Thoughts on Future MFE Program.

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Introduction

I'm going to stick my neck out and be blunt about what I understand are the realities of the fusion options and from that indicate possible priorities for a future program. I will assume that the purpose of the MFE program is to develop a viable fusion energy source and not to permanently study the plasma physics. Physics understanding can define the box in which a reactor might be crafted. It is necessary but, given there is a box of finite volume, it is not then the main problem for realizing fusion.

In 1956, Bas Pease, later director of the UK fusion program made the following comment, "…Our vision is of a power station, sited perhaps on the coast, with a pipe bringing water from the sea, helium leaving by the chimney and electrical power flowing into the grid. We do not know what to put inside the power station (laughter)…"

We've come a long way since then, baby, with tremendous progress across the board, and real prospects for significant gain in ITER but we should not forget four important points:

- Operating steady state or repetitively pulsed at high power density has never been demonstrated, and could be a fundamental obstacle to achieving a viable reactor.
- High availability will be difficult to achieve in a complex fusion reactor, and there is essentially no data.
- As identified in the charge, with D-T reactors, the challenge of developing radiation-resistant materials may be greater than producing net energy. Thick liquid "lithium" walls are only a practical alternative for options that are in some sense cylindrical (spherical).
- The ultimate fusion fuel is deuterium, and it may be possible to reduce wall damage issues by removing some of the tritium produced by D-D before it decays.

Generic Considerations

A lot can be understood through system studies. Many decades ago my colleagues and I produced the paper "Cost Assessment of a Generic Magnetic Fusion Reactor," Fusion Technology, 9, 2, 1986. The methodology, notably Jerry Delene's costing model, was used by John Holdren in his ESECOM fusion study. The main points, only D-T was considered, were that, although challenging, there was no absolute reason an MFE reactor could not be viable, and more or less, all MFE reactors are the same.

I am in the process of updating the original paper and have found some interesting trends in U.S. and European systems studies:

- Magnetic fusion reactor studies over recent decades have shown a steady decrease in their neutron wall loading e.g., the U.S. ARIES-team studies: http://aries.ucsd.edu/ARIES/ and "The EU power plant conceptual study, "G. Marbach, I Cook, D. Maisonnier, Fusion Engineering and Design, 63-64, 1, 2002

From: "Sheffield, John" <jsheffield@utk.edu>
Subject: RE: White paper
Date: July 17, 2012 8:25:47 AM EDT
To: Robert Rosner <rrosner@ci.uchicago.edu>

Bob:
I should have added words of clarification on possible roles for the U.S program in stellarators. The wealth of options includes many coil configurations from the continuous helical ones of the Japanese LHD to the intestinal looking ones of W VII-X (NCSX). The challenge is to find the simplest coil set that will achieve good confinement at high beta with a workable divertor. The question is what one can get away with. In this regard, important contributions can be made (albeit at lower beta) by small stellarators with electron cyclotron heating, such as the one at U. Wisconsin (I hope it's still funded). If we can't build a big device this experimental area, this is a good opportunity for small university programs to do good science.
Best regards,
John.

- I suspect that this is partly because the development of radiation-resistant materials has progressed more slowly than anticipated, and designers are more cautious about assuming how long a blanket might last, and what power flux they could handle.

- These studies, with good reason, generally assume higher thermal-electric conversion efficiency.

- Unit costs have gone up by more than inflation—a part of the reason for the increase in ITER costs.

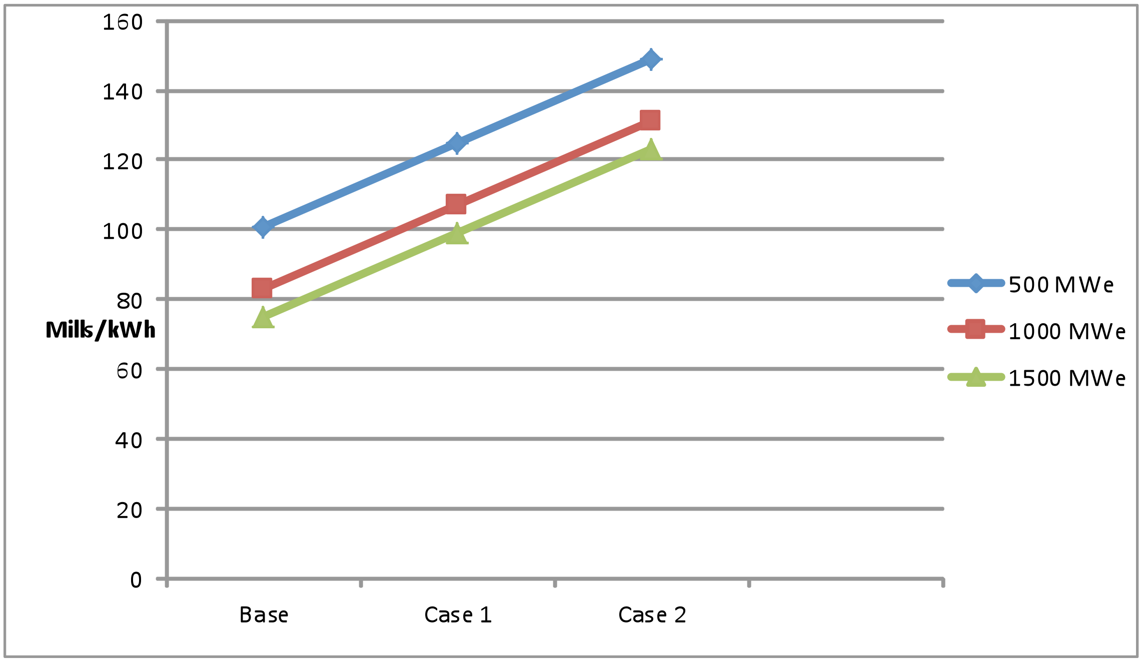
The importance of the 7 bullets above enters into the cost of electricity (COE) in the following manner:
COE = Const.[$C_{cap}F_{CR0} + C_F + C_{om}$]/[$P_e$ x 8760 x f_{av}] + annual waste disposal

$C_{cap}F_{CR0}$ = Capital cost (including interest and owners cost) x fixed charge rate e.g., 0.1.
C_F = "fuel" costs, i.e., deuterium + annual replacement costs—blanket, targets, etcetera.
C_{om} = annual operations and maintenance costs.
P_e = net electric power.
8760 hours in a year.
f_{av} = availability (capacity factor)

- The capital cost depends strongly on the construction time, which in turn depends upon the complexity of the system.
- The "fuel" costs for a given fusion power and component lifetime are more or less independent of the chosen wall loading (MW/m^2), but the availability will be impacted if more frequent replacement is required.
- As to operations and maintenance, one can learn from fission reactor experience, and there may be a moderate inverse dependence on fusion power or net electric power.
- Obviously, the COE goes down strongly as the net electric power is increased, but the costs go up with increasing fusion power so it is important to minimize the recirculating power.
- As to the availability, this is by far the least known of any parameter in the COE formula. I suggest that achieving high availability i.e., > 0.80 will be the greatest challenge for a fusion reactor. The availability of a system depends upon the failure rate of its components and the time to repair or replace them, and there is hardly any data on reactor fusion systems.

The reason I have gone through this is to help understand the relative importance of the various MFE options.
As pointed out in previous FESAC reports there are two main categories:
External control—tokamak, stellarator, and RFP.
Self ordered—FRC and spheromak.
All are toroidal, but in regard to reactor configuration, the former are toroidal, the coils go through the center of the plasma. The later are either cylindrical or spherical—the coils do not go through the plasma.

From a generic point of view, for a fixed fusion power, net electric power, input power to the plasma production, and 14 MeV flux on a solid blanket, the base COE of toroidal, cylindrical or "spherical" is the same, see figure above. By base I mean everything other than the magnets and, where needed, plasma compression systems; i.e, the volume of blanket and shield is similar, the size of the buildings, hot cells, heat transfer systems, generators and BOP are the same or similar. This is illustrated in the figure for an example case, where the additional COE for an extra 1 and 2 $B base capital cost is also included to allow for the left out magnets and where needed compression systems. As in the original study this points out that to first order all MFE reactors are the same. The devil is in the details. The point of presenting this analysis is to make the point that it is the detailed virtues of a particular approach that really matter, and use this to lead into a logic for the program that goes in parallel with ITER.



The base costs are for toroidal, cylindrical or spherical systems, excluding magnets and compression systems. Case 1, allows for an additional 1$B in initial capital cost, i.e., before interest and owners costs. Case 2 is for 2 $B. Don't get hung up with the mills/kW.h. It's the relative values that matter.

This example uses the following parameters:

P_F= 2250 MW, p_{wn} = 3.0 MW.m^{-2}, A_w = 600 m^2, a_w/a = 1.10, 0.5($\Delta_{bgs1} + \Delta_{bgs2}$) = 1.5 m, g_n = 1.15, P_{aux} = 50 MW, P_{th} = 2570 MW, η_e = 0.45, P_{eg} = 1157 MW$_e$, f_{rec} = 0.136, P_{enet} = 1000 MWe, f_{av} = 0.80, and 6 years construction time.

Toroidal system

R/a = 4.0, κ = 2.0, a_w = 1.63 m, R = 5.91 m, volume of blanket and shield V_{bsg} = 1117 m^3.

Cylindrical system

a_w = 2.5 m, L = 38 m, leading to V_{bsg} = 1170 m^3.

Spherical

a_w = 6.91 , leading to V_{bsg} = 1109 m^3.

1. I expect some people will say," But in my system I can do something for less." Maybe, but if it is something generic like the radial build of the solid blanket and shield, or operation at higher power density then, presumably it would apply to all the systems.

2. While lower electric power may be desirable, it is hard to see (generically) how, with limits set by 14 MeV neutrons, it could have the same, let alone lower COE than at higher P_e.

3. The above analysis is for a solid blanket. On its own, it does not allow one to choose among any of the configuration options that have a finite enough physics volume to permit a viable reactor to be considered. Therefore we should consider the additional features for each option, for a given field on the main coils what is the value of beta x B_{plasma}^2 (a measure of the fusion power density), what is the divertor? recirculating power, a ease of maintenance. It is factors such as these and a genuinely lower cost for the components of the fusion island beyond that assumed in the base calculation that will help us make a decision on an optimum path(s).

My bias is that a stellarator, among the externally controlled systems, will turn out to be the best solution, because it has similar physics properties to a tokamak, doesn't suffer massive disruptions, and has the lowest recirculating power of any system. But I have concerns about the divertor possibilities. The tokamak is a fine workhorse for the present to test the plasmas and nuclear technologies, but unless the possibility of disruptions can be guaranteed it ain't a power plant.

I have this imagined a scene in which tokamak salesmen go in to see power plant executives. The executives are excited about the prospect for new, clean, reasonably economic power. Then one of the proponents says, "Incidentally, it may switch off periodically." (I don't think he even needs to add, "and blow a hole in the wall." An executive shouts out, "You mean at 5 o'clock in the evening?" "Could be." "Don't call us we'll call you."

A problem for choosing a stellarator option is the sea of opportunity in magnetic configuration space as compared to the line for tokamaks. This is illustrated in a figure I created for the 1988 IAEA fusion meeting.

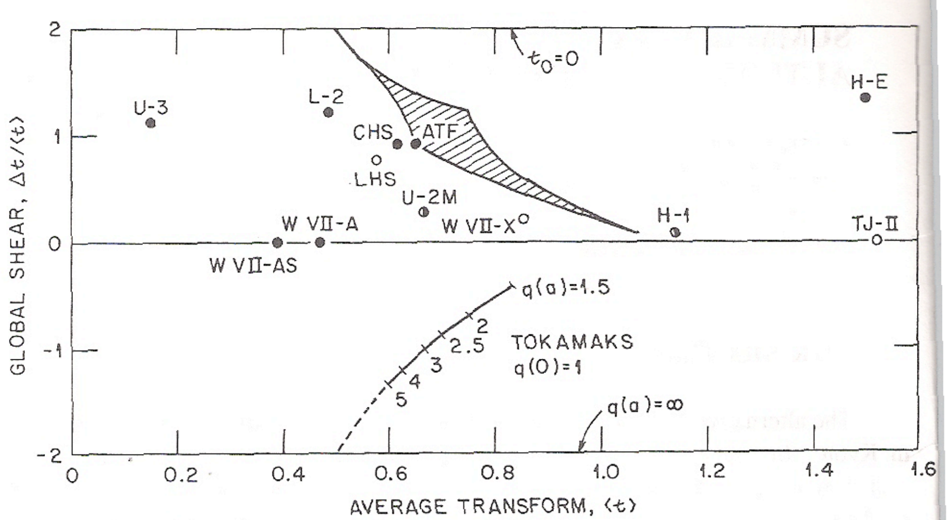


FIG. 1. Shear versus central rotational transform, showing the operating region for a number of existing and proposed stellarators and for the tokamak configuration.

It's a pity the NCSX didn't go ahead. It would have helped fill in some gaps. In its absence it will be important for the U.S. to be deeply engaged in the foreign programs, and use our theoretical and computational strengths to refine our understanding of where the optimum configuration might lie. Particularly important is to find the simplest coil configuration(s) that lead to good confinement and beta, robust flux surfaces, and a credible divertor.

As to the spherical torus, I suggest that it can be a great vehicle for a Fusion Test Facility, because of its open structure and acceptable plasma parameters. But as a reactor with a thick inboard shield it suffers from a relatively lower level of beta.B^2 compared to a conventional tokamak, for a given field on the toroidal coil. Also, as a copper coiled system it's recirculating power is uncomfortably high.

The RFP has interesting physics as a complement to the other systems, but unless some clear way can be found to make it ultra-long pulse or steady state I don't see it as a reactor.

This brings me to the compact tori and in particular the FRC. It's hard in MFE to ignore an achieved beta of 60 to 90 %, and has the highest beta.B^2. However, there is an issue of the plasma lifetime, which needs to be resolved. Assuming that encouraging data signs from colliding FRCs continue. See, "Creation of a high-temperature plasma through merging and compression of supersonic reversed field configuration plasmoids," J. Slough et al,. Nucl. Fusion, 51, 053008, 2011, the MFE program should be placing more emphasis on this area. However, for D-T systems and solid blankets, as explained above, it is not obvious to me they could lead to an interestingly lower COE, unless the capital costs of their magnets and compression systems are way cheaper and their recirculating power is low.
I believe that their main importance comes if radiation-resistant materials damage turns out to severely limit solid blankets, and thick liquid walls become more important. An important COE issue will then be the achievable repetition rate. Anyway, I would increase R&D in this area, and support independent systems studies to get broader agreement on the virtues of this approach. I'll come to non-DT fuel below.

Availability

It is critical for the program to do more analysis of what will be required to achieve a useful availability for the reactor e.g., ≥ 0.80, and relate it to the development of the plasma and nuclear technologies. The level of R&D for technologies is woeful, except for those related to ITER (and there we only do a part of the supporting program). Experimental successes over the past decades have depended strongly on earlier plasma technology developments (including diagnostics); the future isn't going to be different. I suggest that the imbalance between R&D on these technologies and confinement experiments needs adjusting.
A Fusion Test Facility is essential, operating in parallel with ITER to provide the data base on component (and sub-system) performance and availability as we proceed to a DEMO. ITER does not have the power density or duty factor to do the complete job. Such a test facility could be more than one facility with different ones focusing on different issues e.g., while many issues relate to the 14 MeV neutrons there are others that relate to high heat load and plasmas impinging on material surfaces.

Alternative Fuels

When we talk about fusion fuel being limitless, we are referring to deuterium. While D-^{3}He and p-^{11}B are intriguing, I believe that a catalyzed deuterium reactor should be the ultimate goal. The challenge for this fuel as for other alternates to D-T is the higher average temperature ≥ 35 keV required couple with better confinement and of course higher beta x B^2. But it is not out of court for tokamaks, stellarators and FRCs (assuming for all the their best simultaneous physics parameters are achieved. One possibility with a catalyzed D-D reactor that would alleviate the neutron-materials problem would be to remove as much as possible of the tritium produced before it burns. The stored tritium would decay to ^{3}He to be recycled, see figure below.

"Impact of tritium removal and He-3 recycling on structure damage parameters in a D-D fusion system", M.E. Sawan, S.J. Zinkle, and J. Sheffield, Fusion Engineering and Design, 61-61, 561, 2002.
"Energy "Deuterium-Fueled Power Plants with Tritium Suppression", John Sheffield and Mohamed Sawan, Fusion Science and Techology, 780, 2008.

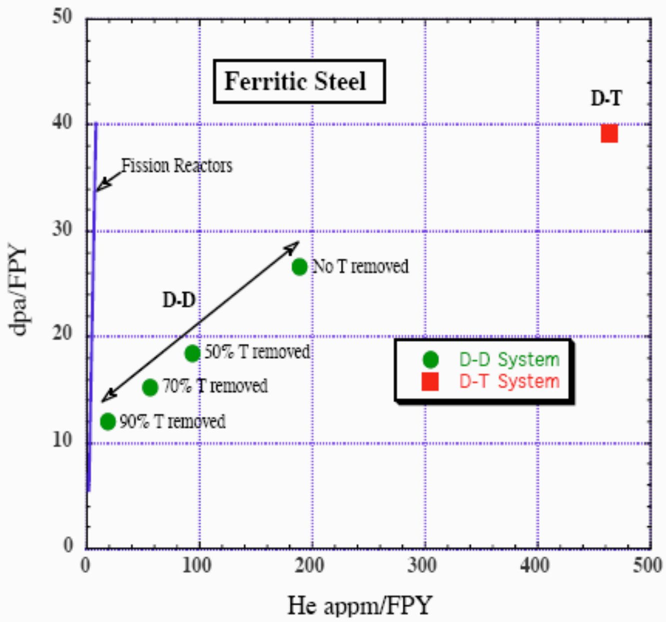


Figure I. dpa and He production rates in ferritic steel for D-T and D-D systems for the first wall of a ferritic steel/H_2O shield.

This approach appears to be a possibility for tokamaks and stellarators, and in batch-burning systems such as compact tori and inertial fusion energy. Of course, in the latter two cases, thick liquid lithium walls might provide a solution to the neutron problem.

Summary

While supporting ITER so we can capitalize on it, we should look to the future and put more emphasis on the stellarator and FRC. While paying more attention to materials issues, we should look at other options that could use tritium-suppressed deuterium or liquid walls. We should put effort into developing options that would be more readily maintainable. R&D for diagnostics, and plasma and nuclear technologies, is woefully underfunded and should be increased. An FTF of one kind or other is needed as a complement to ITER to spur component development in "steady state" and nuclear conditions.

I note, finally, that the MFE program continues to make important advances every year, and I am convinced it will lead to a viable fusion reactor. Sometimes, with all the rhetoric from proponents of this or that configuration, it is hard sometimes to see the commonality in development needs for all the potential approaches. Nevertheless as the old joke goes, "I'm sure there's a pony in there somewhere."