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Abstract
The US is proposing a prototype of a dual coolant liquid lead–lithium DEMO blanket concept for testing in the International Thermonuclear Experimental Reactor (ITER) as an ITER test blanket module (TBM). Because safety considerations are an integral part of the design process to ensure that this TBM does not adversely impact the safety of ITER, a safety assessment has been conducted for this TBM and its ancillary systems as requested by the ITER project. Four events were selected by the ITER international team (IT) to address specific reactor safety concerns, such as vaccum vessel (VV) pressurization, confinement building pressure build-up, TBM decay heat removal capability, tritium and activation products release from the TBM system and hydrogen and heat production from chemical reactions. This paper summarizes the results of this safety assessment conducted with the MELCOR computer code.

1. Introduction

An attractive blanket concept for a fusion reactor that has been explored by both the US and EU is the dual coolant liquid Pb–17Li (DCLL) breeder design [1–4]. As shown in figure 1(*a*), reduced activation ferritic steel (RAFS) is used as the structural material. Helium is used to cool the first wall and blanket structure, and the self-cooled breeder Pb–17Li is circulated for power conversion and for tritium breeding. A SiC_f/SiC composite insert is used as a magneto-hydrodynamic (MHD) insulation to reduce the MHD pressure drop of the circulating Pb–17Li and as a thermal insulator to separate the high temperature Pb–17Li from the helium cooled RAFS structure. For the reference tokamak power reactor design, this blanket concept has the potential of satisfying the design limits of RAFS while allowing the feasibility of having a high Pb–17Li outlet temperature of 700 °C. As a participant in the International Thermonuclear Experimental Reactor (ITER) test blanket module (TBM) programme, the US is developing an ITER TBM based on this blanket concept.

Because safety considerations are an integral part of the design process to ensure that the DCLL TBM does not adversely impact the safety of ITER, a safety analysis has been conducted for this TBM and its ancillary systems. At the present time, the safety assessments of TBMs address a number of concerns or issues that are directly caused by TBM

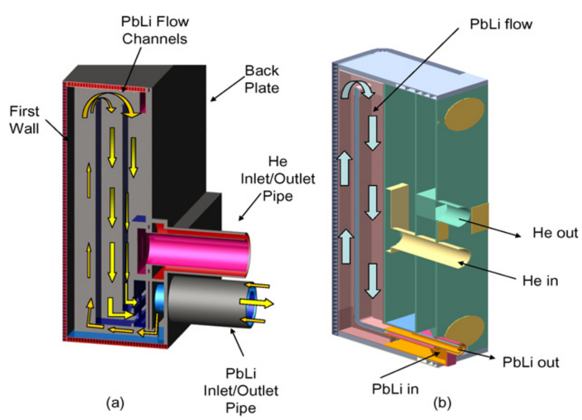

Figure 1. DCLL design schematics for (*a*) the reference tokamak reactor blanket and (*b*) the ITER TBM.

system failures [5], such as

(1) vacuum vessel (VV) pressurization,
(2) vault pressure build-up,
(3) purge gas system pressurization,
(4) temperature evolution of the TBM,
(5) decay heat removal capability,
(6) tritium and activation products release from the TBM system and
(7) hydrogen and heat production from chemical reactions.

The following sections of this paper present a general description of the DCLL TBM and its associated ancillary equipment, safety-related source terms of the DCLL TBM system components, an assessment of the TBM system during a selected accident event sequence and a summary of our findings.

2. TBM description

As shown in figure 1(*b*), the DCLL TBM described in [6] is approximately a box that is 64.5 cm in width, 194 cm in height and 30.5 cm in depth. This TBM will occupy one half of an ITER TBM test port. The 0.4 cm thick ferritic steel first wall (FW) of this TBM is clad with a 0.2 cm thick beryllium layer. Fast flowing helium in toroidal channels behind the FW provides cooling to both the first and the second walls of the TBM. Two Pb–17Li breeding zones are radially situated behind the second wall. SiC-composite inserts in these breeding zones provide thermal insulation for the TBM walls from the poloidally flowing Pb–17Li. In addition, these inserts serve as an electrical insulator to reduce the MHD forces on the flowing Pb–17Li. A 5 cm thick back-plate forms the outer radial edge of the TBM.

The TBM FW and structure are cooled by 8 MPa helium. This helium enters the module at 340 °C and exits the module at 420 °C. This helium is delivered to the TBM by pipes at the back of the TBM. Once outside of the ITER VV, these pipes run approximately 80–90 m to a heat exchanger located in the ITER tokamak cooling water system (TCWS) vault. Here, the helium rejects the TBM FW/structure heating to water through an aluminium tube heat exchanger.

The inlet and outlet temperatures of the Pb–17Li in the self-cooled breeder zones of the TBM can be controlled at temperatures between 340 °C and 450 °C, and 440 °C and 700 °C, respectively. The operating pressure for this system is 0.4 MPa. The pipes that supply the Pb–17Li to the TBM are concentric pipes that run from the TBM into the TBM test cell, where they enter the shell side of a helium-cooled heat exchanger.

A second cooling system supplies helium to the tube side of the Pb–17Li heat exchanger and rejects heat to a water-cooled aluminium tube heat exchanger that also resides in the TCWS vault. The 8 MPa helium inlet and outlet temperatures for the Pb–17Li heat exchanger is 200 °C and 360 °C, respectively.

3. Source terms

Source terms of this TBM generally fall into three categories: radioactivity (tritium, breeder and structural material activation products), heat (nuclear or chemical) and pressure (non-condensable gases such as hydrogen and helium).

Radioactive source terms. Tritium will be bred in both the Pb–17Li and the beryllium FW cladding of the TBM. The tritium production rate for the liquid breeder is estimated to be 1.59×10^{-6} gm s^{-1}. Based on the tritium permeation calculations for the DCLL TBM and its supporting ancillary systems, the structural material of the entire TBM system will contain 235 mg of tritium, the FW beryllium layer will contain 33 mg and the breeding material will contain ∼2 mg [6]. When these tritium sources are combined, the total tritium inventory is 270 mg, which is small in comparison with the tritium inventory produced within the ITER VV during normal operation of 450 g [7]. Of the 2.33 gm of tritium bred annually in the Pb–17Li, 7.5% of this is lost to the ITER confinement building. This permeation rate is presently about twice what the ITER International Team (IT) would like to have, so more design options are being considered.

Previous safety studies show that the radioactive isotopes of Pb–17Li that are a safety concern are Po-210 and Hg-203 [8]. Neutronics calculations have been performed for the DCLL TBM with the ONEDANT module of the DANTSYS 3.0 discrete ordinates particle transport code system [9]. After 30 000 full power ITER pulses without cleanup, the entire Pb–17Li inventory is predicted to contain only 1.8 Ci of Po-210, and 36 Ci of Hg-203. If these two inventories were to be released to the environment by way of a stack, the doses for Po-210 and Hg-203 at a 1 km site boundary during average weather conditions would be 0.08 mSv, and 0.002 mSv, respectively [10]. These conservative dose estimates are much less than ITER's site boundary dose limit (50 mSv) [11].

The five isotopes that dominate the F82H radioactivity at shutdown are Fe-55, Mn-56, W-187, Cr-51 and Mn-54, respectively [9]. However, F82H radioactive isotopes are in a solid form that is difficult to mobilize. One mechanism that can mobilize them during accidents is surface oxidation of the F82H structural material by steam. Reference [12] estimated the rate of F82H steel oxidation based on data taken for the ferritic steel HT-9 [13]. Assuming that the resulting radioactive oxides were to be directly released to the environment by way of a stack during average weather conditions, the estimated site boundary dose rate is $\sim 6 \times 10^{-3}$ mSv d^{-1} for the TBM at 700 °C. The top dose contributors are: Ta-183 (69%), W-187 (14%), Co-60 (7%) and Mn-54 (3%). As was demonstrated by [12], TBM FW temperatures during accident conditions do not remain above 700 °C for more than several hundred seconds. Given this information, it appears there should be little safety concern regarding this source of radioactivity during accident conditions.

Chemical energy source terms. Chemical energy and hydrogen are released when Pb–17Li comes in contact with water. This could occur in the ITER VV during accidents that cause a simultaneous spill of the TBM Pb–17Li and ITER FW/shield cooling water. At the present time, ITER has specified a TBM Pb–17Li inventory limit of 0.28 m^3 based on the assumption that 100% of the lithium in this volume will react to produce the ITER hydrogen limit for this reaction of 2.5 kg. A larger Pb–17Li volume would be allowed if it can be demonstrated by calculations or data that not all of the lithium will react. However, experiments have not yet been conducted that are prototypical of the contact mode anticipated for TBM accidents in ITER, which is an atomized spray of Pb–17Li into a pool of water. The test of [14] comes close, where Jeppson examined the pouring Pb–17Li into excess water. For that test, 20 g of liquid metal at 600 °C was poured into 4000 g of water at 95 °C, resulting in ∼50% of the lithium in the Pb–17Li pour sample reacting to form hydrogen. However, since the total breeder volume for the TBM plus ancillary equipment is presently estimated to be ∼0.4 m^3, more reaction tests may be needed to resolve this issue for this TBM.

A second chemical energy and hydrogen generation source is the reaction between the TBM FW beryllium cladding and steam. The quantity of beryllium on the TBM FW clad is 4.6 kg, which is less than the 10 kg beryllium limit set by ITER. While the mass of hydrogen that can be generated by the TBM FW beryllium is not a significant ITER safety concern, the chemical heat generated (330 MJ) is a safety concern regarding the thermal integrity of the TBM FW. As a consequence, models developed to analyse TBM accidents included the beryllium–steam reaction rate information specified for ITER [7].

Nuclear energy sources. The nuclear source terms that the TBM must handle during normal operation and accident conditions are plasma surface heating, nuclear heating, decay heating and plasma disruptions. During the flat top portion of a full power D-T 500 MW ITER pulse, the average TBM FW heat flux will be 0.3 MW m^{-2}, with a peak heating of 0.5 MW m^{-2} over 10% of the FW area. The TBM FW neutron wall loading will be 0.78 MW m^{-2}. For the TBM nuclear energy multiplication of 1.006, the resulting total TBM thermal heat load is approximately 1.38 MW [9]. The decay heat for the DCLL TBM is low because of the material choices for this TBM and the moderate neutron flux and fluence level that this TBM will experience during ITER operation. At shutdown, the total decay heat is ∼22 kW with the largest contributor (68%) being the Pb–17Li. The decay heat levels after 1 hour, 1 day and 1 year are 3.5 kW, 1.0 kW and 0.1 kW, respectively. The reference ITER disruption will deposit 1.8 MJ m^{-2} of energy on the TBM FW and must be accounted for in accident analysis for the TBM.

Pressure source terms. The ITER IT has specified a limit on the quantity of non-condensable gases that a TBM can contain based on fouling of the ITER vacuum vessel pressure suppression system (VVPSS) by such gases during large break in-vessel loss-of-coolant accidents (LOCAs). The present limit for helium is 45 kg. The DCLL TBM has two ancillary systems that contain helium: the FW/structure and Pb–17Li secondary helium cooling systems. Both systems contain less than 20 kg of helium each. Given the fact that the upper limit on hydrogen generation for the DCLL TBM is ∼5 kg, this TBM should not present a pressure source term problem for ITER.

4. Accident analyses

As an initial examination of the safety impact that TBMs will have on ITER, the ITER IT asked the participating parties to analyse the following four accident scenarios: (1) in-vessel TBM coolant leaks, (2) in-TBM breeder box coolant leaks, (3) ex-vessel TBM ancillary coolant leaks and (4) complete loss of active TBM cooling. In addition to these base case scenarios, the ITER IT also requested several parametric cases per accident scenario to determine the influence that modelling assumptions have on the results for the base case. In this paper we will only summarize the results of one of these scenarios, but a complete discussion can be found in [12]. The following paragraphs of this sub-section describe the results obtained for the ex-vessel TBM ancillary helium coolant leak accident scenario.

Method of analysis. A modified version of the MELCOR 1.8.5 code [15, 16] was used to analyse the ex-vessel TBM helium coolant leaks accident scenario. The input model developed for MELCOR includes the TBM, the TBM ancillary equipment and ITER relevant enclosures. In total, the model consists of 30 control volumes, 37 flow paths, 72 heat structures, 6 valves, 1 rupture disc, 1 pump and 2 circulators.

The TBM was modelled by two Pb–17Li control volumes (representing the breeding zones), seven helium control volumes (representing the coolant for the FW, second wall (SW), ribs/divider plate, and top, bottom, side and back-plates), and 54 one-dimensional heat structures representing the F82H structure of the TBM. Pseudo three-dimensional heat conduction is achieved among these heat structures through MELCOR user defined control functions.

The pipes, heat exchangers (HX), temperature control valves and pumps or circulators were modelled for all the three cooling systems of the TBM, which are (1) the Pb–17Li breeder cooling loop, (2) FW helium cooling loop and (3) Pb–17Li secondary helium cooling loop. A pressure relief valve is also attached to the top of the Pb–17Li drain tank that vents into the TBM test cell at a tank pressure greater than 4 MPa. The water side surface temperature of the He-water HX was set at a temperature of 35 °C to simulate the ITER heat removal system.

The free-volume of the test cell, TCWS vault and VV are also simulated in this model, but not the thermal inertia of the walls of these enclosures. The relief valve from the test cell to the TWCS vault was modelled to open at a pressure differential of 20 kPa and to reseat once the differential drops to 1 kPa. The VV free-volume was modelled as a time-specified control volume with the transient conditions set to those determined by running a MELCOR model developed for the ITER multiple FW cooling channel break accident [17]. Iteration between this model and the TBM model resulted in the desired VVPSS response to the TBM accident.

ITER pulsed operating conditions for this model were established by running this MELCOR model from an initial ‘hot standby’ condition of 460 °C through consecutive ITER 500 MW D–T pulses. The TBM model was operated with temperature control valves set to give FW helium and Pb–Li inlet and outlet temperatures of 340 °C and 450 °C, and of 460 °C and 650 °C, respectively. It was found that the pulse equilibrium conditions for the model are obtained within two consecutive pulses starting from ‘hot standby’ conditions.

Identification of causes and accident description. For this accident, a double-ended pipe break of the TBM FW helium cooling loop is postulated to occur, discharging helium into the TBM test cell during plasma burn. Since no active

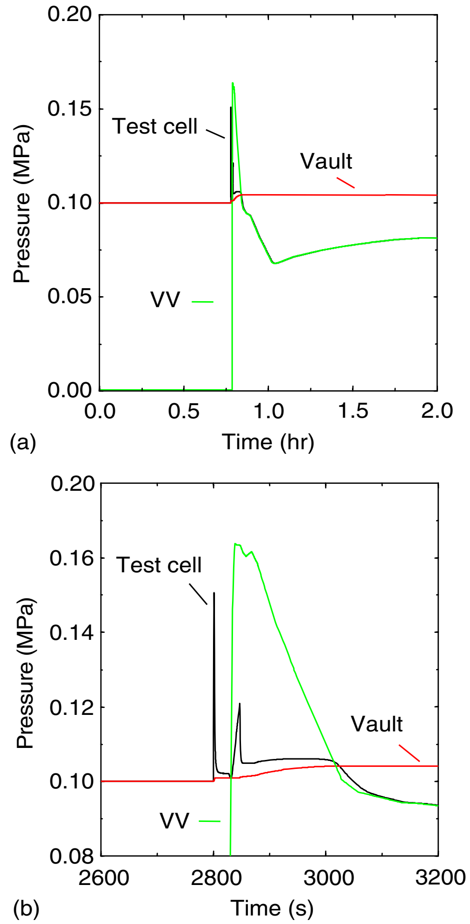

Figure 2. (*a*) Test cell, TCWS vault and VV pressures and (*b*) expanded view following break during an ex-vessel DCLL TBM coolant leak accident.

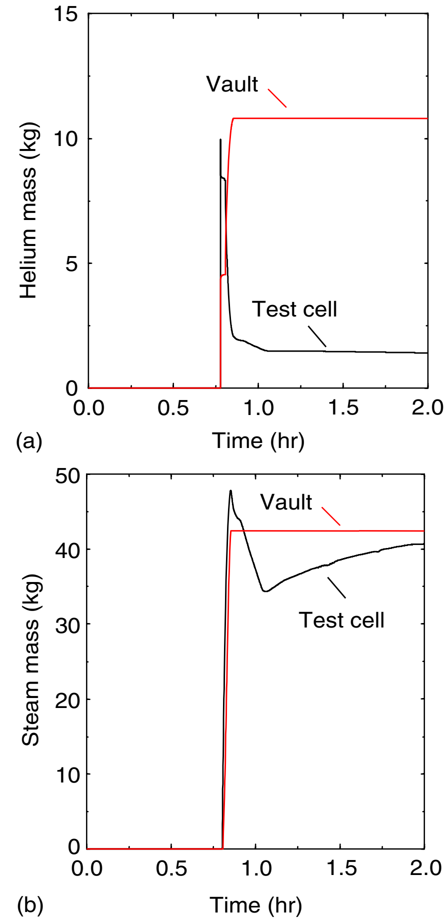

Figure 3. Test cell and TCWS vault (*a*) helium masses and (*b*) steam masses during an ex-vessel DCLL TBM coolant leak accident.

plasma shutdown is to occur, ITER will continue to operate at full power, and because TBM FW cooling has been lost, the temperature of this wall will rise until the beryllium clad melts, releasing beryllium vapour into the ITER plasma. At a temperature of 1278 °C [18], the TBM FW beryllium evaporation rate will cause the ITER plasma to disrupt. The intense plasma disruption that ensues will deposit 1.8 MJ of plasma stored thermal energy onto the TBM FW and generate runaway electrons that when lost from the plasma are assumed to cause multiple TBM and ITER FW cooling tube failures within a 10 cm high toroidal strip. Consequently, a blow-down of ITER FW cooling water occurs, injecting water and steam into the ITER VV. This pressurization causes the ITER VVPSS to open and forces steam into the TBM through the failed TBM FW. After the coolant inventory is lost, the TBM will be cooled by radiation to the VV. The accident is assumed to begin 100 s prior to the end of the flat top of a 500 MW pulse, or 400 s into the pulse, to guarantee peak TBM temperatures at the time of the accident. In addition to this accident sequence, a hypothetic variant case was also considered during which it is assumed that the induced plasma disruption further damages the TBM box such that the Pb–17Li content of the TBM spills into the steam filled ITER VV.

Transient analysis results. Figures 2–4 contain some results for this accident scenario. Figure 2 presents the pressures predicted for the test cell, TCWS vault and the VV. Because the break is assumed to occur within the test cell, the test cell pressure is seen to rapidly rise following the TBM FW helium cooling system pipe break. The pressure vent line for the test cell opens after ∼400 ms, but the test cell pressure continues to rise reaching 0.15 MPa at 1 s. The test cell pressure decreases beyond this time, as the TCWS vault pressure increases from the helium venting into it from the test cell. At 45 s, the test cell to vault pressure differential has decreased to 1 kPa and the test cell vent valve reseats. At ∼90 s after the ex-vessel pipe break, the TBM FW heats to a temperature where the beryllium clad melts. The evaporation of this beryllium melt induces a plasma disruption that ruptures ITER FW cooling channels, venting FW cooling water into the VV. As the VV pressurizes, steam flows through the failed TBM FW helium cooling system and into the test cell, causing the test cell pressure to rise a second time. The test cell vent line reopens at 106 s, venting steam into the TCWS vault. By this time, the VVPSS has activated and the VV pressure decays after reaching a peak pressure of 0.163 MPa. Within 300 s of the initial pipe break, the VV and test cell become sub-atmospheric as the VVPSS continues to condense the steam in the VV. The test cell vent

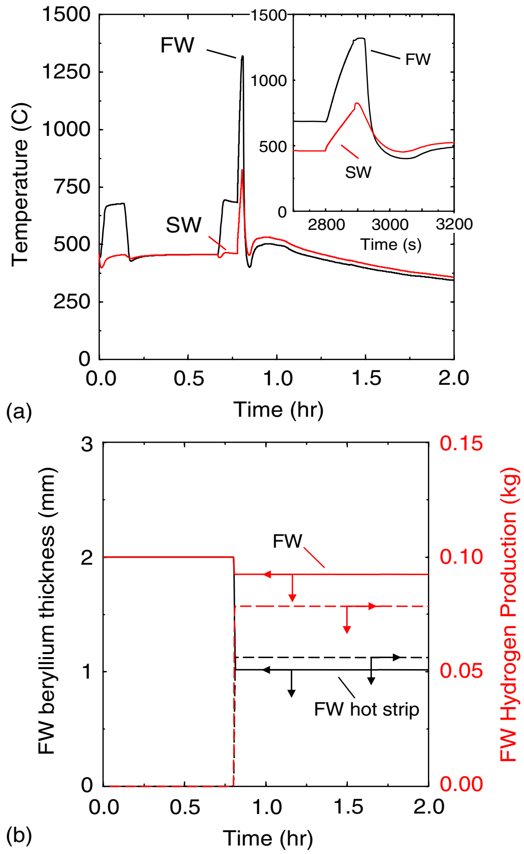

Figure 4. (*a*) FW and second wall (SW) temperatures and (*b*) FW hydrogen production during an ex-vessel DCLL TBM coolant leak accident.

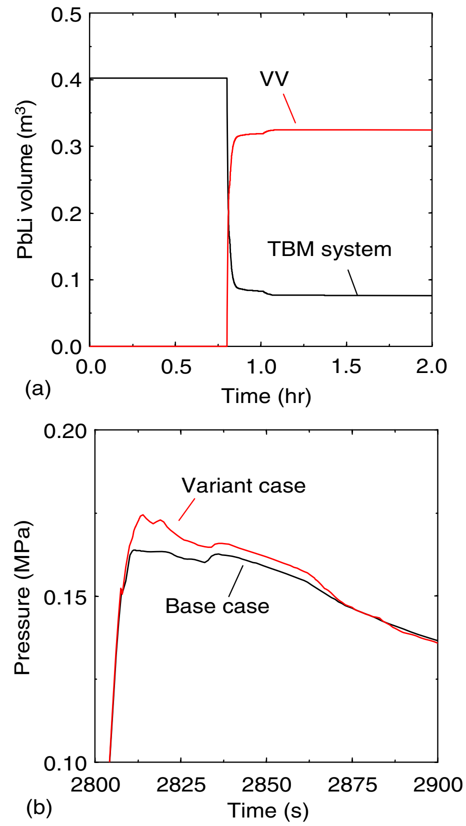

Figure 5. (*a*) Pb–17Li volume and (*b*) VV pressure comparison during a variant ex-vessel DCLL TBM coolant leak accident with a simultaneous in-vessel blanket break.

link closes, leaving the vault pressure 3.4 kPa above its starting value.

Figure 3 contains the predicted helium and steam masses in the test cell and TCWS vault during this accident. The masses of helium in the test cell and TCWS vault 4400 s after the TBM FW cooling system pipe break are 1.5 kg and 10.7 kg, respectively, of the ∼13 kg total lost from this system. The mass of helium that enters the VV is 0.75 kg, which is below the quantity of helium that would threaten the safety function of the VVPSS.

Figure 4 presents FW temperature and beryllium oxidation for this accident. The TBM FW beryllium reaches a temperature of 1278 °C within 90 s of the loss of FW cooling caused by the TBM helium pipe break. At this temperature, the beryllium evaporation rate disrupts the plasma. Past this time, the temperature continues to increase due to the beryllium–steam reaction, but once the steam pressure in the VV starts to decrease this reaction slows and the FW temperature begins to decay. By 4400 s, the FW temperature drops to 340 °C. The predicted quantity of hydrogen generated by the beryllium–steam reaction is 0.15 kg, which is well below the ITER limit of 2.5 kg for this reaction.

Figure 5 contains results for the variant case of this accident. Figure 5(*a*) gives the volume of the Pb–17Li predicted to enter the VV and the volume that remains in the TBM system during this event. In ∼100 s, 0.32 m^3 or ∼2920 kg of Pb–17Li leaks into the VV. The quantity of hydrogen generated by the ensuing Pb–17Li-water reaction is ∼1460 g based on the data of [14]. The Pb–17Li that remains in the TBM system resides primarily in the Pb–17Li ancillary system, and should only come into contact with steam. Because the Pb–17Li-steam reaction is relatively benign, and only 25 g of steam enters the Pb–17Li ancillary system during the time frame analysed, the quantity of hydrogen generated should be less than the ITER allowed limit for Pb–17Li-water reactions of 2.5 kg. The primary reason that steam is prevented from entering the TBM system is the expansion of the helium cover gas from the accumulator of the Pb–17Li ancillary system. Since the pressure of this gas is higher than the steam pressure in the VV, the net flow of gas is primarily from the TBM into the ITER VV. The impact on VV pressure of this hydrogen, the latent heat liberated from the Pb–17Li, and the 0.75 kg of helium that enters the VV is shown in figure 5(*b*). The maximum VV pressure is predicted to be only 15 kPa higher than the base case scenario.

5. Summary and future directions

A preliminary assessment of the safety impact on ITER of a DCLL TBM concept shows that the anticipated radiological inventories are small in comparison with those produced in the ITER VV due to normal operation of ITER. Possible hydrogen sources were examined in this assessment and the conclusion was drawn that the maximum quantities produced during accident conditions should be less than the ITER limit of 2.5 kg per chemical reaction. Pressurization of the ITER VV, TBM test cell and TCWS vault by the helium coolant from the TBM ancillary system does not pose a serious threat to these confinement structures.

As the ITER TBM Programme moves forward, the ITER IT seeks licensing approval for TBM operation at the same time that ITER obtains licensing approval. This means that in the near future, the safety assessments of the TBMs will have to be brought into line with the safety assessment already performed for ITER-FEAT. To accomplish this, the ITER IT is asking the TBM participating parties to perform failure modes and effects analyses (FMEAs) on their TBM systems to determine likely accidents that bound the consequence of accidents within four event categories: operational, anticipated, design basis and beyond design basis. Based on this FMEA, accidents will be selected per category for the TBM parties to analyse. Some of these accidents may be those already analysed in the preliminary safety analysis described in this paper. The TBM analysis work is to be completed by January 2007, in order to include the results in ITER's Report on Preliminary Safety (RPrS). This RPrS is the document required to obtain a construction permit for ITER.

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