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Mid Century Carbon Free Sustainable Energy Development Based on Fusion Breeding *

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ABSTRACT Fusion has often been billed as the ultimate 21st century sustainable energy source. However, not only is the pace of the program glacially slow, it seems to recede further and further into the future. For instance, when the ITER Tokamak was approved in 2005, the date for the first plasma was 2016. As this is written in 2018, the date has moved back to 2025. It has receded nearly one year for every calendar year! Furthermore, even if ITER is successful, there are many, many fundamental obstacles between it and a commercial, sustainable pure fusion reactor. This paper shows that fusion breeding is a better way, one that could lead to substantial fusion power not too long after midcentury. The reason is that the requirements for a fusion breeder reactor are much relaxed from those of a pure fusion reactor. Fusion breeding is the use of fusion neutrons both to boil water and to breed nuclear fuel for thermal nuclear reactors. Pure fusion is only the former. Fusion breeding's transition to a power source for the economy could follow rapidly a success by ITER, the National Ignition Facility or both. This paper summarizes years of effort and advocacy for fusion breeding instead of conventional fusion.

INDEX TERMS Fusion power generation, fusion reactors, tokamaks, magnetic confinement, inertial confinement, solar energy, nuclear power generation.

I. INTRODUCTION

Nuclear power is clearly one of few options for large scale, sustainable, carbon free power by midcentury. Because fuel for thermal nuclear reactors might well be limited, there is some push to develop breeder reactors. Two review articles have recently summarized some of this work [1], [2]. The amount of available nuclear fuel is a subject of some dispute. Hofferet *et al.* [3], measuring the fuel in terawatt years, estimates about 60-300. Freidberg and Kadak [4] estimate a much larger resource, likely between 500 and 1000. While this paper certainly cannot sort out these conflicting estimates, there is one thing everyone does agree on. As fuel for thermal reactors, only about 1% of the uranium resource is available, that part which is the fissile component ^{235}U, and furthermore thorium has no fissile component. Thus breeding of either ^{233}U from thorium, or ^{239}Pu from ^{238}U could become essential. This article hopes to point out to the nuclear, electrical engineering, and other scientific and technical communities that there is another possible breeding option, fusion breeding, which the author has advocated for 20 years now. His papers have been published in the controlled fusion literature [5]–[7], a subset of the scientific literature with limited exposure. The hope here is to acquaint a much larger community, to the possibility of fusion breeding.

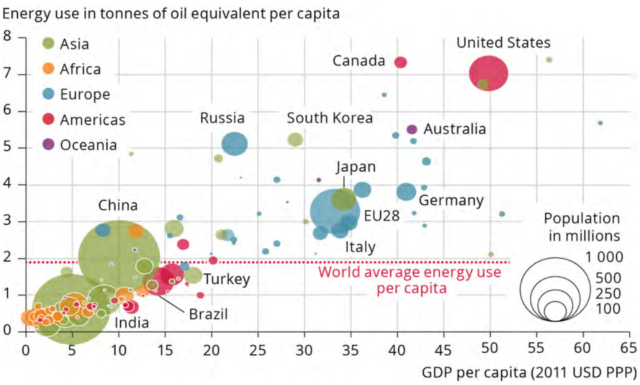

FIGURE 1. **Energy use versus GDP for a variety of countries. To relate the tons of oil per capita per year, note that the United States used about 8 kW per capita. From this one can easily get the per capita use of power in kilowatts for any other country shown.**

To see the need for power for development of the entire world, simply look at a graph of per capita GDP versus power use per capita. They abound on the Internet, all about the same, and one example, provided by the European Environmental Agency, for 2011, is shown in Fig. 1, (here the vertical axis is in tons of oil per year, or a power).

The billion or so people in the United States, European Union, Russia and Japan use an average of about 6 kW per capita, or 6 terawatts all together. But the world uses $\sim$ 12-14 terawatts, so the other 6 billion people in the world use about 1 kW each. Obviously the world is very unequal in power use, and development means that a great deal more power must be produced. For instance consider the case of China. The graph shows that in 2011 the average Chinese used about 25% of the power of the average American. In 2000, this figure was about 10%. Over the past decade or so, China and India between them have been bringing on line about one coal fired power plant per week. China is now by far the world's larges carbon emitter and this will not stop any time soon, despite their large manufacturing effort in solar photovoltaic semiconductors.

In fact, it is the developing world, not the more developed world that is increasing its use of power. Again graphs abound on the Internet. There is one well-respected source of energy statistics, one often cited by other essays and that is the from the BP petroleum company. Shown in Figure 2 is a plot of energy use, in billion tons of oil equivalent, by different countries, taken from the BP review of world energy (8):

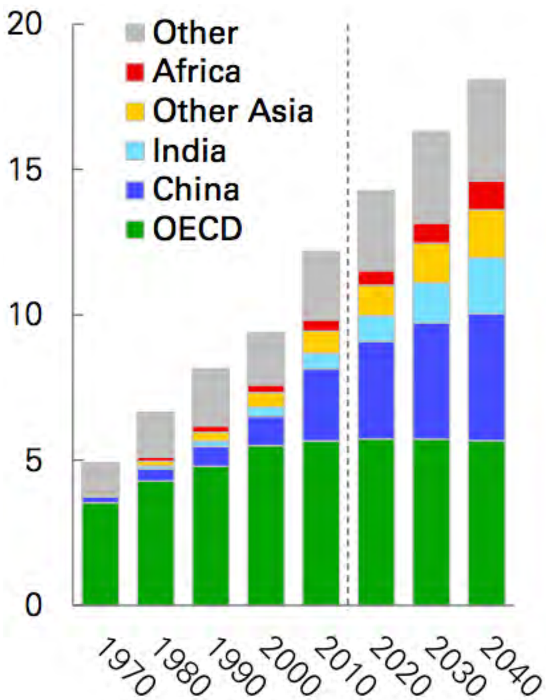

FIGURE 2. from BP energy outlook 2018; It shows the evolution of primary energy demand per region. It is the less developed parts of the world that are increasing energy use as they struggle to end their persistent poverty. To the right of the dashed line are BP's extrapolations of current trends.

But how will the world get the required energy? Right now the world gets 85% of its energy from fossil fuel. But not only is this a finite and diminishing resource, the use of it on the scale needed for world development could well produce adverse climate or other environmental problems. The current emphasis is now on the development of carbon free power.

II. SOLAR AND NUCLEAR, TODAY's CARBON FREE ENERGY

The options for massive development of carbon free power are few. Two possible options, which are available right now, are nuclear and solar (solar photovoltaic and solar thermal, wind and bio fuels). Often these are considered as separate power sources, but for convenience, here we consider them together and call them 'solar' because the source for all of them is the sun's energy that shines on the earth right now, or perhaps in the last year in the case of biofuel. This paper uses the term solar as an overall term, and solar photovoltaic or solar thermal for the particular solar power source. There does not seem to be a universally accepted terminology for these power sources (see EIA and BP graphs, Figs (5 and 6); the former counts hydro power as renewable, the latter separates it out). Fossil fuel, by contrast, as its name implies, is stored solar energy from millions of years ago. This paper argues that nuclear is the most viable, and that fusion breeding can be a mid century option in support of nuclear power. Pure fusion is a much longer-term option, if indeed it is an option at all.

There is already a large constituency advocating for solar power. This is enormously controversial, the believers say it can soon meet nearly all of our needs, the skeptics say no. Obviously, this paper will not settle it. However, this author counts himself among the skeptics (9). Furthermore, while many respected, established scientists believe that fossil fuel may well give rise to destructive climate change, many other equally qualified scientists, including the author (10) not only dispute this, but claim that so far the additional CO_2 in the atmosphere is a net benefit, CO_2 being a vital nutrient for plants (11).

The government and private dollars supporting solar are massive. The American government's General Accounting Office has tabulated the federal support for climate science. Note that support is for development of a field where the basic science underlying it is well known' in some cases for thousands of years. The graph is shown in Figure (3).

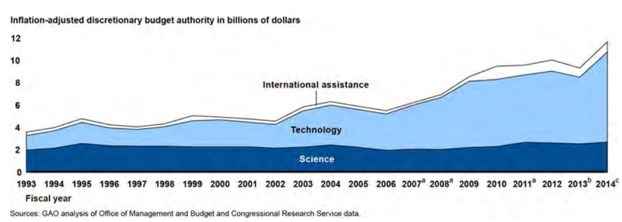

FIGURE 3. The GAO chart of dollars spent for climate change and solar power.

Clearly a great deal has been spent on the development of solar power in the last 20 years, in the United States alone, at least $140B. Not only that there are considerable subsidies for the implementation of solar power. Here the U.S. Energy

Information Agency keeps track of the actual subsidies for various forms of energy. This bar graph is shown in Fig. (4) where the subsidies from 2013 and 2016 are compared.

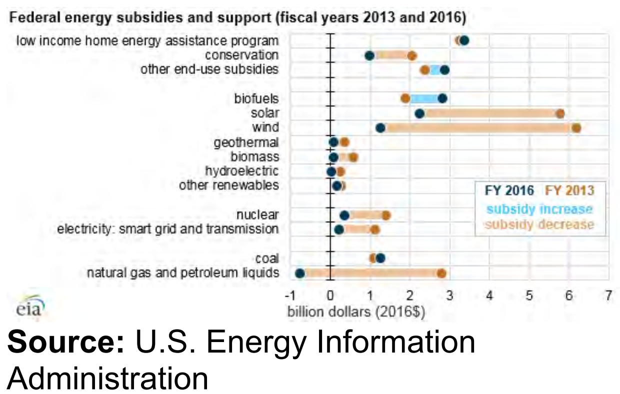

FIGURE 4. **The government subsidies, as compiled by the U.S. EIA for a variety of energy sources and their evolution from 2013 to 2016.**

Clearly support is substantial, especially for what they define as wind and solar, although it has decreased significantly between 2013 and 2016. However subsidies for biofuels have increased by about a billion per year. Although solar groups claim the subsidies for fossil fuel greatly exceeds that for solar, the U.S. EIA clearly does not see it that way. The total support is still on the order of \$10B per year, a very substantial amount. As a single example, buyers of the first 200,000 Tesla's get a government rebate of \$7,500, or a total government subsidy of \$1.5B for that alone, obviously for the very richest car buyers. In fact there are claims that Elon Musk has built his business on federal subsidies, so far \$4.9B as of 2015 (12).

The next question is what have we gotten for this investment and subsidy. Two graphs of the consumption of energy by various energy sources in the Untied States, provided by the U.S. EIA (13,14) are shown in Figs (5 A and B).

Notice that solar and wind is a very tiny portion of even the renewables, which are themselves a small portion of the total American energy. However it may be significant that their portion has increased in 7 years. In 2009 solar and wind were 0.8%, while in 2016 they were 2.6%; in other words their fraction has tripled in 7 years. Some argue that this means a renewable energy revolution is underway. If they keep growing at this rate, in 25 years, they will overtake all of American energy. Perhaps, but more likely they will not be able to sustain this growth; once a source begins to take on a measurable fraction of the total, things get a lot tougher.

BP also weighs in on the current and future of renewable energy (8). Figure (6) is their graph of various energy sources, not just for the United States, but worldwide.

Notice the BP chart confirms the current use of renewables, ~1%, but does estimate that they will play a larger, but still small role (10-15%) in 20 years. Certainly BP does not estimate that they will take over. However their estimate is itself speculative. As we have seen the use of renewable energy does depend on government subsidies, which in turn depends on the changeable political will of the particular country.

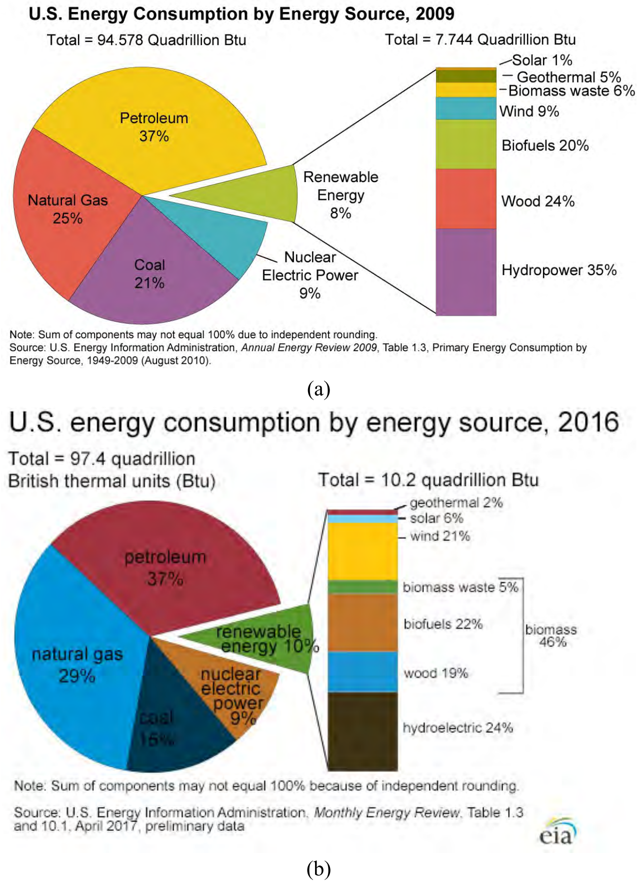

FIGURE 5. **A. The American energy budget in 2009 according to the U.S. EIA, and B, the same for 2016.**

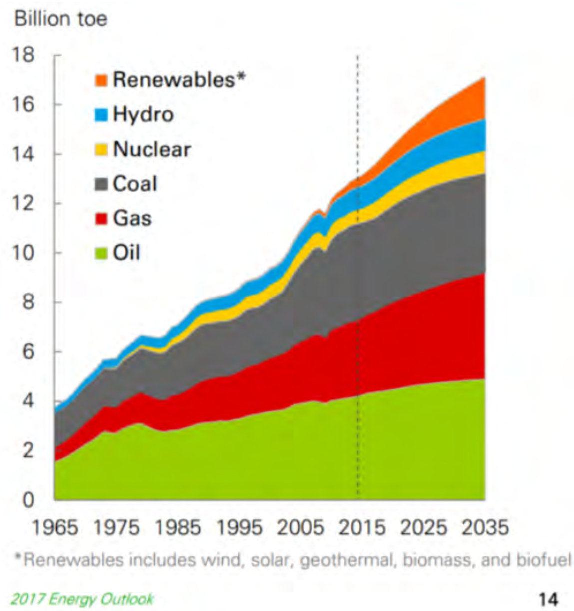

FIGURE 6. **BP's graph of different energy sources up to the present, and their estimate of it for the next 20 years.**

Furthermore, as renewables demand more and more land for their solar panels and windmills, more and more landowners, who want their land for other purposes may well rebel and/or greatly raise the price. Also, there are technical problems, the problem of massive energy storage for when the sun does not shine or the wind does not blow is still unsolved, as it has been for a century. In addition, solar photovoltaic, solar thermal and wind are inherently sporadic; as their fractional contribution increases, the grid has more and more difficulty adjusting.

Let us turn to nuclear energy, a discussion that will be very brief. So far virtually all nuclear reactors in the world are light water reactors (LWR's), which use the hydrogen in the water to slow down the MeV neutrons produced. For odd atomic mass actinides, the reaction cross section greatly increases for low energy neutrons, thus earning the title thermal nuclear reactors. An LWR is typically fueled with about a ton of ^{235}U mixed in with about 24 tons of ^{238}U, so that the fuel is enriched to about about 4% ^{235}U, and as such has no proliferation risk unless the proliferator has isotope separation facilities. Also there is no criticality risk. Each year an LWR is refueled, and the reactor discharges its fuel and waste; this contains the 24 tons of ^{238}U, a ^{235}U enrichment of about 1%, and about 200 kg of actinides and about 700 kg of intermediate Z radioactive reaction products which typically have a half life of ~30 years (15).

There has been a great deal of research into more optimum reactors including the CANDU, which uses deuterium instead of hydrogen as a moderator, the gas cooled pebble bed reactor, and the molten salt reactor (MSR). Several of these more modern reactors are designed to be passively safe; that is the reactor cools down by itself when the cooling power is turned off, or if the reactor is unpowered for any other reason. It is interesting that a Korean company, Thorcon, is now advertising modular MSR reactors, which it claims will be cheaper than coal (16).

So which will it be, nuclear or solar? Fortunately, there is a gigantic laboratory in Europe; France and Germany. France has decided to go nuclear and at this point about 80% of its electricity is powered by nuclear reactors. Germany decided to embark on an 'energiewende', or energy transformation. It is decommissioning its 17 nuclear reactors and is emphasizing solar, especially wind and solar photovoltaic. At this point, about 25% of its electric power is supplied by wind and solar photovoltaic. However according to Energy Central, an organization, which compiles energy statistics, a kilowatt hour (kWh) in Germany costs about 35 cents, and in France, about 19 cents, or about half the price the Germans pay. Furthermore, since the energiewende, kWh prices in Germany have been rising fast, quadrupling since 2000 despite subsidies of ~\$10B per year by the government. More and more Germans seem to be getting disenchanted with the energiewende (17). France on the other hand has one of the lowest energy prices in Europe. Figure (7) is a graph of the development of prices for a kWh in Germany, France and the United States, taken from the German consumer advocacy group NAEB (in German). German electricity is much more expensive than French and this is with only 25% from solar in Germany. France, by contrast, has about 80% of its electrical energy from nuclear.

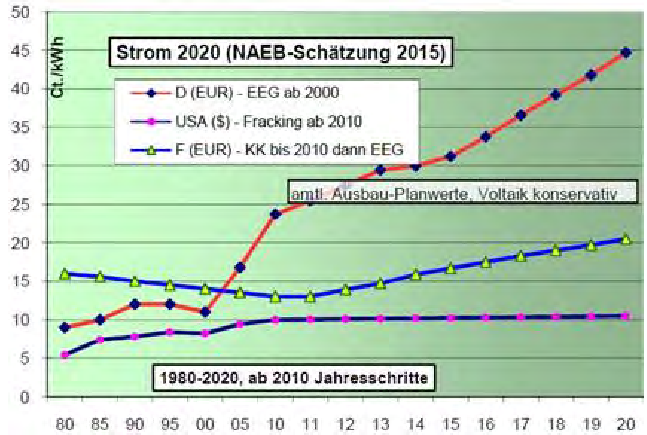

FIGURE 7. **The development of energy prices in Germany, France and the United States from 1980 to 2020, notice the change of scale of the horizontal axis after 2010.**

In addition, the French emit considerably less CO_2 per capita into the atmosphere than their German neighbors. In fact with the energiewende, the Germans still use a great deal of soft coal to produce power when the sun does not shine, the wind does not blow, or to replace lost nuclear power. Figure (8) is of the per capita CO_2 emission for European countries, calculated by dividing the CO_2 emission calculated by BP in 2014, by the population then. Clearly the average Frenchman emits about half the CO_2 of the average German.

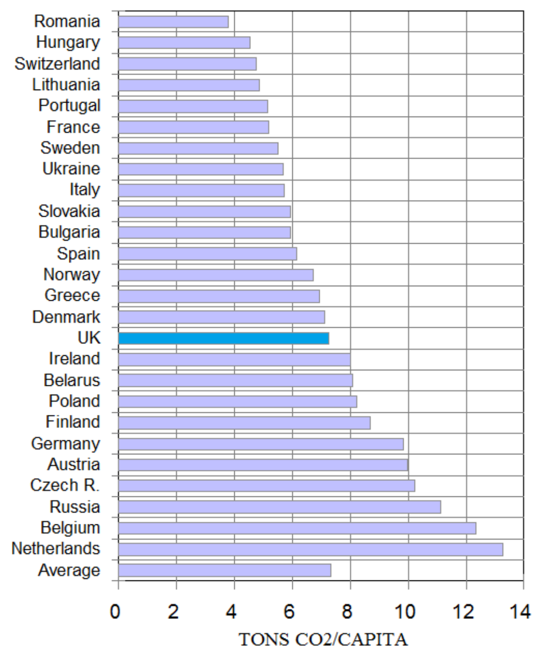

FIGURE 8. **Yearly tons of CO_2 per capita put into the atmosphere by a variety of European countries. France puts about half the CO_2 into the atmosphere per capita, as does Germany.**

At least at this point, honors in the competition go to France. To those who claim that nuclear power is too expensive, or is environmentally unsound, there is a one-word answer: France. The French use nuclear for 80% of the electric power, they do it without going broke, and without trashing their environment. While there will likely be room for both nuclear and solar power as carbon free options for midcentury, this article regards current evidence as favoring nuclear as being the main source. The 'gigantic laboratory' in Europe confirms this, at least at present.

Furthermore, Germany is a very rich country, if it wants expensive energy, it can certainly have it. Figure (1) shows that there are many poorer countries which simply cannot afford it, but still are unwilling to give up the benefits to civilization that inexpensive fossil fuel provides. Nuclear power could well be a follow on for these countries. For instance India is currently very active in developing advanced nuclear reactors.

However thermal nuclear reactors use only a tiny fraction of the total resource, well under 1% of the available uranium and thorium. In that sense, nuclear fuel is also a finite and diminishing resource. In fact it is almost certain that there is more fossil fuel for a fossil fuel based economy than there is ^{235}U for a thermal nuclear reactor based economy (3). However breeding could use nearly all of this resource. This would allow the world to use 30 or more terawatts, at least as far into the future as the dawn of civilization was in the past. In realistic any sense, it is a sustainable resource.

III. THE BASICS OF FUSION BREEDING

Fission reactors can be engineered to breed fuel by using fast rather than thermal neutrons, but the breeding rate is low and these reactors are much more expensive and complicated than thermal neutron reactors. Using them would imply a staggering cost. Furthermore, their fuel inventory is large; they need a great deal of fissile material just to get started (15).

Much less well known is that fusion can also be used to breed nuclear fuel, and if this can be developed, it would have many advantages over fission breeding. For nearly 20 years, this author (5-7) has argued that the goal of the controlled fusion project should be shifted to fusion breeding that is the use of fusion neutrons to breed fuel for separate nuclear fission reactors.

A portion of the nuclear industry is advocating for fission breeders. The private dollars supporting this advocacy are large. The pure fusion project has received significant government support, although nothing like what the solar effort has received. Shown in Fig (9) is the year-by-year American support for the magnetic fusion project, in 2014 dollars, as obtained by the Fusion Power Associates, from the US Department of Energy. Note that this is for the support of scientific research of a fundamental nature.

Fusion proponents, for the most part, see fusion as an inherently safe energy source with minimal issues of hazardous waste and an inexhaustible fuel supply. They would prefer not to tie their fortunes to fission, which might not even want them, and which they see as having issues of safety, proliferation, and long-term radioactive waste. But they should

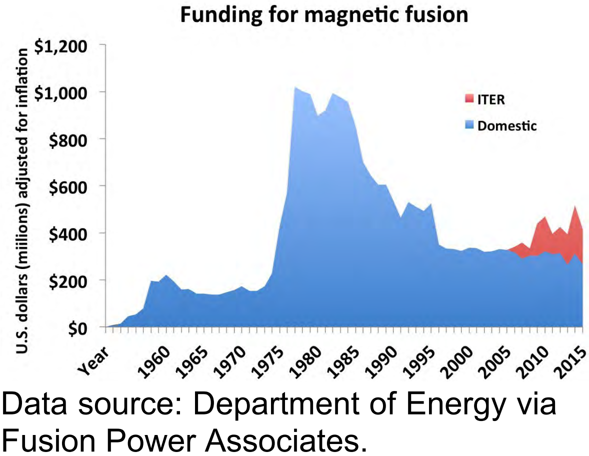

FIGURE 9. The US Support of magnetic fusion, year by year in 2014 dollars. The support is significant, but is not nearly what solar power development has received.

consider realities. As we will see, fusion breeding is at least an order of magnitude easier to achieve than pure fusion power. It should be possible, whereas commercial application of pure fusion may turn out not to be. Even in the best of circumstances, commercial fusion breeding should be available quite a few decades earlier than commercial pure fusion. Thus it could serve as an intermediate objective, of genuine economic value, on the path to pure fusion.

The numbers of people advocating fusion breeding are few; dollars supporting this effort are zero, although to some extent fusion breeding can ride the diminishing coattails of support for pure fusion. However fusion breeding has enormous potential advantages over fission breeding. In all probability, assuming a serious effort, fusion breeding could not only generate $\sim$ 10 terawatts, but could do so not long after mid century.

The author has written a series of articles on fusion breeding, culminating in a review article, published open access in the fusion literature (6), as well as an article solicited by that journal editor for its special issue on strategic opportunities in fusion (7). Collectively, these articles have well over a hundred references. While some of the work presented here is original, it is also a brief review of earlier work. Presenting only the original work without reviewing the previous work would render this paper virtually incomprehensible. This review points in one direction and one direction alone, namely that fusion breeding is the only option for fusion, at least if the world hopes for wide scale fusion power in the 21st century. However the fate of the fusion project, in the general scheme of things, is small potatoes. *What is important is that fusion breeding is a potential carbon free, sustainable, economically and environmentally sound power source with little or no proliferation risk, which might be ready not too long after midcentury.* It is one of very few such possibilities, yet it has largely been ignored. The use of fusion breeding instead of pure fusion could cut decades and decades, and save tens and tens of billions of dollars from the timeline and cost of developing pure fusion; assuming pure fusion can be developed at all. Hence the author regards this as extremely important.

The crux of the argument is that an economical fusion breeder economy could follow relatively quickly a success by ITER (the International Tokamak Experimental Reactor) being built in France, or NIF (the National Ignition Facility), a laser fusion facility in the Lawrence Livermore National Laboratory in Livermore, CA, or both, certainly by mid century or shortly thereafter. A pure fusion economy will take many additional breakthroughs, which might or might not be possible to achieve.

Pure fusion is the use of the 14 MeV fusion neutron's kinetic energy to power a heat exchanger, for instance to boil water. Fusion breeding uses this same kinetic energy to boil water, **and** what, for want of a better term, we will call the neutron's potential energy to produce half to three-fourth of a ^{233}U from thorium. However, when this is burned in a conventional nuclear reactor, it produces about 100–150 MeV, effectively increasing the neutron energy by about an order of magnitude. It is this order of magnitude increase in reaction that renders fusion breeding much more achievable for commercial power use than pure fusion. Furthermore, the breeding reactions are exothermic, effectively multiplying the neutron energy by a factor M, usually considered to be between 1.5 and 2.

As the nuclear industry is currently configured, using mostly light water reactors (LWRs), less than 1% of the uranium resource (that portion which is naturally occurring fissile ^{235}U) and 0% of the thorium (thorium has only a single naturally occuring isotope and is not fissile) is available as nuclear fuel. Either fission breeding or fusion breeding makes nearly the entire resource available. However, as a fuel producer, fusion breeding is about an order of magnitude more prolific than fission breeding, its competitor. To illustrate, a single fusion breeder can fuel five LWRs of equal power. It would take two fission breeders, at maximum breeding rate to fuel one, implying a staggering cost. Furthermore, a fission breeder needs a great deal of fissile material just to get started; a fusion breeder needs none (15).

The reason fusion breeding is so much more prolific as a breeder is very simple. Whether the reaction is a fission or fusion reaction, each reaction produces 2-3 neutrons (in the fusion reaction this is after neutron multiplication, which is possible because the fusion neutron has a much higher energy than the fission produced neutron). In fission, one of these neutrons is needed to continue the chain reaction; in fusion one is needed to breed the tritium from lithium, so in either case one or two neutrons are available for other purposes. Of course in either case there are losses, so probably somewhere between half and one neutron per reaction is available for breeding ^{233}U from ^{232}Th, or ^{239}Pu from ^{238}U. However the fission reaction produces about 200 MeV, while the DT fusion reaction produces only about 20 (actually a 14 MeV neutron and a 3.5 MeV alpha particle). Hence for reactors of equal power, a fusion reactor generates about 10 times more neutrons, and therefore breeds about 10 times more nuclear fuel than a fission reactor does. In other words, a fusion reactor is neutron rich and energy poor, while a fission reaction is energy rich and neutron poor, a perfect match.

It is important to understand that fusion breeding and hybrid fusion are not necessarily synonymous (4). Fusion breeding is only one manifestation of hybrid fusion, but it is by far the optimum. More typically, hybrid fusion means a fusion and fission reactor as a single unit. Perhaps in this case, the role of the fusion reactor might be to supply neutrons to a subcritical fission reactor. But this would be hopelessly complex and dangerous. A fission reactor is complicated enough, and nobody asserts that a fusion reactor will be simple. Furthermore, such a reactor stores hundreds of megajoules of plasma energy, and gigajoules magnetic of energy (i.e. tons of TNT) in close proximity to a ton or so of plutonium. An uncontrolled quench of the superconducting magnets would be enormously destructive. In such a quench, the magnetic energy is released in some uncontrolled manner. While obviously many precautions are taken, uncontrolled quenches do happen. A few years ago, one occurred at CERN. It took the machine off line for over a year. But CERN is a tunnel tens of miles long. An uncontrolled quench in the confined space of say ITER would undoubtedly destroy the building and much around it, scattering any nearby plutonium all over, if the reactor were a 'conventional' fusion fission reactor.

Edward Teller made a relevant statement, as quoted by Richard Garwin (15,18). Teller was discussing breeder reactors, which have a large loading of plutonium, but his statement applies equally well to 'conventional' hybrid fusion reactors, which also have a large inventory of plutonium and/or other fissile material in close proximity to stored energy equivalent of a ton or so of TNT.

"For the fast breeder to work in its steady state breeding condition, you probably need a half ton of plutonium. In order that it should work economically; it probably needs more than one ton of plutonium. I do not like the hazard involved. I suggested that nuclear reactors are a blessing because they are clean. They are clean as long as they function as planned, but if they malfunction in a massive manner, they can release enough fission products to kill a tremendous number of people. But if you put together 2 tons of plutonium in a breeder, one tenth of 1% of this material could become critical. I have listened to hundreds of analyses of what course a nuclear accident could take. Although I believe it is possible to analyze the immediate consequences of an accident, I do not believe it i.e. possible to foresee the secondary consequences. In an accident involving plutonium, a couple of tons of plutonium can melt. I don't think anyone can foresee where 1, or 2, or 5% of the plutonium will find itself and how it will get mixed with other materials. A small fraction of the initial charge can become a great hazard." Surely this warning also applies to a 'conventional' hybrid reactor, where a ton or so of plutonium is in close proximity to a ton or so of TNT's worth of magnetic energy.

This article takes the view that the nuclear industry has known for over half a century how to build and safely operate critical thermal reactors. There is no need for subcritical reactors. Criticality is not a problem for these reactors; ultimately fuel supply might well be. Thus there is no fission reactor inside a fusion breeder.

In a fusion breeder, it is very important that blanket be a liquid, perhaps a molten salt such as FLiBe, in which some thorium is dissolved. This liquid would flow continually from the fusion reactor to a reprocessing plant, where the tritium and ^{233}U (actually ^{233}Pa, which decays by beta decay to ^{233}U in a month or so) would be continually removed. Hence, there would be no accumulation of fissile material anywhere near the fusion reactor, and as soon as the ^{233}U is separated out, it is dissolved in ^{238}U, so there is no build up of material with proliferation potential and there is no criticality issue.

The key to fusion breeding's ability to generate mid-century power is that the demands on the fusion reactor, whatever it is, are greatly reduced for fusion breeding as opposed to pure fusion (5-7, 10). Furthermore, a great deal more is known about what the plasma of a fusion reactor can and cannot do, than was the case in the 1970's and 80's when hybrid fusion was last seriously discussed by the major labs.

Fusion breeding is not a new idea. Andrei Sakharov (19) and Hans Bethe (20), two giants of 20th century physics both advocated it instead of pure fusion.

So far several magnetic fusion devices (all tokamaks so far) have produced about 10-20 Megajoules of fusion neutrons. However NIF was designed to produce also about 10-20 Megajoules, but during its five years of operation, it has produced only about 10-30 kilojoules (21). While inertial fusion (laser fusion in the case of NIF) is likely to ultimately be a contender, at this point it is not, so this paper considers only magnetic fusion.

IV. MAGNETIC FUSION: THE TRIPLE FUSION PRODUCT

An important measure of the capability of any magnetic fusion device is the triple fusion product product $nT\tau$, where n is the density in m^{-3}, T is the temperature in keV, and τ is the energy confinement time in seconds. At fusion temperatures, the DT fusion reaction rate $< \sigma v >$, is roughly proportional to the ion temperature squared. For instance at 10keV, $< \sigma v >= 1.19 \times 10^{-16} cm^3/s$, while at 20 keV, it is, 4.29×10^{-16}. Since the fusion power per unit volume is $n_D n_T W < \sigma v >$, where the n's are the deuteron and triton number density, and W is the fusion energy per reaction, 14 MeV for the neutron and 3.5 for the alpha particle, this power density is roughly proportional to n^2T^2. However the input power density is simply nT/τ, so the ratio of fusion power to input power, the Q of the device is roughly proportional to $nT\tau$. Reference 6 enumerates the triple fusion product of a number of magnetic fusion devices. The largest value is 1.6×10^{21}, by the Japanese tokamak JT-60. For a stellarator, the largest value up to now is from the Japanese stellarator LHD and is 4×10^{19}. Every other fusion device has a triple fusion product at least two and a half, and more often as much as 5 or 6 orders of magnitude below what JT-60 has achieved (6).

V. THE TOKAMAK PROGRAM

The development of fusion has proven to be extraordinarily difficult. In its early days, many seemingly promising concepts were carefully considered and rejected before settling on the tokamak, now the most highly developed device. A tokamak is a toroidal plasma, which is confined by both, a toroidal magnetic field provided by external coils and a poloidal field produced by the plasma current. The plasma has cylindrical symmetry about the vertical axis passing through the center of the horizontal torus. Hence the tokamak is what one calls a two dimensional configuration, as the plasma has no dependence on the coordinate angle which goes around toroidal axis. A transformer drives the plasma the current. However the transformer has only so many volt seconds, so at some point the current can no longer be driven. An important area of tokamak research then is finding a steady state (or perhaps pulsed high duty factor) way of driving the current. There has been a great deal of research on driving currents with microwaves, neutral beams, as well as what is called the bootstrap current, a method of current drive inherent in the two dimensional configuration (a purely cylindrical plasma has no bootstrap current). Another problem the tokamak confronts is disruptions; this is the sudden release of the plasma energy in some uncontrolled manner. For instance in JET, about 10 mega joules of plasma energy (about 5 pounds of TNT) can be released. A great deal of progress has been made in avoiding disruptions, and JT-60 has demonstrated disruption free operation for 30 seconds, the maximum time of their pulse power, in fusion breeding relevant regimes,. However just because the tokamak has run disruption free this long does not mean the problem has been solved, a fusion reactor after all, has to run disruption free for months or years. Hence the two major plasma physics problems which the tokamak confronts, are driving the current steady state, and avoiding disruptions.

It has taken tens of billions of dollars and nearly 50 years of development to get the tokamak to where it is right now. Shown in Fig (10) is a plot of the advance of the triple fusion product, (5) from about 1970 to about 2000. The period shown corresponds to the period of building larger and larger tokamaks. At about 2000, the curve leveled off, no more larger tokamaks have been built; they became too expensive. However tokamak science has advanced in other ways, for instance JET and JT-60 have both run with longer pulses, and several superconducting tokamaks have been built.

There have been three large tokamaks, JET in England (set up by the European community), TFTR in Princeton in the United States, and JT-60in Japan. Large here means that 40 megawatts of external power, mostly neutral beams, have been used to power them. Each runs with megamp currents, magnet fields of 3-5.5 Teslas and aspect ratios of about 3 (i.e. about a 3 meter major radius and a 1 meter minor radius). Both TFTR (22) and JET (23) have run with DT,

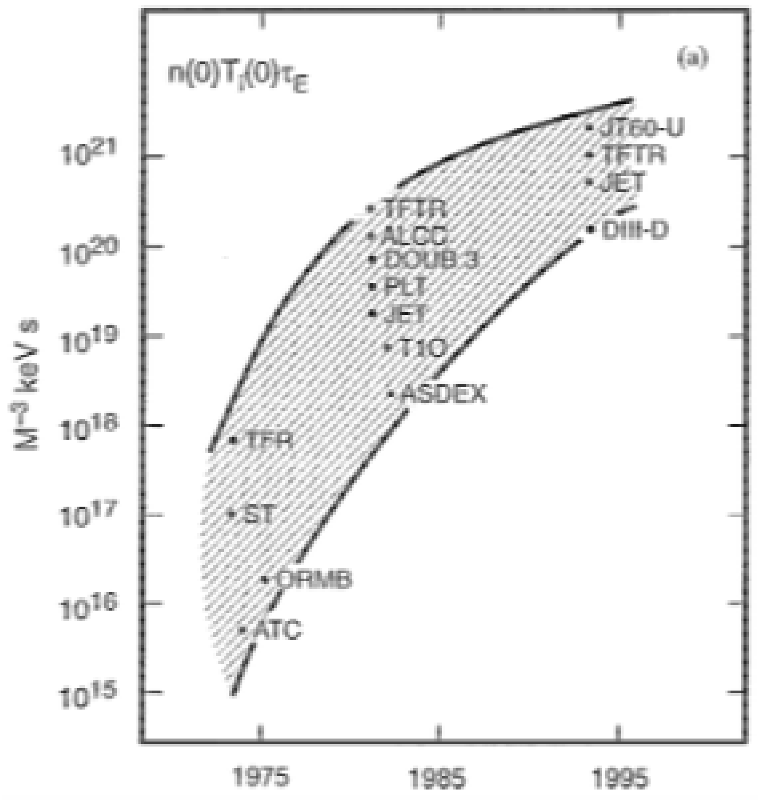

FIGURE 10. **The fusion triple product as a function of year, from about 1970 to about 2000, for various tokamaks as indicated. The increase arose both from learning more about tokamak physics, an also from building larger, more capable tokamaks. However by about 2000, the increase ended because the price of larger, more advanced tokamaks got too high. If all goes well with ITER, the curve should show a very great increase by about 2025.**

producing about 10^{19} neutrons with a Q of about 0.5 in runs of several seconds. Unfortunately TFTR has been disassembled. JT-60 has produced comparable discharges (24-29), but only in DD, these lasting as long as 30 seconds. It is not equipped to handle tritium or high fluxes of 14 MeV neutrons.

The success of the tokamak program up to now has convinced the world to join together to build a prototype reactor, ITER, now being constructed in France, and supported by 7 signatories, Europe, the USA, Russia, China, Korea, Japan and India. The original plan was for an 8 meter major radius device which would be expected to achieve a $Q = 10$, producing about 1.5 GW of neutron power, driven by 150 MW of neutral beam and microwave power (30). The pulse length was to be 400 seconds and the proposed cost about \$20B, \$10B capital cost and \$10B operating cost for 10 years. The USA pulled out of the project, claiming the cost was too high. For our purposes here, we call this device Large ITER. Ultimately the partners decided to build a more modest tokamak, having a 6 meter major radius, hopefully achieving $Q = 10$, producing 500 MW of fusion power with 50 MW of neutral beam and microwave power driving it, for the same 400 seconds (31). With the lower cost, the USA reconsidered and rejoined. The machine would contain about 1000 cubic meters of plasma (Large ITER, $\sim$2000). The plasma energy in this machine will be many hundreds of Megajoules, enough to melt a ton of copper. The magnetic energy is $\sim$5 GJ, or over a ton of TNT. Depending on just how this energy is released, a major disruption may or may not do extensive damage to the machine. Hence avoiding major disruptions is a crucial task for ITER. The proposed cost had been reduced to \$10B, half for capital, half for operation for 10 years. The machine is being constructed in Carderache, France and is expected to begin operation with DT plasmas in the 2035 time frame. A schematic of ITER, taken from the ITER web site (32) is shown in Fig 11.

VI. THE SCIENTIFIC PROTOTYPE

This section deals with a digression on the American magnetic fusion program and a suggestion of where it should go from here. Until the disassembly of TFTR, the United States was one of the leaders of the world fusion program. Since then, as other countries built tokamaks, and especially tokamaks with superconducting toroidal magnetic field coils, the USA has fallen way behind. Our magnetic fusion program for years were centered on two tokamaks, D3-D at General Atomics in San Diego, and Alcator at MIT, both rather old and

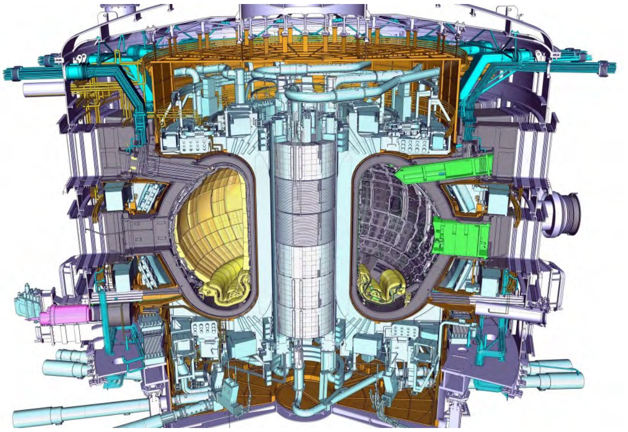

FIGURE 11. A schematic of ITER taken from its web site, www.iter.org. The major radius is 6 meters and the plasma volume will be about 1000 cubic meters. It is expected to use about 50 MW of neutral beam and microwave power to generate about 500 MW of fusion power.

small tokamaks by current standards, and NSTX, a spherical tokamak at Princeton. Considering the modest size of the machines, they produced excellent physics. However realistically, the United States has not been playing in fusion's major league for years. To make matters worse, recently NSTX has blown a large coil and is off line for at least a year, and Alcator has been shut down, leaving only D3-D.

The American fusion community is now at a crossroads. What to do? Build an ignition device? Try a different configuration? Fix and upgrade NSTX? The program has been becalmed for nearly two decades since the triumph at TFTR. This author sees only a single viable option: build 'The Scientific Prototype', a path suggested since 1999 (5,6,33). This is a proposed tokamak about the size of TFTR, having Q$\sim$1, generating $\sim$40 MW of fusion power. At this point it does not look that different from TFTR or JET, but there are significant differences. The scientific prototype will be designed to run steady state for long periods of time (days, weeks, months...) and will continuously breed its own tritium. If the fusion effort does not start to breed tritium now, when will it? This would mean a liquid or flowing blanket for the machine.

In short, The Scientific Prototype will address the problems, on a smaller machine, that ITER will not and cannot address, even granting it the maximum success. To succeed, the scientific prototype will have to solve the problems of disruptions and current drive for days to months long operation, as well as supply its own tritium. It is difficult to see how fusion can progress very far without the knowledge the scientific prototype would provide. While the 'scientific prototype' had been proposed as a stepping-stone toward pure fusion, adding thorium to the flowing blanket would also make it a vital stepping-stone for fusion breeding. It would then begin to breed small amounts of ^{233}U. For the first time, the fusion program would produce something the world could actually use.

It is certainly not clear to this author what the cost and timeline for the scientific prototype would be. However if the United States makes a serious effort for its design, (i.e. a somewhat larger TFTR, because a breeding blanket must be added on), construction and operation, and if the project is successful, it is not unreasonable to think it could finish its job, at a reasonable cost by about 2040, just when ITER, hopefully will be succeeding with DT. If both are successful, a path opens up to rapidly develop fusion breeding; or alternatively, one would be on a new plateau for the continued development of pure fusion.

VII. THE STELLARATOR PROGRAM

If tokamaks have any serious competition in MFE, it is almost certainly from stellarators. A stellarator is a three-dimensional configuration, one much more difficult to both construct and analyze, and which almost certainly has more loss channels than a tokamak. External magnetic fields maintain the plasma equilibrium. There are two large stellarator experiments, LHD (34) in Japan and Wendelstein 7, just recently constructed and turned on in Germany (35-37). The latter used a toroidal field of about 3T, has a major radius of 5.5 meters and an aspect ratio of about 10. It contains about 30 cubic meters of plasma. Both rely on very complicated superconducting coils to generate the twisted, toroidal fields; fields that are as much like two-dimensional fields as possible. It is only recently that theory and computational techniques have advanced to where these coils can be designed and build. A schematic of Wendelstein 7's field coils, taken from its web site, is shown in Figure 12. Each coil is about 3.5 meters in height. It is a very complicated, inherently 3 dimensional configuration.

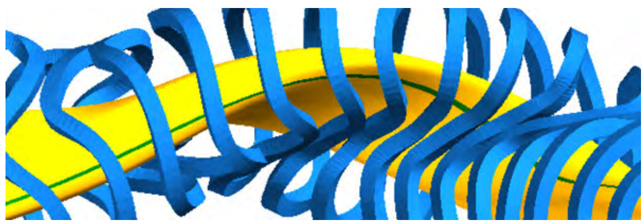

FIGURE 12. A schematic of the superconducting field coils of Wendelstein 7 taken from its web site, http://www.ipp.mpg.de/w7x. 50 individual, oddly shaped field coils provide the field, which inside the plasma, is as 2 dimensional as possible.

According to its web site, LHD has achieved a triple product of 4×10^{19}, a factor of 40 below JT-60, while Wendelstein has achieved about 10^{19} as of fall 2016. One reason the triple product is less, is that JT-60 has a confinement time of about a second, whereas LHD and Wendelstein (so far) have a confinement time more like 0.1 seconds. Possibly this reflects the fact that a stellarator has more loss channels than a tokamak due to its 3 dimensional configuration. However Wendelstein 7 had achieved this nearly right out of the starting gate. It still has to install a diverter and turn on its neutral beam heaters; right now only 10 MW of millimeter wave power (by gyrotrons) for electron cyclotron heating heats it. However since there is no plasma current, disruptions are hardly a problem and the machine runs routinely in steady state. Whereas a long discharge in JT-60 is 30 seconds, a long discharge in Wendelstein 7 is 30 minutes.

VIII. PURE FUSION's SCIENTIFIC DILEMMA

To see pure fusion's scientific dilemma, let's stipulate the best possible outcome from ITER, (31). Say it achieves Q$\sim$10, producing 500 MW of fusion power and had the plasma heated and current driven by 50 MW of beams and/or microwaves soon after 2035. While ITER is an experimental device, not a power plant, let us imagine a power plant having its parameters. What would it mean as far as energy production goes? Since electricity is typically produced with an efficiency of $\sim$1/3, the device would produce 170 MWe. However, it needs 50 MW to drive it. But beams and microwaves are not produced with 100% efficiency, again 1/3 is a better estimate, so 150 MWe is needed to drive the tokamak, leaving all of 20MW for the grid! Of course one could calculate a higher estimate by stipulating higher efficiencies. In fact higher efficiency power plants have been designed, but is a question of a tradeoff between their cost and efficiency. Up to now, 1/3 is really about right and corresponds to nearly all experience. Furthermore, the total beam and microwave systems used to heat the plasma and drive its current, struggle to reach even that efficiency. Also, given the size and cost of ITER, even if it were fully ignited and took no external power, its size and cost for 170 MWe would still render the device totally uneconomical.

To make pure fusion economically feasible, first of all, ITER's Q would have to be increased by at least a factor of 3 or 4. Secondly, the device would have to be made smaller and cheaper while increasing the power by at least a factor of 5 or 6 (a typical power plant has about 3 GW thermal and about 1 GW electric power). As will become apparent soon, this means the tokamak would have to operate in physics regimes far beyond what it has operated in successfully so far. Finally since the device would be both smaller and more powerful, the neutron wall loading would be at least an order of magnitude greater. These are not minor details; they would take decades and tens of billions of dollars to achieve, assuming they could be achieved at all. At best pure fusion could be a 22nd century power source. But the need could well be for carbon free power much sooner.

The ITER web site makes rather vague references to a DEMO reactor, which would produce electricity economically after the success of ITER. But an obvious question then is whether one can sufficiently improve tokamak performance so that a DEMO is feasible. Unfortunately the answer is probably not. Tokamak performance is constrained by at least 3 restrictions which we have called conservative design rules (CDR's). These are limits of the current, plasma pressure and plasma density. These have been fully discussed in [6], [7], and [38]. They are not controversial; they are well grounded in theory and have been extensively confirmed by experiment as discussed in the references. However the tokamak community has been reluctant to admit that these constraints, well known individually, when taken together severely restrict the possible fusion power. The details of these particular limits are worth sketching.

Without going into to too much tokamak jargon, the main limits are on pressure and current. If the current it too high, a variety of MHD and tearing modes become unstable. This maximum current is proportional to the toroidal magnetic field as well as a bunch of geometric factors. Then there is also a maximum pressure the plasma can contain; exceed this and it is unstable to what are called ballooning modes. Since only ions react, but both electrons and ions contribute to the pressure, the fusion power depends on temperature ratio. Here we assume the ion temperature is twice the electron temperature, as is characteristic of todays beam heated tokamaks. (22-29). In a reactor, the temperatures are more likely to be equal, reducing the power. It turns out that this maximum pressure is proportional to the current, so the maximum current really determines everything. Once the plasma pressure is set, one needs to set the temperature so that the fusion rate maximizes. Note that the fusion rate is $\mathrm{Wn}^2 < \sigma \mathrm{v} >$ (see Section II). Since the pressure is specified, the fusion rate then maximizes, at that given pressure, at the temperature where $< \sigma \mathrm{v} >/\mathrm{T}^2$ maximizes. This is at a temperature of about 17keV, considerably less than the temperature where $< \sigma \mathrm{v} >$ maximizes if it were unconstrained by pressure limits.

These considerations together give rise to a simple formula for maximum possible fusion power (6). It is

$$P_{fus}(MW) < 0.11\kappa^2 \frac{[a(m)B(T)]^4}{R(m)} \tag{1}$$

where P_{fus} is the neutron power in megawatts, a and R are the minor and major radius in meters, B is the toroidal field in Teslas and κ is the eccentricity of the assumed elliptical cross section. It is nearly always constrained to be less than about 2. This has been fully discussed in Refs. (6,7 and 38). The formula has worked for all neutron-producing tokamaks (TFTR and JET) as well as for the designs of both ITER and Large ITER. For instance the hot ion mode in TFTR ($a = 0.9$, $B = 5.1$, $R = 2.6$, $\kappa = 1$) has generated about 9 MW of neutron power, and Eq. (1) predicts an upper limit of about 19 MW.

It is amazing that there is such a simple formula for the maximum fusion power dependent only on the magnetic field and the geometry of the tokamak. Play with the parameters in Eq. (1) any way you want. It will be apparent that an economically interesting power is not available for reasonable size and magnetic field. A pure fusion tokamak reactor will have to figure out a way to get around conservative design rules. This has never been done.

The maximum fusion power produced by JET (23) and TFTR (22) are about half of the maximum that CDRs would specify. The same is true for the design powers of both ITER (31) and the original Large ITER (30). It is also true of the design power of ARC (39) a tokamak proposed by MIT based on new high temperature superconducting, demountable magnets. Numerous experiments on

JT-60 have conclusively confirmed the conservative design rules (6,16-21, 38). Furthermore studies of the disruptivity (this is the reciprocal of the time between disruptions) on JET (40) has confirmed that once conservative design rules are violated, the disruptivity increases very abruptly. The tokamak community has been reluctant to admit the combined effect of these constraints on power, even though individually, each constraint individually is well known. However, recently Friedberg et al. (41) have come to a similar conclusion. If tokamaks remain constrained by conservative design rules, they are very unlikely to develop into economical pure fusion reactors. A tokamak, which is a pure fusion reactor, would have to operate well beyond the constraints imposed by CDRs.

IX. SOME OTHER NOT SUCH WONDERFUL PURE FUSION FACTS

These 'not such wonderful pure fusion facts' involve time and dollars. The American magnetic fusion budget has been hundreds of millions of dollars per year; the rest of the world invests at least this much, and most likely much more. This has been going on for over half a century. Hence the total spent on magnetic fusion, world wide, mostly to get tokamaks to where they are now, is in the many tens of billions of dollars. Early on in the program, many other concepts were investigated and ultimately rejected. Do not forget that these machines were designed and built, over decades, by the sharpest minds, and most experienced practitioners in the business, worldwide.

Hence any sponsor, whether in the public or private sector (42), who hears a proposal that someone will develop commercial fusion in a few years for a billion or two, is justified in being extremely skeptical. This is especially true where some of the concepts now receiving private sector support had been carefully studied, yet ultimately rejected by the major labs and their sponsors (6). Of course it is always remotely possible that a genius will invent commercial fusion in his or her garage, but one should consider realities. The odds of success, while perhaps not zero, are infinitesimal. If a sponsor wishes to invest his hard earned dollars in such a scheme, this author can only wish him luck.

The not so wonderful fusion fact here is that after 50 years of examining many different concepts, it is extremely unlikely that any short cut exists.

Another not so wonderful fusion fact is the time for ITER approval and development. It was first proposed in the 1985 summit meeting between President Reagan and First Secretary Gorbachev. The machine was then called INTOR. A design team was set up and worked on it for years and an international partnership involving Russia, Europe, the USA, China, Korea and Japan was set up. They received approval to build the machine in about 2002. However another problem cropped up: where to build it. Both Europe and Japan put in strong proposals, and the partners vote split, three for Europe, and three for Japan. This led to about a three-year hiatus, until the partners finally agreed on Europe. India, by then had also joined the partnership. It was approved in 2005 and final design and construction were planned. First plasma was expected in 2016 and the cost was to be about 5B Euros.

However the construction and design hit one snag after another. In 2010, the cost had escalated to 19B euros, and the first plasma was to be in 2019 (43). It got delayed nearly a year for every year elapsed! At this point it has been delayed further and first plasma is expected in 2025, and DT experiments are expected to begin in about 2035 (44). In other words it will have taken 50 years (!) from the initial proposal, just to get to DT operation, in other words to get to the starting gate. This is longer than the career of the typical physicist.

The not so wonderful fusion fact here is that large fusion experiments take a very, very long time to get underway. This has proven to be a fact of life.

Another not so wonderful fusion fact involves cost. The capital cost of ITER was initially estimated as about 5 billion euros. But by 2010 it had escalated to 19 billion. Now it is said to be $20 billion, but it wants another $5B to meet its milestones (44). Rumored and whispered estimates have put the cost much higher. Whatever the actual cost, suffice it to say, that the sponsors, the ones who have to come up with the scarce, hard won dollars, euros, yen, whatever, are not overjoyed.

Here is Senator Diane Feinstein [45], at the time chair of the subcommittee on Energy and Water Development of the Senate on the rapidly increasing cost of ITER:

"We provide no funding for ITER until the department (of energy) provides this committee with a baseline cost, schedule and scope."

Many have blamed a chaotic international management structure for these problems, a management whose key personnel has changed several times. A management allowing some partners pay in cash, some in kind, and where huge components are manufactured in in different countries, with different manufacturing cultures, thousands of miles apart, without sufficient overall supervision and coordination. Yet they have to fit together with micron tolerance. ITER for years has always managed to dodge these bullets, but the escalating cost and constantly changing management is a real concern.

Another not so wonderful fusion fact is that these large fusion experiments are very, very expensive.

But let us consider other confinement systems besides the tokamak. To see this, let us imagine attempting to develop fusion via the stellarator route, at this point the tokamak's closest competitor. The Wendelstein 7 web site does not seem to give cost or milestone schedule. However it does say that design began in 1994, and first plasma was in 2016, a 22-year development phase. To complete its job, at the least it would have to add a divertor and neutral beams for additional heating. This would take years, more likely decades. And it might fail; it might never find it has the confinement of a tokamak.

But let's stipulate success. It has almost certainly already solved the steady state and disruption problems; let's say that by say 2025 it also produces fusion type plasmas with tokamak (i.e. JT-60) like confinement. Then what? The next step would obviously be a Large ITER size effort, a 1.5 GW fusion power, and 2000 cubic meter plasma. Most simply, this means that every linear dimension of Wendelstein 7 would be have to be about 4 times as large. In other words it would require a 22-meter major radius with 14-meter tall superconducting magnets, nearly 3 times the linear dimension of Large ITER, about half the size of a football field, just for the bare reactor, with field coils as tall as a 4-story building. This does not look inexpensive. Considering the size and complexity, it would almost certainly take as long as the design of ITER took (probably much longer), and its construction would take at least as long and would cost at least as much (probably much more). All this is to begin a decades long process, starting about 2025, perhaps finishing in 2055, just to get to where ITER is right now. Furthermore, where would one the get the tens of billions needed to do this? Would any sponsor, or group of sponsors come up with this sort of money when ITER itself is in such an uncertain state? This author's answer is no.

Nobody can deny the tremendous accomplishment of the Garching group in developing Wendelstein 7. Perhaps the USA should give it some support, as a hedge, especially if they would be willing to help out with our scientific prototype (assuming the United States builds it) over the next few decades.

Any other potential fusion device is even further behind. Reference 6 enumerated the triple fusion product and contained energy of a variety of competing confinement concepts; all except the stellarator are many orders of magnitude behind the tokamak, and several have Achilles heels which will prevent them from ever becoming commercially viable power producers. We have little choice but to continue to dance with the lady we came in with.

Another not such wonderful fusion facts, is that for large-scale 21st century power, looking into alternate magnetic concepts is not a productive approach. They are too far behind; the dollars and time needed to develop an alternate configuration for 21st century power are simply not there.

What lesson do we learn from these not such wonderful fusion facts? This author learns that if one hope for commercial fusion, well integrated into the world's economy by century's end, there is little choice but to continue with ITER, and then only if the objective is switched to fusion breeding. The time, dollars, and most likely the scientific feasibility as well, for any alternative are simply not there. There is little hope that there will be a direct route from ITER to a pure fusion reactor; there are too many fundamental obstacles to overcome. However there is a very reasonable hope for ITER to develop into a fusion breeder. In fact after a success by ITER this could happen rather rapidly, especially if the USA develops, and has success with the scientific prototype.

X. THE SOLUTION: FUSION BREEDING

This author's key assertion here is that pure tokamak fusion is not feasible this century if indeed it ever is. The scientific, technical, dollar and time hurdles are just too great. While the ITER web site makes reference to a commercially viable DEMO after the success of ITER, there is no talk of the scientific hurdles it must overcome. This article has pointed out many such hurdles between a success with ITER and commercial fusion. However the demands on the tokamak for fusion breeding are much less. Specifically a tokamak breeder like ITER can operate within the constraints of conservative design rules, a commercial pure fusion tokamak cannot. It must break through them somehow. Hence fusion breeding is not only possible, but very likely inevitable. The need for sustainable carbon free power by century's end may well be that great.

In pure fusion, the 14 MeV neutrons coming from the DT fusion use only their kinetic energy heat an element of a heat exchanger, for instance to boil water. In fusion breeding, it does this, but also uses the neutron's potential energy to breed enough nuclear fuel to produce ten times more fission power than fusion power. That is, if one 14 MeV fusion neutron produces a single ^{233}U, and this is burned in a separate conventional nuclear reactor, it produces about 200 MeV, effectively multiplying the neutron energy by about an order of magnitude.

For breeding, the neutron is first inserted into a neutron multiplier, for instance beryllium, lead, uranium or some other material. (Even pure fusion needs some neutron multiplication, since the reaction produces only a single neutron, so none could be lost.) If one desires fusion breeding, the first thing one must do after the fusion reaction is to get more neutrons. After all, that fusion neutron must be used to breed tritium from lithium so as to fuel the fusion reactor, and even then no loss could be tolerated. The thing that saves fusion breeding (and even pure fusion) is the neutron's high energy (14 MeV), much higher than a typical fission neutron's energy (~2MeV). Using a high-energy neutron, one can generate additional spallation neutrons by bombarding a target, which is a neutron multiplier, perhaps Be, Pb or U. Typically the 14 MeV neutron produces a total of 2 or 3 spallation neutrons of lower energy. Hence the fast neutron produces 2–3 slower neutrons. One of these is used to breed tritium, i.e. to keep the fusion reactor going. The remaining neutrons can be used for other purposes.

Once the tritium is bred, the remaining slower neutrons are fed into either ^{232}Th or ^{238}U. This paper considers only the former, since the latter breeds plutonium, a material to avoid as much as possible. The thorium absorbs a slow neutron to become ^{233}Th, but this is unstable to double beta decay. It has a half-life of 22 min and then decays to ^{233}Pa (protactinium), which is also unstable and decays to ^{233}U with a half-life of 27 days. But ^{233}U is a perfectly good fissile material (46), i.e. a nuclear fuel for thermal neutron reactors, just like ^{235}U and ^{239}Pu. In fact ^{233}U even has certain advantages over ^{235}U as a fuel. Some ^{232}U is inevitably mixed in and this has a high-energy gamma in its decay chain, meaning the fuel must be handled remotely in a large industrial facility.

This makes diversion by terrorists or other non-state actors virtually impossible.

How much nuclear fuel is produced depends on the blanket design, and this paper does not get into that. The number of ^{233}U's produced per fusion neutron is complicated to calculate and depends on the blanket design. There are many blanket designs in the literature, some too complicated to show for our purposes here (they are inherently very, very complicated), some too simple. A reasonable compromise taken from Ref (47), is shown in Fig (13)

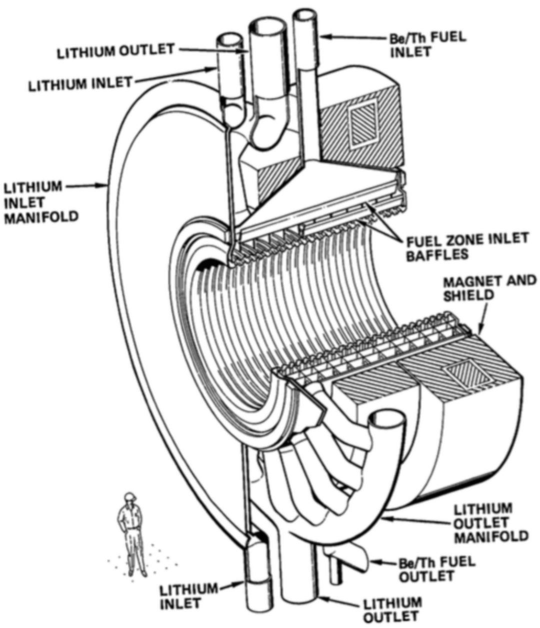

FIGURE 13. A schematic design of a fusion-breeding blanket taken from an early LLNL report (47), available on the web site www.ralphmoir.com.

The lithium and a combination of thorium and beryllium enter in this schematic via separate pipes. They are taken out through separate outlet pipes; the tritium is separated from the lithium outlet, and the protactinium is separated out from the Be/Th outlet. (Actually a more modern concept is to have all three inputs come in via a single pipe in which the molten salt FLiBe, with thorium dissolved in it enters. Both thorium and protactinium are soluble in FLiBe.). The protactinium is mixed immediately with ^{238}U where it soon becomes a fuel mix of the proper concentration, typically about 4% fissile, 96% fertile as used in today's LWR's. Thus once this fuel mix is made, there is no proliferation risk without isotope separation, a difficult and painstaking industrial process, far beyond the means of any terrorist groups.

One particular design [48], [49] has each fusion neutron producing 1 T after all losses, and 0.6 ^{233}U's. Since the breeding reactions are exothermal, the neutron energy is multiplied by about a factor of M in the blanket. Recent studies estimate the M factor can vary between about 1.5 and 2 (48,49), so not only does this reactor generate fuel for thermal nuclear reactors, it also roughly doubles the power of the fusion reactor. Typically these blankets expect to produce about 0.6 ^{233}U's from each fusion neutron. But each ^{233}U, releases about 200 MeV when burned, so the 14 MeV neutron ultimately produces 120 MeV of nuclear fuel, or the neutron energy produces about nine times as much nuclear fuel, to be burned in separate reactors away from the fusion reactor. This enormous increase in energy, about a factor of 10 increase in Q over the neutron power of the fusion reactor alone is reflective of the fact that fusion is neutron rich and energy poor, while fission is energy rich and neutron poor; a natural symbiosis.

Also the 14 MeV neutron releases roughly a total of from 21–28 MeV in its own blanket if M is between 1.5 and 2. Furthermore the fusion alpha particle releases 3.5 MeV.

This paper will not get further into the blanket details, but a molten salt FLIBE blanket, containing lithium, beryllium and fluorine has been discussed in the literature. The lithium breeds the tritium and the beryllium multiplies the neutrons. Also uranium, protactinium and thorium are all soluble in it. One web site, (50) has references to and links to several blanket designs for fusion breeding, including several old LLNL reports on the subject, which would be difficult to access in any other way. Also UCLA has a large program in blankets, studying many possible options (51).

Let us see what this means for a Large ITER sized fusion reactor. It produces 1.5 GW of neutron power. However since the breeding reactions are exothermic, this is multiplied an M of say 1.8 in the blanket, so in the blanket 2.7 GW is generated. To this, one adds the one-quarter of the neutron energy, which is the alpha particle energy, so the total fusion reactor power is about 3 GW. However in addition the blanket produces about 15 GWth of ^{233}U fuel. This is enough to fuel five 1GWe (3GWth) conventional light water reactors. At this point the tokamak driver power, seen earlier as a showstopper, becomes a perturbation, and we neglect it.

A crucial fact is that this estimate uses the designed parameters of Large ITER. As noted, this Large ITER breeder would operate within the limits of the conservative design rules. This is an extremely important point. Any pure fusion reactor based on the tokamak would have to somehow find a way to get around the conservative design rules. In 50 years of operation, tokamaks have never done this. Hence if fusion breeding is the goal, there would be no need to develop a DEMO, who knows how many decades and how many tens of billions of dollars later, assuming it is possible at all, An ITER like reactor is just fine as a breeder.

Now let us do a very rough estimate of the cost of the fuel produced. This is based to a large degree on what the cost of an ITER scale reactor would be. Unfortunately the cost of ITER has been increasing very rapidly; making any estimate difficult and speculative. The original cost of Large ITER was to be $10B in capital cost and $10 in operating cost for 10 years. It is now realized that this estimate for the capital cost was unrealistically low. Let us assume that the capital cost of a Large ITER based reactor will be $25B. The machine is assumed to last 30 years. Let us assume the same billion dollars per year operating cost.

Thus as a very rough estimate, let us say the capital and operating cost will be ~\$2– 2.5B/year (6). It is a reactor, which generates 1GWe. That is the 1.5 GW neutron power, when multiplied by an M of between 1.5 and 2, and combined with the alpha power gives a total fusion reactor power of ~3 GW thermal, or about 1GWe. Assuming it runs all year, and sells the power for ten cents per kWh, it earns about \$0.9B. But it also produces 5 GWe of nuclear fuel. To recover the additional \$1.1B, it would have to sell the nuclear fuel for about 2–3 cents per kWh. This estimate is certainly not exact, and as capital and operating costs of ITER, and an ITER based reactor become clearer, it can be revised. If the development of high temperature superconducting (HTS) REBCO demountable magnets for the tokamak ARC (39), proposed by MIT is successful, and a fusion breeder is based on it, the price of the manufactured ^{233}U fuel would be less still, probably about 1-2 cents per kWh.

Undoubtedly people more familiar with the economics and finances of nuclear reactors would come up with more accurate estimates when the time comes. However at this point, the estimated cost does not seem to be any kind of showstopper. Gasoline, at a dollar per gallon, is 2.5 cents per kilowatt-hour. If it powers a standard generator to produce electricity, the fuel cost of electricity would be about 7.5 cents per kWh. Uranium fuel today costs just under a penny per kWh. Using fuel bred by a fusion reactor would increase the cost of the fuel, which is a small part of the total cost of nuclear produced electricity, by a penny or two per kWh.

XI. THE ENERGY PARK

Fusion breeding envisions an energy infrastructure called 'The Energy Park.' In it, there is one fusion reactor fueling for instance five LWRs of equal power. An LWR typically is fueled by about 25 metric tons of uranium, with an enrichment of about 4%. As the reactor burns up this fissile uranium, it also converts some of the ^{238}U to ^{239}Pu; some of this plutonium burns, and some remains in the fuel mix. After about a year, the fuel is discharged and the reactor is refueled. In the spent fuel are about 200 kilograms of plutonium and other actinides (that is elements with atomic number greater than 92), and about 800 kilograms of fission products. These are elements of intermediate atomic number, for instance cobalt 60, strontium 90, barium 137 etc. These typically have half-life of 30 years or less (6,15). The 24 metric tons of ^{238}U mostly just goes along for the ride.

The fusion breeder produces ^{233}U, but this is immediately diluted with ^{238}U so there is no proliferation or criticality risk from the fuel. Bethe (20) suggested, as an alternative, that this ^{233}U be diluted with half ^{238}U and half thorium. This way, there is less proliferation protection, but also less plutonium in the spent fuel, and also some additional ^{233}U is bred. As the wastes from these are discharged every year, the transuranic elements, those with atomic number greater than 92, principally plutonium and americium, but others as well (i.e. those with proliferation risk) are separated out and burned in a single fast neutron reactor of about equal power, for instance the integral fast reactor (IFR), which has been developed at the Argonne National Lab (52,53). It is also very significant that the developers have shown that the IFR is passively safe; turn off the cooling power, and the reactor slowly powers down and turns itself off. This and the breeding of ^{233}U would be done behind a high security fence. The British are now building a much more powerful version of an IFR, they call it PRISM. Its specific purpose is to treat their large plutonium stockpile (54). If a more advanced thermal nuclear reactor is used instead of an LWR, perhaps the CANDU (CANadian Deuterium Uranium) developed by the Canadians (55) or perhaps a molten salt reactor (MSR), originally developed by Oak Ridge National Laboratory (56), the requirements on both the fusion reactor and IFR in the energy park could be relaxed. In the energy park, there is neither long-term storage, nor long distance travel of any material with proliferation potential; it is all burned or diluted in the park behind a high security fence. Only fission products would be retained there. Some have commercial value and would be separated out and sold. The rest would be stored for 300–500 years until they become inert. This is a time scale human society can reasonably plan for. It is far different from storing for instance plutonium, in say Yucca Mountain, where one must be concerned with storage for half a million years or so (the half life of ^{239}Pu is 24,000 years).

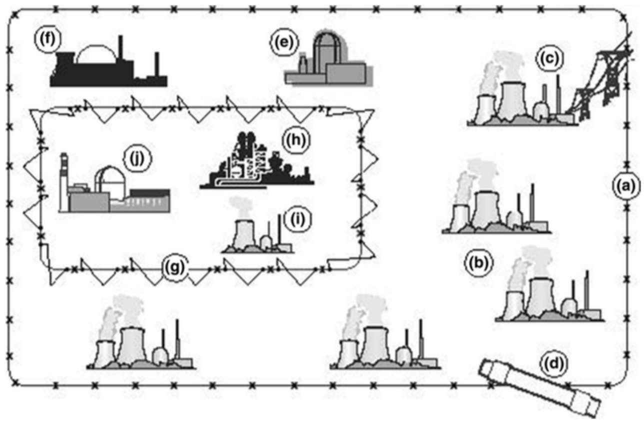

FIGURE 14. The energy park: A. low security fence; B. 5 thermal 1GWe nuclear reactors, LWRs or more advanced reactors; C. output electricity; D. manufactured fuel pipeline, E. cooling pool for storage of highly radioactive fission products for 300–500 years necessary for them to become inert; F. liquid or gaseous fuel factory; G. high security fence, everything with proliferation risk, during the short time before it is diluted or burned, is behind this high security fence; H. separation plant. This separates the material discharged from the reactors (B) into fission products and transuranic elements. Fission products go to storage (E), transuranic elements got to (I); I, the 1GWe IFR or other fast neutron reactor where actinides like plutonium are burned; J. the fusion breeder, also producing 1GWe for a total of 7 GWe produced in the energy park.

To view the energy park in the most extremely simple way, for illustrative purposes, only thorium comes into the energy park, and only about 7 GW electric power, and/ or manufactured liquid or gaseous fuel, for instance hydrogen, ammonia, gasoline goes out. Figure 14 is a schematic of the energy park. It is more than a dream, but much less than a careful plan.

If both ITER and the scientific prototype are successful in the 2040's time frame, there does not seem to be any reason why the world could not begin to build several hundred to a thousand energy parks by mid century or not too long thereafter. It would be a sustainable, economically and environmentally sound energy infrastructure with no proliferation risk. It could provide at least 30 terawatts as far into the future as the dawn of civilization was in the past. All of its components except the fusion breeder exist now or are being actively developed.

Several energy parks, but without the fusion breeder and transuranic element burner, exist now in Canada (55) and Japan (57). However, currently this is neither a sustainable, nor an environmentally sound energy infrastructure. The supply of fissile material is limited to less than 1% of the potential energy resource, and the transuranic wastes build up. The fusion breeder would solve the first problem; the IFR, the second.

Once the energy park has been developed, the world could decide whether it wished to continue with research into DD fusion. DD fusion is not much of an energy producer, but it is a very prolific breeder (the various reactions produce a total of ∼4 MeV). The reaction breeds both tritium and ^{3}He, both of which are excellent fuels for a pure fusion reactor. There is no need to separately breed any fuel (T); or to go to the moon for it (^{3}He). It is a genuine 'infinite' energy source. However the decision on whether to continue with research into DD fusion, or to just settle for DT fusion breeding and energy parks, is not ours to make; our great, great, great, great . . .. grand children can decide this. Our generation could provide maximum help to them by developing fusion breeding now.

XII. CONCLUSIONS AND POLICY IMPLICATIONS

If one hopes to have magnetic fusion providing substantial power by midcentury, there are several important policy implications for at least the American MFE program:

Switch the goal from pure fusion, to fusion breeding.

Continue with ITER; hopefully straighten out its management problems.

The American magnetic fusion program should focus virtually all of its resources around the scientific prototype. It should run steady state for months in DT and should breed first, its own tritium, and secondly some ^{233}U.

Putting scarce dollars into alternate confinement configurations will not produce widespread, economical fusion power in this century.

Support the IFR, not only as an energy producer as its designers think of it, but also as a burner for actinides produced by thermal nuclear reactors.

If both ITER and the scientific prototype are successful, the world would be ready to build a large number of energy parks shortly after mid century.

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