Journal of Fusion Energy, Vol. 23, No. 4, December 2004 (© 2005)
DOI: 10.1007/s10894-005-5615-y

The Fusion Hybrid as a Key to Sustainable Development

Wallace Manheimer[1]

If world development is to continue, mid-century energy requirements are daunting. For world development, per capita energy use in the developing world must be brought up to levels in the already developed world. Restrictions on how much CO_2 mankind can responsibly put into the atmosphere may complicate the task further. Studies show that by 2050 the world will require an additional 10–30 terawatts (TW) of carbon free power, at least as much additional, as the 10 TW generated today with fossil fuel. This paper suggests that the fusion hybrid is one of rather few possibilities for generating this power economically, in an environmentally acceptable way, and with little proliferation danger.

KEY WORDS: Fusion energy; fusion–fission hybrid.

INTRODUCTION

This author, over the past few years, has argued that the American fusion program be shifted from pure fusion to the fusion fission hybrid, and has also argued that national programs are a more sensible approach than a world wide consortium such as ITER [1,2]. This paper takes the logic a step further and considers more carefully both the proliferation and cleanup, as well as the power issue. It proposes, as more than a dream, but certainly less than a careful plan, an 'energy park', a self contained unit a square mile or two in area which supplies about 7 GW of electrical power or hydrogen, emits no CO_2, has little or no proliferation problem, and cleans up its own waste. The fuel is supplied by a fusion reactor, which is the key to the energy park. The waste cleanup is done by a combination of fission, fusion, and patience. There is niether long time storage nor long distance travel for materials with proliferation risk or long lived radio nuclides. Thus only thorium comes into the park, and only electricity and hydrogen go out.

This paper develop the argument for the energy park, but does so in a way that is self contained. That is it considers the needs of the world as a whole, where a great deal of additional power is needed rather quickly, but a world where pumping more and more CO_2 into the atmosphere could present an unacceptable climatic risk.

As of this writing (April, 2005), the ITER issues seems to be coming to a head. By the time this paper is published, ITER may have agreed upon a site, it may still be in limbo, or it may have died; the author's crystal ball is very cloudy here. But even if a site is selected, there is no guarantee it will be built. The fate of the superconducting supercollider in the United States demonstrates that even after construction has begun on a large science project; it does not always go to completion if grave doubts persist. With ITER, any of the six partners could pull the plug; at the very least, this would delay the project. Thus this author will reiterate, and hopefully sharpen the arguments against ITER. However, it would be foolhardy to ignore the possibility that ITER may be built. Accordingly, development plans are suggested both with and without ITER.

---

[1] To whom correspondence should be addressed. Wallace Manheimer, retired from Naval Research Laboratory, Code 6790 Washington, DC, 20375. E-mail: manheime@ccf.nrl.navy.mil or wallymanheimer@yahoo.com.

On one hand, the world needs a great deal of energy to power civilization and continue world development. On the other, there are limits to how much carbon we can responsibly put in the atmosphere without causing destructive climate change. Studies have shown that the world requires (depending on assumptions) an additional 10–30 TW of carbon free power by 2050. It is easy to see that this must be true. Today the world's 6 billion people use over 10 TW. Population growth alone to 10 billion people by 2050 implies 20 TW. However today, 15–20% of the people in the developed world use the lion's share of this power. Full world development would turn this 20 TW to perhaps 50–100 TW. Fortunately, there is one other trend, long evolving in the developed world, and beginning in the developing world, and this is is to use power more efficiently. This brings the needed power back down to 10–30 TW by 2050. However to avoid possible disastrous climate change, that is to stabilize atmospheric CO_2 at 'only' twice the preindustiral level, this additional power has to be carbon free [3]. In the absence of carbon free sources, China and India are very greatly increasing their use of coal. An entire issue of IEEE Spectrum (November, 1999) was dedicated to the environmental risks thereof. However right now, China and India have little choice but to proceed.

This additional necessary 10 TW is about what the world generates today with carbon. (Power and energy figures used here are available at the U.S. Department of Energy web site, http://www.doe.gov, or http://www.eia.doe.gov.) Another paper explores means by which this might be accomplished [4]. The startling thing about Ref. [4] is that there are not that many options, and some explored there are quite far out. Any would require changes to the world's energy production and distribution system far greater than what has occurred in the last half century.

Even the most optimistic proponents of pure fusion admit that it can play no role in meeting this crucial mid century requirement. But can the fusion hybrid coupled with transmutation of nuclear waste? This author argues that it may be able to do so, although with an accelerated research and development program which would have to be sustained for nearly half a century. If the United States is unwilling to lead this effort, it is possible that China and India would. These are the countries with rapidly accelerating development, countries with the most need for carbon free power quickly, and also countries with highly educated work forces. Making this case admittedly involves many scientific areas other than plasma physics, areas in which the author is not an expert. Excellent survey references on the nuclear science are Richard Garwin's book [5], the NRCs study of transmutation [6], and Lockheed Martin's table of the nuclides [7]. The author relied heavily on these.

This paper sketches out, in survey overview form, the climate constraints, the energy resources, and finally sketches out how fusion might play a role in meeting crucial mid century energy requirements and do so economically, with proliferation resistance, and in an environmentally benign manner.

GLOBAL WARMING AND ENERGY REQUIREMENTS

Fossil fuel is inextricably tied to concerns of global warming and greenhouse gases. But CO_2 is not a pollutant in the sense of say SO_x or NO_x, it is inextricably tied to the way civilization is powered. It cannot be legislated away, regulated away, or emissions traded away. In fact CO_2 is not a pollutant at all, it is a nutrient for plants; without atmospheric CO_2, life on earth would not be possible. The ways to reduce atmospheric CO_2 are few, namely by using energy more efficiently, or by using carbon free energy; the alternative is to end civilization as we know it today.

Nevertheless there is strong political pressure world wide to restrict CO_2 emissions. One can hardly look at the popular press without seeing evidence, both scientific and anecdotal, that human induced global warming is present and is accelerating. For instance the January, 2005 issue of Discover magazine summarized the 100 most important science stories of 2004. Number one was their assertion that evidence for global warming, due to human intervention in climate, is now conclusive. The article also described various unpleasant consequences of it over the next century, and even now. However, it is also important to realize that as regards present day warming, the science is still controversial. Most numerical models of global climate change predict more warming in the temperate and polar regions. However, both Greenland (U.N. Intergovernmental Panel on Climate Change (IPCC) web site) and Antarctica (USA Today Web site, Jan 13, 2002) have been cooling significantly over the last half century. In the mid latitude regions, North America is a large emitter of CO_2. However it is also a big carbon absorber as well, due to the large amount of its land dedicated to forest and agriculture. In fact it is almost certain, that at present, North America is not a net source of atmospheric CO_2, but a sink [8]. In the tropics, The Maldive Islands, because they are so low, are often said to be in imminent danger due to rising sea level, due to melting of polar ice caps. However measurements of sea level there show it fell by 30 cm in the past 50 years [9].

While the presence today of global warming is disputed, certain facts are indisputable. A google search of atmospheric CO_2 gives an enormous amount of data showing a large and steady increase in CO_2 during the industrial age. Figure 1a shows the increase during the industrial age. It is an amalgam of two graphs, one from 1750 to 1980 taken from measurements of the Law Dome Antarctica ice cores. It joins nearly seamless to another from 1980 to 2004 taken from measurements in Samoa. Figure 1b is the record of the last 400,000 years taken form Vostok ice cores in Antarctica. Clearly the CO_2 concentration has never been as high as right now; also it is increasing rapidly on the human time scale.

Second, many scientific organizations have taken corporate positions that human interference in climate is a real threat. For instance the American Meteorological Society adopted a statement on Feb 9, 2003 saying (AMS web site) "Human activities are a major source of climate change. Of great urgency are the climate consequences of increasing atmospheric abundance of greenhouse gases ... from energy use, agriculture and land clearing". However the statement points out the difficulty of achieving consensus because of "...the long time scales over which buildup of greenhouse gases is occurring, but also because of the wide range of climate change projections, and their timing and severity." The American Geophysical Union (AGU) issued a similar statement in Dec 2003. In other words, the possibility of human induced climate change is now taken very seriously by the scientific societies with the most expertise. However they also appear to counsel skepticism as regards specific doomsday scenarios. The bottom line, to this observer is that CO_2 buildup in the atmosphere is a serious issue and is likely to get more serious in the coming decades.

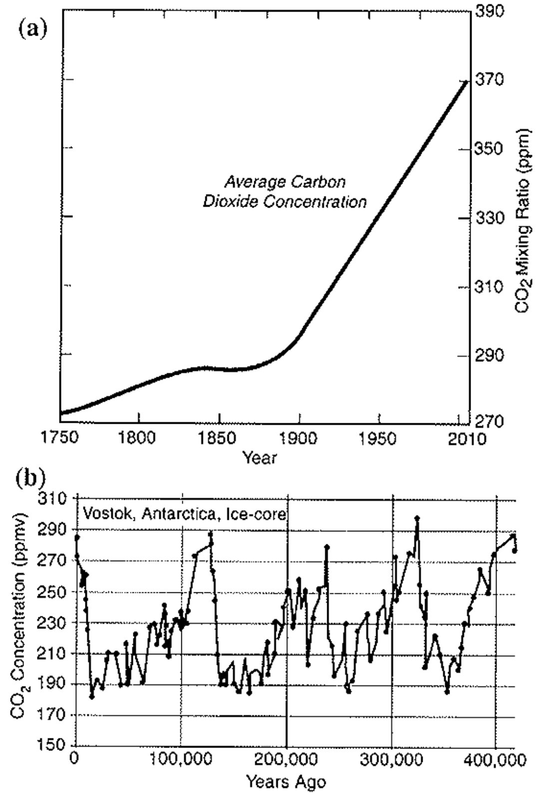

Fig. 1. (a) Buildup of atmospheric CO_2 during the Industrial Age; (b) Global concentration of CO_2 of the last 400,000 years.

The world has reacted to climate change principally via the Kyoto agreement which aims to limit emission in 2010 to the levels in 1990. Europe has mostly signed the agreement, but the United States and Australia have rejected it. It does not include the developing world. England, which made a large shift from coal to natural gas after 1990, and Russia, which greatly deindustrialized at the end of the communist era will be in compliance. However, no other signatory now is on target to meet Kyoto restrictions. For instance in 1990, the world generated 10 TW, of which about 85% was from fossil fuel. In 2005, the world will generate about 13 TW, of which about 11 is from fossil fuel. Of the 15% non-fossil fuel, the great bulk is hydro electricity and nuclear. Other renewables have played a tiny role.

Kyoto is both too strong and too weak [4]. It is too strong because it limits emission in a way that will greatly harm at least the American economy for very little if any climatic little benefit. It is too weak, because by mid century, much greater restraints will almost surely be required to avoid possibly disastrous climate change. It is also too weak because any global change agreement which excludes such countries as the United States, China, India, Brazil, Indonesia, Mexico,... is meaningless. But most important, the agreement is seriously flawed because it concerns only the emission side and not the energy side. To be meaningful, any agreement must also plan for developing carbon free power sources.

ENERGY RESOURCES

We briefly examine here the non-renewable and renewable energy resources, starting with non-renewable resources. Shown below is a table of available resources in TW-years, along with the carbon content per Joule, normalized to that of natural gas [4]:

Source	Energy (TW-years)	Relative carbon content
Coal	5000	1.6
Oil	1200	1.3
Natural Gas	1200	1.0
Mineable Uranium[a]	60–300	0

[a] Using only the 0.7% in ^{235}U.

Clearly a great deal of energy is available from fossil fuels, enough to last for hundreds of years at 20 TW. Here the CO_2 emission is the constraining factor. One approach the developed world is currently embarked on is to shift to fuels with lower carbon content, from coal to oil to gas. However, this goes contrary to the availability of the fuel. For fossil fuels to be usable on the scale needed by mid-century, sequestration of the carbon emission will almost surely be required. But if CO_2 gas is sequestered in the ocean or underground, there is always the danger that it will leak out. If it is solidified, the volume of the solid will be more than that of the original coal, so where does one put it? How much energy does all this take? How much does this cost? The US DoE is studying sequestration.

Regarding nuclear power, it is environmentally benign in the sense that it does not emit CO_2. But the startling fact is how little mineable uranium fuel there is compared to fossil fuel. At the world's present rate of consumption, about 300 GW electric or about 1 TW thermal, there is plenty of uranium and its price is low. Nevertheless should nuclear power be expanded by an order of magnitude, as might be required to support world development, there is simply not enough mined uranium. However there are three possible ways of increasing the uranium supply. One is to mine the seas for Uranium. Oceans have 3.2×10^{-6} kg of uranium (or 1.8 MJ) per cubic meter. Multiplying by the ocean's vast volume, one has an additional 80,000 TW years of fuel supply. However the very low concentration of uranium means that enormous quantities of sea water must be processed. To get 10 TW, one has to process a flow of five times that of all the world's rivers, assuming 100% extraction.

The other two ways of extending the uranium resource is by breeding. This effectively uses all of the uranium instead of the 0.7% of ^{235}U in natural ores. Furthermore, with breeding, the energy of thorium also becomes available. There is about three times a much thorium as uranium (see http://www.world-nuclear.org/info/inf62.htm), so with breeding, one increases the uranium resource by well over a factor of 100. There are two approaches to breeding, via fission and via fusion. A fission breeder has the advantage that the technology is here and now, although it is not used at present. However it has disadvantages as well. It can typically supply only itself, and perhaps breed a small amount of additional fuel. However as ultimately the fuel in a breeder is nearly pure plutonium or uranium 233; each breeder is a significant proliferation risk. A fusion breeder is certainly not here and now, but it has advantages over a fission breeder if it could be made to work. These include the fact that a single fusion breeder can supply many fission breeders, and also that a fusion breeder produces nearly pure fuel with few other waste products.

Of course environmentalists favor switching almost completely to renewable energy. John Holdren has estimated the "conceivable harnessable renewable energy flows" for the world [Ref 5, p.217] as shown below:

Source	Terawatts	Comment
Solar photovoltaic (PV)	1.5	1% of land, 20% efficiency
Hydropower[a]	1.0	all practical sites
Biomass	0.6	10% of land, 0.8% efficiency
Ocean Thermal	0.3	2% of absorbed sunlight, 2% efficiency
Wind power	0.03	windiest 3% of land, none at sea

[a] From doe web site.

Some comments: First of all, the sum of all of these does not come close to the 10–30 TW required for sustainable development. Second, to develop these would be an enormous job. The average solar energy flux, at mid latitudes, on the surface of the earth is about 200 W/m^2. At 20% efficiency, to supply all electric power to the United States (~0.5 TW) would require solar collectors of about 12,500 km^2. This is enormous compared to any other man made structure. All of the PV shipped from 1982 to 1998 cover only 3 km^2. Furthermore, could one really build such a large structure and keep it sufficiently clean? Also there is the problem that the land could not be used for anything else and energy storage would be needed for night time power. It seems likely that Holdren is overly optimistic as regards solar power. Regarding biomass, the large land use, comparable to all agricultural use today, reflects the inefficiency of photosynthesis. Biomass would be competing for a limited supply of land with food, lumber, cotton, etc. Hydropower is today roughly half utilized. The one area where Holdren appears to be overly pessimistic regards wind power. The US DoE has estimated much greater potential. In particular, there are large areas in the upper Midwest and Great Plains where wind power is sufficient to generate 5 W/m^2 (or 5 MW/km^2)s of electrical power, regarded by DoE as economically feasible. It asserts that as much as 20% of the power of this region, including such cities as Chicago, Milwaukee and Minneapolis, could be supplied by wind. Furthermore, wind power runs day and night, and the land can be simultaneously used for other purposes such as grazing and farming. So far 6 GW of wind power is in place in the United States today, about 30 in Europe, and one in India, already more than Holdren's estimate. There is considerable potential for additional growth. However, it is unlikely to be enough to make a dent in the carbon free power required by mid century. Thus while renewable power can contribute, it does not seem able to produce power in nearly the quantity needed.

DIFFICULTIES WITH NUCLEAR POWER

There are at least four difficulties with nuclear power which we will now briefly discuss. First, and not generally well recognized, is that the amount of mined uranium is rather small compared to resources of fossil fuel if only mined ^{235}U is used. It certainly cannot support world development on the scale required. However, the main thesis of this paper is that the amount can be increased by well over two orders of magnitude by breeding fuel, and we propose fusion as the best way to breed. The second worry, after the Three Mile Island and Chernobyl nuclear accidents is the safety of nuclear power plants. It seems that the nuclear industry is addressing this issue with plants of advanced design such as the Westinghouse AP600 plant, which is passively safe, that is all valves are in the safe position when they are not powered. Also there are such newly developed plants as the gas cooled pebble bed reactor which are also passively safe. The department of energy now has in place the generation four program to maximize safety and minimize production of nuclear waste.

Another area of concern with nuclear power is proliferation. We will consider the raw fuel safe from proliferation if it is a subcritical uranium mixture. In this case, the raw fuel can only be used to make nuclear weapons if it is enriched, something which takes the resources of a fair sized country. However the same is not true of plutonium fuel. This can be separated out chemically with techniques that are standard in the nuclear industry. While pure ^{239}Pu is the most potent bomb making material, just about any isotopic mixture of plutonium can be fashioned into a nuclear bomb [5, p. 318]. Hence, if a nuclear power plant uses plutonium as a raw fuel, there could be great proliferation risks. It must be well guarded to prevent misuse.

Probably the main difficulty with nuclear power is the waste. A one GW electric light water reactor (LWR) is fueled each year with about 25 tons of uranium, or which about 1200 kg is ^{235}U (Just over 4% enrichment). Each year it burns about 1000 kg of ^{235}U and discharges each year 4 tons of non-radioactive decay products as well as 21 tons of radioactive products with the following inventory: 20 tons of uranium containing 0.9% ^{235}U, 200 kg of plutonium, 21 kg of minor actinides (10 of neptunium, 10 of americium, and one of curium), 760 kg of fission products, most with typical half life of about 30 years or less. However, it also discharges the following long lived radio isotopes (half lives of hundreds of thousands years or longer) 18 kg of technetium 99, 16 of zirconium 93, 9 cesium 135, 5 of palladium 107 and 3 of iodine 129. [5, p. 121]

The present strategy is to cool the wastes in storage pools by the plant, and then when the most intensely radioactive material has decayed away, put the rest into a geological repository, Yucca Mountain in the United States. As part of this strategy, the nuclear industry has developed techniques to chemically separate this waste into its components. For instance waste element A might need container α, while element B, β. Also standard are reprocessing techniques to chemically separate out the uranium and plutonium to 99.9% purity. The direct placement of the waste in the repository is called the once through strategy. However, Yucca Mountain has generated great controversy in America, and this is for its 100 GW of nuclear waste. If the world were to generate 10 TW of nuclear power, it would need 100 Yucca Mountains. An alternative is to reprocess the spent fuel to take out the plutonium and use this as nuclear fuel. The French do this in their commercial program. In America, reprocessing is illegal in the commercial power industry, but government reactors reprocess. Critics have pointed out that with reprocessing, the fuel is recycled through reactors many times, greatly increasing the proliferation risks, and producing more plutonium along the way.

PURE FUSION AND FUSION FISSION

Magnetic Fusion

The worldwide magnetic fusion has concentrated on the tokamak approach for the last 30 years. There have been three large tokamak experiments using 40MW or more of neutral beam power, JT-60 in Japan, JET in England, and TFTR in the United States; but TFTR has been decommissioned in 1998. Only the latter two have run with DT plasmas. In some of its shots, JET and TFTR have achieved about 10^{19} neutrons in a one second pulse, for a power of about 20 MW and a Q of just under unity [10, 11]. The tokamak effort has been extremely successful. A review of tokamak performance up through the late 1990's has recently been given by the author [1]. For instance one important tokamak figure of merit is the triple fusion product $nT\tau$, where n is the central density, T the central temperature and τ the confinement time. It is closely related to the neutron production rate. In Figure 2a is shown a very rough plot of the triple fusion product as a function of year [1] and (b) is shown the number of transistors on a chip as a function of year (Moore's law) [12]. The latter has been called a "25 year record of innovation unmatched in history". But the slopes of the two graphs are about the same. However there is one important difference. At every point along the curve in Figure 2b, industry was able to produce something useful and profitable. The tokamak program, despite its success, is still several orders of magnitude away from producing anything economically viable; and the cost of the follow on projects gets *very* high.

Since the follow on projects become so expensive, the magnetic fusion project is in some turmoil. The world has tentatively decided to unite to build a single large tokamak ITER. This is a reactor which would cost about \$6.9B according to the ITER web site (ITER.org), including a 10 year construction period, a 10 year operating period, and a decommissioning period. It would generate about 400 MW thermal, or about 140 MW electrical. However these are Jan, 1989 dollars. Using the American consumer price index, this translates into \$11B in November, 2004. Until about 5 years ago, ITER was to cost twice as much and generate four times the power [13]. We call these two, ITER and Large ITER. It has been 20 years since ITER (then INTOR) has been proposed by then Secretary General Gorbachev. In this time; nearly the time for TFTR to be proposed, designed, built, operated, and decommissioned; the world has been unable to come to agreement.

While ITER was not designed as a commercial reactor, to get an idea of its energy costs, let us imagine it were. Assume the same construction cost, same yearly operating cost and same decommissioning cost, but 10 years to construct and 30 years to run, as is typical for a power plant. The cost of electricity would be about \$0.6 per kw-h. The large ITER would reduce this to \$0.3 per kw-h. However,

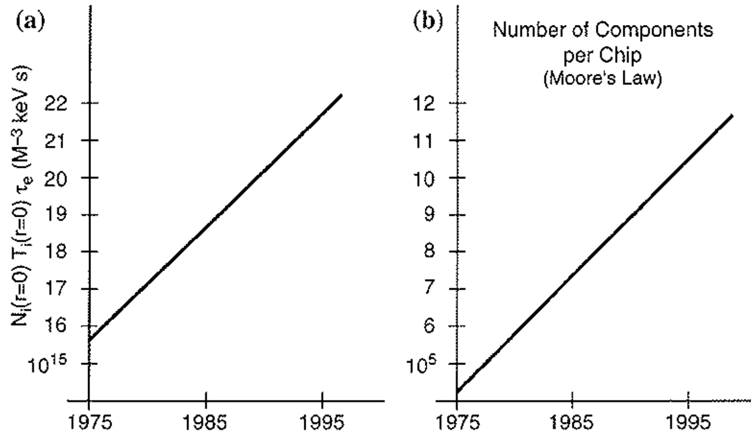

Fig. 2. (a) A plot of triple fusion product for tokamak from about 1975–1998; (b) a plot of Moore's law.

Aries has also done a number of studies of reactor cost (http//aries.ucsd.edu) and has typically come up with costs between 5 and 10 cents per kw-h. But these are paper studies of reactors operating in various advanced plasma regimes, second stability operation, large boot strap current, or reverse shear mode operation. Typically the Aries studies assume much larger magnetic fields (6 to 11 Tesla) and densities as much as two and a half times larger than ITER (over six times the power production). To do our calculations of cost estimates, we use ITER estimates, as this is the more conservative estimate. It is a machine which has already been designed in great detail; the world is ready to let out contracts to build it. The estimates of both its cost and the plasma regime are achievable in all likelihood. If the advanced operating regimes assumed in Aries work out as hoped, this would reduce the power cost for either pure fusion or for the hybrid. However our point is that by utilizing the hybrid, it may not be necessary to invoke more speculative advanced operating regimes of Aries to come up with an economical power source.

As of today, there are six ITER partners, Japan, Europe, USA, Russia, China and Korea. They are split on where to put it, with Japan, Korea and USA voting for Japan, and Europe, Russia and China voting for France. This deadlock has persisted for over a year already. In the United States, another tokamak, a burning plasma experiment, FIRE, demonstrating ignition and only ignition, was originally planned as a backup should ITER fail to be approved. However without knowing the ultimate fate of ITER, the U.S. Department of Energy has already cancelled plans for FIRE. It seems as if Europe and Japan have no plans of their own for follow up large tokamak experiments either.

This author believes that one reason for the difficulty with building ITER is that it is only a prototype, and furthermore, a prototype where there is no agreement on the next step. When society publicly or privately invests $10 billion (or $20B for large ITER), it does not do so for a prototype for who knows what. It expects something real and valuable, a nuclear deterrent (for the declared nuclear powers), a micro electronics industry, an aircraft industry, a nuclear submarine which hides in the ocean depths, etc. All of these cost $10–20B to develop. As we will see, the great advantage of the hybrid is that large ITER is no longer a prototype, but an end in itself. It has the potential of generating power economically, with great proliferation resistance, and in an environmentally acceptable way.

Inertial Fusion

This plans to compress a DT pellet with a high power laser or other driver. Like the tokamak effort, there has also been a 30-year effort in laser fusion, but not all of it has been supported for energy production. The major effort at this point is at the Lawrence Livermore National Laboratory (LLNL) in California, where a megajoule solid state laser, the national ignition facility (NIF) is under construction. However the goals of this project are defense, that is, nuclear weapon stockpile stewardship, as well as the study of high density physics. There are obvious applications to energy, but important aspects such as laser efficiency, or high duty cycle operation are not emphasized in NIF.

In the United States, there are other inertial fusion programs. The largest laser operating now is the 30 kJ Omega laser at the University of Rochester. This program is in support of LLNL, but also it does direct drive experiments, mostly with an energy application. Recently they have compressed a DD pellet and produced about 10^{11} neutrons [14] (equivalent to about 10^{13} neutrons in a DT pellet for Q of about 10^{-3}). However the efficiency of the laser is around 1%, whereas the neutral beams which drive tokamaks are about 50% efficient. The Naval Research Laboratory (NRL) in Washington D.C. also has a program based on its NIKE laser, a one quarter micron KrF laser. The main application is energy via direct drive. Also at NRL is an ELECTRA program to examine other aspects of energy production, increasing laser efficiency, duty cycle, etc. Elsewhere the French have a high power laser program geared mostly to defense applications, and the Japanese have one focusing on energy production.

The US DoEs Plans for Fusion Implementation

In 1990, with the Large ITER, DoEs plan called for full US participation and to have a commercial reactor in operation by 2040 [2 and DoE web site]. In 1996, the US fusion budget was slashed by 30% and the program goals were changed to fusion science. In 1998, the US pulled out of Large ITER. Then in 2003, the US decided to rejoin ITER as a full partner, but with a lower financial commitment than earlier. "A Plan for the Development of Fusion Energy" dated March 5, 2003 [DoE web site] now speaks of a commercial reactor, the demo, on line in 2038, 2 years earlier than the 1990 schedule, even though 13 years had already been effectively lost and budgets reduced.

This new schedule relies on "an ongoing level of highly coordinated international programmatic activities." But this does not seem to be happening. Over a year has already been lost with the squabble between Europe and Japan over where to site ITER. The proposed American budget for its part of ITER and the demo is \$24B over 35 years, or \$0.7B per year, about triple the current budget. Also there is no discussion of whether the demo will produce power economically, namely whether it uses the more conservative estimates of ITER, or the more aggressive, speculative estimates of Aries. There is certainly nothing to indicate large power production by 2050.

The Fusion Fission Hybrid

Our contention is that by going back to the fusion fission hybrid, fusion might play a key role in meeting mid century, carbon free world energy requirements. This is hardly a new idea, at the dawn of the fusion project it was well known. [15, 16]. In it, a DT fusion reactor is surrounded by a blanket which contains ^{238}U or ^{232}Th as well as lithium, and other material to slow and multiply the neutrons. Each fusion neutron cascades in the blanket to generate two to four total neutrons. One of these must be used to breed the tritium from the lithium; the rest can be used for other purposes.

The basic reaction is that a ^{238}U or ^{232}Th can absorb a neutron to generate ultimately ^{239}Pu, or ^{233}U. However the plutonium cycle would create a raw fuel which is an enormous proliferation hazard so we consider the thorium cycle. The ^{233}U could be mixed with ^{238}U in a subcritical mixture, i.e. about 4% ^{233}U, and used as nuclear fuel. From a proliferation standpoint, ^{233}U has an additional benefit. Neutron reactions generate ^{232}U as well, usually about 0.1%. This decays by emitting a gamma ray in its decay chain. A critical mass of ^{233}U would give a lethal dose at a range of 1 m in 20 min. Thus the raw fuel has to be handled remotely (standard in the nuclear industry). Furthermore, this gamma ray is much easier to spot remotely than would be plutonium which decays through alpha particle emission.

Let us briefly digress to discuss the proliferation aspects of pure fusion. If a pure fusion reactor is used as intended, with only lithium in the blanket, it breeds only tritium, and there is no proliferation hazard. However if the operator of a fusion power plant slips some uranium into the blanket, the fusion neutrons are a very prolific source of plutonium, and this is an enormous proliferation hazard. Any fusion power plant operated, at least in the United States will almost certainly involve an intrusive government presence to see that no plutonium is clandestinely made.

To see the potential of fusion breeding, let us consider what each fusion neutron can do. In the blanket, there is a neutron multiplier, perhaps beryllium or lead, so each fusion neutron generates other neutrons. These neutrons react with the blanket and structural material as they cascade and are finally absorbed. The final fusion products and energy released by a single fusion neutron are calculated with Monte Carlo codes. One such calculation [17] including the effect of structural material shows each fusion neutron generating 1.1 triton, 0.73 ^{233}U and 35 MeV deposited in the blanket (the nuclear reactions in the blanket multiply the 14 MeV neutron energy by about 2.5). The triton must be bred to keep the fusion reaction going while the ^{233}U can be used to power a fission reactor. However the ^{233}U liberates about 200 MeV when it burns in a conventional nuclear reactor.

Thus, the Q of this fusion reactor is increased by about a factor of 10! Instead of using the kinetic energy of the fusion neutron to boil water, this scheme uses its potential energy to create 10 times more fuel. Let us look at this from the point of the nuclear reactor. Say the fusion reactor is the large ITER, and it produces about 1.5 GW of neutrons as in the original design. This 1.5 GW of fusion neutrons then generated about 15 GW of ^{233}U fuel. This is enough fuel to supply five 3 GW thermal, or 1 GW electric nuclear power plants of current design. The synergy here is that fusion is neutron rich and energy poor, while fission is energy rich and neutron poor. They are a perfect match.

There are many possibilities for the fusion blanket, but one that is particularly attractive [17, R. Moir, Private communication] is a flowing molten salt blanket, a mixture of LiF and BeF_2 called Flibe. The light elements serve as moderators to slow down the neutron and the Be also serves as a neutron multiplier and the Li of course breeds tritium. Both UF_4 and ThF_4 are soluble in it. As it flows into and out of the reactor, it can be continuously reprocessed, thorium added and ^{233}U taken out and mixed with ^{238}U in a subcritical mixture.

Finally, let us estimate the cost of this nuclear fuel. We base our estimates on ITER scaling for a reactor. Our earlier estimate of the cost of electricity from the Large ITER was about \$0.30 per kw-hr. However now ITER is a fuel producer and its Q has increased by about a factor of 10. Thus, used as a breeder, it produces fuel at a cost of something like three cents per kw-h. (Of course the estimates for ITER counted breeding only tritium, breeding both T and ^{233}U would undoubtedly increase the cost somewhat.) For comparison, oil or gasoline at $1 per gallon is equal to about three cents per kw-h. As recently as middle 70s, about 20% of American electricity was generated with oil and even today about 3% is, so this is a fuel cost power plant operators are apparently willing to pay. Thus the tremendous advantage of the hybrid, for both the world and the fusion project, is that Large ITER is no longer a stepping stone to who knows what; it is an end in itself.

FUSION FOR TRANSMUTING NUCLEAR WASTE AND REDUCING PROLIFERATION DANGER

Since geological repositories for spent nuclear fuel generate so much opposition, another possibility is to transmute the waste with neutrons from some other source. The possible sources are thermal neutron reactors, that is LWRs (light water rectors); fast neutron reactors, that is ALMRs (Advanced Liquid Metal Reactors); accelerators or fusion reactors. The National Research Council (NRC) reviewed the first three. While recognizing the possibilities for transmutation, their report was rather negative. Transmutation certainly cannot be a substitute for the first, or even second repository [6].

Regarding reactors, the neutron energy spectrum is governed by what is required to keep the reactor going. In an LWR, it is a thermal neutron spectrum, whereas in an ALMR it is a fast neutron spectrum (several hundred keV to 2 MeV). A disadvantage of the fast neutron reactor is that the long lived fission products are best transmuted by thermal neutrons. However by surrounding the core with a moderator, it might be possible to have thermal neutrons outside and transmute material there. The neutrons generated in a reactor can burn waste, but they also produce waste. The key parameter is the burn rate minus the production rate.

Accelerators can be used for transmutation as well. A beam of protons with energy about 1 GeV and current of 0.25 A slams into a lead target. Typically each proton produces about 30 spallation neutrons of about 2 MeV each, or about 5×10^{19} per second. These can be used for transmutation. In the Los Alamos accelerator proposal, the neutrons are coupled to a subcritical reactor which burns principally the plutonium. However, the NRC points out the difficulties with the accelerator scheme as well. The design is necessarily very compact, so that both neutron fluxes and power densities are as much as an order of magnitude higher than in a conventional reactor. Furthermore, both the accelerator and subcritical reactors are complex facilities which must work seamlessly together.

Some of the problems with accelerators and reactors may be alleviated by fusion. First of all the NRC report points out that "Although this approach is technically feasible, its use involves several practical problems – a major technical problem is the requirement for production of very high neutron source intensities, ..." Hence a paucity of neutrons characterizes both accelerators and reactors. In fact, in the accelerator case, most of the neutrons are generated by the plutonium being transmuted. But we assert here, fusion is neutron rich and energy poor. Let us quantify this by calculating the number of neutrons produced by the basic reaction in each. A thermal reactor produces at most 2.2 neutrons per reaction [17]. Since one is needed to continue the chain reaction, there is 1.2 left for other purposes. The reaction energy is 200 MeV, so this is 6×10^{-3} n/MeV. In fact the situation is worse than this, the neutron which continues the chain reaction also ultimately adds to the waste stream, so the effective number is in reality smaller. A fast neutron reactor produces at most 2.5 neutrons, or 7.5×10^{-3} n/MeV, with the same proviso. The accelerator gives 30 neutrons, but it takes 2 Gev since the accelerator is tytpically 50% efficient, so it gives 1.5×10^{-2} n/MeV. A fusion reactor produces a 14 MeV neutron and a 3.5 MeV alpha particle. But after neutron multiplication, each neutron produces atleast one other. One is needed to breed tritium to keep the reaction going, so fusion gives atleast 4.5×10^{-2} n/MeV. Thus by this yardstick, fusion could have great promise.

It has other advantages as well. While a Large ITER sized tokamak produces a tremendous amount of neutrons, they are spread over a large area ($\sim$1000 m^2). At 1 MW/m^2, this is about 5×10^{17} neutrons per m^2, or about twice that after neutron multiplication. Furthermore, a fusion reactor can control the neutron spectrum to a great degree. If thermal neutrons are required, the first blanket could be a multiplier, backed up by a moderator, followed by the utilization region. If a fast spectrum is required, the moderator can be eliminated in that part of the blanket.

There have been several studies of using fusion neutrons for eliminating waste. Generally the American efforts [18, 19] have focused on plutonium, whereas the Japanese have focused on the long lived fission products [20, 21]. This author prefers the latter approach. First of all, plutonium is a perfectly good nuclear fuel. Why not just burn it in a critical reactor, a technology with which the world has long experience. Furthermore, a fusion reactor will be an extremely complicated system. To couple it to a subcritical reactor with a large inventory of plutonium seems quite risky. This is particularly true where the plutonium is separated by only a thin wall from the plasma, a plasma which may in fact disrupt. One authority called it "an accident waiting to happen" [R. Moir, Private communication].

Let us consider one possible strategy for dealing with nuclear waste. First separate out the uranium and use this to mix with ^{233}U to produce new proliferation resistant fuel. Then separate out the plutonium. This is weapons material, so the key is to burn it right away in a reactor on the site of the reprocessing plant. Possibly the minor actinides could be separated out and burned along with the plutonium. Since 1000 kg of burned ^{233}U generate about 200 kg of plutonium, one burner should service about five LWRs producing the same power. This plutonium burner feeds electricity onto the grid. For the plutonium burner, one could use either a thermal neutron reactor or a fast reactor. The former is a simpler, more conventional reactor, but burning the plutonium is more difficult. With slow neutrons, about 60% of the n Pu reactions are fissions, the rest are absorptions which build up the plutonium mass and transmute to higher actinides. However, as long as no uranium is present to generate more plutonium, these higher actinides will ultimately burn as well. A fast reactor fissions all isotopes of plutonium, so it burns it more cleanly. However this reactor is more difficult to build and operate, and therefore is more expensive. Either way, the plutonium would be burned in a conventional reactor. Since destroying plutonium is the main goal here, neutron economy is not an important figure of merit. Particularly, we would not want any uranium mixed in with the plutonium, as this will produce additional waste to treat. Perhaps the plutonium could be mixed with a very stable nucleus such as iron to minimize the waste stream, but wasting neutrons. Alternately it could be mixed with lithium to ease the tritium breeding requirements of the fusion reactor. The key is simply to burn the plutonium in a reactor with which the world has had long experience. If burned in a thermal neutron reactor, there are many decades of experience, if burned in a fast neutron reactor, there is still a body of experience.

This leaves the radio isotopes, about 700 kg are short lived (half life typically less than 30 years) and 50 kg are long lived. Then separate out the short lived isotopes and let them decay away in a storage pool for perhaps several centuries. Each year, each reactor adds about 700 kg of radio isotopes with 30 year half life (about a 40 year reciprocal decay rate) to the pool. Hence the steady state mass of radio isotopes in the pool is about 30,000 kg. Every decade or so, the material in the pool would have to be run through the separation plant again to remove the stable decay products. Since the wastes of American nuclear reactors have been kept in cooling pools for over 40 years now, and this includes plutonium and long lived isotopes, cooling pools appear to have this capacity.

It is the long lived isotopes which would be transmuted by fusion neutrons. Let us consider a few examples to demonstrate the possibilities and dilemmas facing transmutation. Most long live isotopes are best transmuted by slow neutrons. Consider one of them, ^{99}Tc. It has a half life of 200,000 years and is a great threat to a geological repository because many of its compounds are water soluble. It has a 20 barn cross section for absorbinig a slow neutron and becoming ^{100}Tc. This quickly decays to ^{100}Ru which is stable. However if a flowing molten salt blanket is used, Tc will precipitate on the surfaces facing the molten salt. Thus if this blanket is used, the ^{99}Tc must be encapsulated.

A more difficult problem is the Cs. This is produced in at least three isotopes, ^{133}Cs which is stable, ^{135}Cs which has a half life of about 2 million years, and ^{137}Cs with a half life of 30 years. If isotope separation is part of the process, the procedure is simple. Let the ^{137}Cs decay naturally and transmute the ^{135}Cs, ultimately to ^{136}Ba which is stable. If isotope separation is not part of the separation process, then all of the Cs must be treated. The ^{133}Cs ultimately transmutes to ^{134}Ba, which is stable. However, this wastes a neutron transmuting a stable element to another stable element. The ^{137}Cs has a very low absorption cross section, less than two orders of magnitude lower, so it goes along for the ride. After transmutation of the other cesium, it is separated out and cooled in a storage pool.

As a final example consider the fission product ^{14}C, which is produced in very small quantities. This has a neutron absorption cross section of 10^{-6} barns, so there is no possibility of transmuting this. However ^{14}C exists naturally in the environment. The amount produced by nuclear power plants will be tiny compared to what occurs naturally.

Let us consider a very rough calculation of the possibilities for transmutation using fusion neutrons. Assume a large ITER type reactor. After neutron multiplication, let us assume the neutron flux is 10^{18} per m^2s. If each transmutes a long lived radio isotope, this is 5 kg of material transmuted per m^2 per year if the atomic mass is 100. Hence 50 square meters, or 5% of ITERs wall area could be used to potentially transmute the long lived wastes from five LWRs. Thus, whatever other constraints a more careful analysis adds, a fusion based transmuter appears to have sufficient neutrons to do the job.

Transmutation may or may not be able to treat all of the long lived fusion products. Also some of the U and Pu may not fully separated out (about 0.1%) and may remain in the waste stream. Research and development may be required for separation technology as well as fusion. However fusion based transmutation, coupled with conventional burners for the actinides may either eliminate the need for a repository or greatly reduce it. World wide, there is a big difference between 1 or 2 repositories and 100 or more. While treating the waste products adds to the fuel costs, sequestration would also add to the cost of fossil fuels.

TWO POSSIBLE STAGED DEVELOPMENT PROGRAMS

This author has long argued against a world consortium such as ITER for the development of fusion power [1,2]. It will always be low on the priority of national leaders and will be constantly buffeted by strong political winds as relations between the various partners inevitably improve and deteriorate. Better to let the international collaboration be done at the level of the scientists who are devoted to the project, rather than at the level of presidents and prime ministers who are not. Thus, the first staged development plan involves only national programs. However since ITER has had so much effort behind it, it may well be built, and in any case it is imprudent to ignore it. Hence the second plan involves ITER.

A National Plan

The first goal is to build a tokamak the size of TFTR but which runs high duty cycle in a DT plasma. This is a plasma regime about which much is already known. We call this the scientific prototype. Most likely it would mean operating with super conducting toroidal field coils. The major and minor radii of TFTR were about 2.5 m and 0.5 m. However one must include now a breeding blanket, which we estimate at 1.25 m, making the major radius now 3.75 m. We assume that it can be run at $Q \sim 1$, so 40 MW of beam power give about 40 MW of neutron power for a wall loading of about 0.5 MW/m^2, about a factor of two or three less than the large ITER. It is certainly sufficient to do initial studies of blanket and wall materials. In the ITER plan, about 2 m^2 wall portions can be pulled in and out to test different blanket concepts. In the scientific prototype, perhaps 0.5 m^2 modules could be planned.

While the scientific prototype would operate in a largely known plasma regime, there would still be significant plasma research to do. The problem of major disruption still has not been fully solved in tokamaks. For instance very interesting data in JET [10]showed $Q \sim 1$ in a plasma which ultimately disrupted. However by backing off to $Q \sim 0.7$, the discharge lasted as long as the current pulse. The scientific prototype would have a certain maximum disruption rate (possibly zero) that it would be designed to withstand. It would have to pick parameters to get as close as possible to this allowed disruption rate, but not exceed it.

The scientific prototype would not explore ignited plasmas, but would otherwise provide an enormous amount of crucial information. This includes operating at steady state, operating with DT plasmas, and testing blanket materials and concepts. One could breed small but significant quantities of ^{233}U and/or destroy small but significant quantities of nuclear waste.

Let us give a rough estimate of the cost. ITERs total cost is \$11B for a 6 m machine, Large ITER costs \$22B for and 8 m machine. This suggests a scaling law $\$ \sim R^{2.5}$, so the scientific prototype would cost about \$3.4B. Of course ITER's costs considered only breeding tritium, whereas this program would consider both breeding ^{233}U and destroying long lived radio isotopes. This would undoubtedly increase the cost. The scientific prototype would go on for 20 years, or perhaps 15 in an accelerated development program. However its cost is low enough that it could be sustained in a national program.

After 15–20 years of experience with the scientific prototype, if successful, the next step would be to build a reactor the size of Large ITER, but as a breeder and waste transmuter. We call this the commercial prototype. This would necessarily get into ignited plasmas. If during the period of the scientific prototype, there were also an ignited plasma experiment, say Ignitor, which the Italians have proposed building, this would undoubtedly help greatly. On the other hand, if no burning plasma experiment is done earlier, the commercial prototype would have to look at a burning plasma for the first time. The commercial prototype would take us to somewhere around 2035–2045. It would be a rather large step from the scientific prototype, but at least it is a step to a commercially viable end product. If successful, the world builds several hundred ITER sized breeder/transmuters to cleanly generate multi terawatts of carbon free power by mid century.

An ITER Based Plan

Let us assume that the world decides to build ITER. This would be a machine somewhere between the scientific and commercial prototypes and represents a larger step than the former. Hence the ITER project would undoubtedly take more time to complete. One advantage of ITER is that the plan calls for wall modules 2 m^2 which can be put in and taken out. Therefore, partners interested in a hybrid based economy can perform studies with wall modules for producing ^{233}U and for transmuting long lived radionuclides. Partners interested in pure fusion could study blankets appropriate to it. After the completion of ITER, partners interested in a fusion hybrid economy could take the relatively short step to the commercial prototype (i.e. Large ITER), while partners interested in pure fusion could take what seems to them to be the next step toward it.

THE ENERGY PARK

This author's vision for sustainable world development is sketched in Figure 3. We call it an energy park. The basic module is a nuclear reactor, for instance an LWR which generated 1 GW electric, or 3 GW thermal power. Five of them are in the park. These are the best nuclear reactors that can be developed, perhaps AP600s, perhaps the gas cooled pebble bed reactor, perhaps a Generation IV reactor. Then all of the development of advanced burner reactors over the last half century will be utilized in the park. There is no need to develop a totally new, single reactor which does everything.

The reactors are supplied by a single fusion reactor which breeds ^{233}U from ^{232}Th and immediately mixes the fuel into a subcritical mix. The waste from the reactors goes to a cooling pool for some specified time. From there it goes to a reprocessing plant where the uranium, plutonium, long, and short lived radio isotopes are separated out. The long lived ones go to the tokamak for transmutation. Recall our estimate that 5% of the wall area could transmute waste from five reactors. The short lived radio isotopes would go back to the cooling pools. These pools would need a capacity of about 150,000–200,000 kg. The plutonium separated out goes immediately to a reactor designed to burn it, and it produces electricity for the grid. Possibly it could also aid in the tritium production. Regarding neutron

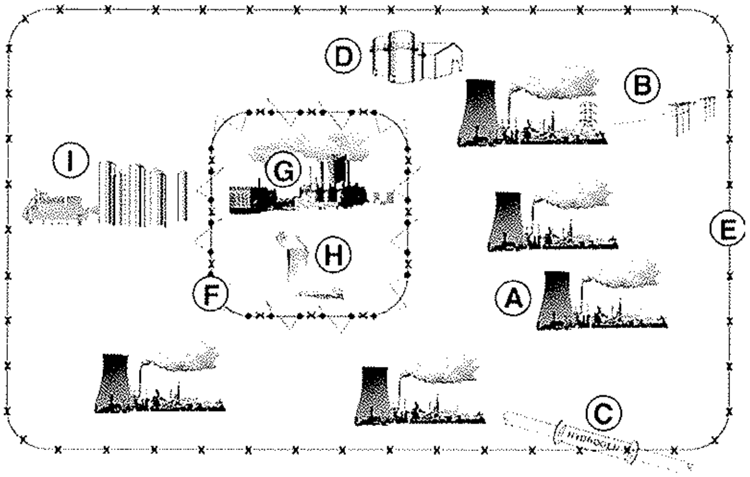

Fig. 3. The energy park. (A) Thermal neutron reactor, (B) electricity going out, (C) hydrogen pipeline, (D) storage pool for cooling spent fuel, (E) low security fence, (F) high security fence, (G) reprocessing facility, (H) Plutonium. Burning reactor, (I) fusion fuel producer/transmuter.

economy, it is crucial in the fusion plant, important in the five standard reactors, and not important at all in the plutonium burner. The role of this reactor is principally to destroy plutonium, not generate electricity or breed fuel with maximum efficiency.

The plutonium burner and reprocessing plant, and possibly the fusion reactor would have to be in a highly secure area. The remainder of the park would be in a lower security area. While the plutonium wastes would travel from the reprocessing plant to the burner, there would be no long distance travel and no long time storage. There would be no long distance travel for the radio isotopes either. If the reprocessing plant had much more capacity than needed for the six on site reactors, it could serve perhaps two or more energy parks. If could also serve as a reprocessor if subcritical fuel was exported. Then there would still be no long time storage, but there could be some intermediate distance travel for raw, untreated nuclear waste.

So there it is: seven reactors in the park, each producing about 1 GW in electric power or hydrogen. Either could be exported to smaller countries unable to build an energy park. The park treats its own waste and keeps material with proliferation danger stored, but only for short times before it destroys them. To this author, it seems to be a possible vision for sustainable world development by mid century or shortly thereafter.

A very important additional advantage of this fusion hybrid sustainable development concept is that it gives the world experience with fusion. This may, in the distant future, lead to a pure fusion economy. This would have tremendous advantages; nearly unlimited fuel, virtually no waste, and a small but manageable proliferation problem. However, this is not our decision to make. The people to make this decision are 50–100 years from even being born. Setting up a fusion hybrid economy may be the best way in which we can help our decedents make the wisest choice.

ACKNOWLEDGMENTS

Any author attempting a paper such as this must rely on many written sources and people to provide help once he leaves his own field of expertise (plasma physics in my case). This author is extremely fortunate in the time and expertise shared by Ralph Moir of LLNL on nuclear science, and Marty Hoffert of NYU on world development. Also he would like to thank Martin Lampe of NRL and Doug Lightfoot, retired from McGill University for a number of useful suggestions.

REFERENCES

1. W. Manheimer, *Fusion Tech.*, **36**, 1 (1999).
2. W. Manheimer, *J. Fusion Energy*, **20**(4), 131 (2001, cc2003).
3. M. Hoffert, *et al.*, *Nature*, **395**, 881 (1998).
4. M. Hoffert, *et al.*, *Science*, **298**, 981 (2002).
5. R. Garwin and G. Charpak, *Megawatts and Megatons* (Alfred A. Knopf, New York, 2001).
6. Nuclear Waste, Technologies for Separation nd Transmutation, *NRC Study* (National Academy Press, Washington, D.C., 1996).
7. *Lockheed Martin Table of the Nucleides*, http://www.ChartOfThe Nuclides.com.
8. S. Fan, *et al.*, *Science*, **282**, 442 (1998).
9. N. Morner, M. Tooley and G. Possnert, *Global and Planetary Change*, **40**(Jan) 171 (2004).
10. M. Watkins, *et al.*, *Phys. Plasmas*, **3**, 1881 (1996).
11. D. Mansfield, *et al.*, *Phys. Plasmas*, **3**, 1892 (1996).
12. D. L. Flamm and G. K. Herb, *Plasma Etching Technology – An Overview, in Plasma Etching, an Intorduction*, Ed: D. M. Manos and D. L. Flamm, (Academic Press Inc. 1989).
13. R. Aymar, *IEEE Trans Plamsa Sci.*, **25**, 1187 (1997).
14. Sunahara, *et al.*, *Phys. Rev. Let.*, **91**, 095003 (2003).
15. A. Sakharov, *Memiors*, (Vintage Books, New York, 1990, p. 142).
16. H. Bethe, *Phys. Today*, May (1979).
17. R. Moir, *Fusion*, vol. 1, Ed.: E. Teller, p. 411 (1981).
18. Y. K. M. Peng, *et al.*, *16th IEEE/NPSS Smyp. Fusion Eng.*, **2**, 1423 (1995).
19. W. M. Stacey, *et al.*, *Fusion Sci. Tech.*, **41**(March) 116 (2002).
20. A. Stanovsky, *et al.*, *Fusion Sci. Tech.*, **43**, 569 (2003).
21. M. Saito, *et al.*, *Prog. Nucl. Energy*, **40**(3, 4) 621 (2002).