ALTERNATIVE DIVERTOR COLLECTOR SYSTEMS

FOR INTOR*

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1. INTRODUCTION

A single null poloidal divertor was considered as the design option for INTOR in the previous study phase. The target in the divertor chamber was a solid tungsten plate with or without protective lithium film. Since there is no experimental program to test the target and pumping methods at this stage, it is imperative that we should try to look into as many alternative concepts as possible. Each concept can thus be tested out at an early stage of INTOR so that a workable solution can be assured. Three new target concepts and external fuel recycle methods are proposed and discussed in this report. To improve the erosion rate or the target life time, the use of a two null divertor which can operate alternatively as two single null divertors is also suggested. Since there is plenty of space behind the divertor chamber and the shielding does not have to be in contact with the divertor target, the shielding does not present a problem whether it is a single or double null divertor system.

2. WALL EROSION PROBLEMS

The plasma conditions in the scrape-off layer and on the divertor target for INTOR are listed in Table 1 [1,2]. These are the results of transport modeling by considering 99% recycle. The particle flux to the divertor can be estimated consistently from sheath model [3,4]. The total energy of the impinging ions on the target for T_i = 190 eV and T_e = 250 eV at the plasma edge is

$$\varepsilon_i = 2\ kT + Z\ (\frac{kT_e}{2})\ \ln\ (\frac{T_e m_i}{T_i m_e}) = 1.4\ \text{keV}. \qquad (1)$$

Normalized to the total particle and power load the particle flux on the target can be calculated from

$$\Gamma = \frac{Q}{2.9\ \varepsilon_i} \qquad (2)$$

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The erosion rate for several material for various energy and particle fluxes can be quickly estimated from the erosion rate graphs given by Cecchi [4] and listed in Table 2. The sputtering erosion for a solid target is a severe problem. To limit the erosion rate to less than 1 mm/year it is necessary to operate the divertor at 0.1 kw/cm^2 level of power load. Such designs will be discussed in the next section.

Table 1. Divertor plasma conditions for 99% recycle.

Power to the divertor	80 MW
Total particle load	$1.5 \times 10^{23} s^{-1}$
Ion energy on target	1.4 keV
Plasma edge ion temperature	190 eV
Plasma edge electron temperature	250 eV
Availability	0.25

Table 2. Erosion rate of divertor target for 99% recycle.

Power density	1 kw/cm^2	0.1 kw/cm^2
W	7 mm/yr	0.6 mm/yr
Mo	11 mm/yr	1.0 mm/yr
V	5.5 mm/yr	0.6 mm/yr
TZM	11 mm/yr	1.0 mm/yr

3. DIVERTOR TARGET CONCEPT

Three alternative target design options are proposed here in addition to the flate plate with protective lithium film. The target will be assembled from a module of 10 cm x 10 cm tube array as shown in Fig. 1. The tube can be aligned parallel to the magnetic field or transverse to the magnetic field as shown by Figs. 2 and 3. The tube array is constructed such a way that every other tube

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is set back to leave a gap in the longitudinal direction between the tubes to allow the plasma to pass through. Therefore, the neutrals will be scattered to the back side of the target and pumped away. Since only 1% of pumping is required, it is very easy to obtain 1% of transmission coefficient from such a design. The tube grill like target will be sitting inside the gaseous chamber. The volume of particles to be pumped can be regulated by the gas pressure. The great advantage of this method is that the inner branch of the divertor (at smaller radius) is no longer obstructed.

Because of the high erosion rate, the target has to be operated at a low power level in order to survive a reasonably long period of time, following which, the target surface would be replenished. For the tubular construction, the total surface is $\frac{\pi}{2}$ times larger than the flate plate which was 70 m^2 given in the previous design. Therefore, total area per divertor is about 110 m^2, the erosion rate for 0.25 machine availability is less than 1 mm/year for a molybdenum target. The power density is less than 0.1 kw/cm^2, thus the thermal hydraulic design is simple. The tube can even be cooled by steam and a reasonably amount of thermal energy can be recovered.

The second target design method is shown by Fig. 4. Since each branch of the divertor plasma resembles a beam, the targets are placed on both sides of the plasma slab and contoured in such a way that they are nearly tangential to the flux. Since the targets are not intersecting the separatrix where the plasma is peaked, the power and particle flux on the targets are nearly uniform. Because of the grill-like structure of the target, the plasma will reach the off-set tubes and the scattered neutrals can be pumped from the backside. The total target area is almost double the previous design. The target life time will double to two years and the thermal load is reduced to 0.05 kw/cm^2.

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The third method is to use straight forward gaseous targets. The plasma
will be slowed down by the gas, dispersed, neutralized, and radiate some of it's
power. The gas may be hot, but the chamber wall will be thermally shielded by
tube arrays. The life time and thermal performance of the wall shield should be
better than the second case since the gas temperature is lower and more evenly
distributed.

4. DIVERTOR OPERATION METHODS

As discussed in the introduction, the shielding space is not a problem.
The use of a double null divertor gains many advantages over the use of a single
null divertor. The PDX experimental result shows that the power load to the
divertor is equally distributed to inner and outer branches of the single null
divertor [6]. Because the target area is smaller in the inner branch, the power
density would be higher. For the double null divertor, approximately 90% of the
power flows to the outer branch which has a larger area. Then the advantage of
using the two null divertor is that the power and particle densities will be
more evenly spread. The total target area will also be doubled; therefore, 1 mm
of target thickness will last 4 years.

To pump 1% of the total particle flux of 1.5×10^{23}/sec, there is still
1.5×10^{21} particles/sec to be pumped. The tritium through-put would be
7.5×10^{20} particles/sec which still gives very large tritium inventory. It
would be better to find a way to recycle the tritium inside the tokamak. A
method to accomplish this is to put a D & T getter pump inside as shown by Fig. 6
or use the getter as D & T filter. He and a fraction of other impurities can be
removed by an external pump. D & T can be released later as fuel. The advantage
of the getter pump is that the impurities will not be released during the remission
process and the fuel is free of impurities and He. Each divertor can be operated
as divertor and gas puffing fueling alternatively. Both divertors will use the same
pumping facility with the pumping path controlled by a gate valve.

5. REVISITING OF THE HIGH EFFICIENT DIVERTOR

In the past year, because of the concern of excessive pumping requirement and tritium inventory, it was considered desirable to recycle the fuel and keep the plasma edge cool. The diffusion at the plasma edge has to be enhanced due to the large recycling. This greatly increases the particle load on the target. From the scaling law of the bulk plasmas diffusion coefficients [7]

$$D = 500 \left(\frac{v}{a}\right)^3 + 1.25 \times 10^{17}/n_e \qquad (3)$$

we can estimate the bulk plasma confinement time for INTOR to be about 3 sec. The particle leakage flux would be 1.5×10^{22} which is one order of magnitude less than the recycle case. The plasma edge temperature is usually about 3 keV and electron temperature is higher than the ions. The total ion energy on the target is as high as 15 keV due to the effect of sheath potential. This again reduces the sputtering yield by a factor of 10. The combined effect of less particle flux and higher energy will reduce the erosion rate by two orders of magnitude. With regard to the target life time, it is better to operate the divertor at high efficiency. The tritium through-put is about 7.5×10^{21}/sec, which is 10 times larger than the recycle divertor. These issues and pumping problems are under study.

6. THERMAL CONSIDERATION

For a heat flux of less than 0.1 kw/cm^2, the thermal hydraulic design of the target is well within the state of the art. Here we would like to investigate the possibility of using superheated steam as a coolant so that the thermal energy can be recovered. Let us consider a tube 20 cm long with an inner diameter of 1 cm and wall thickness of 3 mm. To drive a steam turbine directly, a suitable choice of steam pressure is 100 atm and mean temperature is 400°C. For a through

the tube velocity of 40 m/sec, the heat transfer coefficient is 4.64×10^{-4} kw/cm^2°C [8]. The heat flux at the inner wall is 0.16 kw/cm^2, thus the temperature difference between the inner wall and steam is 350°C. The temperature increase at the exit end of the tube can be calculated from the equation

$$\rho V C_p \; \frac{dT}{dx} \; \frac{\pi d^2}{4} = \pi D \cdot q \qquad (4)$$

we obtain $\Delta T = 35$°C. The thermal characteristics are given in Table 3. It can be concluded that the superheated steam cooling and thermal energy recovery are feasible.

Table 3. Thermal characteristics for molybdenum tube cooled by superheated steam.

Tube length	20 cm
Wall thickness	3 mm
Steam pressure	100 Atm
Steam velocity	40 m/sec
Steam temperature	400°C
Exit temperature	435°C
Inner wall temperature	810°C
Outer wall temperature	840°C

7. CONCLUSION

The preliminary analysis shows that a divertor system can be designed with a target life of 4 years at a power density of 0.1 kw. The benefit of this power density level is that a molybdenum target can be cooled by superheated steam and thermal energy recovery is possible.

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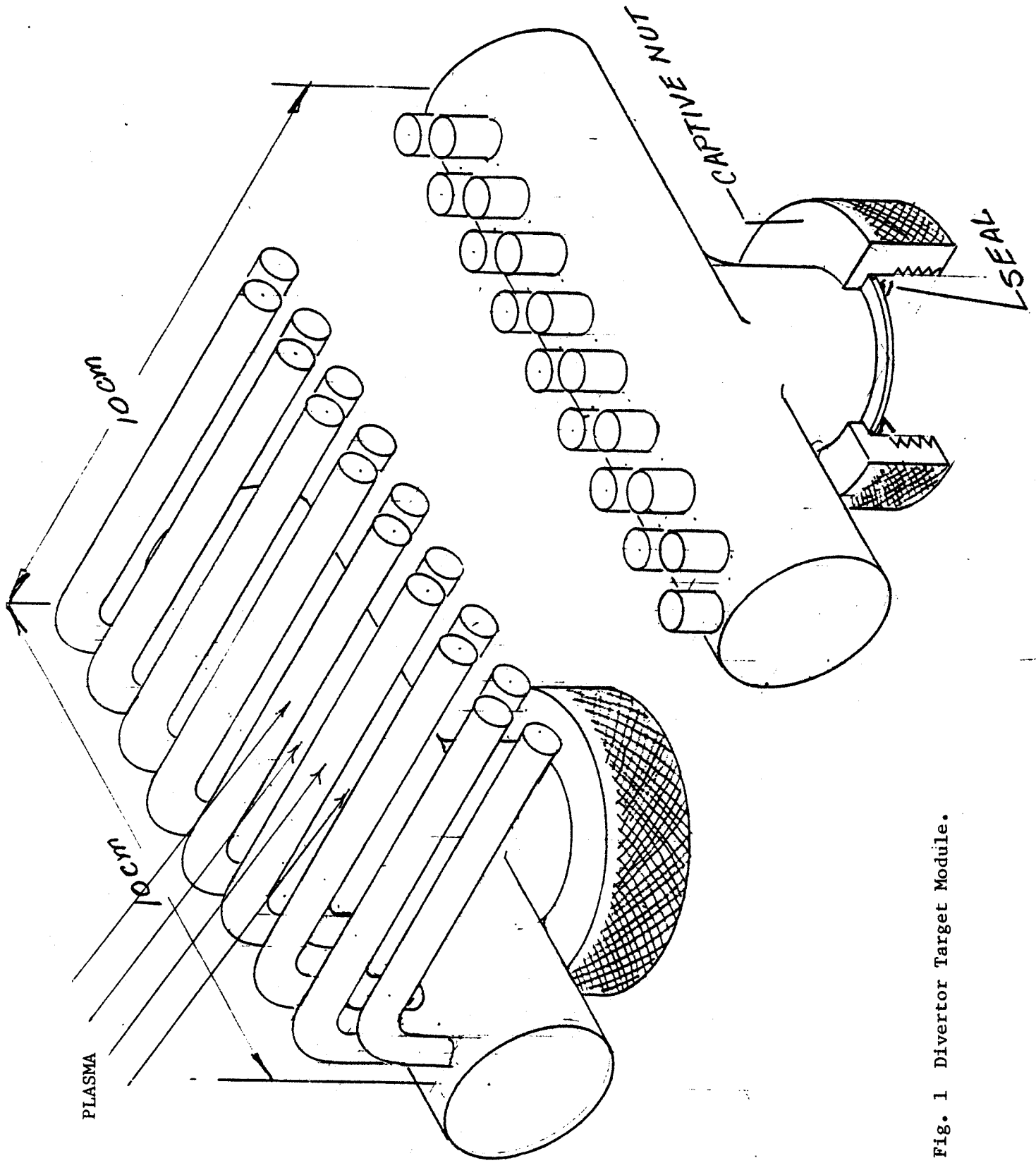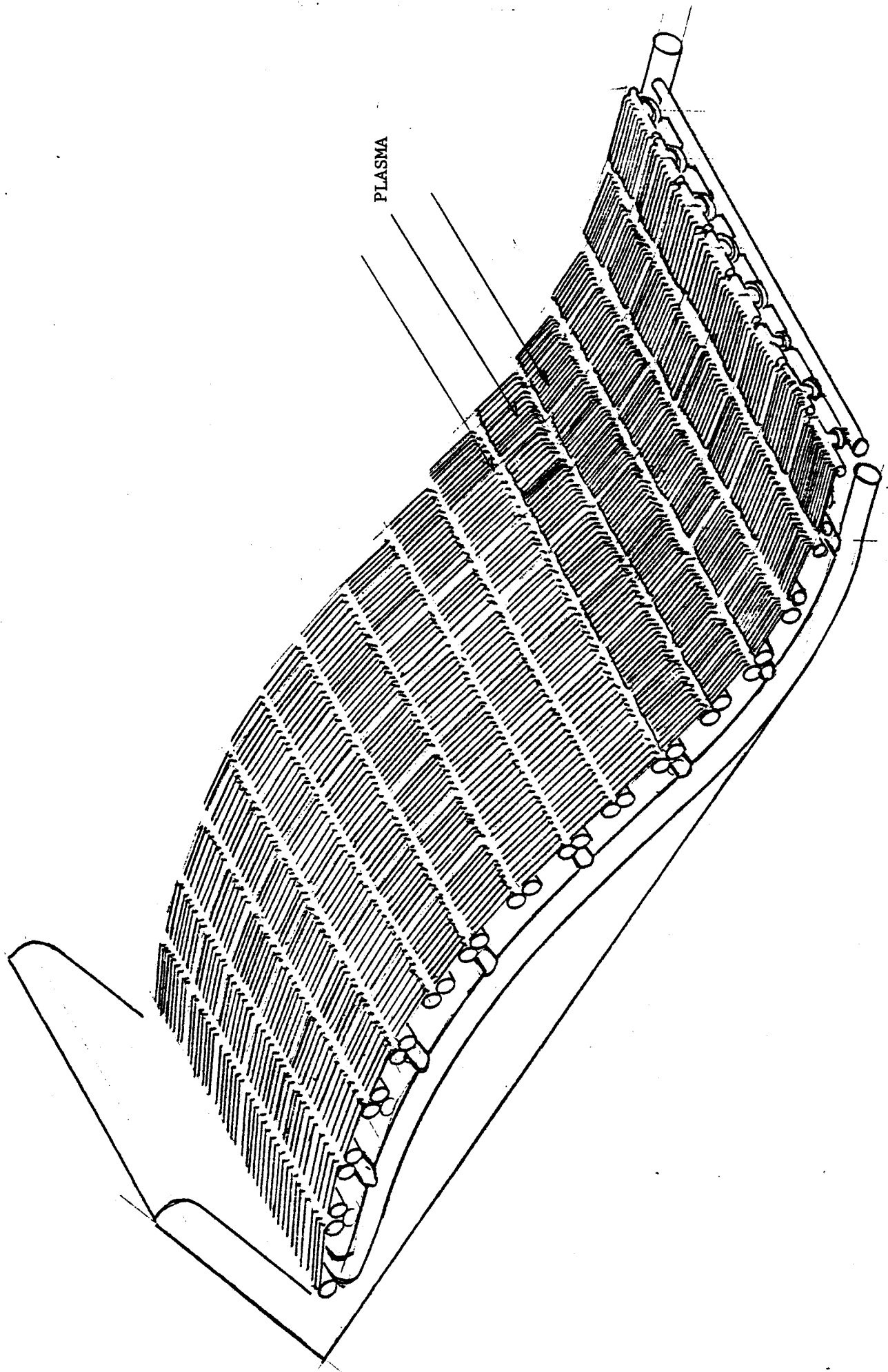
Fig. 1 Divertor Target Module.

PLASMA

Fig. 2 A section of Divertor Target assembled from the modules where the tubes are oriented in the transverse direction.
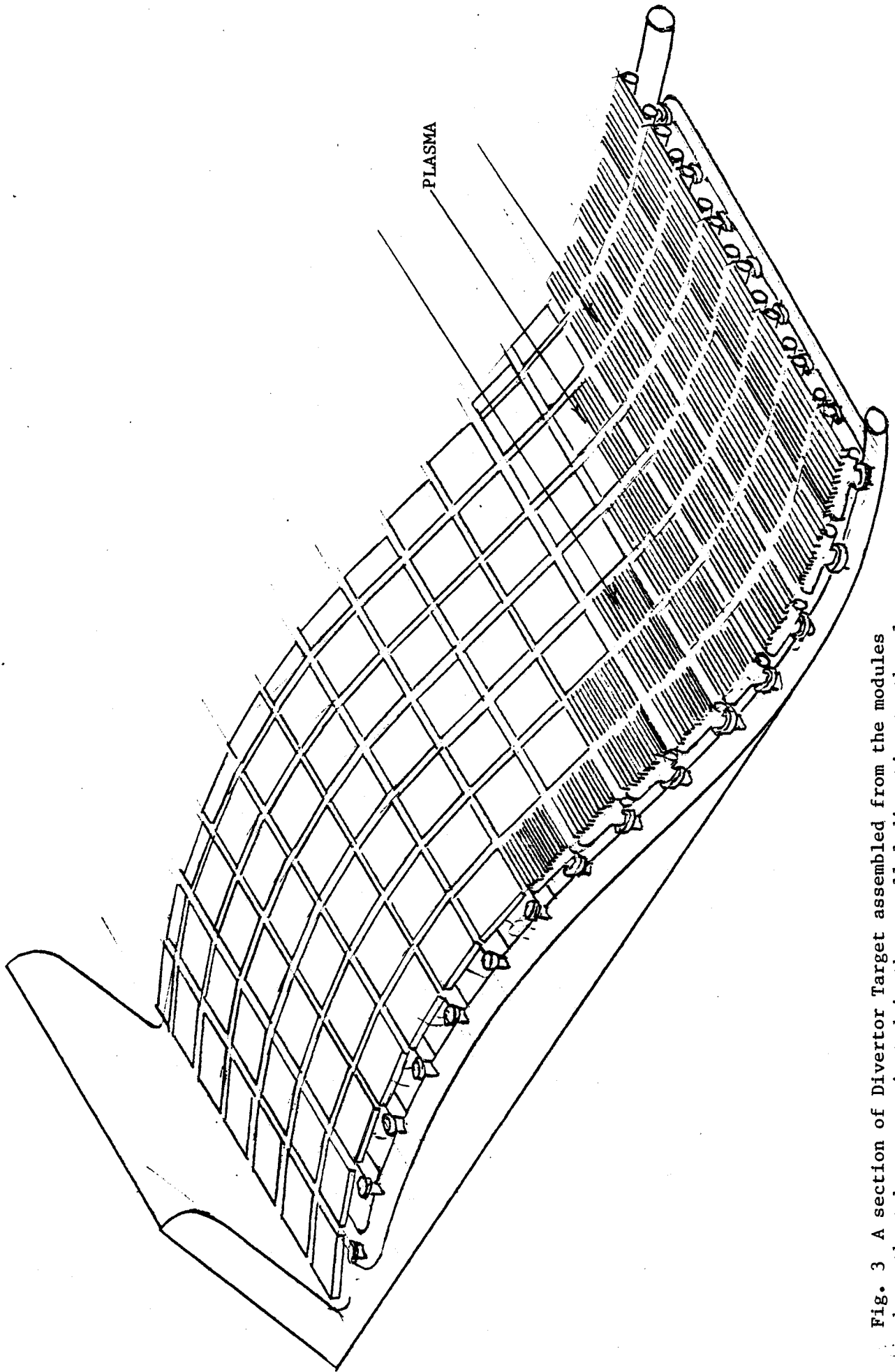
PLASMA

Fig. 3 A section of Divertor Target assembled from the modules
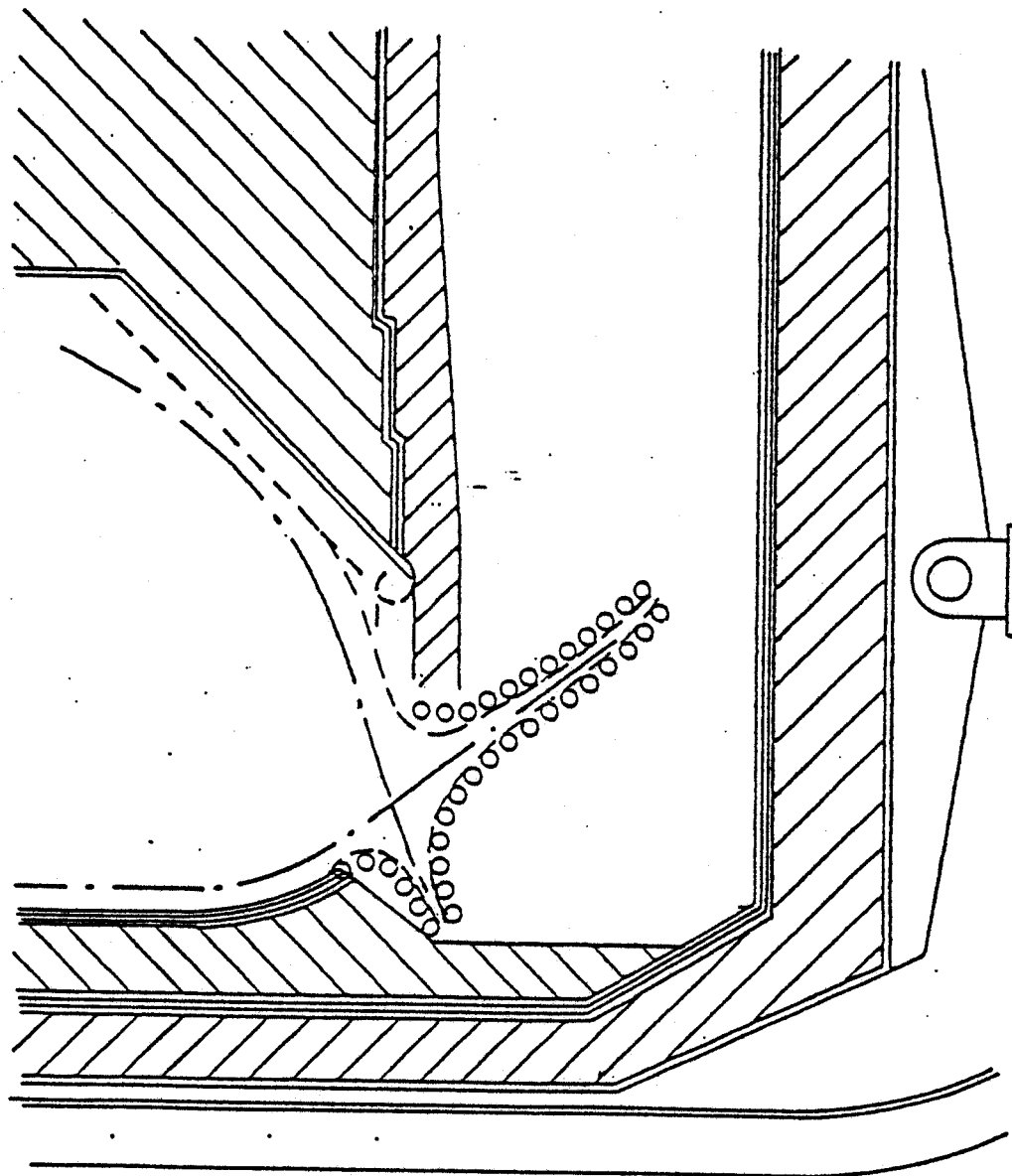where the tubes are oriented in the parallel direction to the plasma.

Fig. 4 The targets are placed on the sides of the plasma slab on each branch of the divertor.
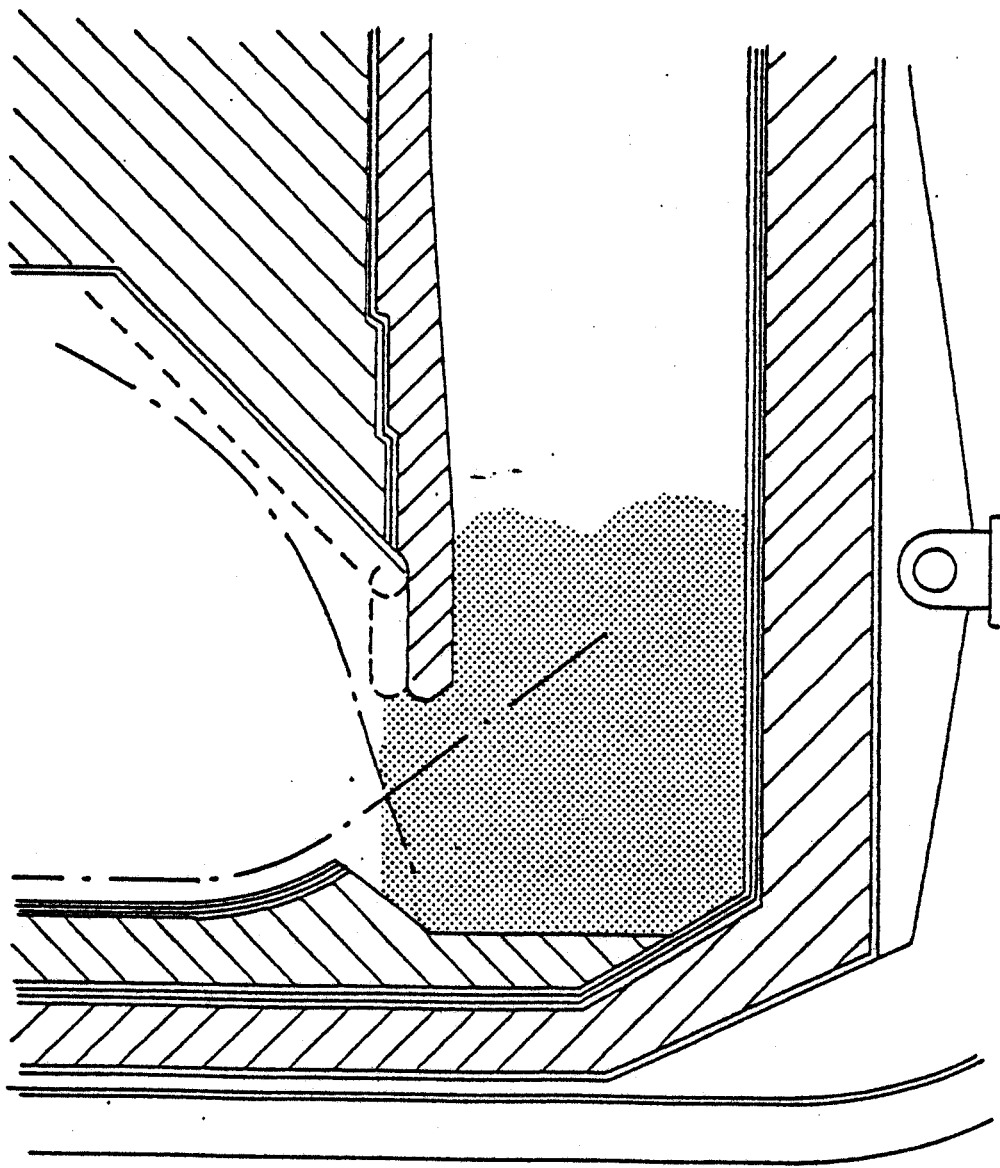
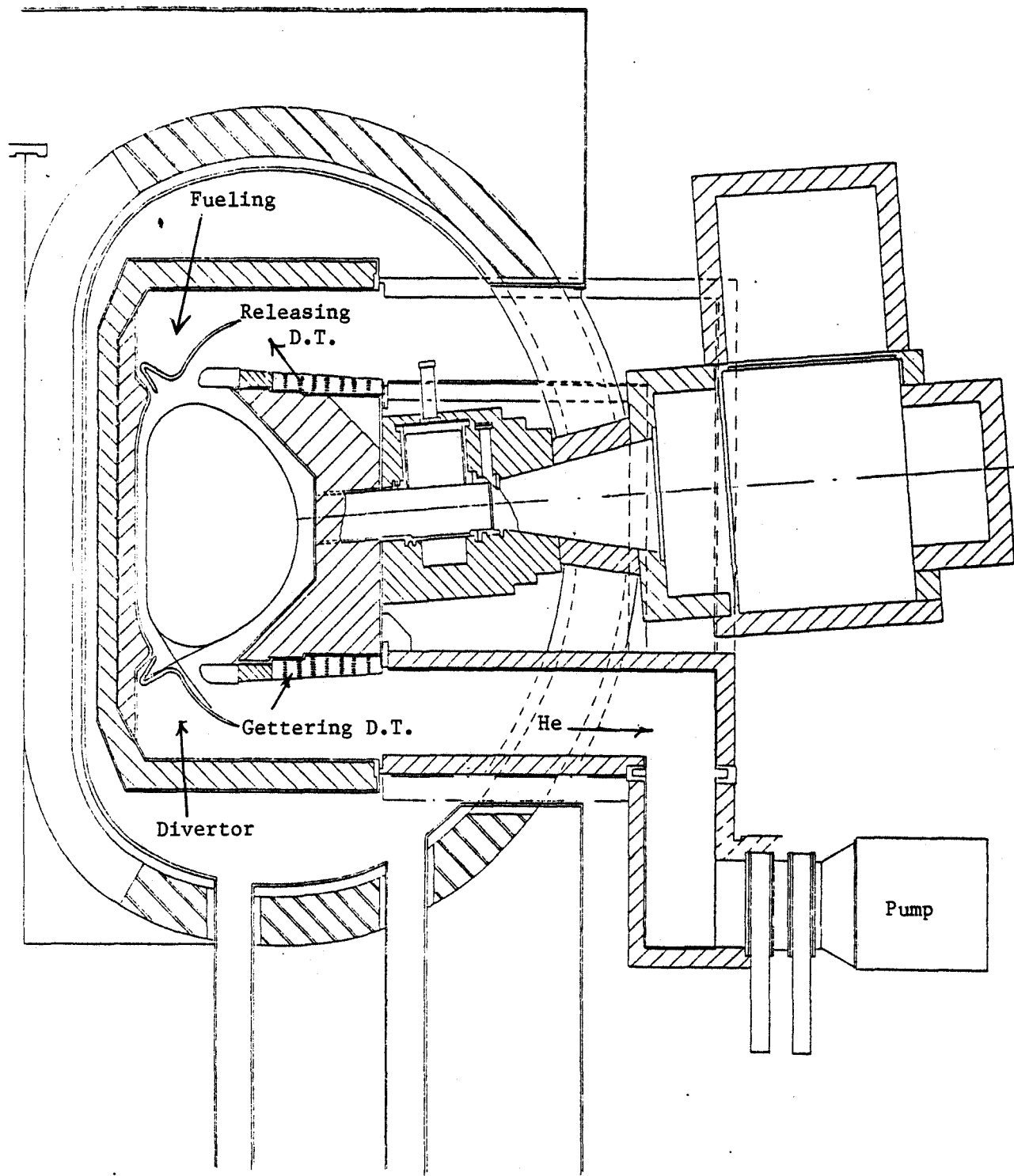Fig. 5 Gaseous target and the chamber wall is thermally shielded by water cooled tube modules.

Fig. 6 The proposed operational methods for double divertors. The divertor on the top is releasing D & T fuel into the plasma where the one at the bottom is pumping. During the pumping phase the D & T fuel is trapped and only He ash is removed.