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***Abstract*—'Fusion for Energy' (F4E) is designing, developing, and implementing the European Helium-Cooled Lead-Lithium (HCLL) and Helium-Cooled Pebble-Bed (HCPB) Test Blanket Systems (TBSs) for ITER (Nuclear Facility INB-174). Safety demonstration is an essential element for the integration of these TBSs into ITER and accident analysis is one of its critical components. A systematic approach to accident analysis has been developed under the F4E contract on TBS safety analyses. F4E technical requirements, together with Amec Foster Wheeler and INL efforts, have resulted in a comprehensive methodology for fusion breeding blanket accident analysis that addresses the specificity of the breeding blanket designs, materials, and phenomena while remaining consistent with the approach already applied to ITER accident analyses. The methodology phases are illustrated in the paper by its application to the EU HCLL TBS using both MELCOR and RELAP5 codes.**

Keywords— fusion safety; fusion breeder blankets; accident analyses; ITER, DEMO, test blanket system, TBM, TBS

I. Introduction

Testing the tritium breeding modules (TBM) in ITER [1], and the need to include them in the ITER licensing [2], offers a unique opportunity for further development, improvement, and validation of the methodology for breeder blanket (BB) accident analysis [3]-[7]. The safety approach and accident analysis methodology for ITER is very well defined, as demonstrated by the successful construction licensing [8]. However, due to the later inclusion of the TBM testing program in the ITER agreement, the TBS safety demonstration was somewhat detached from the ITER machine safety at the beginning of the project.

Safety studies for fusion facilities are commonly conducted using codes originally developed for fission reactor accident analysis. Some of these codes have been modified, and have additional physical models to treat fusion-relevant phenomena [10]-[14]. For example, fusion-adapted versions of MELCOR are widely applied for fusion accident analyses [3], [9], [13], [23]. The underlying fission safety codes have undergone development and validation using extensive separate and integral effects experimental databases [18]-[20]. These huge international efforts (including the 2D/3D program [18] and many computational benchmark problems) using phenomena identification and ranking tables (PIRT) [21] and improved simulation models have led to development of a best estimate methodology for fission safety. The fusion-modified codes are validated against the limited available fusion experimental data or through benchmarking against validated code(s) or code version(s) [15]-[17]. Note that experimental data for many BB (accident) phenomena are not yet available.

This work is devoted to establishing a systematic integrated ITER-TBS/DEMO-BB accident analysis methodology for simulating fault response of the breeding blanket and its interaction with the rest of the machine/plant. The methodology consists of several phases: 1) selection of accident scenarios based on failure modes and effects analysis (FMEA) studies, 2) elaboration on these to develop accident analysis specifications (AAS) via the use of PIRT to identify required physical models to aid in code selection, 3) development of TBS models using the codes selected, and 4) qualification of the models via comparison with finite element calculations, code-to-code comparisons, and sensitivity studies.

The outlined methodology addresses the challenge in performing accident analysis for the EU TBS in an environment lacking experimental data on TBS phenomena. According to the French INB order 2012 [24] some TBS sub-systems and components are Protection Important Components and the application of the methodology provided in this paper to the ITER TBS accident analyses is a Protection Important Activity. For this reason the compliance with French INB order was a fundamental requirement for the work described hereafter.

II. Selection of Reference Accident Scenarios

As described in [5] and [7], the procedure developed for the selection of reference accident scenarios for ITER [22] has been used to identify scenarios for the EU TBS. The accidental conditions, or postulated initiating events, which might give rise to a release of radioactivity were determined from a FMEA evaluation; a set of reference accidents was then identified, by grouping individual accident initiators that have similar consequences, which are outlined in [4].

III. Development of the Accident Analysis Specifications

In the presented methodology, the reference scenarios are elaborated on to provide AAS. These are used, together with PIRT, to identify the requirements to be met by the analysis codes and TBS models. In this manner the limitations of individual analysis codes may be identified, and, where necessary, modelling approaches to overcome these limitations can be proposed.

The definition of the accident analysis specifications for each scenario is performed in seven steps: (i) list the systems potentially engaged in the scenario; (ii) identify the phenomena that are likely to occur and list the required code models; (iii) select the most suitable code and version for analysis according to the predefined criteria; (iv) specify the input to the model development; (v) list the expected output of the accident analyses; (vi) define the accident sequence; (vii) prepare an accident flow chart. The key elements of these steps are described below, with reference to the HCLL TBS.

A. Phenomena Identification Tables and Required Code Models

The identification of the phenomena that potentially could occur within the reference accident scenarios is assessed in a two stage process. Initially, a review of existing analysis results is undertaken to obtain direct information on the more significant phenomena occurring in normal operation and the selected reference accident sequences. Secondly, a review of phenomena based on the physical processes imposed by the accident, system design, operating conditions, safety functions and materials of construction is performed to provide a more comprehensive basis for the assessment. This approach resembles that adopted for the PIRT procedure.

For the HCLL TBS, the phenomena were grouped under ten sub-headings: power source; flow; heat transfer; phase change; lead-lithium (PbLi) modelling; chemical reactions; non-condensible gases; material properties; numerical coupling and system I&C modelling. The results from each of the reviews were compared and consolidated to produce a single set of phenomena that could potentially influence the progression of the accident sequences. An excerpt from this list for the PbLi modelling is presented in TABLE I.

TABLE I. LIST OF HCLL TBS PHENOMENA FOR PBLI MODELLING

Phenomenon/Parameter	Location	Impact on Accidentss
PbLi representation: Heat transfer; Chemical reactions with steam/air; Power source in PbLi (neutron heating and decay heat)	Breeder Unit (BU), PbLi ancillary equipment.	Chemical reactions, release of Tritium to atmosphere. Moveable source of thermal inertia and decay heat.
Flow/mixing of liquids - PbLi and water	Vacuum Vessel (VV).	Rate and overall reaction of compounds.
PbLi – impact of magneto-hydrodynamic (MHD) phenomena	BU.	In normal operation, magnetic fields generate significant contribution to PbLi pressure drop across TBM and influences the local flow distribution and heat transfer. In accident, mainly affect dynamics of PbLi flow.
PbLi flow in normal operation and in accidents (including drain to tank)	BU,VV.	Rate of draining of BU. PbLi flow regime within VV (droplet size, pooling). Heat transfer from spilt PbLi.

B. Code selection

The list of phenomena, described above, form the basis for an assessment of the code models within the code selection procedure.

For the HCLL TBS, the code selection criteria included model availability, coverage of phenomena, verification status, and the ability to resolve local and 2D/3D effects. The code selection process has been limited to the assessment of different versions of the RELAP5 and MELCOR codes, as prescribed by F4E. The specific code versions that have been considered are RELAP5/MOD3.3, RELAP5-3D, MELCOR 1.8.2 (fusion adapted), MELCOR 1.8.5 (fusion adapted multi-fluids version), and MELCOR 1.8.6 (fusion adapted).

The individual versions of the MELCOR and RELAP5 codes have, in many respects, similar capabilities and attributes. In TABLE II the list of phenomena presented in TABLE I is repeated with statements indicating the ability of the codes to model specific phenomena; a more extensive evaluation was undertaken for key models and correlations. Thus the relevant similarities and differences between the codes (and where appropriate, between code versions) were identified.

TABLE II. HCLL TBS CODE MODEL ASSESSMENT FOR PBLI MODELLING

Parameter / Phenomenon	MELCOR	Uncertainty	RELAP5	Uncertainty
Flow/mixing of liquids - PbLi and water	There is not sufficient data available to develop a mechanistic model to predict the interaction between flows of PbLi and water and the subsequent chemical reaction. It is noted that the heat transfer from split PbLi will increase the pressurisation of the VV which needs to be captured in the analyses.	High (bounded)	The same comment on the MELCOR code versions also applies to the RELAP5 codes.	High (bounded)
PbLi – impact of MHD phenomena	The constraints of the MHD phenomena on the flowing liquid Pb-Li can be modelled by suitable inputs for the loss coefficients (fusion adapted version of MELCOR 1.8.5). However, in most accidents the PbLi flowrate is very low. MHD effects also impact the local flow distribution which in turn influences the wall-to-fluid heat transfer.	Medium	The MHD effects on the flowing PbLi can be modelled in RELAP5-3D through user input loss coefficients. However, the impact is judged to be low due to the low flowrate of the PbLi. As discussed for MELCOR the MHD effects can influence the local wall-to-fluid heat transfer.	Medium
PbLi Flow in normal operation and in accidents (including drain to tank).	Can only be modelled by fusion adapted version of MELCOR 1.8.5.	High	This can only be simulated by RELAP5-3D.	High

In terms of modelling capability, a newer code version might be preferred (e.g. MELCOR 1.8.6). However, for fusion-adapted MELCOR, version 1.8.2 has undergone the most extensive verification and validation, including a line-by-line review of fusion modifications to the source code. Applied to the HCLL, coverage of physical phenomena becomes the most critical aspect of the decision; amongst the code versions considered, only MELCOR 1.8.5 and RELAP5-3D include PbLi as a working fluid, and for that reason these code versions were selected. Though not as extensive as for 1.8.2, MELCOR 1.8.5 has been subject to verification via comparison studies with standard (fission) MELCOR 1.8.5 and pedigreed MELCOR 1.8.2, and has been used in other safety assessments involving PbLi [3], [23].

C. Accident Analysis Specification

The overall method used for the definition of accident specifications was based on the following steps:

- Definition of the accident analysis approach,
- Purpose of scenario (definition of objectives and acceptance criteria),
- Definition of accident initiating events and progression,
- Identification of system operation/data.

Both the objectives and the definition of initiating events and aggravating failures used the TBS Preliminary Safety Report (and FMEA study) as starting points. Based on this information, the potential accident progression and key phenomena were identified and compared with those derived in *Section II.A* above.

The acceptance criteria for each scenario have been selected based on the objectives defined. The specific safety design requirements given in system requirement documents were used as the basis for acceptance criteria where available.

IV. Development of the Breeding Blanket and Ancillary Systems Models

In the next step, accident analysis models were constructed using the selected MELCOR and RELAP5 codes. The TBS models cover all TBS systems and controls, and their relevant ITER environment. F4E requested flexible generic models able to handle a wide spectrum of accidents with minor adaptations, whilst maintaining consistency with ITER analysis models.

During development of the TBS models, the following MELCOR code-specific issues were identified and addressed:

- The effect of Control Volume nodalisation on MELCOR time steps (Courant time-step limit)
- Correction of helium gas properties within fusion-adapted MELCOR 1.8.5
- Changes to MELCOR sensitivity coefficients required to properly treat transition to turbulence in the helium coolant system (HCS) and TBM coolant channels

Although the MELCOR model of the TBS includes all sub-systems and main components, we will limit our description below to the TBM and PbLi loop.

A. TBM / breeder units (BU) nodalisation

The design intent of the MELCOR model of the HCLL TBM (and the TBS in general) is to provide the necessary level of detail whilst achieving a practical transient calculation time. Past experience has shown that MELCOR calculations are significantly limited by the Courant time-step limit which has a direct dependence on the nodalisation. This influenced the hydraulic control volume (CVH) nodalisation adopted for the TBM first wall (FW) and other major flow paths. The level of detail is judged sufficient to capture maximum temperature responses, as confirmed by a nodalisation sensitivity study.

A significant feature to be captured by the HCLL TBM model is the draining of the PbLi during accidents and the consequent re-positioning of the power source from the decay heat. This has been achieved by nodalising all eight BUs (numbered BU1 to BU8 from bottom to top) over the entire elevation of the TBM. The model calculates a uniform PbLi temperature across each BU.

The explicit representation of BU and associated cooling channels over the full height of the TBM makes the HCLL TBM model large and complex. To limit the size of the model, the two columns of BU are not resolved separately. Instead, the general symmetry of the TBM about the vertical stiffening grid (VSG) is exploited; a single column of BU is modelled with adjustments to the CVH, flow links (FL) and heat structure (HS) input made such that at each elevation the power, coolant flow, heat transfer and inventory of both columns are represented. One flow path, representing 12 coolant passages, models an upwards helium flow within the FW/SW as illustrated in Fig. 1 (left). A similar second flow path models a downward helium flow in the remaining 12 coolant passages. This arrangement captures the equal cooling of the upper and lower halves of the TBM provided by the FW design while significantly increasing the modeled FW volumes, thereby increasing the permitted simulation time step which is fixed by the Courant limit.

The nodalisation of the PbLi regions within the HCLL TBM is shown in Fig. 1 (right). The TBM PbLi volumes fall into one of three general categories: inlet/outlet pipes and manifolds represented by six CVH volumes; distribution and collection regions nodalized using 8 CVH volumes; and a single CVH volume used for each BU.

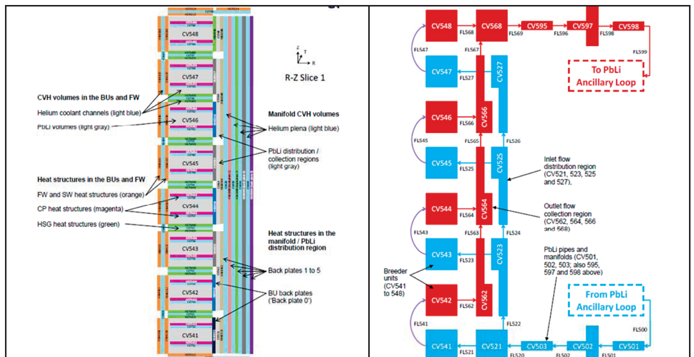


Fig. 1. MELCOR HCLL TBM nodalisation: coolant channels control volume and heat structure (left) and PbLi-filled regions (right)

B. TBS PbLi ancillary system

The MELCOR model of the PbLi ancillary system has been constructed to meet the requirements of a deterministic safety assessment. In particular, the model is designed to predict the pressure (both the gravitational pressure head and that generated by cover gas over pressure) that will drive leak flows and to represent the draining of the PbLi inventory of the TBM and ancillary system into the PbLi storage tank.

The MELCOR nodalisation of the PbLi ancillary system is illustrated in Fig. 2. The model represents the pipework of the main flow paths, the cold trap and storage tank, together with the associated cover gas supplies, circulation pump, valves, bursting disc and pressure relief valves that protect the TBM and PbLi system from over pressure. The system's control logic and Plant Safety System (PSS) signals are also modelled.

V. Representation of the ITER environment within TBS accident Analyses

Two approaches are proposed for the representation of the ITER environment of the TBS. The first consists of incorporation of a limited representation of the ITER building and systems within the TBS model. This is applicable only in cases when the TBS has a very weak impact on the ITER machine. The second and preferable option is coupling of the TBS and ITER models in order to simulate the interaction of both systems. These two approaches are discussed below.

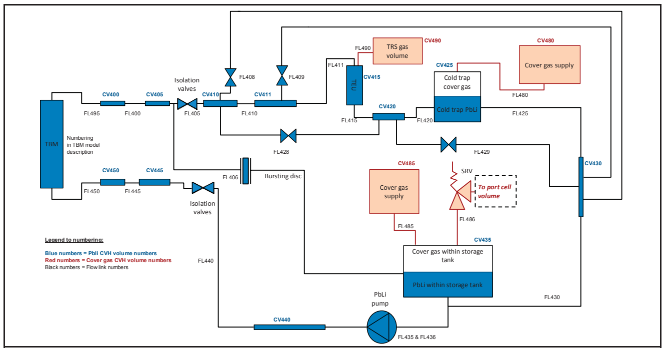


Fig. 2. The MELCOR PbLi loop model nodalisation scheme

A. *Model of the ITER environment inside the TBS Model*

The analysis of the TBS accident sequences require the assessment of fluid leakages, possible chemical reactions, and the transport of radionuclides within the VV, Port Cell, Chemical and Volume Control System (CVCS) area, Tokamak Cooling Water System (TCWS) vault, and connecting shafts. Therefore, these areas are included but coarsly nodalized (e.g. with a single volume) in the TBS model. Models of ventilation flows, leakage flows and engineered pressure relief paths are provided between the nodes representing the buildings and environment, as well as heat structures modelling the tokamak building to represent the heat absorbed from gases and steam released during accidents.

B. *Coupling of the TBS and ITER Machine MELCOR Model*

In order to assess the impact of accidents originating in the TBS on the accident response of the ITER machine, the interaction of these systems must be captured. Examples of this include in-vessel leakage of helium or PbLi that may cause a plasma disruption and ex-vessel leakage of helium that may lead to pressurization of the port cell or triggerring of the ITER Central Safety System (CSS).

In addition, the response of the ITER machine may influence the progression of an accident within the TBS through a range of mechanisms, including:

- The pressure within the VV affects the leak rate of PbLi from the TBM.
- The composition of the VV atmosphere influences PbLi-air reactions and hydrogen producing PbLi-steam reactions within the TBM.
- Variation of the port plug (PP) coolant temperature and flow rate – the PP acts as a heat sink to the TBM if HCS flow is lost.

In general, these interactions between the TBS and the ITER machine are sufficiently strong that a coupled analysis is required, with the accident response of both systems represented.

Direct integration of the TBS MELCOR model and the ITER machine MELCOR model into a single overall combined model is not possible since MELCOR cannot represent both liquid PbLi and liquid water (used as the primary coolant in the ITER machine) within a single simulation.

Therefore, a loose coupling of two models is used to represent the transient interactions of the ITER machine and the TBS. The selected method for coupling the ITER and TBS models is to perform a sequence of analyses, with a coordinated exchange of data between the two models:

- Boundary data describing the conditions within the ITER VV / buildings (computed by the ITER machine model) will be imposed on the TBS model.
- Boundary data describing leakage flows from the TBS (computed by the TBS model) will be imposed on the ITER machine model.
- Consistent TBS Plant Safety System (PSS) and ITER CSS actions will be imposed on both models.

Iteration between the two models will ensure that self-consistent results are obtained. The MELCOR EDF (External Data File) package provides facilities to transfer leak flow rates, enthalpies and other data between models to support this form of coupled analysis.

VI. Qualification of the Breeding Blanket and Ancillary Systems Models

The TBS accident analysis methodology includes qualification activities to assess the ability of the developed TBS models to represent the phenomena and transient responses associated with the accident sequences defined in the AAS. For the HCLL TBS, the models have been evaluated via a test matrix that includes 1) comparisons of the MELCOR and RELAP5 predictions with available finite-element analysis (FEA) results from the TBM design description documents (DDD) in steady state and normal pulsed plasma plasma operations, 2) further MELCOR and RELAP5 comparisons in normal operations and a series of test transients designed to cover a representative range of accident-relevant phenomena, and 3) sensitivity and uncertainty studies in more complex accident scenarios. A small subset of the test matrix is shown in TABLE III; these are only part of 12 cases with 19 variations executed in 24 code runs.

TABLE III. Qualification Analysis Summary

#	Case Title	Scenario and runs executed
	Comparison with the TBM design analyses	
2	TBM 400 s plasma power pulse using NBPC model variant	TBM model analysis of a 400 s power pulse to support comparison with DDD finite element analysis. MELCOR and RELAP5 simulation
	Analysis of HCLL TBS normal operation	
7	TBS test transient 2: Loss of Coolant Accident (LOCA) due to in (vacuum) vessel leak	In-vessel FW LOCA occurring close to end of 400 s plasma pulse. Helium leak from FW to VV occurs at 429 seconds. No PbLi leak. MELCOR and RELAP5 simulation
	Sensitivity study analysis cases	
11	S3: PbLi draining & leakage into VV Case 1BU-1 Case 2BU-1&2 Case 2BU-1&3 Case 2BU-1&8 Case SLIT	PbLi leak to VV occurs close to end of 400 s power pulse, with variation of leak path models. Investigate PbLi leak location and representation on leak rate and total leak flow. MELCOR simulation only Circular leak at mid height of BU1 represented by one MELCOR FL. Circular leaks at mid height of BU1 and BU2 Circular leaks at mid height of BU1 and BU3 Circular leaks at mid height of BU1 and BU8 Slit-shaped leak extending over the complete height of BU1. In all cases the same leak area as in 1-BU1 has been used. Note that the BU1 is the lowermost BU and BU8 is the uppermost BU.

A. *Comparison with finite element design analyses*

Comparison of MELCOR and RELAP5 simulations of a 400 second plasma power pulse (case 2 in TABLE III) with design FEA results (labeled DDD in the figures) are shown in Fig. 3. The RELAP5 FW coolant temperature peaks at 379°C at the end of the pulse (430 seconds), just 1°C above the MELCOR value and ~3°C below the finite element results. Similar results had been obtained for the maximum FW temperature with RELAP5, which peaks at 518°C compared to 524°C in MELCOR and 529°C in the finite element results.

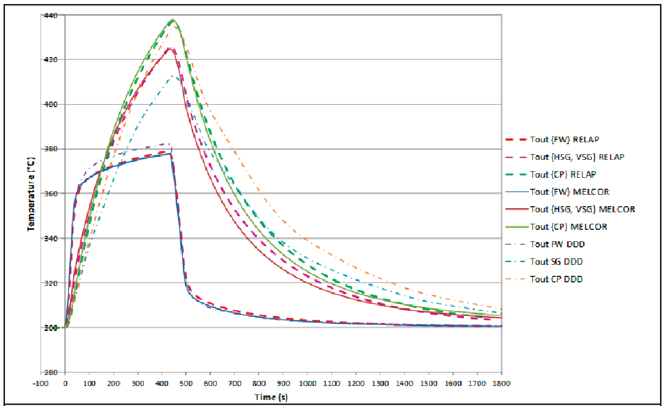
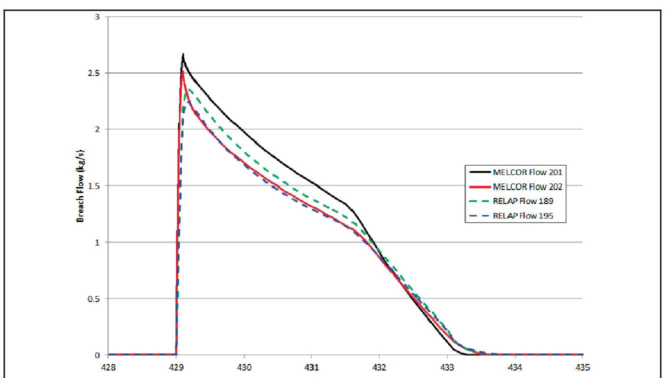


Fig. 3. Helium coolant temperatures during a 400 second power pulse

B. *Code to code comparison*

The accident in Test Sequence 2 – In-Vessel LOCA (case 7 in TABLE III) represents a double ended guillotine break of the FW helium flow channels within a horizontal plane at the mid-elevation of the TBM. The helium LOCA occurs close to the end of the plasma pulse, and results in a disruption. The PbLi BU remains intact for the duration of the accident. The coolant pressure response agrees well between both models, as do the break flow rates (Fig. 4). Good agreement was also demonstrated between the codes' results in the impact of the closure of the isolation valves on the discharge rate. The total coolant discharge to the VV is 21.8 kg and 20.9 kg for MELCOR and RELAP5, respectively, which correspond to 54% and 52% of the total HCS helium inventory of 40 kg.



Description: Mass flow in break from upward-flowing FW channel	MELCOR	RELAP5
Segment connecting TBM Stage 1 manifold to breach:	Flow 201	Flow 189
Segment connecting TBM Stage 2 manifold to breach:	Flow 202	Flow 195

Fig. 4. Mass flows from the in-vessel LOCA breach (zoom 428-435 sec)

C. *Sensitivity studies*

The uncertainty in leakage flow of liquid PbLi following a breach within a BU has been addressed via a sensitivity study. The main parameter investigated is the location of the BU in which the breach occurs. Multiple breaches and breach geometries have been also considered, however, the total breach area remains constant throughout the analyses. The sensitivity study determines the magnitude of the PbLi leak rate into the VV, together with any variation in the leaked PbLi inventory. The analyses cover the accident scenarios presented in case 11 of TABLE III.

As shown Fig. 5, there is very little difference between the four cases in the total amount of PbLi discharged into the VV (~2200 kg). The slightly lower total discharge in case 2BU-1&8 (2178 kg, a reduction of 1%) is a result of earlier isolation valve closure in this simulation, which restricts inflow from the PbLi ancillary system.

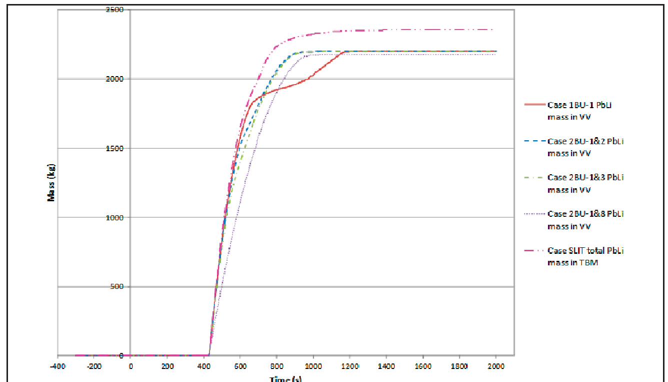


Fig. 5. MELCOR PbLi Leak study (case 11) – PbLi masses within the VV

TABLE IV shows the impact of the breach locations on the leakage rate of PbLi into the VV. The peak flow rates vary from 14.2 kg s^{-1} (for case 2BU-1&8) to 16.78 kg s^{-1} (for case 2BU-1&3), a difference of ~18%. In each case the peak PbLi leak flow occurs <1 second after the start of the leak. The comparison of the residual PbLi mass within the TBM indicates no difference between the four sensitivity cases; this mass is determined largely by the elevation of the lower leak path, which is unchanged between the four cases analysed above. Similarly, there is little variation in the resultant pressure in the VV calculated for each case.

TABLE IV. COMPARISON OF PBLI LEAKAGE BU BREACH LOCATION SENSITIVITIES RESULTS

	Location sensitivity cases	**1BU-1**	**2BU-1&2**	**2BU-1&3**	**2BU-1&8**
	Leak location				
Peak PbLi leak flow kg s^{-1} /time s	Upper leak: Lower leak:	N/A 15.62/429.11 Total 15.62	7.67/429.11 8.06/429.11 Total 15.73	7.93/429.15 8.77/429.13 Total 16.78	5.38/429.19 8.82/429.13 Total 14.2
Maximum PbLi mass in VV, kg (approximate time reached, s)		2200 (~1250)	2199 (~1050)	2198 (~1050)	2178 (~1130)
Residual PbLi mass in TBM, kg		196	196	196	196
TBM / VV pressure equalization approximate time (s)		1350	1100	1100	1130
Final pressure in VV (MPa)		0.02293	0.02293	0.02303	0.02296

D. *Uncertainty analysis*

The impact of uncertainties associated with the accident analyses needs to be addressed to provide sufficient confidence in the level of conservatism in the results. An expert review of areas of uncertainty (including an uncertainty PIRT) is planned and will be reported on in a subsequent dedicated paper.

VII. Applications of the Methodology

Finally, the qualified models must be applied to analyse the selected accident scenarios defined in the TBS PrSR. The process consists of the following activities:

- Adaptation of the TBS generic MELCOR/RELAP5 model for the analysis of the specific accident.
- Execution of the accident analysis using the selected code or codes (application of more than one code model provides for an additional qualification of the models).
- Analysis of the results.
- Comparison with previous results and analogous accidents in ITER, other TBSs, or similar accidents in the same TBS.
- Modifications/corrections of the TBS generic models if deemed necessary in above two bullet points.

The methodology has been applied to a 32 hour loss of offsite power (LOOP) in both the HCLL and HCPB TBSs, using both MELCOR and RELAP in order to further qualify the models via code comparison. The analyses of loss of flow accidents in each TBS using MELCOR is on-going. These are TBS accidents with very limited impact on the ITER machine. In the next analyses, model coupling will be used to investigate TBS accidents that might have stronger effect on the ITER machine and require the simulation of interacting phenomena and processes that take place in several systems.

VIII. Summary and Conclusions

A comprehensive methodology for fusion breeding blanket accident analyses that addresses the specificity of the designs, materials, and phenomena while remaining consistent with the approach already applied to ITER has been developed and applied to the EU HCLL and HCPB TBSs. The strong points of the methodology are the use of PIRT to identify requirements to be met by the analysis codes; development of high quality TBS models; the loose coupling of different codes or code versions in order to simulate multi-fluid flows and phenomena overcoming the codes' limitations; qualification of the models by comparison with finite element analyses and code-to-code comparisons; and uncertainty analysis utilizing sensitivity studies. We believe that the developed methodology is applicable to accident analyses of other TBSs to be tested in ITER and as well to DEMO breeding blankets.

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