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ABSTRACT

The SIRIUS-P conceptual design study is of a 1.0 GWe laser driven inertial confinement fusion power reactor utilizing near symmetric illumination of direct drive targets. Sixty laser beams providing a total of 3.4 MJ of energy are used at a repetition rate of 6.7 Hz with a nominal target gain of 118. The spherical chamber has an internal radius of 6.5 m and consists of a first wall assembly made from carbon-carbon composite material, and a blanket assembly made of SiC composite material (Fig. 1). The chamber is cooled by a flowing granular bed of solid ceramic materials, non-breeding TiO_2 for the first wall assembly and breeding Li_2O for the blanket assembly. Helium gas (P = 0.15 MPa) is used in a fluidized bed outside the reactor to return the particles to the top of the reactor. A moving bed is chosen over a fluidized bed because of its superior heat transfer capability. The heat transfer in a moving bed depends on the level of agitation and on the effective thermal conductivity of the solid material and the interstitial gas, whereas in a fluidized bed, it is entirely dominated by the thermal conductivity of the carrier gas. This paper describes the two-dimensional thermo-structural steady state analysis of the first wall elements at several critical locations utilizing the finite element analysis code, ANSYS [1], with r-θ modeling. The stresses are dominated by bending due to the internal pressure of the He gas; modifying the shape of the tube from purely elliptical, while keeping the area constant reduces the stresses.

INTRODUCTION

SIRIUS-P has a unique first wall cooling system design. The first wall assembly consists of 12 modules, each with an equal number of tubes which cover the spherical shape of the chamber from top to bottom and have a constant cross-sectional flow area along their entire length. The coolant is a moving granular TiO_2 bed of 300-500 μm particles in helium gas at a pressure of 1.5 atm. The gas is moving upward, while the granular solid material is moving downward under gravity and hindered by the helium gas flow in the opposite direction. The velocity of the granular solid material is constant at <1.5 m/s. According to the conservation of mass principle and since this is an incompressible fluid, the flow cross-sectional area must be constant. The general shape of the SIRIUS-P chamber is spherical, therefore it is a challenging task to achieve a constant cross-sectional flow area in the first wall. An innovative idea for the coolant tube geometry along its length has been introduced (the details are discussed in [2]). The shape of the cross-sectional area of the coolant tube changes along its length to keep the cross-sectional flow area

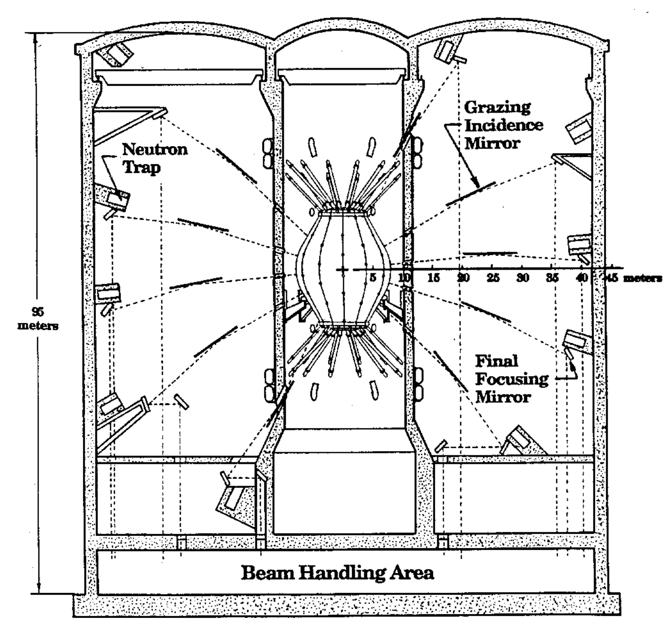

Fig. 1. SIRIUS-P reactor building showing the laser beams and the reactor cavity.

constant. At the chamber midplane the coolant tubes take an elliptical shape with the major axis along the circumferential direction. The cross-sectional area approaches a perfect circle near the top and bottom. At the top and bottom the shape of the cross-sectional area of the coolant tube is elliptical with its minor axis along the circumferential direction (Fig. 2). This insures that the velocity of the granular bed is constant at the first wall where the surface heat load from the x-rays and ion debris is very high. Two power conversion options were considered, a conventional Rankine cycle (SIRIUS-PR) and a helium gas Brayton cycle (SIRIUS-PB). In the case of the Brayton cycle, the first wall coolant is used in a topping cycle mode to achieve He gas at 1000°C. The peak steady state temperature of the first wall in this case reaches 1850°C at a poloidal angle of 158° measured from the top; the maximum tensile stress is 85.6 MPa along the fibers, and 50.2 MPa normal to the fibers. A similar analysis was performed for SIRIUS-PR and will be reported.

FIRST WALL MATERIAL PROPERTIES

The first wall tubes are made of 4-D weave carbon-carbon composite. The 4-D weave carbon-carbon is constructed by running fibers in three directions in one plane, 60 degrees apart, commonly called the U, V, and W plane. This results in

Table I
Some Physical and Mechanical Properties of the
4-D Weave Carbon-Carbon Composites

	Z	U, V, W
Coefficient of thermal-conduction (W/cmK)	0.7	2.5
Tension		
Strength (MPa)	103.4	55.16
Modulus (GPa)	-	48.265
Strain (%)	-	0.14
Compression		
Strength (MPa)	89.6	41.37
Modulus (GPa)	110.3	41.37
Strain (%)	1.3	0.12

Poisson's Ratio = 0.02 - 0.1
Coefficient of thermal expansion = $5x10^{-7}$ 1/°C.

a material with differing properties in the in-plane and perpendicular directions. Table I shows a set of properties of the 4-D weave carbon-carbon composites [3&4].

POWER CYCLES

With the capability of high temperature performance of the first wall assembly, two different power cycles are considered. The first is the Rankine steam cycle and second is the Brayton helium gas cycle. The first wall geometry stays the same for both cycles. The first wall thickness is 1.0 cm and is made of the 4-D weave carbon-carbon composite. The internal characteristic dimensions (a and b) of the elliptical coolant channel are (a = 12.35 cm and b = 3.99 cm) at the midplane, and (a = 3.01 cm and b = 8.25 cm) at both extremities (top and bottom). The pressure of the helium gas in the first wall channels is 1.5 atm. The coolant velocity in the first wall is 1.17 m/s in the case of the Rankine cycle and 0.92 m/s for the Brayton cycle. Table II shows a summary of the parameters used in this analysis for each cycle.

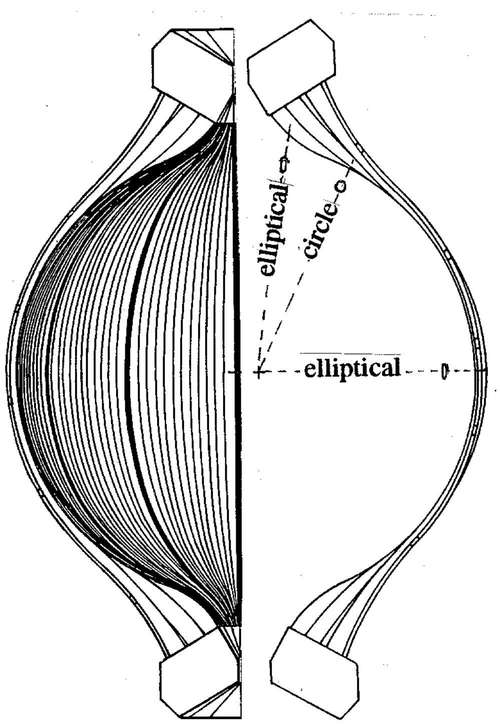

Fig. 2. Cross section of the first wall assembly showing the cross section of the first wall coolant tubing.

Thermal and Structural Analysis

2-D finite-element thermal and static stress analysis have been performed for five different cases. Two of these cases are for the Brayton power cycle, and three are for the Rankine power cycle. The following is a summary of the cases that have been considered in this study:

a - Brayton cycle
- Case 1B: midplane [rounded narrow end]
- Case 2B: lower extremity [elliptical]

b - Rankine cycle
- Case 1R: midplane [rounded narrow end]
- Case 2R: midplane [elliptical]
- Case 3R: lower extremity [elliptical]

Because of symmetry in the thermal and static loadings, and symmetry in the geometry of the first wall, only half of the cross-sectional area of the coolant tube will be considered in the thermal and static stress calculations. Figures 3a, b and c show the temperature distribution (for the five cases) in the first wall at the midplane and Figs. 3d and e at the lower extremity. In the stress analysis the results are for the combined effects of thermal and static loading during steady state operation. Figures 4a, b, c, d and e show the stress distribution normal to the fibers. Figures 5a, b, and d show the stress distribution along the fibers. Figure 6 shows the displacement distribution. Table III shows a summary of the results of the structural analysis for all five cases.

Table II
Parameters of SIRIUS-P Rankine and Brayton Cycles

Subject	Rankine	Brayton
Coolant velocity (m/s)	1.17	0.92
At the midplane		
Bulk temperature of TiO_2 (°C)‡	675	1000
Surface heat flux (W/cm^2)	150.85	137.1
Heat transfer coefficient (W/cm^2K)‡	0.314	0.293
a (major axis) (cm)	12.35	12.35
b (minor axis) (cm)	3.99	3.99
At the lower extremity		
Bulk temperature of TiO_2 (°C)‡	834	1182
Surface heat flux (W/cm^2)	150.85	137.1
Heat transfer coefficient (W/cm^2K)‡	0.3102	0.285
a (cm)/b (cm)	3.0/8.25	3.0/8.25

‡Calculations of the bulk temperature of TiO_2, and coefficient of heat transfer have been performed in [2].

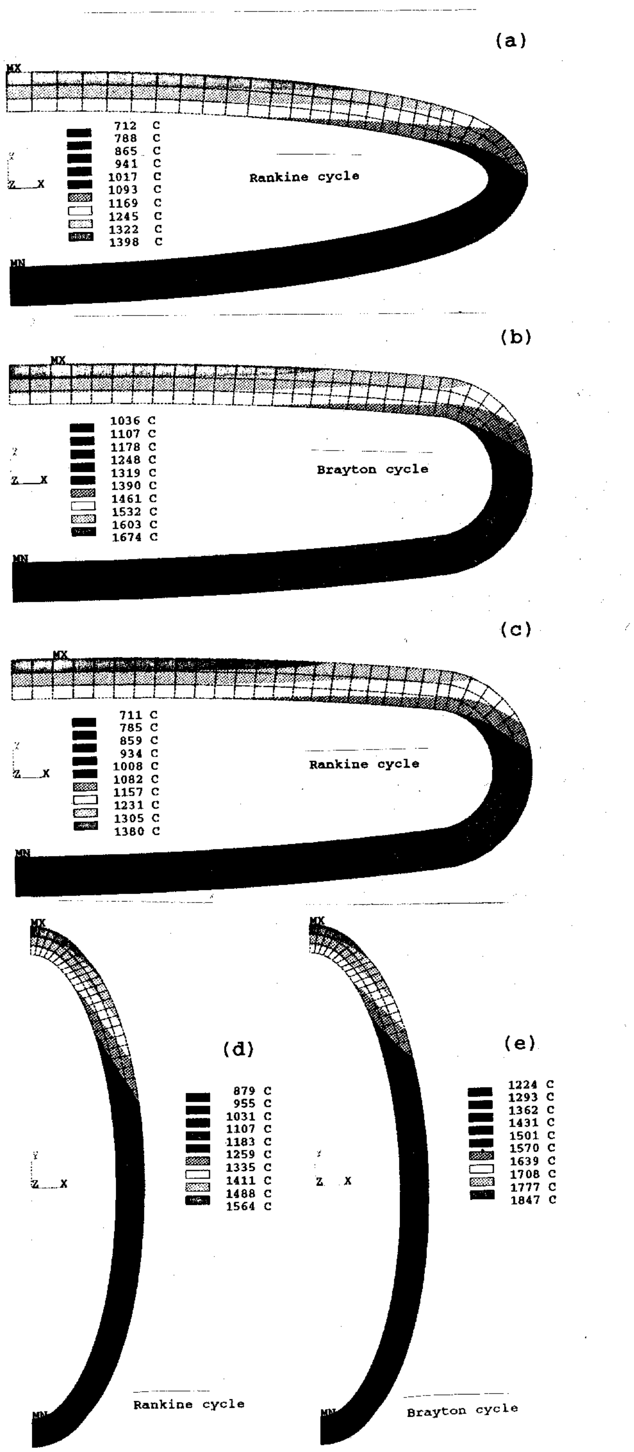

Fig. 3. The temperature distribution in the first wall at the midplane (a,b&c) and at the lower extremity (d&e).

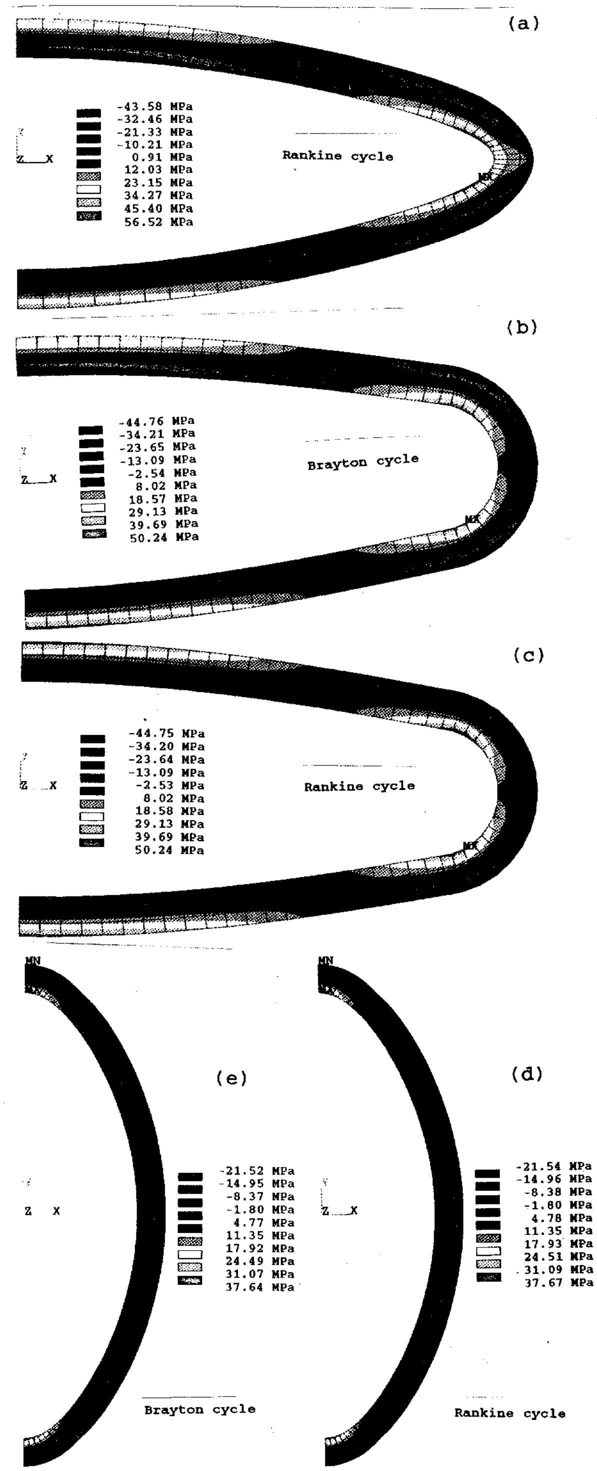

Fig. 4. Stress distribution normal to the fibers of the first wall at the midplane (a,b&c) and at the lower extremity (d&e) due to static and thermal loads (internal gas pressure = 1.5 atmg).

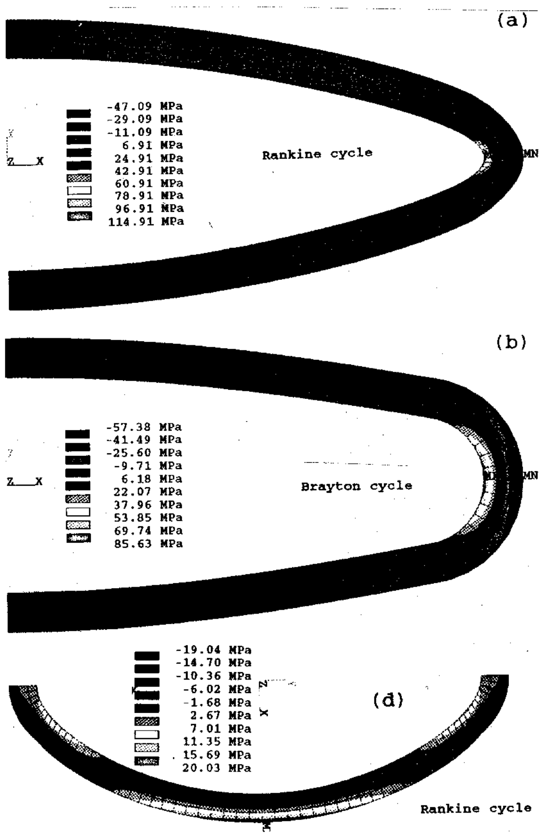

Fig. 5. Stress distribution along the fibers of the first wall at the midplane (a&b) and at the lower extremity (d) due to static and thermal loads (gas pressure = 1.5 atm).

Table III
A Summary of the Results of the Structural Analysis for All Five Cases Considered

Subject	Case 1	Case 2	Case 3
Brayton cycle			
Maximum temperature (°C)	1674	1847	
Maximum tensile stress (MPa)			
1) along fibers	85.63	20.04	
2) normal to fibers	50.24	37.64	
Maximum compressive stress (MPa)			
1) along fibers	57.38	19.05	
2) normal to fibers	44.76	21.52	
Maximum shearing stress (MPa)	43.22	14.64	
Maximum displacement (cm)	0.0822	0.01755	
Rankine cycle			
Maximum temperature (°C)	1380	1398	1564
Maximum tensile stress (MPa)			
1) along fibers	85.64	114.91	20.03
2) normal to fibers	50.24	56.52	37.67
Maximum compressive stress (MPa)			
1) along fibers	57.39	47.09	19.04
2) normal to fibers	44.75	43.58	21.54
Maximum shearing stress (MPa)	34.23	45.0	14.65
Maximum displacement (cm)	0.0822	0.0792	0.1752

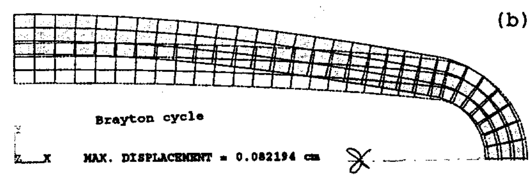

Fig. 6. Displacement of the first wall at midplane.

CONCLUSIONS

1. All of the thermal stresses (normal to fibers, along fibers and shear stresses) are minute compared with the stresses due to static loads.
2. It is expected that the highest stresses occur at midplane because the shape of the cross-sectional area is the flattest at that point (a/b = 6.21 at the midplane compared to a/b = 2.74 at the lower extremity).
3. The stresses are dominated by bending due to the internal pressure of the He gas, and more analysis needs to be done to reduce the resulting stresses at midplane. This can be achieved by reducing the major axis of the cross-sectional area and keeping the same first wall thickness, since the stresses are proportional to the largest characteristic dimension in the cross-sectional area.
4. For the Rankine cycle, the maximum stress along the fibers at the midplane is 114.91 MPa for an ellipse of a = 12.35 cm and b = 1.995 cm for a pressure of 1.5 atm. The maximum stresses along the coolant tube wall fibers at the lower extremity are 20.03 MPa for an ellipse of a = 8.25 cm and b = 3.01 cm for a pressure of 1.5 atm. Notice that the cross-sectional areas at both locations is the same.
5. It is also evident that 3D modeling for the whole tube from top to bottom including bi-axial stresses will be needed to obtain more complete results.

ACKNOWLEDGMENT

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