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POWER BALANCE IMPLICATIONS IN FUSION REACTORS*

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Because a fusion power reactor is basically an energy amplifying system, a detailed analysis of the energy flow through the power plant is fundamental to any technological assessment of fusion power. The purpose of this paper is to examine the energy balance and its technological implications for four fusion reactor concepts: the mirror concept, the theta-pinch concept, the tokamak concept and the laser-pellet concept.

The energy amplification potential of the plasma and blanket can be cast in terms of a total energy-multiplication factor, Q, which I define as the ratio of the total fusion-produced energy (plasma plus blanket energy release), W_t, to the externally supplied energy absorbed by the plasma, W_a. Thus

$$Q \equiv \frac{W_t}{W_a} \quad . \qquad (1)$$

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The energy, W_a, includes the energy necessary to both initiate and sustain the plasma burn.

The quantity, Q, can be resolved into two components, one which depends primarily on plasma physics and the other which depends on blanket design. The plasma-physics component will be designated "the fusion-energy-multiplication factor," Q_f; the blanket-design component

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will be designated "the blanket-energy-multiplication factor," M. Thus

$$Q \equiv Q_f \cdot M \quad , \tag{2}$$

where

$$M \equiv \frac{E_t}{E_f} \quad , \tag{3}$$

E_t is the total energy release per fusion event (including energy release within the blanket) and E_f is the fusion energy release per fusion event (17.6 MeV per D-T fusion event).

Current fusion reactor blankets yield M values in the range 1.1-1.4. In fusion-fission concepts the blanket may incorporate fissionable material which would yield significantly greater M values, e.g., 5 to 30. For the purposes of my analysis I shall take an M value of 1.4.

A critical value of Q, Q_c, is associated with the energy (or power) break-even condition,[1] that is, the condition at which the net electrical output of the power plant, W_n, equals zero. The value of Q_c is determined by the energy handling and conversion efficiencies of the overall system; if all these efficiencies were 100%, then Q_c would equal zero. The parameter Q_c is a measure of the inherent energy efficiency of the concept and represents a useful engineering parameter for fusion power plants. Moreover, at a given M, it defines the power break-even value of Q_f.

If the overall plant efficiency, η, is defined as the ratio of net electrical output, W_n, to total fusion energy production, W_t, then it can be shown that η is given by[1]

$$\eta = \frac{Q-Q_c}{Q} \cdot \eta_e \quad , \tag{4}$$

where η_e is designated "the effective conversion efficiency of fusion energy" and is given by

$$\eta_e \equiv \alpha\eta_d + (1-\alpha)\eta_t \quad , \tag{5}$$

where α is the fraction of the total fusion energy recovered by direct energy conversion with efficiency η_d, and η_t is the efficiency of the thermal energy-conversion system. I shall assume that η_t is 40% in all the power balance analyses. As in my specification of an M value, this assumption is somewhat arbitrary. The purpose of fixing M and η_t is not because they are unimportant parameters but, rather, because they represent common design features of each concept, and I wish to focus on the unique requirements of each concept.

By combining Eqs. 2 and 4 we obtain the following expression for η,

$$\eta = \frac{Q_f - Q_c/M}{Q_f} \cdot \eta_e \quad . \tag{6}$$

Note that η is determined both by the plasma physics parameter Q_f and the engineering parameters Q_c, M and η_e.

For illustrative purposes I will define $\eta = 30\%$ as a milestone for a fusion power plant with $\eta_t = 40\%$, that is, $\eta = 0.75\eta_t$ should be regarded as a technological goal for fusion power. On the basis of this study, I conclude that the milestone condition ($\eta = 30\%$) implies the following requirements for fusion reactors:

1. The efficiency of the neutral beam injectors for mirror reactors must approach 88%.

2. The efficiency of the magnetic energy transfer system in the theta-pinch reactor must approach 96%.

3. Tokamak reactors will have to achieve Q values of $\sim$30. The capital costs for tokamak reactors are very sensitive to the burning cycle characteristics.

4. The efficiency of the laser in the laser-pellet reactor must exceed 12%.

REFERENCES

1. M. Nozawa and D. Steiner, "An Assessment of the Power Balance in Fusion Reactors," ORNL-TM-4421, January 1974.