Divertor Target Design for the UWTOR-M Stellarator Power Reactor

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DISCLAIMER

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DIVERTOR TARGET DESIGN FOR THE UWTOR-M MODULAR STELLARATOR POWER REACTOR

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ABSTRACT

Modular stellarators offer a unique opportunity for innovative divertor target design by virtue of the discreteness of their diverted flux bundles. Well focused flux bundles leave the separatrix at discrete locations, emerging from the toroid between the coil legs and then reenter the toroid. This paper describes a divertor target design which recovers the energy at a high temperature and prevents neutron streaming through the divertor slots.

INTRODUCTION

UWTOR-M is a 4800 MW_{th} modular stellarator power reactor[1] with 18 twisted coils and 108 divertor slots. A cross section of the reactor is shown in Fig. 1.

The natural divertor in the stellarator family of devices occurs as a consequence of the existence of the magnetic separatrix bounding the region of closed nested flux surfaces. Inside the separatrix the enclosed magnetic flux

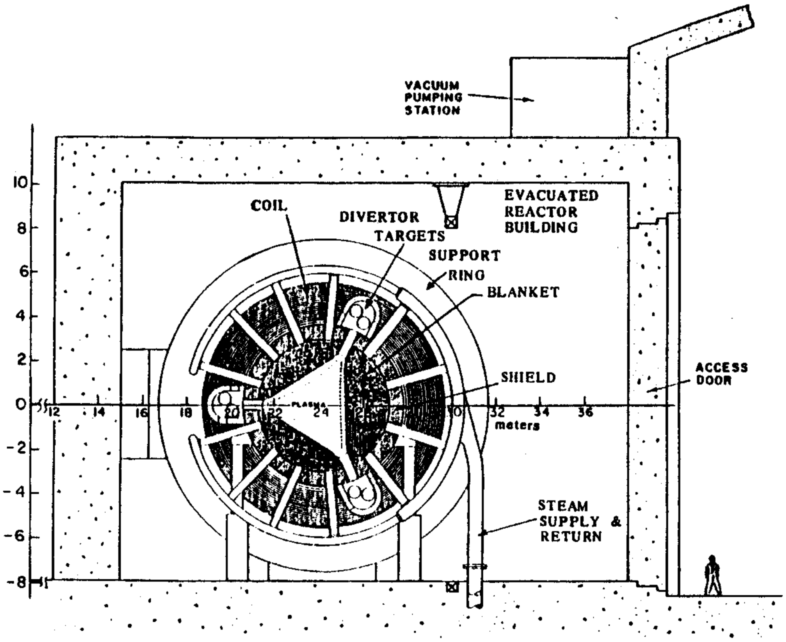

Fig. 1. Cross section of the UWTOR-M reactor.

links all of the magnet coils. Outside the separatrix, however, the flux links some, but not all, of the coils. Thus, some of the flux must emerge from the spaces between magnets, but to conserve flux, it must reenter the device at some other location. It is this property of the magnetic flux external to the separatrix which forms the basis for the magnetic divertor and is typical of any toroidal magnetic confinement system characterized by a magnetic separatrix. The difference between the stellarator family and the other toroidal magnetic systems is that the null, and therefore the separatrix, occur naturally in the stellarator, while other systems, such as the tokamak, have to drive the null artificially by special placement of poloidal field coils.

A systematic study of the properties of ℓ=3 modular stellarators with coils which have large lateral deformation has been performed. The divertors in these configurations have been found to be highly localized and modular in nature, resembling small bundle divertors distributed over the surface of the torus.

The modular divertor is the adopted impurity control mechanism in UWTOR-M. Each divertor slot has two cylindrical divertor targets designed to recover the energy in the divertor region at a high temperature so that it can be converted at a high efficiency in the power cycle. The stationary cylinders are made of actively cooled shield material which prevents neutron streaming through the slots. A graphite surface cylinder rotates about the stationary cylinders at a nominal speed of 100 RPM. The particles striking the rotating surface are neutralized and pumped out. The surface energy is radiated to the cooled surrounding housing and the cooled stationary shield cylinders.

Rotating targets are not new, for example Vershkov et al.[2] discuss rotating limiters for tokamaks. However, to the best of the authors' knowledge a rotating hollow shell divertor target has not been previously proposed. The rotating hollow shell greatly mitigates two serious engineering problems inherent with rotating targets. First, it substantially reduces the weight and second, it provides a practical means for cooling the inner structure and bearings of the target.

DESCRIPTION OF DIVERTOR TARGETS

The divertor targets shown in Fig. 2 are cylindrical in shape, nominally 2.5 m long and 60 cm in diameter. The axes of the targets are perpendicular to the paper. The modules can be removed as a whole for maintenance.

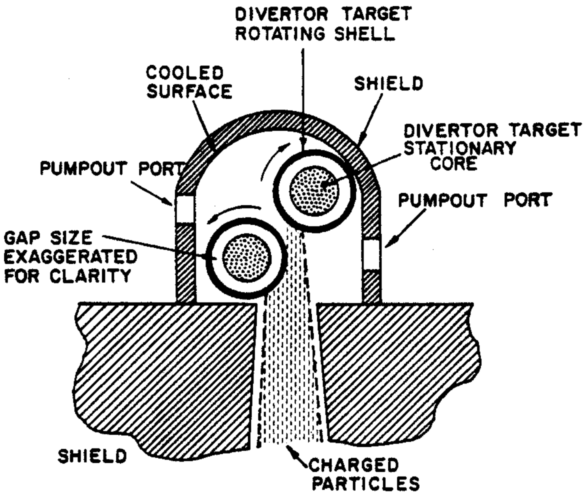

Fig. 2. Cross section of module containing two divertor targets.

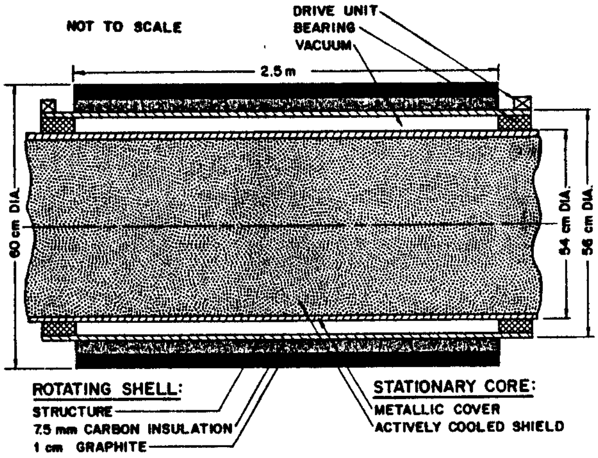

Fig. 3. Cross section through length of a single divertor target.

Figure 3 is a cross section through the length of one target. The center of each target consists of a stationary cylinder, 54 cm in diameter, called the core which is predominantly

1422 steel and serves as a shield for the neutrons streaming through the divertor slot. The core is steam cooled to 500°C. Surrounding the core is a hollow cylindrical shell, with a 56 cm inner diameter and 60 cm outer diameter, that rotates at ~ 100 RPM. It is this shell which makes this design unique, and most of the rest of this paper will be concerned with it. The shell is struck by the ions coming through the divertor slot and the resulting heat load is spread over the entire surface by the rotation. Neutron heating in the shell is negligible in comparison to the surface heat load. The shell is cooled by radiation to its surroundings in the module which are steam cooled to 500°C. The steam is then used in the power cycle at a high conversion efficiency.

The shell consists of three overlapping layers (see Fig. 3). The outer layer is graphite 1 cm thick, the middle layer is 7.5 mm carbon fiber insulation and the inner layer is a metallic structure 2.5 mm thick. The shell is separated from the core by a 1 cm vacuum gap and is supported by bearings at both ends. The shell could be driven electromagnetically, much like the rotor of an electric motor. To minimize torsion in the shell there should be a drive unit on both ends of every divertor target.

HEAT TRANSFER

Two main concerns over the graphite layer are its average temperature and the cyclic temperature fluctuations during each rotation. Extensive computer calculations using finite difference methods were performed to determine how changes in different parameters affected the heat transfer and temperatures in the shell. These calculations are presented elsewhere.[1,3] In the interest of brevity, only the results of the calculations are summarized here.

The outer graphite layer of the shell has an average heat load of 31 W/cm^2 over its entire surface area. The insulation beneath the graphite is so effective that almost all of this heat is radiated away from the outer surface. Very little heat is conducted towards the core. The average graphite temperature can be obtained from Fig. 4 which estimates the average graphite temperature as a function of emittance. It was assumed that all metallic surfaces used for radiative heat transfer will be covered with a thin layer of graphite. This increases the heat transfer rates and lowers the temperature of the shell. The emittance of the graphite is likely to be between 0.6 and 0.8[4,5] depending upon its type and directional orientation. Sputtering, which will roughen the shell surface, will most likely increase the emittance. It can be concluded from Fig. 4 that an average graphite temperature of 1500-1700°C is likely. Such a temperature does not appear to be a problem.

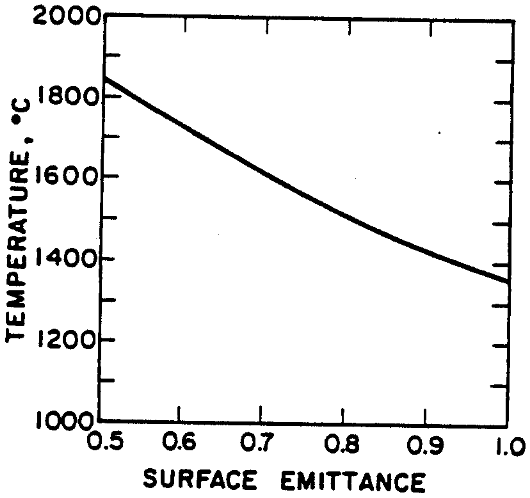

Fig. 4. Average graphite surface temperature as a function of surface emittance.

Figure 5 shows the temperature history of a point on the graphite surface during one period of rotation for a particular case for steady state conditions. It shows a typical cyclic behavior of the temperatures. For this case the temperature fluctuates 83°C during each rotation. Graphite is very resistant to thermal shock[6,7] and for this case it does not seem that the thermal stresses will be excessive.

Calculations have shown that the only parameter which has a drastic effect on the magnitude of the temperature fluctuations is the thermal conductivity of the graphite layer perpendicular to its surface. The graphite thermal conductivity can vary by two orders of magnitude, from ~ 0.015 to ~ 2.0 W/cm-°C, depending on the graphite type and directional orientation. The surface temperature fluctuation during each rotation falls in the range of 30-300°C as a function of the graphite thermal conductivity. With a 30°C temperature fluctuation the thermal stresses will be very small. Con-

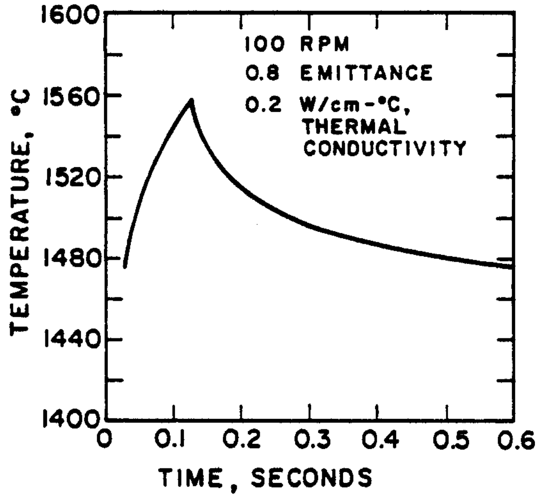

Fig. 5. Temperature history through one rotation of a point on the divertor target graphite surface.

structing the graphite shell with a thermal conductivity perpendicular to the surface of ~ 2.0 W/cm-°C would all but eliminate thermal stresses.

Changes in emittance from 0.5 to 1.0 had no perceptible effect on the shape of the surface temperature profile although the average temperature would change substantially. Varying the rotational speed of the shell from 50 to 200 RPM has a marginal effect. A speed of 100 RPM would be adequate.

GRAPHITE SPUTTERING

The 8.8 keV He, D and T ions streaming through the divertor slot sputter the graphite surfaces of the divertor targets.[1] The reactor exhaust rates for the different ion species are:

D	3.23×10^{22}	atoms/sec
T	3.32×10^{22}	atoms/sec
He	1.5×10^{21}	atoms/sec

giving a total reactor exhaust of 6.7×10^{22} atoms/sec. The resulting erosion of the graphite limits the life of the divertor targets and the byproducts could contaminate the plasma.

The sputtering coefficient is uncertain and depends upon the ion energy, angle of incidence and graphite surface temperature. Recent experiments indicate that a sputtering coefficient of ~ 0.1 is possible for the UWTOR-M divertor targets.[8,9] The erosion rate of a target as a function of the reactor exhaust rate is plotted for different values of sputtering coefficients in Fig. 6. A sputtering coefficient of 0.1 at the UWTOR-M operating point gives an erosion rate of 2 mm every full power year. For this, a 1 cm thickness is sufficient to last the planned three years between maintenance periods of the UWTOR-M blanket. A higher sputtering coefficient would require a thicker layer of graphite which can be accommodated without compromising performance.

STRUCTURAL CONSIDERATIONS

The inner layer of the shell is its structure. The structure will be cooled to ~ 800°C by radiation inwards across a vacuum gap to the core which is steam cooled to 500°C. The structure is insulated from the outer graphite layer by a 7.5 mm thick layer of carbon fiber insulation. This insulating material makes use

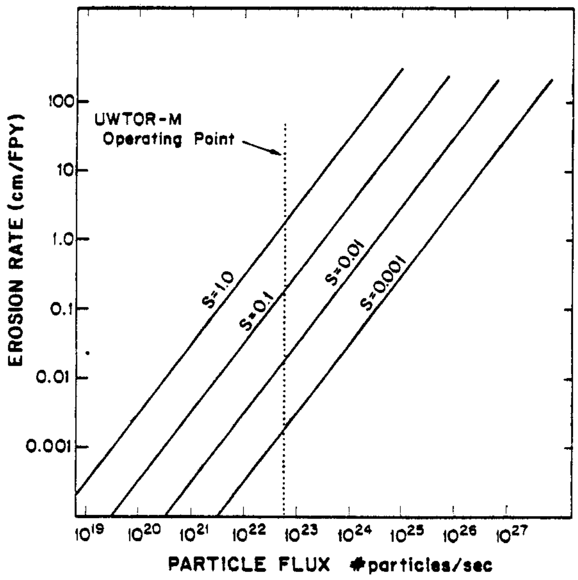

Fig. 6. Erosion rate of the outer surface as a function of the particle flux for different sputtering coefficients S.

of the extreme anisotropy of graphite to achieve a very low thermal conductivity of ~ 0.0015 W/cm-°C.[10,11]

In the present design[1] the structure is assumed to be TZM (molybdenum alloyed with 0.5% Ti and 0.1% Zr). The structure must resist the bending stresses due to the weight of the shell, while torsion can be neglected because it is assumed that the shell is driven from both ends. The weight of the shell depends mostly on the thickness of the graphite which in turn depends on the sputtering rates. For example, a shell with a graphite thickness of 1 cm will weigh 96 kg and produce a maximum tensile stress of about 7.7 MPa.[1] For TZM, the tensile strength at 870°C is given as 570 MPa.[12]

BEARINGS

Designing the bearings for the divertor targets is perhaps the most difficult problem. They must be reliable and must be capable of operating in a vacuum at a relatively high temperature in a severe neutron environment.

However, there are some mitigating factors. The dead loads on the bearings are low, on the order of 940 N, the thrust loads are cancelled by the opposing drivers, the tolerances are not critical and the revolution frequency is only 100 RPM. Although conventional lubricants are excluded, graphite powder would make an excellent substitute. A clever design could take advantage of the sputtered graphite from the outer surface to provide continuous lubrication for the bearings. Dissimilar metals and sintered materials are also possible candidates.

CONCLUSIONS

On the basis of the present analysis it is concluded that rotating shell divertor targets are very attractive for magnetic fusion devices which have discrete flux bundles such as the modular stellarator. The large surface area can dissipate a high heat load which in turn is recovered very efficiently. The lifetime of such divertor targets is long enough to make them compatible with typical changeout cycles for fusion reactor blankets.

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