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# ENGINEERING DESIGN OF A LIQUID METAL COOLED SELF-PUMPED LIMITER FOR A TOKAMAK REACTOR*

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# ENGINEERING DESIGN OF A LIQUID METAL COOLED SELF-PUMPED LIMITER FOR A TOKAMAK REACTOR*

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## Abstract

A lithium cooled self-pumped limiter has been designed as the impurity control system for the TPSS high-β power reactor conceptual design. The limiter removes helium by trapping impinging helium ions in freshly deposited vanadium surface layers in a slot region. No hydrogen is removed and no pumps or vacuum penetrations are used, thereby eliminating penetration shielding and reducing tritium handling. The limiter is composed of a vanadium alloy structure with a 2mm tungsten cladding on the front face and leading edges for sputtering control. Up to ~ 3cm of vanadium trapping material is deposited in the slot region during 5 years of operation. A key design feature is the use of a calcium oxide electrical insulator which coats the limiter coolant channels to reduce MHD pressure drops. A combination of high lithium coolant velocity, made possible by the insulator, and mid-limiter manifolding has been used to obtain acceptable material temperatures with moderately high heat fluxes (3-5 mw/$m^2$). Overall, a limiter lifetime of ~ 5 years is predicted by stress and lifetime analysis. This would permit maintenance free impurity control operation between first wall/blanket replacement periods.

## Introduction

The Tokamak Power Systems Studies (TPSS)[1] goal was to explore and develop ideas that would lead to improvements in the tokamak as a power reactor. For the impurity control system we sought innovative ideas that could reduce the cost and complexity of the system while also increasing reliability. A lithium cooled, self-pumped limiter system was designed which appears to offer substantial advantages over the alternatives of a pumped limiter or divertor. In particular, the system eliminates vacuum pumps and ducts (except for a small startup system) and associated penetration shielding, and reduces the tritium processing system; a savings of ~ 35M$ results from these reductions. The mass power density of the reactor is higher because of the reduction of 700 metric tons of penetration shielding. The helium removal efficiency, at 7.5%, may be significantly higher than obtainable with pumped systems. Lithium cooling offers several advantages for tokamaks in areas of tritium breeding, thermal efficiency, and compatibility with advanced materials. Finally, improvements in reliability, though hard to quantify, may be realized by using a less complex system that does not need frequent replacements.

## Self-Pumping

The self-pumping concept is described in Ref. 2. Briefly, the concept is to remove helium in-situ by trapping in freshly deposited metal surface layers of a limiter or divertor. A key requirement is for the deposited material to trap helium much better than hydrogen. It has been demonstrated experimentally that nickel preferentially traps helium[3,4] and that several other materials (iron, vanadium, niobium, molybdenum, and tantalum) are believed capable of preferential trapping. The selective trapping of helium in certain metals is the result of the negligible solubility of helium in the lattice. The injected helium will diffuse through the lattice until it reaches a trapping site where it can come out of solid solution. Hydrogen, on the other hand, remains in solid solution until it diffuses to the surface and escapes. Other plasma contaminants, notably oxygen, can be removed by the self-pumping system by chemically combining with the deposited metal.

The self-pumped system requires no in-burn pumping of hydrogen. Protium, formed by the D-D reaction, needs to be removed, but natural diffusion into the coolant has been calculated to be adequate to remove the protium, limiting its plasma concentration to ~ 1%.

Several important properties of self-pumping materials are uncertain particularly in the high neutron irradiation environment of future reactors. Two design parameters affecting the system lifetime are the trapped helium concentration, and the maximum operating temperature for selective helium trapping. We have estimated these parameters at 30 at% average concentration and 0.7 of the melt temperature, respectively. These are optimistic but hopefully feasible values which need experimental assessment, as does mechanical properties of the deposited surface.

## Limiter Configuration

The limiter design is shown in Fig. 1. Design and plasma related parameters are summarized in Table 1. The design is similar to a pumped limiter except for the absence of pump ducts behind the limiter. Helium trapping is done on both sides of the slot region. The limiter is constructed of 2mm thick vanadium alloy. A 2mm cladding of tungsten is used on the front face and leading edges for sputtering control. (Without the cladding the erosion rate of the vanadium structure is excessive.) Vanadium is used as the reference trapping material because of its thermal properties, compatibility with the first wall and limiter structure, and its lack of serious activation products. Nickel and iron are alternative trapping materials. Pure vanadium metal is added to the slot region via pellet/dust injection, at a rate of about three times the α -production rate. The injected vanadium is ablated and conveyed to the slot surfaces along field lines. The surfaces continuously increase in thickness as fresh material is added. The trapped helium containing layers are thus continuously buried with fresh surface material.

Plasma parameters important to the limiter design are a high radiation fraction (75%), which minimizes transport power to the limiter, and a low edge temperature (50eV) which permits the use of a high Z cladding for erosion control.

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TABLE 1.

Limiter Design and Plasma Related Parameters

| Parameter | Value |
|---|---|
| Concept | Slot, self-pumped, MHD Insulated, Li cooled limiter |
| Structural material | V-15Ti-5Cr (2 mm) |
| Front face and leading edge cladding material | W (2 mm) |
| Helium trapping material | V (Fe, Ni) |
| Insulator type | CaO coating |
| Limiter location | bottom |
| Front face shape | constant heat flux |
| Front face area | 60 $m^2$ |
| Slot-trapping area | 120 $m^2$ |
| Plasma major radius | 6.0 m |
| Neutron wall loading | 5.0 $MW/m^2$ |
| Fusion power | 1950 MW |
| Total plasma heating power, ( $\alpha$ + current drive) | 490 MW |
| Plasma radiation fraction | 0.75 |
| Surface heat flux, (transport + radiation) limiter front face, average: | 3.3 $MW/m^2$ |
| peak: | 6.6 $MW/m^2$ |
| Surface heat flux - leading edges | 5.0 $MW/m^2$ |
| Surface heat flux - trapping sites | <0.2 $MW/m^2$ |
| Plasma edge temperature | 50 eV |
| Net erosion rate, front face and leading edges | ~ 0 |
| Helium removal efficiency (helium removed/helium edge current) | 7.5% |
| Limiter lifetime (at 75% availability) | 5y |

As shown in Fig. 1 liquid lithium enters and exits the bottom of the limiter. The inlet and discharge manifolds can be either a concentric pipe or separated by one sector length in the toroidal direction. This design has the advantage of removing heat first from the front face where the heat flux is high. Another advantage of mid-limiter manifolding is that the coolant is exposed to a high heat flux over a distance of 0.8m instead of the full length of the limiter (1.6m).

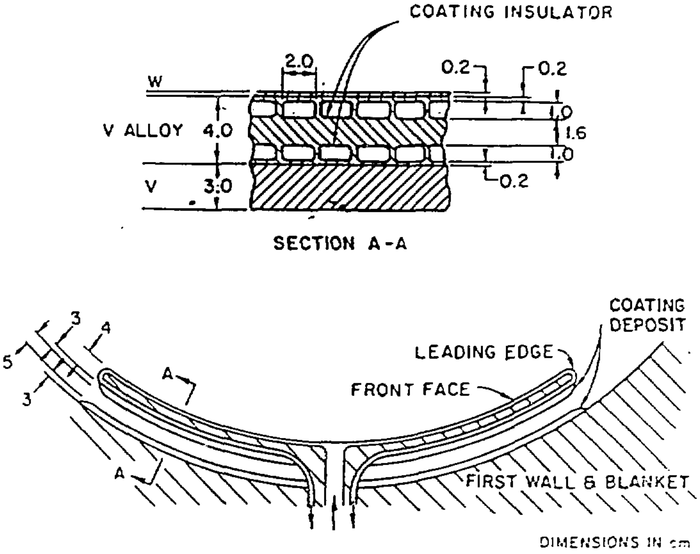

Figure 1

Self-Pumped Slot Limiter Design.

The cross section and dimensions of the coolant channels are also shown in Fig. 1. A calcium oxide "coating" insulator is applied on the inside of the coolant channels. The coating is several microns thick which is adequate to substantially reduce MHD pressure drop while presenting a negligible heat transfer resistance. Based on our study it appears essential to use some type of insulator for pressure drop control in liquid metal cooled impurity control components. An alternative to the coating insulator is a laminated insulator structure consisting of an insulator covered by a thin metal layer. This has the advantage that the insulator is not in contact with the lithium, thus avoiding possible chemical problems.

The purpose of using an electrical insulator in the coolant channel is to reduce the MHD pressure drop so that the coolant velocity can be increased. The reduced pressure drop alleviates the primary stress problem while the increased coolant velocity reduces the structural temperature and temperature gradient in the system (hence reducing the thermal stress problem). The equations for pressure drop in a straight duct in a uniform transverse magnetic field (to the flow direction) are,

$$\Delta P = \ell V B^2 \sigma_w t/a \qquad (1)$$

for thin conducting walls (laminated insulator) and

$$\Delta P = \frac{\ell V B \sqrt{\sigma \mu}}{a} \qquad (2)$$

for non-conducting walls (coating insulator), where $\ell$ is the axial length of the channel, V is the coolant average velocity, B is the magnetic flux density, $\sigma_w$ is the electrical conductivity of the thin wall, $t_w$ is the thickness of the thin wall, $\sigma$ is the electrical conductivity of the liquid-metal coolant, $\mu$ is the viscosity of the coolant, and a is the half-width of the coolant channel in the direction of the magnetic field. It can be seen that the pressure drop is proportional to $B^2$ for a laminated insulator and to B

TABLE 2.

Thermal Performance of Limiter (at end-of-life)

| | |
|---|---|
| Coolant average velocity (m/s) | 5.0 |
| Total pressure drop (MPa) | 0.25 |
| Total coolant mass flow (kg/s) | 1621 |
| Total energy deposited (surface heat load & nuclear heating) (MW) | 275 |
| Coolant inlet temperature (°C) | 230 |
| Average coolant temperature rise (°C) | 40 |
| Coolant outlet temperature (°C) | 270 |
| Max. structure temp.,°C<br>Allowable (V-alloy), °C | 757<br>750 |
| Max. pressure, MPa<br>Allowable (bending stress), MPa | 0.25<br>4.2 |
| Max. Coolant/Structure Interface Temp., °C<br>Allowable (insulator), °C | 410<br>480 |
| Max. coating (vanadium) temp.,°C<br>Allowable (70% melting point), °C | 970<br>1240 |
| Max. coating (tungsten) temp., °C<br>Allowable (70% melting point), °C | 862<br>2300 |

for a coating insulator. Thus, if B = 5T, a factor of 5 is gained immediately through the use of a coating insulator. Furthermore, the quantity $\sqrt{\sigma\mu}$ in Eq. (2) is one order of magnitude smaller than $\sigma_w t$ in Eq. (1). Therefore, a factor of 50 in pressure drop can be realized if a coating, instead of a laminated, insulator is employed.

## Heat Transfer Performance

Thermal performance of the limiter is summarized in Table 2. The average coolant velocity in the limiter (front and back channels) is 5 m/s which results in a total pressure drop of only 0.25 MPa. This illustrates the advantage of using the coating insulator in the coolant channels. The low system pressure provides significantly improved design margins for primary stresses (hoop and bending). The thicknesses of the structural material of the manifolds and the inlet and discharge pipes outside the blanket modules can also be reduced. Furthermore, the low pressure design should be safer than a high pressure system.

The relatively high coolant velocity (5 m/s) is needed in order to maintain the coolant/structure interface, the structural material, and the coating deposit temperatures below their limits. The interface temperature should be below 480°C in order to make the coating insulator work. The calculated maximum, interface temperature is approximately 410°C. The maximum coating temperature (970°C) for vanadium shown in Table 2, is calculated based on a vanadium thickness of 3 cm at the end of life (EOL) of the limiter. This is ~ 60% of the melting temperature. The allowable temperature of tungsten on the front face and leading edges of the limiter is also assumed equal to 70% of its melting point. The calculated maximum tungsten temperature of 770°C is based on the assumption that the contact between tungsten and vanadium alloy is perfect and there is therefore no resistance to heat transfer at the interface. Since the allowable temperature for tungsten is extremely high (2300°C), it is not likely that this temperature limit will be exceeded even if some contact resistance exists at the interface.

The most limiting design condition comes from the structural temperature at the leading edges. This is the result of the relatively high heat flux (5 MW/m$^2$) at the leading edge. The allowable temperature for V-15Cr-5Ti is 750°C while the calculated maximum temperature of the vanadium alloy at the leading edge is approximately 750°C. This indicates that little or no margin is available at the leading edge and the heat flux there should not exceed 5 MW/m$^2$.

The high coolant velocity (5 m/s) results in a low coolant temperature rise (40°C) through the limiter. The coolant inlet temperature was kept low (230°C) in order to satisfy the structural temperature requirement at the leading edge. These two factors resulted in a coolant outlet temperature of 270°C which is much lower than the average coolant outlet temperature from the blanket. The total energy deposited in the limiter (275 MW) is approximately equal to 10% of the thermal power of the fusion reactor. This thermal energy could be used to preheat the feedwater in the steam generating system. Alternatively, Li coolant could be channeled from the outlet of the limiter to the inlet manifold of the blanket to remove the heat in the blanket.

## Stress and Lifetime Analysis

The stress distribution through the slot limiter and the lifetime of the limiter has been analyzed by two separate methods. First, a 2-D finite element analysis, using the ADINAT and ADINA codes, was performed, which provided the temperature and stress distribution through the entire limiter cross section. Second, 1-D stress and lifetime calculations were performed which analyzed the time evolution of materials properties, stresses, and strains in the limiter. This analysis includes the combined effects of material deposition, radiation creep, radiation swelling, and radiation induced changes in mechanical properties on the lifetime. Overall, both methods predict that the limiter should be able to operate for a period of approximately five years under the reference operating conditions.

The stress distribution through the limiter surface structure is shown in Fig. 2. These calculations were made assuming that the plate is totally constrained from expansion, which is believed to be the most severe stress constraint. During the burn cycle, the stresses through the plate are generally compressive, and during the dwell cycle, the stresses are generally tensile. The maximum difference in stresses between the burn and dwell cycles is ~ 1000 MPa which is quite high. If the reactor operated in a high cycle mode, then these high

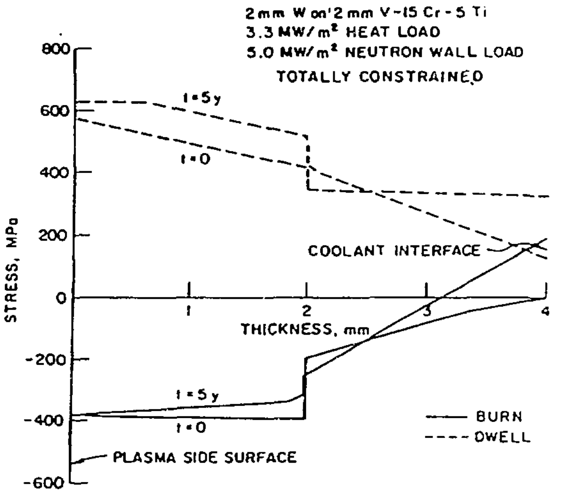

Figure 2

Stress distribution through the limiter front surface at start of life and after 5 y. The plate is assumed to be totally constrained from expansion.

stresses would likely lead to fatigue or crack growth failure. However, this type of failure is not predicted to be a problem here, because of steady state operation.

The effects of radiation on the limiter plate were analyzed. For most of the limiter life, the uniform elongation is predicted to be less than 2%. During normal operation, a reduction in ductility will not affect the limiter operation, but there will be less of a safety margin to accommodate accidents and off-normal events. The peak swelling and creep rates in the limiter plate are shown in Fig. 3. The peak level of creep is expected to reach ~ 3%, while the peak level of swelling is predicted to reach 10%. Creep and swelling tend to occur in opposition to each other, however, so that the total change in dimensions is essentially zero. Since there is a net volume increase with swelling, the increase in dimension will occur in the thickness direction of the plate where the stress levels are relatively low. The total amount of swelling is somewhat high, but it should be noted that the long term swelling response of materials under fusion conditions is quite uncertain at present.

## Discussion

A number of issues may have a significant impact on the design. These include: (1) allowable temperature and thermal-mechanical properties of the deposited coating, (2) heat flux and coolant velocity distribution at the leading edges, (3) reliability of the coating insulator, and (4) integrity of the interface bonds between the tungsten and V-15Cr-5Ti.

Finally, there are uncertainties in the long term effects of 14 MeV neutron damage.

Design alternatives include the use of an all tantalum structure instead of the V alloy-W cladding, laminated type insulators, and other trapping materials (Fe, Ni, etc).

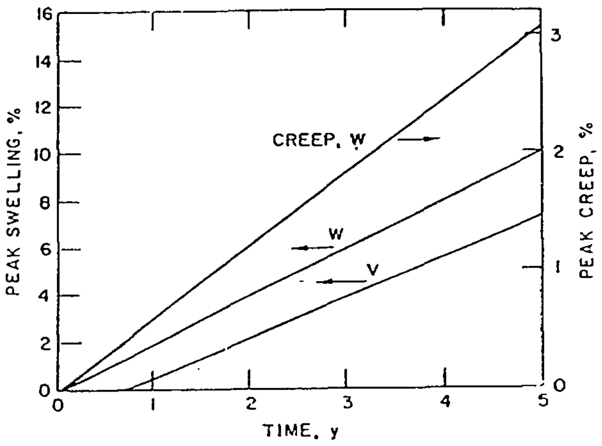

Figure 3

Peak swelling and creep in the limiter plate during 5 y operation.

## Conclusion

A self-pumped, lithium cooled limiter has been designed as part of the TPSS project which sought ways of improving the attractiveness of tokamak fusion reactors. The system offers advantages in reliability, simplicity, cost, and helium removal efficiency over a divertor (although a self-pumped divertor is also possible) or a pumped limiter. Lithium cooling is not an advantage per-se for impurity control components, but is necessary for compatibility with the use of a lithium cooled tokamak where it offers numerous advantages. The design uses an electrical insulator coating the coolant passages to reduce MHD pressure drops. With the coating insulator, the major engineering design issue is similar to water cooled components, namely, the front surface and leading edge heat loads. In order to minimize the surface heat loads it is desirable to radiate a high fraction of the α heating and current drive powers from the plasma.

Detailed stress calculations have been performed for the limiter design. In general, steady state operation is of great help in minimizing the stress problems, a conclusion in line with other studies.

The ambitious goal of obtaining a limiter lifetime of ~ 5 years appears possible, with key uncertainties being the leading edge heat loads and stresses, and self-pumping materials characteristics.

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