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Overview of progress on the European DEMO remote maintenance strategy

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HIGHLIGHTS

- The remote maintenance strategy is applicable to the range of tokamak and component options currently under consideration in Europe
- The remote maintenance development work is concentrating on the application and limits of the immature technologies that pose the greatest risk to the feasibility of the maintenance strategy
- Position control during the handling of the in-vessel components is one of the areas of high risk and a system is being developed and will be tested prior to concept design to demonstrate the feasibility and capability of a system capable of real time incorporation of changing kinematic data provided by a structural simulator running in parallel
- In-vessel recovery and rescue and the pipe joining technology form two more of the high risk areas where developments are being concentrated

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ABSTRACT

The EU-DEMO remote maintenance strategy must be relevant for a range of in-vessel component design options. The remote maintenance project must provide an understanding of the limits of the strategy and technologies so as to inform the developing plant design of the maintenance constraints. A comprehensive set of maintenance requirements has been produced, in conjunction with the plant designers, against which design options can be assessed.

The proposed maintenance solutions are based around a strategy that deploys casks above each of the vertical ports to exchange the blanket segments and at each of the divertor ports to exchange the divertor cassettes. The casks deploy remote handling equipment to open and close the vacuum vessel, remove and re-install pipework, and replace the in-vessel components.

A technical design risk assessment has shown that the largest risks are common to all of the proposed solutions and that they are associated with two key issues, first; the ability to handle the large blanket and divertor components to the required positional accuracy with limited viewing and position feedback, and second; to perform rapid and reliable pipe connections, close to the blankets, with demonstrated quality that meets the safety requirements.

1. Introduction

The commercial viability of a future fusion power plant (FPP) is heavily dependent on high availability [1]. The EU DEMO reactor design must demonstrate rapid and reliable remote maintenance techniques, and a reasonable availability, compatible with the economic performance of a FPP.

The aim of the current phase of the European DEMO remote maintenance project is to develop a maintenance strategy based on sound remote handling practice and technologies, relevant for a range of in-vessel component design options. At the pre-conceptual design phase the component designs are relatively immature;

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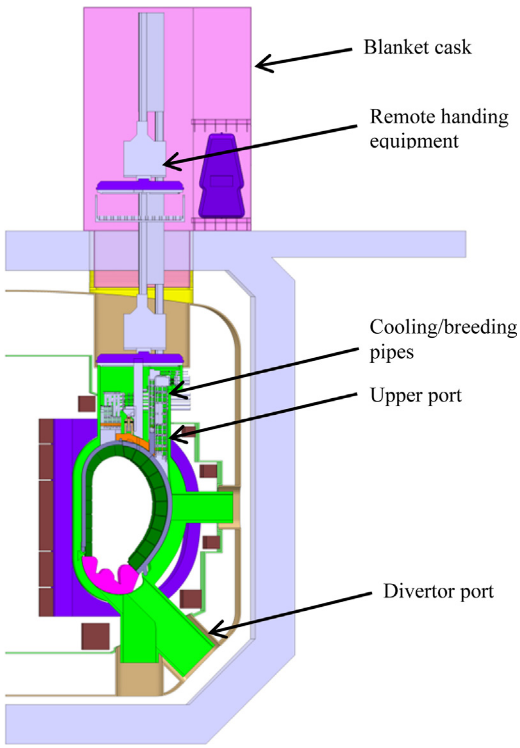

Fig. 1. The proposed maintenance strategy.

however the maintenance strategy is being developed in parallel to ensure that the developing plant designs can take into account the maintenance requirements.

The proposed maintenance strategy deploys casks above each of the vertical ports to exchange the blanket segments and at each of the divertor ports to exchange the divertor cassettes. See Fig. 1. The casks deploy remote handling equipment to remove pipework and open the vacuum vessel and then to remove and replace the in-vessel components.

Alternative maintenance solutions for this strategy have been proposed which have varying pipe layouts, vessel opening options and cask deployment arrangements.

2. Maintenance strategy drivers

2.1. Demonstrate technologies

The European DEMO is required to demonstrate the technologies necessary for a commercial fusion power plant [2]. This requires the remote maintenance concept design process to identify the immature technologies that have the greatest threat to the feasibility of the concepts.

This has been undertaken through a technical risk assessment. See Section 3.

2.2. Minimize in-vessel operations

It is vital to minimize the remote handling operations required in or close to the plasma chamber due to the high temperatures and high radiation levels present during maintenance. These conditions make remote operations more difficult due to the limited visual and physical feed-back available for the handling systems. See Section 3.1.3.

Furthermore, the consequences of an unrecoverable failure during in-vessel operations are very severe because they result in high

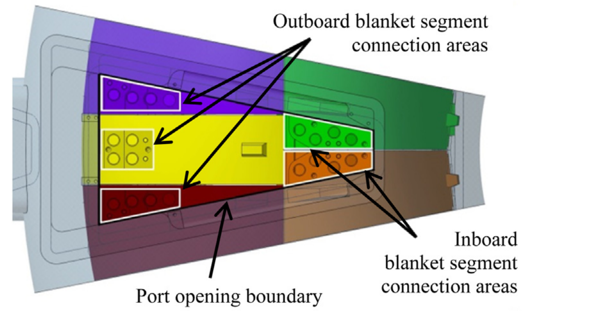

Fig. 2. The vertical port opening showing the vertically accessible areas of the blanket segments.

costs and long delays and require extensive rescue equipment to be available. See Section 5.3.

This has driven the requirement for the segmentation of the blankets and divertor cassettes to ensure that at least a small part of each of the in-vessel components is visible through the port opening for the handing connection and service connections. See Fig. 2. Therefore the in-vessel maintenance system requires access to all the vertical and divertor ports.

This allows the handling of the components and service connections to be performed from within the vessel ports, not from inside the plasma chamber where the environmental conditions are significantly more severe. See Section 4.3.

The in-vessel maintenance strategy is discussed in more detail in Section 6.

2.3. Minimize maintenance duration

A fusion power plant must have a high availability to be commercially viable [3], there is therefore a strong cost driver for rapid maintenance operations. DEMO must demonstrate power plant relevant availability, from which a FPP level of availability could be extrapolated. This requires the minimization of the number of in-vessel components. It has also led to proposals to use less mature technologies that have the potential to complete operations faster than more established technologies such as; advanced control algorithms, see Section 3.1 and the use of laser welding. See Section 3.2.

2.4. Small port size

The toroidal field (TF) coils, poloidal field (PF) coils, and the associated inter-coil support structures are permanent components that limit the size of the ports through which the in-vessel components must be exchanged. This in turn limits the size of the in-vessel component handling systems and therefore their load capacity and stiffness. It also limits the space available for removing and replacing pipes and other in-port services and equipment. See Fig. 3.

3. Technical risk assessment

The work to develop a remote maintenance strategy has studied the technical design risks that could impact the performance or feasibility of the remote maintenance systems, and has resulted in several targeted activities being initiated in order to mitigate the risks as far as possible by the time of the concept design review.

The concept design technical risk assessment has shown that the largest risks are common to all of the currently proposed in-vessel component maintenance solutions. The most critical risks are primarily associated with the ability to rigidly handle and control the heavy in-vessel components to a high degree of accuracy,

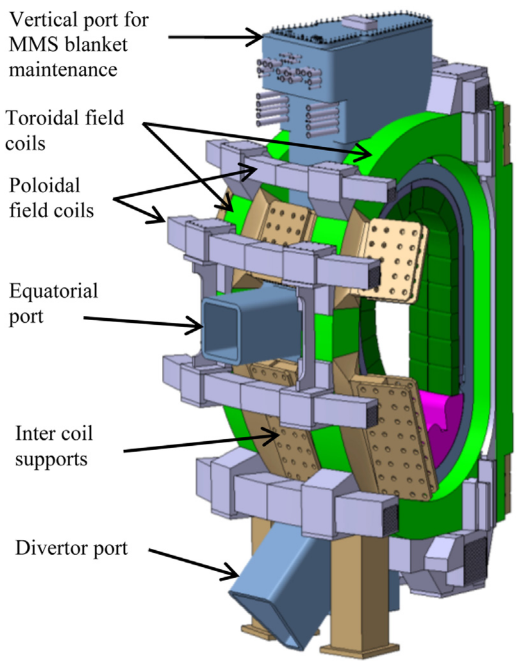

Fig. 3. The port sizes are limited by the TF and PF coils and the inter-coil supports.

and to rapidly and reliably; join, test, and qualify pipe connections for operation in a nuclear environment.

The technical risks for the blanket maintenance were presented at a pre-concept blanket maintenance design review along with the work required to mitigate them in order to maximize the feasibility of the maintenance strategy at the concept design review.

3.1. Handling heavy components

Handling the in-vessel components (IVCs) is challenging because they are large, heavy, and will deflect significantly under their own weight. There is also a requirement to have small clearances between the plasma-facing IVC to maximize tritium breeding and minimize neutron streaming, ideally as little as 20 mm.

The blanket segments could be 12 m long and weigh up to 80 t [4] and although the divertor cassettes will be smaller and lighter, they are deployed horizontally—developing a considerable moment about the end-effector. Manipulating and installing such massive components while maintaining tight clearances is a considerable challenge, especially considering the remnant magnetization of the Eurofer IVCs [5].

The design strategy allows the handling systems to be deployed from the vessel ports and does not foresee any handling for planned maintenance to occur from inside the plasma chamber, where harsh radiation conditions limits the use of many fundamental RHE components and complicates recovery and rescue.

These constraints limit the accuracy and frequency of measurements that could be made from inside the plasma chamber of the position of the in-vessel components during maintenance. Poorer and less frequent measurements limit the position feed-back available for the control system, impairing its ability to compensate for the deflections in the components and in the deployment system.

Establishing the feasibility of handling the in-vessel components requires research and development work in a number of key areas:

3.1.1. Physical sensing

Research and development work has started this year to investigate the range and capability of sensors that could be used to determine the component positions in the high temperature and radiation conditions in vessel.

Options include laser measurement from within the port, proximity sensors and limit switches. In addition, shielded viewing systems are being considered that could provide visual data at discrete intervals by briefly opening a shield door. This could provide confirmation of the maintenance status and feed actual position data back to the structural model and the virtual reality model through analysis of the image.

3.1.2. Structural simulator

A structural simulator is being developed that will be capable of estimating the changing deflection of both the components and the handling system in real time.

The simulator will use multi-body dynamics methods and will aim to include multi-physics effects to incorporate self-weight, electromagnetic loads and thermal effects from thermal and gamma radiation and internal decay heating.

3.1.3. Adaptive position control system

A position control system is being developed that will interface with the structural simulator in real time, adjusting the control parameters and kinematic model to accurately control the position of the manipulator and component as their deformation changes.

The control system will be used to develop a range of algorithms and techniques to assess their suitability for the control of flexible, under-actuated systems. It will also be capable of using a range of sensor input-data to investigate the effects on control performance.

3.1.4. Physical trials

The feasibility and limits of the handling system can only be established through the integration of the elements above, followed by handling trials in a representative test rig facility and further development as required.

The requirements for a test rig facility are under review and the design and build of the facility and the end-effector and sensors are planned for completion by the end of 2017 to allow testing and refinement to occur during 2018. This will provide substantiated evidence of the feasibility of the handling concepts in time for the maintenance system concept design review at the end of 2018.

The test rig facility will be capable of providing a payload of variable mass and stiffness and will feature a range of sensor feedback systems, enabling the control performance to be established for a wide range of tokamak configurations and conditions.

3.2. In-bore pipe welding

As a result of the highly restricted space in the tokamak ports, pipes feeding the IVCs have to be closely grouped, see Fig. 4, precluding any orbital joining processes. As such, in-bore welding is considered to be the only viable way to join the pipes in the ports.

To minimize the plant shutdown, the weld process must be as rapid as possible. Maintenance duration estimates [6] have shown that, due to the number of pipe connections to be made, the welding process adds a significant amount to the maintenance critical path.

It is crucial that in-bore welding is demonstrated as a reliable joining method for pipes, as the size and layout of the ports and much of the remote maintenance strategy hinges on the use of such technology. Laser welding has been identified as the preferred in-bore technique due to its speed. It also benefits from improved failure mode criticality compared to welding with an electrode–which could stick to the work piece.

Weld trials have been started at Cranfield University, see Section 7.1. The developing weld tool design will be tested in a suitable test rig facility.

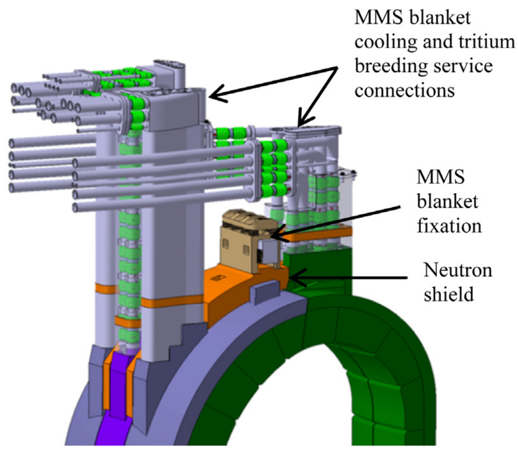

Fig. 4. 2014 pipe layout concept in the vertical port.

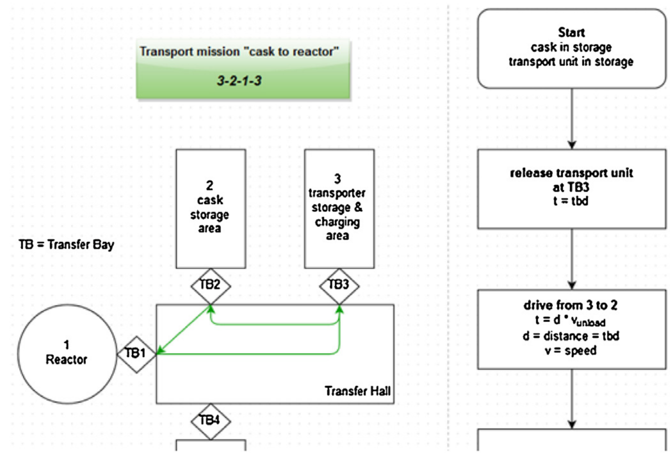

Fig. 5. Example logistics tool process description.

4. Systems engineering approach

Developing the design of a fusion power plant is challenging due to its size and complexity, but also due to the large number of interrelated and conflicting requirements that must be balanced between; physics, operation, maintenance, safety, availability and cost.

A thorough systems engineering approach is vital to ensure that the optimum balance between these requirements is achieved. The EU DEMO design approach is described by Federici et al. [7].

Within the remote maintenance work package this means a systematic approach, that integrates with the plant and component systems engineering processes, to analyze the functions, gather requirements and consider failure modes and reliability.

4.1. Requirements capture

A complete set of system requirements has been developed for the remote maintenance system, starting from the functional flow for the system.

Due to the immature nature of the plant and component design it was also necessary to have detailed discussions with the interfacing plant and component designers to fully understand their requirements and constraints, and to be aware of possible future changes. Where concept designs had not been proposed it was often possible to agree on likely options and thereby build a requirements set to reflect generic maintenance requirements for each item of plant requiring remote maintenance.

Each requirement was recorded in the requirements management database DOORS (Dynamic Object Oriented Requirements System) in which it could be linked to parent plant level requirements above and, as the subsystem requirements are developed, to child requirements below to ensure the remote maintenance subsystems deliver the required maintenance functions.

For each requirement the rationale, source, and verification acceptance criteria were recorded. The output from this database formed the remote maintenance system requirements document.

Interface requirements were also captured. These are where assumptions have been made about the functions, performance or features of other interfacing systems such as the blankets, pipe work or balance of plant components. These interface requirements are then included in the requirements for that system or, where they cannot be readily met, it begins the discussion to achieve the optimum balance between the conflicting requirements.

The development and management of the requirements is a continuous process. A comprehensive set of requirements is a necessary basis to drive the design development and to agree the interfaces with the plant design. It is also used for the evaluation of design options during the design development and to measure the success of the design during design reviews.

4.2. RAMI analysis

Minimizing the criticality of failure modes is essential to ensure the remote maintenance system can achieve the plant availability and safety requirements. A Functional Failure Modes, Effects and Criticality Analysis (FFMECA) has been undertaken for each of the nine remote maintenance subsystems and they are updated as the subsystem designs evolve.

Following a design iteration, analysis of the updated functional FMECA shows whether the failure mode criticality has been improved and it will also show the consequence of changes to the requirements. The FMECAs are currently being used to develop the top level Reliability, Availability, Maintainability and Inspectability (RAMI) analysis.

The sequence of operations and the RAMI data have been used to develop a maintenance duration estimate [6]. Due to the immature level of the design and therefore the input data for the duration estimate, it is not appropriate to make conclusions based on the absolute duration, however it can be used to identify which operations are likely to be on the critical path and to get an idea of which operations are adding the most time to the maintenance duration.

Ultimately the RAMI analysis will seek to confirm that the remote maintenance system can meet the DEMO plant availability requirements and the number of remote maintenance systems required to operate in parallel to achieve the availability required for a fusion power plant.

A logistics tool is currently being developed, see Fig. 5, that will enable the rapid comparison of maintenance durations for different options, with the ultimate aim of providing quantitative feedback to DEMO plant designers on the availability of different reactor architectures.

5. Environmental conditions

Calculations have been made for the in-vessel radiation levels and component temperatures during maintenance.

To keep the component surface temperatures down to 100 °C during maintenance it is necessary to maintain cooling to the vessel and the components that are not being removed and to have an in-vessel ventilation rate of approximately 10 kg/s.

Further remote maintenance specific calculations for the dose rates and decay heat in the pipes and outside the bio-shield will be needed in the coming years.

6. In-vessel maintenance strategy evolution

In 2012 it was established that the optimum maintenance strategy was to extract the blankets through vertical ports and divertor cassettes through an angled or horizontal port.

In 2013 a solution was proposed [8] in which a series of casks are delivered to each port to remove pipework and port seals and to exchange the in-vessel components. See Fig. 6.

In 2014 an alternative solution was considered for the upper port in which a single vertical transport cask is delivered to each vertical port and separate horizontal casks deliver remote handling equipment and components that are deployed by the vertical transport cask. See Fig. 7.

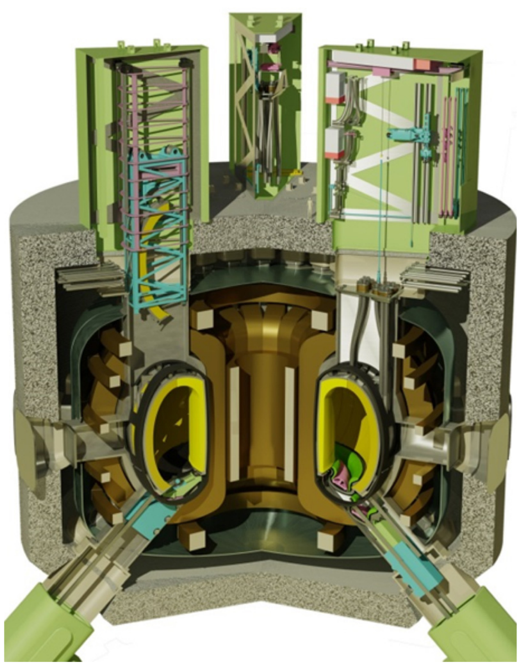

Fig. 6. 2013 remote maintenance solution.

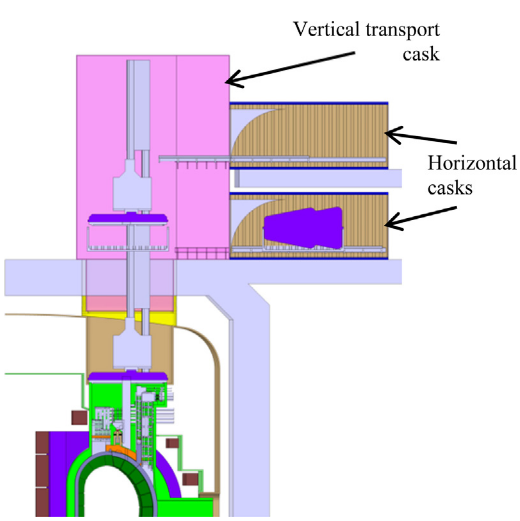

Fig. 7. 2014 remote maintenance solution.

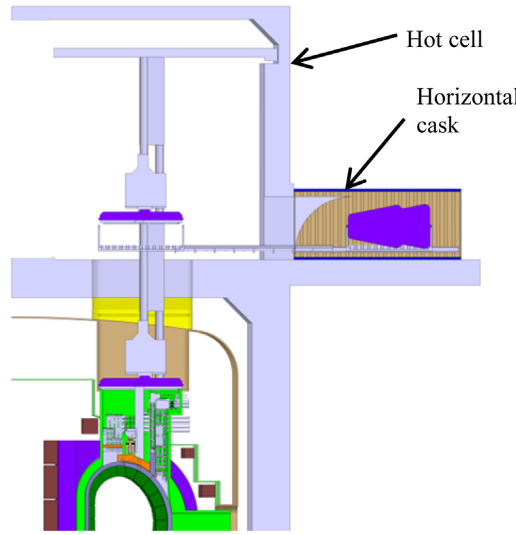

Fig. 8. 2015 remote maintenance solution.

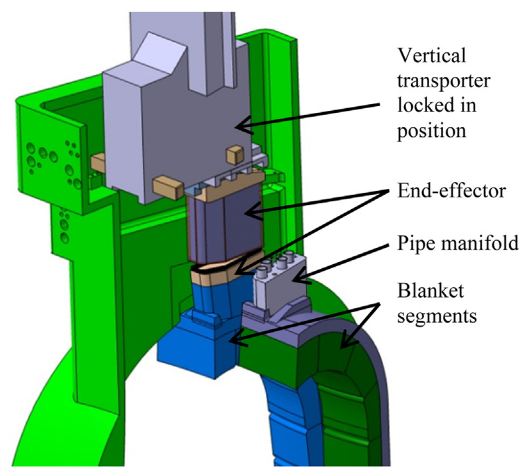

Fig. 9. Blanket handling end-effector.

We are currently looking at a development of the 2014 solution in which the vertical transport cask is replaced by a hot cell on top of the ports. The horizontal casks deliver the components and remote handling equipment to the cell which contains the transfer equipment required to deploy them. See Fig. 8.

A comparison between the 2015 and 2014 solutions will be possible once the RAMI analysis and duration estimate are complete.

6.1. Blanket handling

A spatial layout of the end-effector has been proposed, see Fig. 9. Work is starting to validate the layout by designing the mechanisms required to achieve the kinematic motions. The motors and bearings will be specified and the stress and stiffness of the resulting structure analyzed.

The layout proposal involves a vertical transporter to deploy the end-effector. When it is in its deployed position, it is mechanically locked to the vacuum vessel to form a rigid platform from which the end-effector can work.

6.2. Divertor handling

Concepts are being developed for a divertor cassette deployer that is moved through the divertor ports using a hydraulic

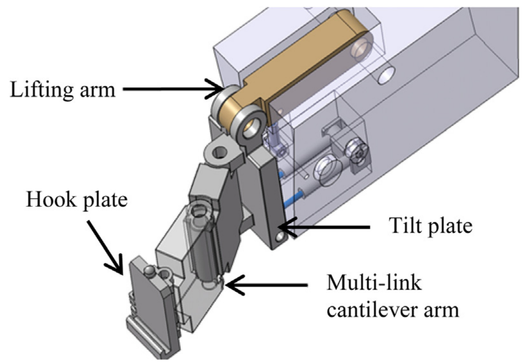

Fig. 10. Divertor cassette deployer main components.

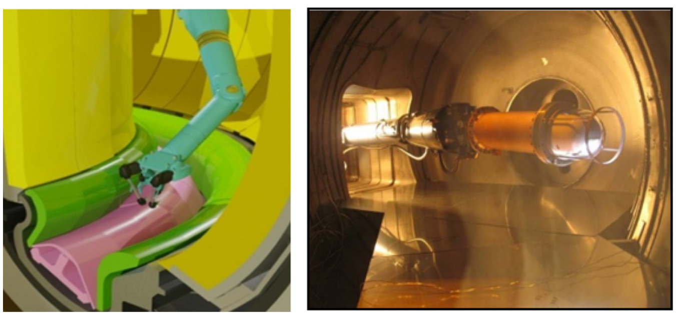

Fig. 11. Left: DEMO MPD concept. Right: In-Vessel Inspection Device (IVID) being tested for Tore Supra.

transporter. It attaches to the divertor cassettes using a hook plate to extract or replace the cassettes. See Fig. 10.

6.3. Recovery and rescue

Wherever possible, remote handling equipment will be designed to self-recover from failures. Inevitably however, there will be failure scenarios that are un-recoverable. These scenarios must be highly unlikely in order to minimize the duration of maintenance interventions and preserve the plant availability. In any case, there must be a rescue option available to allow the DEMO plant to return to service.

Designs for a Multi-Purpose Deployer (MPD) are being developed to provide these rescue options. See Fig. 11.

7. Ex-vessel maintenance strategy

7.1. Cask transfer systems

A cask transport system has been proposed in which autonomous trolleys are used to lift the horizontal casks and move them between the tokamak ports and the Active Maintenance Facility. The trollies only add a small height to the cask, allow the cask to be highly maneuverable, and have excellent rescue options in the event of unrecoverable failure. See Fig. 12.

7.2. Contamination containment door

A double lidded door system has been proposed to contain the contamination within the ports and within the RM casks when they are not connected to each other. It minimizes the spread of contamination and the production of secondary waste.

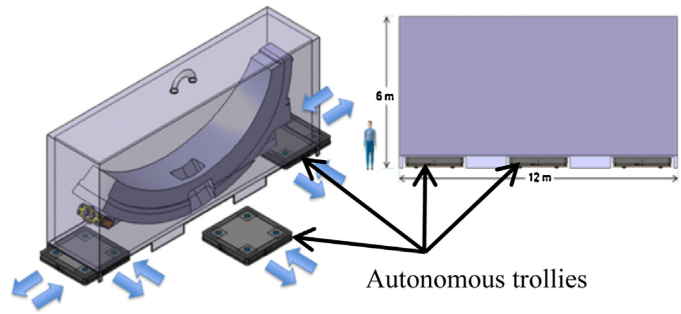

Fig. 12. Cask transfer system proposal.

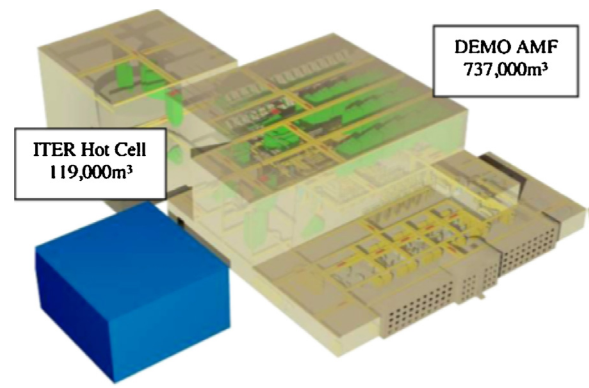

Fig. 13. DEMO Active Maintenance Facility.

7.3. Active maintenance facility

The Active Maintenance Facility (AMF) is required to store casks, dismantle components, and maintain the remote handling equipment. The AMF for a power plant is likely to be large and complex; Thomas et al. [9] estimate its volume to be in excess of 700,000 m^3, many times the volume of the ITER hot cell building and the volume of the Tokamak building to be in excess of 100,000 m^3. See Fig. 13.

The DEMO AMF concept was developed in 2012 and updated in 2013. Further work is underway in 2015 to update it to match the developing maintenance strategy and to improve the process flow through the facility.

8. Pipe joining technologies

8.1. Laser welding

Another area identified by the technical risk analysis as requiring development is the service joining systems that must be capable of rapidly achieving reliable joins that can be demonstrated to meet the requirements of the safety regulator.

Laser welding has been identified as an ideal technology due to its speed, provided it can be demonstrated to work reliably. To this end, trials have been conducted at Cranfield University using P91 as a substitute for Eurofer, currently assumed as the material for the pipes. See Fig. 14.

A good weld form was created once the correct shield gas mix had been identified, but the heat affected zone had unacceptable hardness that would require a long heat treatment process to resolve.

A hybrid laser and Metal Inert Gas (MIG) arc set-up was tested along with a reduced cooling rate achieved by applying a defocused laser to the joint after welding. Hardness levels were reduced but not to the level of the parent material. Further trials are planned to start later in 2015.

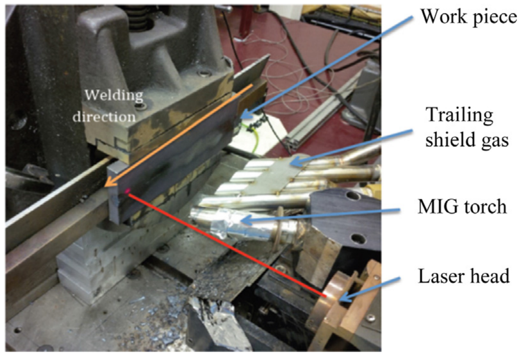

Fig. 14. Laser/MIG hybrid welding.

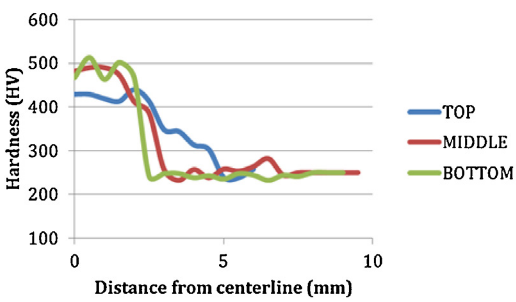

Fig. 15. Hardness of the laser weld in P91 steel.

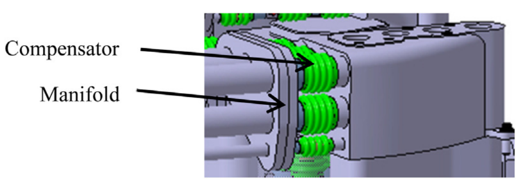

Fig. 16. Manifold joint with pipe compensators.

Fig. 15 shows the Vickers Hardness level at three points through the weld, the top of the weld being closest to the laser source.

8.2. Mechanical pipe connections

Investigations into available industrial technology to provide mechanical connections were undertaken, including investigations into manifold joints and proposals for novel mechanical clamp connections. The pipes require compensators to provide some flexibility to reduce the forces induced by differential thermal expansion and to help with the alignment of the connections. See Fig. 16.

8.3. Non-destructive testing

A full set of requirements have been compiled for the Non-Destructive Testing (NDT) required to validate the joints and looked at a number of suitable technologies. The current proposal to check the weld compliance with acceptance criteria is to visually inspect the weld using a compact optical fiberscope, and volumetric inspect using ultrasonic techniques. A concept for applying a vacuum near the welding joint for helium leak testing has also been proposed.

9. Summary and outlook

The remote maintenance strategy has important implications for the DEMO architecture as a whole; it is vital that the RM strategy is developed in parallel to the component conceptual designs in order that the maintenance requirements can inform the component designs and ensure remote maintenance compatibility.

The remote maintenance strategy is applicable to the range of tokamak and component options currently under consideration within Europe.

Remote maintenance development work is concentrating on the application and limits of the immature technologies that have the greatest threat to the feasibility of the strategy; in particular, the position control during the handling of the in-vessel components, in-vessel recovery and rescue, and pipe joining technology.

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(1) RACE; Remote Applications in Challenging Environments. Part of the United Kingdom Atomic Energy Authority. Working on systems engineering, blanket segment replacement, control systems and structural simulator.
(2) VTT; Technical research centre of Finland. Working on the divertor cassette replacement.
(3) KIT; Karlsruhe Institute of Technology in Germany. Working on the logistics model, contamination control door and mechanical pipe connections.
(4) CIEMAT; Centre for energy, environment and technology research in Spain. Working on RAMI, radiation conditions and non-destructive testing.
(5) IST; Instituto Superior Técnico in Portugal. Working on the cask transfer systems.
(6) ENEA; Brasimone research centre in Italy. Working on the divertor replacement with VTT.
(7) CEA; Commission Energy Atomic in France. Working on recovery and rescue equipment.

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