EUROFUSION WPRM-PR(16) 13998

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Multicriteria Selection in Concept Design of a Divertor Remote Maintenance Port in the EU DEMO Reactor using an AHP Participative Approach

Preprint of Paper to be submitted for publication in Fusion Engineering and Design

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Multicriteria Selection in Concept Design of a Divertor Remote Maintenance Port in the EU DEMO Reactor using an AHP Participative Approach

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Abstract

The work behind this paper took place in the Eurofusion remote maintenance system project (WPRM) for the EU Demonstration Fusion Power Reactor (DEMO). Following ITER, the aim of DEMO is to demonstrate the capability of generating several hundreds of MW of net electricity by 2050. The main objective of this paper was the study of the most efficient design of the maintenance port for replacing the divertor cassettes in a Remote Handling (RH) point of view. In DEMO overall design, one important consideration is the availability and short down time operations. The inclination of the divertor port has a very important impact on all the RH tasks such as the design of the divertor mover, the divertor locking systems and the end effectors. The current reference scenario of the EU DEMO foresees a 45° inclined port for the remote maintenance (RM) of the divertor in the lower part of the reactor. Nevertheless, in the optic of the system engineering (SE) approach, in early concept design phase, all possible configurations shall be taken into account. Even the solutions which seem not feasible at all need to be investigated, because they could lead to new and innovative engineering proposals. The different solutions were compared using an approach based on the Analytic Hierarchy Process (AHP). The technique is a multi-criteria decision making approach in which the factors that are important in making a decision are arranged in a hierarchic structure. The results of these studies show how the application of the AHP improved and focused the selection on the concept which is closer to the requirements arose from technical meetings with the experts of the RH field.

Keywords: Concept Design, Remote Handling, DEMO, AHP, Systems Engineering

1. Introduction

In the EU Demonstration Fusion Power Reactor (DEMO) design one important consideration is the availability and short down time of the power plant [1]. The objective of this paper is to present the results of conceptual studies in supporting divertor remote handling (RH) activities in DEMO. The availability is greatly affected by the efficiency of reactor maintenance. Avoiding complex operations in the vessel and reducing the complexity of the design of the components are the main guidelines. The inclination of the divertor maintenance port has a very important impact on the RH. The design of the divertor mover, the principle of the locking system, the tooling and the end effectors are dependenting from this design choice. In the reference scenario, the divertor maintenance port is inclined of a 45° angle, Fig. 1.

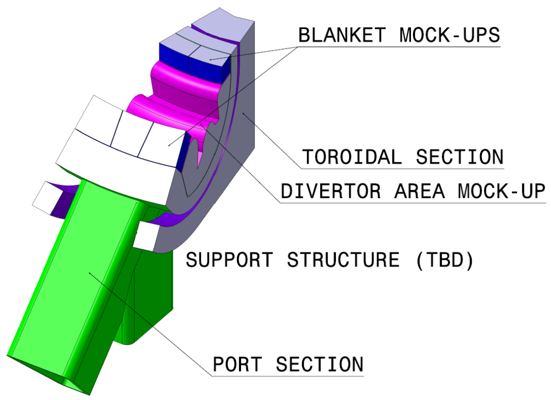

Fig. 1 System basic configuration of the platform

In this early stage of the tokamak design, according to a system engineering approach [2], it is important to evaluate and study different other configurations. Therefore, we conducted an analysis of different options for the inclination of the port. In the DEMO tokamak design it is assumed to have sixteen ports for the maintenance of the divertor. For each port, three cassettes shall be handled for the operation of installation and removal. The results and the methodology of this investigation are illustrated in the following sections.

2. Reference scenario and alternative concepts generation

In the following paragraphs will be described the alternative concepts investigated in this preliminary phase of the RHE conceptual design. In particular pros and cons of each scenario are reported.

2.1. Reference scenario: 45° lower port

The reference configuration of DEMO divertor port is shown in Fig.2.

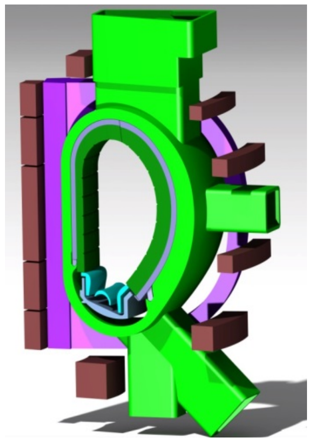

Fig.2 DEMO 45° divertor port

The maintenance port for the remote handling operation of the divertor is inclined of 45°. The main advantage of this solution is the independence of the remote handling operations between blankets and divertor. Moreover, in this configuration the divertor cassettes can be driven inside (and outside) the vessel following a straight path. The divertor cassette is in the same orientation from initial position to the installation and vice versa. It is not required any rotation to the divertor mover system or to the end effector. These studies were also based on the previous divertor cassette handling assessment [3].

The sequence of the removal of the central cassette is shown in Fig. 3. This configuration is also suitable for the current position of the poloidal and toroidal field coils and the current profile of the port.

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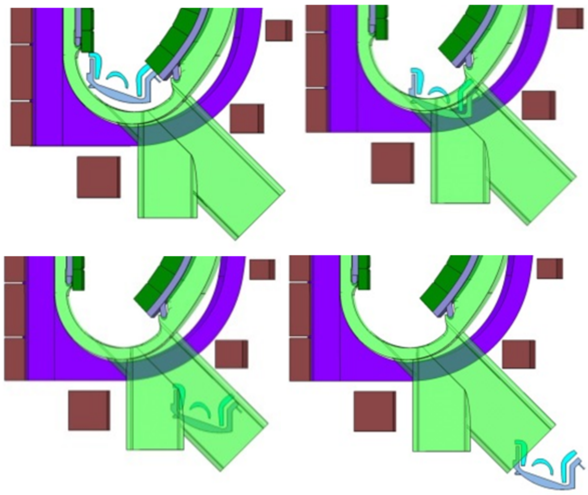

Fig. 3 Removal sequence of the central cassette with the 45° divertor port

2.2. Horizontal lower port

The first alternative concept generated for this analysis is the configuration of the reactor with a horizontal port for the maintenance of the divertor, Fig. 4.

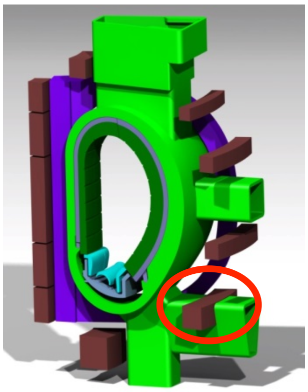

Fig. 4 DEMO Horizontal divertor port

The horizontal configuration has an incompatibility with the current position of the TF coils, [4]. Nevertheless, the coils configuration has not been fixed yet. Therefore, if the horizontal configuration could result the best option from the RH point of view, the possibility to update the position of the coils could be taken into account in the future studies.

In order not to effect the current design of the blanket and its remote handling system, the connection of the port and the vessel was left inclined of 45°, Fig. 5.

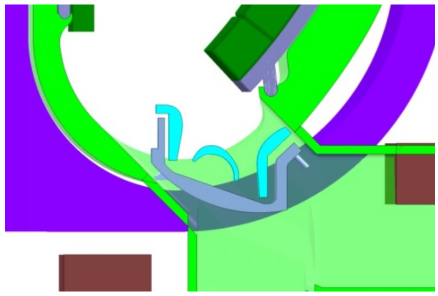

Fig. 5 DEMO Horizontal port-Vacuum Vessel connection

In this configuration, during the transportation of the divertor, it is assumed that the divertor mover shall be able to drive the divertor cassette horizontally. The lifting of the cassette in position in the vacuum vessel shall be performed by the end effector. The sequence of the operations is shown in Fig. 6.

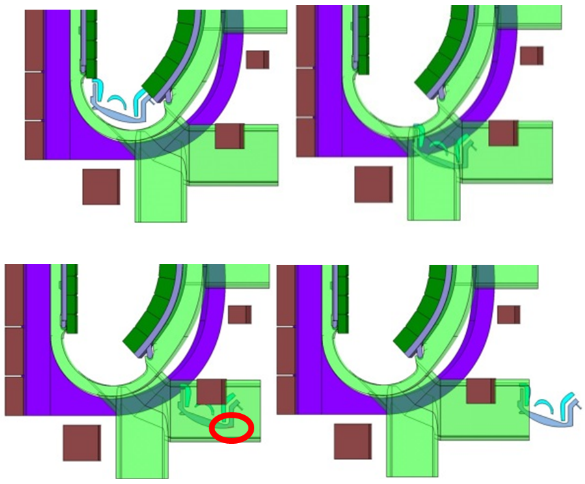

Fig. 6 Divertor cassette removal sequence in the horizontal port

The orientation of the divertor cassette cannot be the same during the entire operation because of the interferences with the current profile of the port.

Two were the possible actions proposed. Modify the size of the port or rotate of a minimum of 5° the divertor cassette and lowered it of about 200 mm, in order to avoid any collision with the port, as shown in the sequence in Fig. 7. These operations are effecting the time of the divertor maintenance.

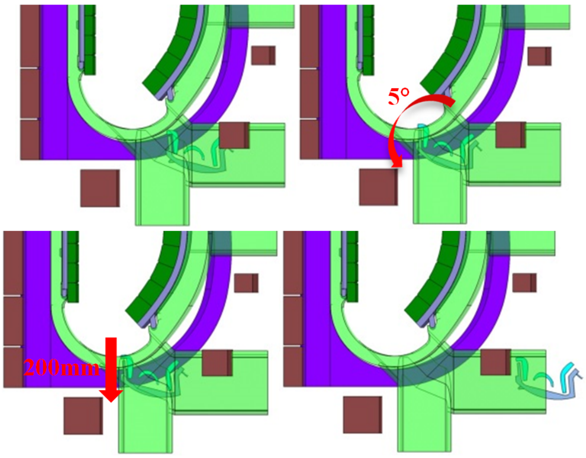

Fig. 7 Proposed divertor removal sequence for the horizontal port

2.3. Hybrid Lower port

The second alternative concept generated is the configuration of the reactor with the maintenance divertor port combination of the 45° solution and the horizontal. This configuration, named hybrid, is show in Fig. 8.

Fig. 8 DEMO divertor hybrid port (45° + horizontal)

This configuration does not require changes in the current position of the magnetic coils.

The kinematic sequence for replacing the cassettes in this port configuration is shown in Fig. 9. It was observed the necessity to rotate of about 10° the divertor cassette, in order to avoid collisions with the upper ceiling of the lower port, Fig. 10.

Therefore, the divertor mover shall be able to drive the cassette horizontally and lift it of 45°.

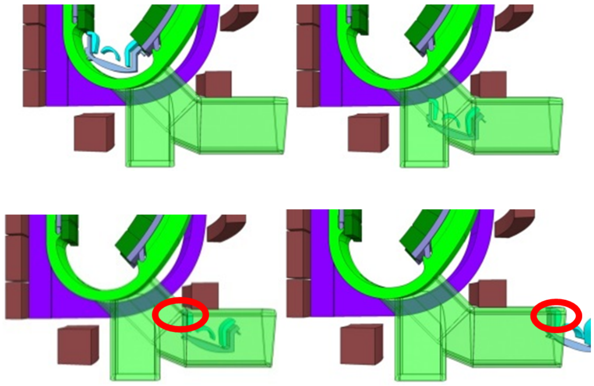

Fig. 9 Divertor cassette removal sequence in the hybrid port

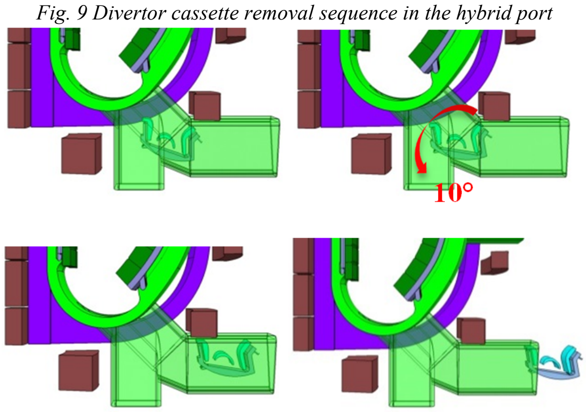

Fig. 10 Proposed divertor removal sequence in the hybrid port

2.4. Vertical ports

In opposition with the different configurations of the lower port, the vertical ports were also taken into account in this study. Two possible principles to perform the maintenance operation on the divertor were analysed. The first one proposed a vertical lower port, which combines the vertical port foreseen for the vacuum pumping operation and the lower port foreseen for the divertor maintenance. The second one proposed the vertical upper port, foreseen for the RH operation of the blanket system. It was highlighted that these configurations have a relevant impact on the current design of the blanket system and its remote handling operations.

2.4.1. Vertical Lower port

The configuration of the vacuum vessel with the vertical lower port is shown in Fig. 11.

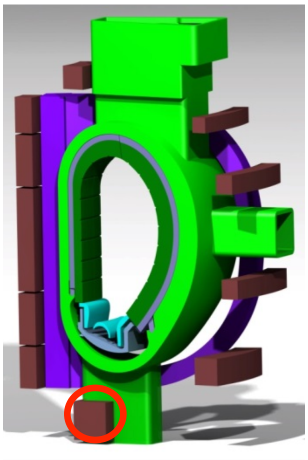

Fig. 11 DEMO divertor vertical lower port configuration and interference with the toroidal field coil

This configuration is in conflict with the current position of the magnets. Both the toroidal and the poloidal coils Fig 11 and Fig. 12.

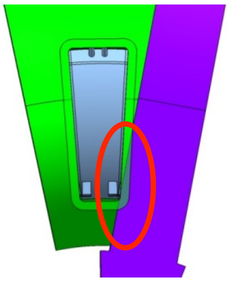

Fig. 12 Interference with the vertical lower port and the poloidal field coil

The interference with the poloidal field coil in Fig. 12 was observed by designing the lower port section with the minimum size in order to guarantee enough space for the divertor cassette.

In this solution a relevant parameter in the design phase was also the minimum size of the divertor pipes after the operation of cutting, Fig. 13.

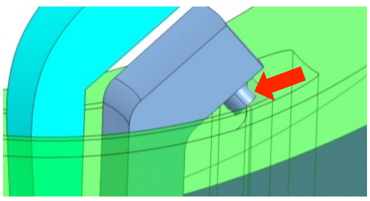

Fig. 13 Divertor pipes sizes after cutting operation

The sequence of installation/removal of the divertor cassette can be performed by a divertor mover able to lift and lower the cassette in vertical direction. An example is shown in Fig. 14.

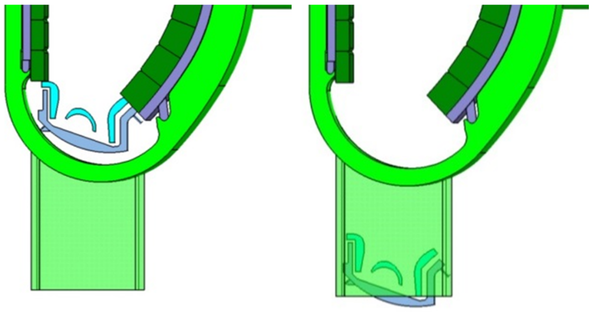

Fig. 14 DEMO divertor removal sequence in the vertical lower port

2.4.2. Vertical Upper Port

The last configuration generated for this preliminary study proposed the divertor cassettes removal from the vertical upper port, Fig. 15.

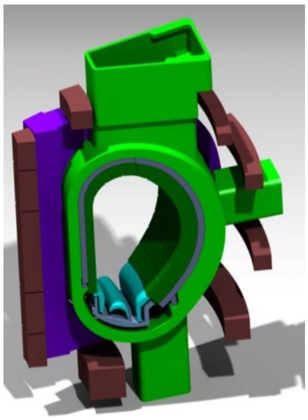

Fig. 15 DEMO divertor vertical upper port

A high level consistency analysis was conducted between this design choice and the assumptions made in the baseline documents such as DEMO Plant Requirement Document (PRD)[1] and WPRM Project Management Plan (PMP) [5]. An additional preliminary analysis was conducted in order to evaluate the possibility to remove the cassettes from the vertical upper port. The main goal was to address all the critical issues related to this design choice, evaluate all the impacts on the plasma facing components and their remote handling tools design. In order to access to the divertor area from the vertical upper port, the remote handling equipment (RHE) shall work in-vessel, where the level of radiation is very high. In detail, according to the preliminary assessment of DEMO Remote Maintenance [6], the maximum photon absorbed dose rates of typical materials used by RHE is 2000 Gy/hr in-vessel and 80 Gy/hr in a port after one month by the last plasma pulse. Because of this, all the RHE shall be designed to withstand an aggressive level of radiation. Moreover, in the assumptions of the WPRM´s PMP [5] was reported that "*Specific maintenance schemes will have to be used that eliminates complex in-vessel operation*". It should be also noted that designing RHE that could work in aggressive environment has a big impact on investment cost. Again, WPRM´s PMP [5] also reports: "*The development of the remote maintenance system for DEMO will be driven by the need of minimizing plant down-time and maximizing availability, the strongest driver to a low cost electricity".* As above highlighted, there are some aspects which are not consistent with the most important drive concepts of the DEMO design approach [1]. However in order to remove the divertor cassettes from the vertical upper port two solutions were proposed feasible with the current design of the tokamak. In the first solution, the Central Outboard Blanket Segment (COBS) shall at first be removed in order to leave enough space to uninstall the central and the other cassettes. This solution avoids impacts on the design of the Blanket Segments (BS), but has heavy effect on the time spent for RH operations of the plasma facing components, moreover the COBS uninstalled during the cassettes RH activities shall be stored in a dedicated area. It should be noted that these aspects could not be negligible, because they contribute to the increase of the time for RH maintenance. In this case, the design choice could be not consistent with the maximization of the availability of the tokamak [5].

Problems of interferences shall be investigated as well. Fig. 16 shows the interferences between the bounding box of the divertor cassette with the Left Outboard Blanket Segment (LOBS) and the Right Outboard Blanket Segment (ROBS).

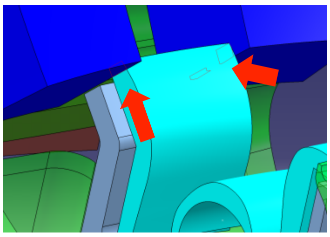

Fig. 16 Interferences of the divertor cassette with LOBS and ROBS during vertical lifting

In this configuration one possibility for the handling of the cassettes could be the dome area, Fig. 17. The estimated weight of a single cassette is assumed to be 17.2 tonnes [7]. Moreover, after its lifecycle the dome area will be weakened by the high loads and radiation level[6]. Studies on the embrittlement of the cassettes materials shall be carried out to define if at the end of a cassette lifecycle the dome could be able to withstand the total weight of the divertor cassette during the RH operations.

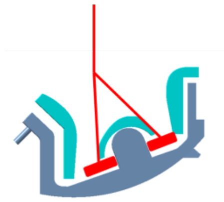

Fig. 17 Vertical lifting principle of the divertor cassette

The kinematic sequence of the first solution is shown in Fig. 18. In particular, the upper part of the COBS is removed at first and then the divertor cassettes are lifted from the upper port of DEMO vacuum vessel.

The second solution proposed changes at the current design of the BSs and their RHE [8]. In particular the COBS shall be divided in two different segments: upper and lower segments, Fig. 19. These changes will have a heavy impact on the design of the BS but also on theirs RHE. Furthermore estimated time for the RH operations is also increased. The simulation of the second solution is shown in Fig. 20.

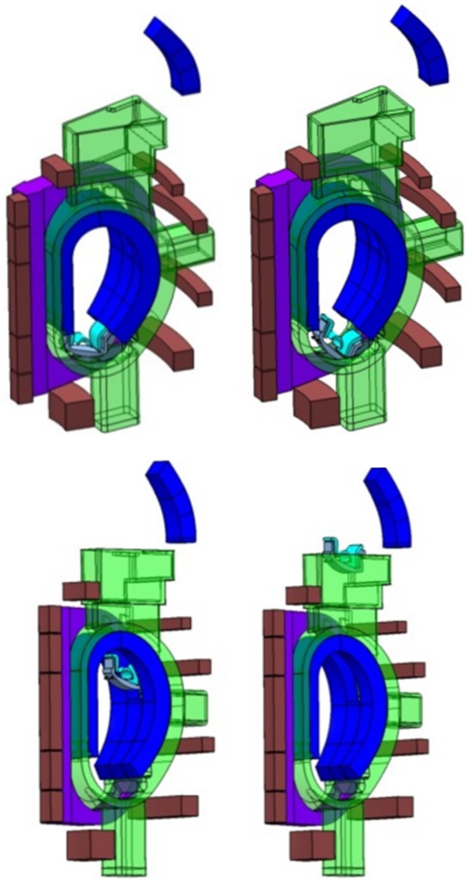

Fig. 18 First proposed divertor removal sequence in the vertical upper port

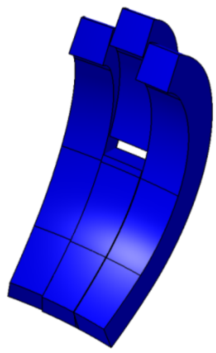

Fig. 19 Proposed COBS modification

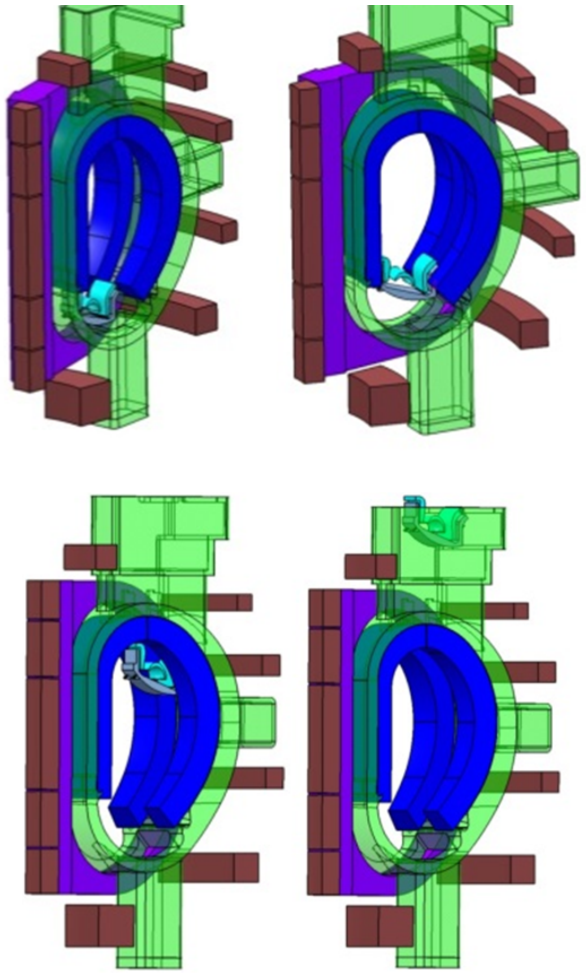

Fig. 20 Second proposed divertor removal sequence in the vertical upper port

It is clear that these solutions are inconsistent with the current RH assumptions: "*the divertor RH activities shall be carried out with the presence of the Blanket Modules*". [6]

As a consequence the time to spend in the RH activities is increased with a decreasing of the DEMO availability. This aspect is clearly non-consistent with the needs cited in DEMO´s WPRM PMP[5].

3. Evaluation of the concepts using Analytic Hierarchy Process (AHP)

We compared the different solutions using an approach based on the Analytic Hierarchy Process (AHP).

The Analytic Hierarchy Process (AHP) is a technique developed by Thomas L. Saaty in the 1970s [9], and hence well established as an instrument to perform a multi-criteria decision analysis. According to this technique, the factors that are important in making a decision are arranged in a hierarchic structure. Arranging goals, criteria and alternatives in a hierarchic structure gives the opportunity to provide an overall view of the relationship between elements related to a decision process, and to help decision makers understand whether the elements in each level are of the same order of magnitude, so that they can be compared homogeneously. Thus, the main advantage of using AHP lied in the analytical nature of the methodology.

AHP could be a very important tool in the DEMO remote maintenance development, starting from the pre-concept design. It can support the selection of the most feasible conceptual solutions, being an iterative instrument that can follow the design process until final design.

This work represented a preliminary test of the methodology in DEMO design, even though already tested with valid results by the authors [10].

We carried out the study with the valuable participation of four research groups, which provided the AHP evaluation questionnaires: ENEA, CREATE, the RoVir team at VTT and members of the CCFE.

We designed a decision hierarchy based on a set of criteria, which are listed below:

- Tokamak impact: general impact on DEMO tokamak current design
- RHE impact: impact on DEMO Divertor Remote Handling Equipment design (including End-Effectors, tooling etc.)
- RH operations: independence of DEMO Divertor Remote Handling operations with the other components
- Failure recovery: impact on the DEMO tokamak system availability

The AHP hierarchical structure in this study was composed of two sub-levels: the criteria and the concept alternatives.

Once the hierarchical decomposition of the problem was completed, we prepared a set of questionnaires based on paired comparisons for all elements belonging to each level of the hierarchy. Respondents were asked to provide information via Excel files containing all the pre-defined comparisons. We provided them also support documentation about the models and the method.

The comparison resulted in defining a set of weights matrices, which eventually lead to the final scores. The comparison between elements was made using a scale of numbers that indicated how many times more important (or dominant) one element was over another with respect to the criterion to which they were compared [11]. All the n elements involved in the comparison were placed on the rows and columns of the matrix, obtaining a square matrix. The generic element of the matrix of weights was the result of the pairwise comparison between two attributes using the scale reported in Table 1, and hence it was equal to the ratio of the weights of the corresponding elements [9].

Table 1 The scale used to make comparisons with AHP

Intensity of importance	Definition	Explanation
1	Equally important	Two activities contribute equally to the objective
3	Weakly more important	Experience and judgment slightly favor one
5	Strongly more important	Experience and judgment strongly favor one activity over another
7	Very strongly more important	An activity is favored very strongly over another; its dominance demonstrated in practice
9	Absolutely more important	The evidence favoring one activity over another is of the highest possible order of affirmation

All judgments which came from the respondents were checked for consistency using the consistency ratio test (CR):

$$CR = \frac{CI}{RI} \quad (3.1)$$

The consistency index (*CI*) was obtained from the equation 3.2, where λ_{max} is the principal eigenvalue of the matrix of weights and *n* its dimension.

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (3.2)$$

In equation 3.1 *RI* is a random index, and its values can be estimated from matrices with random entries. Thus, the estimate of the weights is generally accepted if *CR* does not exceed 0.10 [9]. This check, which is widely reported adopted in AHP literature, gives the opportunity to drop questionnaires which answers are too close to randomness.

4. Results of AHP and selection of the best concepts

A total of 14 researchers (2 CCFE, 3 CREATE, 4 ENEA, 5 VTT) contributed sending their answer. In order to proceed with the calculation of the final results, according to the established practice, only consistent judgments were taken into account. Of the 70 total worksheets received, 2 were missing information, and 30 contained non-consistent judgments (CR < 10). Hence, 38 resulted to be valid judgments, and were the only ones taken into account for the final calculation.

All the respondents' answers were assumed to be equal in weight. The global aggregated results illustrated below don't take into account the groups, but treat the respondents as a unique group.

The best solution selected was the Hybrid Lower Port (26,2%), followed by the Horizontal Lower Port (24,8%), 45° Lower Port (24,6%), Vertical Lower Port (15,3%) and Vertical Upper Port (9,1%). More information is reported in Fig. 21 and Fig. 22: the global and relative weights given to criteria.

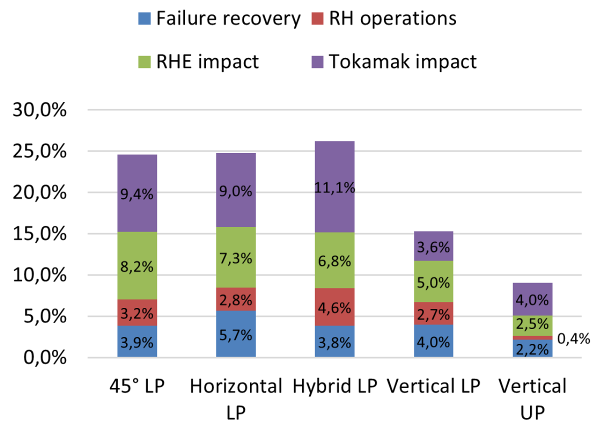

Fig. 21 Final weights of the 5 concepts for all the groups

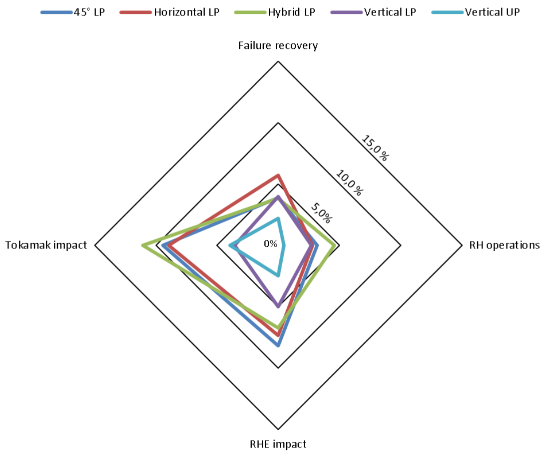

Fig. 22 Final weights of the 4 comparison criteria

The results were then calculated and compared for each research group as well. It is highlighted a preference of the lower ports from CREATE, VTT and CCFE. ENEA expressed a strong preference for the vertical upper port and VTT a strong preference for the Horizontal port, see Fig. 23.

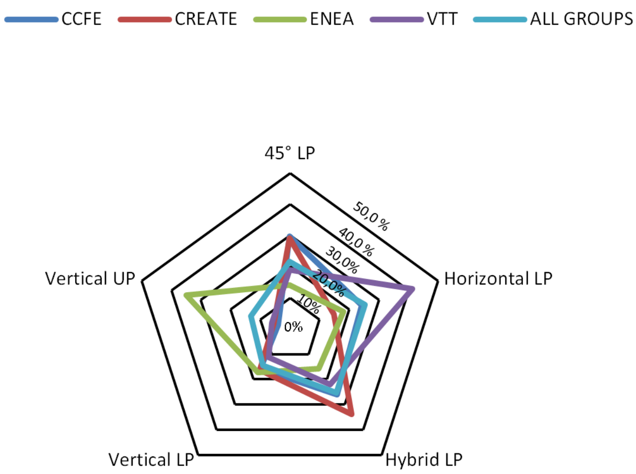

Fig. 23 Favourite concept configuration for each research group

Regarding the criteria that were used to compare the concepts, all groups agreed on the relevant importance of the "Tokamak Impact" (the effects on the current design of the global reactor). Of the three remaining criteria, ENEA gave a strong importance to "Failure Recovery", CREATE on both "Failure Recovery" and "RHE Impact", CCFE on "RH Operations". See the results of the comparison criteria in Fig. 24.

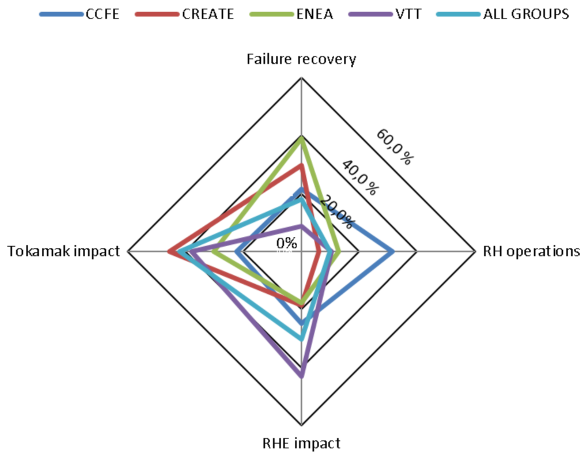

Fig. 24 Final scores of the comparison criteria for each research group

This analysis had the objective to compare five concepts, providing a possible classification of the solutions to guide further design activities in 2015, in which AHP could also be re-iterated together with the detailing of the concept design phase. This evaluation study was a preliminary high level assessment for future development, where a more detailed model will be used to select the final solution.

5. Conclusions

This work focused on the impact of the inclination of the maintenance port on the RH operations in DEMO reactor. Starting from the reference scenario, the 45° port, four other options were compared using an approach based on AHP. The methodology allowed prioritizing alternatives basing on several design criteria that were prioritized as well. The method could support further investigations in the next engineering phases scheduled in the 2015 activities as well. At the same time, the methodology allowed the collection of information coming from different teams located in different research centres. This could enable further cooperation opportunities in the optimisation of the WPRM activities in the DEMO projects. Different scenarios will continuously be studied in order to determine the most suitable cassette handling solution.

While experience from ITER was a strong starting point for this study, and a valuable reference, the methodology gave the opportunity to evaluate several different scenarios that are distant from ITER. Therefore, the approach proposed in this work can also be exploited for future applications in DEMO reactor design phases, such as the cassette fixation and tooling.

6. Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

The authors would like to acknowledge all the participants from CCFE, CREATE, ENEA and VTT for their contributions in the AHP; Eng. Gioacchino Micciché from ENEA Brasimone (BO), for the constructive discussions concerning the topic surveyed in the present article and for the help in the selection of the comparison criteria due his long expertise in the RH; Risto Tuominen from VTT Tampere, for his precious advices, counsels, and expertise.

References

[1] J. Harman, Plant Requirements Document, in: EFDA_D_2MG7RD (Ed.), 2014.
[2] A. Kossiakoff, W.N. Sweet, S. Seymour, S.M. Biemer, Systems Engineering Principles and Practice, Wiley, 2011.
[3] D. Carfora, G. Di Gironimo, J. Järvenpää, K. Huhtala, T. Määttä, M. Siuko, Preliminary concept design of the divertor remote handling system for DEMO power plant, in: Fusion Engineering and Design, 2014.
[4] J. Harman, EFDA Power Plant Physics & Technology WP13 Reference DEMO CAD Model Specification, (2013).
[5] A. Loving, Remote Maintenance Work Package Project Managament Plan in, 2014.
[6] A. Loving, O. Crofts, N. Sykes, D. Inglesias, M. Coleman, J. Thomas, J. Harman, U. Fischer, J. Sanz, M. Siuko, M. Mittwollen, Pre-conceptual Design Assessment of DEMO Remote Maintenance, in, EFDA, 2013.
[7] P. Frosi, S. Villari, G. Ramogida, V. Cocilovo, Final Report on Deliverable DIV-1-3-2-01 -Draft of Load Specification for Divertor Cassette and steel supporting structure for VT and Dome., in, Eurofusion IDM, 2015.
[8] I. D., D. Cooper, K. Keogh, D. Middleton-Gear, Report for Tasl Agreement WP13-DAS07-T05 Blanket Segment Remote Maintenance, in, 2013.
[9] T.L. Saaty, How to make a decision: The Analytic Hierarchy Process, European Journal of Operational Research, 48 (1990) 9 - 26.
[10] G. Di Gironimo, D. Carfora, G. Esposito, C. Labate, R. Mozzillo, F. Renno, A. Lanzotti, M. Siuko, Improving concept design of divertor support system for FAST tokamak using TRIZ theory and AHP approach, Fusion Engineering and Design, 88 (2013) 3014-3020.
[11] T.L. Saaty, Decision making with the analytic hierarchy process, International Journal of Services Sciences, 1 (2008) 83–98.