Thermal analyses of a HCPB blanket for DEMO reactor

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Outline

1. Introduction
2. Transient thermal analyses
3. Impact of thermal contact conductance
4. Ex-VV and In-VV LOCA analyses
5. Conclusions

Introduction

- Development of a demonstration fusion power plant (DEMO) is considered as a crucial step towards fusion energy. Two major goals have to be achieved:
  - ✓ Fuel self-sufficiency (all the tritium has to be produced by the reactor)
  - ✓ High grade heat extraction (for electricity production).
- Breeding blanket is the key component to ensure these two objectives. Helium Cooled Pebble Bed (HCPB) blanket is among most studied blanket concepts worldwide.
- This work is a thermal analysis on a new version of this concept that is currently developed in KIT. The scope is to investigate some critical aspects of the design in order to evaluate the performances, in particular:
  - ✓ Blanket thermal behavior under DEMO typical pulse
  - ✓ Impact of thermal contact conductance between pebble bed and walls
  - ✓ Blanket behavior under two loss-of-coolant accidents (LOCAs).
- A 3D slice model which reproduces a section of the blanket module has been used.

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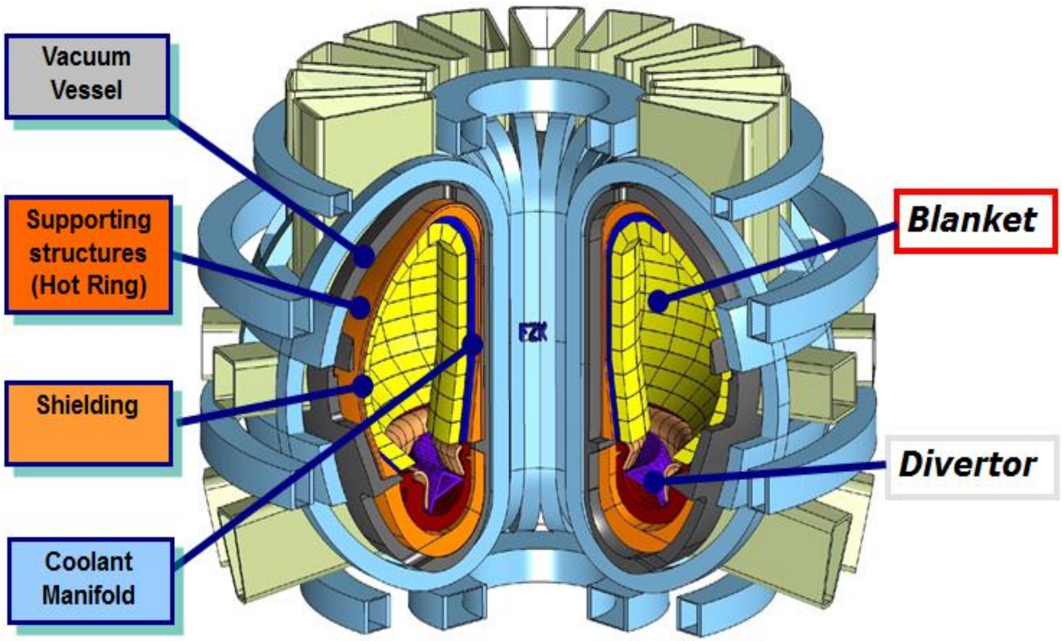
Blanket Design and ANSYS Model



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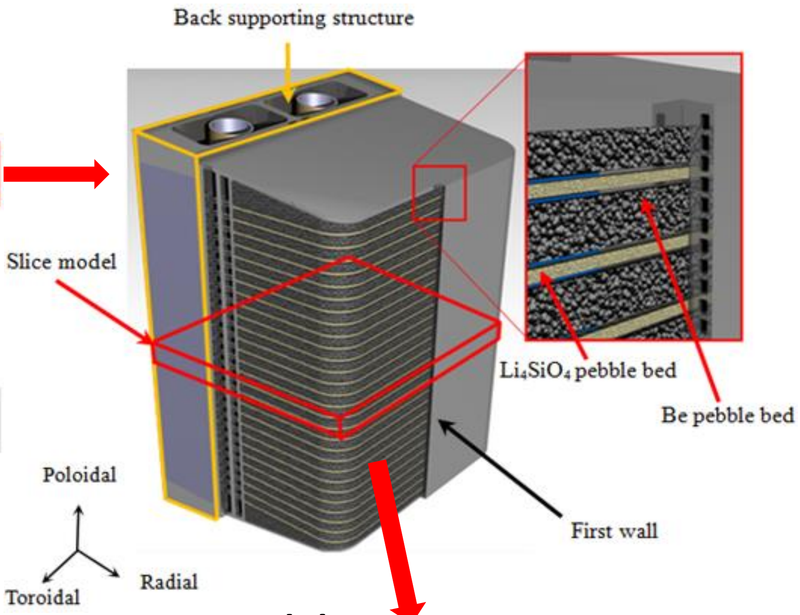
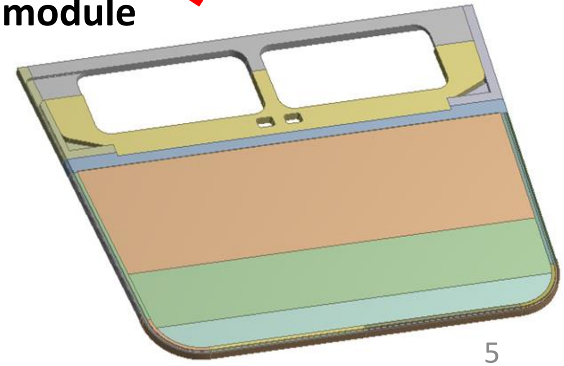
KIT design of a DEMO



HCPB module

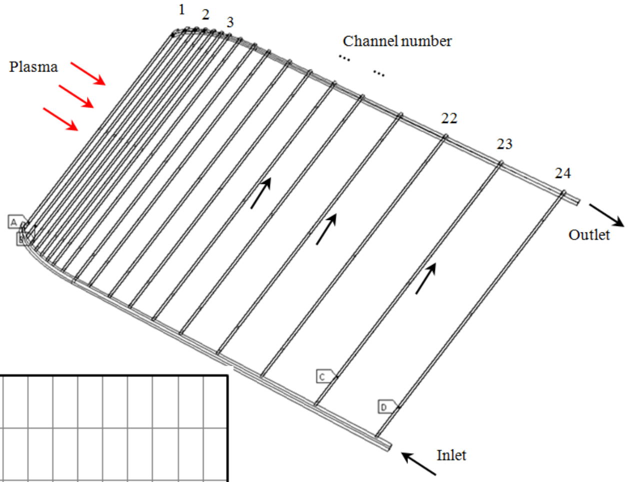
- The blanket has a “sandwich” layout of flat Cooling Plates and alternating Li_4SiO_4 and Beryllium pebble beds.
- 3D slice model consists of half thick of Li_4SiO_4 and Be pebble beds, and a CP and one and half cooling channels of FW.
- By using this slice model, we can save computation time.

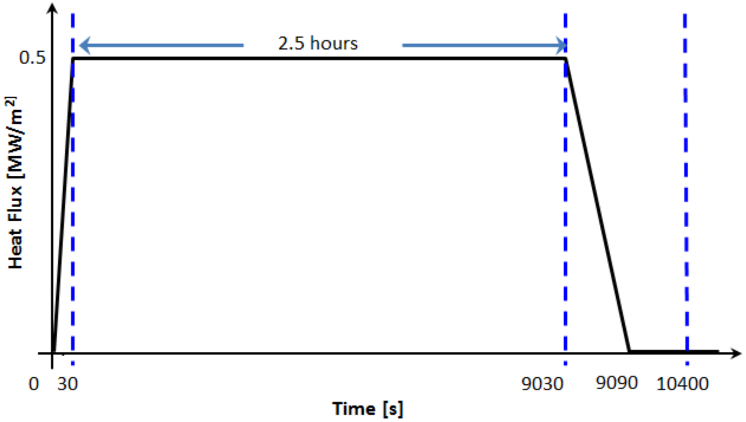


3D-Slice model

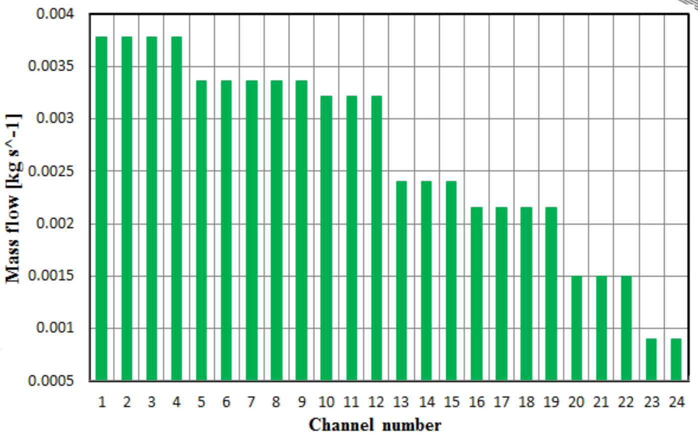
Boundary Conditions

- A heat flux of 0.5 MW/m^2 to FW lasts for a period of 2.5 hours (with a 30-second ramp-up and a 60-second ramp-down) following the plasma pulse.
- Volumetric heat sources have the same time-dependence of the heat flux.
- Mass flow rate in each channel of FW is ~87 g/s.
- Optimized mass flow rates in channels of CP are used.
- 1D finite element method (FluidLine technique in ANSYS) is used to simulate heat exchange between coolant and blanket.



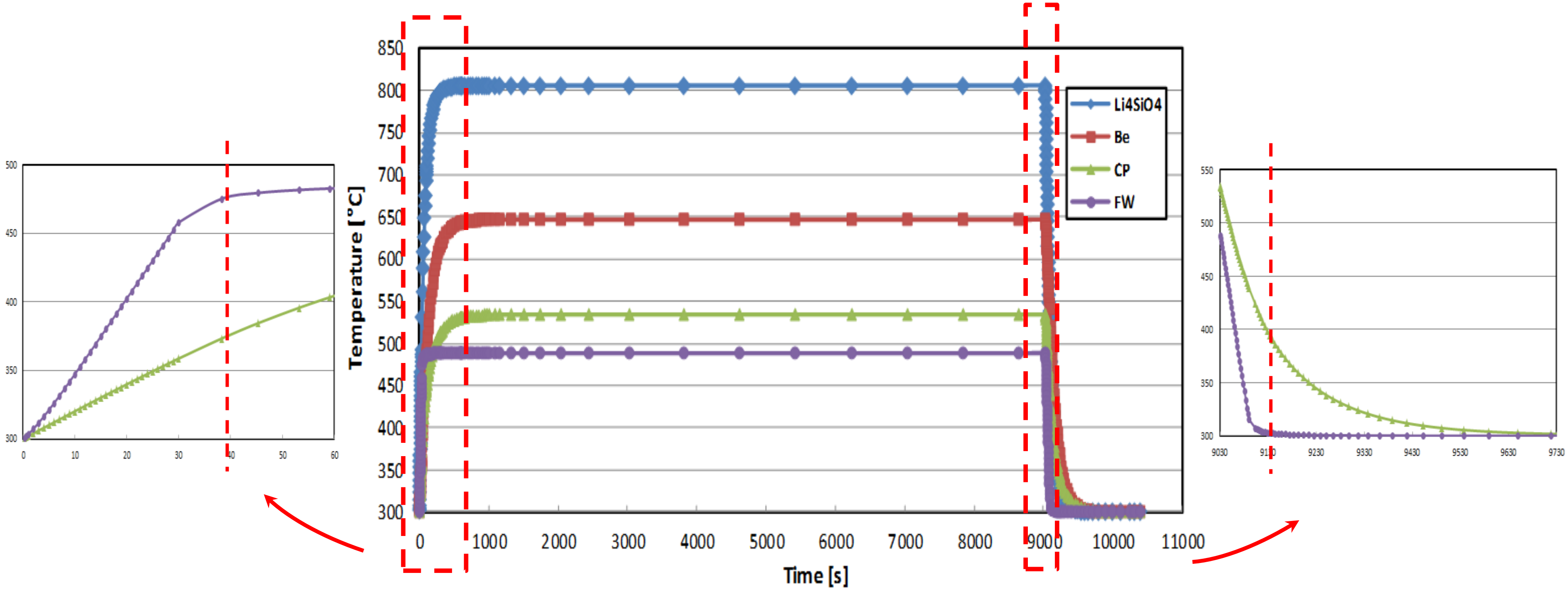


Heat flux



Mass flow rate in CP channels

Maximum Temperature Evolution



- FW is heated up quickly, when FW reaches high temperature; other sub-componets (especially CP) are still “cold”. At ~900 s, the blanket reaches the “steady state”.
- At the plasma pulse end, FW is cooled down quickly than others.
- These temperature differences cause thermal stresses in blanket structure.
- The temperature field at critical time points will be used to thermo-mechanical assessment.

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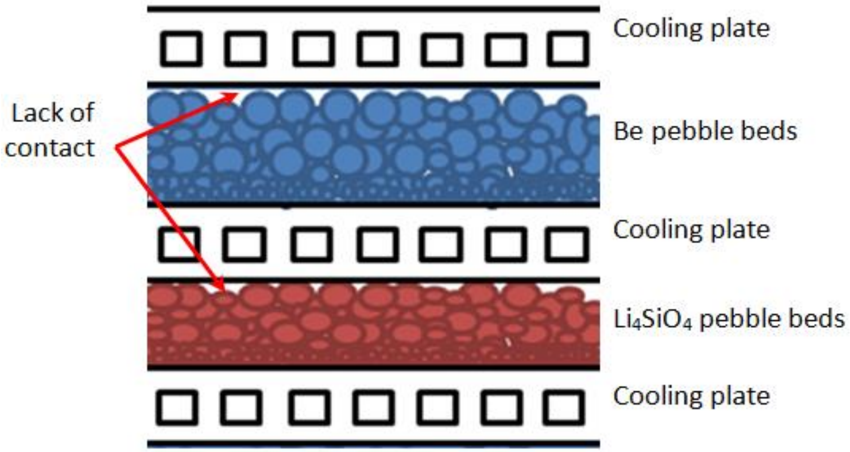
Background

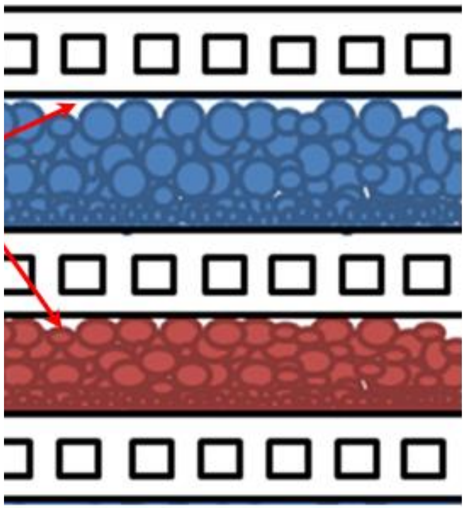
- Thermal contact conductance (TCC) between pebble beds and wall has a notorious influence on heat transfer between pebble beds and walls.
- The current HCPB DEMO Blanket adopts the “sandwich” layout.
- Due to cracking, plastic deformation, relocation of the pebbles, the contact area between pebble beds and wall may change.
- TCC is thus changed accordingly.



- This part investigates the impact of the change on temperature of the blanket.

Boundary Conditions

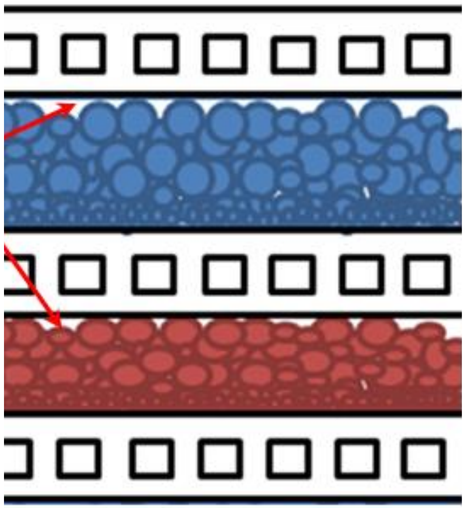
- The input TCC values have been set varying from “0.0TCC$_0$” to “TCC$_0$”*.
- In the extreme case that the pebble beds in one side totally lose the contact with one cooling plate.
- The heat transfer at the gap has been conducted by purge gas.
- According to Gan et al. [1], the gap distance is assumed 0.29 mm
- According to Song et al. [2], Fourier’s law of heat conduction can be used here. The heat transfer coefficient ($h=k/\delta$) for the gap is 991 W/m^{2}K.



* where TCC$_0$ is the original value.

[1] Y. Gan, Thermo-mechanics of pebble beds in fusion blankets, PhD thesis, Forschungszentrum Karlsruhe, 2008
[2] S. Song, M.M. Yovanovich, F.O. Goodman, Thermal Gap Conductance of Conforming Surfaces in Contact, Journal of Heat Transfer, 115 (1993) 533-540.

Results of TCC Sensitivity Study



$TCC_{Li4SiO4\text{-}wall}$	$0.0TCC_0$	$0.1TCC_0$	$0.25TCC_0$	$0.5TCC_0$	$0.75TCC_0$	TCC_0
$T_{max.\ Li4SiO4}$, °C	1610	889	838	818	811	807
$T_{max.\ Be}$, °C	709	670	666	665	664	649
$T_{max.\ EUROFER}$, °C	627	547	539	537	536	536

$TCC_{Be\text{-}wall}$	$0.0TCC_0$	$0.1TCC_0$	$0.25TCC_0$	$0.5TCC_0$	$0.75TCC_0$	TCC_0
$T_{max.\ Li4SiO4}$, °C	826	811	809	807	807	807
$T_{max.\ Be}$, °C	1257	747	695	674	666	649
$T_{max.\ EUROFER}$, °C	587	544	539	536	536	536

- EUROFER and Li_4SiO_4 are not sensitive to TCC, while Be pebble bed is very sensitive to TCC.
- Lack of contact may locally cause beryllium overheating, hindering the purge gas flow.
- Therefore, it’s important to ensure a high thermal contact conductance value.

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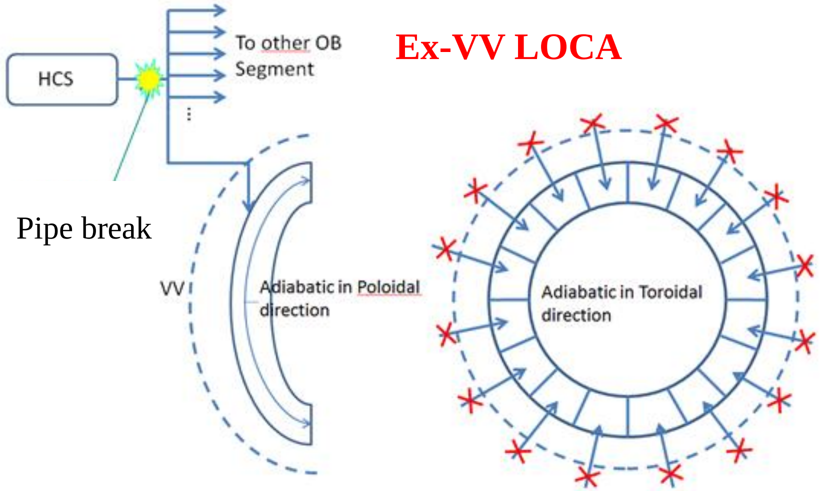
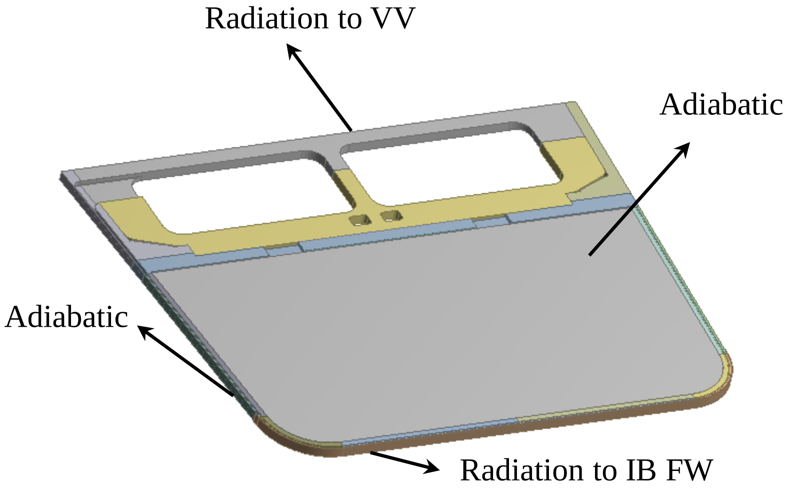
Boundary Conditions of Ex-VV LOCA

- Simulation time (till 26h after accident initiation)
- Assume: HCS to OB break; Helium lost immediately; Fast plasma shut down system operative



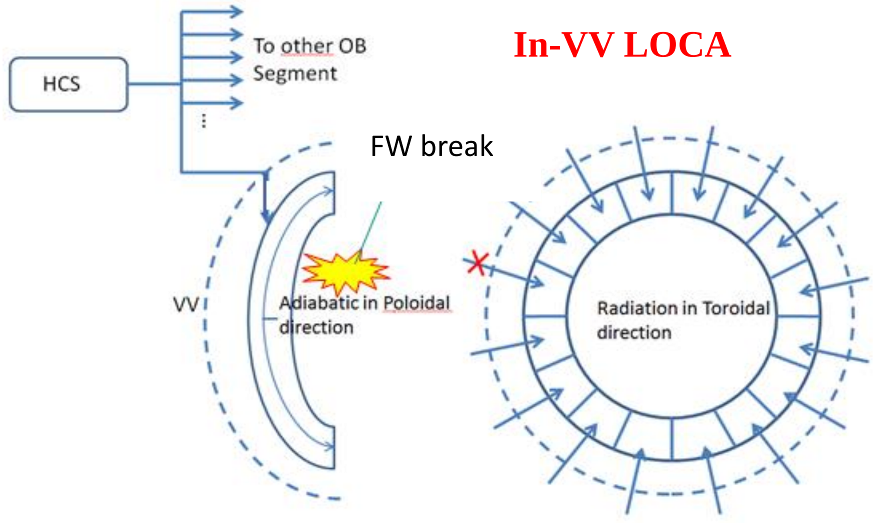


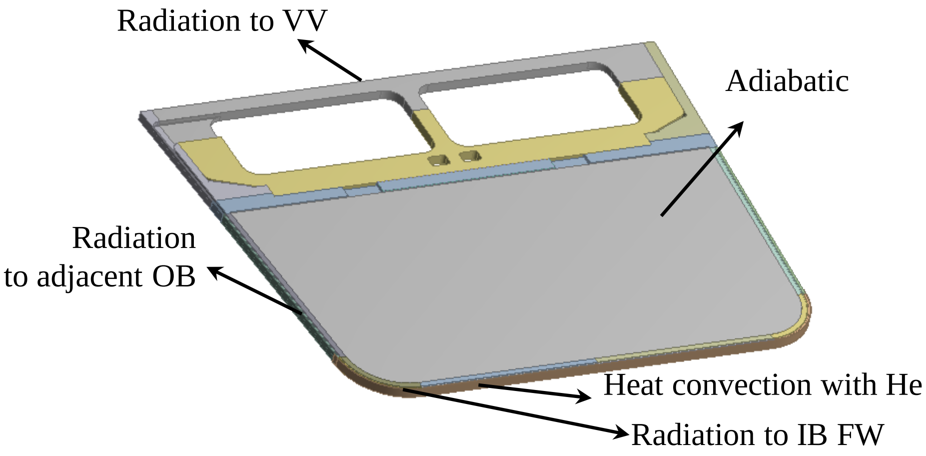
- Afterheat is the only remaining heat source
- The heat is removed only by radiation
- Radiation to VV considered @120^{o}C, emissivity=0.35
- Radiation to InBoard FW considered @500^{o}C, emissivity=0.35

[1] D. Carloni, Q. Kang, S. Kecskes, Thermal analysis of accidental blanket temperature, KIT/INR report, 2013.

Boundary Conditions of In-VV LOCA

- Assume: FW break; Helium lost immediately; Plasma shut down immediately

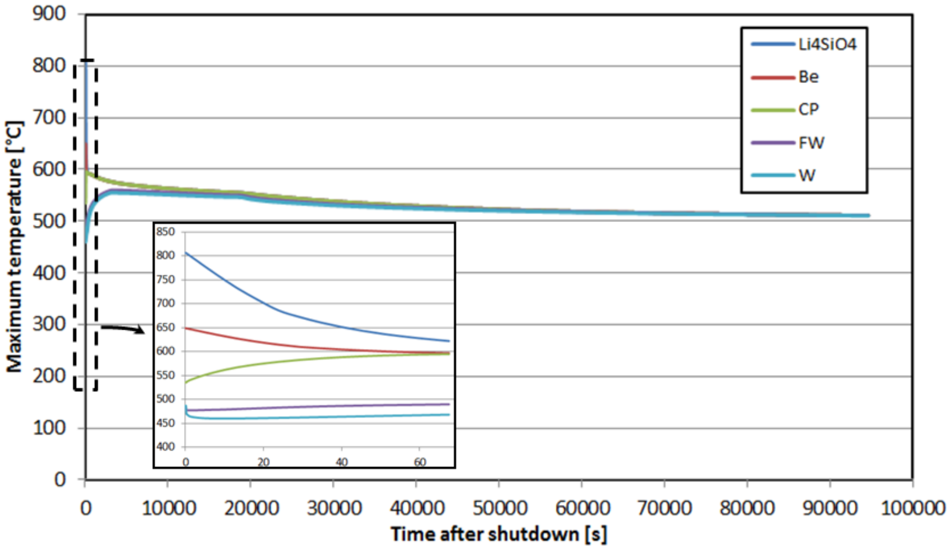




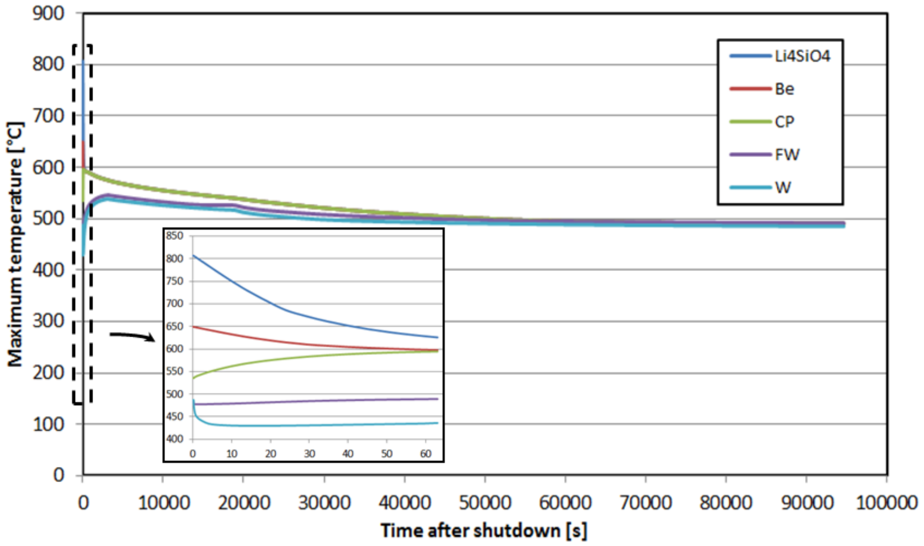
- Afterheat is the only remaining heat source
- Radiation to VV considered @120^{o}C, emissivity=0.35
- Radiation to IB FW & adjacent OB considered @500^{o}C, emissivity=0.35
- Heat transfer coefficient @ h=4 Wm^{-2}K^{-1}

[1] D. Carloni, Q. Kang, S. Kecskes, Thermal analysis of accidental blanket temperature, KIT/INR report, 2013.

Maximum Temperature Evolution



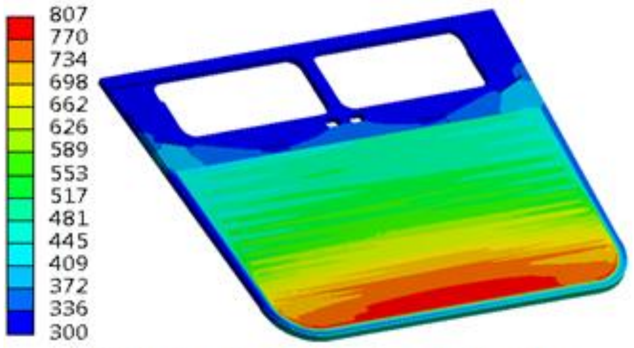
Ex-VV LOCA



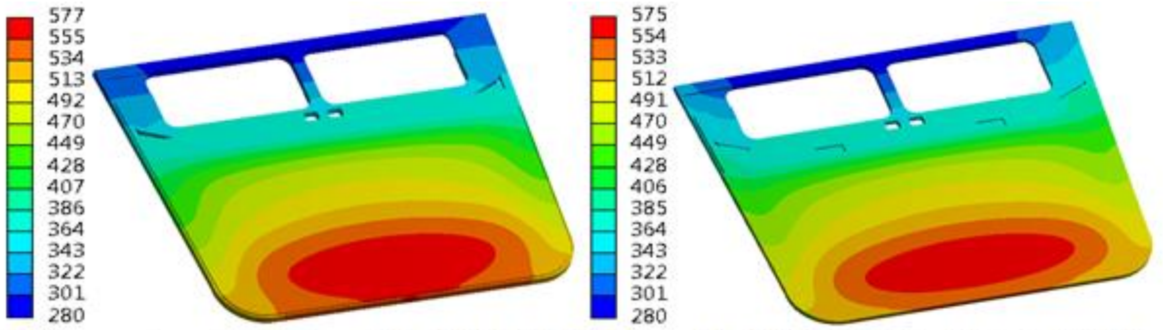
In-VV LOCA

- For both accidents we observe a very similar thermal behavior, after plasma shutdown, Li_4SiO_4 and Be pebble beds are gradually cooled down by radiation, never exceeding design limits.
- While the FW temperature increases firstly, reaching a maximum of 577 (575) ℃
- FW is far from reaching melting point(about 1400 ℃)

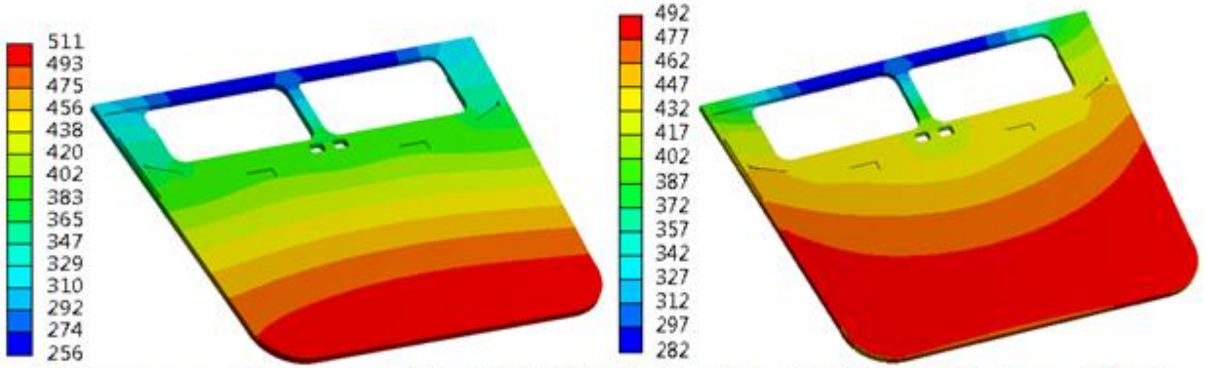
Temperature Distribution Comparison



(a) Steady state temperature distribution



(b) Temperature distribution of Ex-VV LOCA (left) and In-VV LOCA (right) at t= 3153.6 s



(c) Temperature distribution of Ex-VV LOCA (left) and In-VV LOCA (right) at t= 94608 s

- Under the assumed conditions, In-VV LOCA is less severe than Ex-VV LOCA due to the helium leaked into the vacuum chamber.

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Conclusions

- Transient thermal behavior of the blanket under DEMO typical pulse has been investigated. The results are the basis for future thermo-mechanical assessment.
- The impact of thermal contact conductance between pebble beds and wall on blanket temperatures has been analyzed. The result shows:
  - ✓ that the thermal contact conductance has a sensitive influence on the temperature of Be pebble bed while exerts a limited influence on that of lithium orthosilicate pebble bed and EUROFER.
  - ✓ the lack of contact may cause a local overheating of the Be pebbles, with possible hindering of the tritium extraction capability of the purge gas.
- Ex-VV and In-VV LOCA analyses (DBA with plasma shut-down) show that the temperature of first wall is far from melting and temperatures of other sub-components are inside allowable limits.

Thank you for your attention!