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Parametric modelling of EU-DEMO remote maintenance strategies and concepts

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ABSTRACT

One of the major challenges in the commercialisation of fusion is maintaining the powerplant reactor in a sufficiently short period of time to achieve commercial levels of plant availability. To inform the development of an appropriate remote maintenance strategy for EU-DEMO, a simplified, parametric model, called the Maintenance Duration Estimator (MDE) has been created to model potential remote maintenance strategies for the in-vessel Components. This tool will inform the development of practical and efficient remote maintenance technologies and methodologies for EU-DEMO. Using the MDE model, it has been estimated that EU-DEMO will be able to achieve the required minimum 30% lifetime plant availability over a 20 year operational lifetime. Here we will present the structure and functionality of the MDE, as well as some case studies of analysis performed.

1. Introduction

As a technology DEMOnstrator, economic factors won't be the major driving factor for the design and operation of EU-DEMO systems and procedures. However, any fusion power plant based on the DEMO design will have a strong economic motivation to complete maintenance in an efficient and timely manner. For the purpose of designing and evaluating remote maintenance systems, there is a requirement on the remote maintenance systems to complete any maintenance operations within a predefined period of time [1].

For a planned maintenance campaign, the current requirement is that an in-vessel maintenance campaign last no longer than 250 days. Of these 250 days, 30 days are assumed to be allocated for a cooldown period, to enable short lived radionuclides to decay away and the structure of the vacuum vessel to cool to a safe temperature. The final 30 days of a maintenance campaign are assumed to be for vacuum pump down and conditioning operations. This leaves a maximum of 190 days to complete all in-vessel maintenance operations, including the installation of new breeder blankets and divertors. The MDE was used to estimate whether the current maintenance strategy and tooling concepts are able to meet this challenging requirement.

Unplanned maintenance, due to hardware or process failures during a planned outage, or due to the failure of power plant hardware during power generation will also impact the availability of EU-DEMO. This work includes an attempt to investigate the potential impact of failures of remote maintenance equipment on the critical path of EU-DEMO maintenance. Due to the current design and reliability information available about the EU-DEMO power plant systems, it was not possible to estimate the impact of EU-DEMO plant failures.

2. Structure of the MDE model

The MDE was created using Microsoft Excel®, as this is a well understood program and enabled to MDE to be shared and modified easily and without the need for specialized or expensive modelling software.

2.1. Model components

In order to create the maintenance model, the following aspects of a maintenance campaign were defined in the MDE:

- The critical path of in-vessel maintenance activities, based on the current in-vessel layout.
- The simplified logistical activities required to support the in-vessel maintenance activities (delivery to RM tooling, collection of removed items of in-vessel hardware, etc).
- The time taken to perform specific in-vessel maintenance activities, informed by the current RM tooling concepts and operational experience gained maintaining the JET reactor.

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In addition to these, the following other durations were simulated:

- The recovery activities to recovery from a simulated failure of a specific piece of RM tooling.
- The time taken to recovery from a non-compliant weld on the blanket pipework.

2.2. Assumptions

Due to the early stage of the EU-DEMO design process, it was necessary to make a number of assumptions about the location and maintenance requirements of various pieces of in-vessel hardware [2]. The duration of specific in-vessel and ex-vessel maintenance operations have also had to be estimated, using operational experienced

The assumptions are reassessed on a regular schedule to ensure that they are still relevant and valid.

3. Maintenance scenarios investigated

Using the MDE, several different maintenance scenarios were investigated to inform the development of various RM systems and strategies.

3.1. Duration of various in-vessel maintenance campaigns

3.1.1. Duration of planned breeder blanket maintenance campaigns

Using the MDE it was estimated that replacing all of the installed breeder blanket segments would take between 825 and 155 days, depending on the number of ports being maintained in parallel. This means that it is necessary to operate a minimum of four RM systems simultaneously, assuming a hot cell based maintenance strategy, and 6 RM systems if using a cask based RM system, to meet the required 190 day target duration.

The use of maintenance casks increases the duration of breeder blanket maintenance by an average of ˜13%. This is due to the additional logistical operations and enabling activities required to support the deployment and operation of contamination control casks.

3.1.2. Duration of planned divertor cassette maintenance

For divertor cassette maintenance, the duration of in-vessel maintenance is approximately half to duration of a blanket maintenance campaign. This is due to the smaller number of pieces of in-vessel hardware, and the simplified layout of in-vessel pipework reducing the number and duration of in-vessel maintenance activities.

Use of casks adds ˜20% to the total duration of the maintenance campaign, requiring that a minimum of three casks to be operated in parallel to achieve the required maintenance duration. A hot cell based maintenance system also requires a smaller number of RM systems to complete a maintenance campaign within the target duration of 192 days (Table 1).

3.1.3. Duration of un-planned recovery operations

In the event of an unrecoverable failure of a piece of in-plant hardware, the failed item of in-vessel hardware would need to be removed from the port and replaced before EU-DEMO could return to an operational state. In this scenario, only a single sector of EU-DEMO would need undergo in-vessel maintenance. In this scenario, it has been assumed that there is not a defined allowable duration for this recovery maintenance (Figs. 1 and 2).

Table 1
Duration of a single sector maintenance campaign.

EU-DEMO Port	Cask Maintenance (days)	Hot Cell maintenance (days)
Upper port	45	39
Lower Port	25	21

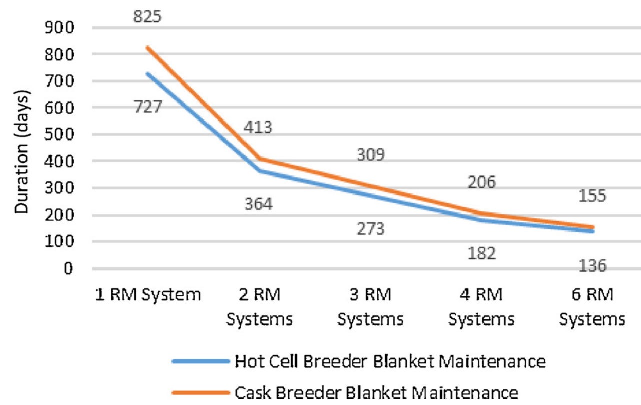

Fig. 1. Estimated duration of breeder blanket maintenance, in days.

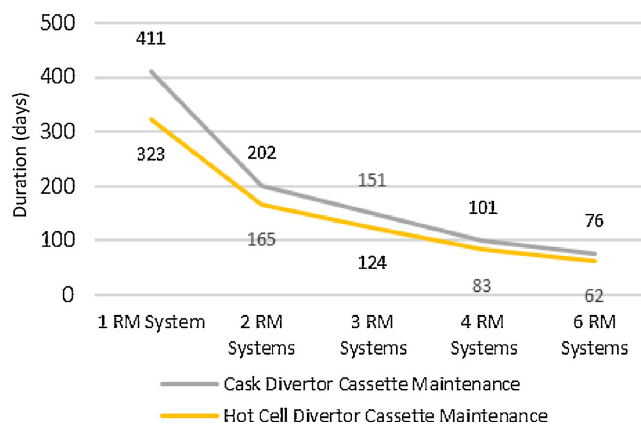

Fig. 2. Estimated duration of divertor cassette maintenance, in days.

3.2. Impact of the double null on maintenance durations

As part of a wider assessment of the 2016 Double Null configuration of EU-DEMO [3], the modified maintenance campaign was modelled in the MDE to assess the impact of the design changes required to enable the installation and maintenance of the upper divertor, shown in Fig. 3.

Four different configurations of the double null concept have been developed, but out of these only the two edge cases in terms of

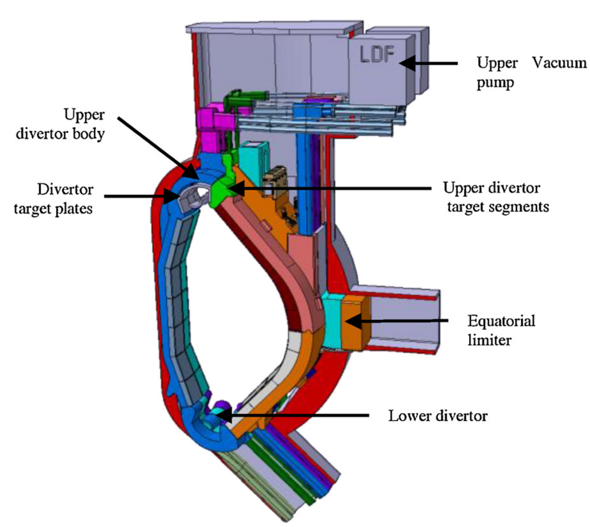

Fig. 3. 2016 Double Null configuration assessed as part of the 2017 study [3].

Table 2
Description of the two different assessed double null concepts.

Design Factor	1A	2B
Equatorial blanket segmentation	Central outboard blanket only	Full outboard blanket segmentation
Divertor target plates	None	Additional divertor armor
Radial Blanket segmentation	Radial segmentation	Radial segmentation

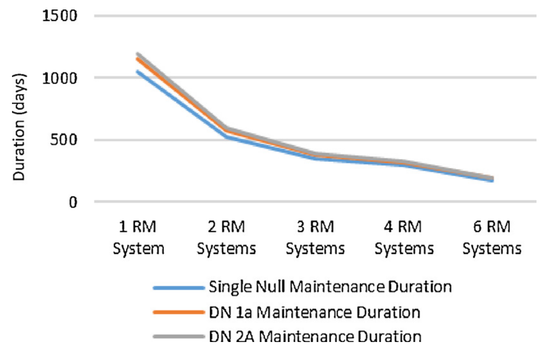

Fig. 4. Estimated duration of maintenance operations for the double null concepts.

maintenance complexity, 1A and 2B (described in Table 2), were modelled in the MDE.

When compared to the single null baseline configuration of EU-DEMO, the double null adds a maximum of 13% to the duration of a maintenance campaign, in the case of the 2B configuration, and 9% in the case of the 1A configuration (Figs. 4 and 5).

These durations are based on very early design information, and will need to be updated as more detailed design information becomes available. In future work, the maintenance model will need to be updated as the Double Null concept matures, to enable comparative analysis of the single null and double null maintenance concepts (Table 3).

3.2.1. Assessment of the impact of pipe cutting and welding activities and technologies

Currently it has been assumed that it will be necessary to use welded pipe connections for all in-vessel components, due to the levels of neutron bombardment and material degradation expected close to the plasma. As part of the development of a suitable pipe cutting and welding tool, laser cutting and welding technologies were compared to current mechanical pipe cutting and in-bore TIG welding systems, and their impact on the estimated maintenance durations were assessed.

Using the MDE, it has been estimated that using a laser based pipe cutting system saves approximately 400 h, while a laser based welding system only saves ˜27 h. The limited impact is due to the current

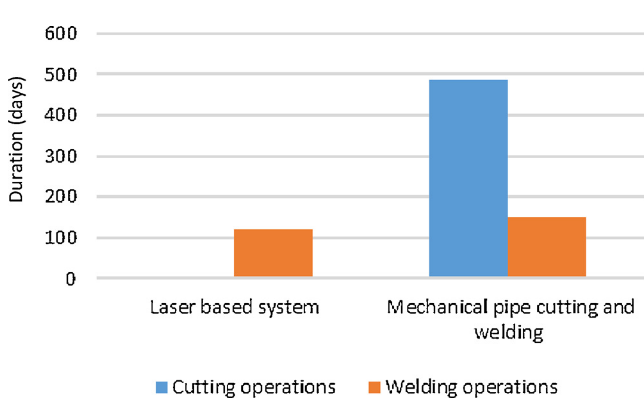

Fig. 5. Duration of pipe cutting and welding operations, comparing laser and mechanical technologies.

Table 3
Proposed classes of EU-DEMO maintenance campaigns.

Type of maintenance outage	Scheduled Frequency		Duration (days)
	Full Power Years (FPY)	Calendar years	
Short Term	0.02	0.04 (12 days)	4
Minor	0.49	1.05	64
Major	1.58	3.7	192

requirement for post weld heat treatment on all pipe connections, which is the factor contributing.

As the concepts for both mechanical pipe cutting and welding systems become more mature, this assessment will be updated to help inform the concept development and technology down-selection process.

3.2.2. Impact of planned ex-vessel maintenance campaigns on EU-DEMO's lifetime availability

In power stations, there is a strong economic motivation to reduce the duration of power plant outages, as this reduces the power plant availability and reduces the lifetime revenue for a commercial power plant. The MDE was used to model DEMO's operational lifetime for 20 calendar years, to investigate the impact of the various maintenance campaigns on the lifetime power plant availability.

The Operational Concept Document for DEMO [4] describes the proposed maintenance schedule for the EU-DEMO, and describes three different types of scheduled maintenance campaign:

The short term maintenance campaign is scheduled to occur after 12 days of DEMO power plant operations, and would be to perform very rapid maintenance of power plant hardware outside of the DEMO bioshield. Minor maintenance campaigns will occur annually and enable more comprehensive maintenance and inspection of plant hardware and equipment, but it is currently assumed that no maintenance activities will occur within the bioshield.

There is very little information about the frequency and timing of maintenance and inspection operations while will occur during these maintenance outages. Currently it is assumed that all in-vessel maintenance activities, including the replacement of breeder blankets and divertor cassettes, will occur during the Major maintenance outages, which are scheduled for after ˜3.7 calendar years, or 1.58 years of continuous plasma pulsing (1.58 Full Power Years). It is these maintenance campaigns which have been modelled in the MDE.

As shown in Fig. 6, maintenance activities, including the vacuum pumping operations necessary to enable in-vessel maintenance, account for between 12–29% of DEMO's lifetime. Increasing the number of RM systems operating in parallel reduces the total maintenance duration and therefore increases the power plant's availability.

When assessing the impact of the different ex-vessel maintenance operations, the short term maintenance campaigns account for 18–20% of the assumed 20 year lifetime, while minor maintenance campaigns account for 8–10% of EU-DEMO's assumed 20 year lifetime. Significant portions of DEMO's lifetime has been allocated for regular, preventative maintenance campaigns, and this has restricted the lifetime plant availability.

To mitigate this issue, the design of ex-vessel power plant hardware

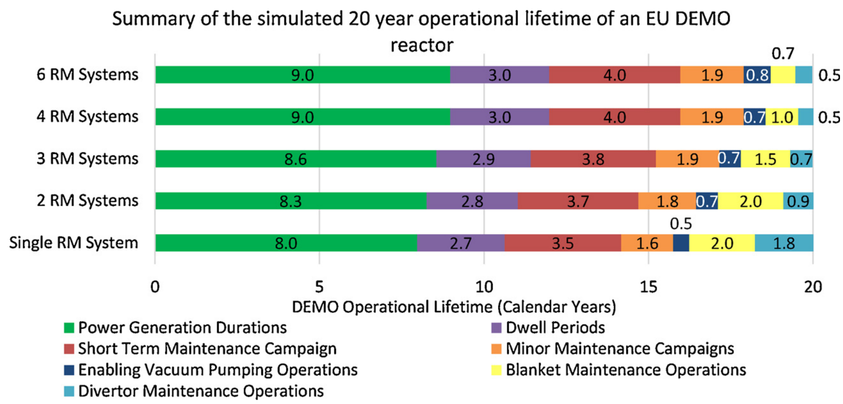

Fig. 6. Breakdown of the DEMO's simulated lifetime, assuming a Hot cell based RM system.

and systems should be designed in such a way to simply inspection and maintenance activities, as well as maximizing the time between planned maintenance outages as much as possible, as this will increase DEMO's the total time spent generating power, and therefore the commercial viability of fusion as a viable energy source.

4. Conclusion

As an example of a commercial nuclear power station, EU-DEMO needs to minimize the reactor downtime, to maximize the potential revenue of a power station and to minimize the potential risk to plant personnel during maintenance operations. The MDE was created to enable a simplified comparative analysis of various DEMO maintenance strategies and configurations, and has provided insight into the impact of parallelization of in-vessel maintenance, has assisted with assessment of various pipe cutting and welding operations.

The MDE model has also reiterated the need to engage with EU-DEMO system designers wherever possible to ensure that all power plant systems are designed to simplify the maintenance operations and ensure that, where necessary, any maintenance operations requiring remote intervention are suitably well defined and understood to allow suitable remote maintenance tooling and procedures to be developed to minimize plant downtime.

Acknowledgement

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