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FOR THE
STARFIRE COMMERCIAL TOKAMAK POWER REACTOR

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FIRST WALL AND BLANKET DESIGN FOR THE STARFIRE COMMERCIAL TOKAMAK POWER REACTOR

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The first wall and blanket design concepts being evaluated for the STARFIRE commercial tokamak reactor study are presented. The two concepts represent different approaches to the mechanical design of a tritium breeding blanket using the reference materials options. Each concept has a separate ferritic steel first wall cooled by heavy water (D_2O), and a ferritic steel blanket with solid lithium oxide breeder cooled by helium. A separate helium purge system is used in both concepts to extract tritium. The two concepts are compared and relative advantages and disadvantages for each are discussed.

Introduction

First wall and blanket mechanical design options are being developed for the selected reference materials option. The rationale for the materials selection is the subject of a separate paper[1] at this Symposium and will not be discussed here. The table below briefly summarizes the selected materials.

First Wall

Structure: Ferritic steel (Alternate: Austenitic stainless steel)

Coolant: D_2O, heavy water

Blanket

Structure: Ferritic steel (Alternates: Titanium alloy or austenitic stainless steel)

Coolant: Helium

Breeder: Lithium oxide

Two different mechanical design concepts for the reference materials option are presently being developed and further analyzed to assure that design requirements are satisfied in the areas of thermal hydraulics, power cycle efficiency, tritium breeding, tritium recovery, fabricability, and structural integrity. The concepts will also be compared to determine how well they satisfy these important STARFIRE design objectives:

- minimize probability/consequences of accidental contact of incompatible materials;
- maximize reliability of system and components, to increase availability;
- maximize maintainability by minimizing need for, and time required for, standard maintenance operations;
- minimize inner wall/blanket/shield thickness (Δ^i_{BS}), to reduce reactor size and maximum magnetic field; and
- minimize outer wall/blanket/shield thickness, to minimize TF and EF coil size.

The final choice for the mechanical design concept will be made following these analyses and comparisons.

Selection of the mechanical design concept for the helium cooled blanket is strongly dependent on the individual and combined characteristics of the selected structural material, coolant and breeder. Of critical importance is assuring satisfactory adherence to minimum and maximum temperature constraints placed on the solid breeders[1]. Minimizing the blanket thickness, manifold and header size are also of major importance, in order to minimize required reactor size.

Both the design concepts being evaluated use the approach of individual blanket modules of similar shape and size which are built up into wedge-shaped first wall and blanket circumferential sectors. This approach, discussed in another paper at this Symposium[2], has several advantages. It permits more accurate tailoring of the blanket to match neutron wall load values at specific positions around the plasma cross section. Accommodation of local discontinuities such as vacuum ports and rf ducts is simplified. Replacement of individual modules can be performed in the hot cell, while the reactor continues normal operation following installation of a replacement sector. The reactor is thus shut down only for the time needed to remove the sector containing a faulty first wall or blanket component and to install the replacement sector.

A water-cooled first wall, mechanically and structurally separate from the blanket, was selected for both the blanket design concepts. The separate first wall concept permits simple replacement (in the hot cell) of a failed first wall panel without also requiring replacement of the more expensive blanket module behind it. The use of water coolant for the first wall in the reference design accommodates the selected neutron wall load (P_{nw}) value of 3.5 MW/m^2 with negligible pumping losses. The two additional disconnect/reconnect operations for the first wall water coolant headers, necessary for removal of a blanket sector, are not considered a major addition to the time required for that operation.

Discussion of Design Concepts

Two mechanical design concepts are being considered for the blanket. In the first concept, the module walls are pressurized to the coolant static pressure. The solid breeder is contained in sealed tubes, arranged in a staggered rod bank pattern, which are cooled by cross-flowing the helium over them. In the second concept, the helium coolant flows inside tubes each of which is surrounded throughout the module by the solid breeder. This section discusses the two concepts, and the water-cooled first wall common to both.

Pressurized Module Concept

The pressurized blanket module has essentially the form of a slightly tapered parallelepiped, as shown in Fig. 1. Four of the sides are aligned to follow the two planes formed by the wedge-shaped blanket sector and two planes extending radially, from approximately the plasma center. The front face is semicircular and the back face is a shallow semiellipsoid. Module width (distance along sector chord) is variable to match sector width at any point. Module depth and thermal hydraulic parameters (breeder zone details and coolant mass flowrate) may be adjusted to match the actual neutron wall load for any position in the blanket sector.

Each module has one coolant inlet and two coolant outlets at the rear face, which attach to manifolds wrapping around the blanket sector. The manifolds connect all modules in the sector together and run to vertically aligned headers (large diameter pipes) at the top and bottom of the sector. The headers are mechanically attached to inlet and outlet feed pipes which remain in the reactor when a sector is removed.

Helium coolant enters the module through the inlet at the rear face and flows radially toward the front face (nose) through plenums formed by the double walled module sides. The helium enters the semicircular nose area where the flow is divided into channels with flow direction alternating between adjacent

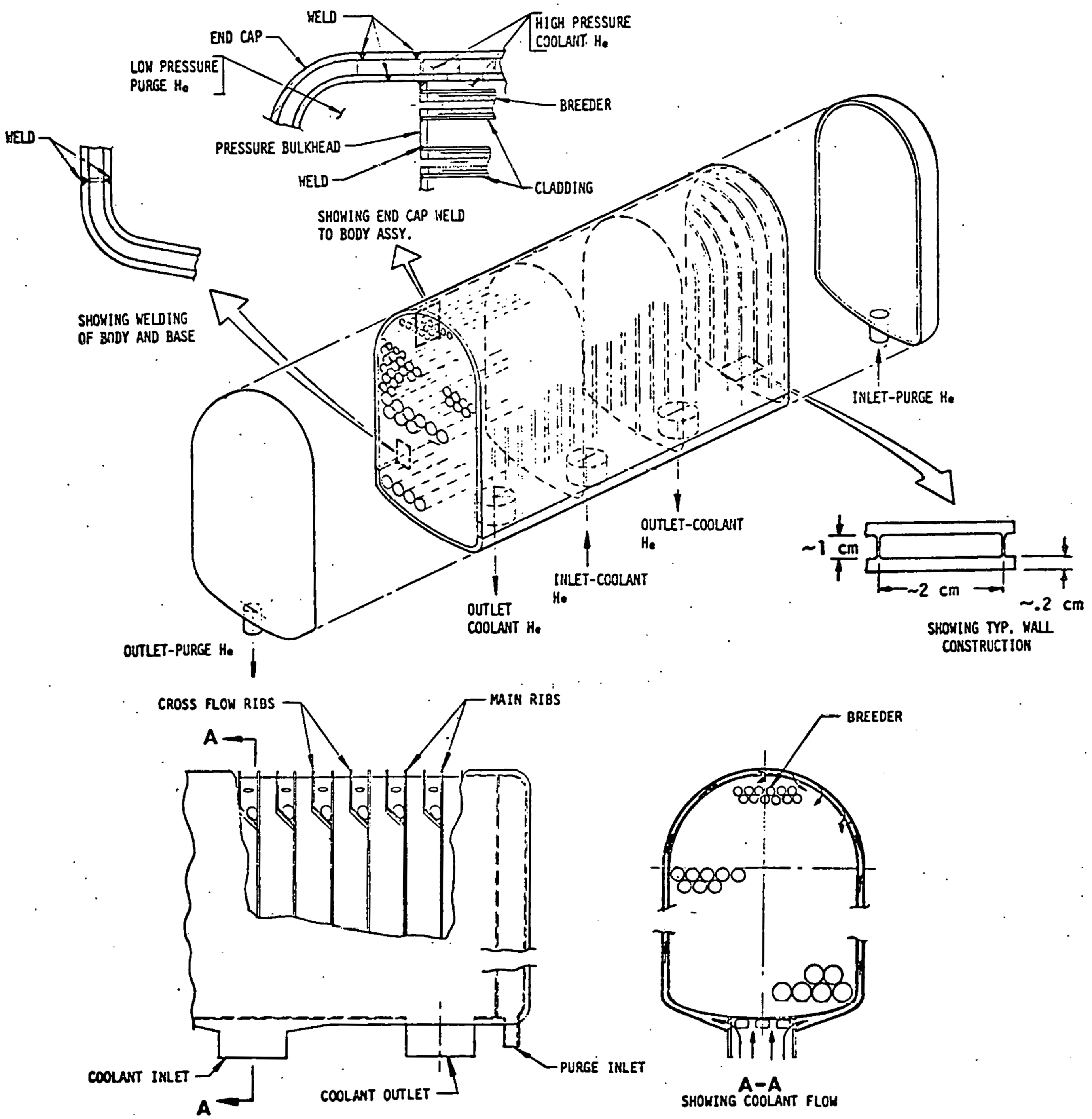


Figure 1. Helium-Cooled Blanket - Pressurized Module Concept.

channels. The helium then enters a plenum region through ports in the nose inner wall and flows radially through the breeding region. The flow then enters a second plenum region and exits to the outlet manifolds.

The breeding zone of the pressurized module contains circular breeder tubes, which extend across the full module width (toroidal direction). The tubes are in rows, with successive rows staggered to produce an equilateral pitch. Each tube consists of a structural shell, Li_2O breeder, and end fittings for the purge gas system. The shell is sized for a differential pressure (collapse) equal to the coolant static pressure. The compacted lithium oxide breeder inside the shell has a small central axial hole. The purge gas is introduced into the cell through the fitting at one end, flows through the breeder center hole, and exits through the fitting at the other end. The helium (at ∿ 1 atm pressure) permeates the breeder, and collects the tritium in the form of T_2O or LiOT with oxygen supplied through a low partial pressure of oxygen in the helium.

The breeder tube diameter varies through the depth of the blanket, from ∿ 1.8 cm near the nose to ∿ 4.0 cm at the rear, in order to maintain breeder temperatures within minimum and maximum temperature limits[1] as volumetric heating rates decrease with depth through the blanket. The breeder temperatures are sensitive to changes in the heat conductance value (assumed to be ∿ U = 2000 W/m^2-°K) for the structure/breeder interface. Further work is needed to optimize breeder tube design details to assure that required values of conductance can be reliably maintained throughout the blanket design life.

Heat generated within the breeder is conducted through the breeder to the tube structure surface. The helium coolant, flowing across the rows of tubes, removes this heat by convection. Thermal-hydraulic characteristics of the coolant flow across the breeder tubes are based on well-established empirical relationships for cross-flow tube bank heat exchangers. Spacing of the tubes is based on an equilateral pattern for adjacent tubes with 1.15 D spacing between tube centers (i.e., the gap between any two adjacent tubes is equal to 0.15 times the tube diameter). This permits a relatively high packing fraction for the tubes. Total pumping power required for the breeding zone only is ∿ 0.5 MW (pump work) for the reactor, which is negligible in comparison to the power required for the rest of the helium coolant system. Total pumping power for all 24 blanket sectors is estimated to be ∿ 50 MW (pump work), or ∿ 1.3% of total reactor thermal power with nearly all the losses occurring in the manifolds. This value includes all pressure losses occurring in the sectors between the inlet and outlet header disconnects.

The pressurized module makes efficient use of structural material to keep the structural volume fraction as low as possible in order to enhance tritium breeding. The module sides are designed with outer and inner walls joined by ribs. This design is structurally more efficient than a single pressurized wall. The use of two walls also provides a flow channel around the blanket perimeter through which relatively cool helium from the inlet manifold flows radially toward the blanket nose, keeping all the pressurized outer wall at ∿ 300°C or less. The inner walls experience virtually no differential pressure. Tie rods span the long width direction of the module in a square pattern with ∿ 10 cm spacing. These rods react the pressure loads applied to opposite walls, further reducing the required wall thickness. In the short width direction, a combination of tie rods and thin bulkheads is used to react pressure loads on opposite walls. The bulkheads also provide support for the long breeding cells by holding them in close-fitting holes to prevent any significant deflection of breeder tubes between bulkheads. The possibility of using the breeder tubes as structural members, to eliminate tie rods in the long width (tube axial) direction, will be investigated.

Coolant inlet temperature and outlet temperature for the pressurized module concept are 250°C and 500°C, respectively. A key feature of this concept is that it permits the maximum coolant temperature to be approximately equal to the maximum temperature of the module wall structure. This is important because it maximizes the power cycle efficiency for the helium coolant. The only highly pressurized structure in the module with a temperature nearly equal to coolant outlet temperature is the outlet manifolds at the rear of the blanket. All other structure in the module, with the exception of the breeder tubes near the rear of the blanket, will experience temperatures no greater than the coolant outlet temperature. The breeder tubes near the rear of the blanket are estimated to have a structural temperature approximately 30°C higher than the local coolant, or ∿ 530°C. Most of the structure will be at considerably lower temperatures, and will be sized for loads resulting from thermal gradients and reactions to pressure loads.

The pressurized module concept for the reference blanket has been analyzed to determine a preliminary estimate for volume fractions, using both ferritic steel alloy and titanium alloy Ti-6242S as structure. The table below shows the results.

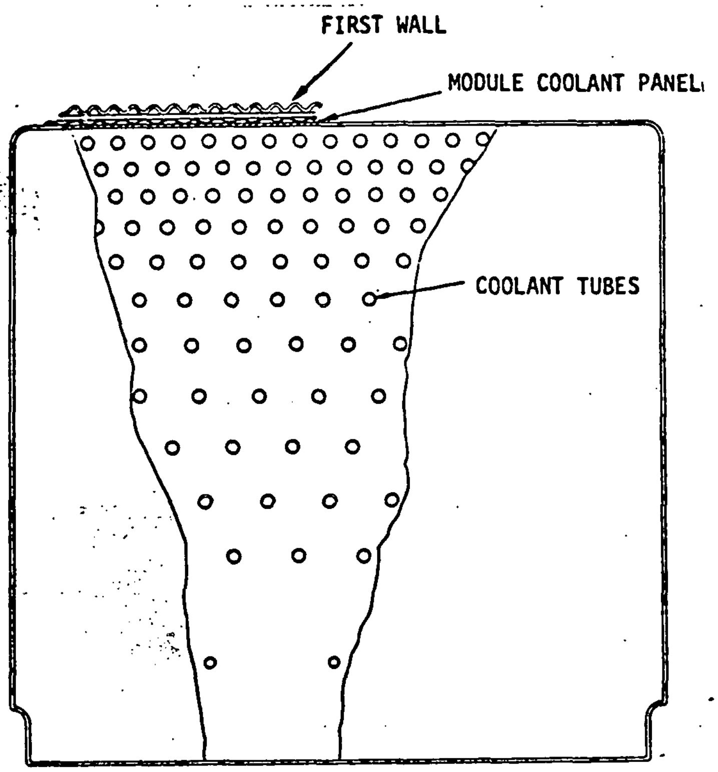
	Ferritic	Ti-6242S
% V Structure	14.9	11.1
% V Li_2O*	57.2	57.2
% V Void/He	27.9	31.7

* Volume required by breeder without accounting for voids.

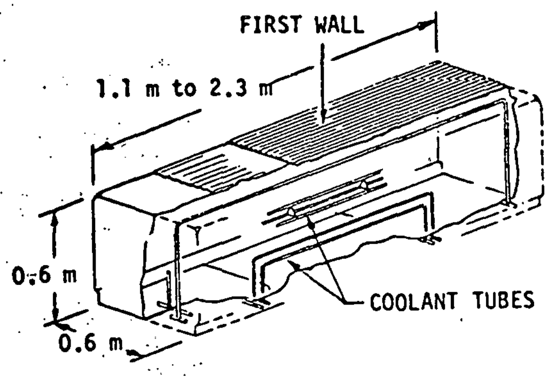
The lower structural fraction for the Ti-6242S results from the higher allowable stresses compared to the ferritic steel. From the standpoint of design and fabricability the titanium alloy seems superior to the ferritic steel because (a) its ductile-to-brittle transition is significantly less than room temperature, (b) no preweld heat treatment is required, and (c) postweld heat treatment (other than annealing) is not required.

Pressurized Tube Concept

In the second concept for the helium cooled blanket (Fig. 2), helium coolant is contained in tubes which are surrounded by the breeder (essentially the reverse of the concept previously described). The tubes are each in a U-shape. The tube end regions are aligned radially along the module ends, with the center region running lengthwise through the module. The ends of the tubes are manifolded so that each module has only one inlet and one outlet fitting for the coolant. These fittings are located on the flat back face of the module. The purge gas system consists of a separate network of porous tubes, each located at the approximate center of any four adjacent tubes forming a square pattern. The tubes are connected to a separate header system at the module ends which connect to inlet and outlet fittings at the rear face of the blanket.



BLANKET CROSS SECTION



ISOMETRIC OF BLANKET MODULE

Figure 2. Helium-Cooled Blanket - Pressurized Tube Concept.

The outer wall of the module is sized to contain the ~ 1 atm static pressure of the helium purge gas. The wall is actively cooled by helium; construction is similar to that of the water-cooled first wall. Active cooling is considered necessary because the breeder conductivity is too low to adequately conduct heat away from the outer wall to maintain a satisfactory maximum structural temperature.

The module walls enclose the breeder which fills the module and surrounds the tubing network. Tube spacing, inside diameter, and length vary through the blanket depth to achieve equal coolant temperature changes and equal coolant pressure drops for all the tubes. Preliminary thermal-hydraulics analysis indicates that tube inside diameters should vary from ~ 1.2 cm at the front to ~ 0.8 cm at the rear of the blanket. Approximately 170 tubes are required for each module. A narrow gap between the breeder and the tube outer surface has been conservatively assumed for heat transfer calculations. Coolant inlet and outlet temperatures have been assumed to be 225° and 475°C, respectively. Outlet temperature was reduced from the 500°C assumed for the previous concept to keep the maximum tube temperature to ~ 530°C. Pressure drops for the blanket have been estimated to be 16 to 18 psi at the 750 psig coolant static pressure. This results in pumping power losses of ~ 2% of reactor thermal power.

Inner Blanket Concept

For both concepts, the inner blanket is presently assumed to be water-cooled and non-breeding, to minimize Δ^{i}_{BS}. However, should neutronics analysis show that additional breeding on the inboard wall is needed for either concept, a modified breeding blanket design would be adopted for that region. The design would essentially consist of the first 30 to 40 cm depth of the standard breeding blanket concept. Blanket depth and manifolding diameter would be adjusted in this region to maintain the desired Δ^{i}_{BS} and still achieve the necessary additional breeding and adequate heat recovery.

First Wall Concept

The first wall concept for the reference design is essentially a water-cooled flat panel. The basic concept is common to both the reference and alternate blanket concepts. Details of the design will be developed later in the study. For the present, the mechanical design concept used is that adopted previously in the ANL-EPR study[3]. In this design, cooling is accomplished by circulating pressurized water in a network of channels that line the plasma side of the panel. The channels are formed by bonding preformed steel sheet to a second, flat steel sheet. Each panel section spans several blanket modules, and has one inlet and one outlet coolant line which connect to manifolds at the rear of the blanket module. These manifolds connect all first wall panels and the water-cooled inboard blanket within a single blanket sector. The manifolds terminate in headers in the vicinity of the helium blanket coolant headers, and are in turn attached mechanically to inlet and outlet feed pipes which remain in the reactor when the sector is removed.

Comparison of Blanket Concepts

Figure 3 presents a comparison of the two blanket concepts previously discussed in terms of design requirements and design objectives. The pressurized tube concept has the relative advantage of structural simplicity compared to the pressurized module concept. The high pressure coolant is contained by tubes rather than by the irregular shape formed by the module walls. The circular shape is structurally more efficient for containing the high pressure. The reduction in the number of stress concentration regions could be expected to result in somewhat greater assurance against the occurrence of coolant leaks. Fabrication would be simpler for the pressurized tube concept, although the development of a method to fill the module with breeder to the desired 80% of theoretical density is a concern.

However, the pressurized tube concept has several inherent relative disadvantages. First, the maximum temperature of each tube will be ~ 40-50°C above the coolant outlet temperature. The wall thickness of the

CATEGORY	PRESSURIZED MODULE CONCEPT (P-MOD)	PRESSURIZED TUBE CONCEPT (P-TUBE)	COMMENT
DESIGN REQUIREMENTS			
o THERMAL-HYDRAULICS			
- COOLANT OUTLET TEMP.	✓		∿ 40-50°C HIGHER FOR P-MOD
- PUMPING POWER	✓		∿ 1-2% MW(th) IN BLANKET FOR P-TUBE
- STRUCTURE TEMPERATURE	✓		P-MOD WALLS COOLED BY HELIUM TO <300°C
o POWER CYCLE EFFICIENCY	✓		∿ 2% HIGHER FOR P-MOD
o TRITIUM BREEDING	- - -	✓	LOWER VOID FRACTION FOR P-TUBE
o TRITIUM RECOVERY	- - -	- - -	ADEQUATE TRITIUM RELEASE FOR BOTH CONCEPTS
o STRUCTURAL INTEGRITY		✓	SIMPLICITY OF PRESSURIZED TUBES PARTLY OFF SET BY NEED FOR ACTIVELY-COOLED MODULE WALL
o FABRICABILITY		✓	SAME COMMENT AS ABOVE; FILLING MODULE WITH BREEDER WILL REQUIRE DEVELOPMENT PROGRAM
DESIGN OBJECTIVES			
o MINIMIZE PROBABILITY/ CONSEQUENCES OF ACCIDENT	- - -	- - -	NO SIGNIFICANT DIFFERENCE
o MAXIMIZE RELIABILITY		✓	SIMPLICITY OF PRESSURIZED TUBES PARTLY OFF-SET BY NEED FOR ACTIVELY-COOLED MODULE WALL
o MAXIMIZE MAINTAINABILITY	- - -	- - -	NO SIGNIFICANT DIFFERENCE
o MINIMIZE FIRST WALL/ BLANKET THICKNESS		✓	PRESSURIZED TUBE CONCEPT REDUCES TOTAL VOID FRACTION IN BLANKET

✓ = RELATIVE ADVANTAGE

Figure 3. Comparison of Helium-Cooled Blanket Concepts.

tubes must therefore be sized to the maximum allowable structure temperature and the coolant outlet temperature determined accordingly. For the pressurized module concept, maximum structure temperature of the pressurized outer wall is ∿ 500°C which occurs in the outlet tube at the rear of the blanket. Given the inherent differences between maximum coolant temperature and maximum structure temperature for the two concepts, for any arbitrary maximum structure temperature limit the pressurized module concept should permit coolant outlet temperatures ∿ 40°C higher than for the pressurized tube concept. Second, for the pressurized tube concept the pumping power required for the blankets and manifolds together is estimated to be ∿ 3.0% of reactor thermal power; this compares to ∿ 1.3% for the pressurized module concept. The difference amounts to ∿ 66 MW (work), and would significantly reduce net efficiency for the power cycle. The requirement for an actively cooled module wall is a significant added complexity and may possibly result in a significant reduction in blanket breeding capability. This requirement will be further investigated.

Further evaluation of the two concepts will be performed in the areas of structural analysis, thermal-hydraulics, and neutronics to aid in the selection of the design concept to be adopted for the STARFIRE reactor and optimized as an integral part of the reactor design.

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3. W. M. Stacey, Jr., et al., "Tokamak Experimental Power Reactor Conceptual Design", Argonne National Laboratory, ANL/CTR-76-3, 1976.

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