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Can Fusion and Fission Breeding Help Civilization Survive?

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* Journal accidentally misspelled name as Manheiemr, use this for computer search purposes.

Abstract

As apparent from the title, this author feels that civilization faces a real threat, one which will become obvious and serious within the lifetimes of many readers of this article. This threat is not global warming, but lack of affordable energy. We take for granted turning on a light, or adjusting our thermostats in winter or summer, or filling our cars gas tank; and lose sight of the fact that there are huge and complicated industrial systems which make this possible. But as we run out of petroleum and natural gas, and worry about the environmental and climatic effects of burning coal on the required scale, how can this continue? This paper makes the case that breeding nuclear fuel, by both fusion and fission, is the only way our civilization as we know it, can continue beyond the next half century or so.

I. Introduction:

As any fusion scientist knows, one difficulty with the project has been the constantly receding milestones. But how much longer will this be acceptable to society? As we will see, mid-century energy requirements are daunting. Should the fusion project do business as usual and ignore this, or jump in and try to contribute? The advocates of fission breeders are certainly jumping in. This author advocates that the fusion project also jump in, and feels the only way to do so is to switch the focus of the program from pure fusion to the fusion hybrid. He has written several papers over the years advocating this [1-5]. The fusion hybrid is hardly a new idea. It was first suggested by Andrei Sakharov around 1950 [6], and Hans Bethe strongly advocated it in 1979 [7]. Few scientific ideas come with a higher pedigree.

In conventional fusion, the reaction produces a 14 MeV neutron and a 3.5 MeV alpha particle. The kinetic energy of these products is used, for instance to boil water. In the fusion fission hybrid, one uses the neutron's potential energy to breed ten times more fuel. The 14 MeV neutron is first sent through a neutron multiplier which generates 2-4 neutrons for each fusion neutron [7]. One of these must be used to breed tritium from lithium, and one or more of the others are used to breed ^{233}U from ^{232}Th or ^{239}Pu from ^{238}U. As a rule of thumb, we consider the reactor as breeding one fissile element and one triton from each fusion neutron [8].

However when the fissile element burns, it typically releases about 200 MeV, so the energy of the reaction is increased by about an order of magnitude. As we have always said, fission is energy rich and neutron poor, while fusion is energy poor and neutron rich. In this sense they are a perfect match. In fusion terminology, the Q of the reaction is increased by this order of magnitude.

One very important thing this extra order of magnitude can buy is time, which as we will shortly show, is a crucial and very limited commodity. To take an example, the world seemingly has agreed to build ITER[9, and www.iter.org], a large tokamak, in France. When fully operational, perhaps 20 or more years from now, it is designed to produce about 400 MW of fusion power. While not designed as a reactor, one can divide the neutron power by the yearly cost to get a very rough estimate of the cost of electricity of an ITER power plant. It is totally uneconomical. Not only that, there is no clear idea in the magnetic fusion community on what the next step should be to get commercial power. Maybe it would be another tokamak whose performance is somehow enhanced, maybe a stellarator, maybe a spherical tokamak, maybe something yet to be invented. To use the current parlance, ITER is in real danger of being a bridge to nowhere. But now let us imagine that it had the extra order of magnitude gain which it could achieve simply by becoming a hybrid. This author's *very* rough calculations [4] indicate that this *could* become an economical power source. Thus magnetic fusion could save the years and decades it would take to figure out the next step beyond ITER, and start to contribute much sooner to world development with ITER like devices.

In fact Ref.[4] also made the case that fusion neutrons are in a sense the cheapest. A fusion reactor produces a neutron with a 17.5 MeV reaction, or about $4.5\text{x}10^{-2}$ neutrons per MeV. A fission reactor, whether with a fast or slow neutron spectrum produces a neutron in a 200 MeV reaction, so it produces roughly $7\text{x}10^{-3}$ neutrons per MeV. An accelerator produces about 30 neutrons from a 1 GeV proton, however since the accelerator is typically at most 50% efficient, this is at best $1.5\text{x}10^{-2}$ neutrons per MeV. Any facility, whether endothermic or exothermic has a size which scales roughly as its power. In this sense, fusion is by far the most efficient way to produce neutrons, which are really the costliest part of any nuclear cycle. For instance to transform one element to another, say ^{239}Pu from ^{238}U, or to transform a long lived radionuclide to an inert element, one needs neutrons and only neutrons. Using a fission reactor, this transformed element will be very expensive, with an accelerator, expensive; but with a fusion reactor (if one can be made to work), cheap!

Reference [4] proposed, as 'more than a dream, but certainly less than a careful plan' an 'energy park', where a single ITER sized fusion reactor feeds 5 conventional burners. Within the energy park is a sixth burner to burn the plutonium produced. Some of the fusion neutrons were also to be used to transmute long lived radioactive waste.

We fusion advocates say our power is infinite and clean; but so do fission breeder advocates. We will shortly discuss this more fully. Breeder advocates also understand mid century requirements all to well, and claim to be able to meet them in an economically and environmentally acceptable way [10-15]. In my opinion, they make a strong case. A large part of the 10 nation Generation IV nuclear fission cooperative development program is focused on developing breeder reactors [*A Technology Roadmap for Generation IV Nuclear Energy Systems*, Dec.2002, DoE web site (≡Gen IV)]. The goal of Gen IV is to begin deployment of these reactors by about 2030. One thing the Gen IV roadmap envisions is the development of a portfolio of systems rather than a single system. They envision different systems working symbiotically. In that sense, the concept of the fusion fission 'energy park' developed in [4], and reviewed here, is consistent with their overall philosophy.

The feasibility of mining the seas for uranium as an alternate to breeding appears to be extremely remote. We argue that coal with or without sequestration is far too valuable as a transportation fuel to use in large stationary power plants. Also we show that renewables cannot come close to meeting mid-century requirements. The purpose of this paper is not only to argue for the fusion hybrid, either as a stand alone system or in combination with fission breeders. It is also to demonstrate that the options for mid century CO_2 free power are few indeed, and that a crunch which could actually threaten civilization is approaching faster than most people believe. To this author, fission breeding and fusion breeding are the only two reasonable possibilities for large scale carbon free energy in this century. While this paper is addressed principally to the fusion community, at least in part as a wake up call, the author hopes it will be of interest to a larger community as well.

With breeder advocates actively proposing their scheme for mid century power for world development, and with fusion advocates silent here, events threaten to pass us by. As an example, consider two recent occurrences. When Susan Hockfield was inaugurated as president of MIT in May 2005, one of her first acts was to organize an energy task force to see how MIT could contribute to energy research for the next half century or so. This resulted in a *Report of the Energy Research Council*, dated May 3, 2006 (available on the MIT web site www.mit.edu/erc/docs). The executive summary mentioned advanced nuclear reactors, affordable fossil fuel, and carbon sequestration. There was no mention of fusion. Finally on page 18 there was a mention of the MIT fusion center, as a group, to help develop superconducting wires for transmission lines. Fusion was finally mentioned in a very brief paragraph on page 23 of the report; and MIT has one of the strongest fusion programs in the country.

A second occurrence was an email circulation on the web initiated by the preprint of an article called *URANIUM, what is to be done?* by Brendan McNamara, a fusion scientist in England. In it he advocates development of advanced nuclear reactors as a stopgap until fusion is ready to take over around 2050. This prompted an email exchange, shared among a large group, written by fission breeder advocates (I happened to be on the list of recipients). One had the following take on McNamara's article (response italicized):

Thank you very much for sending the article by Brendan McNamara. I think it is well written but unfortunately, from my perspective, only about 80% correct.

My disagreement is mainly…..

(1) Considering the background of the author, it is not surprising that he thinks that fusion will be the ultimate solution to mankind's energy needs. I respectfully beg to differ. Even if controlled fusion were ever to be achieved, the engineering problems associated with it are such that it will not be possible to harvest energy in an economically viable way. Moreover, it will not be safe nor clean…..

As I see it, the only long-term solution to mankind's energy needs is fast-neutron fission technology (i.e., fast breeder power reactors and the attendant fuel recycle technology). This technology has been proved on a laboratory and pilot scale. It now needs to be developed to the commercial level.

In other words, fission breeder advocates are unwilling to play their assigned role as a link between a fossil fuel present and some future fusion nirvana. They see themselves as this nirvana, and they make are beginning to make a strong case.

In this article we examine the energy situation, with the goal of seeing what role a fusion hybrid might play. Take any poll in the United States and ask what the energy of the future should be; renewables, i.e. wind, solar, biomass, etc would win in a walk. There is only one problem; this energy unlikely to be available in anywhere nearly the necessary quantity. Much data is already in, and it is not very encouraging, if one hopes renewables will become a large scale power source. We also explore the idea of liquefied coal, along with other hydrocarbons as a transportation fuel. We then turn to examine the much more credible claims of breeder advocates. Is there a role for fusion even if the breeder advocates' claims are realized? This author's answer is an emphatic yes. One key reason is that development of breeders is limited by a natural and rather slow 'speed limit' for producing nuclear fuel. A fusion reactor can produce nuclear fuel with virtually no speed limit. Furthermore, if fission breeders fall short, the case for fusion breeders becomes even more compelling. The author sees the future powered by some combination of fission breeders as well as fission burners supplied by fusion and/or fission breeding.

As this author sees it, by 2050 and on through the remainder of the century, the world population ought to stabilize at about ten billion people [16], and power use, at about 30 TW. Of this about 20-25 TWth would be from nuclear power fueled by fission and or fusion breeding, implying about a 20 fold increase in nuclear power production. This would be augmented by about 5-7 TW from hydrocarbons (with CO_2 sequestered to the extent possible), mostly coal, and mostly for transportation, implying a reduction of about a factor of 2 in carbon based fuels. Finally it would be augmented by about 3-4 TW from renewable sources, or a scale up by about a factor of 2 in hydro power and biofuels and about a factor of 20 for other renewables.

II. The energy supply and CO_2 situation

Today the world uses about 13 terawatt. Of this 41% is for residential, commercial and industrial use, 37% is for electricity generation, and 22% is for transportation. About 85% comes from fossil fuel. (Energy figures without specific attribution are usually gotten from the DoE web site.) Almost half of the remainder comes from nuclear power, and nearly the other half comes from hydro power and biofuels. Other renewables play a tiny role at this point. 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 TWth of carbon free power by 2050 [16]. It is easy to see that this must be true. Today the world's 6 billion people use over 13 TW. Population growth alone to 10 billion people [16] by 2050 implies 20 TW. However today, 15-20% of the people in the developed world use the lion's share of this power. This is graphically shown in Fig. 1, which graphs nations' per capita energy use versus per capita GDP in dollars. The two are very strongly correlated, there are no points on the upper left or lower right. Countries above the line use energy less efficiently, countries below, more. [Compiled by D. Lightfoot from information available from Energy Information Agency (EIA), (www.eia.doe.gov/emeu), also see www.mcgill.ca/gec3/gec3members/lightfoot].

Full world development by 2050, i.e. moving countries low on the graph to the levels of the wealthier countries, 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 to use power more efficiently. This brings the additional 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.

But 10 TW is about what the world generates today with carbon. Another paper explores means by which this might be accomplished [17]. The startling thing about Ref. [17] 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. Ref. [17] argued for a series of Manhattan project scale efforts to bring this about.

One other important trend over the last few centuries has been the reduced carbon content in energy production as the world has shifted from wood to coal to oil to natural gas to nuclear [16]. However with the sharp increase in natural gas price and continuing reluctance to build nuclear power plants, this is now, unfortunately, being reversed. The United States, China and India are now constructing 850 conventional coal fired power plants (750 in China and India). The US DoE is proposing to build a single advanced coal fired plant, one which can more easily capture and sequester CO_2. However this one plant will most likely be on line well after the 850 conventional plants. (18, and M. Hoffert private conversation, May 2006) And this is only China and India. Africa, South America and the rest of Asia will be unwilling to be left behind much longer. The CO_2 problem is on track to get much worse before it gets better.

The energy supply situation is scarcely more encouraging. As this is written, American politicians are throwing a tantrum over $3/gallon gasoline. In the petroleum industry, the Hubbert's peak [19] is the time of maximum petroleum production; production decreases after that no matter what incentives are offered. It also corresponds to about half the resource being used (Ref. 19, Chapter 3). The Hubbert's peak in the United States was in about 1970 and production has been decreasing since. The IEA estimates the Hubbert's peak to be at about 2015 (20), and their estimates of supply and demand go to 2030. Others say that the peak is visible only in our rear view mirrors (19,21). The IEA estimate of petroleum production and requirement up to 2030 is shown Fig (2) along with the graph of petroleum production taken from Ref. (Ref. 21, p 46 and www.lifeaftertheoilcrash.net). Clearly a crunch is coming very quickly on a human time scale (or perhaps it has already arrived).

Let us set up the case for fission or fusion breeding. To do so, we must estimate the available fuel and its carbon content. These estimates are subjective, and of course the amount of a resource depends to some extent on its price. However as we see with oil today, even a sharp increase in price does not necessarily mean a sufficient quantity becomes available. While recognizing that there is some elasticity in amount of the resource, we do use using the estimates of Ref[17], as shown in the (augmented) table below

Source	Energy (TW-yrs)	Relative Carbon content
Coal	5000	1.6
Oil	1200	1.3
Natural Gas	1200	1.0
Mined Uranium Burner*[%]	300	0
Mined Uranium Breeder[♣]	45,000	0
Thorium Breeder[$]	135,000	0
DT fusion[&]	16,000	0
DD fusion[@]	infinity[#]	0

* Using only the 0.7% in ^{235}U, taking maximum estimate from Ref [17].

[%] This figure is itself controversial. Ref [19, Chapter 8] disputes it, claiming there is much more uranium in lower grade ores, concluding that "the breeder reactor is not needed". However Ref [17] which we cite disputes this; furthermore, the economics and energetics of the lower grade ores for burners might be very unfavorable. Even if Deffeyes is correct on the amount of uranium, one can still argue strongly against an energy systems that throws out more than 99% of the potential fuel and creates ^{239}Pu mines that will last for, hundreds of thousands of years. Here we will stick with the estimates of Ref. [17], and the references it cites.

[♣] Multiplying the available uranium burner resource by 150. The actual number is much larger since lower grade ores and existing depleted uranium become available as well.

[$] Assuming 3 times as much thorium (Ref . 22, p154, www.world-nuclear.org.info/inf62.htm)

[&] Limited by lithium supply

[@] DD fusion is marginal as a reactor, but it breeds tritium, ^{3}He, and produces neutrons which could breed nuclear fuel.

[#] By infinity, we mean a fuel supply which does not run out on the million year time scale.

Let us imagine a steady state world population of 10 billion, which uses energy at a rate of 30 TW. Then coal will give us about 160 years, gas and oil about 40 each, and uranium burners, about 10. However a uranium breeder gives at least 1500 years, and a combination of uranium and thorium breeders give a total of at least 6000 years, or about as far in the future as the dawn of civilization was in the past. On any reasonable human time scale, fission breeders constitute an infinite energy source, certainly more so than DT fusion which has been promoted as such, but will supply world energy at 30 terawatts for about 500 years.

Fission breeders have already been built, and several are still operating. In any reasonable plan for world development, they must be regarded as a very strong contender. However this author makes the case that there will also be an important role for fusion, even if fission breeders live up to their advance billing. Of course it is possible that for technical, economic, proliferation or societal reasons, they may not live up to their promise. Then the case for rapid (i.e. large scale energy production by mid-century) development of fusion breeding is even more compelling.

Uranium phosphate is soluble in water; so much uranium is in the worlds oceans. It is extremely dilute, about 1.8 mega joules of ^{235}U per cubic meter [17]. But multiplying by the ocean's vast volume we come up with the 80,000 TWyrs. However Ref. [17] pointed out that to extract uranium at the 10 terawatt level (for a burner) one would need to capture the uranium in five times the flow of all the earth's rivers. This seems to mean taking a ocean current which samples a large region, the Gulf Stream for instance, and placing in it one or more stationary man made structures which extract all the uranium flowing by. This seems so difficult, that we do not consider it here.

Therefore it seems very possible that a real crunch, one that threatens civilization, is coming in no more than twenty to thirty years, and in a worst case scenario, it may be emerging today. There are only two possible answers on this time scale, coal and nuclear burners; nothing else is ready to produce power on the required scale. We show in the next section that renewables are very unlikely to fill in the gap. Hence over this time, the world will be building many conventional coal and conventional nuclear burner reactors; there is simply no stopping this. Later in the century, but hopefully before mid-century, fission and or fusion breeders will have to be well positioned to take over if civilization without great climate change is to continue. In any case, where options for carbon free power for the mid-century world are so few, fusion breeding should be actively pursued.

III. Renewable energy

The renewable energies which are most used to date have been hydroelectricity and biofuel, with the world using about half a terawatt of each. Regarding hydroelectric, there is potential for about another half a terawatt, and let us stipulate that this will be developed by 2050.

Biofuel in the United States is mostly wood chips, a byproduct from paper manufacture, and it is used to produce electricity for the grid. The Unites States uses about as much of this as it does hydro power. Less developed countries still get significant power from burning dung. There seems to be little additional room for further development here (how much paper do we need to produce?). However ethanol has been much in the news lately, and we will discuss this shortly. Let us stipulate another half a terawatt of biofuel by 2050. The other renewable energies are wind and solar.

This author has recently had one experience with these forms of renewable energy. At a conference on global warming in Ottawa in May 2006, the attendees were treated to a lunch by St. Lawrence College, in Kingston, Ontario. The food looked strange, and to me at least, tasted inedible. I quickly found out why. The university is a strong proponent of renewable energy and the president gave the plenary address. He proudly announced that the food we were eating was the food of the future, produced by renewable energy. His food only took 10% of the energy to produce. Hopefully it is not the food of my future. As soon as I could, I snuck out to a pub for a normal lunch.

Wind has a great potential and already about 50 GW of wind turbines are in place world wide, mostly in Europe. However they only produce power when the wind is blowing, typically some fraction of the time. Therein lies the difficulty with wind power, its intermittent nature; the same is true of solar power. For instance Eon-Netz, (www.eon-netz.com) the largest wind power company in Germany has 7 GW of wind power installed in 2004 (out of 16.4 GW in Germany), but delivers only 1.3 GW to the grid, or about 18% of capacity. The sort of intermittent wind behavior Eon_Netz is dealing with is shown in Fig(3), redrawn from their 2005 annual report. The average power input ranges from near zero to an amount above 35% of the maximum grid power.

Wind power is rather expensive also. Hydro Quebec, in incorporating wind power into its system paid about $0.09 (Canadian) per kWhr, as opposed to its cost of about $0.03 per kWhr for its hydro generated power [23]. In 2004 EonNetz paid 0.09 Euros per kWhr to its wind farm operators, and was able to do this because of a state subsidy of 3.6 billion Euros for wind power. Thus at this point, wind power is not economically competitive with other sources and it depends on rather large subsidies. That is not to say wind power should be discouraged or should not receive the subsidies it does. Rather this author feels it should be encouraged, but one must have a realistic view of what it can and cannot do.

Even if the cost of wind and solar could be made competitive with other sources, they will never be stand alone power sources unless some method could be devised for storing the energy to use when the wind is not blowing or at night, or to send it with very low loss over very long distance. For instance superconducting power lines could be used to send solar power from the day side of the earth to the night side; or to ship wind power from North Dakota, where it is abundant, to New York City or Los Angeles where it is not.

Unfortunately it seems that it will be a very long time, if ever, before the energy storage or transmission problem can be solved.

There are also difficulties in integrating an intermittent supply into an existing electric grid. Eon-Netz estimates that wind power can only supply at most 10% of the power on an electric grid before the grid becomes unstable or very wasteful (like a car which has to burn fuel idling at a traffic light). This is also the experience of Hydro Quebec, which added wind power to its hydro sources came up with about the same estimate [23]. Since the wind can at times feed in more power than the gird is able to accept, the Eon-Netz experience is that as more wind power capacity is added its utilization fraction decreases, even though the total power to the grid from wind increases. Other sources, for instance The American Wind Energy Association are more optimistic about wind power think that it could deliver as much as 20% to an electric grid with some modifications to the grid (www.awea.org). Also the U.S. Department of Energy estimates that wind could contribute as much as 20% of the power to the upper Midwest, including such cities as Chicago, Milwaukee and Minneapolis (DoE web site). However this is a rather windy region of the country.

The country that has made the largest commitment to wind power is Denmark. About 24% of its power in 2004 was from wind power, up from 12% in 2000. This may appear to be a violation of the maximum wind power that can be added to a grid, but it is not. Denmark is a member of the Nordel grid, connecting it with Norway, Finland and Sweden. As a fraction of the grid, wind power was 2% in 2000 and 8% in 2004. (Nordel annual reports, www.nordel.org). It will be very interesting to see what fraction of the Nordel grid can come from wind power as the Danes attempt to expand it beyond 10%.

Organizations opposed to wind power (Industrial Wind Energy Opposition, www.aweo.org, and *A Problem with Wind Power*, Eric Rosenblum, linked on the web site) point out other problems. Despite the large commitment to wind power, the Danes have apparently been unable to decommission any fossil fuel plant and will be unable to meet their Kyoto treaty commitments. When the wind is blowing optimally, wind farm operators must sell power to the grid at a large loss. When the wind is not blowing, they must buy expensive grid power. While this may at first seem contradictory, it likely reflects what may be a principle of economics. If you have a commodity to sell only at particular times of your choosing, and to buy at other times of your choosing, you will buy high and sell low.

We now discuss ethanol. This has been in the news a great deal lately, particularly the fact that Brazil has achieved energy independence in part by mixing ethanol, distilled from sugar grown on its farms, with gasoline. However it is important to remember several things. First of all, until 1850, the United States, with a population of under 30 million, used mostly biofuels, and as a result deforested virtually the entire eastern half of the country. Second, the land used for growing crops for fuel could also be used for other things, food, cotton, lumber, etc. Finally it is important to remember that photosynthesis, the process that converts sunlight to plant energy is a very inefficient process. This explains the why so much more land is needed for biofuels than for direct solar of wind power.

Let us look a little more carefully at the Brazilian ethanol. The Earth Policy Institute (www.earth-policy.org) and others report the Brazilian ethanol production at 4 billion gallons, or about 100 million barrels. However a barrel of ethanol has only about 2/3 the energy content of a barrel of gasoline, so the Brazilian ethanol crop is equivalent to about 60 million barrels of oil, or about 3 days, or 1% of American oil use. If we imported the entire Brazilian ethanol production, we would hardly notice the difference.

The Earth Policy Institute suggests ways that ethanol production could be increased in the United States by harvesting corn, wheat and rice stalks, which are usually not used (but do go back to fertilize the farm land), or by using switch grass grown on prairie land. They estimate that about 20-30 billion gallons could be produced this way, perhaps equivalent to 5-7% of our oil. However, what would this land be used for if it were not producing ethanol? Are other crops, food, lumber, cotton, etc. more or less valuable than the ethanol?

Furthermore, Brazilian ethanol crop is harvested largely with human labor. In the United States, or Canada, with mechanized agriculture, the chemical fertilizers, as well as the tractors and harvesters all use petroleum products, so the fuel used must be subtracted from the energy value of the ethanol. In fact one authority has claimed that more energy is used in producing ethanol in the United States and Canada than the ethanol itself ultimately gives back (Ref. 19, page 186). In our terminology, the Q of ethanol is less than unity. Another study at Argonne National Laboratory (google Argonne National Laboratory Ethanol Study) claims that the Q is greater than unity, but is only about 1.3. Again in our terminology, the process has a tremendous amount of circulating energy. Surely we in the fusion community would not dream of peddling a reactor with a Q of only 1.3. At best, ethanol is marginal as an energy producer, at worst it is a net loser.

To this author’s mind, the case for a large increase in biofuels is far less compelling than that for wind power. Biofuel uses land that might be more profitably used for something else, and it takes a significant amount of energy to harvest.

To summarize, while renewables can help ease a fossil fuel crunch, the experience with them so far does not extrapolate to their being an important source of mid-century energy. We speculate that with a large development effort they may produce as much as 3-4 TW of renewable power in our hypothetical mid and late century world. Of this about 1 TWe is hydroelectricity, 1 TW biofuels and the rest solar and wind power.

IV Coal, tar sands, and oil shale for transportation

As we have seen, coal will supply our assumed steady state world population of 10 billion at 30 TW for 160 years. But well before the end of the century there will be great pressure on coal supplies (coal's own Hubbert's peak) as well as problems with global warming if the CO_2 is not sequestered.

A much more reasonable alternative to large scale coal fired power plants, in the author's opinion, are large scale nuclear reactors, supplies by fission and/or fusion breeding. But what about the 22% of energy used for transportation, particularly the road, air and small boat transportation where neither electricity nor direct nuclear power is practical. Here is where coal can play a crucial role.

The popular press has greatly played up hydrogen as a transportation fuel. But the American Physical Society has studied this [www.aps.org, report on the hydrogen initiative] and has concluded that while this may be possible, there are innumerable fundamental scientific hurdles to be cleared. They are talking at least decades before hydrogen powered transportation will be ready. Although we recognize that at some point hydrogen may take over, we consider liquefied coal as a transportation fuel for at least the next few decades and perhaps for the entire century. If nothing else, this fits into the existing infrastructure much better than hydrogen would.

Coal as a transportation has been successfully used at least twice where countries have been cut off from the world oil market [Ref. 19, Chapter 5]. The first case is Nazi Germany (google Nazi Germany coal liquefaction) and the second is South Africa under apartheid, where the Sasol Corporation set up factories for liquefaction (google Sasol South African coal liquefaction). There are two basic processes, both pioneered in Germany early in the last century. The first is called the Berguis coal liquefaction process; the second is called the Fischer Tropsch process. Both of these were subsidized by Germany, and Hitler, recognizing the need for liquid fuels, especially pushed German industry to develop these using Germany's abundant coal resources. In World War II, the Berguis process was mostly used for high quality aviation and motor fuel, while the Fischer Tropsch process was mostly used for lower quality diesel fuel and lubricants. In 1944, the last full year of the war, Germany produced about 125,000 barrels of oil per day in this way. When General Patton entered Germany, and much of this fuel fell into his hands, he used this captured fuel for his final push into Germany.

South Africa under apartheid was another country cut off from the world oil market, and to cope it liquefied its coal resources. The company set up by the apartheid government, Sasol, is in business to this day, and produces about 150,000 barrels a day for the domestic market. Sasol is speaking with other countries about setting up coal liquefaction plants. They have approached Governor Brian Schweitzer and he is apparently very interested in setting up a liquefaction plant in Eastern Montana, where there are huge coal reserves. China and Sasol have signed a deal to set up factories to generate about 2 million barrels of oil per day, dwarfing South Africa's domestic production.

On April 24, 2006, Clarence Miller, the director of DoE’s Office of Sequestration, Hydrogen and Clean Fuels, of the Office of Fossil Energy testified before congress suggesting that the time could be ripe for setting up large scale coal liquefaction in the United States. It has also been suggested that the United States Government set up coal liquefaction plants to supply the United State military with oil for its own use. The justification would be national security. The military uses about 800,000 barrels of oil per day, and the estimated capital cost of the conversion factories was put at $80 billion. Paid off at 6%, this translates to a capital cost for the oil of about $17 per barrel.

There are serious issues with coal liquefaction involving efficiency, cost and environment. Only about 60% of the energy of the coal is transferred to the liquid fuel, so the process is not very efficient. However additional research might well improve the efficiency. Even so it may be worth living with this inefficiency to have a secure supply of liquid fuel. In our hypothetical mid century world using 30 TW, if 3-5 TW were used for transportation, and it were all done by liquefied coal, this would mean about 5-8 TW of coal would be used. The coal resource would last for nearly 1000 years at this rate.

Another key consideration is the cost of the fuel. As we have seen, the capital cost alone is nearly $20/barrel. The process is costly in other ways as well. Estimates are that it is cost effective if the price of a barrel of oil is somewhere between $35 and $45. As of this writing, the cost of oil is more like $70 per barrel. But how long will the cost of oil remain that high? If Mathew Simmons [21] is to be believed, it will not get lower, or at least not get much lower. Today China and India, and tomorrow the rest of the world will put tremendous pressure on the oil market. South Africa, to protect its investment in Sasol, has imposed large tariffs on imported oil. Possibly an effective strategy for the United States would be to have the government set up a coal liquefaction industry to produce oil for the Unites States military as has been suggested. That way a tremendous base of experience would be built up which would be invaluable for industry if it ever comes to using the process for the civilian sector.

Another concern is environmental. To environmentalists, clean coal is an oxymoron; some compare it to safe cigarettes. Proponents of the process say it is relatively clean. In the basic industrial process itself, many of the most harmful pollutants, for instance sulfur and mercury, are removed. For the 40% of the coal energy that is wasted, it may be possible to sequester the CO_2. However for the 60% that is turned into motor fuel, this will produce CO_2 like any other petroleum product. But in our hypothetical mid century world, only about half as much fossil fuel will be used as today.

In conclusion, despite its development by international pariahs, liquefaction of coal seems like fascinating option, one which should be actively explored. China apparently is gearing up to produce liquid fuel this way. At least twice in the past, countries have been willing to pay the price of using it, and perhaps now this price is actually less than that of oil.

As an alternative to coal is tar sand in Alberta, [24 , google Tar Sands Sanity check]. It is a petroleum resource roughly comparable to Mid East oil. Another similarly sized resource is the oil shale in Wyoming, Colorado and Utah. While these are huge potential oil resources, as we will see, they are not really viable energy resources.

Right now considerable development is going into developing tar sands, about 1.2 million barrels of oil per day are produced today, and projections for 2012 range to values as high as 4.8 million barrels per day. However producing this oil is difficult, energetically intensive and environmentally harmful to the local water, land and air. The tar must be heated by electricity which is now generated by gas fired power plants. Measuring by this electricity, producing one barrel of oil takes about 2000 cubic feet of natural gas, which is itself the energy equivalent of about 0.4 barrels of oil. Furthermore, the process takes other heavy equipment, increasing the cost and reducing further the energy balance. As natural gas prices increase, the alternative being considered is to switch to coal fired plants, creating even worse environmental problems. Thus energetically the process is marginal, and the tar sands (and similarly the oil shale) are much more a petroleum than energy resource.

One approach then is to use nuclear power plants in Alberta to process the tar sands. This would minimize at least the air pollution. The idea is to trade stationary nuclear power for portable transportation fuel. The Q of the process may be greater or less than unity, but this is of less importance. What important is that transportation fuel is manufactured from stationary power plants.

To summarize, while hydrogen may, in decades become a transportation fuel, requiring a totally new infrastructure, there are other approaches to producing transportation fuel which would use the existing infrastructure.

V Nuclear energy

A. Nuclear Burners:

Nuclear power has been criticized as dangerous and expensive almost since its birth. However in the past 25 years, the industry has compiled an impressive safety record, certainly much better than that of the coal industry. Also, the World Nuclear Association has put out a press release in December 2005 claiming that nuclear energy is now the lowest cost energy that power companies deliver to customers [www.world-nuclear.org/economics.pdf]. The 400 nuclear power plants worldwide generate about 20% of the world's electricity. At 400 GWe (~1.2TWth), the price of uranium is low and supply is no problem.

Today, virtually all nuclear power plants employ thermal reactors, which burn more fissile material than they produce. Typically a plant is fueled with uranium that has been enriched to about 4% in the fissile ^{235}U isotope, and the rest is ^{238}U (the fertile material) [22, much of the information here can be found in this reference]. With a uranium isotopic mixture this dilute, it is not possible to make a nuclear weapon without further enrichment. Thus, the raw fuel of a conventional nuclear power plant is not itself a proliferation hazard. As the ^{235}U burns, some neutrons are absorbed in ^{238}U and this produces fissile ^{239}Pu, which further fuels the reaction. Typically one-third of the fuel is replaced each year. In the fresh fuel in a once-through fuel cycle, the only fissile material is ^{235}U, but by the end half or more of the energy is coming from fission of ^{239}Pu.

After about a year, a typical 1 GW electric (3 GW thermal) nuclear power plant has burned about 1000 kg of uranium. It discharges each year about 23 tons of used fuel with the following inventory: 22 tons of uranium containing 0.9% ^{235}U, 230 kg of plutonium, 46 kg of minor actinides (22 of neptunium, 22 of americium, and 2 of curium), and 1000 kg of a radioactive mix of fission products, most with half lives of 30 years or less. Also included are the following long lived radio isotopes (only mildly radioactive because their half lives are 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. The plutonium discharged by the plant can be chemically separated out, and this is a proliferation hazard. Authorities disagree on just how serious a proliferation hazard it is, and we will discuss this shortly. However it can also be nuclear fuel, so a nuclear plant returns about 20% of its fuel if the plutonium is reprocessed.

Because the discharged spent fuel is highly radioactive, it is not regarded as a proliferation hazard. No terrorist group could work with it without being quickly killed by it, unless it used special large scale industrial remote handling facilities to separate out the plutonium. Reprocessing to extract the plutonium is not done in the United States for commercial reactors, but it is done for weapons production. France does do commercial reprocessing, using facilities built for their weapons production. However since the price of uranium is presently rather low, there is no economic incentive to build new facilities, and some in the United States think the French reprocessing is a proliferation hazard because it sets a bad example.

The American approach to nuclear waste is the so called ‘once through’ approach. The fuel is burned once and then the plan is to take it to a geological repository (Yucca Mountain). The decision therefore is to forego any benefit of additional reprocessed fuel in favor of reducing the proliferation hazard. Once the fuel is placed in the repository, the initial heat load is from the short lived wastes. However once these burn out, after several hundred years, the heat load is mainly from americium which has a half life of 241 years, followed by plutonium with a half life of 24,000 years. Thus over the longer term, any geological repository becomes a plutonium mine. For this reason, as well as uncertainties as to whether the repository will be geologically stable for the required length of time, 200,000 years or more, repositories have generated rather intense opposition, at least in the United States. Yucca Mountain is years away from ever being used.

B. Nuclear breeders up to now

While the price and supply of uranium is no problem now, if nuclear power were to scale up to 20-25 TWth (7-8 TWe) supply would quickly become a crucial issue. For this reason breeders are of interest. Breeders, whether fission or fusion based, can use all of the energy in the uranium, rather than the 0.7% current reactors use. Furthermore, the thorium resources become available.

Although the details of thermal reactors and breeders are extremely complicated, and this author is hardly qualified to get into them, the fundamental basis for the distinction is rather simple. Neutrons produced in a fission reaction typically are produced with energies ranging from several hundred keV to perhaps 2 MeV. A thermal reactor takes advantage of the fact that the fission cross sections maximize for thermal (i.e. approximately room temperature) neutrons, so neutrons are slowed down byletting them collide with light elements (the moderator) inserted into the reactor. However when thermal neutrons react with the fuel, they produce fewer neutrons when the fuel atom splits. As a hypothetical example, let us say that in a reaction, the thermal neutron produces on the average 2.4 neutrons. One neutron is needed to continue the chain reaction. Let us say that 0.7 a neutrons are lost in various waste processes. This leaves 0.7 neutrons to breed more fuel for use in the reactor so not all the fissile material used gets replaced.

A breeder almost always works with the fast neutron spectrum. The cross sections for fission are less, so care must be taken to minimize lost neutrons. This generally means that available material for coolants is must have very low neutron absorption cross sections, greatly restricting the choice of coolants. The most common coolant up to now has been liquid sodium, although, although liquid lead, and lead bismuth eutectics are also possible. The advantage of the fast spectrum is that when a fission reaction takes place, more neutrons are liberated. To continue our hypothetical example, let us say that in the fast reaction, 2.8 neutrons are liberated. One is needed to continue the chain reaction. If the loss is now 0.7 neutrons due to waste processes, this leaves 1.1 neutrons for useful purposes. One additional neutron continues to fuel the reactor, so as a fuel atom is burned, another is created by the fertile material. This then leaves 0.1 neutrons to produce fuel for another reactor. Clearly this is gives a geometric progression for the amount of fuel bred. In our hypothetical example each reactor produces in a year enough fuel for 0.1 reactors to run a year. This gives a doubling time of about seven and a half years. Actually more accurate estimates give productions rates of 0.05-0.07 per year, or doubling times of more like 10-14 years, so our hypothetical example was not too far off. This rate, or doubling time, essentially gives a ‘speed limit’ for how fast breeders can advance.

The advantage of a breeder was realized very early on in the development of nuclear power, and some of the first nuclear reactors were breeders. The Experimental Breeder Reactor I (EBRI) was set up at the Idaho National Energy and Environmental Laboratory (INEEL) in

1951. This was followed by EBR II, generating 60 MW . Internationally fast breeders had been built by Britain, France, Russia, Japan and Germany. The largest of these was Super Phenix in France which generated 1.2 GW. It ran for several years until the French government shut it down in 1997. Its predecessor, Phenix, generating 200 MW is still operating. Probably the country that has had the most success with breeders is Russia. Its initial plant, BN-350, on the Caspian Sea was used to desalinate 80,000 metric tons of water per day, as well as to produce 130 MW of electricity. Its successor, BN-600 generates 600 MW and operates today.

China is constructing a breeder and India is seriously considering breeding ^{233}U from ^{232}Th instead of ^{239}Pu from ^{238}U. One advantage of the thorium cycle, in addition to India's large thorium deposits, is that the breeding can be done with thermal neutrons.

While there have been successes with fission breeders, as any casual newspaper reader knows, they have also been plagued by difficult problems. Compounding these difficult problems is the fact that they seem to have acted as a lightning rod for opposition by environmental groups in many nations. Many articles and books, varying from legitimate opposition to out and out hysteria, have been written, claiming that breeders are a danger that the world simply cannot tolerate. In the next two subsections we discuss the promise of fission breeders as seen by their advocates, and also the difficulties then have had in the past, and may still have in the future.

C. The hopes of fission breeder advocates

We fusion scientists sell our product as infinite and clean; but so do fission breeder advocates. DT fusion is limited by lithium supplies and fission breeders are limited by uranium and thorium supplies. As we saw in Sec II, there is about 10 times as much energy in uranium and thorium as in lithium; fission breeder advocates are selling more of an infinite energy source than we are.

But what do fission breeder advocates mean when they say their source is clean? As we have seen in Section VA, the waste products from fission fall into two categories. First there are the highly radioactive wastes. Almost all of these have half lives of 30 years or less. Secondly there are the actinides, mostly ^{239}Pu, but higher isotopes and higher Z actinides as well. These have half lives of typically tens of thousands of years. They are the real threat to a repository. Their heat load keeps building up secularly on the human time scale, and over the thousands of years, if the repository can tolerate the heat load, they become ^{239}Pu mines which sit there for hundreds of thousands of years Nobody can say for sure whether any repository will be geologically stable for this required time.

What fission breeder advocates mean when they say that their source takes care of the waste products is the following. While nuclear reactors, thermal or fast, generate about the same fission products (the true waste), there is one crucial difference. The breeder burns nearly all the actinides whereas a once through burner does not. Thus the only waste products the breeder produces are the radio isotopes. However most of these have half lives of 30 years or less. If ten half lives is the time the waste products must be stored and isolated, we are talking of 300 years. This is a time scale human society can reasonably plan for, and this is the approach fission breeder advocates take. It is a very far cry from the thousands and thousands of years an actinide repository must plan for. Thus fission breeder advocates make very credible and convincing cases when they say their source is clean.

We now briefly examine two proposed breeders in Gen IV, the integral fast reactor (IFR) and the molten salt breeder reactor (MSBR). The IFR [25] was developed by Argonne National Laboratory as a follow on to EBR II. It ran for years with no major problems. It was a liquid sodium cooled reactor designed to be passively safe, so that the reactor would safely shut down in the event of the failure of any critical component. By integral, the designers meant that the fuel reprocessing was on site at the reactor, so there would be no transportation of any material with proliferation risk. An important innovation of the IFR was the use of metal rather than oxide fuel. Since the former is a very good heat conductor, it minimized temperature gradients in the reactor. This was regarded as a significant safety feature.

The fuel was metal pellets stacked in slim stainless steel tubes. Every year or so, some were removed and with a particular chemical process, the transuranic elementswere separated out and reconstituted into fuel pellets and fed back to the reactor. The other material, the radio isotopes were to be sent to a cooling pool and/or repository. The reactor fuel was a mixture of ^{238}U and ^{239}Pu and of course could be proliferation risk, since the plutonium could be separated chemically. However the IFR minimized the proliferation risk by having this fuel exist only in the reactor core and the associated processing facility always inaccessible and highly radioactive. Any proliferators would have to first get the fuel out of the reactor and then separate the plutonium without killing themselves in the process. The developers of the IFR contend that this would be virtually impossible for terrorists to do. However the IFR does need a large initial amount of fuel to get the reactor started and to keep it going, considerably more than a conventional burner reactor does.

It is noteworthy that the IFR did pass two tests confirming that it is passively safe. In April 1986, coincidentally the same month as the Chernobyl disaster, the reactor operators simply turned off the coolant pumps. The reactor safely powered down with no damage. In a second test, operators shut off the all electricity to the reactor and the same thing happened.

Although the IFR can breed fuel for other reactors, its designers saw benefit in its flexibility. It could operate as a net burner of plutonium, a net breeder, or in a breakeven mode. In the latter case, it is initially fueled, and enough ^{238}U is kept on site to refuel it for the life of the reactor, perhaps 50 years or more. That way, there is never the transport of any nuclear fuel.

Development of the IFR continued from 1984 to 1994, ending three years before the scheduled completion of the project. The U.S. government saw it as a proliferation hazard and shut it down. The proponents of the project certainly did not agree [26], and saw it as mistaken decision on the part of the government, one which will postpone American energy independence for decades.

The molten salt breeder reactor (MSBR) is a rather different concept from the IFR. It uses the ^{232}Th to ^{233}U cycle rather than ^{238}U to ^{239}Pu [27-30]. One reason that fast neutrons are required for breeding in the plutonium cycle is that at low energy, plutonium has a large absorption cross section. As it absorbs neutrons it builds up higher plutonium isotopes as well as higher actinides. However the absorption cross section for ^{233}U is significantly less. This means that the thorium cycle can breed using thermal neutrons, and this is the basis of the MSBR. Like any breeder it also has the advantage that it does not generate actinides in its waste stream, so the wastes have lifetime of perhaps 300 years. Also, the amount of fuel contained is typically much less than in an IFR. To slow down the neutrons, the MSBR uses a graphite moderator, which is one of few materials that can both stand up to the flow without corroding and can slow down the neutrons as well. The MSBR technology is also thought to be applicable to a fusion hybrid as well, and a preliminary design of a fusion hybrid power plant using this technology has been published [31].

In a fission breeder of the MSBR variety, the fuel is dissolved in a molten salt and it flows into and out of the reactor. The fact that uranium and thorium salts are both soluble in the flow is the crucial fact that allows the reactor to be viable. Because it flows out on a continuous basis, the fuel can be reprocessed on the fly. The fission products can be taken out and the fuel can be maintained at just the right mixture of thorium and uranium. It is also claimed that the MSBR is passively safe.

One aspect of the MSBR which its advocates consider an advantage is that once the ^{233}U is in the reactor for a while, neutron reactions breed ^{232}U. This isotope is highly radioactive, so it is not at all an optimum material for a terrorist. In the decay chain of ^{232}U is a very high energy gamma ray. Not only does this make the material impossible to manipulate except with remote handling, it also makes it easy to find. A small amount of it can even be found from a space. However a difficulty of the MSBR is in the reprocessing; this is a rather complicated chemical engineering task, and there are different sorts of problems depending on whether the reprocessing is done fast (in days) or slowly (in months).

Nevertheless the MSBR, like any other nuclear reactor, is not proliferation -proof. In the absence of U-232, U-233 is an excellent bomb material. When a Th-232 nucleus absorbs a neutron, it becomes Th-233 which promptly decays to Pa-233 (protactinium), which in turn decays, with a half-life of 27 days, to U-233. Since the fuel can be continuously reprocessed, U-233 with very little U-232 can be obtained by chemically separating protactinium from the stream. The lesson is that international oversight, of any nuclear fuel cycle, is needed for insurance against proliferation.

An MSBR was constructed at Oak Ridge National Laboratory and it ran from 1965 to 1969 at a power level of 7 MW(th) [27-29]. At this time, a rapid build up of nuclear power plants was envisioned, and amounts of uranium were thought to be small. Since then, new deposits of uranium were found, and nuclear power did not scale up as quickly as originally envisioned. Ultimately it came down to a competition between the MSBR and the IFR, with the IFR winning the support until it too was shut down in 1994.

With Gen IV there is a renewed interest in the thorium MSBR. In Edward Teller's last scientific publication [30], he advocated constructing MSBR's underground and configured so as to breed only enough ^{233}U to fuel itself. This eliminated all transportation of material with proliferation potential, and the reactor would be safe from any kind of terrorist attack, even a crash of a large aircraft. Radioisotopes produced would be kept on site until the plant was decommissioned, perhaps as long as 200 years. After that, the material could either be buried there and left for a few hundred years longer, or taken to another repository.

D. Difficulties of fission breeders.

The world has had long experience with fast breeder reactors, and until Gen IV, virtually all programs have been abandoned, including those in the United States, England, France, Germany and Japan. The performances of the breeders have been anything but unalloyed triumphs [32, 22, chapter 5], and various opposing groups have jumped on the slightest difficulties. The world's first commercial breeder was the Fermi 1 plant set up near Detroit. It was a 200 MW plant that began operation in1963. It was shut down in 1966 when it was found that a loose piece of zirconium was blocking the flow of the sodium coolant, and damage to the plant was discovered. This was repaired, but in 1970 a sodium coolant fire delayed reopening of the plant. Its operating license renewal was denied in 1972. Despite the general success of the Russian BN 135 plant, its operation was disrupted by sodium mixing with water, which resulted in a two hour sodium fire [http://insp.pnl.gov/-profiles-beloyarsk-be_design.htm].

The largest breeder set up has been Superphenix in France, a 1.2 GWe sodium cooled breeder. It was in operation between 1985 and 1997. Toward the end of its life it did deliver the 1.2 GW to the grid, but before that, it was plagued by delays, caused mostly by leaks of the liquid sodium. Also its power was considerably more costly than that of other sources. While liquid sodium is a common industrial material, Superphenix used it on a gargantuan scale never before attempted. Garwin [22, p133] quotes Bernard Magnon, the plant director as saying in 1996 "I think running Superphenix is a good lesson in modesty". The reactor not only had technical problems, but it was a lightning rod for opposition by environmental groups. When the socialists won the election in France in 1997, the environmental ministry was taken over by the Greens, and one of their first actions was to shut down Superphenix. Now France says it is shelving plans for breeders until mid century or later.

Japan has also had a failure with a breeder program. Their Monju breeder reactor has a serious sodium leak in 1995. However in an internal investigation, authorities covered up the extent of the accident. When this was discovered, the general manager detailed to investigate committed suicide! Breeder plans for Japan now are on indefinite hold.

Thus despite our quoting a breeder expert in Sec I saying that *This technology has been proved on a laboratory and pilot scale. It now needs to be developed to the commercial level,* opponents of breeders would probably jump in and say that the technology has been disproved. But if we eliminate breeders, what else is there? A typical article in this vein was by Feiveson [33]. He argues against not only breeders but all nuclear power, breeders and burners with or without reprocessing. He points out the dangers, particularly as regards to environment and proliferation, and suggests that over the next few decades the nuclear industry asymptote down to zero. But the striking thing about his article is that it contains no suggestion at all for how to power the 21st century world. That's not his department.

Another issue that breeder advocates dismiss is the issue of the long lived radio active wastes, for instance ^{99}Tc, with its 200,000 year half life. They point out that because of the long half life, their activity is low, and not that much is produced. Therefore one might just leave them with the more radioactive materials and let them remain in this repository [34]. Perhaps, but this author is not so sure. References [22,30] and Gen 4 do express concern over these elements. ^{99}Tc is particular threat to a repository because many of its compounds are water soluble and over time can leak out. Furthermore there is the quantity produced. As we have seen, each year a 1 GWe reactor produces about 50 kg of these long lived radionuclides. In our hypothetical mid century world, with 8 TWe of nuclear power, this is 400 metric tons per year, produced right where people live. This may be a larger concern than the breeder advocates think.

There are also serious objections to breeders as regards proliferation. One aspect of the sodium cooled breeder is that it requires a large amount of plutonium to fuel it. There are dueling articles between George Stanford (a retired physicist who worked on the IFR project until it was terminated in 1994) [35] and Richard Garwin (an iconic figure in American science) [36] in *Forum on Physics and Society* on the proliferation dangers of this large amount of plutonium. Ultimately both seem to agree that the reactor plutonium is not ideal bomb making material, but both also agree that even a small, less than ideal bomb, a bomb which 'fizzled', could create a real disaster if it were set off in say Manhattan.

In the same article and elsewhere [22, p133], Garwin also quotes Edward Teller's concern [36] of the large amount of plutonium in a breeder, and the consequences of an accident:

"For the fast breeder to work in its steady state breeding condition, you probably need half a ton of plutonium. In order that it should work economically in a sufficiently big power producing unit, 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, which can happen in principle, they can release enough fission products to kill a tremendous number of people. … But if you put together two tons of plutonium in a breeder, one tenth of one percent 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 is possible to analyze and 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 one or two or five percent of this plutonium will find itself and how it will get mixed with other material. A small fraction of the original charge can become a great hazard."

Possibly the MSBR, using much smaller quantities of ^{233}U, and which is chemically much less destructive, and much easier to find, would allay Edward Teller's fears. In any case, as fusion and plasma scientists, we will not be the ones to sort it out. But if one argues strongly against a breeder, shouldn't one also say how civilization will continue to be powered?

VI: Review of the fusion hybrid energy park

Reference [4] sketched out one possible approach to mid to late century sustainable development, the fusion hybrid energy park. This is one fusion device, delivering 1GWe, but also powering five 1 GWe LWR type nuclear burners. In the energy park, the ^{232}Th – ^{233}U cycle was selected because 1) the proliferation danger of the raw fuel is the same as today's reactors, 2) Uranium is much less dangerous (chemically) in the event of a mishap, and 3) also in the event of a mishap, the ^{233}U is much easier to find than is plutonium. There is a sixth burner which burns the plutonium and other actinides produced. The long lived radionuclides go back to the fusion reactor for transmutation into inert elements. Nowhere in the energy park are there large quantities of plutonium.

For the fusion reactor in Ref. [4], a tokamak was selected. The reason is that the greatest accomplishment in fusion so far, the generation of about 20 MW of fusion power, in a one second pulse, about 10^{19} neutrons, with a Q of about 0.5, was done on TFTR and JET in 1997, two tokamaks [38,39]. Furthermore, there were plans to scale this tokamak up to a much larger sized tokamak, ITER. Ref. [4] argued that while ITER could not be an economical power plant, an ITER sized device might be economical if it were run as a hybrid fuel producer. ITER was certainly not designed as a reactor, so it is very difficult to estimate the cost of power such a device might produce in any quantitative way. However on ITER's web site, the construction, operating and decommissioning costs are specified. If it were run as a reactor, producing the expected power, at its operating cost, and then the other two costs were figured in, one can estimate the power cost. More details are given in Ref [4]. This rough calculation gave a price for ^{233}U bred from an ITER scale device of about $0.03 per kilowatt hour, roughly equivalent to gasoline at a dollar a gallon. For this reason, the energy park in

Ref [4] featured a tokamak as the fusion source. Development plans for the tokamak were suggested with or without the ITER international collaboration.

Recently a new possibility for the fusion reactor has emerged. The Naval Research Laboratory has suggested a plan to develop economical direct drive inertial fusion based on a KrF laser driver [40]. An important part of this plan is not only the fusion pellet, but also the development of the related technologies for increasing laser average power and efficiency, injecting the pellet, issues of first wall, etc. This is the multi institution HAPL program, centered at NRL (google HAPL high average power laser). So far the record neutron production in direct drive inertial fusion seems to be at the University of Rochester, where they have imploded cryogenic targets with their 30 kJ Omega laser. With a DD target, they have generated about 10^{11} neutrons, equivalent to about $2x10^{13}$ neutrons in a DT target [41]. Thus inertial fusion has to advance by nearly 6 orders of magnitude just to get to where tokamaks were in 1997 (and still are today). Also right now the neutral beam efficiency is at least an order of magnitude greater than the laser efficiency. There are plans to scale up all of these parameters which are being worked out at NRL and its collaborating institutions. While it is impossible to tell whether this scale up will be successful or not, it is important to note that these plans start from where we are today and go right up to an economical reactor. Magnetic fusion, by contrast, does not seem to know what the next step after ITER should be. If the planned scale up in the NRL approach runs out of gas one order of magnitude short, using a hybrid rather than pure fusion might make up the difference. Furthermore, it might be that the hybrid approach is preferable even if a pure fusion reactor proves viable. For instance by the time the fusion reactor is ready, there may be a large legacy of nuclear burners which could very well need fuel. However the energy park concept can work with any fusion reactor.

This author’s vision for sustainable world development, the ‘energy park’ is sketched in Fig (4). The basic module is a nuclear reactor, for instance an LWR which generated 1 GWe. Five of them are in the park. These are the best nuclear reactors that can be developed, perhaps AP600’s, perhaps the gas cooled pebble bed reactor, perhaps a Generation IV burner reactor. Then all of the development of advanced burner reactors over the last half century will be utilized in the park.

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. Reference [4] estimated that that 5% of the wall area of an ITER sized tokamak could transmute waste from the 5 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. Regarding neutron economy, it is crucial in the fusion plant, important in the 5 standard reactors, and not very important in the plutonium burner. The role of this reactor is principally to destroy plutonium, not generate electricity or breed fuel with maximum efficiency.

It is likely, but in this author's opinion, not absolutely certain, that the plutonium burner would have to be a fast neutron reactor. The reason a fast neutron reactor is advantageous is that for thermal neutrons, plutonium has high neutron absorption cross section. Thus some of the plutonium atoms burn, while others build up to higher isotopes and higher actinides. If ^{238}U is the fertile material in the reactor, there is no beating this because as plutonium atoms are burned, more are created from the ^{238}U.

However if the fertile material is not ^{238}U, this problem may not apply. Let us first think of mixing plutonium with a completely inert material, say iron, the most stable nucleus. Then the plutonium burns and builds up higher isotopes and actinides. However because no more plutonium is produced, these other elements will ultimately burn as well. But with no fertile material, over time, it gets harder to keep the reactor going. It may be that it has to be refueled more often. On the other hand, it may be possible to use ^{232}Th as the fertile material as well. This does not build up higher actinides nearly as easily and in fact it would produce fuel ^{233}U fuel for the other reactors. Perhaps lithium could also be added to this reactor to generate tritium for the fusion reactor, easing the burden on it.

It could be a significant advantage that the fusion hybrid energy park and fusion breeding rely much less, and possibly not at all, on fast neutron reactors. At least right now, the world has had much, much more experience with thermal neutron reactors, and these reactors should be exploited to the maximum extent possible.

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 unless the energy park served other off site reactors. Also long time storage of actinides would be greatly minimized.

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. It could also export the nuclear fuel as long as the agreement including sending the waste back to the energy park for treatment. 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.

VII Coexistence of fission and fusion breeders

The fusion fission energy park was devised assuming there was no such thing as a fission breeder. But what if fission breeders work as well as their advocates hope? Is there still a role for fusion breeders? This author's answer is an emphatic yes. We have hypothesized a mid century world of 10 billion people using 30 TW, 20-25TW nuclear, 5-7TW fossil fuel, mostly coal, and 3-4 TW renewables. But let us imagine the world in 2030, just when the first Gen IV breeder will come on line. Between now and then, the world's people will still demand a better life style. Not even Malawi, the lowest named country in Fig (1) will willingly accept its position. Let us say that in 2030 the world population is 8 billion and a total world power use is 20 TW, 7 TW more than today. There is only one option between now and then, namely to build about 10 TWth more conventional power plants, say 5 TWth of coal (recall the United States, China and India are already building over 800 (~2.4 TWth) coal fired plants) and 5 TWth of thermal nuclear reactors. In 25 years these 1600 nuclear burners will burn up let's say about 60 TWyrs of the uranium resource, and these burners will constitute a large legacy that must be fueled far into the future. If these have a 40 year lifetime starting in 2030, this will burn up another 200 TWyrs of uranium, bring the resource well past its own Hubbert's peak.

Now let us imagine the world that breeder advocates would like to power. In 2030, Gen IV breeders begin to come on line. As we have seen, about 20% of thermal reactor fuel is returned, and if this is separated out, it will be available to start breeders. Once this is used up, breeders will compete for fuel with a large existing stock of burners. Furthermore, at this point, as breeders begin to come on line, there will most likely be enormous pressure, for climate and global change reasons, to decommission most of the additional coal fired plants built before 2030, necessitating the construction of even more nuclear power plants. It is easy to see that even if breeders come on line as fast as their proponents hope, there will be a real mid-century fuel crunch. Chang made this point [13]. Shown in Fig (5) is a graph redrawn from his paper showing the fastest that the world can produce nuclear power, making some rather optimistic assumptions about how fast breeders can come on line. The 'speed limit' for fission breeding is apparent. Clearly by 2030, nuclear reactors are limited by fuel to produce well under the 2-3 TWe assumed in our hypothetical model, and well under the 6-8TWe by 2050 as assumed in our model.

However if fusion breeding comes on line in say 2040 or 2050, this can breed nuclear fuel very prolifically; there is essentially no inherent speed limit to the build up of fuel. To this author, it seems as if there is a need for fusion breeders, even if breeders meet the expectations of their supporters, if world development is to proceed as hoped. Thus even only as an adjunct to fission breeders, fusion breeding could have a key role in powering the mid century world.

Let us imagine other possible symbiotic relations between fusion and fission breeding. In a mid century steady state world generating 8 GWe of nuclear power, with a 5% per year 'speed' limit on fission fuel production , they would power about 400 GW of thermal reactors of today’s design. However these 400 reactors exist today, by 2050 there will undoubtedly be many more of them. These could be fueled by fusion breeding.

Let us also consider proliferation. Clearly a reactor like the IFR minimizes proliferation danger if it fuels only itself. If it produces fuel for other reactors, there will be large scale transportation of plutonium fuel around the country and world, and this is obviously very risky. One could envision a world where fission breeders breed only for themselves. Then existing and future burners could be shifted to ^{233}U fuel, and this could be produced by fusion breeders, which supply them with fuel with 4% enrichment. Transportation of this fuel is much less of a proliferation risk

If fusion and fission breeders are both successful, eventually they may each find a niche, or they may compete with one another. It seems as if fusion breeders could have some real competitive advantages. While fast neutron reactors are possible in principle, the fact is they have had difficulties up to now, certainly much more difficulty than thermal neutron reactors have had. Possibly fast neutron reactors will always be more difficult and/or more expensive to build. This could be an advantage for fusion breeders and the energy park, which rely much more on thermal neutron reactors.

Also the energy park has the capability of treating the long lived radio isotopes, whereas the fission breeder advocates seem to sweep this problem under the rug. These arguments are not to denigrate fission breeders, by all accounts they have a much better chance of supplying energy for mid century world development than fusion. Rather it is to argue that there is a role for fusion for mid century development, and since the development of pure fusion is so distant, hybrid fusion breeding appear to this author the only way. If fission breeding does fall short, the case for fusion breeding becomes even more compelling. On the longer time scale, there are so many possible combinations of fission breeding, fusion breeding, fast and slow neutron fission reactors, and pure fusion that this author certainly cannot sort them out. However as far a mid century power is concerned, the race is on. We have to run the race to win the prize. It does not seem to this author that the fusion community is doing that.

VIII Conclusions

The goal of world development must be to bring all the nations low on Fig (1) higher up by mid-century or sooner. One possibility is coal, but before the century is out, it will have passed its own Hubbert’s peak. Furthermore, the price of coal may well be unacceptable environmental degradation and climate change. As we have seen, anyone who argues for renewables playing a major part has a *very very* difficult case to make. Nuclear burners based on mined uranium cannot power the 21st century either.

This leaves fission breeding, fusion breeding, or more likely both. Without these, it is difficult to see how the 21st century can be powered in an environmentally acceptable way, and also to see how future centuries can be powered at all. If civilization goes down the tubes in this century, it is impossible to see how pure fusion can be developed to power the next. If someone opposes either fission or fusion breeding, he should say how he hopes to power the world. In fact without either, by mid century it seems almost certain that nations near the top of Fig (1) will begin to slide back down. This is the real threat to civilization. To prevent this will require enormous changes in the energy production and distribution system, certainly changes that are much greater than those occurring in the last 50 years. Fission breeder advocates realize this and realize they have a possible solution; but by embracing the hybrid, we do too. Fission breeder advocates are actively selling their solution for mid century power; we are not.

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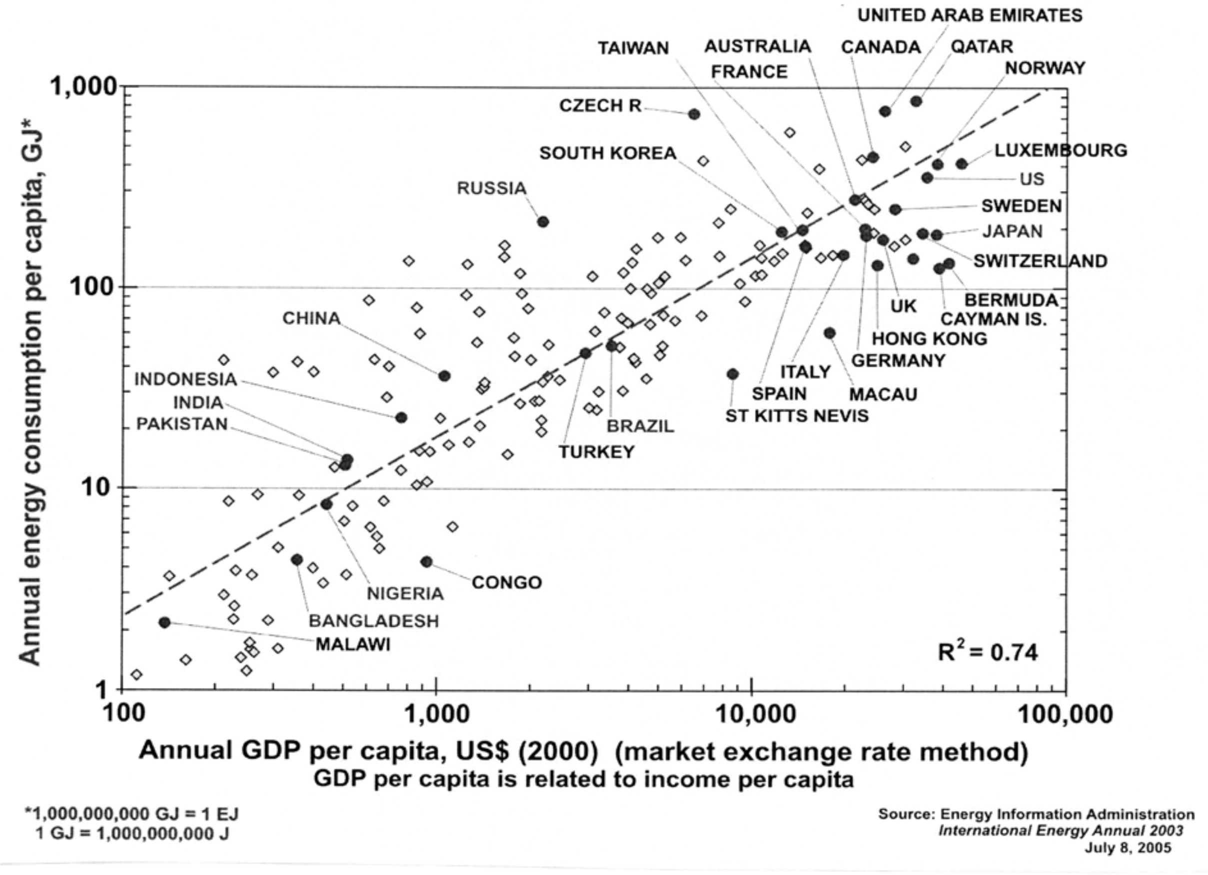

*1,000,000,000 GJ = 1 EJ
1 GJ = 1,000,000,000 J

Source: Energy Information Administration
International Energy Annual 2003
July 8, 2005

Figure 1:

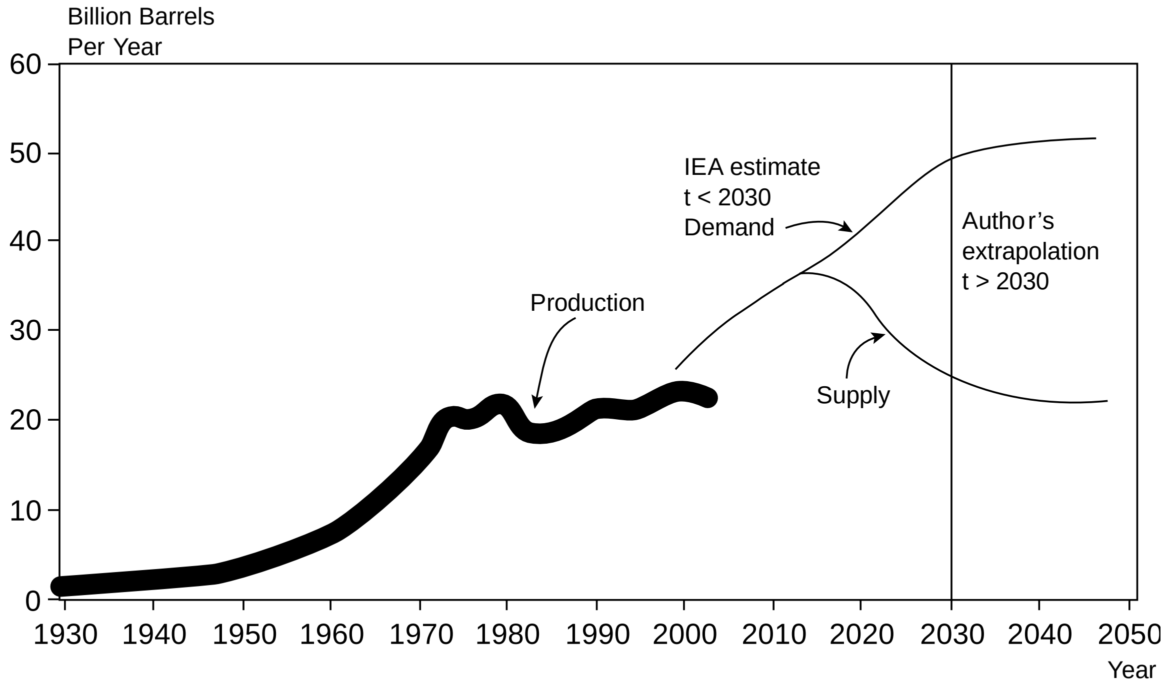

Figure 2. Petrolium production 1930 to 2005 (heavy line) as well as IEA's estimate of petroleum supply and demand up to 2030

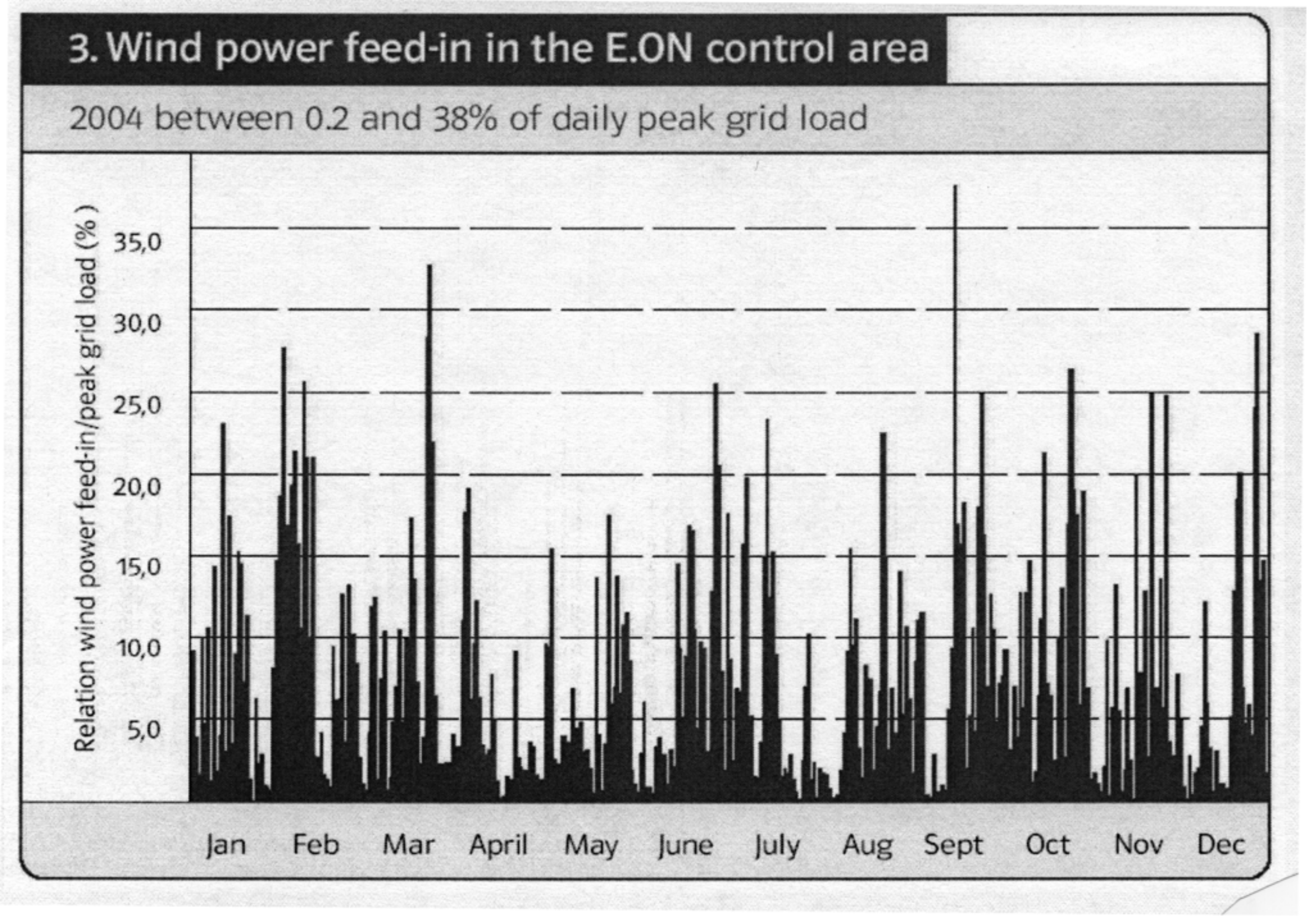
3. Wind power feed-in in the E.ON control area
2004 between 0.2 and 38% of daily peak grid load
Relation wind power feed-in/peak grid load (%)
35,0
30,0
25,0
20,0
15,0
10,0
5,0
Jan
Feb
Mar
April
May
June
July
Aug
Sept
Oct
Nov
Dec

Figure 3

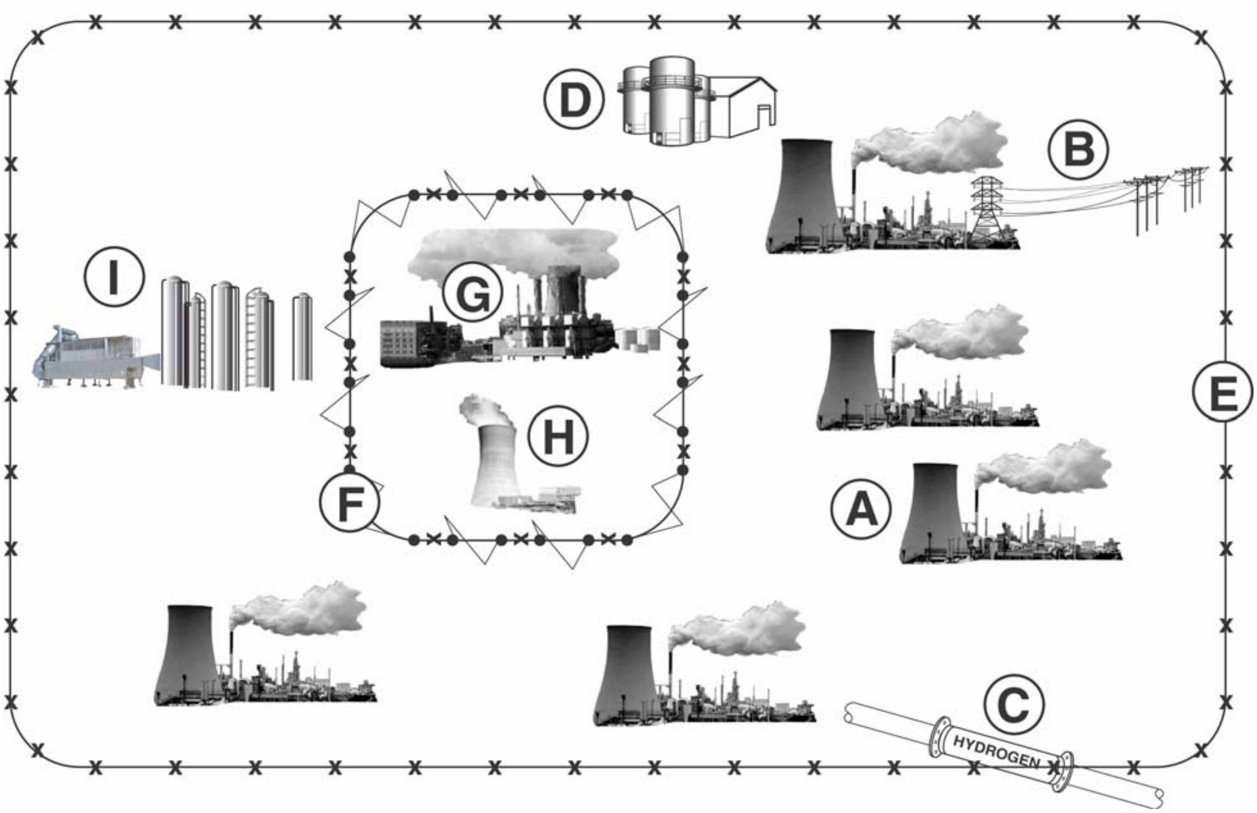

Figure 4. The energy park, A. A 1 GWe nuclear burner, B. electric power line out, C. Hydrogen pipeline out, D. Cooling pools for highly radioactive waste, E. Low security fence, F. High security fence, G Separation facility, H. Plutonium burner, I. ITER sized fusion plant producing a total of 1.5 GW fusion power and an additional 2 GW in the breeding blanket.

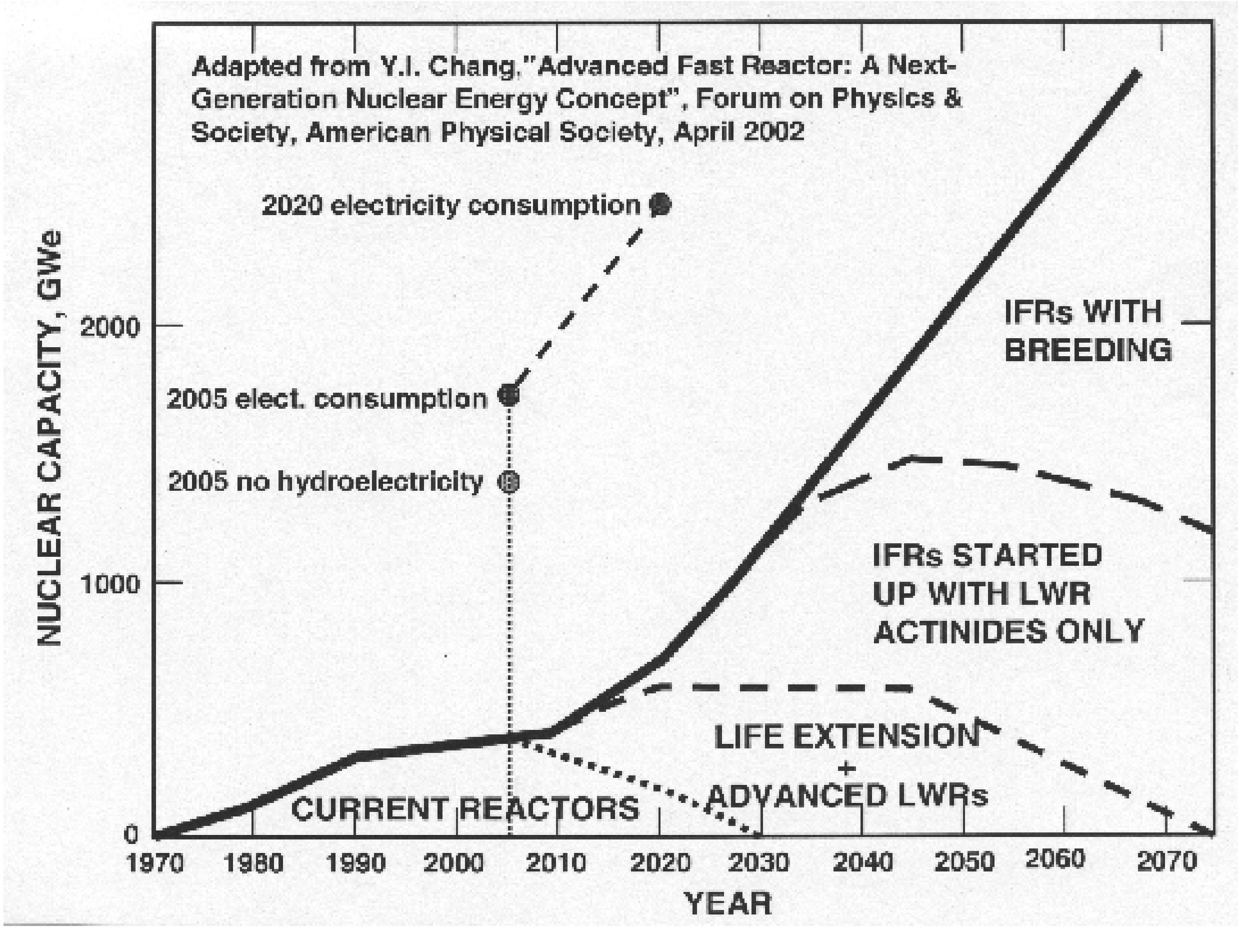

Fig 5. Chang's estimate [13] of how fast breeder reactors can begin to generate electricity