SCALING FOR TORMAC FUSION REACTORS*

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In this paper a set of parameters for a Tormac reactor is developed. The scaling indicates that a Tormac reactor could be constructed with a modest energy output of about 500 megawatts with magnetic fields averaging 20 kG, peak fields of 40 kG, and a plasma radius of about two meters. Wall loading under these conditions can be kept modest. It is further noted that Tormac can be run in a steady state mode. Thus, Tormac makes an economically attractive alternative to tokamak.

Tormac is a stuffed, toroidal, line cusp,[1,2] i.e., its plasma is contained in two distinct regions, an outside sheath region where the magnetic field lines are open and a central or internal high-β region where the field lines are closed within the plasma. The Tormac sheath, which is predicted to be only a few ion gyroradii thick,[3] is made up of toroidal and poloidal magnetic field components. Particles in this sheath are kept from flowing out the open field lines in a mirror-like fashion by magnetic field constrictions some distance beyond the cusp lines.[4]

In the quasi-stationary state, plasma from the interior enters the sheath at the same rate at which it is lost. Since the internal region can be made much larger than the sheath, containment by the combination of the two regions is expected to be much improved over that in ordinary mirrors alone. The resulting favorable reactor scaling has made Tormac an important alternate concept in fusion research. This paper summarizes the results of an analysis and survey of the characteristics of a fusion reactor whose plasma is confined in a Tormac configuration.

Current experimental work on Tormac is centered on the toroidal bicusp[5] shown in Figure 1. At first glance the bicusp does not look like a cusp. However, it does satisfy the basic cusp condition; i.e., all magnetic field lines on the plasma surface have a radius vector which points into the plasma. This is accomplished by having the magnetic field on the inside of the torus dominated by the toroidal component and the magnetic field on the out-

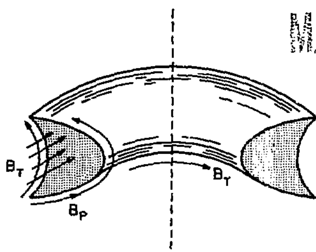

FIGURE 1. Cross section of a Tormac bicusp. The shaded area represents the plasma.

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side dominated by the poloidal component. This then insures that the plasma is confined within a region of absolute minimum-B and its surface is stable to all so-called magneto-hydrodynamic wave modes.

The interior region in Tormac, with its closed magnetic field lines, is also expected to be well-behaved. Unlike other devices, and characteristic of cusp confinement, the central region is a region with only minor pressure gradients. This then insures the MHD stability of the central region and at the same time requires that the entire plasma pressure be supported in the sheath. A pressure profile of the plasma is shown in Figure 2.

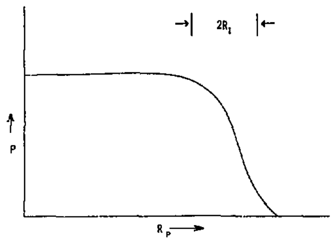

FIGURE 2. Schematic representation of plasma pressure as a function of plasma radius, R_p.

The sheath where the pressure gradient is supported is a region of open field lines. Plasma is held in the sheath in a mirror-like fashion. Thus the ions have a loss-cone distribution, and interparticle collisions lead to the scattering of particles into the loss cone and out of the device. (The mirror problem has been analyzed in detail by the Livermore Group and their results are used in these calculations.) This scattering of particles into the loss cone and along the open field lines is the primary loss mechanism in Tormac, and cross field diffusion to the walls is completely negligible. Thus, the rate of loss of particles from Tormac is determined by the density of particles in the sheath, N_S, the volume of the sheath, V_S, and the mirror containment of a particle in the sheath, τ_M. The Tormac time constant, t_T, is then simply given by $\tau_M V_P/V_S$, where V_P is the plasma volume. It can be shown that $V_P/V_S \approx R_P/2r_i$ where r_i is an ion gyroradius and R_P is the plasma minor radius. Thus,

$$Nt_T \approx 5 \times 10^{10} R_P(m)\, T_i(keV)\, B(kG)\ cm^{-3}sec.$$

The time constant, t_T, derived above assumed that the only particles entering the sheath from the central region arrive by cross-field diffusion. An expected complication is caused by the drifts in the toroidal field that can carry particles into the sheath. This flow of guiding centers will carry particles whose velocity vector lies in the loss cone, so that the rate of loss of particles would be increased beyond the value discussed above. To prevent this flow it is necessary to have a rotational transform. Fortunately, the requirement for such a transform is not nearly as stringent as is required by average minimum-B devices such as tokamaks.

One method of preventing toroidal drifts in Tormac is with a mechanical rotation of the plasma around the minor axis of the toroid. Thus, if a particle rotates around the plasma its drift is averaged and its orbit will be confined to a flow surface. The condition that the particle be confined within a gyroradius is that its flow velocity, v_b, be given by $v_b \geq v_i/A$ where v_i is the ion thermal velocity and A is the aspect ratio of the flow surface.

There is reason to believe that the flow required for a rotational transform might be generated by the plasma. This flow would be the result of an EXB/B^2 drift where the E-field represents the omnipresent ambipolar field of the plasma. Indeed, preliminary experimental measurements in Tormac have indicated a plasma rotation sufficient to prevent toroidal drifts.

A feeling for the magnitude of the rotational transform required for Tormac can be arrived at by comparing it to the tokamak problem. If a tokamak-like poloidal field were introduced into the central region of Tormac it would confine drifting particles to flux surfaces and would serve the same function as mechanical rotation. The intensity of the poloidal field, B_P, required for this function would be related to the toroidal magnetic field, B_T, by $B_P = B_T/2A$. However, the magnitude of B_T in Tormac is already less than B_P in tokamak so that in Tormac the energy density in a poloidal magnetic field, if it were used, would be about 5% of the energy density required for tokamak. Thus, while there is a drift problem and the need for a rotational transform in Tormac, it does not appear that this problem will be of major concern in designing a reactor.

Before evaluating quantitatively what is required for a Tormac reactor there are several qualitative features of such a device that should be noted. These include the probability that Tormac can operate in a continuous or steady state mode, that impurities will not be accumulated in the plasma, and that the cusp or open field lines form a natural diverter system which might at some time serve as a direct energy converting system. These are some of the positive features of a Tormac system. On the negative side must be considered the fact that the magnetic field intensity at the coil structure will probably be twice that required at the plasma surface. It should also be pointed out that Tormac is basically a high-beta device. This leads to certain advantages as well as disadvantages when compared to a low beta system. The advantage is that bremsstrahlung and cyclotron radiation losses in Tormac are negligible and that generally magnetic field intensities are much lower than in the low beta case. On the other hand, as will be seen in what follows, wall loading limitations can be troublesome and relatively high operating temperatures are required.

In order to develop a more quantitative description of Tormac the scheme outlined in Figure 3 is used. In this diagram a portion of the gross power developed is

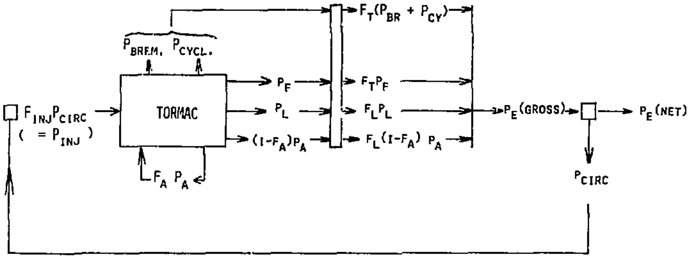

FIGURE 3. Schematic layout of the power flow for Tormac reactor calculations.

reinjected into the plasma using neutral beams with an efficiency, F_{inj}, to help heat the plasma. The plasma is also heated by a partial conversion of the power released in the form of alpha particles, $F_A P_A$, within the plasma. The rest of this energy is converted with efficiency F_L into electrical power, $F_L(1-F_A)P_A$. Other constituents of the energy coming out of the plasma are the power in neutrons, P_F, power *in lost particles*, P_L, *and power in radiation*, $P_{BR}+P_{CY}$. Using this scheme the gross electrical power P_E is given by,

$$P_E(\text{GROSS}) = F_T(P_{BR}+P_{CY}) + F_L(P_L+[1-F_A]P_A) + F_T P_F$$

where F_T denotes the efficiency of conversion from thermal to electrical power.

A quality factor for the efficiency with which the system generates electricity, Q_E, can now be defined as,

$$Q_E = \frac{P_E(\text{GROSS})}{P_{CIRC}}$$

Breakeven is given when $Q_E = 1$ and ignition when $Q_E = \infty$.

In Figure 4 a plot of the R_pB product necessary for a breakeven reactor is shown as a function of the plasma ion temperature. It is interesting to note that the most favorable region for operation is above 40 keV. It is also noteworthy that breakeven can be reached with R_pB products as low as 2 or 3 meter-tesla. In this plot, as in what follows, the electron temperature has been taken as 1/2 the ion temperature. This assumption is arbitrary; however; results will not vary dramatically with electron temperature, and an examination of the electron power balance term does not make this seem too unreasonable. The thermal efficiency, F_T, has been set at 0.4 and the efficiency of generating

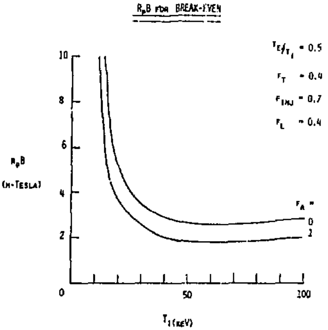

FIGURE 4. Plot of the product of plasma radius times magnetic field intensity as a function of ion temperature for break-even.

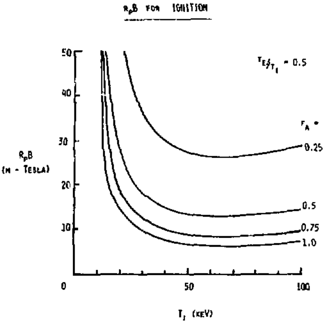

FIGURE 5. Plot of plasma radius times magnetic field intensity for ignition as a function of ion temperature. Curves are given for several fractions of alpha-particle energy absorbed by the plasma.

beams at 0.7. No provision for direct energy conversion is provided. In Figure 5 conditions for ignition are set forth. As might be expected, these conditions are a dramatic function of the fraction of the alpha particle energy deposited in the plasma.

From Figure 4 and Figure 5 it can be seen that reactor parameters of very reasonable size are required for a Tormac system. The problem becomes a little more difficult when a limit is imposed on wall loading.

In Figure 6 and Figure 7 a set of parameters is set out for reactor conditions. These curves are drawn with the limitation that the total power developed is less than 2000 MW and that the wall loading be limited to 4 MW/m^2. For these plots an aspect ratio of 3 is used. The wall loading limit on the inner and outer walls is shown. Because of the small aspect ratio chosen here loading on the inner wall is much larger than that on the outer wall. The magnetic field intensities given are those on the plasma boundary so that the field at some coil surfaces will be about double the indicated field; even so, magnetic field requirements are quite modest.

In conclusion, it can be stated that Tormac as a reactor has a unique operating range. As can be seen from a comparison of Figures 6 and 7, Tormac uses much lower magnetic fields and much higher temperatures than other systems. The low magnetic field intensities tend to lead to large sizes. The higher temperatures could make neutral beam injection difficult. However, as the curves in Figure 6 show, a Tormac reactor could be built with a set of parameters which can easily be met with available technology. Thus, the low magnetic fields, the steady state operation, and the relatively small size make Tormac an economically attractive alternative to tokamak as a reactor.

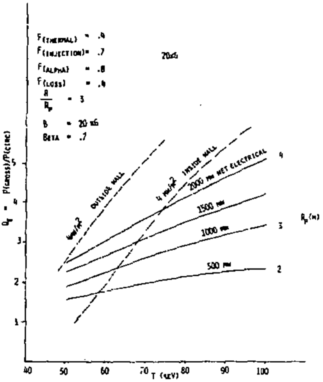

FIGURE 6. Curves for several reactor sizes showing Q_E and size, Rp, as a function of ion temperature. The magnetic field at the plasma boundary is 20 kG.

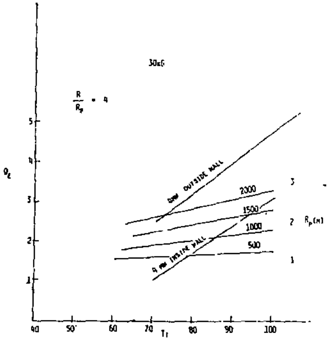

FIGURE 7. Q vs T(keV) for a 30 kG field.

REFERENCES

1. J. Berkowitz et al., 2nd Int. Conf. Peaceful Uses At. Energy (Proc. Conf. Geneva, 1958) 31, 171 (1958) UN, New York.
2. L. S. Combes, C. C. Gallagher, and M. A. Levine, Phys. Fluids 5, 1070 (1962).
3. A. H. Boozer and M. A. Levine, Phys. Rev. Lett. 31, 1287 (1973).
4. M. A. Levine et al., Phys. Rev. Lett. 20, 1323 (1972).
5. M. A. Levine, Bull. Am. Phys. Soc. 17, 1040 (1972).
6. See for instance, D. E. Baldwin, Lawrence Livermore Laboratory Rept. UCRL-78406 (1976).