Energy Futures: An Alternate View

Energy Issues Subgroup A
Submitted by R. A. Nebel
Los Alamos National Laboratory

Introduction

In order to be economically competitive a fusion or fission reactor must have the following characteristics:[1,2]

1. COE in the range of 20-40 mils/kWhr.
2. Unit size of 300 MWe or less.
3. Capital costs must not be the dominant component in the COE.
4. Construction times less than 1 year.

The vision for fusion that emerged at Snowmass is quite different:

1. COE in the range of 75-85 mils/kWhr with hoped reduction to 50 mils/kWhr.
2. Unit size of 1000 Mwe or larger.
3. Capital costs are the dominant component in the COE.
4. Construction times > 4-6 years (i.e. comparable to fission).

Simply put, the fusion vision of the future is incompatible with the deregulated power industry that the public has requested and is now on the immediate horizon. In order for the Snowmass vision to be tractable, the following must happen:

1. Large increases in the costs of fossil fuel due to restricted supply.
2. Heavy government regulation of fossil fuels either via a carbon tax or required carbon sequestration.
3. Re-regulation of the utility industry (i.e. guaranteed market through regulated monopolies) to allow for larger unit size and longer lead time technologies.

If the American public knew that this is the future fusion has in mind for them, I doubt if they would be very supportive of the program. I believe we can and must have a better vision for the public than this Carteresque view of the future. We must not lose sight of the fact that the American public has paid the bills for this program for the last 45 years and they expect and deserve a more positive vision for the future than the Snowmass vision. In this paper I will lay out how we can make our vision compatible with the deregulated utility future.

Conventional Systems

The single best predictor (but certainly not the only predictor) of economic performance for a fusion system is the mass power density. For a conventional system (see figure 1) this can be expressed as:

(1)
$$\mathbf{MPD} = \frac{\eta P_{elec}}{2\pi A \rho G}$$

where P_{elec} is the total power, η is the total efficiency (including the recirculated power), A is the Aspect ratio, ρ is the mass density of the blanket and shield, and G is the annulus geometry factor. G is defined as:

(2) $$\mathbf{G = a(2at + t^2)}$$

where a is the radius to the blanket and t is the combined blanket and coil thickness. The plasma wall load can then be expressed as:

(3) $$\mathbf{P_{wall} = P_{elec}/(4\pi^2 Aa^2)}$$

where P_{wall} is the wall load, and A is the Aspect ratio.

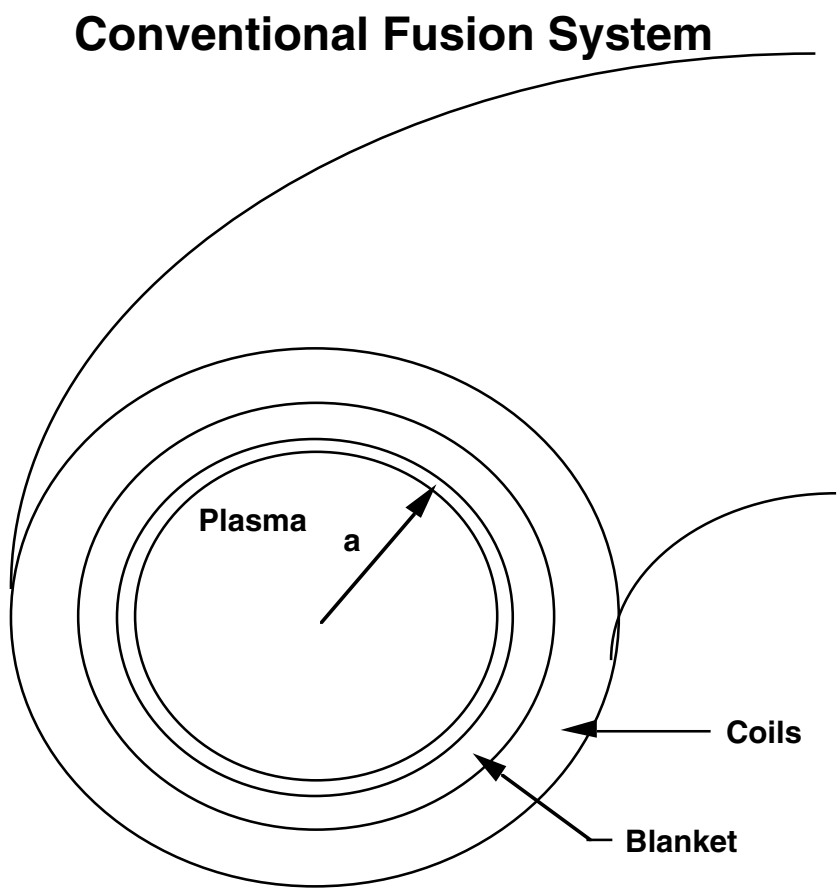

Fig. 1: Conventional fusion system showing a plasma (of radius a) surrounded by a blanket and coil set (of combined thickness t)

The most recent design corresponding to this geometry is the Aries RS design. This is a 1 Gwe Advanced Tokamak design that has COE in the 75-85 mils/kWhr range and a wall load of about 4-7 MW/m^2. Total cost of the fusion power core is roughly 50% of the total plant cost. In a well designed current generation LWR, this number is about 10%. Thus, Aries RS requires about a factor of 5 improvement in its MPD (I'm being generous) in order to be competitive. When this is coupled to a factor of roughly 3 penalty taken (I'm being generous here, too) by lowering the unit size to 300 Mwe, one concludes that the geometry factor (G)

must increase by roughly a factor of 15. This translates to a required wall load of 70-1050 MW/m^2 total wall load requirement, depending on whether the plasma radius is much smaller than the blanket thickness. Typical LWRs and coal plants operate with wall loads of about 0.5-1.0 Mw/m^2. This leads to a couple of conclusions:

1. When the plasma radius gets smaller than the blanket thickness, the effect that increasing the wall load has on MPD and COE show rapidly diminishing returns. Getting a competitive MPD is a very difficult proposition for a conventional fusion system, particularly at small unit size.

2. When it comes to economics, fusion technology is the "dog" and the specific confinement system is the "tail". The economic leverage is in the wall load and the recirculated power, not in the plasma parameters. At present we are spending a lot of resources studying various confinement systems and almost nothing on fusion technology. Twenty years from now we are likely to discover that our advanced confinement system does not produce significantly better performance than today's Tokamak and we'll end up tacking a beautiful tail on a really ugly dog.

Modular Systems

Now let's suppose that we divide the plasma region in figure 1 into several individual plasma chambers (see figure 2) sharing a common coil set. In this case the relationship between the wall load and the total power (equation (3)) becomes:

$$\mathbf{P_{wall} = FP_{elec}(r_{tube}/a)/(4\pi^2 Aa^2)} \tag{4}$$

where F is typically a number between 1 and 2, and r_{tube} is the radius of the individual tubes. I have referred to this device as the RFP Modular Reactor because this particlar scheme will not work for Tokamaks since each tube has A ~ 50. Indeed, I can see methods one might employ to use similar schemes for RFPs, Spheromaks and Electrostatic Confinement, but I haven't yet figured out how to use a similar geometric trick for Tokamaks, Stellarators or FRCs.

The principal advantage of the modular systems is that they allow the attainment of high mass power density without requiring enormous wall loads. Modularity principles are also what allows fission to reach high mass power density with reasonable wall loads. However, there are a number of caveats relating to such systems for fusion applications.

First of all, these systems may require advanced fuels to reach their full potential gains in mpd. If a 14.7 Mev neutron can penetrate several tubes, then the modularity effect may not significantly reduce radiation damage. We may need to introduce coolant/moderators between the coolant tubes. Secondly, it isn't clear how to load balance the tubes. Should they be run simultaneously in steady state or pulsed?

Finally, reducing the cross-section can put severe requirements on transport. Table I shows typical parameters for a modular RFP reactor (MR RFP-1) compared to the Titan reactor design and 2 previous RFP experiments. Using conventional RFP scaling laws, one cannot provide adequate confinement to satisfy the Lawson criterion. However, if the confinement is classical then not only can the Lawson criterion be achieved but the device can also achieve ignition by ohmic heating alone.

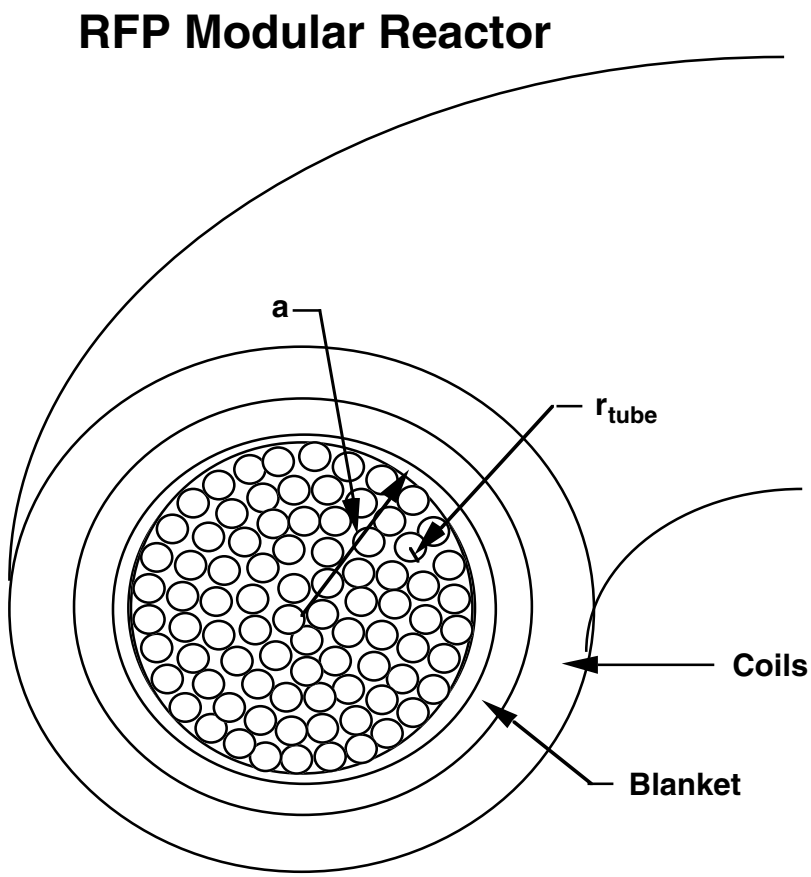

Fig. 2: Modular RFP fusion system showing several plasma chambers (of radius r_{tube}) surrounded by a blanket and coil set (of radius a and combined thickness t).

Although such improvements in confinement will probably not be easy, attaining them may be possible. The best hope for this is that the modular RFP devices have very strong two fluid effects, as evidenced by the magnitude of $1/(\omega_{ci}\tau_A)$. Two fluid effects offer a second avenue of relaxation through the Hall effect[3] and also can introduce large shear flows (Alfvenic) into the equilibrium induced by the nonlinear effects of the instabilities.

Although quasi-neutral devices may be problematic for this type of approach, it is a natural for electrostatic confinement machines. For the oscillating plasma (POPS) scheme the total power scales inversely with the plasma radius so smaller devices have an advantage over larger ones. Figure 3 shows a conceptual Penning Trap reactor[4] which has a large number of cm sized cells placed end-to-end like beads on a string. This particular device has a mass power density and wall load comparable to an LWR.

Conclusions

From the above analysis it is obvious that the principal economic leverage for conventional systems is on the technology side, not on the confinement side. Advanced wall technologies are essential if conventional fusion devices are going to be economically competitive in the deregulated utility environment. Although we can see our way through a lot of the confinement issues facing conventional fusion systems, very difficult technology problems remain.

Machine Parameters

Parameter	Titan	MR-RFP-1	TPE-1RM	ZT-40M
Neutron wall load (MW/m**2)	18	1.8	-	-
Thermal wall load (MW/m**2)	4.6	.46	-	-
a (cm)	60	6.0	9.0	20
<n> (cm**-3)	8.9x10**14	8.9x10**14	3.0x10**13	1.75x10**13
T (eV)	(10-20)x10**3	(10-20)x10**3	600	200
I/N (Amp-cm)	1.79x10**-12	1.7x10**-11	1.7x10**-11	5.45x10**-12
I (Amps)	17.8x10**6	1.7x10**6	130x10**3	120x10**3
β_θ	.23	.25	.35	.10
$\frac{1}{\omega_{ci}\tau_A}$	.02	.201	.73	.43
a/r_i	222	21.3	3.28	11.8
a/r_α	19.0	1.79	-	-
S (Z=1)	2.67x10**9	2.6x10**8	5.3x10**7	3.6x10**5
V_{Dr}/V_A	.04	.40	2.62	0.77
$\frac{aV_A}{\mu}$	6.51x10**8	3.5x10**7	8.4*10**7	2.89x10**8
τ_{eclass} (sec)	5.375x10**3	49.1	.412	1.37

On the other hand, modular fusion systems appear to have tractable technology problems, but much uncertainty remains on the plasma confinement physics. Confinement for quasi-neutral systems must improve significantly over the present data base to make these devices viable. Electrostatic confinement appears to offer a solution to the transport problem, but there isn't an experimental data base to support these beliefs.

This is just one example of how different concepts may offer significantly different reactor manifestations and pathways to economical fusion power. The modular pathway appears hold more promise for some fusion concepts than others. Not all fusion reactors are generically the same as conventional systems.

From the economic fusion power perspective, it isn't clear which of these pathways (conventional or modular) to fusion is the most likely to succeed or even which one is further advanced. One pathway has difficult technology problems to solve and the other has difficult physics questions to answer. What is clear is that our present procedure of evaluating fusion devices concept by concept is inadequate. We should do our analysis by looking forward at where we are trying to go, rather than looking backward at where we have been.

Penning Trap Reactor Vessel

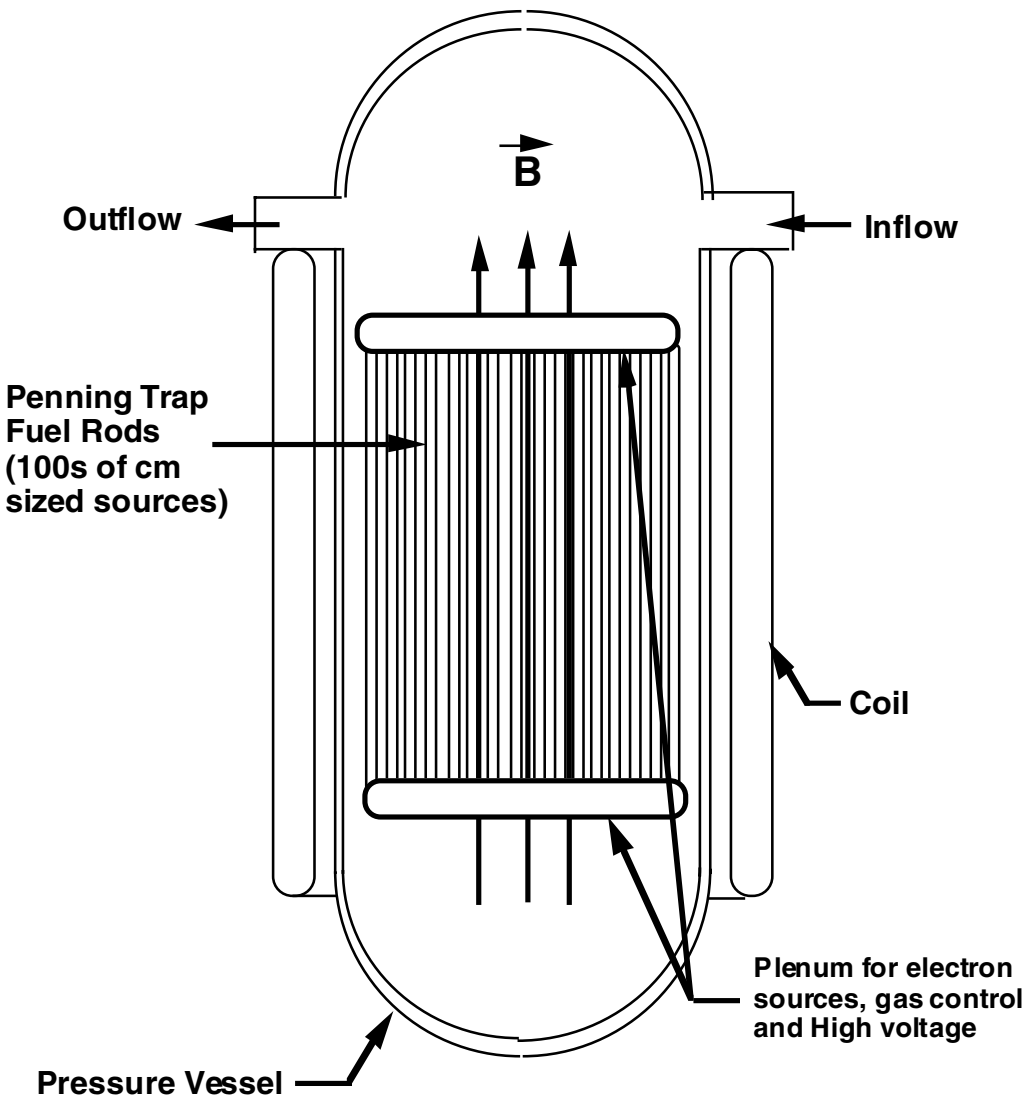

Fig 4: The massively modular penning trap reactor

References

1. J. Joosten, ***Nuclear News 42***, No. 7, 41 (1999).
2. H. B. Ray, ***Nuclear News 42***, No. 7, 46 (1999).
3. R. A. Nebel, Fourth International School of Plasma Physics, S. Ortolani and E. Sindoni eds., 611 (1990).
4. R. A. Nebel, D. C. Barnes, ***Fusion Technology 38***, 28 (1998).