A Preliminary Assessment of the Occupational Radiation Exposure from Maintaining the US ITER DCLL TBM

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A PRELIMINARY ASSESSMENT OF THE OCCUPATIONAL RADIATION EXPOSURE FROM MAINTAINING THE US ITER DCLL TBM

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This paper details an Occupational Radiation Exposure (ORE) analysis performed for the US International Thermonuclear Experimental Reactor (ITER) Dual Coolant Lead Lithium (DCLL) Test Blanket Module (TBM). This ORE analysis was performed with the QADMOD dose code for maintenance activities anticipated for the US DCLL TBM concept and its ancillary systems. Identification of the maintenance tasks that will have to be performed and estimates of the time required to perform these tasks were developed based on either expert opinion or on industrial maintenance experience for similar technologies. This paper details the modeling activity and the calculated doses for the maintenance activities envisioned for the US DCLL TBM.

I. INTRODUCTION

As a Participant Team (PT) member in the International Thermonuclear Experimental Reactor (ITER) Program, the US proposed a Test Blanket Module (TBM) concept called the Dual Coolant Lead Lithium (DCLL) TBM for testing in ITER.[1] This test module is a scaled version of a concept that the US believes will make an effective blanket module for a fusion demonstration reactor (DEMO). As part of the licensing process for ITER, the ITER International Organization (IO) has requested that TBMs that are to be tested in ITER also obtain an operating license. As part of this licensing process, an analysis of the maintenance activities anticipated for the DCLL TBM and the predicted worker doses associated with those activities must be developed. This analysis is called an Occupational Radiation Exposure (ORE) analysis. This paper summarizes an ORE analysis performed for the US DCLL TBM.

The following section (Section II) describes the physical layout of the PbLi equipment of the DCLL TBM that will be a concern from the standpoint of maintenance and the anticipated maintenance activities for this equipment. Section III presents estimated times for anticipated maintenance activities. Section IV presents the approach taken and source terms used to estimate the worker dose for these activities. Section V gives the estimated ORE results for maintaining the DCLL TBM. The final section presents conclusions from this ORE analysis.

II. PHYSICAL LAYOUT OF DCLL TBM

Fig. 1 contains a schematic of the US DCLL blanket concept. This blanket concept has two separate cooling systems. Fast flowing helium in toroidal channels behind the first wall (FW) and axial channels inside the internal PbLi flow dividers provide cooling for these F82H ferritic steel TBM structures. Two PbLi breeding zones are radially situated behind the FW. PbLi is both the tritium breeding material and coolant for these breeding zones. A SiC-composite inserts in these breeding zones provides thermal insulation for the TBM walls from the poloidally flowing PbLi. In addition, these inserts serve as an electrical insulator to reduce the magnetohydrodynamics (MHD) forces on the flowing PbLi.
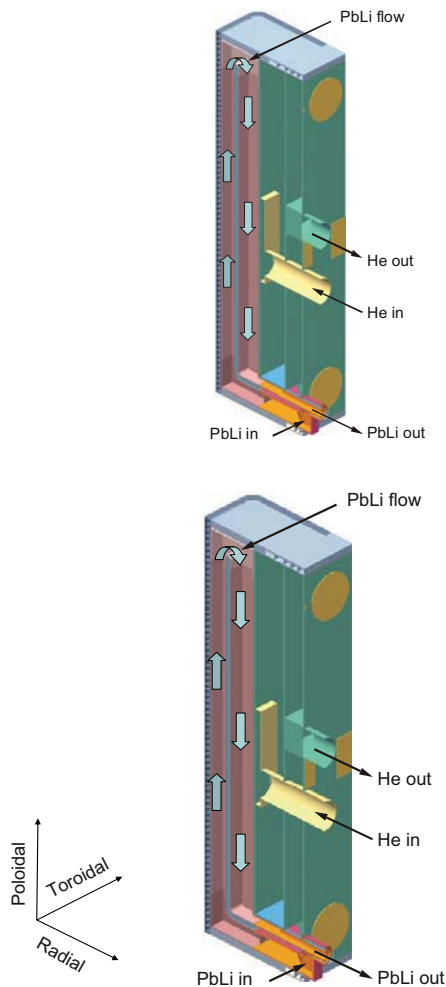
Fig. 1. DCLL design schematics for (a) Reference Tokamak reactor blanket, and (b) ITER TBM.

There are two separate Ancillary Equipment Units (AEUs) that supply coolant to the TBM while it is inserted in an ITER test port. The helium AEU is located in the Tokamak Cooling Water System (TCWS) vault. The PbLi AEU is located in an ITER equatorial port cell behind the ITER biological shield and in line with this test port. Fig. 2 contains a schematic of the PbLi AEU. Inside of the test port, the TBM resides in a water cooled frame and is connected to the AEUs by way of a pipe assembly inside of the port "inter-space" area that spans the distance inside of the ITER cryostat. The majority of the worker dose associated with maintenance of the DCLL TBM is associated with these three components, which are the TBM, tube forest, and PbLi AEU. We describe the anticipated maintenance activities for these components in the following section.
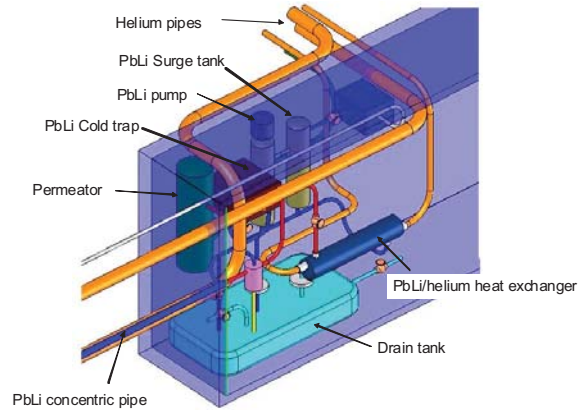

Fig. 2. View of the DCLL PbLi AEU.

III. ANTICIPATED MAINTENANCE ACTIVITIES

The major maintenance activity for the DCLL TBM will be the replacement of the TBM, which will occur approximately every other year during ITER DT operation. The maintenance operations for replacing a TBM assembly are: 1) Removal of the AEU from the equatorial port cell area, 2) Clearing the port inter-space area and removing the TBM Frame assembly from the vacuum vessel (VV), 3) Transporting the TBM Frame assembly to the hot cell for further work, 4) TBM Frame assembly re-installation into the equatorial port cell area, and 5) Reconnecting of all piping and provisioning the AEU to support the TBM operation.

Operations in the equatorial port area are assumed to be primarily hands-on operations as long as the VV test port plug is in place. The TBM frame assembly removal and insertion in the TBM test port is a completely automated process designed by ITER and using ITER's standard port plug removal transporter.

Operations in the port cell area involving the removal of the AEU are considered hands on provided that the proper shielding of the components inside the transporter is installed to limit worker's exposure to radiation. However, the concentric pipe carrying the PbLi flow will have a residual PbLi film on the inside. Special precautions and additional containment tents will be needed around the pipe during cutting and welding operations to avoid containment contamination of other components. Furthermore, special storage and transportation provisions must be available to handle these components.

Hands on operations are also assumed for the port inter-space area to clear all the piping and provide access for the transporter to remove the TBM assembly. It is

expected that once the Bio-Shield is opened, workers will be exposed to higher dose rates. An alternative design would be to consider a fully automated remote handling process to remove all piping and fittings from this space.

The Bio-Shield plug removal and design are still under discussion. The current estimate is based on a Bio-Shield plug design made of blocks that could be stacked around the penetrating pipes and could be removed in pieces thus allowing flexible design and simple operation for plug removal and installation. However further design evaluations and discussions with ITER and the other parties sharing the port are needed to agree on a common design that will accommodate the requirements of both TBMs.

Table I contains the summary estimate of times required to perform the TBM replacement. These time estimates are based on expert opinion and on performing multiple concurrent operations at the same time. As more design details become available and more interaction between the parties takes place, the TBM maintenance procedure will most likely develop further and more accurate estimates can be developed.

TABLE I. Time estimates for replacing the DCLL TBM

Task Description	Total Time (p-hr)
Remove AEU from port cell area	65
Bio-shield plug removal	10
Inter-space pipe removal	50
Port Flange Preparation	15
TBM assembly removal, transportation to and from hot cell, and re-insertion	TBD by ITER
Inter-space pipe assembly and service equipment Installation	105
Bio-Shield Plug Installation	25
PbLi AEU installation	120
Total	390

In addition to the major activity of TBM replacement, components of the PbLi AEU will have to be maintained during the TBM replacement operation. The anticipated maintenance activities will depend on the failure rate of the components of the PbLi AEU. There is very little data on PbLi systems from which to estimate how often a given component of this AEU will have to be maintained or replaced. As a consequence, data from liquid sodium fission reactors was sought first as representative data for this assessment. Unfortunately, literature searches also revealed that there has been little published information on maintenance of US sodium reactors. Two papers gave some overall radiation exposures for two sodium reactors, the Fast Flux Test Facility (FFTF) near Hanford, Washington, and the Experimental Breeder Reactor-II

near Idaho Falls, Idaho.[2] International sodium–cooled and liquid metal reactor experiences were searched as well. Notably, the Dounreay Fast Reactor, a NaK cooled, 50 MW-thermal plant, and the Phenix sodium-cooled plant.[2]

Some component repair times for water system components in nuclear and in typical industrial environments were also assembled and applied to this PbLi flow loop. This water system data mainly came from power generation, both fossil and nuclear, and other commercial industries.[2] Because the PbLi AEU components are much smaller than the components maintained in these power generation industries, an effort was made to find repair times applicable to small size components. For example, an important source of repair times has been given by Ref. (3) for shipboard components. These components are much closer to the TBM in size than the large power plant components. When repair times for PbLi AEU components were not available, the repair times for large-scale components were scaled down to apply to the TBM.

The main PbLi flow loop components, their failure rates and failure probabilities per year,[4] and the average active repair times for some of the AEU components are listed in Table II. The probabilities of component failure in this table are for the anticipated operational time of the AEU, which is 0.528 full power years (FPYs) over the 15 year life time of the AEU.[1] Because the TBM will be replaced about every two years, the PbLi AEU will most likely undergo repairs during this same period of time. However, the probabilities of Table 2 are given as annual probabilities to facilitate the ORE analysis.

IV. APPROACH TAKEN AND SOURCE TERMS

The QADMOD-GP code[5] was used to perform this ORE analysis. This code is a point kernel gamma-ray

TABLE II. PbLi AEU Component Failure Rate and Repair Time Estimates

Component	Probability of failure per year	Repair time (p-hr)
Motor Controller	0.26	5
Pump motor	0.04	100
Pump	0.28	14
Level sensor	0.016	12
Pressure sensor	0.021	12
Temperature sensor	0.18	12
Check valve	0.024	48
Motor operated valve	0.11	15

Flow control valve	0.022	15
Cold trap	0.039	40
Drain tank	0.004	80
Heat exchanger	0.014	60

shielding code, which performs a gamma ray tracing analysis for point-kernel source terms. QADMOD-GP

IV. APPROACH TAKEN AND SOURCE TERMS

The QADMOD-GP code[6] was used to perform this ORE analysis. This code is a point kernel gamma-ray shielding code, which performs a gamma ray tracing analysis for point-kernel source terms. QADMOD-GP will allow for either one distributed source, simulated by up to 27,000 point-kernel sources, or up to 1000 user defined point-kernel source locations for a given calculation. Cartesian, cylindrical, or spherical geometries are allowed for defining shielding regions being modeled, with geometric progression buildup factors, attenuation coefficients and material densities available for some shielding materials. The QADMOD-GP shielding code simultaneously calculates the equivalent dose rate (mSv/hr) for a number of user specified locations.

The primary difficulty in performing an ORE analysis for the DCLL TBM and its PbLi AEU is the very complicated component arrangement of these systems, as can be seen in Figures 1 and 2. Because The QADMOD-GP code allows up to 1000 point-kernel source definitions per calculation, a dose estimate from all of the AEU components can be performed simultaneously, e.g. without the user summing individual component contributions, within a single calculation, provided that the definition of the point-kernel source strength can be accurately defined to simulate the radiation emitted by these components. This calculation is further complicated by a 1 to 2 cm thick permanent lead shielding around each component. To accomplish this source definition, the strength of the QADMOD point-kernel source terms representing each component were based adjusted, if required, on to match dose predictions from the MicroShield code. The MicroShield code [7][6] is a commercially available code from Grove Software. It is also a deterministic code; that is, MicroShield is a ray tracing code. MicroShield uses simple gamma source geometries, which are spherical, cylindrical, annular, or planar sources. The code allows only one radioactive source per calculation, but this single source can include multiple radionuclides that emit gamma rays. A complete radionuclide database is included with this code to facilitate the user in defining decay rates, gamma ray energies and dose conversion factors. MicroShield will allows the user the possibility to define multiple shields with buildup factors of the same geometries as the source, and as with the source terms, the code includes a database

for shield material densities, attenuation coefficients and buildup factors. Figure 3 contains a schematic of our QADMOD-GP model of the PbLi AEU.
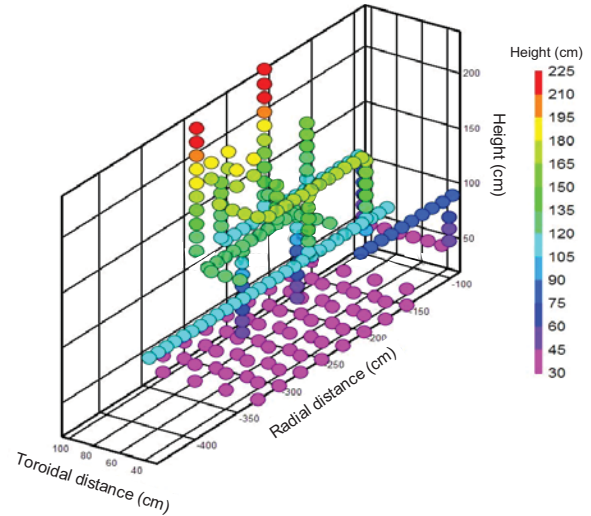

Fig. 3. Schematic of QADMOD-GP model of PbLi AEU.

There will be two sources of radioactive material in the AEU that will produce gamma radiation, activated PbLi and activated F82H corrosion products from the internal surfaces of the TBM. During maintenance, most of the PbLi will reside in the drain tank. However, based on TRITEX facility[87] experience, it was discovered that after draining the TRITEX loop, PbLi films were found on the pipe walls that were on average ~45 mg/cm^2. Similar films are expected to adhere to the inner surfaces of the components in the PbLi AEU. According to activation calculations performed for the DCLL TBM,[1] these PbLi films will be radioactive, with the activity after one week dominated by Pb-203.

In addition to the activated PbLi films, the hot surfaces within the TBM and the PbLi outlet pipe wall will undergo corrosion at the PbLi/Ferritic Steel (FS) interface. The corrosion products from TBM FS surfaces will be activated. These FS corrosion products will mix into the PbLi bulk flow and be deposited, along with the non-radioactive FS corrosion products from the PbLi outlet pipe, on to the inside surfaces of the lower temperature components of the AEU, such as pipe walls, heat exchanger tubes, valves, permeator tubes, etc. The anticipated corrosion rate of these hot surfaces is 20 μm/yr at 450ºC based on experimental data.[8][9] This corrosion will only occur at high TBM temperatures and flow rates (e.g. during a pulse), therefore over the lifetime of the AEU (0.528 FPY) this will translate into ~11 μm of erosion from the hot surfaces. Because the cool area to hot area ratio in the TBM/AEU system is 6 to 1, the re-

deposited corrosion layer thickness in the AEU will will be ~1.8 µm. According to activation calculations performed for the TBM,[1] Fe-55 and Mn-54 will dominate the corrosion film activity one week after reactor shutdown.

There is an added complication for the corrosion products, and that is that unlike the PbLi which is continuously circulating through the neutron radiation field within the reactor, the corrosion products will be deposited outside of this field once they leave the PbLi flow. Once deposited, they will begin to decay. To account for this decay, the following equation was solved to give the concentration, C_i m^{-3}, of the ith radioactive element within the re-deposition layer:

$$C_i = \frac{S_i}{\lambda_i}\left(1 - e^{-\lambda_i t}\right) \qquad (1)$$

where S_i is the source of the ith radioactive corrosion product element (m^{-3} yr^{-1}), t is deposition time (yr), and λ_i is the radioactive decay constant of the ith radioactive specie in the layer (yr^{-1}). With the radioactive source terms defined, the radiation field given off by the AEU can now be determined. This radiation field is illustrated in Fig. 4 in terms of dose rate. With this dose rate and the maintenance activity times defined in the previous section, the anticipated annual maintenance dose can now section, the anticipated annual maintenance dose can now be determined as presented in the following section.
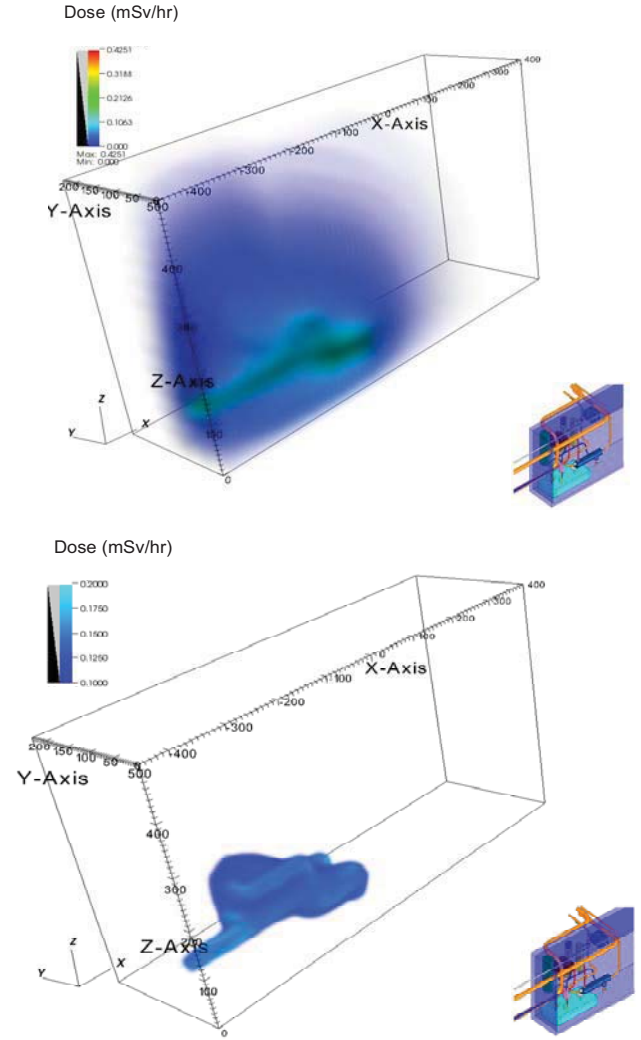

Fig. 4. QADMOD-GP radiation field for the DCLL PbLi AEU.
be determined as presented in the following section.

V. OCCUPATIONAL RADIATION EXPOSURE ESTIMATE

An ORE analysis is based on the product of the dose rate incurred by a technician performing a maintenance activity multiplied by the time required to complete the maintenance activity. An exacting analysis would include a time and motion study in the radiation field produced by the DCLL TBM system. This ORE analysis is based on the maximum dose rate at for a given location of maintenance activity, multiplied by the estimated time to complete that maintenance activity. This time estimate also includes the time required by the technicians in preparation to perform a given maintenance activity, but our ORE assumes that the technician is always in the AEU radiation field, making our estimate conservative.

The dose rates for working around the AEU were obtained from our QADMOD-GP model, but the dose rate for maintenance activities that occur when the AEU and PbLi inter-space pipe assembly have been removed is that cited in Ref. (109) as 100 μSv/hr. The time estimates also include the time required by the technicians in preparation to perform a maintenance activity, but our ORE assumes that the technician is always in the AEU radiation field, making our estimate conservative.

The total dose estimate for replacing the DCLL TBM is 7.4 p-mSv. This operation will be performed approximately every other year, giving an annual committed dose of 3.7 p-mSv/a.

A similar dose estimate for component repair activities on the AEU, when the AEU is placed in the AEU staging area, gives an annual committed dose for AEU component repair of ~1.5 p-mSv/a. This brings the combined annual dose commitment to 5.2 p-mSv/a.

The ITER ORE goal for TBM maintenance is ~1% of the annual maintenance dose for the ITER device. The administrative ORE limit for ITER is 500 p-mSv/a,[9] making the goal for DCLL TBM maintenance ~5 p-mSv/a. The predicted value for this dose is 178 p-mSv/a,[9] making the goal for DCLL TBM maintenance ~1.8 p-mSv/a. Therefore, some additional effort will be required during the final design phase of the DCLL TBM to reduce the ORE dose for this TBM. As mentioned in Section III, one approach is to remotely remove and reattach the pipe assembly. This would reduce the dose for replacing the TBM by almost one-half, resulting in a combined annual dose of 3.4 p-mSv/a, which is very close to being 1% of the. predicted annual dose for all ITER maintenance activities, presently estimated to be 367 p-mSv/a.[9]

VI. CONCLUSIONS

In this paper we have analyzed the anticipated worker radiation exposure for maintaining the US ITER DCLL TBM. Exposure estimates were predicted for the most extensive maintenance operation, which is TBM replacement, and the worker doses anticipated for repair of the PbLi AEU of the DCLL TBM when this AEU is parked in the staging area during TBM replacement. Our estimate for the activities examined is a combined annual dose commitment of 5.2 p-mSv/a, which is slightly above the ITER TBM goal of 1.85 p-mSv/a. The repair times used here are the best available from the literature, but these times generally apply to larger equipment and are probably overestimating actual times for the TBM equipment. As stated earlierAlso, a time and motion study should be conducted as the design matures to give better estimates of the necessary maintenance times in radiation fields, as opposed to the conservative approach

taken here of applying the maximum dose rate for to the entire maintenance operation.

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