

EVOLVE – An Advanced First Wall/Blanket System*

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ABSTRACT

A new concept for an advanced fusion first wall and blanket has been identified. The key feature of the concept is the use of the heat of vaporization of lithium (about 10 times higher than water) as the primary means for capturing and removing the fusion power. A reasonable range of boiling temperatures of this alkali metal is 1200 to 1400 C, corresponding with a saturation pressure of 0.035 to 0.2 MPa. Calculations indicate that an evaporative system with Li at ~1200 C can remove a first wall surface heat flux of >2 MW/m² with an accompanying neutron wall load of > 10 MW/m². Work to date shows that the system provides adequate tritium breeding and shielding, very high thermal conversion efficiency, and low system pressure. Tungsten is used as the structural material, and it is expected to operate at a surface wall load of 2 MW/m² at temperatures above 1200 C.

1.0 Introduction

Recent design efforts in the U.S., through the APEX program (1), have focussed on new systems that have the potential for high power conversion efficiency and for accommodating high power density. One system that has this potential is the EVOLVE (Evaporation of Lithium and Vapor Extraction) concept. The key feature of the EVOLVE concept is the use of the heat of vaporization of lithium (about 10 times higher than water) as the primary means for capturing and removing the fusion power. A reasonable range of

boiling temperatures of this alkali metal is 1200 to 1400 C, corresponding with a saturation pressure of 0.035 to 0.2 MPa. Calculations indicate that a evaporative system with Li at ~1200 C can remove a first wall surface heat flux of >2 MW/m² with an accompanying neutron wall load of > 10 MW/m². The system has the following characteristics.

1. The high operating temperature translates naturally to a high power conversion efficiency.
2. The choices for structural materials are limited to high temperature refractory alloys. A tungsten alloy, e.g. W-5%Re, is the primary candidate as a structural material, with tantalum alloys as the back-up.
3. The vapor operating pressure is very low (sub-atmospheric), resulting in a very low primary stress in the structure.
4. The temperature variation throughout the first wall and blanket is low, resulting in low structural distortion and thermal stresses.
5. The lithium flow rate is approximately a factor of ten slower than that required for self-cooled first wall and blanket. The low velocity means that an insulator coating is not required to avoid an excessive MHD pressure drop.

The areas addressed are first wall and blanket design, tritium breeding, activation and waste, power conversion, first wall thermo-mechanical behavior, tritium extraction, and critical issues.

2.0 First Wall and Blanket Design

The cross-section design of the EVOVE concept is illustrated in Fig.1. In the EVOLVE concept, first wall and primary breeding zone are combined into one unit. Behind this unit, there is as a separate component a high temperature shield at the inboard region and a secondary breeding blanket at the outboard region. Behind the secondary breeding zone there is , as a separate component, an additional high temperature shield, required in order to meet the shielding requirements of vacuum vessel and magnets.

The first wall consists of a tube bank (tube diameter of 4 cm) arranged in the toriodal direction as shown in Fig.2. The tubes are metallurgically joined together to contain the Li vapor from the blanket. Within each tube is another tube which carries liquid lithium. Slits in the inner tube provide the means for the liquid lithium to wick a porous layer of the first wall, like a heat pipe, and vaporize. For a surface heat flux of 2 MW/m², a toroidal segment width of 3 m, and the tube dimensions given above, a boiling temperature of 1200 C (saturation pressure 0.035 MPa) results in a liquid metal velocity in the feed tube of about 1 m/s and a vapor velocity of about 500 m/s. This is about 1/3 of the sonic velocity and results in a tolerable pressure drop.

The blanket consists of a number of trays, stacked poloidally, containing liquid lithium. A space is left between trays to allow the Li vapor to be removed from the blanket. Each tray contains a lithium pool with a height of 10 to 20 cm, which is maintained constant by a system of overflow tubes. The large volume heating of the lithium leads to boiling. The vapor bubbles have to rise in the pool and separate from the liquid metal at the surface. From here the vapor flows a short distance in parallel to the surface before it

enters the vertical vapor manifold. Entrained liquid metal will be separated there. Behind the trays is a manifold, approximately 20 cm thick, for collecting the Li vapor. The total radial thickness of the first wall and blanket is approximately 70 cm.

The neutron flux in the secondary breeding zone, which also operates at 1200 C, is considerably lower than at the front, allowing the use of a variety of blanket concepts. For simplicity reasons, however, a self-cooled lithium/tungsten blanket concept has been selected as reference solution in order to limit the number of materials used and to also allow the generation of high grade heat in this zone. The low volumetric heat generation and the absence of a surface heat flux probably enables a design without insulating coatings, where the MHD pressure drops are kept to a tolerable level with low flow rates. Neither design work nor analyses have been performed for this concept in the frame of this study, because self-cooled blanket concepts have been investigated in a number of blanket and power plant studies. The same statements can be applied to the high temperature shields required both at the inboard and the outboard region for additional neutron shielding of vacuum vessel and magnets. They are also made of tungsten as structural material, cooled by flowing lithium. Tungsten carbide is used as shielding material. Reasonable assumptions about the volume composition of these components have been made for the neutronics analysis.

3.0 Neutronics and Activation

Two-dimensional (2-D) modeling of the front evaporation cooled blanket of EVOLVE is needed to properly account for the poloidal heterogeneity and gaps between trays. The R-

Z geometrical 2-D model used in the calculation includes the FW, trays with Li vapor manifold, secondary breeding blanket, shield, VV, and magnet in both the IB and OB regions. Both the IB and OB regions are modeled simultaneously to account for the toroidal effects. The TWODANT module of the DANTSYS 3.0 discrete ordinates particle transport code system was utilized.

The overall TBR calculated for the reference design using the 2-D model is 1.37. It is based on the conservative assumption of no breeding in the divertor region. 69.8% of tritium breeding occurs in the trays (57.3% OB and 12.5% IB). The OB secondary blanket contributes 27.7% of the total overall TBR (20.2% behind trays and 7.5% between trays). The contribution of the shield is only 2.5% (1% OB and 1.5% IB). Tritium breeding has a comfortable margin that allows for design flexibility.

For a nominal fusion power of 1 GW, Fig. 3 shows the nuclear heating partitioning in the EVOLVE components. Most of the nuclear heating (~72%) is deposited in the evaporation cooled front blanket. Adding the surface heat deposited in the FW implies that ~76% of the total IB and OB energy is deposited as high grade heat in the front evaporation cooled zone (FW and trays) and carried by the Li vapor to the heat exchanger. The peak W structure nuclear heating in the blanket and shield components obtained from the 2-D calculation is given in Table 1. No significant poloidal peaking is observed in the nuclear heating profiles since the source is volumetrically distributed. The secondary neutrons and gamma rays which give large contribution to nuclear heating tend to give nearly poloidally uniform profiles. The peak dpa and helium production rates

are shown in Table 2. No significant poloidal peaking is observed. The peak damage rate in the OB secondary blanket and IB shield is about a factor of ~6 lower than in the FW and, hence, they are expected to have a factor of 6 longer lifetime than the FW and trays. The lifetime of the OB shield is about an order of magnitude longer than for the OB secondary blanket and the IB shield making it a lifetime component.

Two dimensional activation analysis was performed assuming neutron wall loadings of 7 and 10 MW/m² at the IB and OB first walls, respectively. The analysis used the W-5Re alloy as a structure material in the first wall and blanket, and shield. The IB and OB first walls and trays were assumed to be replaced every 5 FPY. On the other hand, the OB secondary blanket, shield and vacuum vessel are assumed to stay in place for 30 FPY. The activation code DKR-PULSAR2.0 was used in the calculations. Figures 4 and 5 show the specific activity and decay heat values induced in the different components as a function of time following shutdown, respectively. In these figures, the term "first wall" refers to the FW and tray as a single unit. As shown in both figures, the W-5Re alloy produces high level of radioactivity after shutdown. The first wall, trays, and secondary blanket dominate the overall activity and decay heat induced in the structure. Some work has been performed to incorporate a secondary heat removal system to accommodate the afterheat, and additional work is planned.

4.0 Power Conversion

There are two coolant streams exiting from the blanket. The front part of the blanket, including the first wall, is cooled by boiling lithium, which carries ~2/3 of the total

thermal power. The lithium vapor exits from the blanket at 1200C and 0.35 bar pressure. The back part of the blanket is cooled by a conventional self-cooled liquid lithium blanket with an exit temperature of also 1200C, which carries the other 1/3 of the thermal power. The reason that a second breeding zone is necessary is to increase the lithium density for tritium breeding considerations. The overall ΔT through the primary blanket is expected to be low since the power is removed through boiling. Additional work is planned to look in more detail at temperature gradients through the blanket.

The two blanket coolant streams will be fed to two heat exchangers to transfer the thermal energy to a helium loop. The reason that He is used for the secondary coolant is that a closed cycle gas turbine can be used for very efficient power conversion. The two lithium streams exit from the blanket operates in series, with the liquid lithium stream to heat up the secondary He from 700 to 800C, while the high temperature lithium vapor super heat the same He stream from 800 to 1000C. The He at 1000C will enter a He turbine for power conversion.

The parameters of the power conversion system are summarized on Table 3. With a very high He temperature, and very high recuperator, compressor and turbine efficiencies, a very high cycle efficiency of 57.7% is calculated. This thermal efficiency includes the pumping power of the secondary He stream, but does not include the pumping power of either of the lithium streams.

5.0 First Wall Stress Analysis

Finite element thermal and stress analyses have been performed for the first wall subjected to surface heat fluxes of 1.5 and 2 MW/m², a coolant temperature of 1200°C, and a coolant pressure of 0.05 MPa. A single tungsten tube of radius 2 cm and wall thickness of 3 mm deforming under generalized plane strain condition is considered. The primary membrane stress in the EVOLVE first wall is so low that neither low-temperature nor high-temperature ratcheting should be a limiting criterion for the surface heat flux. The peak surface heat flux will be controlled either by creep-fatigue (which is not considered here) or possibly by brittle fracture (due to helium-embrittlement). Because of lack of data, we will consider a conservative limiting case of near zero ductility.

Heat conduction and thermal stress analyses were conducted for three cases, all with a coolant temperature of 1200°C. In the first case, a peak surface heat flux of 1.5 MW/m² was analyzed with a solid to coolant heat transfer coefficient of 10,000 W/m²/°C. In the second case, a peak surface heat flux of 2 MW/m² was analyzed for a solid to coolant heat transfer coefficient of 40,000 W/m²/°C and finally, in the third case the same problem was analyzed for an infinite heat transfer coefficient. The temperature distribution for a peak surface heat flux of 2 MW/m² and a heat transfer coefficient of 40,000 W/m²/°C (Fig. 4) shows a peak temperature of 1317°C with most of the heat conduction at the peak temperature location occurring radially. The peak stress intensity is 158 MPa, which easily satisfies the ratcheting limits. Until now we have assumed that tungsten does not undergo embrittlement either due to irradiation or helium embrittlement. No relevant data are currently available. However, it should be noted that

very little ductility is needed maintain the allowable stress limit at a high value. For example, if the uniform elongation remains higher than 2% or the reduction in area at failure is >1%, then the allowable stress is > 300 MPa.

6.0 Tritium Extraction

The tritium solubility in lithium is very high. Therefore, the tritium vapor pressure over lithium is very low, with a reasonable tritium concentration in the lithium. The typical design goal for tritium recovery system is to limit the tritium concentration in the lithium to about 1 appm. At this concentration, the tritium inventory in the breeding is about 200g, while the tritium partial pressure over lithium is 10^{-7} Pa at 600C. With the low tritium partial pressure and reasonable tritium concentration, the tritium recovery process will recover tritium from the liquid phase.

A new tritium recovery process from liquid lithium has been proposed under ITER activities(2). This method is based on cold trapping. Cold trapping demonstrated for tritium recovery to the solubility limit, which is ~250 appm at 200C. The proposal here is to add protium in the lithium so that the tritium concentration can be reduced to 1 appm, while the total hydrogen concentration is about the saturation limit. The attractive feature of this process is that no impurities will be added into the lithium. The cost is that protium will be added, that tritium has to be separated from protium.

With Li(T+H) super saturated in the cold trap, it will precipitate out. There is a large difference in density between lithium (0.5) and LiH (0.8). therefore LiH can be separated

from lithium by gravitational force. (A process called meshless cold trap was developed for the breeder program based on the same principle)(3). The Li(H+T) can then be heated up to 600C, at this temperature Li(H+T) will be decomposed to Li and (H+T). The Decomposed product of Li and (H+T) will be passed over cold trap of 200C, in which Li will be condensed. The (H+T) will pass a permeation window to assure the purity of the hydrogen stream, before it is fed to the Isotope Separation System (ISS) to separate H from T.

A detailed calculation for the design of the ITER ISS was performed based on the reference ITER parameters, with the addition of the (H+T) stream with H/T ratio of 1000. The additional cost associated with the separate the H/T from the blanket tritium recovery system, as well as the additional refrigeration power required, are rather modest(4).

7.0 Critical issues, required R&D

The EVOLVE concept is at an early stage of evaluation. At this stage, it is important to assess the potential of the concept, identify crucial issues, and to define needed R&D work to remove resolve those issues. The critical issues to be addressed in the near future are:

1. Will the backside of the first wall remain wetted under all conditions?

The first wall operates on the same principle as successfully employed in heat pipes where in addition the liquid metal has to be transported over a relatively large distance

by capillary forces. The required surface conditions and the heat flux limits of the EVOLVE concept have to be investigated for relevant magnetic field strengths.

2. *Will the vapor generated in the stagnant boiling pools of the primary breeding region separate fast enough from the liquid metal?*

The high power level in the blanket results in a rather high rate of lithium vapor generation. The important question is; how the vapor will rise inside the pool to the surface and how it will separate there from the liquid metal? The problem becomes more complicated by the presence of the strong magnetic field, damping all fast liquid metal movements.

3. *Will the liquid metal overflow system work and lead to equal liquid metal pressure in each tray?*

The blanket design should result in equal liquid metal height and pressure in every tray, provided the MHD pressure drops in the standpipes can be overcome by small static heads. Using thin-walled inserts in the standpipes can reduce the MHD pressure drop but it should be investigated if this is sufficient or if MHD flow coupling has to be employed to insure the desired liquid metal flow.

4. *Is it possible to fabricate entire blanket segments of tungsten or tungsten- alloys in spite of their low ductility and their limited weldability?*

The EVOLVE FW/blanket design allows for large fabrication tolerances and has minimum requirements on the strength of welds. Most of the welds do not need to be leak proof. Primary and secondary stresses in the blanket structure are minimized by the design. But nevertheless, the feasibility of fabricating these segments with such a material has to be investigated.

5. *How will the structural material behave under intense neutron irradiation?*

There is very little experience with tungsten under neutron irradiation. The general trend is that the material becomes brittle at low fluence. However, all the irradiation experiments had been performed at relatively low temperatures < 700 C and they are not relevant for temperatures > 800 C as envisaged in the entire EVOLVE blanket structure.

6. *Will the high after heat in tungsten cause a safety problem in case of a LOCA ?*

The after heat in tungsten at shutdown amounts to about 2 % of the full power value and is considerably higher than the one in steel. More analyses are required to find out if there is a significant safety problem caused by a LOCA in the EVOLVE system.

8.0 Summary

A new concept for an advanced fusion first wall and blanket has been identified. The key feature of the concept is the use of the heat of vaporization of lithium (about 10 times higher than water) as the primary means for capturing and removing the fusion power. A reasonable range of boiling temperatures of this alkali metal is 1200 to 1400 C, corresponding with a saturation pressure of 0.035 to 0.2 MPa. Calculations indicate that a evaporative system with Li at ~1200 C can remove a first wall surface heat flux of 2 MW/m² with an accompanying neutron wall load of 10 MW/m². Work to date shows that the system provides adequate tritium breeding and shielding, very high thermal conversion efficiency, and low system pressure. Tungsten is used as the structural material, and it is expected to operate at a surface wall load of 2 MW/m² at temperatures above 1200 C. A number of critical issues have been identified, and they will be investigated in the future.

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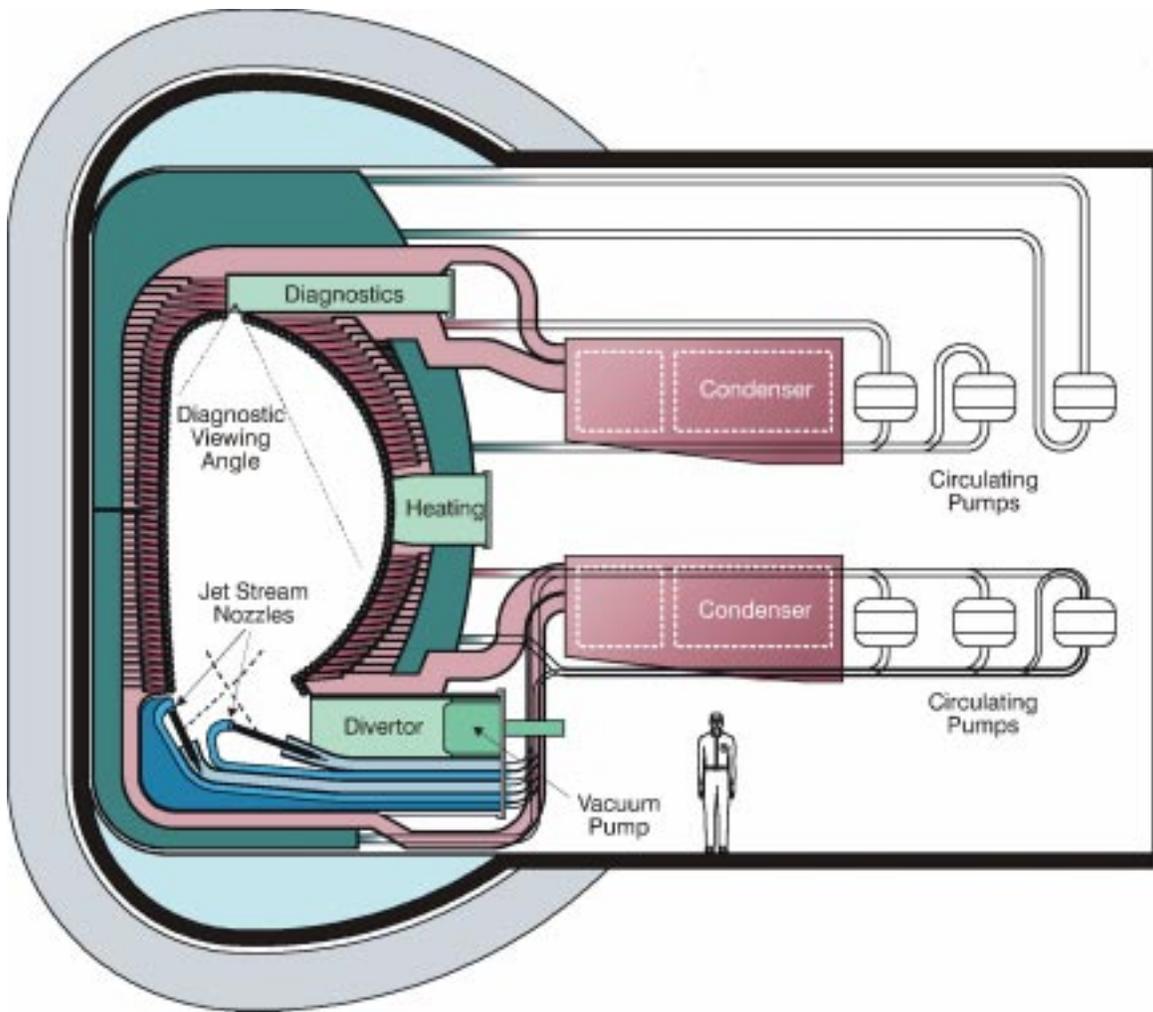


Figure 1. Cross-sectional view of the EVOLVE first wall/blanket concept

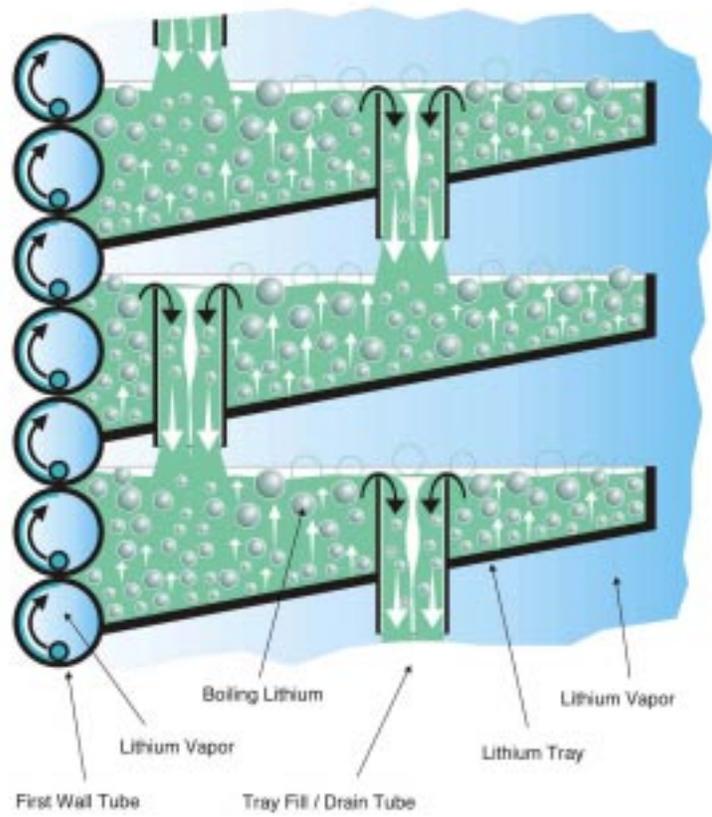


Figure 2. Schematic of EVLOVE first wall tubes and blanket trays containing Li

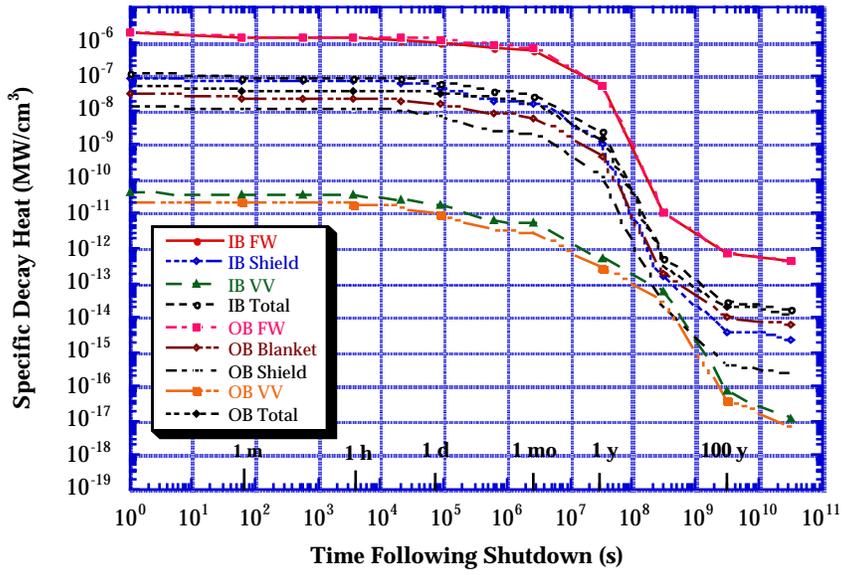
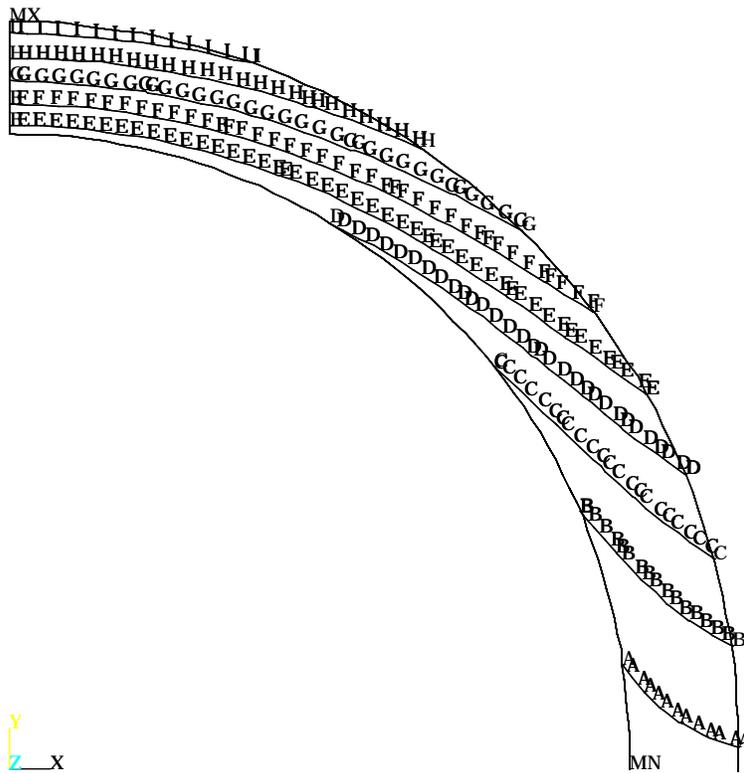


Fig. 5 Decay heat induced in the different components of EVOLVE as a function of time following shutdown.



BFETEMP (AVG)
 DMX =.009968
 SMN =1206
 SMX =1317
 A =1212
 B =1224
 C =1237
 D =1249
 E =1261
 F =1274
 G =1286
 H =1299
 I =1311

Fig. 6 Temperature distribution in W first wall due to a peak surface heat flux of 2 MW/m², coolant temperature of 1200°C and coolant-first wall heat transfer coefficient of 4x10⁴ W/m²/°C (Case 2).

Table 1. Peak structure nuclear heating (W/cm^3) in blanket and shield components

	IB	OB
FW	85.0	105.8
Manifold Backplate	33.3	31.3
Secondary Blanket	NA	26.2
Shield	20.1	4.3

Table 2. Peak dpa and He production rates in the W structure.

	Dpa/FPY		He appm/FPY	
	IB	OB	IB	OB
FW	25.7	34.8	14.0	20.2
Manifold Backplate	7.0	7.0	2.0	2.0
Secondary Blanket	NA	6.1	NA	1.8
Shield	4.3	0.74	1.3	0.12

Table 3. Power Conversion Parameters for the EVOLVE Concept

Parameter	Name	Value
To, K	Turbine inlet temperature	1273
Ts, K	Compressor inlet temperature	308
To/Ts		4.13
r	Compression ratio	2.0
nx	Recuperator efficiency	0.96
nc	Compressor efficiency	0.92
nt	Turbine efficiency	0.92
Beta	Turbine pressure ratio	1.02
Gamma	Gas heat capacity ratio (Cp/Cv)	1.66
Cycle efficiency		57.7%