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Investigation on the “advanced-plus” Helium Cooled Lithium Lead Breeding Blanket design concept for TBR enhancement regarding thermal and mechanical behavior

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In the framework of the European “HORIZON 2020” research program, the EUROfusion Consortium develops a design of a fusion demonstrator (DEMO). The Breeding Blanket (BB) directly surrounding the plasma is a major component ensuring tritium self-sufficiency, shielding against neutrons from D-T plasmas and heat extraction for electricity conversion. CEA-Saclay, with the support of Wigner-RCP and IPP-CR is responsible of developing the Helium Cooled Lithium Lead (HCLL) BB concept. In order to enhance Tritium Breeding Ratio (TBR), an alternative HCLL BB design, called “Advanced-Plus” concept, has been investigated, with the aim to reduce the amount of steel, while ensuring good thermal and mechanical behavior. The thermal behaviors of the horizontal Stiffening Plates (hSPs) with various channels designs in terms of dimensions and layout have been parsed on simplified FE models for verifying and optimizing the HCLL Breeding Zone (BZ) before analyzing a HCLL BB ¼ model. Moreover, sensitive analyses have been carried out for testing various hSPs pitches, alternative Helium hydraulic schemes inside the hSPs as well as the detachable FW option in applying a zero Heat Flux (HF) on the FW. Furthermore, mechanical calculations have also been performed to assess the behavior of the module in faulted condition. The results obtained with the Cast3M-qualified-FEM code are presented and discussed.

Keywords: DEMO, HCLL, Breeding Blanket, thermo-mechanic, Finite Elements

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1. Introduction

In DEMO, the Breeding Blanket (BB) is the component surrounding the plasma which has to withstand severe and various operating conditions while insuring tritium self-sufficiency, neutron shielding and coolant temperature range suitable for heat extraction in order to supply a turbine for producing electricity [1]. Thus, this component is one of the most challenging in DEMO.

One of the key requirements for the DEMO BB is to have a Tritium Breeding Ratio (TBR) above 1.1 for reaching the tritium self-sufficiency function. Several HCLL BB concept have been investigated in [2] regarding TBR optimization. In this paper, the “Advanced-Plus” concept, which is now considered as the reference HCLL BB [3] because of its high TBR capability [4] has been analyzed regarding thermal and mechanical behavior.

The methodology established, the assumptions done as well as the thermal and mechanical results obtained are reported and critically analysed, scrutinizing some open issues on this new reference DEMO HCLL BB concept.

Globally, a numerical approach, based on the Finite Element Method (FEM), has been followed and the qualified-Cast3M-FEM code [5] has been adopted for the calculations.Firstly, the thermal calculation in steady state normal condition has been carried out to assess temperature distribution on a linear-¼ model of the equatorial outboard module in order to validate the Helium channels layout in the hSPs. Secondly, the mechanical analysis of the module in the faulted condition of Loss Of Coolant Accident (LOCA) has been performed on a quadratic-¼ model.

2. HCLL BB general description

In the 2015 DEMO baseline used in the analyses [6], the DEMO blanket is divided in 16 sectors each one made of 2 inboard and 3 outboard segments. The Multi-Module Segment (MMS) approach has been followed for the design. The HCLL BB uses Eurofer steel as structural material, Helium at the pressure of 8 MPa as coolant and the eutectic alloy Pb-15.7Li enriched at 90% in 6Li as breeder, neutron multiplier and tritium carrier. The HCLL BB modules are attached to the Back Supporting Structure (BSS) with Tie Rods (TR) in order to form a segment which can be easily removed [3].

3. HCLL “Advanced-plus” model description

The major features of the “Advanced-plus” concept are the suppression of the vertical Stiffening Plates (vSPs) and the Cooling Plates (CPs). As a consequence of these modifications, #1 the number of in-box Helium manifolds can be reduced to one, #2 the distance between two hSPs has to be decreased for thermal considerations and #3 top and bottom cover plates (CAP) have to be reinforced to withstand the pressure in case of in-box Loss Of Coolant Accident (LOCA).

3.1 Mechanical design

The detailed design of the "Advanced-Plus" equatorial outboard module is shown on the Fig. 1 for a ¼ of model. The generic HCLL BB module consists of a Eurofer box formed by a radial-toroidal "U-shaped" plate (First Wall and Side Walls - FW & SW) in order to accommodate more easily the toroidal change of size along the poloidal direction. The FW of the equatorial outboard module is actively cooled by Helium thanks to 86 cooling channels of 10*15 mm^2 rectangular cross section. The box is closed on its top and bottom by 75 mm thick actively cooled CAPs and on the back by 2 successive 30 mm and 31mm thick Back Plates (BPs) enclosing a 13 mm thick Helium manifold stiffed by TR. The FW is covered on the plasma side by a 2 mm tungsten layer (W). The box is reinforced by an internal grid made of 37 hSPs with a thickness of 5 mm in order to withstand the Helium pressure (10 MPa) in case of LOCA over-pressurization and are actively cooled by Helium thanks to 24 cooling channels per plates of 3*6 mm^2 rectangular cross section each. The hSPs define a poloidal 40.4 mm pitch array allowing the PbLi eutectic breeder flow distribution through the 35.4 mm internal space.

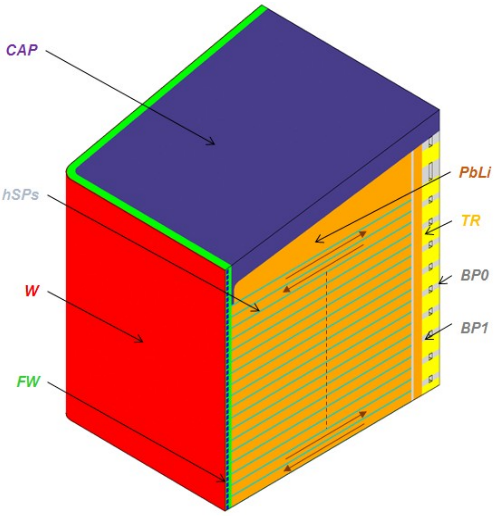


Fig. 1. ¼ "Advanced-Plus" module isometric view.

3.2 Helium hydraulic scheme

Helium coolant comes from the BSS at a temperature of 300°C and enters directly into the FW cooling channels (see Fig. 2). A horizontal cooling scheme has been retained for the FW using a counter-current flow. After flowing through the FW, Helium is collected in a distribution chamber MF1 in the back of the module and distributed in the cooling channels of the hSPs and CAP and then exits into the BSS where it is collected.

3.3 PbLi circulation into the module

The PbLi breeder enters from BSS and is routed to half of the slices in parallel as illustrated on Fig. 2. PbLi flows between two hSPs frontward (radially), and goes to the slice above through the holes designed one other two hSPs (orange arrow on Fig. 1), on the back of the FW, and then radially flows backwards until it is collected by the BSS.

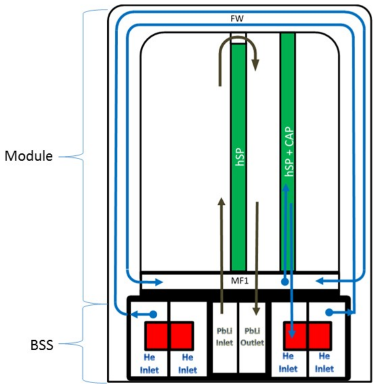


Fig. 2. He and PbLi distribution scheme.

4. Thermal analyses

4.1 Thermal model development

Firstly, thermal FE calculations have been carried out to assess temperature distribution on elementary slices of the equatorial outboard module under steady state condition (see [7]). Different Helium channels layouts have been parsed in order to optimize the power extraction and their cooling effect on the structure. Finally, only the "U-shaped" layout has been retained and is used in the model reported here.

The FEM thermal calculation presented hereafter is done on a representative ¼ equatorial outboard module composed of 19 half hSPs and 43 Helium channels in its FW due to the symmetries. The CAD model has been developed and parameterized in the NX software [8] as well as the mesh pretreatment work. Linear tetrahedral elements have been used and the model is composed of 2.5M of nodes and 12.5M of elements. The thermal problem has been computed and mathematically solved with the Cast3M FEM code [5].

4.2 Thermal assumptions for the FEM calculation

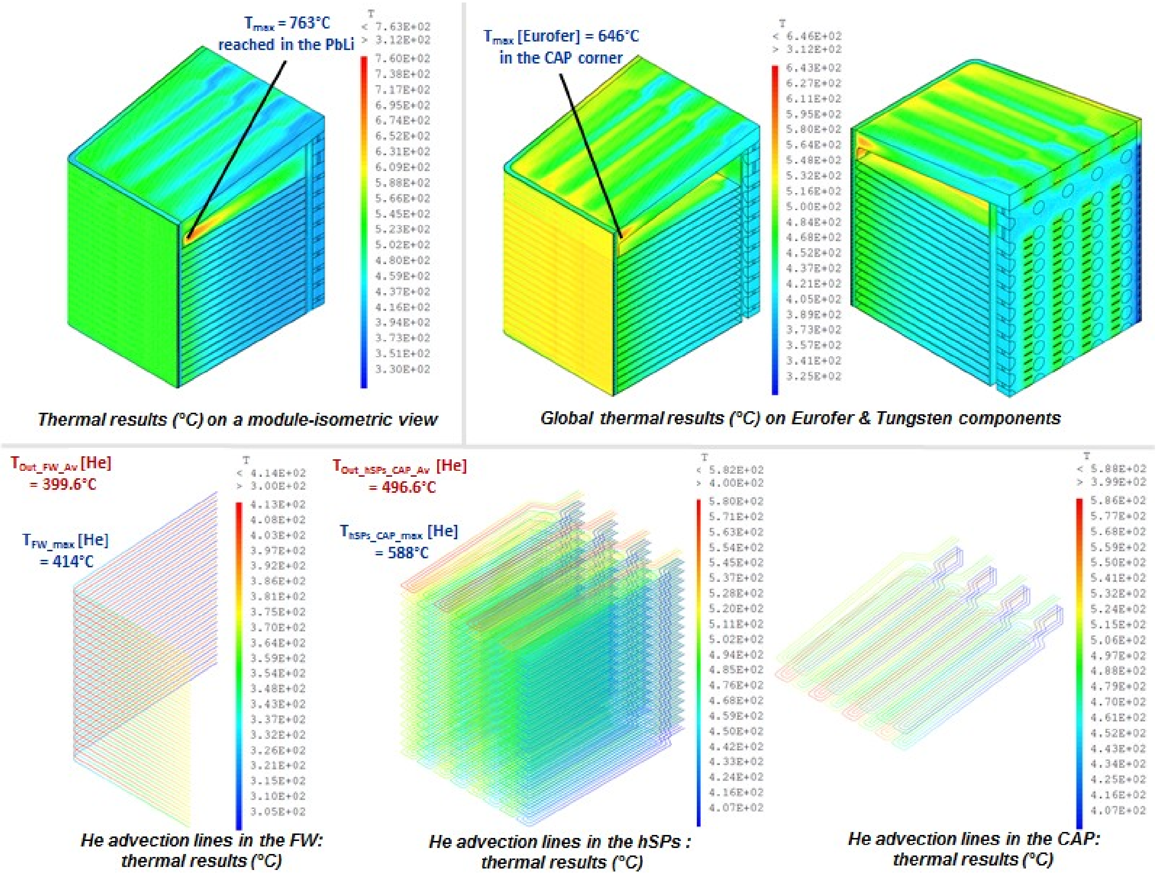
Global calculation assumptions have been taken into account and the following hypotheses and boundary conditions have been considered for solving the physical problem: #1 temperature dependent material properties is used for the Helium, PbLi and Eurofer structure in the thermal simulations, #2 the volumetric heat generation deposited inside the steal and PbLi comes from [4] , #3 a Heat Flux (HF) of 0.5 MW/m² is considered, #4 the Helium inlet temperature in the FW is 300°C, the outlet temperature from the module is calculated, #5 Helium mass flow rate is calculated to recover the power deposited on the module and plasma Heat Flux (HF) in considering the hSPs outlet temperature at 500°C: for the model presented before, its value is 4.78 kg/s, #6 no channels roughness in the channels is considered for the calculations, #7 a Heat Transfer Coefficient (HTC) due to the forced convection with Helium at 8 MPa is calculated for each channels components with the formulas described in Gnielinski equation [9] , #9 proper advection line model is implemented in order to reproduce the thermal effects of the Helium flowing into the cooling channels and #10 thermal coupling between FW outlet advection lines and inlet hSPs advection lines is considered as well as temperature raise in the MF1.

4.3 Thermal results on a ¼ model

Before developing a first ¼ model, sensitive analyses have been performed [6] to look at the effect of increasing the hSPs pitch. The higher the pitch would be, the better TBR could be expected. However, thermal results show that, the higher the pitch is, the higher temperature is expected on the structure even if the mass flow rate per channel increases because of the reduction of the number of hSPs. Thus a compromise has always to be found between these two parameters.

The results described on the Fig. 3 show that the maximum Eurofer temperature in this first thermal "Advanced-plus"-¼ model developed is reached in the CAP volume near the junction with the FW. The hot spot observed is due to the presence of PbLi at high temperature (with a maximum at 763°C) in the corner zone which implies a difficulty for cooling massive sub-components as the CAP. Thus the maximum Eurofer temperature in the CAP is 646°C at the middle of the component. However, the maximum Eurofer temperature in the FW is always below or equal to the limit of 550°C whereas the FW tungsten layer reaches a temperature of 557°C. Moreover, if only the current zone of the module is considered, the Eurofer sub-components' temperature is below or equal to 552°C (maximum 550°C in the FW and 552°C in the hSPs). Concerning thermo-hydraulic aspects, the calculated Helium outlet temperature is 496.6°C allowing to obtain a thermal range near 200°C as expected. In further study, only the CAP slice has to be improved thermo-hydraulically. However, the validation of the structure according to Codes & Standards could maybe be justified even with a very local temperature hot spot. The maximum pressure drop is equal to 0.13 MPa for the hSPs and the CAP and 0.05 MPa for the FW.

Moreover, a sensitive analysis has been done with the aim to analyse the option of a detachable and thermo-hydraulically disconnected FW (in front of the FW module) as a protection against high HF from the plasma. On some modules (less loaded than the equatorial outboard one), the HF could be clearly less important than 0.5 MW/m^2 or even zero in case a detachable FW. This particular case has been studied for evaluating its thermal effect on the structure: conservatively HF = 0 MW/m^2 has been chosen. The calculation without HF shows a maximum Eurofer temperature on the FW decreasing compared to the case with HF. Due to the absence of HF, the maximum temperature on the FW is reached on the back surface of the FW in contact with the PbLi. And, at the same time, the temperature in hSPs increases. The reduction of total power to be recovered by the BB due to HF = 0 MW/m^2 (~20% of the total power) implies a reduction of the total mass flow rate while having the same neutron power deposited to extract. Consequently, with a detachable FW, the design of the modules has to be modified in order to reduce the temperature on the hSPs. A first solution could be to move radially the channels of the FW for cooling down the structure; a second solution could consist in modifying the layout of plates' channels for increasing the HTC (diaphragms could be foreseen) and then maintaining the maximum temperature of the components under the 550°C Eurofer thermal limit.



Thermal results (°C) on a module-isometric view

Global thermal results (°C) on Eurofer & Tungsten components

He advection lines in the FW: thermal results (°C)

He advection lines in the hSPs : thermal results (°C)

He advection lines in the CAP: thermal results (°C)

Fig. 3. Thermal results on an "Advanced-plus" ¼ model.

5. Mechanical analyses

5.1 Mechanical assumptions

5.1.1 Model and mesh development

Mechanical analysis of the module in the faulted condition of Loss Of Coolant Accident (LOCA) has been performed. Only ¼ of the model is calculated by considering the symmetries. The structural material of each part is considered isotropic and elastic. Quadratic tetrahedral elements have been used. The model is composed of 11.4M of nodes and 6.8M of elements.

5.1.2 Loads and boundary conditions

In case of accident, the pressure is applied on the internal surfaces of the FW, the CAP and the first BP and is equal to 10 MPa. Furthermore no pressure has been applied on the hSPs external surfaces due to their supposed equilibrium in case of LOCA. Moreover the pressure is chosen conservatively by considering global system characteristics: #1 The DEMO Pressure Control System (PCS) can insure the nominal Helium pressure of 8 MPa with +/-10% accuracy leading to 9 MPa, #2 in case of failure of the PCS (unlikely/very unlikely), the burst disc has a +/-10% accuracy too which leads conservatively to 10 MPa.

Boundary conditions are used in order to represent the symmetries: #1 the nodes included in the planes of symmetry are fixed along the direction normal to these ones (i.e. in toroidal and poloidal directions in our design) and #2 all displacements of nodes at the back of the box are blocked.

5.1.3 Physical problem resolution and criteria

D-level RCC-MRx §RB3251.13 criteria [10] are used to analyse the box in faulted condition. The temperature chosen to evaluate the stresses for all parts of the box is 550°C (temperature at which the Eurofer mechanical properties decay). The physical properties are taken at this temperature. Moreover, the RCC-MRx stress limit in faulted condition S_m^D at 550°C is equal to 238 MPa.

5.2 Mechanical results

5.2.1 Von Mises stresses on the structure

As illustrated on the Fig. 3 and Fig. 4, stresses above the limits occur in this design and are particularly localized in the area where the FW and the CAP are linked.

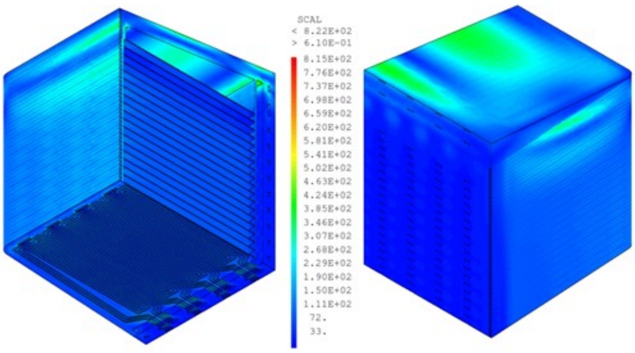


Fig. 4. Von Mises stresses on ¼ module.

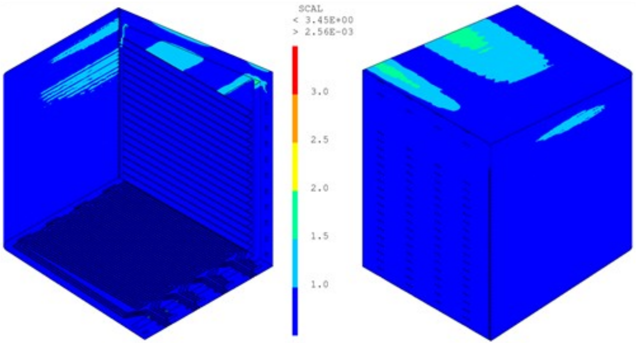


Fig. 4. Ratio of stresses on ¼ module.

The bending effect of the structure is the most significant in the corner and on the FW external surface. Consequently, RCC-MRx stress linearizations have been performed to analyse more precisely these zones.

5.2.2 Linearization in the higher stressed zones

The stress linearization has been performed on the lines described on the Fig. 5 and Fig. 7. Results are summarized on the Fig. 6 and Fig. 8 for the most stressed area of the FW and CAP.

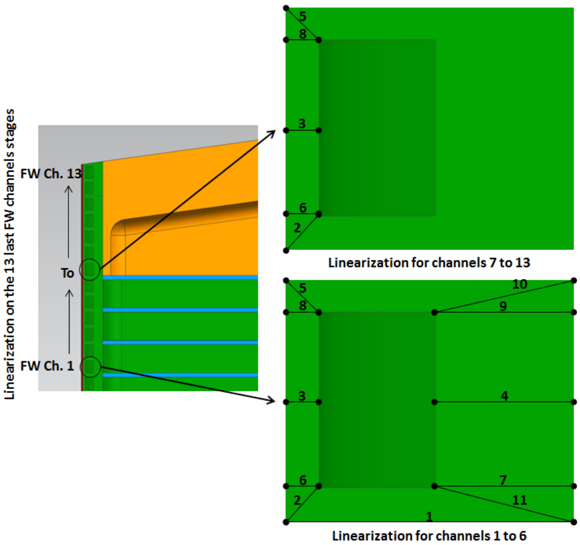


Fig. 5. Stress linearization lines on the FW.

CUT	PmD (550°C) [MPa]	SmD (550°C) [MPa]	PmD / SmD	PmD /1.5*SmD	PmPbD (550°C) [MPa]	PmPbD /1.5*SmD
A	201	238	0,84	0,56	384	1,07
B	255	238	1,07		322	0,90
C	173	238	0,73	0,49	390	1,09
D	325	238		0,91	583	1,63
E	179	238	0,75		539	1,51
F	192	238		0,54	594	1,66
G	117	238		0,33	236	0,66
H	136	238		0,38	340	0,95
I	199	238	0,84		620	1,74
J	130	238		0,36	573	1,61
K	65	238		0,18	228	0,64
L	44	238	0,18		237	0,66
M	52	238		0,15	219	0,61
N	85	238		0,24	373	1,05
O	111	238	0,47		434	1,22
P	89	238		0,25	382	1,07
Q	72	238		0,20	287	0,80
R	74	238	0,31		282	0,79
S	76	238		0,21	283	0,79
T	54	238		0,15	153	0,43
U	59	238	0,25		159	0,44
V	58	238		0,16	140	0,39
W	58	238	0,25		146	0,41

Fig. 6. Results of the stress linearization on the FW.

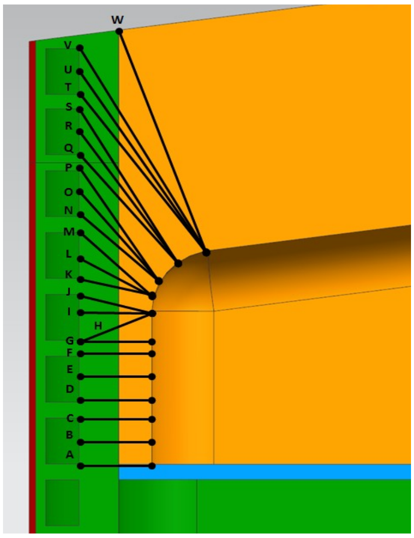


Fig. 7. Stress linearization lines in the corner zone.

FW CHANNEL	CUT	PmD (550°C) [MPa]	SmD (550°C) [MPa]	PmD / SmD	PmD /1.5*SmD	PmPbD (550°C) [MPa]	PmPbD /1.5*SmD
8	2	100	238		0,28	161	0,45
8	3	257	238	1,08		258	0,72
8	5	377	238		1,06	381	1,07
8	6	161	238		0,45	165	0,46
8	8	374	238		1,05	389	1,09
9	2	192	238		0,54	344	0,96
9	3	362	238	1,52		363	1,02
9	5	440	238		1,23	442	1,24
9	6	295	238		0,83	311	0,87
9	8	437	238		1,22	448	1,25
10	2	287	238		0,80	467	1,31
10	3	308	238	1,29		308	0,86
10	5	211	238		0,59	382	1,07
10	6	272	238		0,76	287	0,80
10	8	158	238		0,44	216	0,61
11	2	348	238		0,97	372	1,04
11	3	259	238	1,09		263	0,74
11	5	129	238		0,36	252	0,70
11	6	348	238		0,97	372	1,04
11	8	187	238		0,52	187	0,53

Fig. 8. Results of the stress linearization on the CAP.

During LOCA, some particular area of the global structure are above the limits fixed by the RCC-MRx in D-Level. The FW structure near the channels 8 to 11 (Fig. 5 and Fig. 6) is affected by immediate deformation and immediate plastic instability due to bending effect of the FW near the module corner area. However the over-stresses in the current FW region are relatively reduced comparatively to past models due to the decreasing distance between 2 hSPs. Thus, in the central slices zone some margins are noticed, the FW thickness could be reduced locally and TBR gain could raise. Furthermore, the corner area is more particularly affected by immediate plastic instability due to an important bending phenomenon of the structure for this zone and excessive stresses are noticed too (Fig. 7 and Fig. 8).

However they should be easily reduced by taking into account first the real temperature locally for the S_m^D calculation in further studies and else with a design implementation in the corner.

6. Conclusions

The “Advanced-plus” concept for the DEMO HCLL BB has been studied as the new reference design. Even if the “Advanced-plus” concept shows benefits regarding TBR enhancement [4], some structural improvements are necessary particularly for #1 better cooling of the CAP structure and #2 stiffening more the module in case of LOCA, especially in the corner area.

The design of the “Advanced plus” BB concept is in its early stage. Specific design elements like the BZ layout, the thermo-hydraulic general scheme for the segment, the structural mechanics design especially in the CAP area, manifolds and BSS will have to continue to be implemented by adopting a step-by-step process between the evolution of design and its validation by calculation. The first results, as presented in this paper, are encouraging, but efforts are still required.

Acknowledgments

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