PANEL DISCUSSION ON PROSPECTS FOR FUSION POWER*

Summary of Comments By

CONF-8604175--1

DE86 010035

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Although substantial progress is made every year in fusion research, the projected time to realize the ultimate goal of commercial fusion always seems to be 25 or 30 years away. This shifting schedule reflects the underlying difficulty of developing fusion. Every new technology improves the prospects for success, yet as each fusion mountain is scaled, it serves mainly to bring a better view of the next mountain.

One approach to reconnoitering the upcoming terrain is to conduct a design study of a reactor. Such studies have served the valuable function of differentiating those mountains which should be scaled from those which should not.

By combining the wisdom from all of the studies, we can reach some general conclusions about profitable routes to economical fusion power. The studies also provide answers to questions about the program, such as "Why are so many configurations studied?" and "What constitutes an economic power density?" With respect to the latter question, on the one hand, economic analyses indicate that certain levels of power density will be required for competitiveness; on the other hand, safety analyses indicate that, for inherent safety, the neutron flux to the blanket should be limited. Fortunately, the two requirements have an overlap which leaves a reasonable

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

amount of room to juggle other facets of the reactor. If, eventually, still higher power densities are permitted, then further improvements to fusion could accrue.

The above case is one example which indicates that criteria may be established for a particular key parameter. In fact, the various studies have generated characteristics for the general requirements of all of the key parameters - plasma parameters, magnet characteristics, auxiliary heating, blanket, shields, unit cost, availability, etc. It is important to understand that all of these requirements can be met or are projected to be achieved in the development programs.

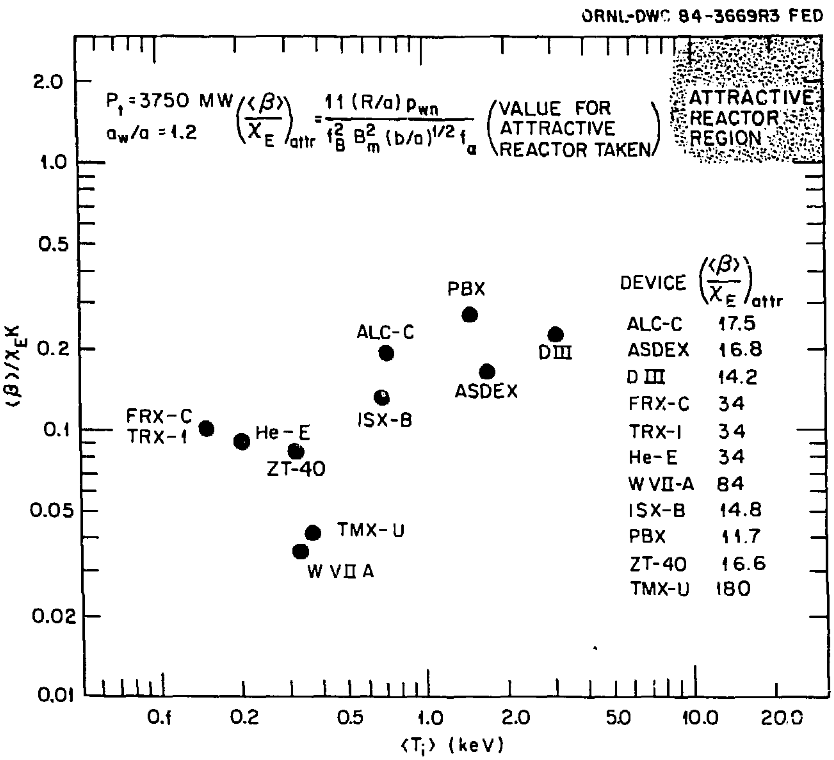
Key issues for the commercialization of fusion are (1) development of an "attractive" reactor configuration, which means a convenient combination of plasma physics capabilities, including not only adequate beta and thermal diffusivity but also impurity control and, ideally, steady-state capability; (2) technology requirements and engineering simplicity; and (3) development of low-activation components to capitalize on the potential for making a fusion reactor with vastly improved waste disposal characteristics compared with a fission reactor.

Two convenient parameters for characterizing physics attractiveness are beta (β), the ratio of plasma pressure to magnetic pressure and the thermal diffusivity (χ_E), which is a measure of the heat loss from the system. Studies of the capabilities of various existing configurations show that most of the configurations can, theoretically, meet the needs of an attractive reactor. Good progress is being made towards the achievement of the goals, as illustrated in Fig. 1, where the achieved value of β/χ_E, normalized to the value required by that configuration to make an attractive reactor, is plotted versus the average ion temperature.

It is appropriate to comment on why such a wide range of configurations is still being studied. Our understanding of the underlying physics - transport in linear or toroidal geometry, the roles of magnetic wells and shear in magnetohydrodynamic activity, electric field effects, microscopic and macroscopic instabilities, the behavior of high-energy particles and electromagnetic waves, etc. - has evolved through tests on a wide variety of configurations, each with particular capabilities in certain areas. This breadth of research in plasma physics and fusion continues to be important to the optimization of attractive configurations.

The various configurations are at different stages of development. This situation reflects in part the extent to which each has been pursued, which in turn depends upon when their virtues became apparent. The tokamak is the mainline of this research program because it was the first to make substantial, well-confined plasmas, and it remains the cost-effective test bed for much of the peripheral equipment (e.g., heating, diagnostics, materials). It is also the most advanced in attaining fusion plasma conditions. While improvements are needed to make it truly "attractive," notably in the area of steady-state operation, the tokamak remains the best candidate for a reactor, since all other devices require even more substantial advances. However, it is premature to focus totally on the tokamak. The requirements for an attractive reactor involve many considerations, and the program is not yet ready to address the relevant trade-offs on, for example, access, maintainability, reliability, safety, unit size, auxiliary heating, coil design and field, and blanket design. The related stellarator concept has steady-state capability with no power recirculated to the plasma. The reversed-field pinch has already achieved reactor-level betas. The tandem mirror offers the possibility of direct recovery for some of the power. The compact torus may lead to a lower power unit. So ultimately, some configuration other than the tokamak may offer the best compromise. In the meantime, the tokamak program is a cost-effective way of tackling the wide range of plasma-related issues. The broader program involving the stellarator, mirror, reversed-field pinch, and compact torus complements the tokamak program and keeps open the routes to what may finally be "the most attractive reactor."

In conclusion, I believe that the fusion program is making substantial progress. The goals are as realistic as at any time in history. It is more collaborative, both nationally and internationally, than ever before. In this environment there has been a great improvement in the connection between the troops in the trenches, who understand the true state of fusion development, and the long-term planners, lurking far behind the front lines, who formulate the strategy for the next major push. Studies of economics, physics, technology, and safety show a number of routes to an economical fusion reactor with the added attraction of relatively low environmental impact. Finally, let me remark that it is gratifying that, as each year passes, the constant estimate of the time to fruition of fusion becomes more accurate.


ORNL-DWG 84-3669R3 FED
P_t = 3750 MW
a_w/a = 1.2
$\left(\frac{\langle\beta\rangle}{\chi_E}\right)_{attr} = \frac{11\,(R/a)\,p_{wn}}{f_B^2\,B_m^2\,(b/a)^{1/2}\,f_\alpha}$
(VALUE FOR ATTRACTIVE REACTOR TAKEN)
ATTRACTIVE REACTOR REGION
$\langle\beta\rangle/\chi_E K$
$\langle T_i\rangle$ (keV)
2.0
1.0
0.5
0.2
0.1
0.05
0.02
0.01
0.1
0.2
0.5
1.0
2.0
5.0
10.0
20.0
PBX
ALC-C
DIII
ASDEX
ISX-B
FRX-C
TRX-1
He-E
ZT-40
TMX-U
W VII A
DEVICE $\left(\frac{\langle\beta\rangle}{\chi_E}\right)_{attr}$
ALC-C 17.5
ASDEX 16.8
D III 14.2
FRX-C 34
TRX-I 34
He-E 34
W VII-A 84
ISX-B 14.8
PBX 11.7
ZT-40 16.6
TMX-U 180