

Flow distribution systems for liquid metal cooled blankets

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Abstract — Previous conceptual design studies for liquid-metal (LM) cooled blankets of a fusion power plant often omit details of the complete flow distribution network required to bring coolant into and out of the blanket, and especially the manifolding required for the transition from a small number of feed pipes to the sometimes large number of parallel channels within the actively heated part of the power core. Manifolding can induce large 3D MHD currents and therefore dominate the pressure and flow distributions within the entire blanket, which is especially problematic for designs with electrically insulated channels.

Within the ARIES-ACT1 power plant study a design concept for flow distribution networks has been developed that attempt to minimize 3-dimensional effects that can lead to large pressure gradients and large uncertainties in flow distribution. Desirable and undesirable design elements are described. Especially risky are those elements that require bends that redirect the flow from parallel to perpendicular to the magnetic field and vice versa, because in those cases the bulk of the liquid metal can act as a short circuit. Fully-developed flow in insulated ducts normally retains “well balanced” electric potentials, preventing large 3D currents; internal flows parallel to the magnetic field can easily disrupt this delicate balance.

Additional to MHD effects also fabrication and maintenance issues were considered. Using SiC_f/SiC as structural material for blanket and manifolding and a complex structure for these parts with an inner and outer pipe separated by ribs required a more detailed consideration of manufacturing as well as joining and cutting possibilities. Available technologies have been taken into account for a possible solution. Trade-offs associated with vacuum vessel and structural ring penetrations as well as pipe connections required for maintenance are discussed.

Results of both discussions concerning MHD and fabrication issues on the final design for ARIES-ACT1 are shown.

Keywords — ARIES ACT1; PbLi; liquid metal; flow distribution system

I. INTRODUCTION

ARIES-ACT1 is an advanced tokamak power plant conceptual design that uses SiC composite as structural material in the blanket and PbLi as the tritium breeder and coolant. The design concept for ARIES ACT1 is derived from the ARIES-AT blanket concept¹. In conjunction with a helium Brayton power cycle, the high primary coolant outlet temperature of about 1030°C allows a thermal efficiency of 58%. The self-cooled blanket and He-cooled W-alloy divertor provide the ability to survive a relatively high power density with an acceptable projected lifetime. In ARIES-ACT1 we attempted to add “robustness” to the design point without major sacrifices in performance.²

The breeding blanket concept for ARIES ACT1 is derived from the ARIES-AT blanket concept¹. Each of the 16 sectors consists of one inboard (IB) blanket containing 8 modules and two outboard (OB) blankets containing 16 modules each using SiC_f/SiC as blanket and manifold material. The blanket modules consist of two concentric SiC_f/SiC pipes with intermediate ribs for stiffening the module against the internal pressure of about 2 MPa. After a fast upward flow along the first wall in the outer annular ring, which allows effective removal of surface heating, the flow path is turned through 180° at the top of the modules into a slower downward flow within the central duct. The use of electrically insulating SiC structures along with PbLi coolant is expected to reduce the MHD pressure drop considerably.²

In the ARIES-AT study all the blanket modules were connected directly to a concentric toroidal manifold, fed by one radial access pipe per sector. This geometry, however, caused very complicated 3D-MHD problems which could result in different flow rates in the modules of a sector. Since available computational tools are inadequate for the analysis of these problems, it was decided to avoid such 3D MHD issues by modifying the design of the coolant manifolds.^{1,2}

Previous ideas for the manifold design for the ARIES-ACT1 power plant focused on a merging of the 8 (IB) or 16 (OB) manifolding pipes up to only one main access pipe per sector and blanket. Many cuttings and joining inside the reactor during maintenance should be minimized with this concept. A

Y-shaped pipe connection between two pipes has been proposed, which ensures symmetry between two module pipes for an equal mass flow distribution, and which keeps the MHD pressure drop low.²

A study about the use of Y-shaped pipe connections for the manifolding structure of a blanket changing from 8 (IB) or 16 (OB) pipes into just one main access pipe has been made with the main focus on fabrication and assembling issues. Several different shapes and flow paths of the manifolding pipes have been taken into account. Figure 1 shows as an example one of the analyzed options. Many (purple) feeding pipes can be seen at the lower part of the blanket and structural ring structure merging to just one for IB and OB2 or two for OB1 feeding pipe going down to the main PbLi ring header. This option of merging pipes in Y-shapes has been found to be very difficult to fabricate and maintain. Especially the merging point within the piece of the Y-shape has been identified to be difficult to merge together keeping all the ribs in the annular gap of the two concentric pipes. Also, the huge jungle of many pipes and pipe connections will be difficult to handle and disassemble during maintenance.

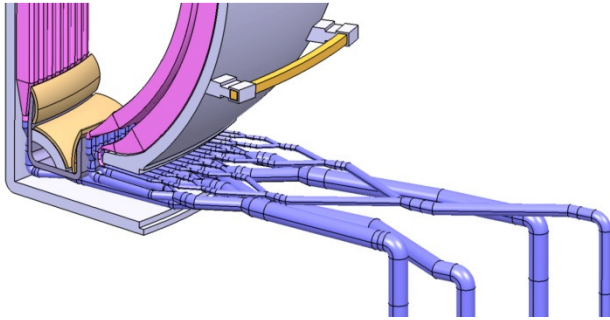


Fig. 1. Previous manifolding concept for ARIES-ACT1 power core

Now, instead of the Y-shape pipe connection, the latest concept for the ACT1 manifold prefers to feed each single blanket module directly from the main PbLi ring header outside the vacuum vessel (VV) without any merging of pipes (see Figure 2 et seq.). All blanket module pipes will be guided straight out down to the main PbLi ring header pipe without any pipe joining inside the reactor. The use of continuous pipes without joining means much less effort concerning fabrication issues and is also an improvement concerning MHD effects, because no change of direction from perpendicular to parallel to the magnetic field is necessary.

To avoid a huge amount of cutting and joining of all these pipes inside the VV, brazing blocks have been introduced. A brazing block consists of two halves, where on each end all 40 pipes are connected. With these brazing blocks only the outside of one brazing block has to be connected or cut during maintenance to get the two halves with still attaches pipes on each end. Small leaks between parallel channels can be tolerated within the block, because all parallel channels share nearly the same coolant conditions. These brazing blocks serve as pipe connections and have been placed several times between blankets and main PbLi ring header (details see chapter III).

The following chapters explain the present design of the ARIES-ACT1 blankets and manifolds, and show a way of disassembling during maintenance as well as a possible fabrication sequence for the ARIES-ACT1 blankets.

II. OVERVIEW OF THE ARIES-ACT1 BLANKET/ MANIFOLD STRUCTURE DESIGN

Figure 2 shows the present design of the ARIES-ACT1 power core, which is described in further detail in Ref. [3]. The plasma is surrounded by breeding blankets and divertor target plates. They are combined with a helium-cooled steel structural ring to form the life-limited replacement units. Each sector contains a single replacement unit that is maintained horizontally through large ports between TF coils. The vacuum vessel is located behind the replacement units with additional permanent magnet shielding located outside the vessel.

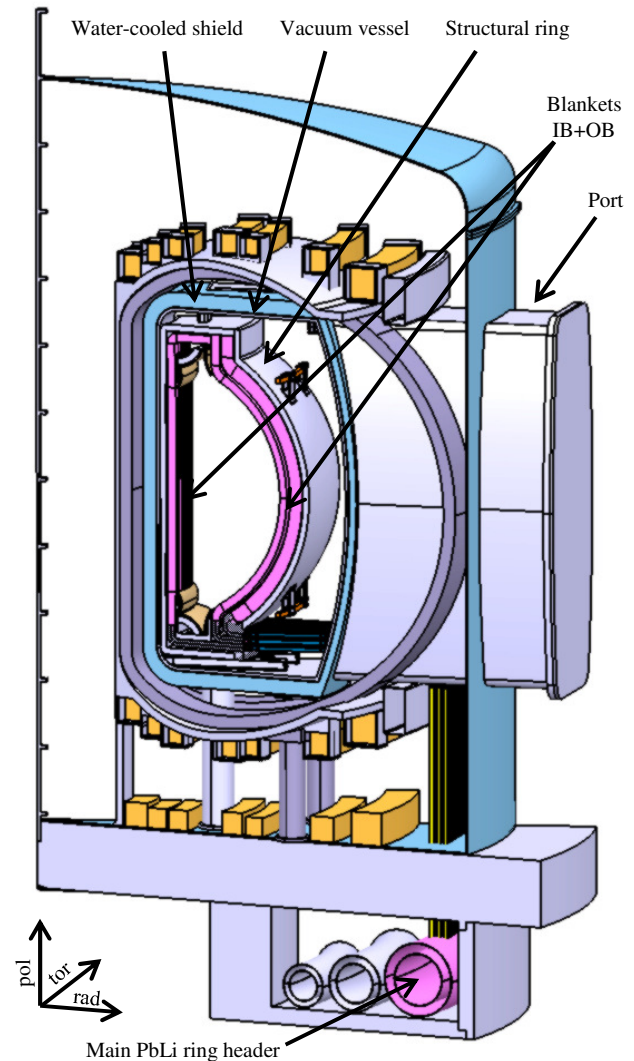


Fig. 2. One ARIES-ACT1 power core segment

Figure 3 shows the lower part of an ARIES-ACT1 sector containing the blanket and manifold structure as well as the divertor, structural ring, vacuum vessel, water-cooled shield and coils after installation inside the reactor. Pipes connecting the blankets with the main PbLi ring header, which is located outside of the vacuum vessel, are not shown in this Figure.

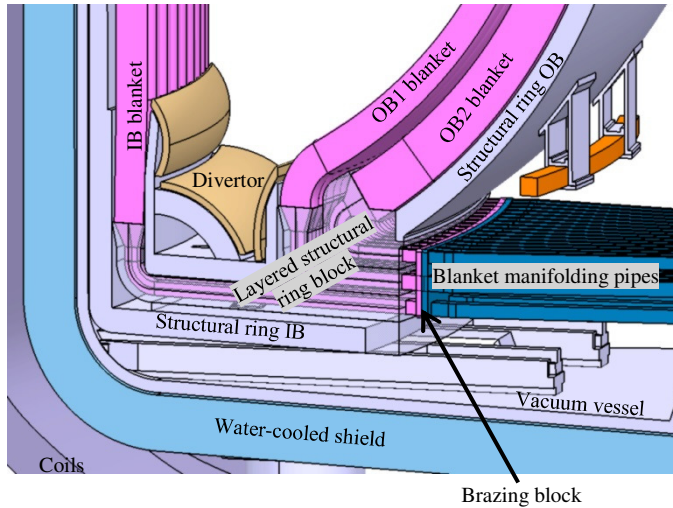


Fig. 3. Detail of one ARIES-ACT1 power core segment

Each sector of the ARIES-ACT1 power core has 1 IB blanket segment consisting of 8 separate modules and 2 OB blanket segments consisting of 16 modules each. Each blanket module consists of two concentric SiC_f/SiC pipes with intermediate ribs. This profile is continued also in the smaller manifold pipes up to the main PbLi ring header. All manifold pipes of one blanket are located at the bottom of each blanket module and embedded in a (transparent shown) structural ring block layer. All of these single layers are bolted together to form the structural ring block, which fills the empty space inside the reactor for shielding as well as closes the gap of the structural ring between the IB and OB segments to keep the function of the structural ring. The divertor is attached to the structural ring block. Close to the outside of the structural ring a pipe connection for the 40 manifold pipes is provided by using a brazing block.

The main functions of the structural ring are to ensure the structural stability of the in-vessel components during all occurring loads such as pressure loads, gravity loads, EM loads and thermal stresses as well as to carry the weight of the blankets and divertors. Cooled with helium, it captures most of the nuclear heating in the structural ring and serves as a heat barrier for the lower temperature parts as vacuum vessel and low temperature water-cooled shield.⁴ The structural ring is divided into an IB and OB sector consisting of ODS steel, as well as a layered structural ring block at the lower bottom, where the manifold/ coolant access pipes of the blankets are embedded. The structural ring block is made of SiC or SiC_f/SiC to resist high temperature up to 1000°C within the blanket and manifold area and will be passively cooled by the embedded manifold pipes. No separate cooling system for these layers is necessary. To avoid a weakening of the

structural ring by guiding the manifold pipes outwards through the structural ring in its full module size, the size of the manifold pipes has been decreased before being guided through it. The cross section of the remaining penetration of the structural ring with 16 OB1, 16 OB2 and 8 IB pipes (as well as a divertor helium supply pipe, which is not shown) for each sector has been reduced to lead to a PbLi velocity of about 1 m/s inside the manifold pipes. This avoids a high MHD pressure drop within these pipes. Differential thermal expansion stresses between the two used materials ODS-steel and SiC_f/SiC are absorbed by the connecting bolts.

One argument for the structural ring block layers was an easy way to combine the necessary addition of shielding material with the structural ring, which avoids additional joints between shielding material and structural ring. Other than in previous designs the structural ring block in the present design has also adopted the function of a shielding block. This means a shortened lifetime of the structural ring block compared to the rest of the structural ring, which has about 20 years lifetime, consisting of ODS steel. But due to the simple design and assembly of the single layers, they can easily be replaced in the hot cell with and at the end of the blanket lifetime after 3-4 years.

III. MAINTENANCE SCENARIO FOR THE ARIES-ACT1 BLANKET/MANIFOLD STRUCTURE DESIGN

The power core maintenance philosophy for ARIES-ACT1 is the same as for ARIES-AT power plants⁵. During maintenance one complete sector consisting of the structural ring, the blankets and the divertors has to be removed horizontally through the large port between the TF coils (see Figure 4).

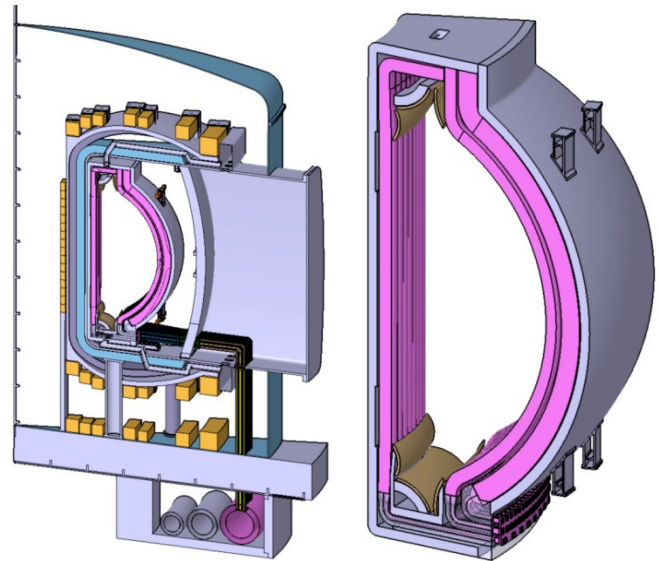


Fig. 4. ARIES-ACT1 power core segment, Cut View (left), removable sector during maintenance, containing blankets, divertors and structural ring (right)

Figure 5 shows a detailed view of the lower part of a complete sector. The sector is still installed inside the reactor

showing all connected blanket PbLi manifolding pipes going horizontally from the structural ring through the shielding block inside the port and down through the bottom of the port to the main PbLi ring header. The helium coolant feeding pipes for the divertor and structural ring are not shown in the following pictures, but can easily be embedded in the structural ring block layers (for the divertor helium pipes) and guided through the shielding block. By using steel for these pipes, their handling is much easier than for the blanket coolant PbLi SiCf/SiC pipes. Cutting and joining points for these pipes are at the same levels as the following explained brazing blocks. Before a sector can be removed, the coolant feeding pipes for the blanket (PbLi), divertor (He) and structural ring (He) have to be cut and removed along with the shielding blocks inside the port.

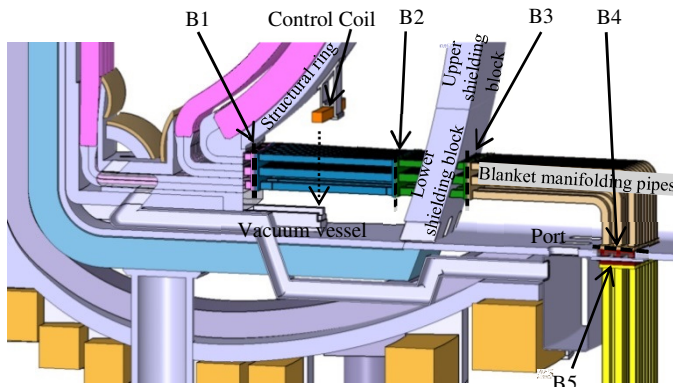


Fig. 5. Flow path and cutting lines of blanket manifolding pipes

As already mentioned, brazing blocks have been introduced as pipe connections for the PbLi SiCf/SiC pipes inside the reactor, to avoid a huge amount of cutting and joining of all the single pipes inside the VV. Each brazing block consists of two halves, where on each end all 40 concentric pipes are already connected. For joining two halves of brazing blocks with attached pipes will be slid into each other and brazed together along the center line between two brazing block halves.

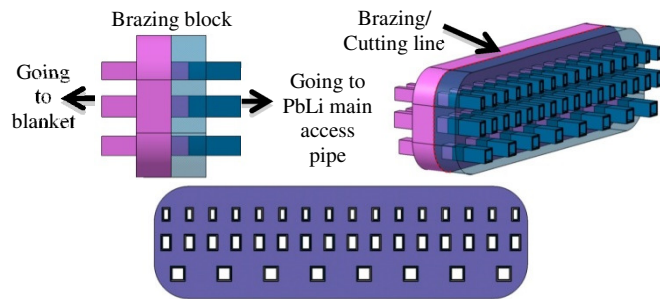


Fig. 6. Simplified sketch of brazing block

Figure 6 shows a simplified sketch of one brazing block. Each of the 40 blanket module coolant access pipes consisting of two concentric pipes with intermediate ribs is brazed to one half of a brazing block (shown in pink and blue). Only the outer pipe is brazed to this block with its outer skin. One side

of a brazing block half has axial extended pipes to achieve an overlapping. Thereby, same levels of brazing and pipe connection are avoided. The PbLi pipes have been designed with different assembly levels at the end of the inner and other pipe and chamfers for easier assembling and to decrease possible cross-flows between the concentric pipes. The following Figure 7 shows details of the overlapping pipes within the connected brazing block (top left) as well as the different assembly levels (top right) and chamfers within the connected pipes (bottom). It is a relatively complicated structure, but ensures an easier assembling and avoidance of large amounts of cross-flow between the inner and outer pipe. Small leaks between parallel channels can be tolerated within the block, because all parallel channels share nearly the same coolant conditions. Very close tolerances have to be kept for assembling of 40 pipes, what could be a challenging task for further research. Research regarding SiCf/SiC joining technologies is still an open issue and ongoing. Especially questions about available tools for brazing large parts inside the VV have to be clarified. Inside the brazing block, the high-pressure inlet still can leak into the low-pressure outlet channels. But this is a problem regardless of the manifold design. Even a single concentric pipe will be difficult to braze between the inner and outer pipe at the connections points. Some additional design work is needed to fully describe how to ensure acceptable leakage rates.

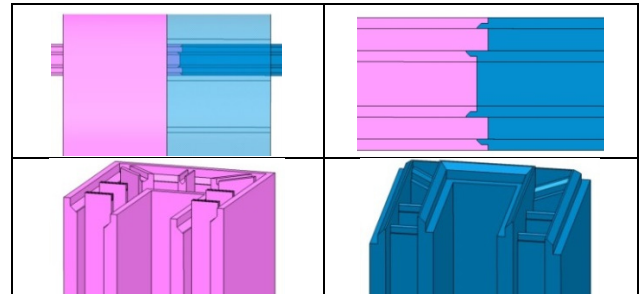


Fig. 7. Details of brazing block/ pipe connection: Top left: pair of two assembled brazing block halves with overlapping of one pipe on one side; Top right: pipe connection with different assembly levels and chamfers; Bottom left: Pipe 1; Bottom right: Pipe 2 (counterpiece of ending)

In Figure 5 also all five brazing blocks and cutting lines necessary for removing a sector are labeled (B1 to B5) and can be found between the structural ring and the bottom of the port, where the pipes are guided through downwards to the main ring header. The first brazing blocks that need to be cut for removing a sector are B3 and B4. The structure with half of the brazing blocks on each side and pipes in between can then be removed. Afterwards, the rail system³ used for maintenance can be inserted and the upper part of the shielding block can be removed. The brazing block inside of the shielding block (B2) is now accessible and can be cut. After removal of the lower shielding block with embedded pipes/brazing block halves also the brazing block close to the structural ring (B1) is accessible and can be cut. If the number of brazing blocks needs to be reduced, brazing blocks B1 and B2 could be combined. But the new brazing block B1 must stay within the radius of the moving area of the control coil, which has to be removed straight down before the complete sector can be moved out.

Also a larger structure consisting of lower shielding block and longer pipes going from B1 to B3 would be the consequence, which will be more difficult to handle.

Brazing block B5 has been inserted for assembling the short pipes going through a flange into the port. The flange is made of steel, which maintains the ability to seal the flange vacuum-tight to the door by bolting and seal welding. The SiC pipes passing through this flange also have to be vacuum-tight at the connection with the steel flange. Technologies of joining ceramics with metals are already available today. But the joining of SiC_f/SiC material with steel needs further research and has to be proven for fusion applications. An example for SiC-Ni-based alloy joining can be found in Ref. [6].

After disassembling and removing all pipes with attached brazing blocks halves, the sector is free to be removed out of the reactor to the hot cells by using a rail system.³ All further disassembly steps for the blanket structure can be done outside of the reactor with better accessibility in the hot cells. Figure 8 shows the lower part of the blanket/structural ring structure with the divertor already removed.

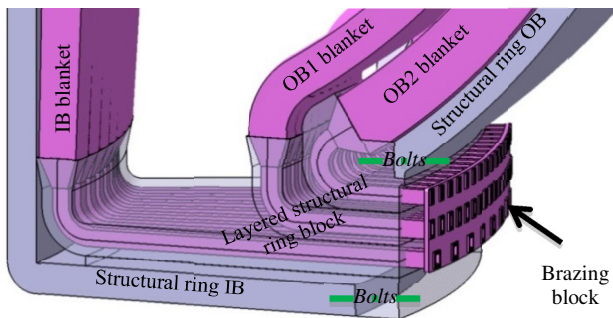


Fig. 8. Disassembling of blankets from structural ring within the hot cells

Within the hot cells the remaining helium supply pipes for the divertors, which are still embedded between two structural ring block layers, have to be removed by cutting them close to the divertor and moving them straight out (not shown in Figure 8). Then the divertors can be unbolted and removed from the structural ring block. After installation of a supporting structure for the structural ring as well as for the blankets the bolts between the structural ring IB and OB segments and the structural ring block can be loosened (see Figure 8). The structural ring block with the manifolds and blankets is then free to maintain.

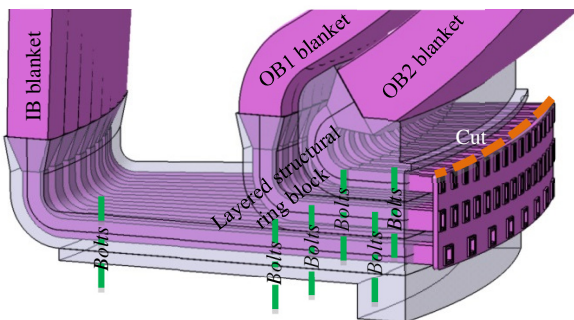


Fig. 9. Disassembling of the layered structural ring block

As seen in Figure 9 after disassembling the IB and OB segments of the structural ring the three blanket segments still remain together, because the single layers of the structural ring block are still bolted together. For disassembling the blanket structure the brazing block half has to be cut first from the PbLi feeding pipes. Then the bolts between the single layers can be loosened. Afterwards the three single structures for IB, OB1 and OB2 (blanket and structural ring block layers) are free to detach from each other. As seen in Figure 10 the three blanket structures have now better accessibility. The structural ring block layers can be unbolted and removed. Parts necessary to be changed can easily be replaced.



Fig. 10. Disassembled blanket segments: IB (left), OB1 (middle), OB2 (right)

The following chapter explains the fabrications steps of one blanket segment, exemplarily for the IB blanket.

IV. FABRICATION STEPS OF ONE BLANKET SEGMENT, EXAMPLE FOR THE IB BLANKET

The IB blanket consists of 8 SiC_f/SiC modules and 2 SiC structural ring block halves, where the manifolding pipes are embedded. With existing technology the fabrication of two concentric circular pipes with intermediate ribs is possible (see Figure 11⁷).

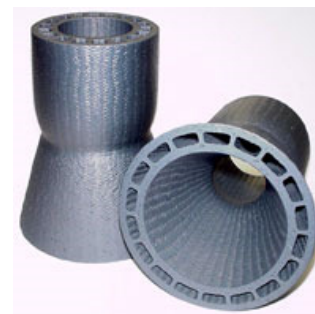


Fig. 11. Active Cooled Ceramic Matrix Composite Thrustcells of NASA⁷

It is assumed and also confirmed from a manufacturer for SiC_f/SiC structures, that with present manufacturing methods also a rectangular blanket structure with a similar inner structure can be fabricated. Figure 12 shows the fabrication steps for one IB blanket segment.

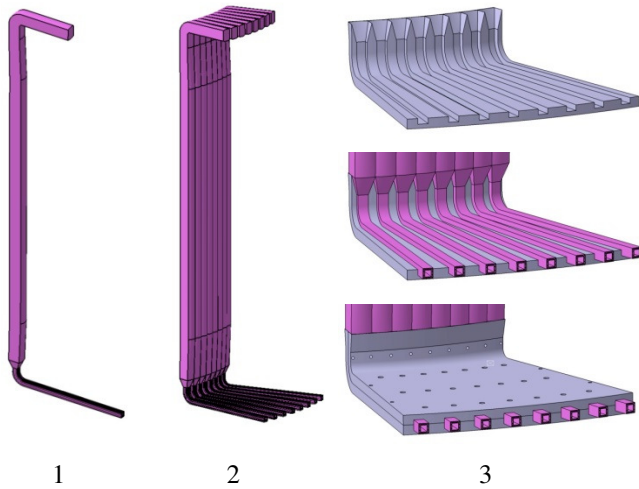


Fig. 12. Fabrication steps of the IB blanket: 1: single blanket module, 2: one IB segment. 3: embedded blanket structure in two half shells of a structural ring block layer

With a total length of about 12.4 m for one IB module, a three-dimensional shape and several layers with different cross sections, the blanket module must be fabricated in several pieces and brazed together to the total length (Figure 12-1). Possible pieces could contain points with the same or similar inner structure like the long straight pipe, the tapering of the pipe or the two bends. After fabricating all of the 8 modules, they are brazed together with the curved shape of the sector (Figure 12-2). This structure is then embedded in one half shell of the structural ring block layer. The two layers are bolted together afterwards (Figure 12-3). Both half shells of the structural ring block have to contain the taper and the channels of 8 modules. After preparing all three blanket segments, they will be bolted together to the structural ring block and can be reassembled in reverse order as described.

V. CONCLUSION

In this paper a detailed design for a PbLi flow distribution system for ARIES-ACT1 power core going from the blanket modules down to the main PbLi ring header has been described. Using SiC_f/SiC as blanket and manifolding material as well as PbLi as coolant there are many issues that had to be taken into account, especially material and fabrication issues as well as possible MHD effects.

Different previous design options included Y-shaped pipe connections for a reduction of all 40 PbLi blanket module

feeding pipes per sector down to only 4 main feeding pipes. With these Y-connections the MHD pressure drop effects could be reduced. But an examination of this design has shown, that the merging points within the Y-shaped pieces consisting of two concentric pipes and intermediate ribs is too difficult to fabricate and join. Within the present design no combining of flows is needed and each blanket module pipe is guided straight out of the VV and down to the main PbLi ring header, what makes manufacturing and joining issues easier. 3D MHD effects are virtually eliminated. For an easy way to join and cut the manifolding pipes inside the reactor a brazing block has been introduced. Each manifolding pipe is brazed onto one half of a brazing block. For cutting and joining only the two brazing blocks halves need to be cut or joined inside the reactor.

There are still open issues, which have to be solved with further research, especially concerning fabrication and joining of SiC_f/SiC pipes and brazing blocks. But overall a promising concept for a simple flow distribution system has been developed.

ACKNOWLEDGMENT

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