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ABSTRACT

A tritium-breeding blanket design is investigated for a D-T Field-Reversed Configuration (FRC) scoping study. The thrust of our initial effort on the blanket has been to seek solutions as close to present-day technology as possible, and we have therefore focused on steel structure with helium coolant. The simple FRC cylindrical geometry has allowed us reasonable success due to the low FRC magnetic field and relatively easy maintenance. In this design the breeder is $Li_2O$ tubes. The design is modular with 10 modules each 2.5 m long. The inner radius of the first wall is 2.0 m and the FW/blanket/shield thickness is about 2 m. The surface heat flux will be radiation dominated, fairly uniform, and relatively low, because most of the charged particles follow the magnetic flux tubes to the end walls. The neutron wall loading is 5 $MW/m^2$. In this design the surface heat flux equals 0.19 $MW/m^2$. The maximum $Li_2O$ tube temperature is 1003°C. The helium exit temperature from the heat exchanger is about 800°C which allows a thermal efficiency of about 52%. The local tritium breeding ratio (TBR) equals 1.1 and is sufficient because in the FRC geometry the plasma has nearly full coverage. The helium pumping power is 1 MW. The coolant routing is optimized to limit the steel maximum temperature to 635°C. The same concept would be applicable to a spherical torus and spheromak.

## I. INTRODUCTION

A helium cooled solid breeder ($Li_2O$) is considered for the FRC first wall and blanket. Oxide-dispersion strengthened (ODS) ferritic steel (developed at Oak Ridge National Lab) is an advanced structural material considered for the reactor components. This new material is exceptionally creep-resistant compared with low activation ferritic-martensitic (FM) steels at temperatures above 600°C. Also, at Oak Ridge National Lab the advanced material program is considering an alternative approach to developing dispersion-strengthened alloys with enhanced high-temperature creep resistance.[1] A new alloy designated A21 is being developed. The alloy is based on an Fe-Cr-Co-Ni-Mo-Ti-C composition. Initial property measurements show that, while the yield strength of A21 is only slightly higher than that of conventional low-activation steel, the creep strength over the range 600°C to 700°C is greatly improved over modified 9Cr-1Mo steel (T-91). Initial property measurements show that, at 650°C, the 10,000 hr rupture stress for the new steel is ≈100 MPa compared to ≈15 MPa for a conventional 9Cr-1Mo steel.

The FRC design is modular with a length/module of 2.5 m. The total number of modules is 10. The solid breeder is $Li_2O$ in the shape of tubes of 90% theoretical density. The cylindrical geometry of the FRC blanket (unlike the tokamak blanket) allows straight $Li_2O$ tubes to be used. The coolant and the purge gas is helium at an average pressure of 18 MPa. In the first zone a single size $Li_2O$ tube is used. The blanket consists of two zones, blanket-I and blanket-II, separated by two rows of steel tubes. The size of the $Li_2O$ tubes in different zones is determined mainly by the temperature limits on the $Li_2O$ solid breeder. The recommended maximum allowable temperature of the $Li_2O$ solid breeder is 1000°C for sintering and the minimum allowable temperature is 400°C for tritium retention. The maximum temperature of the $Li_2O$ tubes at any location of the reactor is determined from the thermal-hydraulics of the specific $Li_2O$ tube zone. The steady state nuclear heating in the different zones is calculated with an average neutron wall loading of 5 $MW/m^2$. The surface heat flux is 0.19 $MW/m^2$. The local tritium breeding ratio (TBR) equals 1.1 and is sufficient because in the FRC geometry the plasma has full coverage. Figure 1 shows a sketch of the radial build (used in nuclear calculations) of the FRC first zone. Table 1 lists the distribution of the constituents of each component and the corresponding average nuclear heating in each zone.

## II. MECHANICAL DESIGN OF THE FIRST WALL AND BLANKET OF THE FRC

The FRC consists of a concentric system of cylinders with the plasma at the core. The inner diameter of the first wall is 4.0 m. The outer diameter of the shield is 8.08 m.

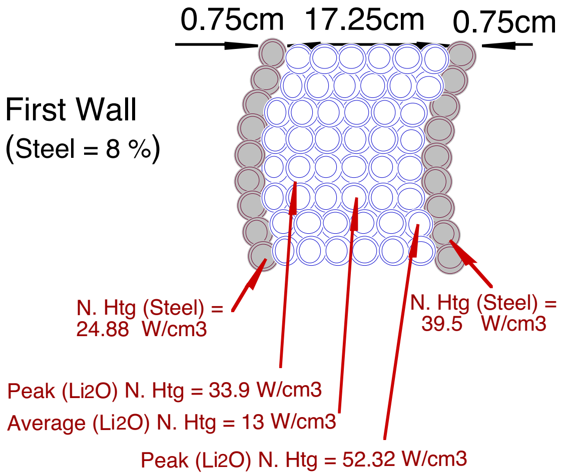

Figure 1. A sketch of the first zone.

The first zone and the outward consecutive layers of the blanket are made of concentric cylinders with the plasma in the center. The first zone consists of a first wall and a back wall made of steel cooled with helium and the space between them is filled with $Li_2O$ tubes also cooled with helium. All the tubes run longitudinally and have a circular cross section. The inner diameter of the steel tubes is 1 cm and the outer diameter is 1.5 cm. The inner diameter of the $Li_2O$ tubes is 1.9 cm and the outer diameter is 3.15 cm. The high pressure boundaries are the steel tubes that compose the first/back wall. One of the advantages of this design is that the $Li_2O$ tubes experience no mechanical loads due to gas pressure because the helium fills the inside/outside of the $Li_2O$ tubes. The thermomechanical integrity of the $Li_2O$ tubes is assured.

The blanket consists of two zones, blanket-I and blanket-II, separated by a layer of steel tubes. Blanket-I and blanket-II, with a thickness of 63 cm each, are filled with $Li_2O$ tubes of 33.8 mm and 50 mm inner and outer diameter respectively. The first, second and the third steel tube layers are composed of two staggered rows of tubes with 21.8 mm and 50 mm inner and outer diameter respectively. The thickness of the shield is 60 cm. All the tubes run longitudinally and have a circular cross section. Figures 1 and 2 show some details of the first zone. Figure 3 shows a detailed cross section of blanket-I with the plasma in the core of the FRC. Table 1 shows a summary of all the inputs into the thermal response calculations and a brief summary of the general dimensions of the FRC.

## A. COOLANT ROUTING

To maximize the power conversion thermal efficiency the outlet helium temperature must be at the maximum attainable value. To achieve maximum power conversion thermal efficiency without violating any of the constraints on the reactor materials' maximum operating temperature, the helium coolant routing must be optimized. The route of the He gas coolant is as follows:

- Cold He (T = 380°C) first enters all steel walls (first wall, blanket walls, and shield (steel)) to keep their temperature below 650°C.
- Then He gas enters (T = 530°C) the $Li_2O$ zones (first zone, blanket-I, and blanket-II) to remove the generated volumetric heating.
- The hot helium exits the blanket to the heat exchanger at about 830°C. The secondary helium exits the heat exchanger at about 800°C.

The helium mass flow rate would be adjusted to make the He exit at a temperature of 830°C. The Brayton power cycle efficiency is about 52% for the cycle He maximum temperature of 800°C. Figure 4 shows the net efficiencies vs. peak temperature for several power cycles: steam, Brayton, and GA/Field cycles.[3]

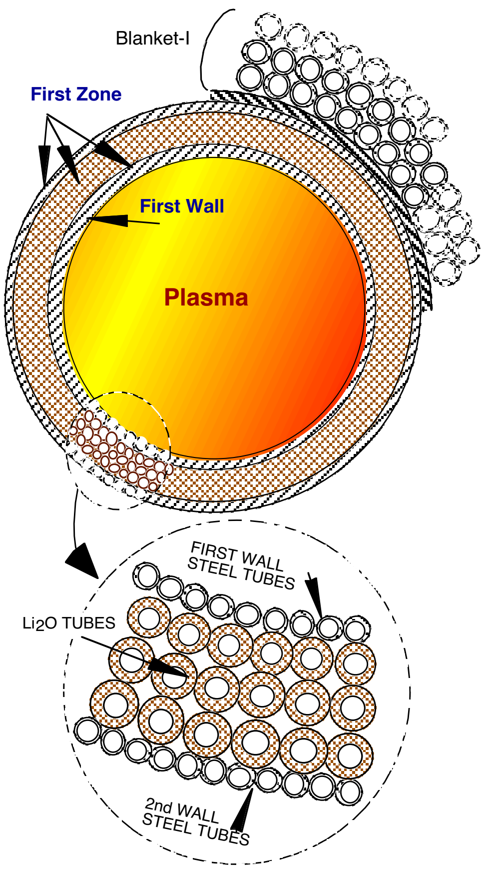


Figure 2. Detail of the first zone of the FRC.

## III. THERMAL HYDRAULICS CALCULATIONS

We assume that the helium coolant has the following parameters:

1. The helium gas flow temperature rise in the first wall is 200°C.

2. The gas pressure is 18 MPa.
3. The properties of helium gas are calculated at the average temperature of the component it cooled.
4. The properties of $Li_2O$ are calculated at the average temperature of the component it cooled.

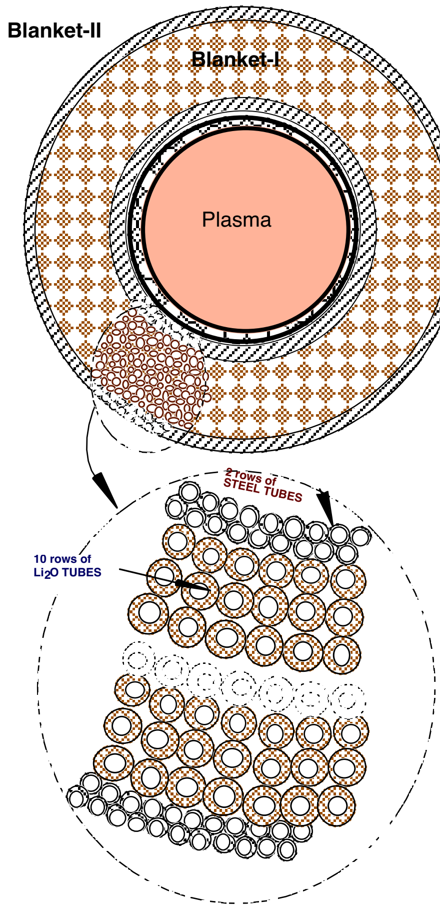


Figure 3. Detailed cross section of blanket-I with the plasma in the core of the FRC.

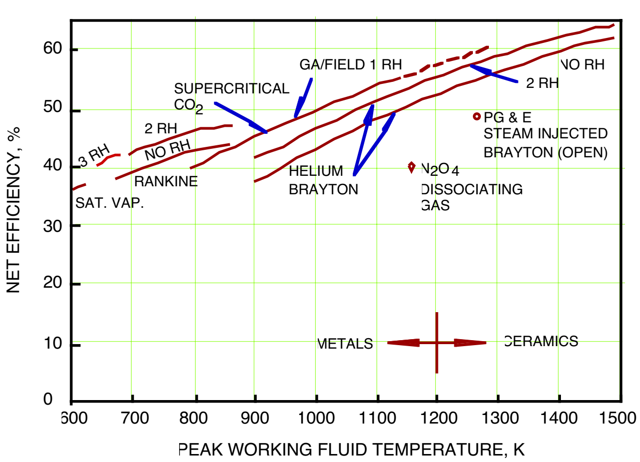


Figure 4. Net efficiencies (extracted from reference 3).

Table 1. The main parameters (dimensions and the specific steady state thermal loads) of the FRC design.

| | |
|---|---|
| Module | |
| Length (m) | 2.50 |
| Number of modules | 10 |
| First zone | |
| 1- First Wall (steel) | |
| Radius from the center of the plasma (m) | 2.0 |
| Outer tube diameter (mm) | 15 |
| Thickness of steel tube (mm) | 2.5 |
| Surface heating ($MW/m^2$) | 0.2 |
| Heating in solid steel ($W/cm^3$) | 38.43 |
| 2- First $Li_2O$ zone | |
| Number of rows | 3 |
| Width (m) | 0.1575 |
| Percentage of $Li_2O$ (without steel) | 30% |
| Percentage of He (without steel) | 70% |
| Outer tube diameter (mm) | 31.5 |
| Average heating ($Li_2O$ +He) ($W/cm^3$) | 13.04 |
| Average heating in solid $Li_2O$ ($W/cm^3$) | 33.12 |
| 3- Second Wall (steel) | |
| Outer tube diameter (mm) | 15 |
| Thickness of steel tube (mm) | 2.5 |
| Heating in solid steel ($W/cm^3$) | 24.88 |
| Blanket-I & Blanket-II | |
| Percentage of steel | 8.3% |
| Percentage of $Li_2O$ (without steel) | 40% |
| Percentage of He (without steel) | 60% |
| a- Blanket-I | |
| 1- Wall-I (steel) | |
| Number of rows | 2 |
| Outer tube diameter (mm) | 50 |
| Thickness of steel tube (mm) | 14.1 |
| Heating in solid steel ($W/cm^3$) | 15.8 |
| 2- First $Li_2O$ zone | |
| Thickness (m) | 0.535 |
| Average heating ($Li_2O$ +He) ($W/cm^3$) | 2.3 |
| Average heating in solid $Li_2O$ ($W/cm^3$) | 5.75 |
| 3- Wall-II (steel) | |
| Number of rows | 2 |
| Outer tube diameter (mm) | 50 |
| Thickness of steel tube (mm) | 14.1 |
| Heating in solid steel ($W/cm^3$) | 1.0 |

b- Blanket-II

1- First $Li_2O$ zone

| | |
|---|---|
| Thickness (m) | 0.535 |
| Average heating ($Li_2O$ +He) ($W/cm^3$) | 0.13 |
| Average heating in solid $Li_2O$ ($W/cm^3$) | 0.325 |

2- Wall-II (steel)

| | |
|---|---|
| Number of rows | 2 |
| Outer tube diameter (mm) | 50 |
| Thickness of steel tube (mm) | 14.1 |
| Heating in solid steel ($W/cm^3$) | 0.07 |

Shield

| | |
|---|---|
| Thickness (m) | 0.60 |
| Percentage of steel | 90% |
| Percentage of $Li_2O$ | 0% |
| Percentage of He | 10% |
| Average heating ($W/cm^3$) | 0.028 |

## IV. RESULTS OF THERMAL HYDRAULICS CALCULATIONS

The total nuclear heating and surface heating (per module) in the steel is 60 MW. The total nuclear heating (per module) in the $Li_2O$ is 120 MW. The helium coolant enters the steel tubes at a temperature of 380°C and exits the steel tubes at a temperature of 530°C. The heat balance requires that the helium mass flow rate be 76.5 kg/s for a 150°C He gas temperature rise. The helium coolant enters the $Li_2O$ tubes after it exits the steel tubes at a temperature of 530°C and exits the $Li_2O$ tubes at a temperature of 830°C. The thermal heat load in the steel tubes is half the thermal heat load in the $Li_2O$ tubes.

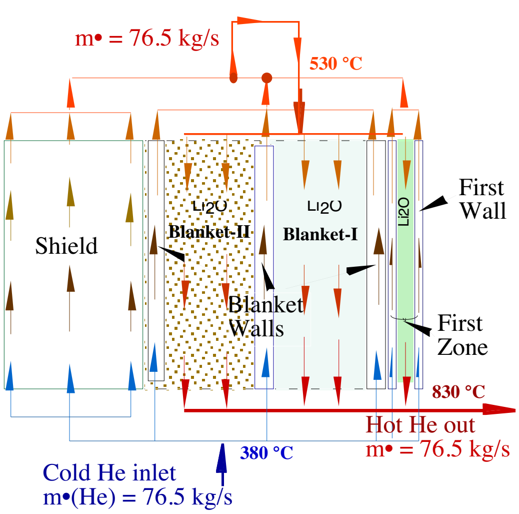


Figure 5. He coolant routing and the corresponding helium coolant mass flow rate and temperature.

Using the same helium mass flow rate of 76.5 kg/s inside and outside of the $Li_2O$ tubes would result in a He gas temperature rise of 300°C. Figure 5 shows a sketch of these results with the coolant routing. Table 2 shows the total steady state heat load, helium gas mass flow rate, and average velocity for each component of one module.

The coolant pressure drop is strongly dependent on the tube size and gas velocity. This limits the lower value of the $Li_2O$ tube radius. The recommended maximum operating temperature of the $Li_2O$ is about 1000°C to avoid sintering, and this limits the maximum radius of the $Li_2O$ tubes. The pumping power is calculated for the in-vessel components and is 0.75 MW. Thermal hydraulics analysis is performed using a finite element code (ANSYS 5.5) to study the effect of the steel tube dimensions on the temperature distribution and the maximum value in the steel tube wall. Figure 6 illustrates the temperature distribution at the first wall steel tube exit. The maximum temperature is 635°C.

Table 2. The steady state thermal load per module, helium coolant mass flow, and helium coolant average velocity in different components of the FRC design.

| Zone | Total heating (MW) | He mass flow rate (kg/s) | He velocity (m/s) |
|---|---|---|---|
| First zone | | | |
| First wall (steel) | 15.7 | 20.17 | 26.4 |
| First $Li_2O$ zone | 67.55 | 48.38 | 3.44 |
| Second wall (steel) | 6.14 | 7.89 | 9.22 |
| Blanket-I | | | |
| Wall-I (steel tubes) | 34.7 | 44.57 | 18.06 |
| $Li_2O$ | 48.76 | 31.32 | 0.68 |
| Wall-II (steel tubes) | 2.2 | 2.82 | 1.14 |
| Blanket-II | | | |
| $Li_2O$ | 3.41 | 2.19 | 0.039 |
| Wall-III (steel) | 0.15 | 0.2 | 0.078 |
| Shield | | | |
| Bulk (steel) | 0.64 | 0.83 | 0.0046 |
| Total | 180 | 76.5 | |

## V. LIMITS ON THE $Li_2O$ TUBE DIMENSIONS

The effect of the $Li_2O$ tube dimensions on its maximum temperature is studied. The maximum temperature of $Li_2O$ would occur at the blanket exit. Figure 7 shows the temperature distribution in the $Li_2O$ tube. The maximum temperature is 1003°C.

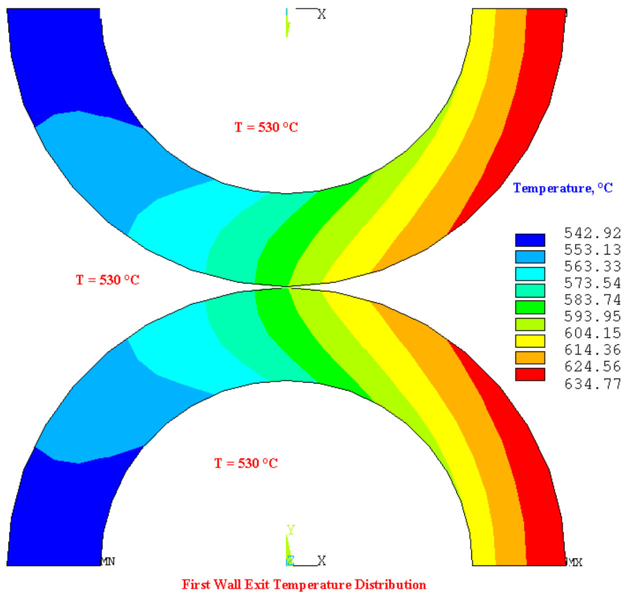


Figure 6. Temperature distribution at the exit of the first wall.

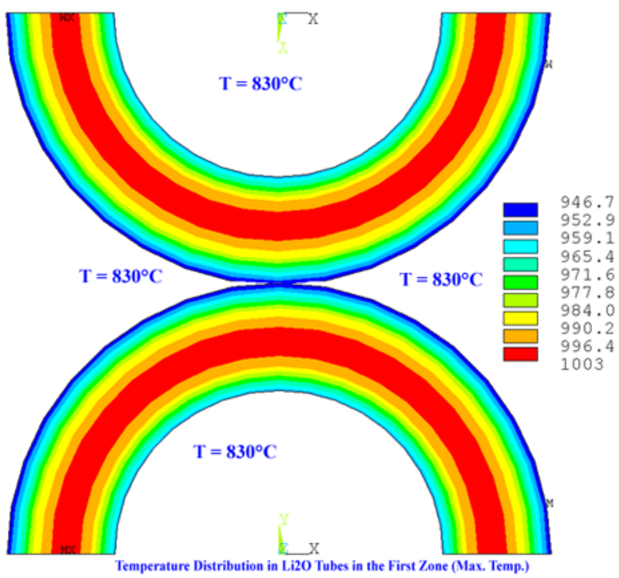


Figure 7. Temperature distribution at the exit of the first zone $Li_2O$ tube.

## VI. MAINTENANCE

The special geometry (cylindrical) facilitates a reasonable practical maintenance scheme that minimizes the downtime and cost. The modular design allows the movement of individual modules in the axial direction. To maintain vacuum integrity inside the reactor during operation a pillow type of overlap is used between modules. To maintain a given module, the pillow is broken at the two interfaces and all the piping disconnected, with the adjoining modules slid away on both sides, far enough to disengage from the module under consideration. This module is moved to a hot cell or maintenance area, and replaced with another standby module. The feed and return is designed to accommodate this scheme. Figure 8 illustrates this scheme.

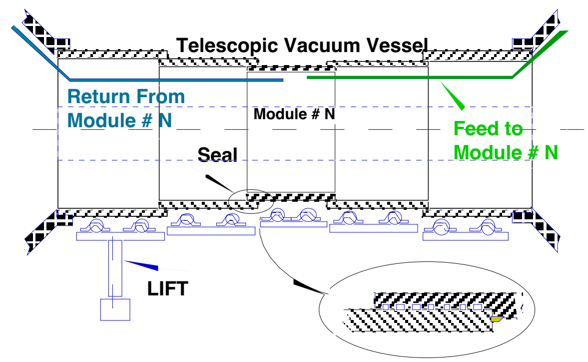


Figure 8. Maintenance scheme of the FRC.

## VII. SUMMARY AND CONCLUSIONS

In this work most of the major engineering issues related to the conceptual design of the FRC fusion core have been addressed. The relative ease of maintenance and the use of steel structure with reasonable thermal efficiency (52%) are assumptions that make it a credible and attractive design. The resulting compact FRC fusion core of the reference case conceptual design possesses a high ratio of electric power to fusion core mass, indicating that it would certainly have favorable economics.[4] The cylindrical geometry and low magnetic field allow removal of single modules containing the first wall, blanket, shield and magnet.[4] The same concept would be applicable to a spherical Torus and spheromak.

## ACKNOWLEDGEMENT

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