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Updates of the removable biological shielding blocks inside of the test cell, part of the test systems of IFMIF-DONES

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ABSTRACT

The International Fusion Materials Irradiation Facility - DEMO Oriented Neutron Source (IFMIF-DONES) is a facility which is designed under the framework of the EU fusion roadmap. It is going to be an essential irradiation facility for testing and qualifying candidate materials under severe irradiation conditions of a neutron field having an neutron irradiation effect on materials like the one expected in a commercial fusion power reactor. The material specimens are irradiated in a containment structure named Test Cell (TC), which is part of the Test Systems (TS).

The first protecting „barrier" against irradiation affecting the surrounding of the TC, are the Removable Biological Shielding Blocks (RBSBs). These ~9 m height, ~80 tons elements, which are formed by stainless steel liners filled with heavy concrete, need to be remotely handled as after the first experiments they will get dose rates above the hands-on limit. Irradiation will also result in a large nuclear heat power deposited in the shielding blocks, therefore needs to be actively water cooled by a system of embedded pipes to control the temperature.

In this paper the updated design of the RBSBs is described, including the latest achievements and proposals for feasible manufacturing, lifting and positioning possibilities of the blocks inside of the TC respecting the given tolerances.

1. Introduction

In IFMIF DONES' heart, in the middle of the Test Cell (TC) there is a 40 MeV incident deuteron beam that hits a Lithium target, which creates a powerful neutron irradiated environment, which is to be used to investigate material properties under severe irradiation in neutron field to mimic the conditions in future fusion reactors [1–3].

In the early design, the main irradiation blocking was a thick solid heavy concrete coffin [1], but as the design evolved through the years, a Maintainable Test Cell Concept (MTCC) design was introduced [2]. This meant the introduction of the Removable Biological Shielding Blocks (RBSBs) placed inside a stationary, thinner-walled Bucket which is a concrete block surrounding the TC as part of the building. The change to a maintainable concept is needed to be able to deal with cooling loop failures in the concrete, however this introduces the need for remote handling, positioning and alignment and the fixation of the blocks. The optimization of geometry, neutron blocking, positioning and lifting of these blocks is the main aim of the work carried out. Due to the optimizations, there were changes affecting the surroundings as well, so close collaboration with corresponding areas (Neutronics, RH, Building, Safety, etc.) was and is necessary to be able to represent and constantly update the most up-to-date progress of the design.

2. Input information

In the early design of the TC, the shielding was designed as one solid

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concrete coffin (Fig. 1 left side) [3] and then as a separately poured concrete bucket (Fig. 1 right side) [4]. Both could fulfil shielding needs, however, the cooling of concrete was unmaintainable, and the mitigation of cooling loop failure seemed to be impossible due to high radiation and therefore the need for remote handling maintenance. To work around this problem, the Maintainable Test Cell Concept (MTCC) design was accepted, and its elaboration started. That was the starting point of the RBSBs, along with other developments.

To decide the thickness of the RBSBs, first the limits have to be set for hands-on maintenance, which requirement comes from the radiological classification used for different zones in IFMIF-DONES. The classification and limits are adopted from the Euratom Directive [5] and tailored to the DONES case (Fig. 2).

A detailed neutronics calculation have been conducted to see the effect of irradiation on a more than 4-meter-thick concrete which houses the Test Cell cavity. Results showed that after 1 m (upstream to beam) and 1.5 m (downstream and sideways to beam) the contact dose rate goes below the hands-on limit for decommissioning, which is set to 650 μSv/hr as a safety measure (hands on criteria means maintain the activated components manually, above this value RH is required) therefore this was set as the minimum thickness needed for the RBSBs. This ensures that in case of a major failure of the system and in case of decommissioning, the remaining permanent concrete (aside from possible hot spots) would be maintainable/decommissionable by hand after the planned facility lifespan of 30 years (Figs. 3 and 4).

3. Evolution of the RBSBs design

The first proposal of the RBSBs layout (see Fig. 5 top left) was designed to have relatively matching weights, 40 mm gaps (first estimation) between blocks to overcome RH alignment problems during assembly, the possibility of cooling pipe connections on top of the blocks, overlapping doglegs to mitigate neutron streaming towards the permanent concrete and to the Access Cell (AC) which is the maintenance area over the TC.

Since then, the outline of the blocks has been simplified to ease design and manufacturing. From that phase, our task was the design evolution of the blocks in collaboration with the IFMIF-DONES TC design team.

The primary aim of our work was evolving the efficiency of the shielding of the RBSBs (with strategically placed overlaps between neighboring blocks), to fulfil all the above-mentioned criteria, with a relatively even mass distribution of the blocks and to work out a maintainable concept design for the blocks.

3.1. Optimization of Dog-Leg shaped overlaps of neighboring blocks

The initial RBSBs outline was a preliminary design proposed as a first approach, which needs further optimization. The target is to keep the gap sizes as a minimum of 40 mm, while achieving better neutron shielding by modifying the blocks and also keeping in mind the manufacturability (narrow protruding parts were to be avoided in general).

Some of the design phases are shown in Fig. 5. The masses of individual blocks must not exceed 120t, which is the maximum load capacity of the Heavy Rope Overhead Crane (HROC) which is located in the AC and going to remotely manipulate the heaviest elements of the TC. During the optimization, we managed to reduce the masses evenly to a level, where there are no blocks that exceed 80t, including their Stainless Steel (AISI 316 L) liners, inner stiffeners, cooling pipes and concrete filling.

During the beginning of the design phase, vertical dogleg shaped overlaps were introduced at the height of the first steps in the blocks (see Fig. 5 bottom third). Based on neutronics calculations, the streaming upwards was above the limit above gaps (Fig 6.), so introducing these additional overlaps aimed to block this streaming spikes.

This design was discarded, as it would cause additional problems, the main one is that the replacement order of the blocks would be bound, compared to the layout without vertical overlaps, and so, replacement time of the blocks would be longer in case of possible failure. In parallel with this study, the conservative design's overlaps were updated and further neutronics calculations on the conservative design, with the improved horizontal doglegs and added PE layer in the Test Cell Cover Plate (TCCP) show great improvement in blocking Neutrons (see Fig. 7).

There are currently ongoing studies on the promising double layered concept by Esteyco company. The most promising feature of that design is that from the two rows only the inner would have cooling, so the cooling in the back row could be omitted. Also, the number of the blocks can be reduced, along with the replacement time of them after a possible failure.

3.1.1. Outcome of the geometrical optimization phase

As neutronics study of the gaps in the MTCC showed (Fig. 7), the

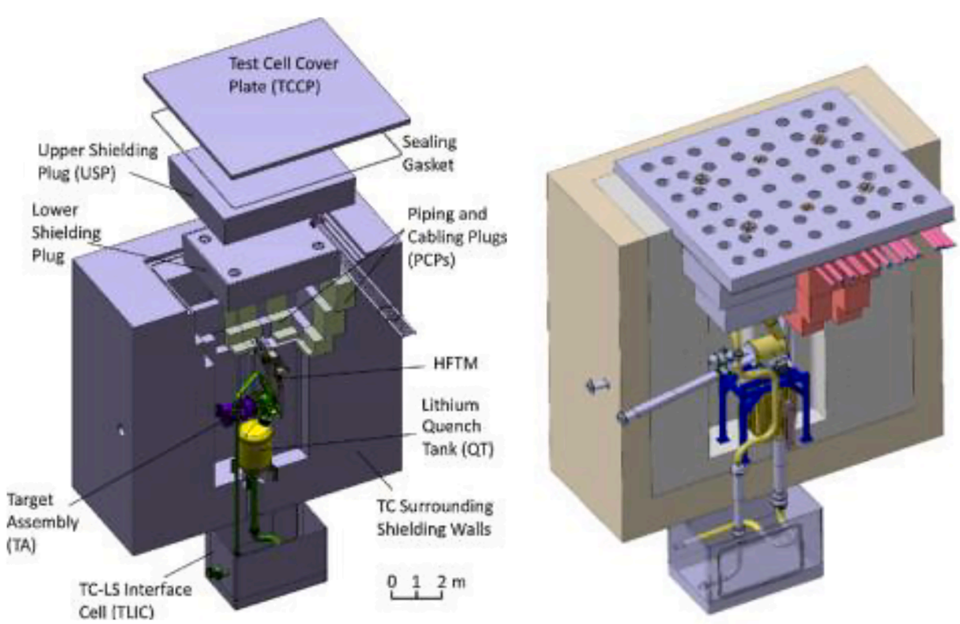

Fig. 1. Previous designs for the TC: IFMIF/EVEDA Coffin like setup (left); IFMIF-DONES monolithic concept (right).

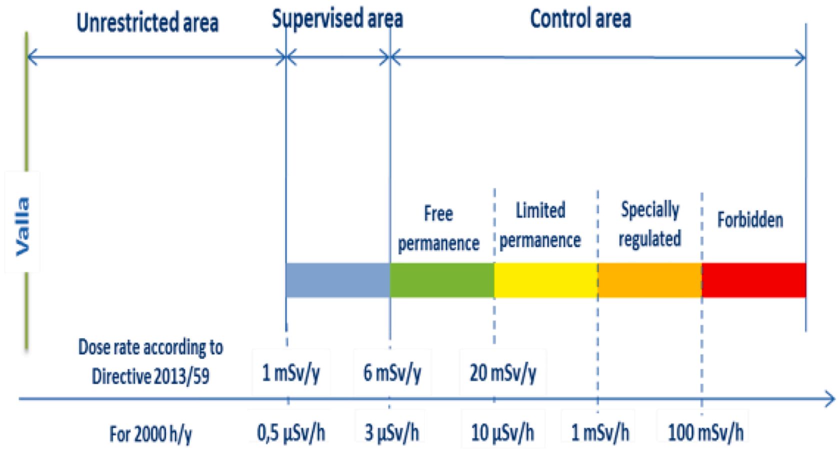

Fig. 2. Radiological classification adopted in the IFMIF-DONES project. [5].

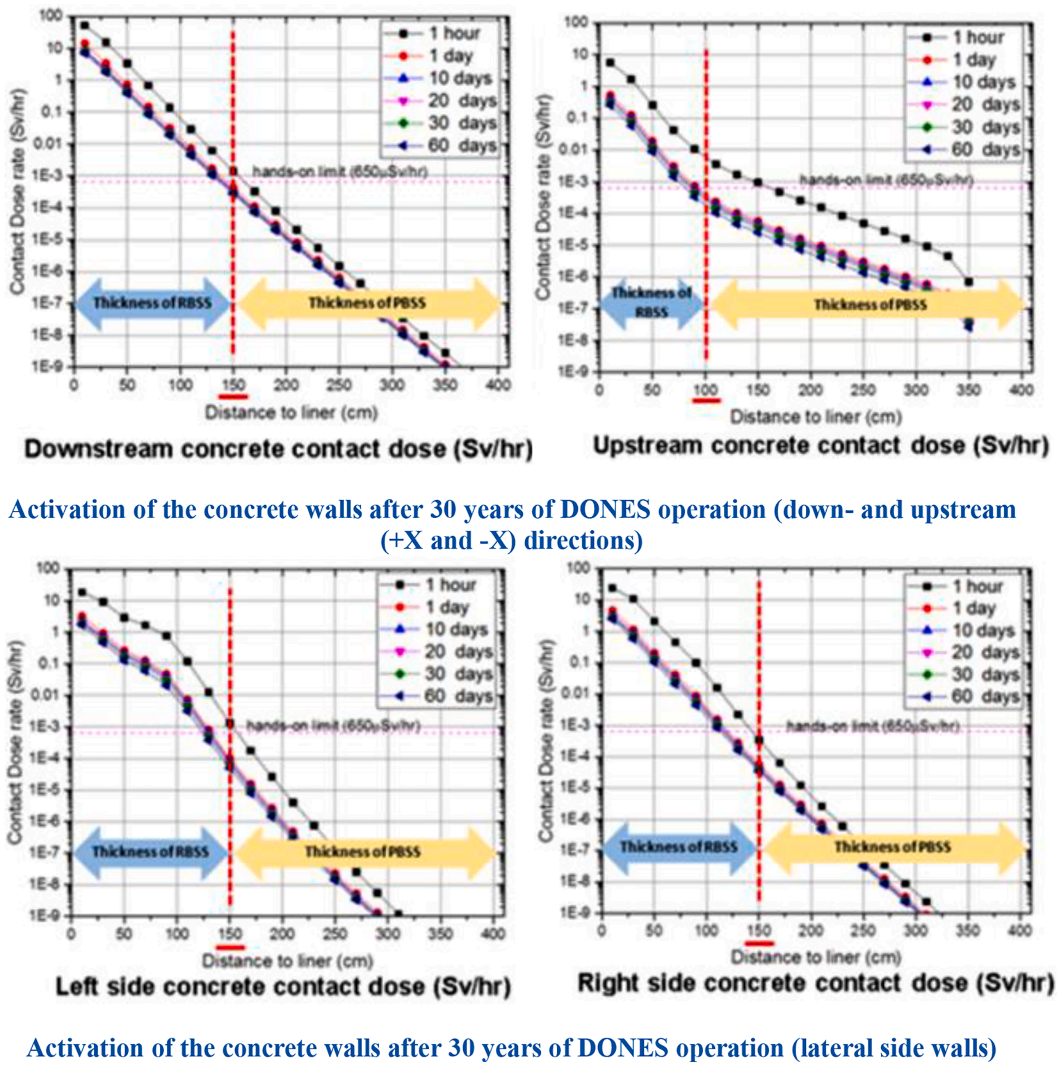

Fig. 3. Activation of the concrete walls after 30 years of DONES operation.

evolved RBSBs satisfy the blocking needs. Neutron streaming through the gaps is observed. Most of the area is below 1mSv/h (white contour). Only exception is the area above the gaps [4]. For this reason, to block the upstream neutron streaming, the Test Cell Cover Plate (TCCP) is planned to have polyethilene (PE) filling. Dose rates for this updated design is shown in Fig. 7.

After the design of the RBSBs was consolidated and sufficient blocking was confirmed by Neutronics calculations, the cooling and stiffening ribs of the RBSBs were designed by Esteyco. The current most up-to-date state of the RBSBs and the whole TC is presented in Fig. 8,

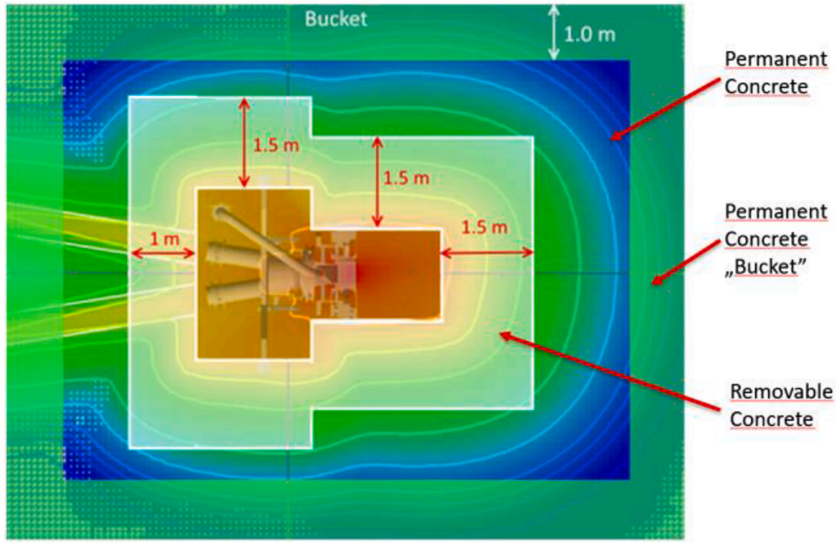

Fig. 4. Separation of biological shielding concrete.

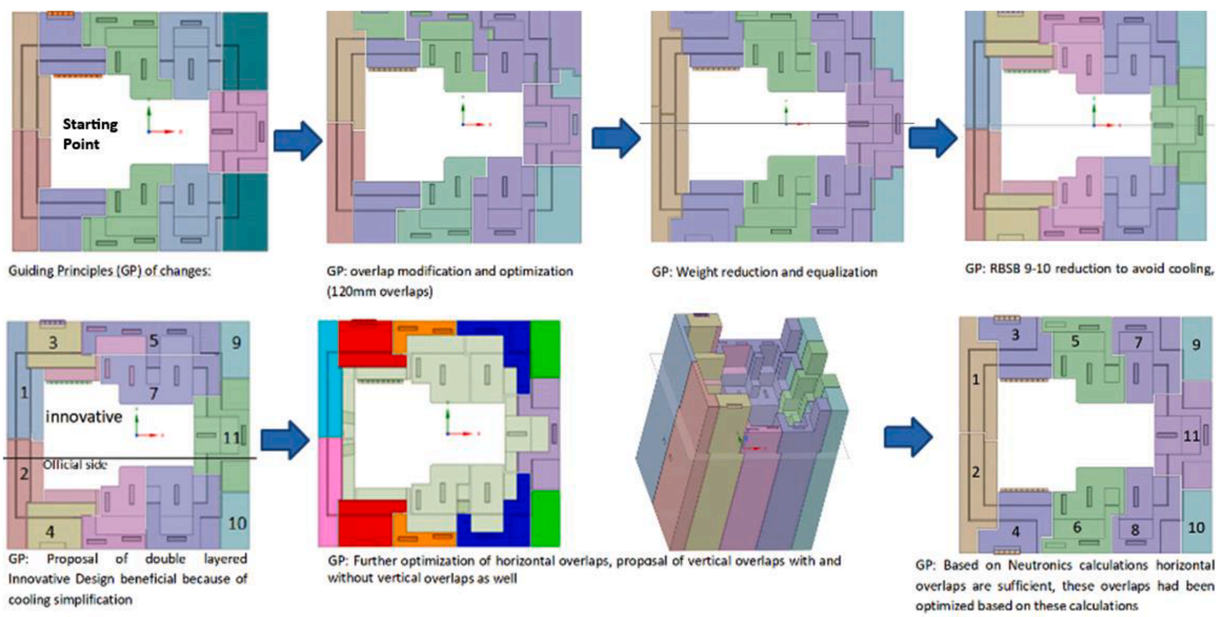

Fig. 5. Different RBSB designs.

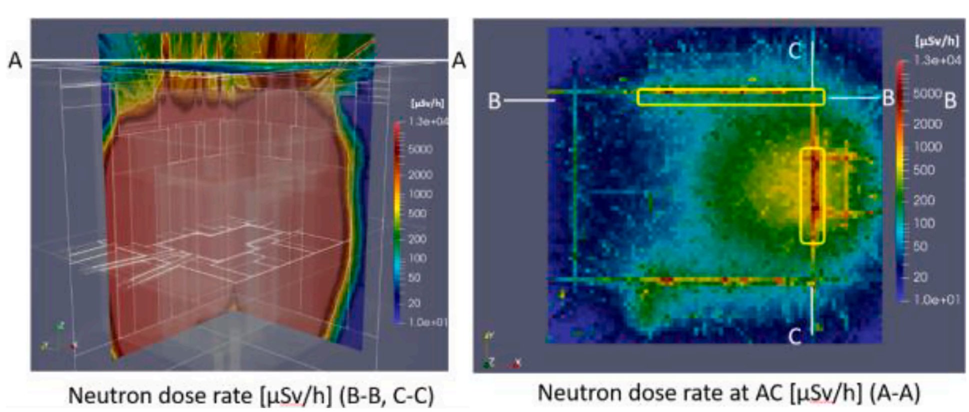

Fig. 6. Neutron dose rate [μSv/h] for the Case-1, plotted along the gaps B-B and C—C (left) and plotted in the AC at the upper surface of TCCP A-A (right). White contour line shows the value of 1000 μSv/h.

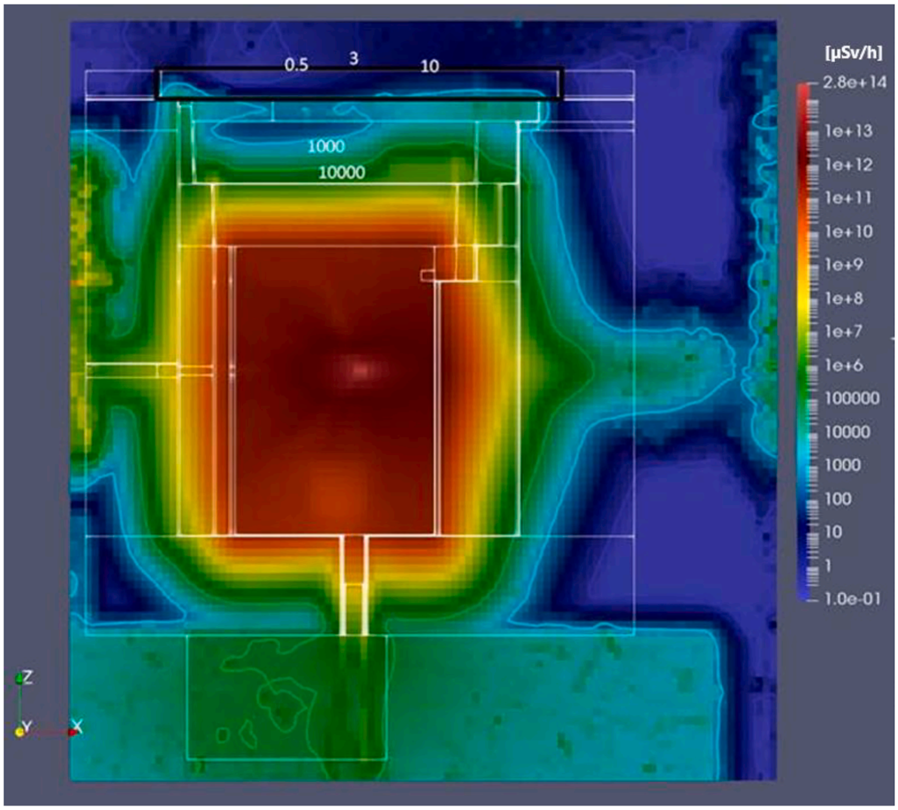

Fig. 7. Neutronics calculations using PE filling in the TCCP at the top of the TC.

with inclusive dimensions, surrounding components, RBSB numbering and masses (which include the uniformly 10 mm thick SS Steel (AISI 316 L) Liners [~8t/m^3 mass], inner stiffening, cooling pipes, and heavy concrete [~3,8t/m^3 mass]

4. Design considerations

RBSBs design must be constantly evolved with new aspects considered. Such aspects are manufacturing, RH lifting, positioning, and decommissioning of the blocks. All these need deeper studies but the trends of these ongoing studies are shortly described below.

4.1. Lifting proposals

Lifting of the components inside of the TC will be done by the Heavy Rope Overhead Crane (HROC) with a maximum load capacity of 120t and the accuracy of ±5 mm in X-Y (horizontal) directions, and 1° rotation around Z (vertical) axis.

Every block need attachment point(s) for remote lifting. For every RBSB, 3 attachment points were considered. These can be individual attachment points at the top surface of the blocks, but they can be merged, and one dedicated point can be applied for each RBSB. Further studies are needed for lifting attachments to the HROC, which will be used to manipulate the RBSBs. The best possible lifting candidates will be chosen according to the available space, reasonable costs, remote handling needs, accuracy and safety.

There are proposals for „grabber" mechanisms, like the one developed for DEMO, the so-called Gripper Interlock [5] (Fig 9.), or an industrial solution from Elebia, NEO 100 [6] lifting hook (Fig 10.).

Both options can hold the weights of the blocks with sufficient safety factor. Further options are to be selected and investigated, both for one lifting point/block and 3 points/blocks as well but these are not mentioned in this paper.

4.2. Reinforcing bar optimization for lifting solutions

Lifting points need rebars penetrating through the RBSBs vertically, attached to their bottom plate to convert tensile forces in the concrete into compressive forces, which are distributed at the bottom of the blocks. The optimization of rebars is calculated and the final results are summarized briefly:

The design tensile yielding strength of a rebar *FRd* is calculated as:

Tensile yield strength of one rebar:

$F_{Rd} = A_s \times f_{yd}$

Rebar sectional area:$As = \frac{d^2 \times \pi}{4}$

Yield strength of steel rebar: f_{yd}

The capacity of one lifting point can be determined by multiplying the rebar strength times the number of rebars per lifting point.

Material: AISI 316 L, Tensile strength, Yield (*Re*)= 290 Mpa

RBSB #11 was chosen for calculation, as this is the heaviest one.

1. $D = 20$ mm rebar, material: 316 L →

$$\mathrm{F_{rd}} = \mathrm{As} \times \mathrm{Sm} = \frac{\mathrm{d}^2 \times \pi}{4}\mathrm{mm}^2 \times 290\ \mathrm{Mpa} =$$

$$\frac{20^2 \times \pi}{4}\mathrm{mm}^2 \times 217\ \mathrm{MPa} = 68172\mathrm{N} = \mathbf{91kN} \tag{1}$$

This is the strength of one bar. Let us assume there are 4 bars at each lifting assembly, that will give us

$$68172\mathrm{N} \times 4_{\mathrm{pc}} = 272688\mathrm{N} = 272.7\mathbf{kN} \tag{2}$$

max capacity of each Lifting point.

Converting the weight of RBSB #11 →

$$77148\mathrm{kg} \times \frac{9.80665\ \mathrm{m}}{\mathrm{s2}} = 756563.43\mathrm{N} = \mathbf{756.6kN} \tag{3}$$

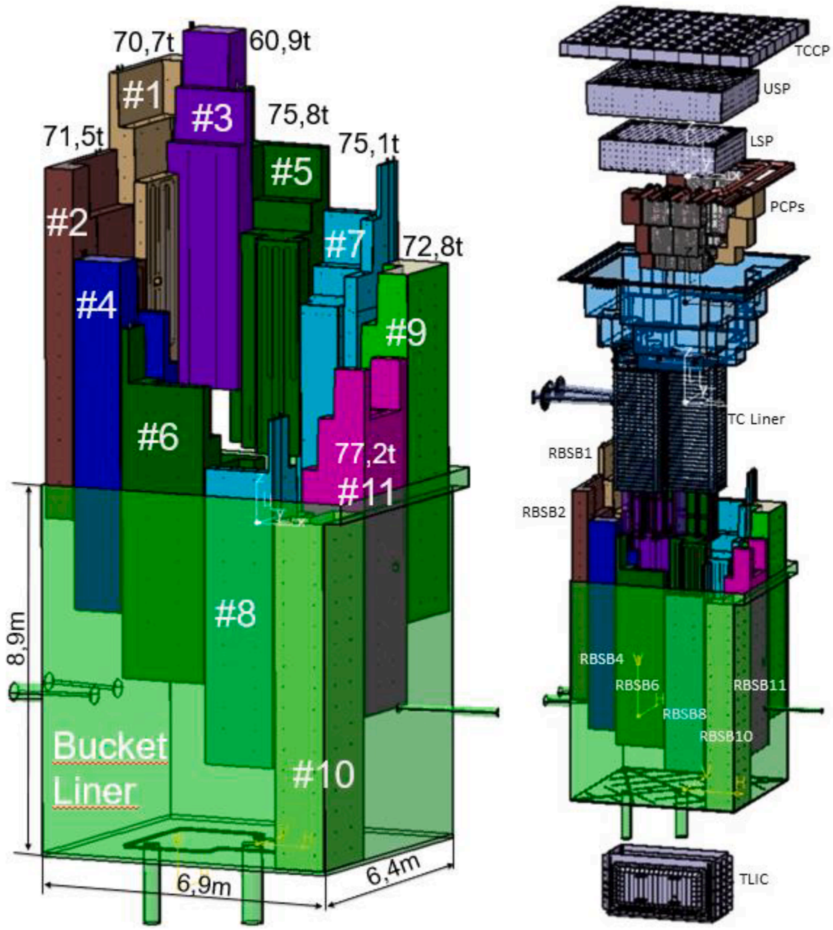

Fig. 8. Left side: RBSB #1 - #11 masses and dimensions
(RBSBs are mirrored to the middle plane, so weights of RBSBs are identical as: #3=#4; #5=#6; #7=#8; #9=#10)
Right side: whole TC 3D CAD model with all the components.

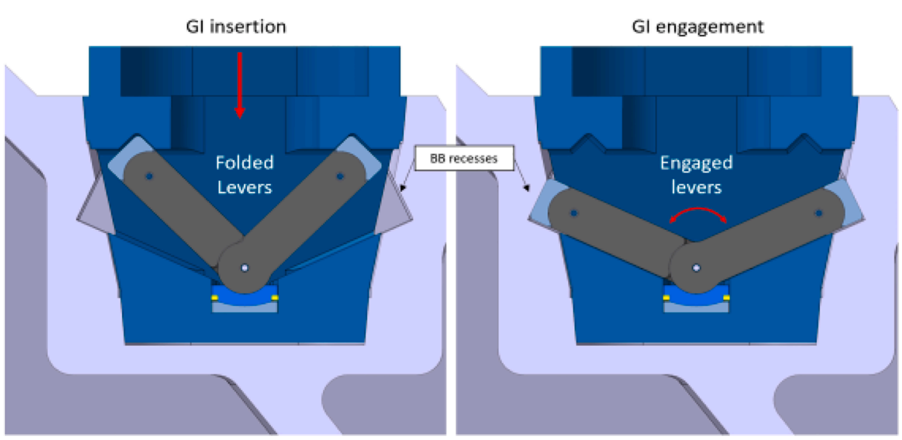

Fig. 9. Gripper Interlock (GI) [5].

$$756.6\text{kN} \div 272.7\text{kN} = \mathbf{2.7\ pcs} \tag{4}$$

3 pieces of lifting points with 4 rebars each, can hold the whole RBSB, which is favorable, because 3 points around the COG, can compensate the rotation both in horizontal and vertical directions (Fig. 11).

2. Stress distributor bottom steel plate calculation, 316 L, 300 × 300 mm steel plates with 200 mm spacing between attached rebars→

$$\sigma = \frac{756563.4\text{N}}{(300\text{x}300)\text{mm}^2} = \mathbf{8.4MPa}(<< 35\text{MPa}) \tag{5}$$

We shall stick to these sizes because even under the total weight load, the resulting concrete stress over the bottom plate (8.4 MPa) is well below the concrete's compressive strength (35 MPa).

For size and mass reduction of rebars, materials with higher strength could also be used. There are examples of such commercially available material standards, which are not presented in this study. Local stress

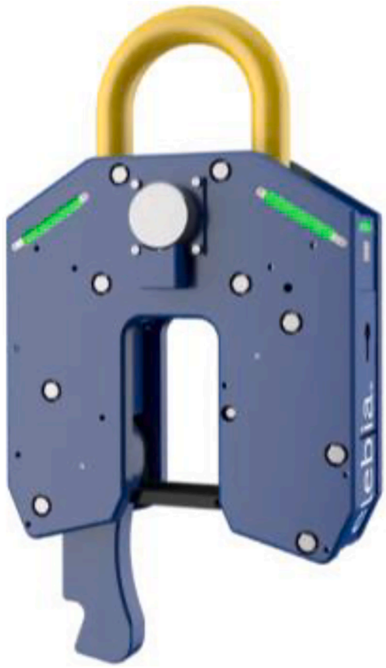

Fig. 10. Elebia NEO100 lifting hook [6].

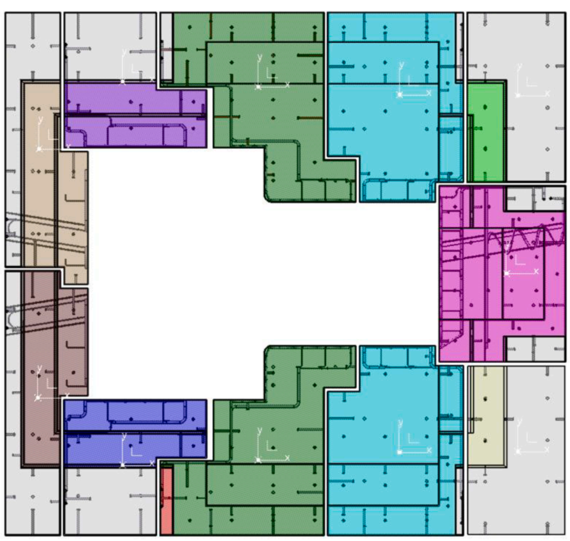

Fig. 11. RBSBs semitransparent top view with Center of Gravity (COG) points (white coordinate systems) of each block.

distribution has not been investigated and could be a further step of the analysis.

4.3. Positioning of the blocks

RBSBs need positioning options at the bottom plate. These can help during the lowering phase of the blocks, to maintain even gaps between neighboring components, but they can also be effective supports during a possible seismic event as well, preventing the shifting of the blocks sideways. In the current design stage, 2 positioners are considered for every block, which can compensate both X-Y directional misalignment and rotation around Z axis, around the center of gravity of the block. Two possible positioning proposals are shown below in Fig. 12, such as industrial pins and hemispheres.

The main advantage of these positioning pins is that they can be fixed after the RBSB liners are manufactured and transported to the scene and are precisely measured. Manufacturing tolerances or misalignment of the female parts can be compensated by the male ones which can be manufactured end welded on site according to exact measurements. This way greater accuracy can be achieved. This method can be used in case of future replacements also, with newly placed male parts.

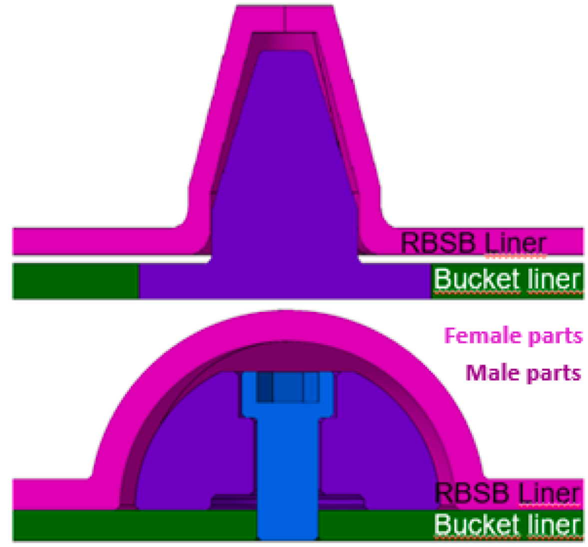

Fig. 12. Positioner proposals- pin and hemisphere.

5. Further studies, manufacturing and decommissioning

As the concept is evolving further, the next steps are to investigate the manufacturing possibilities of the RBSB liners. This can be done from individual steel plates by welding them together, or bended steel plates with welded parts (ongoing study). Possible errors need to be mapped (ongoing study). Manufacturing tolerances need to be investigated and documented (in later stages). Decommissioning of the blocks are also being investigated and explored (ongoing study). Standard techniques for decommissioning of radioactive facilities are considered and their application possibilities are investigated. With contaminated dust reduction as a main aspect and reduction of debris to sizes that fit in regular sized contaminated waste managing coffins. Proposals for the above-mentioned aspects are under development.

6. Summary

RBSBs are huge and heavy (~70–80t) components inside the TC cavity and need to be handled with care, because inefficient optimization of masses or gaps, manufacturing and positioning might cause enormous extra costs compared to the expectations, during their lifespan, decommissioning and waste handling as well. There are still aspects that need to be considered and the RBSBs are not consolidated yet, but we managed to update the overlaps of the blocks, this way significantly improve neutron blocking, and standardized the mass distribution, to ease manipulation. We started to collect the aspects to be examined, which from we started working on the lifting, positioning, manufacturing and decommissioning of the RBSBs. These studies show great progress and give guidance for further research.

Meanwhile progressing further with the above-mentioned studies, the double layered design concept is being prepared by Esteyco based on the one presented in this paper (see Fig. 5).

CRediT authorship contribution statement

D. Oravecz: . **A. Zsákai:** Supervision, Writing – review & editing. **C.**

Melendez: Writing – review & editing. **T. Dézsi:** Writing – review & editing. **S. Becerril:** Writing – review & editing. **J. Castellanos:** Writing – review & editing. **A. Ibarra:** Supervision. **Y. Qiu:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

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