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REVIEW PAPER

Hybrid Fusion: The Only Viable Development Path for Tokamaks?

Wallace Manheimer

Abstract The world needs a great deal of carbon free energy, and soon, for civilization to continue. Fusion's goal is to develop such a carbon free energy source. For the last 4 decades, tokamaks have been the best magnetic fusion has to offer. But what if its development stops short of commercial fusion? This paper introduces 'conservative design principles' for tokamaks. These are very simple, are reasonably based in theory, and have always constrained tokamak operation. Assuming they continue to do so, it is unlikely that tokamaks will ever make it as commercial reactors. This is independent of their confinement properties. However because of the large additional gain in hybrid fusion, tokamaks reactors look like they can make it as hybrid fuel producers, and provide large scale power by mid century or shortly thereafter.

Keywords Hybrid fusion · Tokamak fusion · Magnetic fusion · Global warming and energy requirements

Introduction

Over more than the past decade, this author has argued that the American magnetic fusion project shift emphasis from pure fusion to the fusion hybrid [1–7]. This argument proceeded along two paths; first, this is something the magnetic fusion project could do with reasonable confidence relatively quickly; and second, that with the rapidly approaching energy deficit and concern over global warming, the world needs the hybrid. Since his earliest paper [1], the author has always proposed the construction of a tokamak, with superconducting toroidal field coils, roughly the size of TFTR, JET or JT-60, but run CW or high duty cycle in DT. This is the 'scientific prototype'. The expected average fusion power would be $\sim$20–40 MW and the expected average neutron wall loading would be $\sim$0.1–0.25 MW/m^2. The scientific prototype would produce small but significant amounts of power as well as tritium and/or ^{233}U. It would also have given invaluable experience in wall materials for both pure and hybrid fusion.

If right after the tremendous success of TFTR and JET with DT plasmas, the American magnetic fusion community had attempted to, and succeeded in selling the scientific prototype, right now we would be reaping tremendous benefits: experience with significant fusion power, breeding significant amounts of T and/or ^{233}U, gaining knowledge about different blanket types etc. Fusion science and engineering would now be advancing rapidly on a very broad front. Instead, the American magnetic fusion community attempted to put all its eggs in the ignition basket, proposing a series of ignition experiments (but with no real average power), CIT, BPX, FIRE, and IGNITOR, none of which sold. Would the American fusion effort have been better off if it had instead attempted to sell the scientific prototype? It could hardly be much worse off. There has been no American magnetic fusion device the size of TFTR for more than a decade.

As this author has written the cited series of papers, he was sure each one would be the last. But on learning more on either of the two paths, another paper always seemed appropriate, as does this. While there are several things the author hopes to point out here, the main reason for this

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W. Manheimer has been retired from the U.S. Naval Research Laboratory.

W. Manheimer (✉)
4601 North Park Ave., Chevy Chase, MD, USA
e-mail: wallymanheimer@yahoo.com

paper is his recent conclusion, based on very fundamental considerations, that tokamaks, so far the best magnetic fusion has to offer, are unlikely to make it as economical pure fusion reactors. Accordingly, unlike any paper in this series but the first, this paper will have a fair amount of tokamak nitty gritty. However it definitely does look as if tokamaks can make it as hybrid fuel producers. The extra order of magnitude in gain makes all the difference. Given the coming (and present) energy deficit, tokamaks could play an extremely important role.

This paper, as its most recent predecessors starts section "The Global Warming Hysteria and Energy Situation" with a discussion of global warming (now virtually a hysteria), energy needs, and ways to meet them. As in early papers, it makes the case that nuclear power is the only realistic hope for meeting mid century carbon free power demands. However with high grade ore and a once through cycle, there is not nearly enough uranium for world development. There are numerous ways, the fusion hybrid being one, that this uranium (or thorium) resource can be extended.

Section "Conservative Design Principles for Tokamaks" introduces this author's principles of 'conservative design' for tokamaks. It based principally on the need to greatly minimize, or avoid all together major disruptions, something commercial reactors basically cannot tolerate. Thus no parameter is pushed too close to the red line, motivating the author's term 'conservative design'. This is connected mostly to MHD (ideal and resistive) theory. The two physical processes driving MHD instability are pressure gradient and current, accordingly these are mostly what drive the conservative design principles. Three main principles will be considered in this study. The first one of these is for the normalized beta β_N to be 2.5 or less. This is really the most crucial, because once the plasma beta is specified, the fusion power is a function of only temperature, and it has a maximum at an ion temperature of about 15 keV. Thus for maximum fusion power at the given beta, the density is selected so that this is the ion temperature (with some assumption regarding the electron temperature). However this density cannot be too high, because of the Greenwald density limit, which gives a maximum density proportional to the plasma current. Our second conservative design principle is that the average density cannot be over ¾ n_G. But the current cannot be increased indefinitely either. As the current increases q(a), the safety factor at the divertor or limiter becomes too low, the plasma is unstable to ideal or resistive MHD modes and is likely to disrupt. Hence our third conservative design principle is $q(a) > 3$. With these conservative design principles, the maximum performance of a tokamak is determined by only the magnetic field and the geometry. For circular cross section and large aspect ratio, these constraints take a particularly simple form. These regions of operation in tokamaks are reasonably well known, but their implication as regards commercial power plants have generally not been spelled out.

With these conservative design principles in mind, the data over the last decade from tokamaks able to operate with hot ions ($T_i > 5$ keV; TFTR, JET, JT-60, D3-D and ASDEX) are examined in section "Recent Tokamak Experiments in the Light of these Design Principles". The conclusion is that these conservative design principles are if anything an upper bound on tokamak performance so far. Real live tokamaks do worse. While these conservative design principles are not etched in stone, and with additional insight and development, tokamaks may be able to get around them; they are well based in theory and have constrained large tokamak performance for more than 4 decades.

Section "Power of Proposed Tokamaks Based on Conservative Design" examines proposed high duty cycle tokamaks operating in DT, the scientific prototype, ITER [8] and the original large ITER [9]. A fourth principle of conservative design is specified, namely that for CW or high duty cycle operation in DT, the blanket must be at least 1.5 meters thick. Since 14 MeV neutrons have long deposition lengths in many materials, especially in lithium (obviously an important blanket material), a thick blanket is necessary so that no neutrons escape out the back and activate unprotected material there (e.g. superconducting coils).

We note one proposal on the table that hopes to exceed the restrictions imposed by the conservative design principles. This is GA's proposed Fusion Development facility (FDF) (google GA Fusion Development Facility). With only 1/15th of ITER's volume, it not only hopes to generate 250 MW, more than half of ITER's power, but to do so CW (ITER is still a pulsed device, operating in pulses many minutes long for several shots a day). Also, unlike the scientific prototype or either ITER, it proposes to do this with copper toroidal field coils so there will be very large power consumption in CW operation. Furthermore, it has a blanket only 0.5 meters thick in most places and only 0.25 meters thick in a few places.

There are a few other points to make about the FDF. It hopes to do much better than a tokamak constrained by conservative design rules would allow by operating in what they call advanced tokamak regimes. However going from a JT-60 sized machine to a CW (or high duty cycle) and DT version of it such as the scientific prototype, represents one giant step forward. But going to both an advanced tokamak and also one which operates CW (or high duty cycle) in DT represents two giant steps forward in a single machine. The risks in going to the FDF appear to be greater than in going to the scientific prototype, but this author is not capable of assessing them further. Nevertheless the motivating characteristic behind the FDF and scientific prototype is basically the same; achieve CW operation in a DT plasma as soon as possible. As the author does not have sufficient expertise, there will be no further discussion of the FDF here.

Tokamaks are at present the best magnetic fusion has to offer. However if they are really constrained by conservative design principles, it seems unlikely that they will ever make it as economical fusion reactors. But these conservative design principles do not stop them from making it as hybrid reactors. In section "The Fusion Hybrid", we review the hybrid. The fusion hybrid dates back to the dawn of the fusion project. The earliest reference to it I have found dates back to Andrei Sakharov in 1950 [10]. Hans Bethe advocated it in 1979 [11]. It is difficult to find a scientific idea with a higher pedigree.

Where pure fusion takes the 14 MeV neutron's kinetic energy to boil water, the hybrid uses its potential energy to produce ten times more fuel. As the author has pointed out in every paper in this series, fusion is energy poor and neutron rich, fission is energy rich and neutron poor, a perfect match. There are two possible hybrid routes, one which breeds ^{239}Pu from ^{238}U, the other breeds ^{233}U from ^{232}Th. The author has always favored the latter as there is virtually no proliferation danger from the raw fuel once it is mixed with ^{238}U into a subcritical mix. We could export it, even to countries we did not fully trust as long as they sent back the spent fuel for reprocessing. And indeed why shouldn't the United States, using mostly its brains and technical expertise, become the Saudi Arabia of the mid to late century world?

In the late 1970's and early 1980's, hybrid fusion was taken rather seriously; many of the earliest publications in this journal [12–16] were devoted to it, as well as other publications elsewhere [17–19]. At about this time, the National Academy of Science reviewed it, (but published their report in 1987) [20] and concluded that at the time, the development paths for pure fusion and hybrid fusion were sufficiently similar that development should proceed with only pure fusion. If the situation changes, they said, one could always make the switch. Hybrid fusion was then basically abandoned (but clearly not in this series of papers), at least in the United States.

This author claims that the situation has indeed dramatically changed, and that the switch to hybrid fusion is long overdue. There are a number of reasons. First, research in pure fusion has slowed down. At the time of Bethe's article and the NAS study, breakeven fusion was envisioned in the late 1980's or early 1990's with rapid development after that. This clearly did not happen. Second, unforeseen by the NAS study, world development is proceeding at a breakneck pace with China and India now, and soon the rest of the world, putting enormous pressure on energy supply. Third, we make the case here that the tokamak path, at present the best magnetic fusion has to offer, may well stop short of pure fusion, but be viable for hybrid fusion. Finally, even if magnetic fusion does become economical, it would almost certainly take additional years and decades to get around the constraints imposed by the conservative design principles. This would push its incorporation into the economy into the 22nd century; but the need is for mid century. A development path for large scale power production via hybrid fusion by mid century does appear to exist.

If the magnetic fusion community does adopt the hybrid, would the development path be different from pure fusion over the next few decades? Most certainly it would be. If we are interested in a perfect energy source for the 22nd century, and assuming sponsor have that kind of patience, a single minded focus on ignition might make sense. However if we are interested in a less than perfect source for mid century, we must start now to advance on a broad front as soon as possible. Building a machine like the scientific prototype will allow just that. Hence if the American magnetic fusion community find these four conservative design principles convincing, it should stop letting perfect be the enemy of good enough, change course and emphasize the hybrid instead of pure fusion. It looks to this author as if the tokamak approach to hybrid fusion has a big carrot in front of it; pure fusion, a brick wall.

Section "Other Simple Aspects of the Fusion Blanket" discusses simple aspects of the fusion blanket and makes the case that it is very likely that a hybrid blanket is a simpler development task than a pure fusion blanket. Section "Cost Estimates and a Discussion of their Validity" gives cost estimates, based on ITER cost scaling and discusses their validity. Section "Review of the Energy Park" once more reviews the 'energy park', a possible building block for the mid to late century fusion hybrid driven economy. It was introduced in [5] and reviewed in [7]. It is a few square miles containing 7 reactors, one large ITER sized fusion reactor which supplies the park, 5 conventional reactors, which could even be of today's design, and one plutonium burner. It supplies about 7 GWe in electricity and/or hydrogen. Also in the park are a separation plant and cooling pools. The energy park treats all its own waste with a combination of fission, fusion and patience; only thorium comes in, only electricity or hydrogen go out. Section "Other Aspects of the Energy Park" discusses a few additional aspects of the energy park not mentioned in [5] or [7], and the last section briefly draws conclusions.

The Global Warming Hysteria and Energy Situation

Why call it hysteria? Before counting the ways, look at Fig. 1 and Table 1. Figure 1 graphs many nations' yearly per capita energy use versus yearly per capita GDP in year 2000 dollars. The two are very strongly correlated, there are no points on the upper left or lower right. Countries

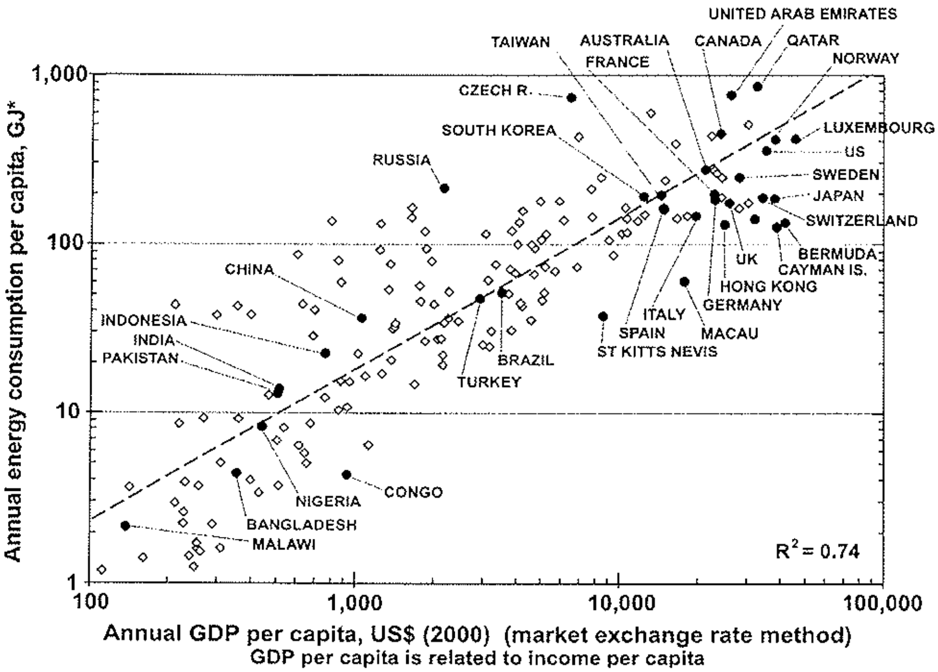

Fig. 1 Energy consumption versus income for a variety of countries in 2000

high up have more educated populations, who live more pleasant, longer lives, and have cleaner environments than countries lower down. One might almost be tempted to describe a country's degree of civilization by its position on the chart. [Chart 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].

The total world power use in 2005 was about 13 TW, of which at least 85% is from fossil fuel. The United States, about 5% of the world's population, uses about 2.5 TW. Let's say that we cut our energy use by 40%, so that our standard of living (going down parallel to the line) would be about like Italy's. (Actually it would be much worse than Italy because distances are much greater in the United States and we have responsibilities as a major world power that Italy does not have). However the goal of world development is to bring all countries up the curve, so let's say that all people now had that standard of living. This would increase world power use to 30 TW now and 50 TW by 2050 when the world population reaches 10 billion. Clearly conservation and new sources of energy are essential for civilization to continue.

The Kyoto accord mandates that each signatory will reduce its carbon input to the atmosphere by 10% from its 1990 levels. How is the world doing in that respect? Table 1 shows yearly carbon input to the atmosphere in million metric tons, from burning fuels, in 1990 and 2005 for a variety of countries. Data is taken from the DoE web site, (www.eia.doe.gov/environment/hmtl and follow prompts to international emission data.) European countries in bold are countries that have never been part of the Warsaw pact. (2005 is the last year shown in the eia tables).

Several things are clear from this table. First of all, one way to decrease carbon input is to have a command economy which has no regard for environmental standards, is uncoupled from a free market; and then collapses. Second, other than former Warsaw pact countries, the only major country even close to meeting its Kyoto mandate is Britain, which made a large scale change from coal to natural gas in the 1990's. That transition is now virtually complete. Third, France emits a significantly smaller amount of carbon into the atmosphere than other European countries its size. The reason is that France has embraced nuclear power to a very great extent. This is a data point supporting the author's contention that a greatly increased role for nuclear power could play a significant role not only in powering the mid century world, but also in reducing carbon emissions. But as we will see, for this to occur, one must find a way of greatly increasing the amount of nuclear fuel available. Fourth, the United States, a non signatory, increased its carbon emission by a smaller percentage than non former Warsaw pact Europe and Japan. As far as the signatories were concerned, their words allowed them clear consciences, but little else. And finally fifth, the role of developing countries is crucial as regards future carbon input. The cases of India and China are well known, but other less well known places, even in Africa are rapidly increasing their carbon input. Even tiny, impoverished Malawi, the lowest named country in Fig. 1, apparently is

Table 1 Carbon input to the atmosphere, various countries, 1990 and 2005

Country	1990	2005	Increase (%)
Europe			
England	**598**	**577**	
France	**366**	**415**	
Italy	**413**	**466**	
Holland	**206**	**270**	
Belgium	**124**	**136**	
Spain	**235**	**387**	
Norway	**34**	**52**	
Sweden	**54**	**59**	
Denmark	**56**	**51**	
Greece	**80**	**103**	
Sum of the above	**2166**	**2516**	**16**
Poland	330	284	
Romania	174	99	
Bulgaria	73	50	
Germany[a]	923	844	
Russia[b]	2044	1696	
United States	4747	5289	11
Asia			
Japan	935	1075	15
China	1454	2844	96
India	288	862	199
Indonesia	85	213	150
Latin America			
Mexico	230	288	25
Brazil[c]	185	218	18
Africa			
Nigeria	68	100	47
Egypt	42	98	133
South Africa	312	423	36
Malawi	0.53	0.86	62
World	**18,330**	**21990**	**20**

European countries in boldface were never Warsaw Pact members

[a] In 1989 West German absorbed East Germany, which had a Warsaw pact economy, so Germany is partially like Warsaw pact countries

[b] Starting 1992 when Russia separated from the Soviet Union

[c] Brazil is in the fortunate situation of being able to generate most of its electricity from hydropower

unwilling to stay where it is. As this author has constantly maintained, world development will not stop for political correctness, the poorer parts of the world will do whatever it takes to share in the life style we in the west enjoy; and we should do everything to encourage this. It will make for a more peaceful 21st century world. Another inconvenient truth for Al Gore is that civilization takes energy, lots of it; and right now, the only way we know to get this energy on the scale required is by burning fossil fuel.

Now let's count the ways that the global warming concern has turned into hysteria. The first exhibit is the April 28, 2008 issue of Time Magazine. Their cover story compares the fight against global warming to WW II; on the cover were the six marines of Iwo Jima planting a tree. What a travesty, what an insult to the few remaining WW II veterans, who faced real bullets, saw their buddies killed, defeated tyrannies of unprecedented evil, and won for us the freedom we now enjoy. The struggles are in no way comparable.

Time and other media portray the science supporting global warming as settled, deniers are flat earthers, or else are in the pay of oil and coal companies. This is certainly not so; many scientists are not convinced and some write blogs (i.e. www.sepp.org) and newsletters (i.e. www.EnergyAdvicate.com). In these, large numbers of scientists who doubt man made global warming are often listed, some are members of national academies, some have endowed chairs at major universities, and others are members of IPCC. This latter group, when writing, say OpEd pieces, often jokingly refer to themselves as Nobel Prize winners, since IPCC shared the Nobel Prize with Al Gore. Recently a petition disputing human influence on global climate change was circulated among scientists by the recently deceased Dr. Frederich Seitz, a former head of Rockefeller University and former president of the National Academy of Sciences. It garnered 32,000 signatures (this author was solicited, but chose not to sign it). It is indeed fair to say that there is a consensus among scientists that global warming has an important man made component; but unanimity?, most definitely not.

In the media, global warming is presented as an unmitigated calamity, but this is by no means clear; surely there will be winners and losers. While there may be coastal flooding, vast areas of Alaska, Canada, Greenland, European Russia, Siberia and Argentina will become much more valuable. In fact Eric the Viking settled Greenland about 1000 years ago at a warm time in the earth's history. These settlements mostly died out as the earth got colder. Just looking at a map, it seems to this author that there will be plenty of room for refugees from Bangladesh, Florida, and America's east coast barrier islands, especially if the migration takes place over a century or two.

But is world wide warming even occurring now? Roughly, smoothing out the bumps, the world temperature record over the past century is as follows: From 1900 to 1940, the earth warmed by ~0.5 F. Then from 1940 to 1970 it cooled by ~0.25 F, note this cooling occurred at a time of rapidly rising atmospheric CO_2. Then from 1970 to 1998 was a rapid rise of ~0.75 F, 1998 being the warmest year on record. This trend is easy to see in the graph despite the rather large fluctuations year to year. To this author it seemed that serious global warming was settling in with a temperature rise of ~0.25 F per decade, or 2.5 F per century. But then a funny thing happened, the temperature rise stopped. 2005 was only very slightly warmer than 1998, every other year since 1998 was cooler. Although this is written in May 2008, this year seems to be cool also, with very harsh winters in the United States, Canada, China, and snow falling in Baghdad, for the first time in decades. In other words, instead of a decade rise of 0.25 F, the temperature reached a plateau. Is this decade of constant temperature a pause in warming? a final leveling off?, or the beginning of a cooling trend? Who can say? The earth's climate is extremely complicated and is always changing with or without human interference.

To treat this problem or non problem all levels of government are attempting to get involved. The courts: Lawsuits are now underway to get the EPA to declare CO_2 a pollutant and regulate its emission. Imagine, every time you turn up your home thermostat, the EPA will be involved. What is lost sight of is that CO_2 is not a pollutant; it is a nutrient for plants. Without atmospheric CO_2, life on earth would not be possible. Regulating non pollutants was never in the EPA's charter. Maybe CO_2 should be regulated, maybe not. If it should, new legislation should be debated and passed by congress, and then signed by the president.

The states: Many now have mandates that a certain fraction of their base load electric power must come from renewable sources (Washington Post, business section, Apr 22, 2008). Some are reasonable and perhaps helpful. For instance Maryland mandates that 9.5% of base load power must come from renewable sources by 2022. Others are simply not living in the real world. For instance Maine (surely one of the states least hospitable to solar power) has a mandate of 40% by 2017. Does anyone have a clue how to do this? That is not the state legislature's problem.

The federal government: Congress has imposed ethanol mandates (and discouraged importing ethanol) so that now 25% of America's corn crop goes to ethanol, replacing 1% of our gasoline consumption. But of course it is much worse than even that. It takes gasoline to produce ethanol (to drive the tractors, fertilize the land, etc.); by some estimates more (K.Deffeyes, Beyond Oil, p8, Hill and Wang, 2005), by some less. Argonne National Lab (google Argonne National Laboratory Ethanol Study) has estimated that ~1 J of oil goes to produce ~1.3 J of ethanol, so taking their more optimistic estimate, that 1% become more like ~0.2–0.3%. As ominous as that situation is in the United States (where much land is taken out of conservation easement for extra corn production, land that was being conserved for a reason), the situation is much worse in Brazil, where that natural ecological treasure, the Amazon rain forest is being steadily cleared, in part to make room for sugar based ethanol production.

One result of this is rapidly increasing food prices, causing great hardship in poorer parts of the world. Despite his usually cloudy crystal ball, predicting this was a cinch for the author [3, 5, 7], and of course for many others as well. Even the media is now coming around. Time Magazine's cover story of April 7, 2008 described the failure of Biofuel. The Washington Post (April 28–May 2, 2008) had a 5 part series on the famine in the poorer parts of the world, especially Africa. In two of these parts, American ethanol production was singled out as a major cause. In an editorial on April 21, the Post described the ethanol mandate as a worth while experiment which failed and should now be abandoned. Bodgan Kipling, in an OpEd piece in Investor's Business Daily the same day, more harshly described it as taking a great deal of food from stomachs the world's poorest to add a spec more gasoline to our car's tanks. He called it a crime against humanity.

In addition to ethanol, congress is considering other mandates. Undeterred by the fact that the main signatories of the Kyoto treaty increased their CO_2 input by 15%, instead of decreasing it by 10%, the Lieberman Warner bill before the senate mandates a 66% reduction by 2050. What replaces the 85% of our energy we get from fossil fuels? Again; someone else's problem. To spur us along congress is thinking of a carbon tax, which at least has the virtue of simplicity; the responsibility for its harm or benefit will be clear. Also congress is considering cap and trade. Here vast new bureaucracies would be set up to apportion and enforce CO_2 emission rights among competing industries. Within the individual industries, different companies could buy and sell emission rights. Already different industries are starting ad campaigns, and lining up their lobbyists. Cap and trade may impoverish the American consumer, but on Madison Avenue in New York, and on K Street in Washington, it is strictly: Let the good times roll!

Despite the foregoing, this author is not a global warming denier, but believes unrestricted carbon input to the atmosphere is a serious problem. This case was laid out earlier [5]. Very briefly, atmospheric concentration of CO_2 is rapidly rising on a human time scale, and is now at a higher level than any time in the past 400,000 years. Also the American Meteorological Society and the American Geophysical Union have issued statements of concern, but certainly not alarm or panic. Thus the scientific societies with the most expertise do take the issue seriously. More recently the presidents of the Academies of Science of 11 large, scientifically sophisticated countries signed a joint statement of concern (www.nationalacademies.org/onpi/06072005.pdf). However this statement advocates adaptation as well as prevention. Very significantly, it envisions a rise in ocean level of 10–90 cm over the next century, certainly not the 20 feet Al Gore suggested in his movie "An Inconvenient Truth".

So carbon in the atmosphere is a problem, along with many other world and national problems such as energy supply, clean water supply, the North Korean (and prospective Iranian) nuclear weapon, radical Islamic terrorism and intimidation, bird flu and other possible pandemics, AIDS in Africa, malaria in tropical regions, the fiscal health of social security and medicare, access to health care in the United States, etc. It is the job of our elected leaders to assess these problems and apportion scarce resources to them. While not making a detailed list, this author does go on record with the opinion that energy supply is a more serious problem than global warming. All human history shows that civilization must have the former, but most likely can adapt to the latter.

Accordingly we now assess the energy situation. Two recent efforts led by M. Hoffert et al. [3, 21] examined energy needs and resources. Their conclusion is that by 2050 the world will need an additional 10–30 TW to develop. This is not far from the very simple estimates earlier in this section. However in order to prevent possibly destructive climate change, this 10–30 TW should be carbon free. They then go on to list energy resources and their carbon content. An augmented version of their table is shown in Table 2. One interesting thing is that DT fusion is not an infinite energy source, but is limited by supply of lithium to about three times the energy supply from coal according to [3].

Coal is clearly available on the required scale, but unless the CO_2 is sequestered, could have adverse environmental effects. But undeterred by this, less developed countries, from Malawi to China are building many hundred coal fired power plants. Regarding sequestration, this appears to be extremely difficult. One must first economically separate the CO_2 from the other much more abundant gases in the waste stream (i.e. nitrogen). If the CO_2 is sequestered in gaseous form, there is the real possibility of a catastrophic release, which would be enormously destructive. There are significant safety issues here which have hardly been examined at all. If the CO_2 is sequestered as a solid, say calcium carbonate, its weight and volume are much greater than that of the original coal. That is for every coal train going to a power plant, there is another five or ten times as long going back the other way. The DoE has recently canceled plans to build a pilot plant with sequestration capability in Illinois when its cost mushroomed to \$1.8B. It seems certain that world wide many, many coal fired plants without sequestration will be built in the next 30–40 years. China and India are already launching one a week. Almost surely the doomsday predictions of the alarmists will be tested.

Table 2 Energy resources and carbon release normalized to natural gas

Source	Energy (TW-yrs)	Relative carbon
Coal	5000	1.6
Oil	1200	1.3
Natural gas	1200	1.0
Mined uranium burner[a]	60–300	0
DT fusion	16,000 (Lithium supply)	0

[a] Based on high grade ore and once through fuel cycle, uses ~1% of the energy resource

Natural gas and petroleum are already in short supply and are concentrated in unstable, unfriendly parts of the world. We are reminded of this every time we fill up our car's gas tank or pay a home heating bill. Despite the rapid rise in price, supply has not especially increased. We may be unwilling to drill ANWR, but with oil at over \$100 per barrel, other poorer parts of the world will not be so reticent. Once a resource begins to be seriously depleted, or passes its Hubbert's peak [22, 23], it depletes whatever the price. Although it is not certain that this is the case with natural gas and petroleum, there are many very knowledgeable people who believe this to be true. Certainly the evidence we all see on price and supply gives credibility to the peak oil pessimists.

In earlier works, this author has examined renewable energy (7 and references therein), as have many others. His conclusion is that while these may provide some of the required power, their intermittent nature and their dilute concentration argue against them ever being more than bit players. The world needs much, much more. We have discussed corn based ethanol here. As one other example, the DoE web site points out that California now has ~13,000 wind mills, but these generate an average power of only ~0.45 GW, the amount of a rather small power station. Of course there is always the possibility of an unforeseen breakthrough. For instance the April 28 issue of Time speculates on genetically modified bacteria increasing the output of biofuels (but does not mention nuclear power!), Ray Kurzweil, in the April 13, 2008 Outlook section of the Washington Post speculates on a combination of biotechnology and nanotechnology. Maybe, but to pin our hopes on these is imprudent to say the least. While keeping our eyes open, let's also get real. The author claims here, as well as in these earlier works (as have many others), that only nuclear power has the capability to provide the carbon free, base load power on anything like the required scale in the required time.

There is now talk of a nuclear renaissance. Nuclear power supplies a significant fraction of world wide base load power today and does so with no carbon input to the atmosphere. While nuclear power has been a lightening rod for strong opposition by environmental and other groups, that situation may be changing. The industry has had a 30 year safety record (certainly a much better safety record than the coal industry), and once nuclear plants are built, they are the cheapest to run of any type of power plant. As environmentalists shift their attention to global warming, nuclear power is making a comeback even among some groups principally concerned with the environment. However if restricted to only mined high grade uranium ore, and a once through cycle, nuclear energy appears to be only a bit player according to Table 2. Taking the most pessimistic figure, nuclear power can only supply the world at 10 TW for 6 years, taking the most optimistic, 30 years. In neither case is the construction of a large scale nuclear industry justified. Fortunately, there are many ways of extending the uranium (or thorium) resource. Several of these are shown in Table 3 and we comment briefly on these. Each has potential, but none is a sure thing at this point, either technically or economically.

While the uranium from high grade ore and a once through cycle is not sufficient to sustain world development, there is much more uranium available. Deffeyes [22] points out that there is a great deal of lower grade ore available; very roughly, as the concentration of uranium in the ore decreases by a factor of 3, the amount of ore increases by about an order of magnitude. But what does this mean for the price of uranium? We are still mining high grade ore, and the nuclear renaissance not yet begun, but the Washington Post (Outlook Section April 27, 2008) points out that in the past decade, uranium prices have gone up from \$9 to \$75 per pound, with a spike in June 2007 of \$135 per pound. It seems likely that with large scale development of a nuclear economy, availability of mined uranium, and its cost, will be an important issue.

Since many of uranium's compounds are water soluble, there is low concentration of it in the world's oceans, about 1.8 MJ of ^{235}U per cubic meter [3]. But multiplying by the ocean's vast volume, one has virtually an infinite energy resource there. Japanese researchers, by using braided structures have extracted the uranium in a way that they think can extrapolate to an economic process. However what is viable on a small scale can obscure the size of the task on the relevant scale. That is the case with uranium from sea water. As [3] points out, to extract 10 TW of ^{235}U, the amount claimed needed to underpin world development, one has to catch all of the uranium in a flow equal to five times all the earth's rivers. That appears to mean putting a large stationary man made structure in say the Gulf Stream and filtering out, with 100% efficiency, all the uranium which flows by. If instead of using ocean flows, if one were to mine the seas, extracting 10 TW means processing 1.5×10^5 km^3 of sea water every year. Let's assume that each person in the world has 1,000 m^3 in his home and work place (more than this author has), for a total of 6,000 km^3. In other words, it would be necessary to process 25 times the volume of all the world's buildings every year. Japanese researchers have been studying extraction of uranium from sea water and have reported some successes. However to extract uranium in truly meaningful quantities, they have to extrapolate their extraction rates by many many orders of magnitude.

Table 3 Possible ways of extending the uranium resource

Mining lower grade ore
Uranium from seawater
Uranium or thorium breeder reactors
Accelerator assisted hybrid
Fusion hybrids

Breeder reactors date back to the dawn of the nuclear era. These use the entire energy resource of the uranium of thorium, rather than the ~0.7% in naturally occurring ^{235}U (plus the small extra amount of ^{239}Pu that is bred in thermal neutron reactors). To get an idea of the vastness of this uranium resource, consider that the world has generated ~400 GW of nuclear powered electricity for ~40 years. This means that in depleted uranium alone, there is enough for 4 TW of electricity for 400 years; and the potential is much greater than that, we have not yet seriously dented the world's uranium supply. Furthermore, for a breeder, the world's thorium, which is estimated at ~3 times the size of the uranium resource, becomes available. By any definition, a nuclear breeder economy is a sustainable resource, able to support the world at tens of TW as far into the future as the dawn of civilization was in the past. Of the ways of increasing the uranium resource, the world has by far the most experience with this. While there have been successes, there have also been failures. One conclusion from all this experience is that power from breeders will be considerably more expensive than power from conventional thermal reactors. Perhaps more significant however, is the fact that even if we were able to switch to a breeder economy immediately, the breeding rate is sufficiently slow that it will not produce nearly enough fissile material fast enough to fuel a large existing stock of thermal reactors. This was discussed in (7 and references therein) as well as in many other places.

Carlo Rubia, the Nobel prize winner and head of CERN laboratory has suggested using large accelerators to produce spallation neutrons [24]. These additional neutrons would produce fissile material from fertile material and the entire system would be a different type of breeder. This author has little experience from which to comment, but there are several aspects worth noting. Although not sold in this form, it is simple to see that accelerators cannot produce uranium for use in a thermal reactor. Note that one takes wall plug electricity which is ~33% efficient to power an accelerator which is ~50% efficient. This accelerator produces 1 GeV protons, so each proton takes ~6 GeV to produce. The proton slams into a lead target, and each proton produces ~30 spallation neutrons. Assuming no loss, each neutron produces one ^{233}U from a ^{232}Th atom. However when we burn the ^{233}U in a thermal reactor, it gives ~200 MeV, so the 30 ^{233}U's produced by the proton just gives back the 6 GeV we started with. In other words the accelerator trades 1 J of coal for 1 J of ^{233}U. Thus accelerators can produce fissile material to start a conventional breeder, or to power their own unique type of breeder, but they cannot produce fuel for today's thermal reactors. Furthermore they would require a totally different nuclear infrastructure from what we have today.

The other way of increasing the supply of fissile material is with a fusion hybrid, the concept this author has been advocating for more than 10 years now. Instead of using the kinetic energy of the fusion neutron to boil water, use its potential energy to breed ten times more fuel. Unlike the accelerator concepts, the fusion reactor is exothermal, so it does have the capability of providing fissile material for today's thermal reactors, therefore fitting much better into today's infrastructure than an accelerator powered breeder. Like the breeder, all the energy in uranium and thorium become available. Furthermore, this energy becomes available for use in today's thermal nuclear reactors. It has another significant advantage as well. Whether a fission breeder, an accelerator or a fusion breeder, what is needed to transmute a fertile atom into a fissile atom is a neutron. What does it take to produce a neutron in an accelerator or a fusion reactor? Whether the neutron producing reaction is endothermic (the accelerator) or exothermic (the fusion hybrid), the size of the reactor ultimately scales with the energy required to produce the neutron. As we have seen, the accelerator needs ~200 MeV to produce a single neutron. The 14 MeV neutron in a fusion also can produce spallation neutrons, perhaps 2–3 total neutrons depending on what the neutron multiplier is. However one neutron is needed to produce the tritium from lithium, so there are perhaps 1–2 neutrons remaining for other purposes. The neutron production reaction is a portion of a total reaction (counting the tritium breeding) of ~20 MeV, so each neutron takes about 10–20 MeV to produce, about an order of magnitude less than the accelerator, i.e. fusion is neutron rich.

Conservative Design Principles for Tokamaks

Conservative Design Principles for Tokamaks

Before proceeding, to keep the units clear, they are listed in Table 4 along with several formulas in these units. Any tokamak run as a reactor can in all likelihood withstand existing levels of transport. What it cannot tolerate are many (or even any) major disruptions. Thus in the relevant parameter space, there is a boundary separating regions where a tokamak may disrupt. A commercial reactor should operate as far from this red zone as possible, thereby motivating the author's term 'conservative design'. While disruptions are still not yet fully understood, they are almost certainly rooted in MHD (ideal and resistive) effects in the plasma, we consider these. MHD instabilities are driven by current and pressure gradient. The first and most important design principle concerns the plasma beta.

Table 4 Units used and some formulas in these units

Units	
B	Tesla
I	Megamps
R,a,$\sigma^{1/2}$	Meters
n	10^{20} m^{-3}
T	keV
β_N,β, q(a)	numbers
Velocity	m/s
Power	Megawatts
Power density	MW/m^3
Wall loading	MW/m^2
Formulas	
β	$4 \times 10^{-2} \frac{n(T_e+T_i)}{B^2}$
q(a) (circular)	$5 \frac{a^2 B}{IR}$

A real breakthrough in these sorts of calculations was accomplished by Troyon and Gruber [25] as well as in their follow up work [26]. Earlier calculations typically picked a profile and examined its stability. As [25] points out, in some cases experiments showed that plasmas were more stable, and this was regarded as confirmation that plasmas could exist beyond a calculated stability boundary. Troyon and Gruber took a different tack. They would start by picking a profile and examining its MHD stability, but if they found it to be unstable, they would vary the profile a little bit and see if they could stabilize it. By doing many such calculations, they would determine the maximum allowed beta consistent with their variation of parameters. They determined that the maximum beta was governed by what they called the maximum normalized beta β_N. In terms of β_N, the volume averaged plasma beta β was given by

$$\beta = 10^{-2}\beta_N I/aB \tag{1}$$

Notice that a is defined as the minor radius along the tokamak mid plane. Their calculations gave a value for β_N, and from this β could be determined. If the plasma had no wall stabilization, they found a maximum stable β_N of about 2.5 or a little greater, and with strong wall stabilization, it might be as large as 5. In our conservative design, we will neglect wall stabilization. In a DT tokamak reactor, the wall is doing enough; absorbing and multiplying neutrons, dissipating heat from fast ions and radiation, being one end of a heat exchanger and breeder of ^{233}U and/or T, etc. Furthermore, the tokamak has either a limiter or divertor, so the wall can only get so close to the plasma. Looking at pictures of divertors in various schematics of tokamaks, the separatrix gets out to about 90% of the wall radius along the plasma mid plane, and of course at the x points, it is further still from the plasma. Also we take Troyon's most conservative value, since it will be furthest from the disruption threshold Thus we take for our first principle of conservative design the condition that β_N is 2.5 or less.

To make further progress while keeping our analysis as simple as possible, we assume a density and temperature profile for the plasma. For elliptical cross section with minor plasma radius a along the mid plane and vertical elongation k, we take parabolic profiles

$$n_e = n_0\left[1 - \left(\frac{x}{a}\right)^2 - \left(\frac{y}{ka}\right)^2\right] \tag{2a}$$

$$T_{i,e} = T_{i,eo}\left[1 - \left(\frac{x}{a}\right)^2 - \left(\frac{y}{ka}\right)^2\right] \tag{2b}$$

where n_e is the electron density, assumed to be twice the deuterium and tritium density and $T_{i(e)}$ is the ion (electron) temperature. The spatially average density is $n_o/2$. The pressure is the product of the two, and the spatially averaged pressure is $n_o(T_{eo} + T_{io})/3$, and both are independent of k. Of course there may be effects from different profiles but they should not be major. For instance at the average beta, the center temperature may be higher (giving more fusion power) but cover a smaller average volume (giving less fusion power).

If density and temperature are totally unrestricted, $\langle\sigma v\rangle$, as a function of temperature, has a broad maximum at a temperature of $T_i \sim 50$ keV. However if β is restricted, the maximum is at a lower temperature because this means higher density. To simplify slightly we consider circular cross section and simply estimate the fusion rate for an elliptical system by multiplying by the elongation k (i.e. by the volume ratio). Since β depends on $T_e + T_i$, whereas the fusion rate depends only on T_i, we must make some assumption here. We assume $T_e = T_i/2$, as is often characteristic of beam heated tokamaks. (If the temperatures were equilibrated, the neutron power would be lower, obviously one can do this calculation for any electron temperature).

Then the neutron power is given by

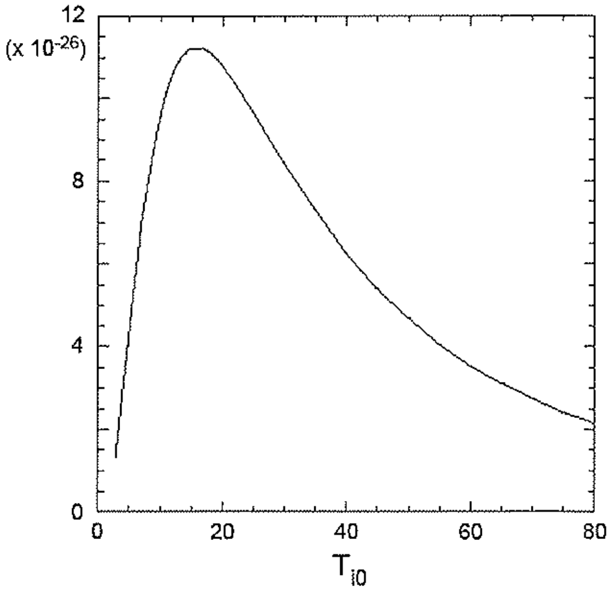

Fig. 2 A plot of reaction rate divided by ion energy squared. The units of the vertical axis are m^3/keV^2 s

$$P_n = 2.2\ \times\ 10^{22}k(2\pi R)(2\pi a^2)\frac{n_o{}^2}{4}\chi(T_{io}) \tag{3a}$$

where $n_D = n_T = n_o/2$ (recall the units of n_o are 10^{20} m^{-3}, and P_n are MW)

$$\chi(T_{io}) = \int_0^1 u\,du\langle\sigma v(T_i(u))\rangle(1 - u^2)^2 \tag{3b}$$

If beta is specified, then the density is proportional to T^{-1}. The function $\chi(T_{io})/T_{io}{}^2$ is plotted in Fig. 2. It has a maximum at T_{io} of about $15 \equiv T_{io}(\beta)$. To get the average reactivity for the plasma, just multiply the ordinate by $T_{io}{}^2$. Now expressing the density at which the maximum fusion rate occurs, we get

$$n_o(\beta) = \frac{\beta_N\ IB}{2aT_{io}(\beta)} \tag{4}$$

To determine $n_o(\beta)$, note that the maximum β_N can be is 2.5, consistent without first design principle.

Now we introduce the second conservative design principle. Decades of plasma experience have shown the tokamaks cannot operate at densities above the Greenwald limit [27, 28] also see www.psfc.mit.edu/~g/papers/aps01.pdf)). While this is more of an empirical law than one grounded in solid theory, it has held for two decades already. The Greenwald density limit (equal to $n_o/2$ for our assumed parabolic density profile) is given by

$$n_G = \frac{I}{\pi a^2} \tag{5}$$

where once again, a is the minor radius along the midplane. There has been some success in operating above the

Greenwald limit by operating with very highly peaked density profiles or by inserting controlled low Z impurities in the outer regions, but these have often not been at the highest power or current level of the tokamak. Often this higher density operation does not persist very long [29].

However the failure mode in approaching the Greenwald limit is often a shrinking of the plasma profile followed by a major disruption. Since major disruptions are basically intolerable in any reactor, we take as our second principle of conservative design that the density cannot be above ¾ of the Greenwald limit, or

$$n_o(G) = \frac{1.5I}{\pi a^2} \tag{6}$$

Notice we now have two possible density limits (Eqs. 4 and 6), one given by a beta limit (more accurately an optimum density) and one by the Greenwald limit. The actual best operation density is the minimum of these. If the density is determined by the beta limit, the maximum fusion power is given by Eq. 3a. However if $n_o(G) < n_o(\beta)$, the beta can stay the same by operation at higher temperature, namely a temperature

$$T_{io}(G) = \left(\frac{n_o\ (\beta\ )}{n_o(G)}\right) T_{io}(\beta) \equiv 15\left(\frac{n_o\ (\beta\ )}{n_o(G)}\right) \tag{7}$$

The reaction rate is higher at this higher temperature, but the density is lower so the net effect is less power production. But if T_{io} is greater than about 50, the temperature where σv maximizes, there is no point in attempting to achieve higher temperature, and one would operate at $T_{io} = 50$, and below the beta limit. Hence for all situations, the maximum neutron power one can achieve in a tokamak operating under conservative design rules is given by

$$P_n = 2.2 \times 10^{22} k(2\pi R)(2\pi a^2)\frac{n_o(\beta)^2}{4}\chi(T_{io}(\beta)) \qquad n_o(\beta) < n_o(G) \tag{8a}$$

$$P_n = 2.2 \times 10^{22} k(2\pi R)(2\pi a^2)\frac{n_o(G)^2}{4}\chi(T_{io}(G)) \qquad n_o(G) < n_o(\beta),\ T_{io}(G) < 50 \tag{8b}$$

$$P_n = 2.2 \times 10^{22} k(2\pi R)(2\pi a^2)\frac{n_o\ (G)^2}{4}\chi(50)) \qquad n_o(G) < n_o(\beta),\ T_{io}(G) > 50 \tag{8c}$$

so this defines the maximum power a tokamak can give according to the first two conservative design rules.

Both density limits depend on the current, and if this could increase indefinitely, there would be no problem. But from ideal and resistive MHD, we know that the q at the limiter or divertor is nearly always greater than three. This then is the third principle of conservative design, namely that $q(a) > 3$. For tokamaks of circular cross section, the relations then simplify considerably since one can express q(a) very easily in terms of current (as given in Table 4). For circular cross section,

$$n_o(\beta) = \frac{5aB^2\ \beta_N}{2Rq(a)T_{io}(\beta)} \tag{9a}$$

$$n_o(G) = \frac{7.5B}{\pi R q(a)} \tag{9b}$$

In this case, the maximum density depends only on magnetic field and geometry as well as β_N, taken to maximize at 2.5, and q(a) taken to minimize at 3.

For noncircular cross section, the q is a function of the flux ψ given by an integral over the flux surfaces. It might seem natural to take the plasma boundary at the divertor separatrix, as we do with the limiter radius in limiter plasmas. However, the integral defining q there has a logarithmic singularity there, so it is customary to take for the plasma boundary the flux surface that contains 95% of the flux up to the separatrix. Since q goes as r^2, and the divertor separatrix is about 90% of the way to the wall, we consider the 95% surface to be at about 87% of the way to the wall and define the q here as q(a) (others have defined it as q_{95}). Still the q here depends on the distribution of current within the flux surfaces, and it is not particularly easy to estimate it accurately. The author has made some rough estimates, and they are typically within 20–25% of the actual value, but does not pursue this here, because for all elongated tokamaks where one needs both I and q(a), namely JET, JT-60, ITER and large ITER, both are given in the references. The density limits as defined by the currents are used, checking only that $q(a) > 3$. While more complicated than circular cross section, the conclusion for elongated cross sections is the same; namely the maximum performance of a tokamak depends only on toroidal magnetic field and geometry.

Let us reiterate our first three principles of conservative design; first, $\beta_N < 2.5$; second, $n_o < 1.5n_G$; and third, $q(a) > 3$. In terms of these principles of conservative design, we have derived maximum neutron production from the tokamak.

Notice that confinement does not come into these principles at all. This is not to say it is unimportant; the confinement and transport determine the external power needed to maintain the plasma profiles. However even if there were no losses (or else for instance an ignited plasma), these three design rules put serious constraints on what a tokamak can and cannot do. Good confinement cannot make things better, bad confinement can only make them worse. In this section we will go through a few numbers and see that by these rules, tokamak reactors do not look like they can ever be economical for pure fusion. That is not to say these rules are carved in stone, with more development and insight (or by using other confinement configuration concepts), one may get around them. But in all likelihood, that will take decades, pushing the large scale incorporation of magnetic fusion in the economy until very late in the century or until the 22nd century. The tremendous advantage of the fusion hybrid is that even constrained by these design principles, tokamak hybrid reactors or fuel factories may be both economical and able to impact the economy by mid century.

Recent Tokamak Experiments in the Light of these Design Principles

This author was involved in tokamak transport in the middle and late 1970's, and in gyrotron development for ECRH in the middle and late 1980's but has been employed in other areas of science since then and has generally not followed tokamak advances. One exception was in the 1997 and 1998 when researching [1]. Twenty years of tokamak data was carefully examined and summarized there. To write this paper, it again became necessary to examine more recent tokamak data. Figuring that any really important advance would ultimately become an invited talk at the fall APS Division of Plasma Physics meeting, the author examined all such invited talks between 1998 and 2007. As a general impression, since 1998, there were none of the tremendous advances as summarized in [1], possibly because the earlier period reflected a time of construction of many tokamaks around the world, whereas no new tokamaks the size of say JT-60 have been constructed. Generally the major advances seemed to be in non inductive current drive using say beam, rf, or bootstrap current drive; or long time operation, or in finding and exploiting various transport barriers. For instance it was realized before 1998 that reverse shear operation could have beneficial effects on transport. But this meant the current profile was not centered, but formed a shell around the tokamak axis. Recent experiments showed that this current shell could be maintained for many current diffusion times. Also total pulse lengths have gotten much longer, seconds in D3-D, approaching 10 s in JET, and tens of seconds in JT-60. However these do not especially affect fusion rate, which is affected by density and ion temperature. Here results were not awfully different from 1998. We summarize some of them here for five tokamaks that run with multi-kilovolt ions, three large ones, TFTR, JET, JT-60, and two smaller ones, D3-D and ASDEX.

TFTR

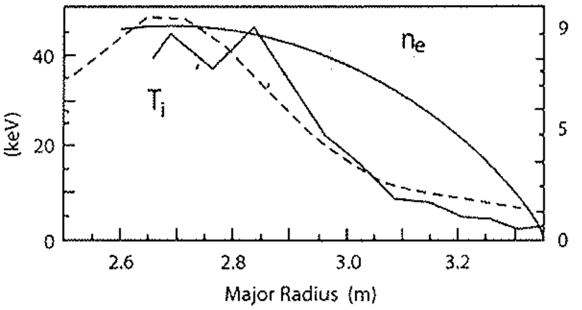

Fig. 3 The density (dashed) and the ion temperature (solid) as compared to the assumed parabolic profile for a TFTR supershot

As TFTR was decommissioned in 1997, there was a single summary of results from it in the APS invited talks over the period specified [30]. Briefly it achieved spectacular results when operating in the hot ion supershot mode. These have peaked profiles, and the beam is important for both heating and fueling the plasma. It achieved a maximum fusion power of 10 MW for perhaps half a second. However it terminated by rapidly dumping all or a significant part of the plasma energy. The major radius was 2.6 m, the limiter radius was 0.9 m and the magnetic field was over 5T. This is all that is needed to get maximum parameters of the device according to the conservative design principles. Figure 3, redrawn from [30] shows the ion temperature and electron density measured in a supershot, as well as the parabolic approximation we have been using, normalized to the measured maximum ion temperature.

In [30] there was a table of parameters of 4 supershots. A portion of the table is presented in Table 5. The rows in bold are from [30], the rows in ordinary type are from conservative design principles. The central ion temperature is much higher than the optimum value of 15 keV, but the beta is still consistent because the hot part of the plasma is so narrow compared to the parabolic profile we have been assuming. In fact, their measured β_N's are smaller than

Table 5 Data from TFTR supershots: boldface, data taken from [30] normal type, calculations based on conservative design principles

Shot number (expt)	1	2	3	4
B	**5**	**5.1**	**5.6**	**5.5**
I	**2**	**2.5**	**2.7**	**2.3**
n_o	**0.96**	**0.85**	**1.02**	**0.85**
T_{io}	**29**	**44**	**36**	**43**
β_N	**2.1**	**2**	**1.8**	**1.5**
q(a)	**4**	**3.2**	**4**	**3.8**
P(neutron)	**0.065**	**9.3**	**10.7**	**2.8**
Shot number (conservative design, $q(a) = 3$ and $\beta_N = 2.5$)				
$n_o(G)$	1.5	1.5	1.7	1.65
$n_o(\beta)$	1.2	1.25	1.5	1.45
P(neutron) (MW)	20	21	31	29

what we have assumed in the conservative design. While they do not give q(a), for their circular cross section one can estimate it easily enough. In all cases $q(a) > 3$, so that the results are consistent with conservative design principles in this respect. There are two rows for the calculation of the central density from conservative design rules for $q(a) = 3$ and $\beta_N = 2.5$, $n_o(\beta)$ and $n_o(G)$. For TFTR, the former is slightly smaller. In the last row of the table is given neutron power from Eq. 8. Notice that the neutron power per the conservative design is at least double the actual neutron power observed. Hence even though TFTR managed to get a much higher ion temperature than 15, it did not help very much. The reaction rate was higher in this region of high temperature, but the density was lower, and the volume of strongly reacting plasma was also smaller; the net effect being less neutron power than the conservative design rules would specify. Thus for TFTR, the conservative design rules over estimate the fusion power, typically by at least a factor of two.

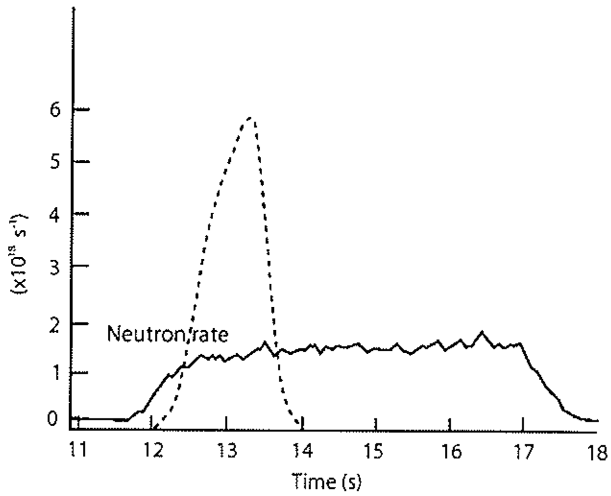

Fig. 4 Neutron rate for a hot ion (dashed) and long lived (solid) shot in JET

Table 6 Data from JET: boldface, data taken from [31] normal type, calculations based on conservative design principles

Shot	Long lived	Hot ion
B	**3.8**	**3.6**
I	**3.8**	**4**
n_o	**0.8**	**0.42**
T_{io}	**8**	**28**
β_N	**1.3**	
P(neutron)(MW)	**4**	**16**
q(a)	**3.4**	**3.7**
Shot (conservative design, $\beta_N = 2.5$ and $q(a) = 3$)		
$n_o(G)$	1	0.95
$n_o(\beta)$	1.1	1.05
P(neutron) (MW)	35	32

JET

This is larger both in volume and elongation than TFTR; both effects tend to increase the plasma performance both as regards density and beta, and it had several invited talks [31, 32]. For the plasma minor radius a, we take 87% of the wall radius (as discussed earlier), or 1.1 meter.

Two modes of operation for JET with DT plasmas were discussed, a long lived mode of operation, where the plasma was in steady state as long as the discharge could be maintained (limited by the duration of the beam), and a hot ion mode, which could only be maintained for about a second before it was terminated in a large amplitude edge localized mode (ELM). This quickly released over 1 MJ, or about 15% of the plasma stored energy. While not as destructive as a major disruption, it is unlikely that a reactor would want to have these events occur very often.

In the long lived mode, the plasma generated 4 MW of fusion power, for the duration of the discharge (~5 s) and the steady state Q was about 0.18. In the hot ion mode, the fusion power was ~16 MW for a Q of about 0.66 at the maximum fusion rate. In Fig. 4, (redrawn from [31]) is shown a plot of neutron rate from the DT shots on JET for both modes of operation,.

In Table 6 we show results for JET, and summarize the predictions from conservative design principles ([31] does not give their value of β_N for the hot ion mode). Here we use Eqs. 4 and 6 for $n_o(b)$ and $n_o(G)$ since JET has an elongated profile. We use $k = 1.8$, $R = 3$, and $a = 1.1$. Now, opposite to TFTR, we find $n_o(G)$ is slightly less than $n_o(\beta)$. The last row shows the predicted power according to conservative design rules. In the long lived mode the fusion power is less not only because β_N is smaller, but also because the central ion temperature is less than the optimum 16 keV. In the hot ion mode, the ion temperature is again much greater than 15 keV, but as with the case of TFTR, this does not give an appreciably larger fusion rate because the volume of the reacting plasma is so much smaller that assumed in the conservative design.

Once again, we see that if JET could operate according to conservative design principles, it would give greater fusion power; so once again, conservative design principles seem to be very much an upper bound for tokamak performance for the case of JET running in DT plasmas. As a rule of thumb, it seems that the best tokamaks have done so far in DT plasmas is to achieve a neutron power about half of that predicted by conservative design rules. Yet even that concedes a lot, so far tokamaks have achieved this only in discharges which terminate abruptly.

JT-60U

JT-60 and more recently its upgrade JT-60U is the largest of the tokamaks, but so far, has not operated with DT. It had a number of invited talks [33–38]. Its parameters are a major radius of 3.4 m, a minor radius of 1.2 m (to the vacuum wall) and an elongation of about 1.4. The maximum magnetic field is about 4.2 T. Although JT-60U has not yet operated with DT, it has operated with DD plasmas, and from the DD neutron rate, they extrapolate to get the DT rate. The JT-60 group has given several invited talks on their experimental results at these APS DPP meetings. In all their reported data, as regards β_N, (virtually always equal to or less than 2.5) q(a) (virtually always greater than 3) and n/n_G (virtually always less than 0.75), their results are consistent with the conservative design rules.

A great deal of their earlier effort consisted in developing what they called a W shaped divertor. Here, they reported their largest amount of fusion power, with the equivalent Q in a DT plasma going above unity, and with a great deal of the improvement coming from the new divertor. Figure 5a redraws their plot of equivalent Q vs current from these references. It reaches a maximum of 1.25. However they point out that these are all transient results. In quasi steady operation, their Q's were below 0.2. This result is similar to the experience of JET. In an earlier talk, they gave a a scatter plot of their q(a) versus β_N. They had a single result of q(a) = 2, a transient result in a plasma where $\beta_N = 1$. In their results for quasi steady plasmas, plasmas lasting longer than 5 times the energy confinement time, all their q(a)'s were greater than 3 and all their β_N's were less than 2.5. A redrawn version of this plot is shown in Fig. 5b.

Regarding density in their earlier results, they were always below the Greenwald limit. In Fig. 5c is shown a redrawn plot of their H factor, the confinement increases when they operate in the H mode as a function of n/n_G. They have a single point at 0.8, at the worst confinement, and virtually all of their data is for $0.4 < n/n_G < 0.6$.

In their later results, they emphasized long time operation. This involved getting bootstrap current of over 50% sustained for a long time and a β_N sustained for over 20 s. Shown in Fig. 5d a plot of β_N as a function of time is redrawn. While sustained for long time, it is still no greater than 2.5. Their q(a)'s were everywhere greater than 3, and their maximum densities reported were at about $0.5n_G$. But they found that in some cases they could increase β_N to 3, and showed some data points where they achieved q(a) = 3 and $\beta_N = 3$ in a long lived discharge. Had they run in a DT plasma with these parameters, it is unlikely that they would

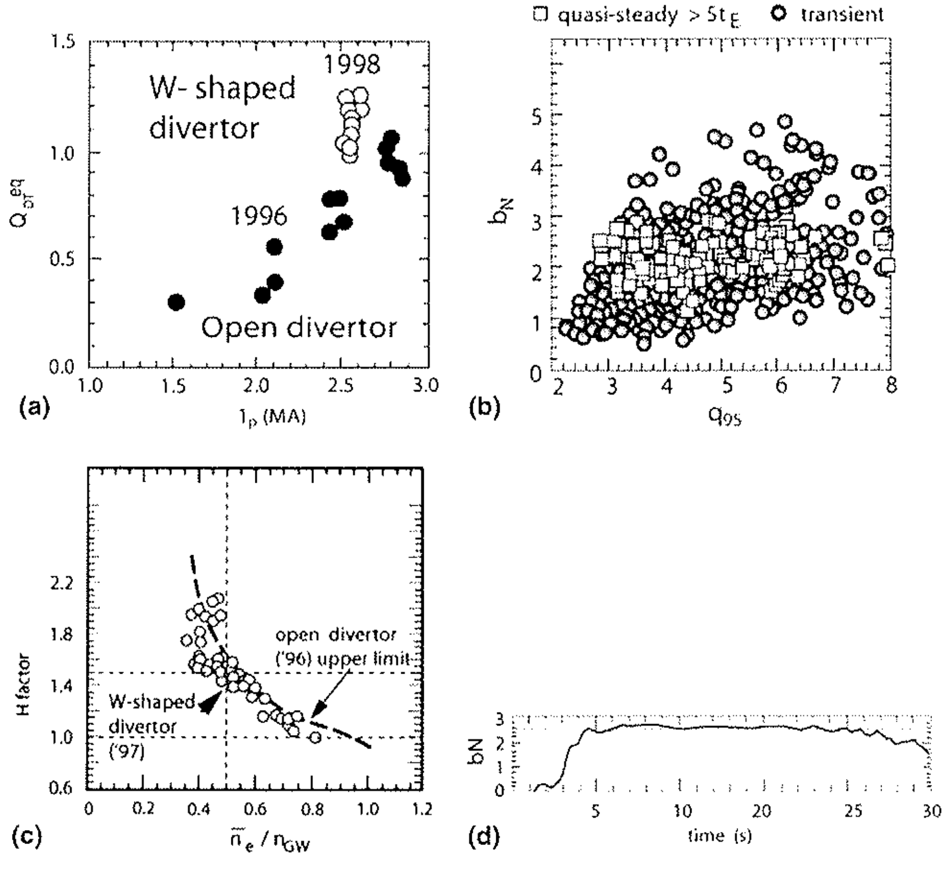

Fig. 5 Data from JT-60U (**a**) Equivalent DT Q for various types of divertor as a function of current, (**b**) Scatter plot of q(a) versus β_N. The long lived shots all had q(a) > 3 and $\beta_N < 2.5$, (**c**) Plot of confinement factor (H) as a function of density over Greenwald density. Except for the point with worst confinement, where the ratio was 0.8, all other points had $(n)/n_G < 0.75$, (**d**) A long lived shot showing β_N leveling off at 2.5 for 20 s

have achieved conservative design values for neutron power because the central ion temperature was about 8 keV rather than the optimum value of about 15 keV. Thus while the recent data from JT-60 is still for the most part consistent with conservative design rules, it does give great confidence that a steady state device like the scientific prototype, with a Q of at least 0.2, and more likely above unity, can be constructed.

ASDEX

This is a smaller machine with about a 1.5 meter major radius, a 0.5 m minor radius and an elongation of about 1.6. There were three invited papers from ASDEX at APS DPP meetings during this time period [39–41]. Generally, these confirm the conservative design rules. The q(a)'s were always greater than three. The β_N's were generally 2.5 or less, however they found they could approach values of nearly three. But as they approached $\beta_N = 3$, they also found that there was enhanced MHD activity, often leading to a disruption. They also found that they could approach, and even slightly exceed the Greenwald density limit, but their normal operating mode was at about half the Greenwald limit.

DIII-D

Where DIII-D is an American machine, and APS meetings were searched, perhaps it is not surprising that this machine had the largest number of invited talks [41–49]. One of their main efforts was to achieve fully non inductive current drive through a combination of ECCD, beam driven and bootstrap current. They found that they could operate for long times with 90% non inductive current drive, and for short times with 100% non inductive current drive. They were also the main group that seeks to challenge the conservative design rules, the crucial parameters claimed here to limit tokamak performance. They do not emphasize q(a) or n_G, but do spend considerable effort to increase the β_N and have had impressive success in some of their experiments.

Much of their work involves plasmas with a minimum of the q profile off center, in other words, the current is in a shell rather than centered at the axis. They find that they can maintain this for long times, and stabilize one of the main limiting modes, the n = 1 resistive wall mode by producing plasma rotation. Where the plasma rotation, if left alone tends to decay, they find that they can keep it going by using additional magnetic coils, both internal and external. One question of course is whether internal coils are ultimately necessary, and if so, whether they can stand up to the intense neutron fluxes in a reactor. Figure 1 of [47] shows that they can achieve β_N's as high as 3.2 in long lived discharges, and as high as 4 in discharges that abruptly terminate, usually via a tearing mode (of course an abrupt termination is the main thing conservative design rules seek to eliminate). However the experiments in [47] all take place at relatively high q(a). It mentions that the q(a)'s are typically between 4 and 5, the one plot of q(a) that they show (Fig. 7) has q(a) going almost up to 6. This means the experiments are at relatively low current, so the Greenwald density is lower, and the plasma β, which is proportional to $\beta_N I$ may not improve that much. Running with q(a) = 3 and $\beta_N = 2.5$, has the same beta and higher Greenwald density than running with q(a) = 5 and $\beta_N = 4$. Thus while conceding that the DIII-D group has had impressive success in pushing the limits imposed by conservative design rules, and may well have more still, the author is not ready to abandon them. He still maintains that they are a good guide for measuring maximum tokamak performance.

Power of Proposed Tokamaks Based on Conservative Design

We now consider proposed tokamaks capable of producing large amounts of fusion power. For ITER and large ITER, reactor sized tokamaks, our assumption is that the existing designs have room for an appropriate blanket which absorbs neutrons, breeds tritium, handles the heat load, etc. But if one wants to build a smaller tokamak, such as the scientific prototype, how thick does the blanket have to be? Here, the author has little expertise so only very qualitative matters are considered. The mean free path of neutrons with energies between about 1 and 14 MeV is about 15 cm in lithium, and about 6 cm in beryllium and thorium. All of these are important blanket materials for either pure or hybrid fusion. The mean free path for breeding and slowing down is even longer. Obviously the blanket has to be many mean free paths thick so as to prevent neutron leakage out the back, along with the activation of materials behind the blanket. Behind the blanket is usually a neutron shield, which itself is not thin.

Many of the references cited on fusion hybrids show schematics of the reactor along with the two meter man standing along side it, and the blanket is about his size. Rarely are dimensions given. One exception is a rough schematic of a blanket shown in [15], reproduced here in Fig. 6. In this schematic, the blanket is between 1.5 and 2 meters thick, and presumably there is no long term neutron leakage or activation of materials in back. Lidsky [12] when discussing a blanket for fission suppressed thorium cycle (discussed in section "The Fusion Hybrid") postulates a blanket 80 cm thick for just the fertile material. Hence, as a very rough rule of thumb, we will specify that the blanket has to be 1.5 meters thick. We will call this the fourth conservative design principle. It applies only where one wishes to design a small (i.e. much less than commercial size) reactor, and it imposes a certain minimum size on the

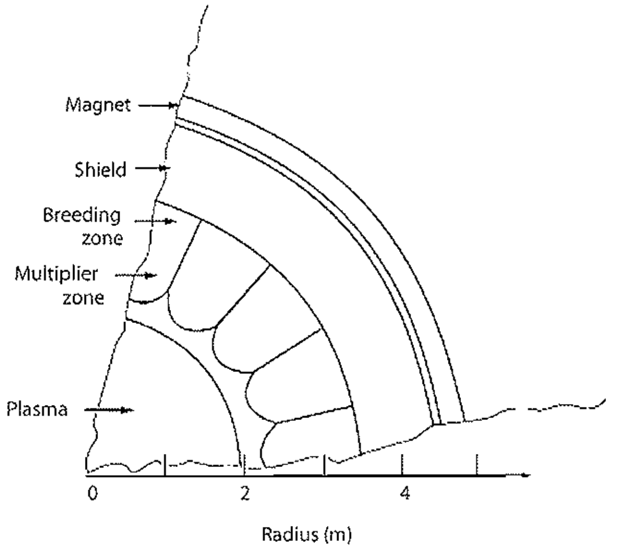

Fig. 6 A typical breeding blanket redrawn from [15]

experimental device which strives for CW operation with DT. This design principle is more approximate than the other three, and it may be possible to design thinner blankets. But remember that the scientific prototype will be operating at high duty cycle, and even small neutron leakage out the back of the blanket, can over time activate the material behind (e.g. the superconducting coils).

Hence the scientific prototype cannot be exactly like say TFTR because its major radius is only 2.6 meters, and the center is filled with all sorts of stuff (e.g. toroidal field coils, etc). Thus we must take a larger major radius. We take a major radius of 4 meters, like TFTR, but now leaving room for a 1.5 meter blanket. The minor radius is 1.3 meters, so as to keep the aspect ratio as in TFTR, and k = 1, that is a circular cross section.

In Table 7 are shown parameters of the scientific prototype, ITER, and large ITER, the latter two taken from Refs. (8 and 9). (Recall that for ITER and large ITER one takes for a the 95% flux surface, or 87% of the way to the wall along the mid plane.) The scientific prototype gives about the 55 MW of neutron power. If one takes the rule of thumb that actual tokamaks produce about half the power of the conservative design estimates, as with TFTR and JET, then the estimate of 20–40 MW seems reasonable for the scientific prototype. Undoubtedly this could be increased further by going to elongated cross sections, but to get both the current and q(a) would require a knowledge of the distribution of the current over the flux surfaces, and calculating that is beyond the scope of this work. However the current density and volume would both be larger, so with an elongation of a typical value like 1.6, one might double the neutron power.

Table 7 Parameters for proposed power producing tokamaks based on conservative design principles

Parameter	Sci. Prot.	ITER	Large ITER
B	5.5	5.3	5.7
R	4	6.2	8
a	1	1.7	2.4
k	1	1.7	1.8
q(a)	3	3.5	3
I	2.3	15	21
$n_o(G)$	1.1	2.4	1.7
$n_o(\beta)$	1.35	3.9	4.1
P(neutron)	55	1500	4000

The conservative design principles show ITER and large ITER both doing better than actual predicted design values. However if one takes the typical estimate that predicted neutron power is about double that achieved, large ITER gives about the design value, but ITER does especially well. It may turn out to do somewhat better than expected. It has higher current density than either large ITER or the scientific prototype. But despite this larger current density, since q(a) is 3.5 according to [8], the current could still be increased by about 15% and still remain consistent with conservative design rules, so power might be increased by 30%. Note that for both ITER and large ITER, the Greenwald density is considerably less than the beta optimized density, meaning that the ion temperature has to be considerably more than 15 (22 for the former, 36 for the latter). Thus they have to run in something like hot ion modes. TFTR and JET have both run in hot ion modes, but so far neither has been able to maintain those discharges for long times, and both ended in disruption or something quite like it. In any case, when quoting power levels expected for ITER and large ITER, we stick to those calculated by the designers, 400 MW and 1.6 GW.

To summarize, the conservative design rules are reasonably well based in theory and so far have constrained tokamak operation. In fact so far, as regards neutron production, a tokamak is doing well to achieve half the neutron rate specified by conservative design. To get powers like 3 GW, as needed in a commercial reactor, but in a tokamak smaller and less expensive than large ITER would stretch conservative design rules well beyond the breaking point. This then is the basis for the author's assertion that commercial pure fusion reactors based on tokamak configurations are unlikely, at least unless one can find a way around conservative design principles.

The Fusion Hybrid

The author has discussed the fusion hybrid and cited work on it in his earlier papers so this section will be brief. The main point is that while pure fusion looks very difficult via the tokamak route if constrained by the conservative design rules, hybrid fusion looks good.

There are two hybrid fusion reactions and two architectures for the reactor. The first architecture is fast fusion—a tokamak reactor is surrounded by ^{238}U or ^{232}Th and the fusion neutrons burn these in situ. The author has always argued against this, largely on safety and infrastructure considerations. The fusion reactor, which may be disrupting, is separated by a thin wall from a fission reactor containing hundreds of pounds of ^{233}U or ^{239}Pu. We have no experience with either type of reactor, but they must work seamlessly together. Ralph Moir has called it "an accident waiting to happen".

The second architecture, preferred by the author and others is called fusion suppressed. The fertile material is mixed in with a liquid or flowing blanket and the fissile material produced is separated out continuously as it is formed. It forms nuclear fuel for existing reactors, and therefore fits in much better with existing infrastructure.

Now consider the reactions. The first has a fusion neutron being absorbed by a ^{232}Th, ultimately producing a ^{233}U; the second has a neutron being absorbed by ^{238}U, ultimately producing ^{239}Pu. In either case, Monte Carlo codes are used to calculate the ultimate fate of a fusion neutron and all its progeny as it cascades through the blanket which contains thorium (or ^{238}U), lithium, neutron multipliers, shields, reflectors, and structural material. The output of the calculation is that the original neutron produces ξ ^{233}U's, λ tritons, and so much energy. For any fusion scheme to be viable, the number of tritons obviously has to be greater than unity. Over the years this author has taken as canonical figures those calculated by Moir [17] for a two zone blanket, the final entry being an engineered blanket (i.e. containing structural material). These calculations are summarized in Table 8. Other authors have calculated similar but different values.

While these calculations make some effort at a realistic geometry, even the simplest configurations such as shown in Fig. 6 are considerably more complicated than what is assumed in the calculations; more realistic geometries such as those shown in other references are more complicated still. Undoubtedly, when confronted with reality, the Monte Carlo codes will need some modification. Hence it is important to build up this experience as soon as possible. This is another reason the author has argued for the scientific prototype over the years. Right now there are no sources of 14 MeV neutrons, so no calculation of their behavior in particular blankets has been benchmarked.

Of the two reactions, the author has always argued for the thorium cycle based on proliferation considerations. In any hybrid scheme (and in pure fusion too for that matter if it is not used in the proper way), the pure fissile material output will always be a serious proliferation hazard and must be carefully monitored. However ^{233}U can be mixed immediately with ^{238}U in a subcritical mix, for instance 4% enrichment as with ^{235}U in today's fuels. At this point, the fuel has no proliferation risk without isotope separation, something well beyond the capability of terrorist groups and small countries. We could export the fuel, even to countries we did not fully trust, as long as they sent back the spent fuel for reprocessing.

However if ^{239}Pu is used and mixed with ^{238}U, the plutonium can be separated out chemically (as the North Koreans have done). The author has considered the advantages of ^{233}U so overwhelming as regards proliferation, that only this route is considered here and in the references.

Taking the numbers in Table 8, consider the output from a single fusion neutron to be 0.75 ^{233}U's and 1.1 T's. However when the ^{233}U is burned in a conventional reactor, it releases ~200 MeV. In other words the 14 MeV neutron produces fuel which releases 150 MeV when burned, as well as 35 MeV deposited in the blanket. If we consider large ITER and its 1.6 GW of neutron power, this translates into about 16 GW of ^{233}U, and does so with a wall loading of only ~1 MW/m^2. In other words, ITER, with rather moderate wall loading (by fusion standards) could generate enough fuel to power five 3 GWth (1 GWe) conventional nuclear power plants. In addition, large ITER itself is a reactor, now generating ~3.5 GWth or 1.2 GWe.

Other Simple Aspects of the Fusion Blanket

The fusion hybrid blankets discussed in the last section, as well as in the references, simultaneously breed T and ^{233}U. Hence at first blush, they might seem more complicated than a pure fusion blanket which only has to breed T. However, this is not so. If many fusion breeders are used in the world economy, some could be used to breed ^{233}U, and others to breed T. For instance, using Table 8, if there are 10 breeders, 6 breeding T and 4 breeding ^{233}U, then the 10 fusion neutrons produce 10.8 ^{233}U's and 11.4 T's; in other words they are more prolific than the single combined blanket. Furthermore, in a single breeder it might be possible to used a segmented blanket, 40% of which breeds ^{233}U, 60%, T.

However there is a much greater advantage to the fusion hybrid as far as the blanket is concerned, namely the neutron wall loading is much less. As we have seen, if large ITER is used as a breeder, a wall loading of 1 MW/m^2 is more than sufficient to breed a tremendous amount of nuclear fuel. As a pure fusion reactor, a much greater wall loading is needed and this is a tremendous engineering challenge. To run large ITER at 3 GWth (1 GWe), a standard power plant, the wall loading would be twice as great. But because of the large cost and size of large ITER, one would like a smaller reactor producing greater power; but this means greater wall loading still. For the demo, the FDF web site mentions wall loadings which might be as high as ~ 6 MW/m^2, and this represents an enormous engineering challenge as compared to the ~ 1 MW/m^2 for a large ITER run as a breeder, and the 1 MW/m^2 is itself no small challenge.

Thus if breeding both ^{233}U and T in a single blanket is too difficult, they can both be bred in separate or segmented blankets. More important, the required wall loading for hybrid fusion is nearly an order of magnitude less than for pure fusion. This should make the blanket problem very much simpler for hybrid fusion.

Cost Estimates and a Discussion of their Validity

There have been many estimates of possible costs of electricity produced by pure fusion starting with a design of some hypothetical power plant. We take a different approach here and base our estimates on the cost of ITER and large ITER; then we discuss very qualitatively how valid these estimates might be. The advantage of this approach is that at least at the starting point, it is grounded in reality. The world is already writing contracts for ITER and has carefully estimated the plasma performance. The same was true of large ITER when it seemed that it would be built. In all likelihood, these cost and performance estimates are reasonably accurate. As we have seen, the expected plasma performance is consistent with the conservative design principles.

On paper, it is easy to increase performance an order of magnitude, simply operate at triple the density or 9 times the power. The problem is that tokamaks do not operate with a β_N of 7.5 or at two and a half times the Greenwald density limit, at least not yet.

Let us review the costs of ITER and large ITER. ITER's total cost is $\sim$\$10B, about \$5B in construction and decommissioning, and 10 years of operation at about \$0.5B per year. It is expected to produce 400 MW of neutron power. Large ITER's cost is about double each of these, but it is expected to produce about 1.6 GW of neutron power. Although this latter power estimate is a little bit of a stretch based on large ITER estimates, it is convenient to think of large ITER as costing twice as much and producing four times the power.

Now let us see how these estimates translate into electricity costs. Since power plants are $\sim$30% efficient, ITER would generate $\sim$130 MWe and large ITER, $\sim$530 MWe. We will work with large ITER–ITER's cost would just be twice the cost per kWhr. Let us say that large ITER runs every year at its operating cost, or \$1B per year. Then let's say that the capital and decommissioning costs are spread over a 30 year life time of a typical power plant, bringing the yearly cost to \$1.3B, or about 25 cents per kWhr. The cost of electricity produced by ITER would be twice as much, or 50 cents per kWhr. Neither power plant is close to being economical. Even if large ITER could run at its full power as predicted by conservative design rules, $\sim$1.3 GWe, it would still be at best marginal as an economic power producer.

But now let us consider large ITER run as a reactor and fuel breeder. As we have seen, it produces enough fuel for 5 conventional 1 GWe light water reactors (LWR's). But this cost includes not only the cost of fuel, but also the cost of running large ITER a reactor. This brings the fuel cost down to less than 2.5 cents per kWhr, let us estimate a fuel cost of 2 cents per kWhr. By contrast, gasoline at \$1 per gallon is about 2.5 cents per kWhr for the raw fuel, but if used to power a 30% efficient power plant, the fuel cost becomes 7.5 cents per kWhr. Using large ITER estimates, the fuel cost is rather low.

But how accurate are the ITER cost estimates when applied to a real reactor? Now we turn to only qualitative estimates. There are several reasons to believer the costs will be lower, several to believe they will be higher. We start with the former. As obvious to anyone in the fusion business, ITER is model number 001; as one learns more, builds up experience and can exploit economies of scale, the costs should go down. Secondly ITER is an experimental device, operated by many highly paid scientists. However a commercial reactor has to operate mostly in the mode shown in Fig. 7, and this should also reduce costs.

But it seems to this author that there are even more reasons to believe costs will be higher. First of all, ITER will run perhaps 1–2 shots per day of 10–20 min each. A power plant has to run CW, or with a duty factor of at least 80–90% to be at all viable. This will undoubtedly raise the cost considerably. Secondly, ITER is an experimental

Fig. 7 Necessary mode of operation for a commercial fusion power plant

device. As anyone who has ever run one of these knows, they are plagued by large amounts of down time. A commercial power plant will have to be engineered with much higher reliability than an experimental device, and this will also increase the cost. Note however that a fuel factory can tolerate much greater amounts of down time than a reactor which produces electricity. Third, for a commercial power plant, capital costs are not given by the government; the utility must borrow from the commercial sector. At an interest rate of 6%, the \$0.3B per year capital cost becomes \$0.6B per year. Finally there is the question of tritium. Little is said about this in the literature, but ITER or large ITER will have to either breed it or buy it. For commercial fusion of course, breeding it is the only option. While this is discussed little, the cost of the tritium is presumably figured into the total cost of ITER. However tritium will not be used for the first few years of operation, whereas in a power plant it will be used from day one. This should increase the cost somewhat as well. Of course for hybrid fusion, there is the additional cost of breeding the ^{233}U which is not included in ITER or large ITER estimates.

It is impossible for this author to be any more quantitative, but it does seem to him as though the cost is likely to be more rather than less. Perhaps the fuel cost for the hybrid would be in the range 3–4 cents per kWhr, rather than 2 cents. This is larger, but still a reasonable and affordable estimate. Direct pure fusion power from large ITER would likely go up to 40–60 cents per kWhr (or 20–30 cents/kWhr if it could run at full power as predicted by conservative design rules). An initially unaffordable rate gets more expensive still. If these estimates are reasonably correct, pure fusion based on tokamaks will never be affordable for large ITER sized devices. However hybrid fusion likely will be. But however these additional factors play out in serious cost estimates, the original starting point of the estimates, ITER costs, are based in reality.

Let us finally estimate the cost of the scientific prototype in terms of ITER cost scaling. Large ITER is an eight meter machine costing \$20B; ITER is a six meter machine costing \$10B. This gives rise to a scaling of $\$ \sim R^{2.5}$. The scientific prototype has a 4 meter radius, so its estimated cost is ~\$3.5B. The fusion base program is ~\$0.25B per year, so 15 years (about the time to do a large fusion experiment) of the base program is more than enough to build and fully investigate the scientific prototype. Furthermore, by offering up a large part of the base program, the American government might well enhance the total program. Of course there will be loud objections that the base program cannot possibly be reprogrammed; it is being starved enough as it is. First vastly increase it, and then worry about adding 'scientific prototypes' and the like. But given the fiscal realities we all operate under, the rapidly approaching energy deficit, and the fact that numerous attempts to sell a burning plasma all failed; really, what else is there to do?

Review of the Energy Park

This author's vision for sustainable world development, the 'energy park' is sketched in Fig. 8. It was discussed much more fully in [5] and [7]. The case was made there that it could produce large scale power by mid century. The basic module is a nuclear reactor, for instance an LWR which generates 1 GWe. Five of them are in the park. These are the best nuclear reactors that can be developed, perhaps

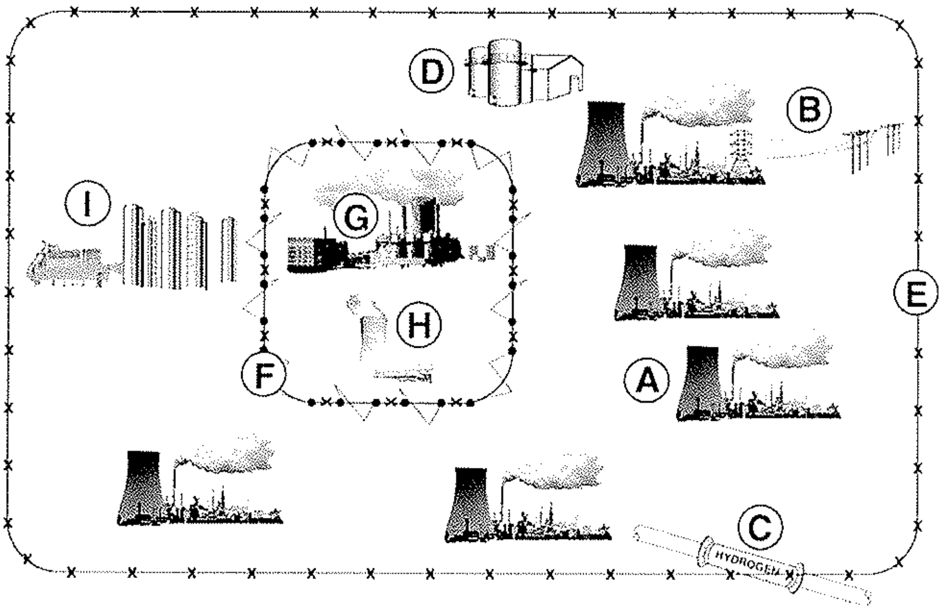

Fig. 8 The energy park, A. A 1 GWe nuclear burner, B. electric power line out, C. Hydrogen pipeline out, D. Cooling pools for highly radioactive waste, E. Low security fence, F. High security fence, G Separation facility, H. Plutonium burner, I. ITER sized fusion plant producing a total of 1.5 GW fusion power and an additional 2 GW in the breeding blanket

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. Yearly, each reactor is fueled with about one metric ton of ^{233}U mixed in with about 24 metric tons of ^{238}U. As waste, each year the reactor produces about 750 kg of highly reactive material, material with half life of 30 years or less; about 200 kg of plutonium and other actinides, and about 50 kg of much less active radio active waste, material like ^{99}Tc with a 200,000 year half life (5 and Refs therein). Except for the few hundred kg converted to actinides, the 24 metric tons of ^{238}U just go along for the ride.

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 5 LWR's each produce ~200 kg of plutonium and higher actinides yearly, so these fuel a sixth reactor of the same size that we call the plutonium burner. It produces electricity for the grid.

Assuming the long and short lived radio isotopes can be separated from one another, the short lived ones go to cooling pools where they would remain for 10–20 half lives; 300–600 years. While this is a long time, it is a time for which human civilization can reasonably plan, not the multi hundred thousand year time span for say Yucca Mountain, which also stores actinides, which constantly build up the activity and heat load. Already cooling pools on reactor sites have held the waste products for 40 years, and these also store the plutonium and higher actinides as well. It should be simpler for the cooling pools envisioned here which would not store actinides.

The long lived radio isotopes go to the tokamak for transmutation. [5] estimated 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. 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. We discuss this in the next section. 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. Experience is also that power from these is less costly than from fast neutron reactors.

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 included 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.

Other Aspects of the Energy Park

It is very interesting that a facility very much like the energy park exists today. It is the Kashiwazaki-Kariwa nuclear plant complex in north western Japan. It is a suite of seven nuclear reactors, located near one another, and has the capability of generating about 8 GWe. To turn this into the energy park, all one would need to do is replace one of the reactors with the fusion reactor which supplies them all, replace one of the other reactors with an actinide or plutonium burner, and add a reprocessing facility. The cooling pools are undoubtedly already on site. The existence of this complex serves to emphasize that the energy park does fit in very well with existing infrastructure.

Let us discuss further the actinide burner. Most nuclear authorities seem to think this has to be a fast neutron reactor, and this certainly might be so. 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 much less net plutonium burning because as plutonium atoms are burned, more are created from the ^{238}U. This is the way the French use recycled fuel in their commercial nuclear program. While they burn the plutonium for fuel in their thermal reactors, they are also regenerating it from the ^{238}U fertile material. They burn it, but they produce it too.

On the other hand, plutonium does not have a large absorption cross section for fast neutrons, so in a fast neutron reactor, actinides only burn. But one might still be able to use a thermal reactor as the plutonium burner. If the fertile material is not ^{238}U, this problem may not apply. It may be possible to use ^{232}Th as the fertile material.

There will still be neutron absorption reactions in the plutonium, so it will build up higher and higher actinides. However there is no source of additional plutonium. As higher actinides are formed, they also burn, so the burning of the plutonium will be much more complete than in a thermal reactor with ^{238}U as the fertile material. The fertile thorium does not build up higher actinides nearly as easily and in fact it would produce fuel ^{233}U fuel for the other reactors. Burning plutonium then is something the world might be able to do with today's thermal neutron reactors, and in the process, would also be building up a supply of ^{233}U, a nuclear fuel which in this author's view is the best long term fuel. It seems that this would be something very useful for the nuclear industry to further examine, possibly with government support.

Let us discuss further the cooling pools. When spent fuel is extracted, standard chemical processes such as PUREX and UREX can extract virtually all (more than 99%) of the uranium and actinides and can also separate the uranium from other actinides. What are left are the radio isotopes, both long and short lived. If the long lived ones can be economically separated out, and transmuted with fusion neutrons, it would be desirable to do so [5].

The short lived radio isotopes would then be put into a cooling pool. Each year, more material would be added, and then after some period of time, maybe 10 years, maybe 50, the pool would be sealed off and left to decay. New radioisotopes would be put in the next pool. The first pool would then cool down for 300–600 years until the waste becomes inert and harmless. Of course there might still be a small amount of actinides and long lived waste mixed in, so a geological repository might still be necessary. However if the waste is treated this way, the repository would not be necessary for hundreds of years. The amount it would have to store is so small that a single Yucca Mountain is probably sufficient to serve the entire world for centuries. Furthermore, after being recycled through the reactor several times, the small amounts of plutonium remaining would have so many different isotopes and actinides mixed in, that in the repository it would hardly constitute a proliferation hazard at all.

Let us conclude by discussing tritium. Taking the estimates from Table 8, each fusion neutron produces 1.1 triton. Assuming 95% of the reactor wall is covered with the breeding blanket, and 95% of that tritium is recovered and inserted back into the fusion reactor, no further losses are tolerable. For instance one could not store the tritium for say 6 months before using it, because another 3% would be lost due to natural decay.

Table 8 Calculation of material produced by a single 14 MeV neutron in various blankets, taken from [17]

Blanket	ξ	λ	E(MeV)
^{232} Th (Homogeneous)	2.5	0	50
Natural Li (7.5% ^{6}Li)	0	1.9	16
^{232}Th + 16% ^{6}Li	1.3	1.3	49
^{9}Be + 5% ^{232}Th	2.7	0	30
^{232}Th and Li (engineered)	0.73	1.1	35

An intriguing issue is whether the LWR's could help with the tritium supply. Fortunately there is some data on this. In order to insure a tritium supply for our nuclear deterrent, the Department of Energy is starting production of tritium at the TVA Watts Barr nuclear facility (Google TVA Watts Barr nuclear power plant). To produce the tritium, some lithium is introduced into the moderators. In the course of burning ~1 metric ton of nuclear fuel, ~3 kg of tritium are produced. In other words, for every four nuclear reactions, one triton is produced. There is a small cost penalty, but no power penalty.

Recall that one fusion neutron produces about 0.75 ^{233}U's, so four of these might produce one triton. If all the LWR's are operated in this mode, the 1.1 tritons produced by the fusion reactor become something more like 1.25 tritons produced by the totality of all reactors, and this could be an important reserve. Depending on the tritium economy, perhaps all LWR's in the park would have to be run as tritium producers, perhaps none. What is interesting is that the fission and fusion reactors now become truly symbiotic. The fusion reactors produce fuel for the LWR's, and the LWR's provide a safety margin for the tritium, which might be needed to keep the fusion reactor running.

Conclusion

For the prosperity and well being of all its inhabitants, the world needs a great deal of energy by mid century. Indeed civilization depends on it. Preferably this energy should be carbon free. The options are few. Can magnetic fusion play a role? For the last four decades, tokamaks have been the best magnetic fusion has to offer. But given conservative design rules, and simple cost estimates, a tokamak pure fusion reactor will at very very best, be marginal. Real life tokamaks do considerably worse. Hence it is very unlikely that they will ever make it as commercial reactors no matter how successful the confinement. Their size and cost are too large, and their power production, too small. However they do have great promise as hybrid fuel producers. In the author's opinion, the focus of the tokamak program should be shifted toward hybrid fusion.

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