Safety Analysis for the US DCLL Test Blanket Module

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Introduction and Presentation Outline

- A copy of the US Dual Coolant Lead-Lithium (DCLL) Test Blanket System (TBS) Preliminary Safety Report (PrSR) was recently transmitted to the ITER IO and is presently under review
  - PrSR also Issued as an Idaho National Laboratory Report (INL/EXT-10-18169)
- Three computer codes were used for this safety analysis at the Idaho National Laboratory (INL): TMAP, MELCOR, QADMOD-PC
- This presentation will describe the: 1) capabilities of these codes, 2) the models developed for the DCLL TBS analyses, and 3) the results obtained from these analyses, in the listed order.
- A summary of the findings of these safety analyses will conclude the presentation
US DCLL ITER TBM Configuration

- DCLL TBM
- Helium system in TCWS VA
- Port cell
- Port inter-space
- Helium pipes
- PbLi AEU
- PbLi pipes
- ITER VV
- TBM
- PbLi Flow Channels
- He-cooled First Wall
- He

484 mm
5 mm
2 mm gap
TMAP used for DCLL TBM tritium inventory and permeation rate analyses (1/3)

- The Tritium Migration Analysis Program (TMAP) calculates the time-dependent response of a system of solid structures (may be layer composite), and a related system of gas-filled volumes or enclosures by including:
  - Multi-specie movement across surfaces governed by molecular dissociation/recombination, or a solution law such as Sievert’s or Henry’s Law.
  - Movement within a structure by Fick’s law diffusion, with optional trapping of a species by structural defects
  - Thermal response of structures
  - Chemical reactions in and convection between enclosures

- TMAP was used to analyze tritium permeation losses from the US Dual Coolant Lead Lithium (DCLL) ITER Test Blanket Module (TBM) with the use of mass transport correlations to estimate tritium transport in flowing PbLi
TMAP used for DCLL TBM tritium inventory and permeation rate analyses (2/3)

Schematic of TMAP DCLL test blanket system model

Permeator $T_2$ transport model

Uncertainties to be resolved by experiments:
- Tritium solubility and the mass transport in flowing PbLi
- Tritium behavior at PbLi/FS interface
TMAP used for DCLL TBM tritium inventory and permeation rate analyses (3/3)

Tritium extraction is an extremely important issue regarding DCLL operational and accident safety, and waste disposal. Cooling system tritium permeation and inventories need to be very low (efficiency > 90%). For the DCLL TBM analysis a ferritic steel vacuum permeator was analyzed.

Of the ~0.7 g of tritium produced annually by the DCLL TBM:

• 69.6% is removed by the permeator and stored on a getter bed
• 12.5% permeates through the helium system into the TCWS vault
• 7.8% permeates through the PbLi piping into the port cell
• 6.1% permeates through the TBM walls into the ITER VV.
• ~28 mg-T remains in the TBM systems: 27.2 mg in structure, 0.6 mg in PbLi, and 0.2 mg in helium (very low inventory compared to tritium in ITER VV)

The ~20% that permeates into reactor building, after detritiation (99% system efficient), ~1.4 mg/a will be released, which is well below the ITER annual release guideline of 2.5 g-T/a. However, without permeation barriers the PbLi AEU does not meet ITER ventilation zoning requirements for the port cell.
MELCOR used to perform safety analyses on the US DCLL ITER TBM (1/6)

- MELCOR can be used to give a more detailed engineering thermal-hydraulic experimental design analysis if needed

- MELCOR is a engineering-level computer code that models the progression of severe accidents in light water reactor (LWR) nuclear power plants, including reactor cooling system and containment fluid flow, heat transfer, and aerosol transport. (Developed by Sandia National Laboratory for the NRC)

- Modifications have been made to MELCOR at the INL for fusion applications, including the addition of oxidation models, fluid freezing, other working fluids (PbLi), and recently an aerosol re-suspension model.
MELCOR used to perform safety analyses on the US DCLL ITER TBM (2/6)

TBM cross-section
- Vacuum vessel
- First wall
- Inter-space
  - Concentric pipe
- Gallery
  - Be/FS/HE/FS/SiC
  - Vacuum breaker to gallery
- Port cell
  - Permeator
  - PbLi system rupture disk and drain tank relief at 80 MPa
- Drain tank
- He pipes

Tokamak Cooling Water System (TCWS) vault
- He/H2O HXs
- 33 control volumes
- 38 flow paths
- 72 heat structures (pseudo 3D TBM conduction)
- 6 valves
- 1 rupture disk
- 1 pump and 2 circulators

Port cell relief vent opens on over pressure venting to TCWS vault
Fusion Safety Program

**MELCOR used to perform safety analyses on the US DCLL ITER TBM (3/6)**

Design Basis Accidents (BDA) analyzed were Loss-of-coolant accident (LOCA) inside of ITER’s:
- Reactor vacuum vessel
- Port cell
- Port inter-space
- TCWS vault annex

Beyond DBA events analyzed
- Complete loss of TBM active cooling (long term station blackout)
- PbLi coolant leak in the port inter-space

Most challenging postulated events are TBM coolant leaks into the port inter-space region. During these events, 8 MPa helium is released into the inter-space causing overpressure of the inter-space and port cell. This pressure is relieved by venting to the TCWS vault. PbLi leaks can also occur without causing pressurization but the concern is mobilizing radioactive material.
MELCOR used to perform safety analyses on the US DCLL ITER TBM (4/6)

Postulated event: a double-ended offset shear break of the TBM helium coolant inlet line. The loss of helium from the helium cooling system initiates a Fusion Power Termination System response within ~3 s, terminating plasma burn and inducing a plasma disruption. The induced plasma disruption causes additional damage to the TBM and ITER FW. The 8 MPa helium injected into the inter-space rapidly pressurizes the inter-space opening rupture disks to the port cell. The port cell pressurizes until relief panels to the TCWS vault open.

Analysis demonstrates the safety function of the ITER VV pressure suppression system was not compromised and inter-space and port cell pressure relief systems maintain pressures below design pressures for these areas, thus meeting ITER TBM safety requirements.
**MELCOR used to perform safety analyses on the US DCLL ITER TBM (5/6)**

The TBM FW failure caused by the plasma disruption results in a VV bypass pathway through the TBM and the failed helium piping into the port cell. ITER radioactive material within the VV is mobilized (dust, HTO, activated corrosion products) by the in-vessel LOCA, transported into the gallery and TCWS vault by steam and released to the environment by leakage.

However, given the high resistance to steam flow in the failed TBM helium coolant channels, only ~10 g of dust and 1.2 g of tritium as HTO are transported into the gallery and TCWS vault from the VV, of which only 17 mg of dust and 2 mg of tritium are released (ACP contribution was negligible). These quantities are well below ITER release guidelines.
**Fusion Safety Program**

**MELCOR used to perform safety analyses on the US DCLL ITER TBM (6/6)**

Postulate event: double-ended offset shear of the TBM PbLi coolant inlet line. The loss of PbLi from the AEU will cause the PbLi pump to trip on a low-level signal from the expansion tank. Because this system does not initiate a FPTS response, the plasma will continue to burn as the PbLi drains from the TBM and AEU into a catch pan located below the broken pipe (PbLi/Air oxidation not considered).

Analysis demonstrates that:

- The intact helium cooling system removes structural heating, eliminating further TBM damage
- The low vapor pressure of PbLi does not pressurize the inter-space, eliminating radioactive release to environment
- PbLi pool takes ~23 hr for the surface to freeze and stop Pb-210 and Hg-203 mobilization (diffusion coefficient in liquid based on theory, in solid based on bismuth in PbLi measurements, difference is $\sim 10^7$)

Because Pb-210 and Hg-203 represent a remediation hazard, a guard pipe for the PbLi pipes is being proposed in the inter-space region.
Shielding codes used for Occupational Radiation Exposure (ORE) Analysis (1/4)

QADMOD-GP, obtained from the ORNL RSICCC
- Point kernel gamma-ray shielding code with geometric progression buildup factors
- Allows one source (sphere, cylinder, cube) or up to 1000 user distributed point sources
- Cartesian, cylindrical, or spherical geometries for defining shield and regions being modeled
- MicroShield code used to benchmark QADMOD-GP sources

MicroShield, commercially available from Grove Software (Lynchburg, VA)
- Deterministic code – ray tracing
- Only simple source geometry (sphere, cube, wall)
- Only one radioactive source but can include multiple radionuclides that emit gamma rays (data base included)
- Possible use of multi shields (with simple geometries)
• Radioactive sources are activated PbLi and F82H corrosion products.
• PbLi radioactivity after one week dominated by Pb-203. During maintenance, most of the PbLi will reside in the drain tank. However, based on TRITEX experience, PbLi films on the pipe walls (~45 mg/cm²) exist after draining.
• PbLi corrosion of TBM (~11 µm at over testing lifetime) produces F82H corrosion products that will precipitate out of the PbLi flow on to the cooler surfaces in the AEU, such as HX tubes, etc. Fe-55 and Mn-54 dominate the corrosion film activity.
QADMOD Results for Occupational Radiation Exposure Analysis (3/4)

Dose (mSv/hr)

ITER VV maintenance dose rate 2 weeks after shutdown is ~ 100 µSv/hr
**QADMOD Results for Occupational Radiation Exposure Analysis (4/4)**

An ORE analysis is the time spent by a person performing maintenance activities in a radiation field times the dose rate incurred performing the tasks.

<table>
<thead>
<tr>
<th>Maintenance Operation</th>
<th>Time Requirement (p-hr/y)</th>
<th>Dose Commitment (p-mSv/a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintenance inside the</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Port Cell</td>
<td>25</td>
<td>1.5</td>
</tr>
<tr>
<td>TCWS VA</td>
<td>130</td>
<td>1.9</td>
</tr>
<tr>
<td>Hot Cell</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TBM-set</td>
<td>160</td>
<td>0.6</td>
</tr>
<tr>
<td>PbLi AEU</td>
<td>65/3</td>
<td>1.4</td>
</tr>
<tr>
<td>TBM replacement</td>
<td>390/3</td>
<td>2.5 to 7.6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>~465</strong></td>
<td><strong>~8 to 13</strong></td>
</tr>
</tbody>
</table>

Estimate of the total ITER ORE dose commitment is 367 p-mSv/a.

An annual value of 8 p-mSv/a represents ~2% of this total, which is high.

Under the ALARA principle, design steps, or different maintenance procedures, should be sought to reduce this dose.

More refined dose calculations and time requirement estimates should also be considered.
Conclusions from DCLL TBM Analyses (1/3)

• The overall impact on ITER safety of the DCLL TBS, based on the accidents analyzed, appears to be small
  ✓ The increase in VV pressurization from helium and PbLi spilling into the VV is < 4% higher than a similar event anticipated for ITER, which is an ITER in-vessel coolant leak.
  ✓ The VV bypass event resulting from a helium spill into the inter-space area releases 40 times less of the ITER VV radioactive inventory to the environment than the VV bypass event resulting from a divertor cooling system ex-vessel large coolant pipe break
  ✓ The inventory of tritium in the TBS is three orders of magnitude less than that in the ITER VV. However guard pipes to meet ITER zoning requirements need to be considered.
  ✓ If all of the Po-210 and Hg-203 that is generated by the DCLL TBS over its lifetime were released to the environment, the dose to the public would be much less than the ITER limit
  ✓ The only areas where the TBM seems to rival ITER in safety hazard is in hydrogen production from PbLi/water reactions and Occupational Radiation Exposure
Conclusions from DCLL TBM Analyses (2/3)

• Special consideration must be given to the Occupational Radiation Exposure (ORE) hazards associated with the PbLi breeding material of the DCLL TBS
  ✓ The gamma radiation field produced by Pb-203 and FS corrosion in PbLi must be respected when maintaining systems that confine this PbLi. Procedures, remote equipment, and portable shields should be considered to further reduce the dose commitments associated with maintaining these systems.
  ✓ Of particular concern are the Po-210 and Hg-203 inventories that develop during operation of this system, primarily because of the hazards of these radioisotopes. Po-210 is $10^5$ times more hazardous than HTO, and Hg-203 is $10^2$ times more hazardous than HTO based on ICRP 68 dose conversion factors.
  ✓ Fortunately, PbLi is a very low vapor pressure fluid and the Po-210 and Hg-203 inventories are small and relatively immobile in solidified PbLi.
Conclusions from DCLL TBM Analyses (3/3)

- Special consideration must be given to the Occupational Radiation Exposure hazards associated with the PbLi breeding material of the DCLL TBS (cont.)
  - However, caution should be used in opening any system that contains activated PbLi films or pools. Sweep gases, temporary glove boxes, and respirators will be procedurally employed to guarantee worker safety
  - Additional R&D is needed to develop methods that either remove or reduce Po-210 and Hg-203 inventories during TBS operation.