EARLY DEFINITION OF THE MAINTENANCE MANAGEMENT PLAN IS ESSENTIAL TO ACHIEVE A FEASIBLE EU DEMO

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Abstract

The development of fusion as a viable power source is moving from the science driven design of experimental devices to the engineering design considerations required to develop a feasible power plant. An effective Maintenance Management Plan is essential because the time spent in maintenance is potentially very large. The Maintenance Management Plan is a well-established document used to control the development and execution of maintenance on plant with complex maintenance requirements, particularly those with nuclear safety aspects to satisfy the regulator that adequate systems are in place. To be effective, the EU DEMO Maintenance Management Plan must be outlined early in the plant design because it requires maintenance-oriented strategies to be defined to reduce the maintenance burden and to achieve the maintenance in a shorter time, with a low risk of failure and with simple recovery scenarios. At the concept design phase, the DEMO Maintenance Management Plan will: define the philosophy, detail the maintenance strategy, outline the design development process, define the classification of maintenance operations and the measures required to minimise the increase in maintenance burden as the design develops. Effective maintenance is mission critical to DEMO.

1. INTRODUCTION

The EU DEMO design requires the plasma facing components to be replaced every few years. The EU Fusion Road Map [1] states that one of the general goals of DEMO is “to achieve: the basis for an assessment of the feasibility and economic viability of a fusion power plant”. This requires an effective maintenance plan, not only to ensure the replacement of the plasma facing components but also the maintenance and inspection across the entire plant, in and efficient and safe manner. This is extensive because almost every item of plant or equipment will have some level of maintenance or inspection and many of the areas contain significant hazards (see section 3.4.2). The plan is also an important tool to manage the rise in complexity of maintenance as the design progresses See Fig. 1).

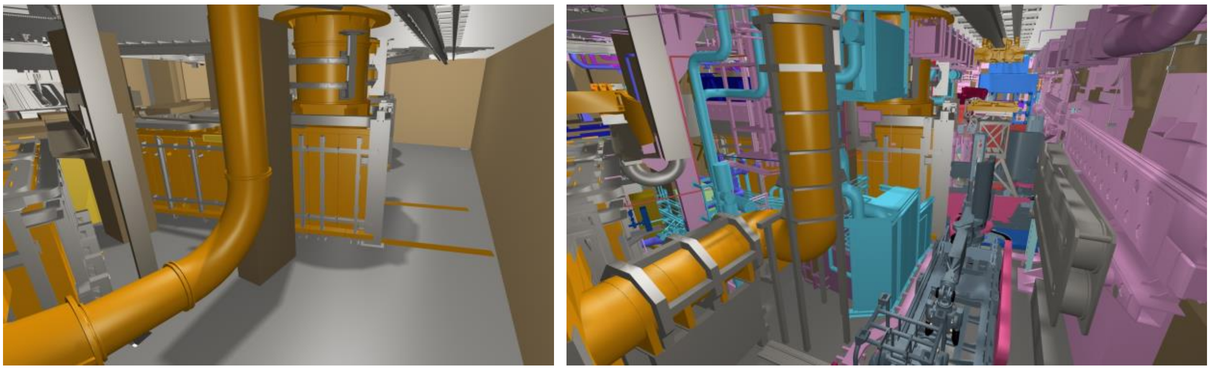

FIG. 1. *ITER NB Cell CAD model before the maintenance systems have been developed (left) and after integration (right).*

The maintenance plan develops as the design develops and will ultimately define the line replaceable units and their schedule of maintenance operations, including: frequency, duration and the flow of materials between operations and storage. It will also define how the maintenance will be carried out and what safety related equipment maintenance records must be held to satisfy the regulator (see section 4).

To be effective, a maintenance plan must be outlined early in the plant design because it requires maintenance-oriented strategies to be defined to reduce the maintenance burden and to achieve the maintenance in a shorter time, with a low risk of failure and with simple recovery scenarios. These strategies need to be agreed and implemented into the tokamak layout at its conception. Examples of the maintenance-oriented strategies are described in section 3.3 “Maintenance Strategy”. These include having all ports available for maintenance, the plasma facing component segmentation and the layout of transfer corridors throughout the plant and up to the tokamak vessel to allow the efficient transport of components and equipment through shield doors and contamination control systems.

Work is therefore required at the pre-concept design stage to define the maintenance plan so that the design driving factors required to enable the plan can be embedded in the developing plant design.

2. FUNCTION OF THE MAINTENANCE MANAGEMENT PLAN

The function of the Maintenance Management Plan is to ensure that throughout their life, assets continue to safely deliver value by performing in accordance with the system requirements. The plan defines the processes through which this is achieved, initially through influencing the design of the plant and then by managing maintenance.

At this early stage of the design of the EU DEMO, the plan is being written to describe the principles and strategies proposed to achieve the key requirements for efficient and safe maintenance. It provides a framework within which the maintenance systems and plant interfaces can be defined and developed. It also ensures adequate processes will be in place for the regular and systematic examination, inspection, maintenance and testing of plant and equipment and the associated record keeping. This is particularly important for safety related equipment to ensure it will meet the statutory requirements for a nuclear plant (see section 4).

Initially the plan will define the:

- high-level maintenance philosophy and strategy, capable of achieving the plant requirements
- Safety Assessment Principles for human risk mitigation; industrial risks as well as nuclear risks (ALARP)
- maintenance system design process for capturing maintenance requirements and the working practices necessary to integrate the maintenance with the plant design
- design data to be produced to allow viable plant solutions to be selected with the minimum through life cost
- measures to control the increase in maintenance burden as the plant design develops
- process to meet the statutory requirements for the maintenance of safety related equipment

3. CONTENT OF THE PLAN AT THE CONCEPT DESIGN PHASE

3.1. Maintenance philosophy

The main aim is to achieve the plant availability with the smallest lifetime cost. The erosion and neutron damage to the first wall components means that the current EU DEMO baseline design requires regular replacement of the blankets and divertors and this requires a complex and costly maintenance system to be deployed in a very challenging environment (see Fig. 2). However, the philosophy must still be applied to make the system as simple and cost effective as possible and to ensure that the complexity of maintenance is minimised for all the rest of the in-vessel and ex-vessel components and systems.

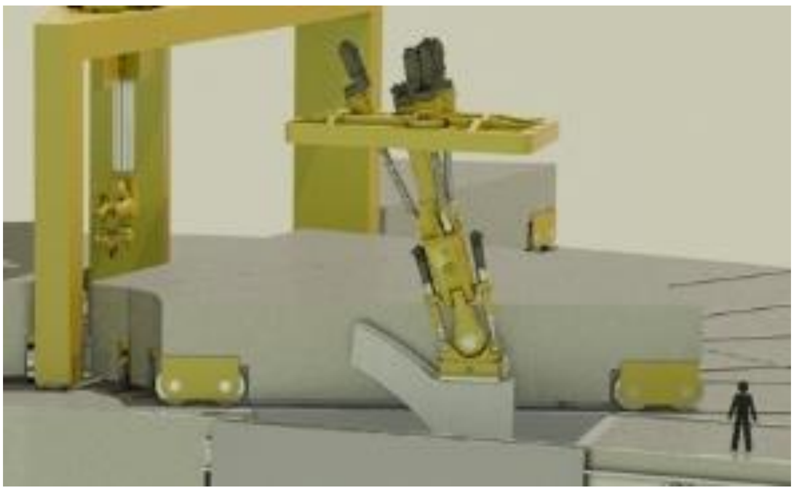

FIG. 2. *Concept of a blanket mover lifting a blanket through the upper port (person shown for scale only)*

3.2. Maintenance drivers

The EU DEMO maintenance has the key drivers of speed, reliability and lifecycle cost.

Speed is driven by the requirement to replace all the plasma facing components in 190 days [2]. This maintenance duration estimate for the current EU DEMO maintenance strategy suggests that four identical in-vessel maintenance systems will be required to operate in parallel to achieve this requirement (see Fig. 3). This estimate is based on just the currently identified maintenance tasks and the assumed access to all of the upper and lower ports for maintenance and an open hot-cell on the top of the machine (see section 3.3).

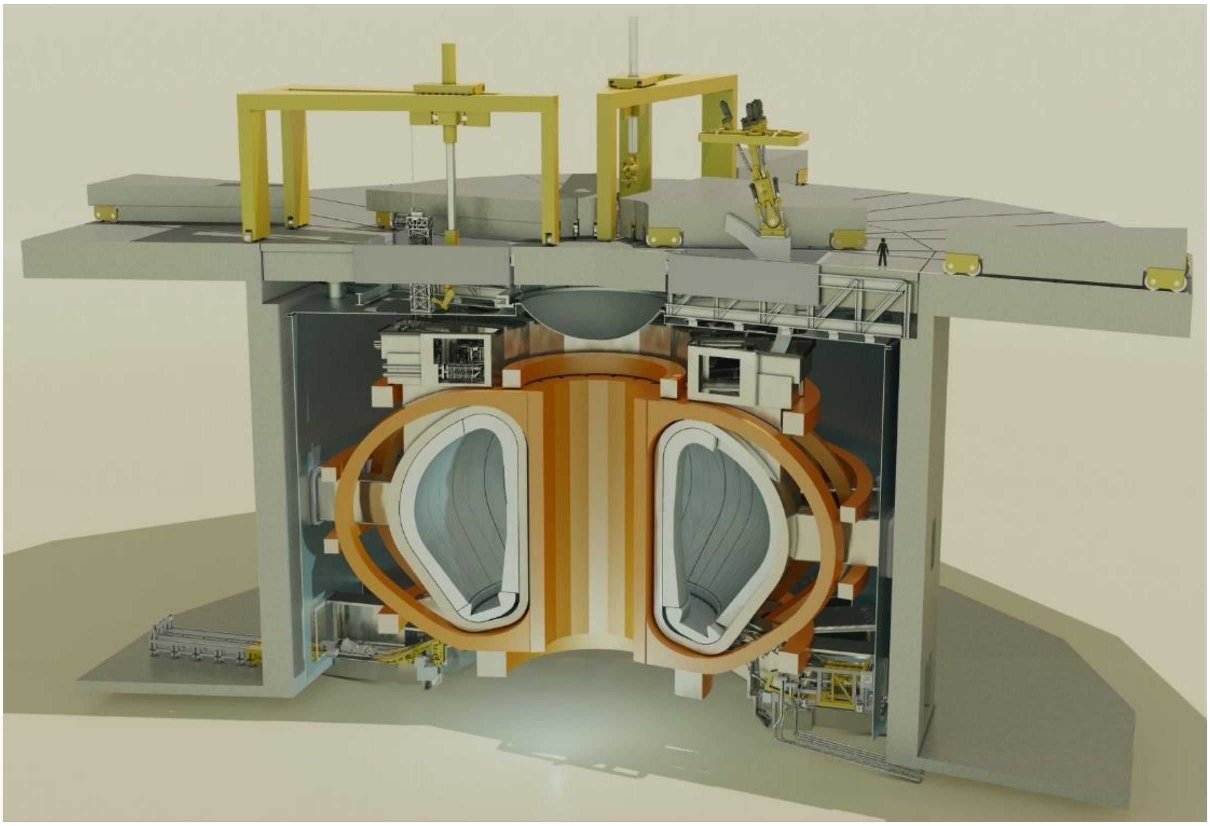

FIG. 3. *Four maintenance systems working in parallel through upper ports*

Reliability of the maintenance systems affects the maintenance duration whilst reliability of the plant reduces the maintenance burden. Both are highly influential on the availability of the plant. Failure of a remote system will have a large impact on performance due to the extended recovery times and this problem is more acute close to and inside the vessel, where recovery operations are more difficult due to space constraints, high radiation levels and long transfer routes.

Lifecycle cost for the maintenance system is to be minimised. It is not possible to obtain accurate lifecycle cost estimates at the early stages of the design process, however, when comparing different options, any significant factors that affect the maintenance full lifecycle cost must be considered during both the plant and the maintenance system down-selection. These factors include; manufacture cost, risks associated with regulatory approval, maintenance speed, decontamination and disposal.

3.3. Maintenance strategy

The need to integrate maintenance-oriented strategies at the early stage of the plant layout is well understood within the EU DEMO design and integration teams and this has led to the current baseline configuration in which all of the upper and lower ports are available for maintenance. This allows the service connection route to be through the port, without the need for toroidal service pipe runs within the vessel. These pipe runs would be extremely difficult to cut and weld and to remove and replace and would add considerable additional recovery systems, maintenance duration, and risk of failure.

Furthermore, and in conjunction with the availability of all upper and lower ports for maintenance, the segmentation of the blankets and divertor cassettes has allowed part of each of the plasma facing components to be visible through the ports, whilst minimising the number of components (see Fig. 4). This has major maintenance benefits: the maintenance system interface with the components is simpler, the maintenance system can operate from within the port (where radiation levels, viewing opportunities, and other sensing and recovery options are all improved), and the handling path is simplified. This last point eliminates the need for a separate in-vessel toroidal transporter which would be time consuming to deploy and difficult to rescue if it were to fail.

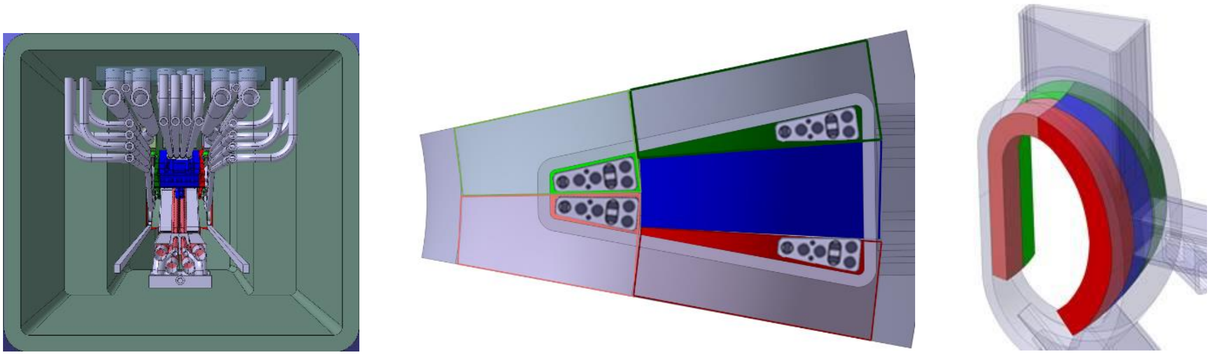

FIG. 4. *Access to the plasma facing components shown in green, red and blue. Left: the divertor cassettes through the lower port. Centre: the blanket segments through the upper port. Right the blanket segmentation.*

A maintenance-oriented strategy to reduce the number of maintenance systems that are required might be to combine maintenance corridors with plant service routing (see Fig. 5). The corridors transport components and equipment to and from the tokamak. The plant services include the primary heat transfer and cooling pipes for the in-vessel components, cryogenic pipes to the magnets and the electrical power and signal conduits. Transport and services tend to follow a similar layout with a ring main or corridor around the tokamak with radial feeds or corridors up to the shielding. All these systems can then be maintained or recovered using the same remote system, deployed along the transfer corridor. The remote system could be similar to that described in section 3.4.1 for the ex-vessel remote maintenance and active pipework could run be under removable shield plates.

The schematic in Fig. 5. shows how this might work for the lower port maintenance corridors (green) combined with the primary heat transfer (PHTS) services (blue), grouped together through hot-cells serving three lower ports.

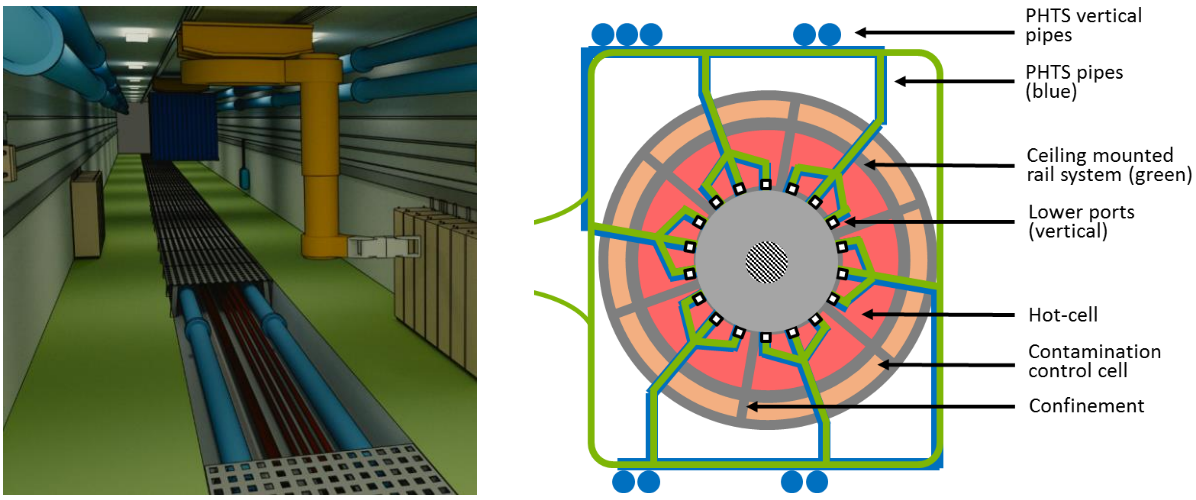

FIG. 5. *Maintenance corridor with manipulator and pipe ducts (left) and plan view of the lower port level maintenance corridors combined with the heat transfer system pipes (right).*

A maintenance-oriented strategy to maximise the speed of maintenance and ease of recovery would be to use a hot-cell above the tokamak through which components and equipment are transferred directly to the ports without the use of casks. This option would require contamination control systems such as air locks, decontamination and bagging but the surface area of the hot-cell exposed to contamination is not dissimilar to that for the casks assuming four sets of casks are used by four maintenance systems operating in parallel.

Maintenance duration calculations [2] suggest that the duration of a planned breeder blanket maintenance campaign with four maintenance systems operating in parallel would reduce from 206 days for a cask-based transfer system to 182 days for the hot-cell configuration. Calculations for the transfer volume required [3] suggest that the hot-cell arrangement uses just 37% of the space required by the cask system. There is also a potential significant cost saving through the elimination of casks because not only is there a cost associated with the manufacture of the casks, but also with their storage because they take up a large area in a nuclear building.

3.4. Design development process

The Maintenance Management Plan must define the design development process. As described above, it is necessary to understand the EU DEMO maintenance strategies and technologies at an early stage in order to inform the developing plant layout and component designs and thereby allow an efficient maintenance system to be integrated into the plant design, ensuring a feasible DEMO design.

However, this process requires the development of maintenance concepts before the tokamak layout has been defined and before the down-selection of component designs has occurred. To do this it is necessary to make assumptions beyond what has been accepted into the plant baseline design so that it is possible to outline maintenance solutions and evaluate the most favourable candidates. These assumptions need to be agreed with the stakeholders, in this case EUROfusion, to ensure that the work being conducted is appropriate and to ensure that the maintenance solutions being considered are flexible and applicable to the range of plant concepts currently under consideration.

This design development process requires care, both to ensure the value and applicability of the selected maintenance concepts, but also to ensure that it is widely understood that the goal of the work is not to develop the final maintenance system design but to provide an understanding of the strategies and technologies that are required for efficient maintenance in order to inform the developing design, even though the final component and maintenance system designs will be different to the assumptions used at this early stage.

3.4.1. Ex-vessel design development

During the ex-vessel plant definition, it is important to define standard maintenance tools and equipment to minimise the variation of systems across the plant. This approach reduces: development and testing, training and spares holding and improves reliability data acquisition and the benefits from lessons learned and performance improvements.

Many ex-vessel maintenance tasks require similar activities. Typical examples include the disconnection of electrical services, pipe connections and mechanical fixtures from large line replaceable units (LRUs) and the transfer of components to waste or to the maintenance facility.

Systems need to be defined for each plant area and should have as much commonality as possible across areas. All plant maintenance must be achievable using the defined system (see section 3.4.4).

A suitable system for ex-vessel maintenance might be comprised of a crane for heavy lifting supported by a tool deployment system, capable of reacting horizontal loads, such as a boom mounted on a mast. Such a system was developed for maintenance in the JET tokamak ex-vessel areas. The JET deployment system is called TARM (Fig. 6). It has recently been refurbished and is available at the RACE facility for testing of maintenance operations, tools and control systems. A range of end-effectors can be mounted to the end of the boom, for instance a dexterous manipulator that can be used for operations such as service connection or for the deployment of lighter equipment such as cutting and welding tools. In the case of the TARM, the Mascot manipulator is deployed (Fig. 6), which includes a 100kg winch.

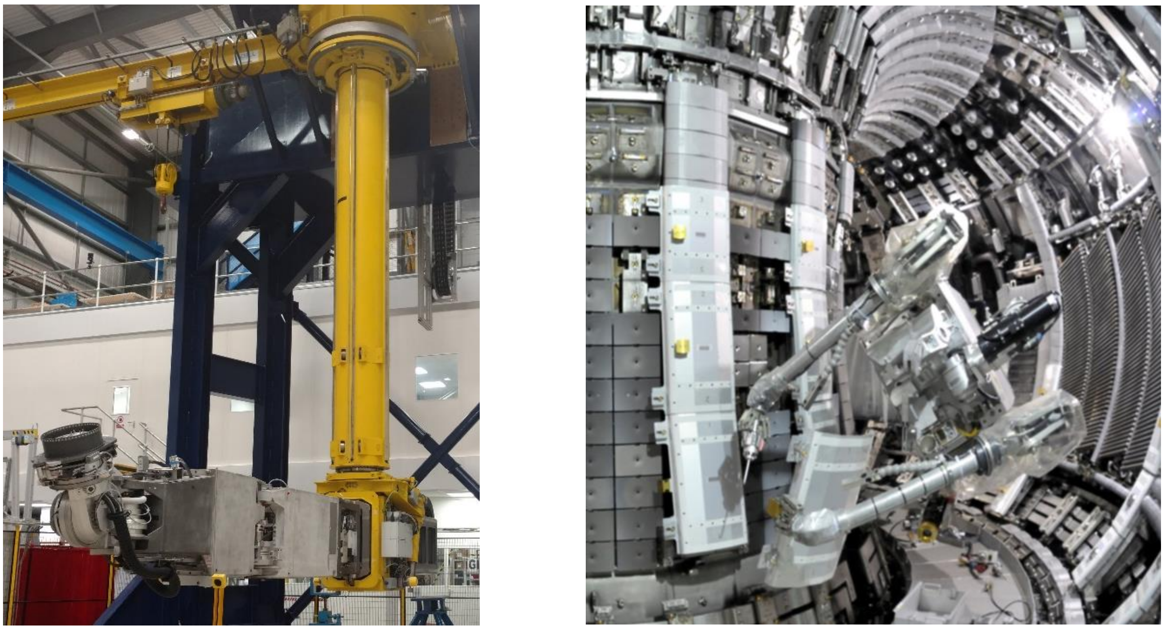

FIG. 6. *The TARM deployment system (left) and the Mascot Manipulator (right)*

3.4.2. Extent of remote maintenance operations

Flexible and dexterous maintenance systems such as the one described above are suited for use on plant which is also maintainable by people. Much of the plant and equipment is too heavy to be handled directly by people so additional requirements to enable remote maintenance are limited to handling features, retained fixings and additional viewing.

This is an important consideration because there are many factors that will drive most operations to be performed remotely, even where it is possible to send in people. These factors include safety risks from radiation and contamination, particularly to meet the ALARP principle, and the limit imposed by the plant annual integrated dose budget. It is also important to include the significant industrial hazards also present for a fusion power plant: high payloads, confined spaces, working at height, magnetic fields, high voltage, high temperatures, cryogenic systems and toxic substances. These factors will increase the extent and usage of remote systems for suitable tasks in order to reduce the nuclear and industrial risk to the DEMO workforce.

3.4.3. Technical risk

A rigorous Systems Engineering approach must be applied to the design of a fusion power plant because it is a highly complex system with many functions and subsystems, often with conflicting requirements that must be balanced to achieve a viable solution. This approach also examines the technical risks and sets mitigation actions to reduce each risk as the design develops.

These risks are held by the stakeholders so before a design can be accepted at design review, the stakeholders must agree that the existing level of risk and the forecast mitigation are acceptable.

The risk mitigation actions are important to the Maintenance Management Plan because many of the actions are to develop and demonstrate technologies that are required for the proposed maintenance strategies. Where the threats become issues, it may be necessary to change the maintenance strategy with potentially significant impact on the plant design.

The highest technical risks for the EU DEMO maintenance have been established for several years [4] and are associated with: the physical handling of large masses through the limited space available in the ports, including the risk of dropped loads [5, 6]; the accurate position control of the large, flexible masses; and the reliable cutting and welding of pipes using tools deployed down the bore of the pipe.

Design development in these areas is being undertaken as part of the technical risk mitigation to demonstrate the feasibility of proposals in each of these technical risk areas. Progress in reducing the risks is monitored as the design develops and the residual risks must be acceptable to stakeholders or alternative solutions must be sought.

Recently the blanket transporter has been through a design review. The residual technical risks remain high [7, 8] and the stakeholders are not happy with the potential associated cost. This is driving consideration of alternative lower risk options with reduced component mass and increased port size. The cost of implementing alternative options at this pre-concept stage of the design process is many times lower than during the engineering design phase.

3.4.4. Plant design development process

Maintenance considerations are required during the plant design process to ensure a balance between plant performance and maintenance requirements. Where the plant maintenance may be remote it should follow the Maintenance Manual and associated guidance to achieve the standardisation required and to follow remote handling best practice. It is not possible to capture everything in the manual and guidance, so the involvement of remote handing engineers is necessary, particularly at design reviews.

The Maintenance Management Plan should define how this process is best achieved and this should be reviewed and agreed by the stakeholders and implemented by the integration teams to maximise standardisation and minimise the maintenance burden.

3.4.5. Classification of maintenance operations

It is useful to classify maintenance operations to give guidance and consistency to the performance of the maintenance systems. In ITER the remote maintenance class is allocated to components based on the frequency of maintenance but in DEMO it may be more appropriate to allocate the classification to procedures based their impact, which is a combination of frequency and consequence of failure. Consequence is a function of the complexity of the operation, the inherent risks and the detriment to plant operation.

One component could have several maintenance operations, with different classifications for the different maintenance tasks. A single maintenance task could have more than one classification depending on whether it is planned during a maintenance period or it is required due to a failure that is preventing plant operation.

For some of the ex-vessel maintenance tasks, particularly those further away from the tokamak, the same maintenance task could be conducted either manually or remotely, depending on the safety risks to personnel (see section 3.4.2) and the requirements for reduced duration or cost. For example, the scheduled replacement of a pump might be done remotely during an off-line maintenance period or if there is sufficient redundancy because this will help to reduce the risk to operators and help to preserve the plant integrated dose budget. However, if the pump were to fail and it was the only reason the plant cannot operate, the additional risk and additional integrated plant dose might be justifiable.

4. CONTENT OF THE PLAN BEYOND CONCEPT DESIGN

This section provides a brief overview of the later stage of the DEMO Maintenance Management Plan, as context for the content described above. It is not covered in any further detail by this paper because although it contains many interesting and important elements, it is similar in form and function to other fusion plants and indeed other industrial plants and this is well covered by existing documents and standards. [9, 10, 11].

The Maintenance Management Plan will ultimately:

- Ensure that adequate arrangements are in place and are implemented for the regular and systematic examination, inspection, maintenance and testing of all plant systems, with emphasis on those which may affect nuclear safety. It further aspires to safeguard and reduce risk of non-compliance with IAEA guidelines on the site licence process [9].
- Provide a guide to maintenance strategy, techniques, processes and procedures to be employed on DEMO for use by all staff with asset management and maintenance responsibilities to enable them to assess the level of maintenance to be applied to a piece of plant or equipment based on the facility needs, safety requirements

and operation demands. It will also enable them to generate the Plant Maintenance Schedules (PMS) and Examination, Maintenance, Inspection and Testing (EMIT) documents.

— Define the EU DEMO maintenance strategy in terms of preventative and corrective maintenance based on the data provided by reliability centred maintenance assessments [10] including: RAMI, lifetime costs, ALARP and licensing requirements, waste management and socioeconomic considerations. The socioeconomic considerations include the impact of the plant on the local economy and infrastructure and the supply of SQEP personnel to meet the fluctuating operation and maintenance of the plant.

5. CONCLUSION

A well developed and implemented Maintenance Management Plan will allow a fresh view of the maintenance solutions, helping to challenge the use of conventional methods where appropriate. This is of most value early in the design cycle to minimise the impact of implementing unfeasible solutions [12]. It would be very costly to develop the facility design, and to fix the spatial constraints, without having thoroughly considered the critical plant maintenance activities, particularly those related to plant safety.

ACKNOWLEDGMENTS

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