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MECHANICAL AND THERMAL DESIGN ASPECTS OF THE BLANKET, AND MAINTENANCE CONSIDERATIONS FOR THE CENTRAL CELL IN MARS

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ABSTRACT

This paper describes the mechanical and thermal design features of the MARS (Mirror Advanced Reactor Study) blanket and presents a credible concept for maintaining the central cell components of the reactor.

INTRODUCTION

MARS is a conceptual design study of a tandem mirror fusion power reactor with thermal barriers.[1] A primary objective of the design is to take maximum advantage of the linear geometry of the power producing central cell both in terms of blanket design as well as simplicity and credibility of maintenance. Some other criteria established early in the design are:

1. A simple, modular blanket design.
2. Avoid making seals between blanket modules.
3. Minimize number of coolant connections.
4. Coolant connections should be reliable and operated by remote control.
5. Blanket replacement accomplished without movement of superconducting coils.
6. Central cell maintenance should be straightforward with minimal downtime.

Tandem mirrors are ideally suited for liquid metal blankets because of the relatively low magnetic field in the central cell and the low surface wall heating. For the MARS blanket, the eutectic $Li_{17}Pb_{83}$ was chosen as the breeding/cooling material and the ferritic steel HT-9 as the structure. The outstanding characteristics of these materials and their compatibility with each other are well known.[2-4] The blanket dimensions and the material fractions were chosen as a result of a trade study in which the blanket thickness was varied as a function of Li enrichment to achieve adequate breeding while maximizing energy multiplication.[3] The resulting parameters are given in Table I.

TABLE I Physical Parameters of the MARS Blanket

First wall radius, m	0.59
Outer diameter of blanket, m	1.96
Depth of blanket module, m	1.80
Thickness of tubular zone, cm	19.2
Diameter of front tubes, cm	10.14
Wall thickness of tubes, cm	0.2
Axial spacing of tubes, cm	10.45
Radial spacing of tubes, cm	9.05
Thickness of beam zone, cm	19
Mass of a blanket module, tonnes	2.9

Although the reactor is designed to be accessible to hands on maintenance ~ 48 hours after shutdown, remote control will have to be used as soon as the LiPb is drained or any of the shield is disassembled. Thus, all the operations intended for blanket maintenance are performed remotely. These operations constitute disconnecting coolant lines, opening up of strategically located service stations and axial translation of blanket modules to the service station. The modules, weighing < 3 tonnes each, are then lifted out of the reactor with an overhead crane and transported to an appropriate repository. Preliminary timelines indicate this maintenance scheme is compatible with a short reactor downtime. Unexpected maintenance of non-blanket components is also developed.

BLANKET STRUCTURAL DESIGN

Figure 1 is a cross section of the MARS central cell showing the blanket, reflector, shield, coil and coolant headers. It can be seen that the blanket consists of a tubular zone in the front facing the plasma and a beam-type structural zone in the back. The tubular zone is composed of two rows of seamless tubes spaced on a triangular pitch, which are bent to follow the contour of the circular plasma in the

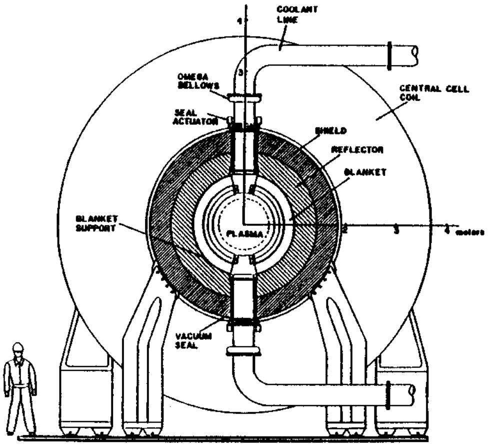

Fig. 1. Cross section of MARS central cell.

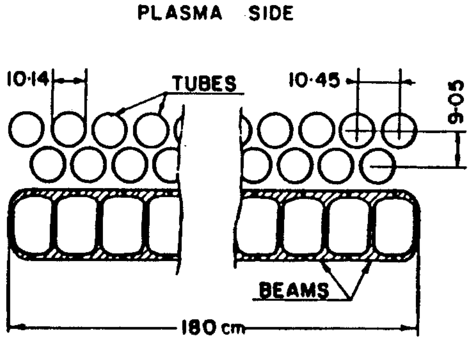

Fig. 2. Cross section of one half of blanket module.

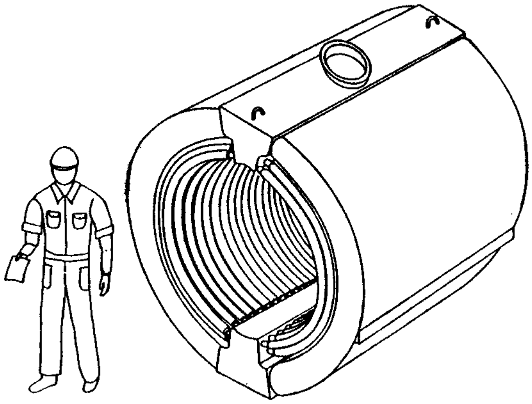

Fig. 3. Isometric view of a blanket module.

central cell. Tubes are appropriate for this application, since they can be thin walled, can withstand high pressures and can be bent to this contour with relative ease. They also insure a uniform flow of coolant in the region where nuclear heating is highest. The tubes terminate in short segments swaged to ~ 60% of the tube area. These segments are welded to the manifolds at the top and bottom.

The so-called beam zone has a dual function. The structural fraction in this area can be higher leading to greater energy multiplication and acting as the support for the blanket. Thus, the blanket is supported on the reflector through stress pads welded to the beam zone and the load path then goes through the shield supports to the rails on the floor. The beam zone is 19 cm thick with rectangular passages, nominally 17 x 11 cm^2 running clear through. This zone can be easily fabricated from I beams bent to shape and welded together. The end caps are specially formed and then welded to the assembly. Figure 2 shows a cross section through one half of a blanket module.

The inner diameter of the blanket module is 120 cm, the outer 196 cm and it is 180 cm deep. Its compactness can be appreciated when viewed next to a 1.8 m man as shown in the isometric of Fig. 3.

In principle, this blanket concept is simple. A single header feeds the breeding/cooling material ($Li_{17}Pb_{83}$) to the manifold in which the magnetic field acts to distribute it evenly in the axial direction. The $Li_{17}Pb_{83}$ then flows down through the blanket tubes and beam zone, collecting into the bottom manifold and exiting through a single exit header. The velocity in the two rows of tubes and in the beam zone is such as to give a uniform temperature within the blanket at any azimuthal angle.

One of the unique features of the blanket design is the way in which the headers are joined to the blanket modules. The scheme is based on a frozen seal of $Li_{17}Pb_{83}$ (which happens to be a good solder), cooled by circulating helium gas. Although this design has been proposed earlier[5], it has been improved to include redundancy, seal verification and continuous leak monitoring.

Figure 4 is a cross section of such a joint with the sealing surfaces amplified. It can be seen that the flanges are clamped together by a set of latches actuated pneumatically from outside the vacuum barrier maintained by the two bellows. This clamp holds the flanges together while the seal is made and provides some mechanical rigidity during reactor operation. The expanded view shows two regions of frozen $Li_{17}Pb_{83}$ with a seal verification and leak detection space in between. The frozen zones are in close contact with a coolant tube which can have hot or cold helium gas circulating, depending on whether the seal is being melted or maintained frozen. The initial sealing material is replaced each time the joint is broken. Seal verification prior to filling the blanket with breeding material is made by evacuating the space between the seals. This space is also equipped with two concentric copper rings separated by an insulator and electrically connected to an alarm. Leaking $Li_{17}Pb_{83}$ along any point on the periphery of the seal shorts the circuit, tripping the alarm. The major advantage of this scheme is that it is self-healing, in that the breeding material always replenishes the seal. Redundancy is provided by having two independent coolant circuits for the two seal zones. These coolant lines penetrate the vacuum barrier at the upper flange on which the actuators are mounted. Thermal stresses at the exit connection can be mitigated by making circumferential slits to isolate the cooled areas and/or by using an insulating layer of ceramic on the inside of the pipe.

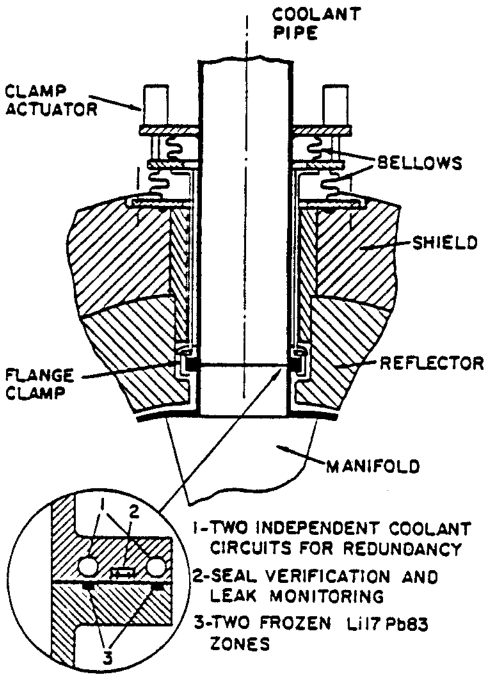

Fig. 4. Cross section of a frozen metal seal joint with amplified sealing surface detail.

Although the initial operating stresses in the blanket are very low, there is some concern that the radiation swelling of the first row of tubes while the manifolds are restrained from motion by the beam zone, will cause excessive bending stresses. The problem can be alleviated by making the connections between the tubes and the manifolds more flexible. Characterization of the degree of swelling and means of correcting the problem are being examined.

THERMAL HYDRAULICS

There are some significant differences in the plasma environment of tokamaks and mirrors which impact the designs of liquid metal blankets. Space limitations and the higher magnetic fields in the inboard side of tokamaks result in severe MHD pressure drops and the high surface heat flux in tokamaks causes difficult heat transfer problems.

The flow of a liquid metal perpendicular to a strong magnetic field is characterized as Hartman flow, namely, it is laminar with a constant velocity profile and a very thin boundary layer. Heat transfer in such a system is dominated by conduction and is, therefore, poor due to lack of turbulence. In mirrors, the surface heat load in the central cell is sufficiently low that poor heat transfer is not a major drawback. Thus, liquid metal flow in tubes is sufficient to cool the first wall.

An exact solution to the problem of conduction heat transfer with both surface heating and non-uniform volumetric heating cannot be obtained. However, a numerical solution is available by the use of finite difference techniques. The energy is obtained from neutronic calculations and the coolant velocity from an energy

TABLE II Blanket Thermal Hydraulic Parameters

Fusion power, MW	2574
Neutron wall loading, MW/M^2	4.24
Surface heat flux, W/cm^2	3.5
Blanket thermal power, MW	2071
Blanket coolant inlet/outlet temp.,°C	350/500
Structure temp. min./max.,°C	350/550
Max. coolant velocity, m/s	1.34
MHD pressure drop, MPa	1.57
Blanket operating pressure, MPa	0.73
Coolant pumping power (60% eff.), MW	27

balance.

With this information, the temperature profile in the tubes can be calculated step by step from the initial temperature distribution. These calculations are summarized in Table II and the temperature distribution in a first row tube is shown in Fig. 5.

MHD CONSIDERATIONS

The dominant force on a conducting fluid moving across magnetic field lines is the MHD effect which increases the pressure drop and retards heat transfer by suppressing turbulence. The major consequence of the high pressure drop is the increase in the pumping power needed to circulate the breeding/cooling material.

The MHD pressure drop is listed in Table II. The total MHD pressure drop is only 1.57 MPa and the operating blanket pressure is ~ 0.75 MPa. The coolant pumping power is 27 MW assuming a pump efficiency of 60%.

CENTRAL CELL MAINTENANCE

The primary aim of the maintenance concept is to achieve a high reactor availability by minimizing the downtime due to routine blanket changeout. At the same time we have tried to make the concept straightforward and as credible as possible by making the operation uncomplicated and adaptable to remote control.

The maintenance concept consists of two parts:

1. Routine blanket changeout which covers:
    a. Scheduled blanket module replacement.
    b. Premature blanket failure.
    c. Breeding/coolant material leaks.
    d. Vacuum leaks at the service stations.

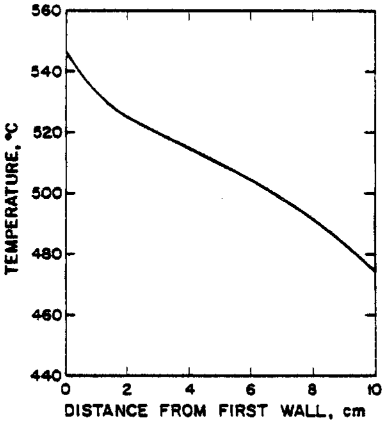

Fig. 5. Temperature profile in a first row tube near the exit manifold.

2. Non-routine maintenance requirements such as:
    a. Failure of a central cell coil.
    b. A water leak in the reflector/shield region.
    c. Vacuum leaks along the central cell other than at the service stations.

ROUTINE BLANKET MAINTENANCE

The MARS central cell is nominally 139 m long and has 41 central cell magnets. There are 72 blanket modules each ~ 180 cm long which are serviced from ten service stations uniformly distributed along the central cell. Each station is capable of servicing seven blanket modules with the two end stations which service eight modules each.

Figure 6 is a cross section of the central cell showing two service stations. The blanket module immediately below the service station and three modules on either side of it are serviced from the same station. The axial length of the module was determined by the space available between central cell coils. Although this scheme requires that some of the spaces between coils have two inlet and outlet headers, it simplifies the concept by obviating the need for displacing coils.

Figure 7 is a cross section of the central cell at a service station. It shows the inlet and outlet headers, the service station cover

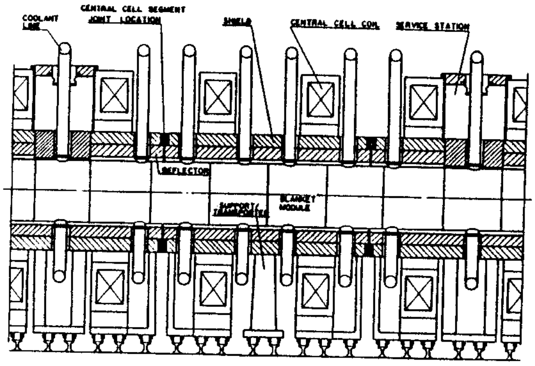

Fig. 6. Lengthwise cross section of the central cell.

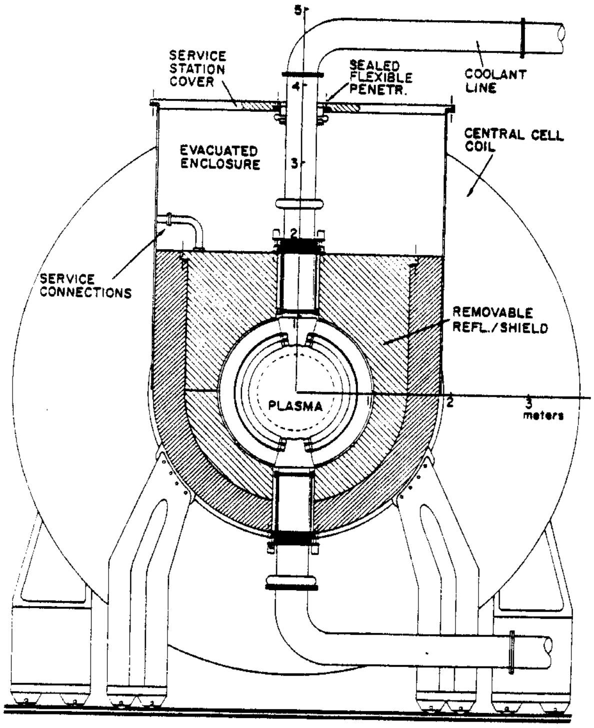

Fig. 7. Cross section of central cell through a service station.

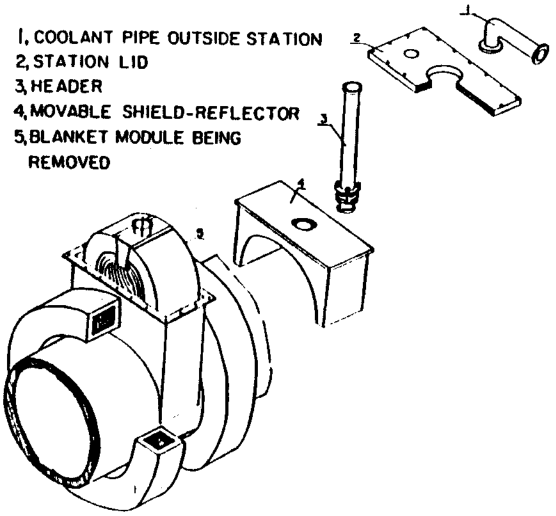

Fig. 8. Sequential steps in gaining access to a blanket module.

flange and the removable upper reflector/shield segment. Once the cover flange is removed, the inlet header disconnected and the reflector/shield segment removed in the sequence shown in Fig. 8, access is provided to the blanket module immediately below. Disconnecting the return header and retracting it slightly frees the module entirely, upon which it can be picked up by an overhead crane, removed through the service station and taken to an appropriate repository. After the headers are disconnected and retracted from the adjoining modules, they are axially translated to the service station and also taken out. A module, drained of the breeding material, weighs only 2.9 tonnes and from Fig. 3, is seen to be very compact. Thus, manipulating it both inside the central cell and outside is deemed to be fairly straightforward.

Several methods have been proposed for moving the blanket modules in the axial direction within the central cell. One method makes use of a robot which rides on the support rails on the reflector, attaches itself to a module and is then pulled back by a cable on a boom lowered into the service station. Another method involves an extendable boom which literally raises the module on a hydraulic pad sufficiently to break it off the support. The module is then retracted while riding on the pad supported on the bottom of the reflector. In either method, there still is the problem of moving the module from the slot adjacent to the service station to the slot below. This is done in the following way. After the reflector/shield segment is removed from the service station, two rather extensive spaces become available on the lower reflector surfaces. Worm screw actuators can be fitted on these surfaces equipped with latches which can attach themselves to the module and pull it into the service station. These actuators are also used in the reverse process, when replacement modules are put into service.

Several additional aspects of this concept have to be pointed out:

1. The service station has a secondary vacuum space to help alleviate the sealing problem at the reflector interface.

2. The headers are equipped with omega bellows to facilitate angular alignment and to make it possible to retract them for clearance at points intermediate to the service station.

3. Coolant connections for the removable reflector/shield segments are made through the service station cover flange.

4. Double bellows are used to seal the actuator mechanism from the vacuum space at each header connection. These bellows make it possible to activate the mechanical latches without penetrating the vacuum barrier.

NON-ROUTINE MAINTENANCE

Unscheduled maintenance occurs in the unlikely failure of non-blanket central cell components which are designed to last the lifetime of the reactor.

This maintenance is accomplished by dividing the central cell into segments consisting of two central cell coils with integral reflector and shield. The segments are sealed to each other at the reflector interfaces by means of expandable joints. Before a segment can be extracted from the central cell, the involved blanket modules must be removed. Then, after disassembling shield segments in the vicinity of the expandable joint, a machining tool is used to cut the joints on either side of the segment. The whole segment, which is mounted on transporters, is then moved out perpendicularly from the central cell. Although one such segment weighs ~ 1500 tonnes, moving it under controlled conditions does not present an insurmountable problem. Once out of the central cell, the failed component is replaced and the segment moved back into operation.

CONCLUSIONS

The blanket design for MARS appears to satisfy the goals which were initially set forth. It is uncomplicated, compact and light, and should be readily fabricable. Heat transfer and MHD calculations show that such a design is extremely suitable for mirrors and requires a low pumping power. The presented maintenance scheme for routine blanket replacement is straightforward and practical, and should result in substantial savings in downtime.

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REFERENCES

1. Mirror Advanced Reactor Study "MARS" Interim Design Report, UCRL-53333, LLNL, 1983.

2. S.N. ROSENWASSER et al. "The Application of Martensitic Stainless Steels in Long Lifetime Fusion First Wall/Blankets", General Atomic Co., San Diego, CA, (*First Topical Meeting on Fusion Reactor Materials*, Miami Beach, FL, January 1979).

3. J.H. HUANG and M.E. SAWAN, "Neutronics Analysis for the MARS LiPb Blanket and Shield", Poster Session 4C-4, *5th ANS Top. Mtg. on Tech. of Fusion Energy*, University of Wisconsin, April 1983.

4. D.K. SZE, R. CLEMMER, E.T. CHENG, "LiPb, A Novel Material for Fusion Applications", *Proceedings of the 4th ANS Topical Meeting on the Tech. of Contr. Nuc. Fusion*, King of Prussia, Pa., Oct. 1980.

5. B. BADGER et al., "WITAMIR - A University of Wisconsin Tandem Mirror Reactor Design, UWFDM-400, Fusion Engineering Program, University of Wisconsin, Madison, WI, Sept. 1980.