from plasma research and which has resulted from the construction of complex plasma experiments. Several government sponsored summaries,[18−20] individual reviews,[21−23] and even a recent conference[24] have addressed the indirect benefits of these spin-offs to society which result from funding the fusion program. *These benefits are real and impressive*! However, essentially all the commercial products come from non-fusion plasmas or equipment not specifically designed to handle fusion plasmas. The use of plasmas to provide UV to dry printed material,[25] the use of RF generated plasmas to process integrated circuits,[26] and the use of RF generated plasmas for etching[27] are examples of commercial products that do not require an actual fusion event, just energetic ions (usually protons) or electrons. It can be convincingly argued that most congressmen do not fund the fusion program to generate "spin-offs", but rather to produce fusion energy! They are happy to accept the benefits that come from this research, but it would be very hard in today's climate to sell a several hundred million dollar a year program on the "chance" that we would come up with a new way to dry ink! Therefore, the rest of this paper will concentrate on only those products that come from fusing plasmas and it will, due to the limited length of this paper, not address the details of devices that could produce these products. One of the most promising candidates for this type of operation is the Inertial Electrostatic Confinement (IEC) concept,[28−29] but many other concepts could also take advantage of the near term commercial products to be discussed below.

There are at least 5 unique products that we can "sell" from fusion reactions before we enter the main market for fusion energy (the generation of electricity):

- high energy neutrons (2-14 MeV)
- thermal neutrons
- high energy protons (3-15 MeV)
- electromagnetic radiation (microwave to x-rays to γ rays)
- high energy electrons coupled with photons to provide ultrahigh heat fluxes.

In order to gain an appreciation for the amount of particles that can be produced per watt of fusion power, Table I lists the conversion values for the 5 most promising fusion reactions. Of course, the exact values depend on the "plasma" temperature and the confinement method. Where necessary, the optimum "temperature" (kinetic energy) for the IEC device was used to calculate the values in Table I.

High energy neutrons can be very useful for the following processes:

- production of radioisotopes (for medical applications and research)
- detection of specific elements or isotopes in complex environments
- radiotherapy
- alteration of the electrical, optical, or mechanical properties of solids
- destruction of long-lived radioactive waste.

Low energy neutrons can be very useful for the following processes:

- production of radioisotopes (for medical applications and research)
- detection of specific elements or isotopes in complex environments

TABLE I

The Amount of Fusion Reaction Products Emitted Per Watt of Fusion Power (Including Major Side Reactions)

Reaction	Neutrons (MeV)	Protons (MeV)	Helium (MeV)
DT	$3.6 \times 10^{11}(14.1)$	—	$3.6 \times 10^{11}(3.52)$
DD	$8.6 \times 10^{11}(2.45)$	p–$8.6 \times 10^{11}(3.02)$ T–$8.6 \times 10^{11}(1.01)$	^{3}He–$8.6 \times 10^{11}(0.82)$
D-^{3}He	$2.3 \times 10^{10}(2.45)$	3.5×10^{11} (3.01) and (14.7)	$3.6 \times 10^{11}(3.67)$
^{3}He^{3}He	—	$9.7 \times 10^{11}(\approx 5.7)$	$4.9 \times 10^{11}(1.4)$
p^{11}B	—	—	$2.2 \times 10^{12}(2.9)$

- destruction of long-lived radioactive waste
- production of tritium for military and civilian applications
- production of fissile material
- destruction of fissile material for nuclear warheads
- production of radioisotopes for portable γ ray sources.

High energy protons can be used for the following processes:

- production of radioisotopes (for medical applications and research)
- detection of specific elements or isotopes in complex environments
- destruction of long-lived radioactive waste.

Electromagnetic radiation (ER) can be used for:

- food sterilization
- equipment sterilization
- pulsed x-ray sources.

Ultrahigh heat fluxes from fusion grade plasmas (FGP's), sometimes called a "Fusion Torch",[30] can be used for:

- ionizing waste materials and separating elements
  - municipal and medical wastes
  - spent reactor fuel elements
  - chemical weapons
  - extractive metallurgy
- production of sources of intense radiation to treat industrial, medical, and municipal wastes.

The production of RF radiation and x-rays using electricity is quite well established because of the high efficiency with which electricity can be converted into these products. Therefore, if there is an application for fusion in the ER area it would most likely be as a source of gamma rays.

A complete discussion of all of the above applications is beyond the scope of this paper. However, the Fusion Torch concept has been described in detail elsewhere.[30−32] Therefore, only a few selected examples will be used here to illustrate the concept of using fusion reaction products for commercial products.

IV. DETECTION OF EXPLOSIVES

With the increase in terrorist activity around the world, the continuation of local insurgencies, and all-out warfare in some countries, it has become even more important to have a reliable, efficient, and economical way to detect explosives. The detection of explosive devices aboard airplanes, in subways, and other public transportation vehicles would help to insure the safety of the civilian population. Unfortunately, the low atomic numbers of the elements that make up explosive devices (C, N, O) are not readily detectable by conventional x-ray techniques and more sophisticated means are required. Fortunately, these elements have unique responses to neutrons and the explosives can be detected even though buried in suitcases, packages, or shipping containers. The level of neutron source required to detect explosives ranges from 5×10^{11} (DD) to 10^{12} (DT) n/s[33]. These neutron sources should be available from < 1 watt of DD fusion power or $\approx$3 watts of DT fusion power (see Table I).

Perhaps one of the most humanitarian applications of explosive identification is in the detection of land mines, many of which now contain no metallic components. The magnitude of the problem was recently illustrated by J. Molander[34] who made the following observations:

- Every month, approximately 800 people are killed and 1,000's are injured by land mines
- An estimated 100,000,000 land mines are now buried in 60 countries

- Every year, 2,000,000 new mines (costing ≈\$5 each) are "planted"
- Every year, only 100,000 mines are cleared at an average cost of ≈\$1,000 per mine
- The Red Cross estimates that in Cambodia, 1 person in 235 has had a limb amputated, mostly from mine blasts
- In Afghanistan, nearly 1/4 of the mine casualties are children
- In Libya, 27% of the arable land remains covered by mine fields dating to World War II.

If small, portable DD or DT fusion neutron devices could be developed with Q values (energy in/energy out) of $> 0.1\%$, power sources of < 1 kW might be used in the field to rid the world of this hazard to the civilian population.

V. THE PRODUCTION OF ^{99}Mo, THE MEDICAL ISOTOPE OF CHOICE IN HOSPITALS

There are ≈38,000 medical diagnostic procedures involving radioisotopes performed each day in the United States[35] and approximately 36,000 involve the isotope ^{99m}Tc ($t_{1/2} = 6$ h), a decay product of ^{99}Mo. By attaching the ^{99m}Tc to a selected carrier agent, it is possible to direct the isotope to a specific location in the body, e.g., the bones, brain, heart, kidneys, liver, lungs, or thyroid gland. By detection of the γ ray emitted during decay of ^{99m}Tc, doctors can ascertain details about the conditions and functions of the body that could otherwise be obtained only by performing invasive surgery. The isotope of choice for most diagnostic procedures is ^{99m}Tc because its short half life minimizes the radiation dose to the patient, because its gamma ray (140 keV) is easily detected, and because it can be combined with many different carriers to concentrate in different parts of the body.[36]

The disadvantage of ^{99m}Tc is that its short half life requires a longer life "parent" that can be made elsewhere, transported to the location of the medical investigation, and then the "parent" must decay into the Tc isotope. In the case of ^{99m}Tc, the parent is ^{99}Mo ($t_{1/2}$=66 hr). The relatively short half lives of the ^{99}Mo/^{99m}Tc pair make these isotopes relatively perishable and requires continuous production to insure a reliable supply.

The U.S. medical community currently uses 60% of the world's supply of ^{99}Mo/^{99m}Tc and is entirely dependent on foreign sources. The U.S. supply of ^{99}Mo is currently produced in only one fission reactor, the NRU reactor in Canada.[35] It is separated from the fission products resulting from ^{235}U breakup, stored on a resin column and shipped to hospitals and clinics in the U.S. and around the world. Once at the location where it will be used, the resin column is treated with saline solution to strip off the ^{99m}Tc which is in turn attached to a chemical molecule for injection into a patient (the ^{99}Mo itself is not injected into the patient). The ^{99m}Tc is transported to the critical organ and the gamma rays emitted during the decay are detected by external counters. Sophisticated electronics then can reconstruct the organ and its surroundings to provide the physicians with valuable diagnostic information. A sample of the scans currently performed using ^{99m}Tc are listed in Table II.

The total U.S. usage of the ^{99}Mo/^{99m}Tc generator is ≈3,000-6 day curies per week. A 6-d Ci is the amount of ^{99}Mo remaining 6 days after its initial formation and is chosen to account for the time needed to separate the ^{99}Mo from other fission products, package it and send it to its ultimate usage point, e.g., a hospital. To calculate the initial number of curies produced in a reactor, the 6-d Ci value must be multiplied by 4.535. Therefore, the amount of ^{99}Mo to be made at the production site is ≈13,600 Ci/week.

There are at least 4 ways to make ^{99}Mo in nuclear facilities:

1. ^{235}U(n,f), the current Cintichem process[35]
2. ^{238}U(p,f)
3. ^{100}Mo (n, 2n)^{99}Mo, ^{98}Mo(n,γ)^{99}Mo
4. ^{100}Mo(p,2n)^{99m}Tc.

If one were to use the current design of capsules for the Cintichem process, i.e., multiple stainless steel tubes with an inner coating of 5 microns of U (93% ^{235}U), then a thermal neutron flux of 7×10^{13} n/cm^2-s would be sufficient to produce 13,600 Ci of ^{99}Mo/week. If a heavy water moderated DT neutron source were used, a source of 8×10^{16} n/s (or 220 kW total DT fusion power) would be required. The same production could be accomplished by one hundred 2.2 kW DT fusion power sources distributed around the U.S., each producing 8×10^{14} n/s. If a DD source were used, then only 180 kW (total) of fusion power would be required.

The cross section for ^{238}U(p,f) is ≈0.5 b at 15 MeV.[38] This means that a D-^{3}He power source of ≈2 MW would be required to make enough protons to produce 13,600 Ci/wk. This could be also be accomplished by one hundred 20 kW D-^{3}He power plants. The advantage of this scheme is that no highly enriched U is required, no moderator is required, and the

TABLE II

Selected Examples of Uses For ^{99}Mo/^{99m}Tc Generators[37]

Examination	Clinical Need or Indication
Bone Scans	Metastases (cancer spread to the bone), osteomyelitis (infections of the MDP skeleton), subtle mechanical injuries of the skeleton that are not visible on ordinary x-rays.
Lung Scans	Used in emergency patients to detect pulmonary emboli (blood clots in the MAA lungs) which left untreated can kill quickly.
Heart Scans	Detection and monitoring of the blood supply of the heart in patients with (perfusion) atherosclerotic coronary artery disease requiring angioplasty, and coronary ^{99m}Tc sestamibi artery bypass graft surgery (this study is frequently done in conjunction with a treadmill test and an EKG).
Heart Scans	Measure pumping function of the heart in patients who have had heart attacks (myocardial infarctions), heart valve problems, and who are being given chemotherapy for tumors (sometimes the heart is damaged by the chemotherapy and it must be stopped if the pumping of the heart begins to decline).
Liver/Spleen Scans	Useful in questions about the anatomy and function of the liver in patients with conditions like cirrhosis of the liver.
Biliary Scans	Used in emergency patients to detect acute cholecystitis (gall bladder infection that is treated by surgical removal of the gall bladder).
GI Bleeding Scans	Used in emergency patients to detect the location of bleeding from the small and large bowel.
Meckel's Scan	Used in pediatric patients to find abnormal areas of acid producing stomach lining that cause ulcers in the small bowel which bleed.
Renal Scans	Used to show the anatomy and function of the kidneys in patients with infections, blood supply problems, kidney stones and kidney tumors, as well as to monitor the function of transplanted kidneys.
Thyroid Scans	Used to show the anatomy and function of the thyroid gland in patients with suspected thyroid cancer, thyroid infections as well as hyper- and hypothyroid states.
Brain Scans	Helpful to study the blood supply to the brain in patients with different types of dementia, including Alzheimer's disease.

level of neutron shielding would be greatly reduced compared to the neutron induced fission concept.

The use of a 14 MeV DT neutron source would allow ^{99}Mo to be produced from isotopes above (^{100}Mo) and below (^{98}Mo). Khater[39] has calculated that using a Mo wall in an IEC device, one could produce 13,600 Ci/wk with a DT power level of 180 kW, or a neutron production rate of 6.5×10^{16} n/s. The advantage of this scheme is that it does not involve fission products and the disadvantage is that it produces a low concentration of ^{99}Mo (≈4 Ci/g of natural Mo). The concentration of ^{99}Mo in the Cintichem process is ≈10,000 Ci/g Mo. One could produce the same amount of ^{99}Mo in many smaller devices but the ^{99}Mo/Mo ratio would be even lower, complicating the design of the resin exchange column.

Finally, the production of ^{99m}Tc directly from ^{100}Mo with (p,2n) reactions would be the cleanest of all the concepts proposed thus far. If the ^{99m}Tc could be produced "bedside" then the short half life would not be a problem and the lack of fission products would greatly reduce the radiation hazards. Unfortunately, the low cross section for this reaction with 15 MeV protons (0.3 b) and the high cost of ^{100}Mo (≈1,000 \$/g) would make this process uneconomical at the present time. However, if a low cost source of ^{100}Mo could be found, D-^{3}He source levels of ≈300 W could produce ≈1 Ci/day of ^{99m}Tc in a hospital.

The above discussion is meant to illustrate that even at low fusion power levels, fusion plasmas can be of considerable benefit. If the Q of the device used can be in the 0.01 range, and many smaller units can be used instead of one large central facility, then wall plug powers of 10–100 kWe are well within reach at all of the usage locations.

VI. DESTRUCTION OF LONG LIVED FISSION PRODUCTS

It is well known that one can irradiate certain long lived fission products with neutrons to shorten their half life and thereby "accelerate" their destruction.[40] However, generating those neutrons in a fission reactor produces more fission products and the excess neutrons can activate the surrounding structure. Another approach to the same end point has been proposed by Khater.[41] He has investigated the effect of irradiating selected long lived fission products with the high energy protons emanating from a D-^{3}He plasma. The resulting (p,n) reactions can convert many of these isotopes to those with much shorter half lives or even result directly in stable isotopes.

Preliminary results from Khater are shown in Fig. 1. Note that the isotopes ^{59}Ni (76,000 y), ^{63}Ni (100 y), ^{79}Se (65,000 y), ^{94}Nb (20,000 y), ^{99}Tc (213,000 y), ^{107}Pd (6,500,000 y), and ^{151}Sm (90 y) all can be converted into stable isotopes with 15 MeV protons. The DT or DD power level required is in the 1–10 MW range, depending on the rate at which the isotopes are destroyed. Even in the case of ^{129}I (15,700,000 y), shortening its half life to 8.9 y by converting it to ^{129}Xe will greatly alleviate the long term waste storage concerns. Other notable examples are ^{135}Cs (2,300,000 y) $\longrightarrow$ ^{135}Ba (1.2d), ^{93}Zr (1,500,000 y) $\longrightarrow$ ^{93}Nb (16.1 y), and ^{137}Cs (30.2 y) $\longrightarrow$ ^{137}Ba (2.55 min). A word of caution is necessary here lest the reader get the impression that all information is in place to proceed with this concept. The fact is that while we know qualitatively the reactions of high energy protons with the fission products, the (p,n) cross sections for many of the reactions are not well known. This means that the rate at which the reactions take place are somewhat uncertain. Experimental measurements of the (p,n) cross sections for the long lived isotopes will be necessary to provide more quantitative information on the level of the fusion power source required.

VII. PRODUCTION OF POSITRON EMITTERS

Positron Emission Tomography (PET) is emerging as a major diagnostic in the medical profession. There are currently 80 PET research centers and 20 companies in the field. This diagnostic relies on the fact that when an isotope emits a positron (β+), it can combine with an electron (β-) to emit two 0.511 MeV gamma rays. These gamma rays reveal where the annihilation takes place, thus pinpointing its location in the body. Today, positron centers use cyclotrons to produce the required isotopes. More than 80% of the PET applications currently use ^{18}F (1.83 h).

It is possible to use either n[42–43] or p sources to produce positron emitters. One interesting approach using neutrons has been proposed[44] in which a heavy water moderated DT or DD neutron source is used to produce thermal neutrons which react with ^{6}Li in a Li_2CO_3 compound. The ^{6}Li(n, ^{4}He)T reaction produces an energetic T ion (2.7 MeV) which in turn promotes the ^{16}O(T,n)^{18}F reaction. The ^{18}F can be chemically separated out and attached to a "carrier" molecule which transports it to the desired location in the body. Bayless[44] has shown that a 20 W DT fusion source can produce ^{18}F at a rate of 5 Ci/hr. The economics of this process must compete with 8-10 MeV proton accelerators which produce $\approx$1 Ci ^{18}F/hr at a capital investment of $\approx$2 million dollars.

Dawson[45] has proposed injecting certain isotopes into a D-^{3}He plasma to make positron emitters from (p,n) reactions. The thresholds for these reactions, and the half lives of the positron emitting isotopes are shown in Fig. 2. The production of positron emitters in an accelerator (usually far removed from the patient) requires that the isotope have a relatively long enough half life so that it will have some usefulness by the time it is processed and transported to the patient. If the isotopes could be made "bedside" in a small device that emits little or no radiation, then other even shorter half life isotopes could be considered. It can be seen in Fig. 2 that protons from the DD reaction (3.02 MeV) have enough energy to make ^{22}Na (2.6 y), ^{18}F (1.83 h), and ^{18}C (20.3 min). In addition, the protons from the ^{3}He^{3}He reaction ($\approx$5.7 MeV) can make ^{13}N (9.97 min), ^{15}O (122 s), ^{17}F (64.5 s), ^{19}Ne (17.2 s), and ^{26m}Al (6.35 s). Finally, the 14.7 MeV protons from the D-^{3}He reaction can easily make all of the above isotopes and the device can be quite easily shielded for use in a populated area. It is found that D-^{3}He power levels of $\approx$10 W (5×10^{12} p/s) can make enough isotopes for medical applications. Even Q values of 0.001 would allow such a unit to be plugged into most medical and industrial electrical sockets.

VIII. CONCLUDING REMARKS

The inescapable conclusion of this paper is that there are many applications for small fusing plasmas that could immediately benefit society. The level of power required is in the neighborhood of 10's of watts

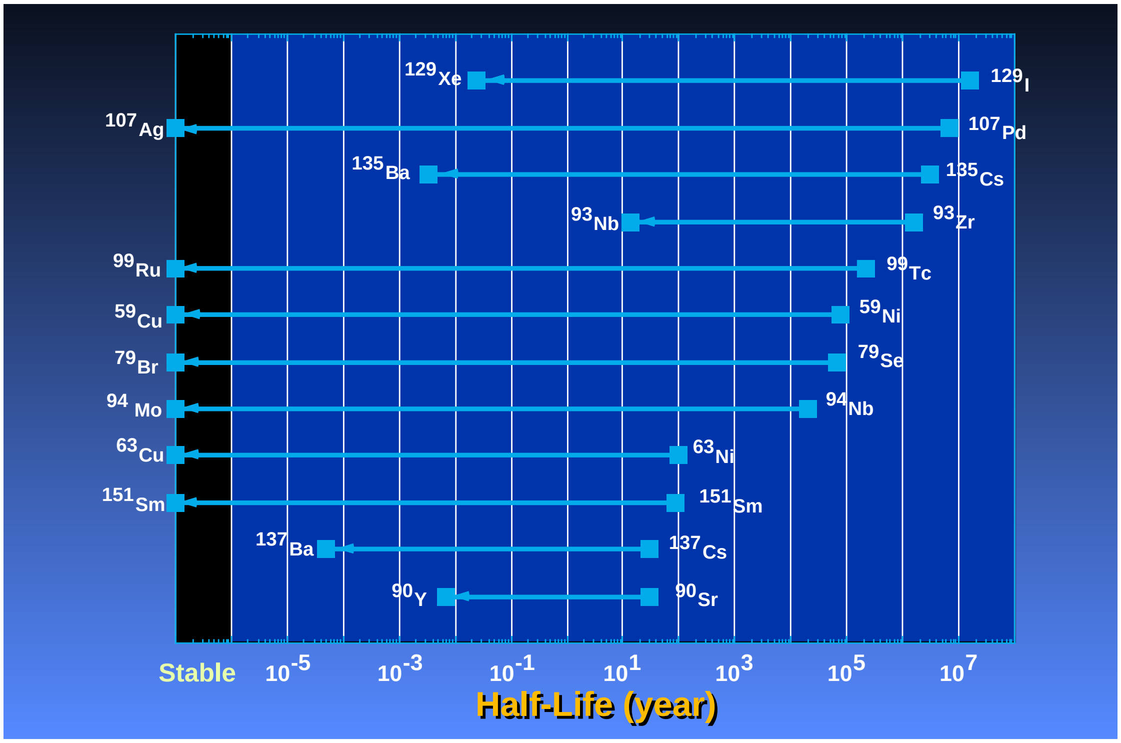

Fig. 1. The irradiation of some of the most troublesome fission products with 15 MeV protons from a D-^{3}He plasma can greatly reduce their hazard potential.[41]

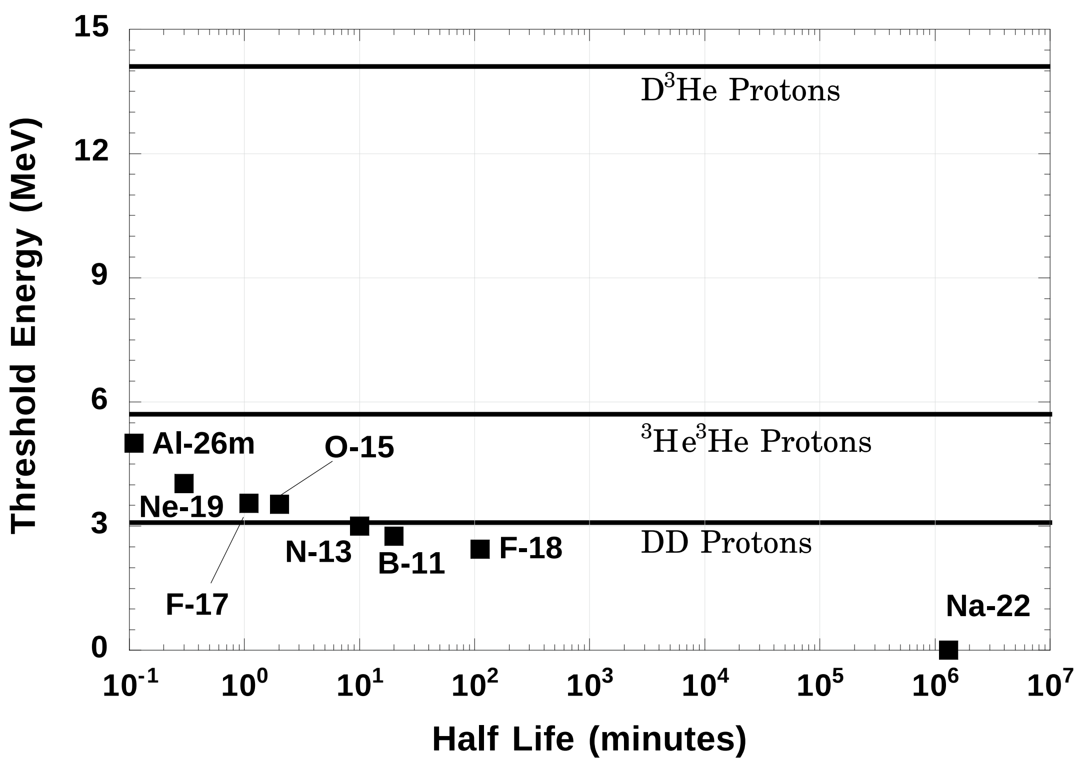

Fig. 2. Protons from the DD, D-^{3}He and ^{3}He^{3}He reactions can produce a wide array of positron emitters.

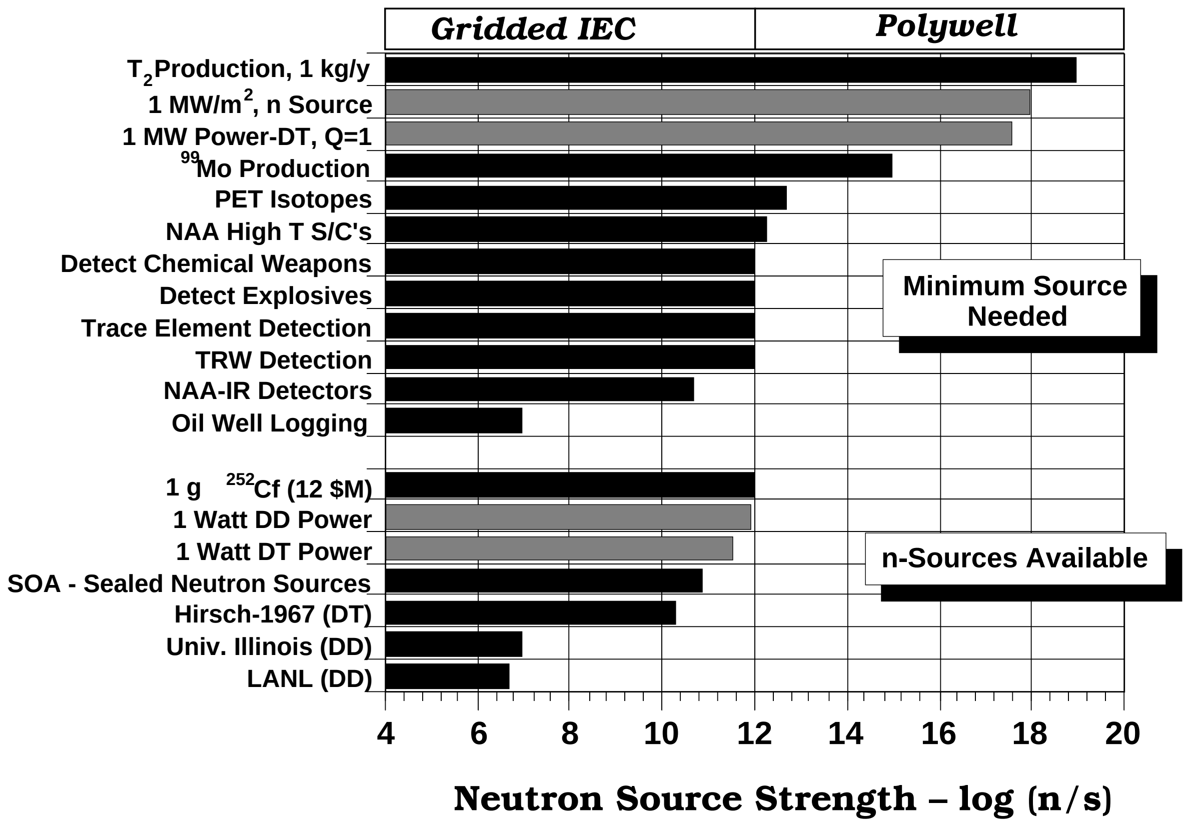

Fig. 3. Some examples of neutron source strength required to make commercially attractive products (upper grouping) and the status of high energy neutron sources currently operating in the laboratory (lower grouping). Note that if the DD fuel is replaced with DT, the neutron production rates would be 50–100 times higher than reported.

to 10's of kW (see Fig. 3). Such low power levels might be achievable in quite different confinement configurations such as inertial electrostatic devices, FRC's, or others not considered for power reactors because of their low Q characteristics.

Another important message from this work is that fusion devices need not be expensive (i.e., greater than 100's of million dollars) to be interesting. Fusing plasmas at the levels quoted here should cost <1–10 $M for the first device and when replicated 10 to 100 times, the cost may well fall below the 1 $M level. Considering the positive public reaction that could be generated by developing devices to detect explosives, detect chemical pollution, and produce medical isotopes, it appears to be a cost effective way to counter the present image that "fusion is always decades away" and that may cost billions of dollars before they produce results.

Following the above approach does not mean that the community has to give up on its dream of a safe, clean, and economical electrical power source, it just means that we can approach it in a different manner. One such path is shown in Fig. 4.

If meaningful near term civilian applications can be generated in the next 10-15 years, the community could use the "profits" (both financial and political) to step up to the next phase, i.e., applications of Q=1-5 devices. These devices could compete in specialty niches such as in Space, remote locations on Earth where solar or wind energy is not viable, or the destruction of toxic materials or "red" waste. Once a reasonable number of small, net energy producing power plants have been operating, the community could then make the ultimate step up to competing with fossil, renewable, and fission energy sources. The time period for each of these phases is uncertain now, but 10–20 years for phase 2 would not be unreasonable. This would bring us to commercialization of fusion electric power by ≈2025–2035, not much different than our previous goal for magnetic fusion. It is tempting to predict that the "net" cost of the broad plan shown in Fig. 4 could be considerably less than our present path. Whether or not that prediction comes true is not the issue here; the very fact that such a possibility exists deserves some further consideration.

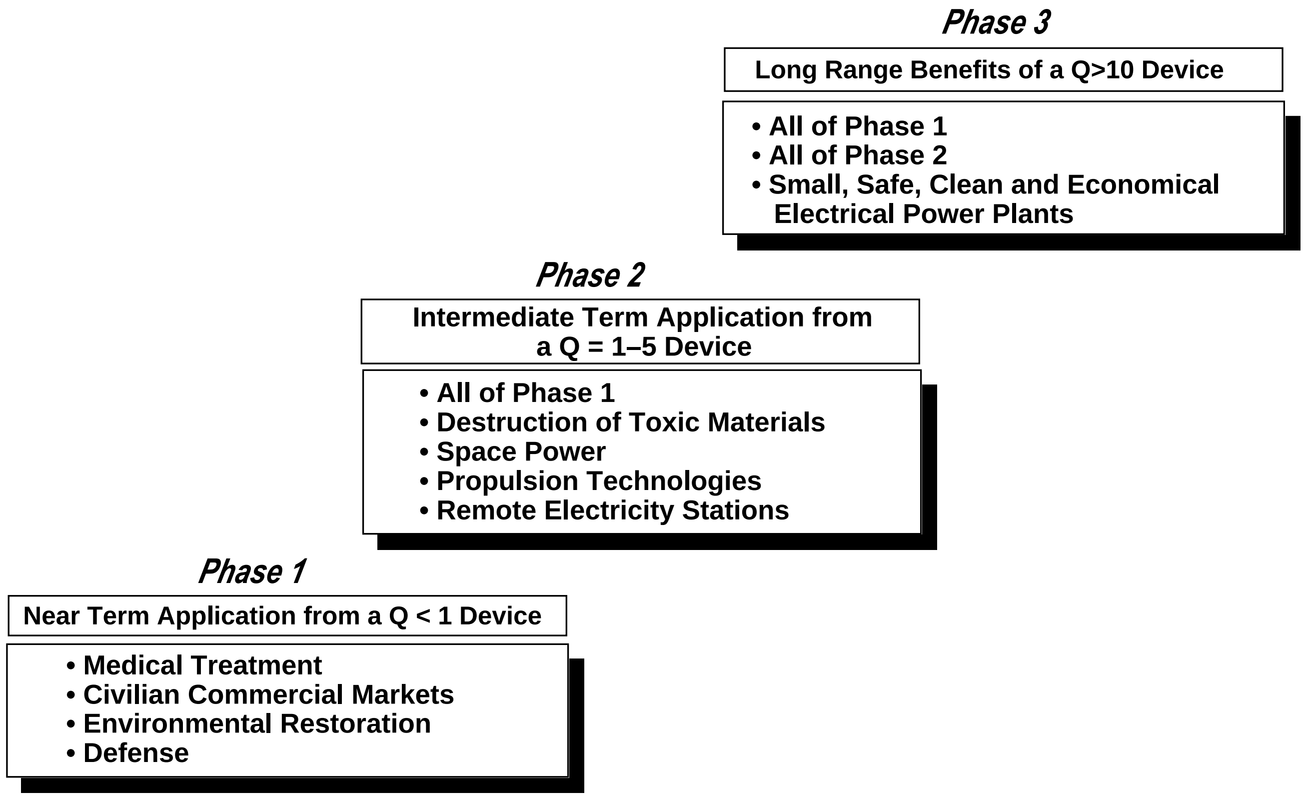

Fig. 4. Another approach to developing safe, clean, and economical fusion power would first rely on commercial products (even with $Q \ll 1$) to generate financial resources that would later allow small electrical generating units to capture niche markets. Eventually, the goal of safe, clean, and economical fusion power plants would be easier for the public to accept.

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