Analysis of Existing and Proposed Maintenance Deployment Systems Toward DEMO MPD Development

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***Abstract*— This article reports on a study of previously existing or proposed maintenance deployment systems with similar functions and structure to that of the proposed multipurpose deployer (MPD) for demonstration (DEMO fusion power plant project). The current MPD design iteration consists of a boom deployment system that is ∼30 m long and can support a payload of ∼1000 kg, while still being able to access the DEMO vacuum vessel through a 2.78 m high by 1.08 m wide port. The purpose of this work is to benefit from previous experience by comparing the mechanical attributes and performance of systems as well as their advantages and disadvantages and any issues encountered to bring design input to MPD design development. The following systems were investigated: Joint European Torus (JET) in-vessel remote handling booms, telescopic articulated remote mast (TARM), Next European Torus (NET) experimental device for in-torus handling (EDITH), Tokamak Fusion Test Reactor (TFTR) Maintenance Manipulator, and Snake-like Robot Arms in Nuclear Environments. Systems that are currently in development for ITER and Chinese Fusion Engineering Test Reactor (CFETR) were also investigated according to their latest available design iterations. This article concludes that these systems, comprising of articulating links to form long-reach slender structures, give rise to challenges with their payload, stiffness, and control. The straight boom style system would be the most suitable design for the current tasks that a DEMO MPD is expected to perform. However, there is no particularly strong candidate without first fully defining the requirements and constraints that a DEMO MPD must adhere to.**

***Index Terms*— Fusion power generation, fusion reactor maintenance, high payload robotics, nuclear fusion, nuclear robotics, remote handling, remote maintenance, tokamaks.**

I. INTRODUCTION

THE demonstration (DEMO) fusion power plant project is a collaboration between 35 nations led by EUROfusion that will bridge the gap between science-driven, laboratory-based nuclear fusion experiments to industry-and-technology-driven energy production. To do this, it requires reliable maintenance systems to ensure that its operations remain competitive within the energy production market. Within the DEMO plasma vessel, there will be extremely high-radiation dose rates that are estimated to be around 2000 Gy/hr [1] after a four-week cool-down period; up to four times, the level anticipated for ITER after a similar period [2].

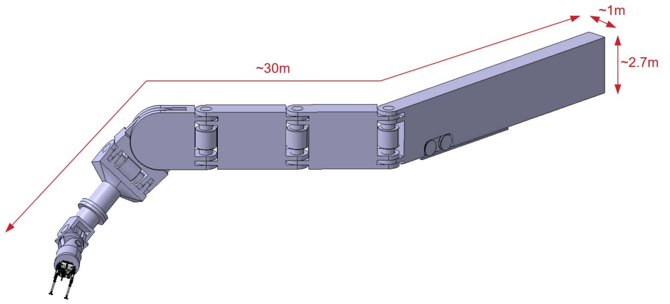

Fig. 1. Current DEMO MPD design iteration of boom-type deployer with fixed link and roller port connection. “MAnipalatore Servo COntrollato Transistosissato (Transistorised Servo Controlled Manipulator) (MASCOT)” shown as placeholder end-effector.

The multipurpose deployer (MPD) is a proposed concept as part of the in-vessel maintenance system that will perform a variety of essential activities, such as inspection, measurements, small maintenance, dust monitoring, and removal and rescue operations, with other optional functions possibly becoming mandatory in the future. These activities are similar to those required of the ITER MPD.

The current design (shown in Fig. 1) consists of a fixed first link with a roller port-support connection to provide additional point-of contact support, followed by a series of articulated links with yaw joints to maneuver the structure along the toroidal path. This design has a target payload of 1000 kg with the joints bringing up to nine degrees of freedom (DOFs) in total. Final end-effector positioning is done by further pitch, yaw, and roll joints to ensure that every point of the inner vessel is accessible. Within this design, gravitational loads do not act against most of the supporting joints. The purpose of this work is to benefit from experience by comparing previous maintenance deployment systems and ones currently in development as well as their advantages and disadvantages to bring input to MPD design development.

II. PREVIOUSLY EXISTING DEPLOYER SYSTEMS

A. JET Remote Handling Boom

The Joint European Torus (JET) is a tokamak fusion experiment that is currently the only functioning tokamak in the

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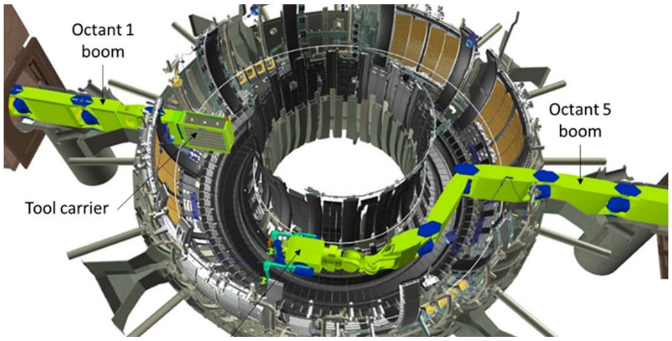

Fig. 2. Simulation of JET booms performing maintenance activities within a cross section of in-vessel JET.

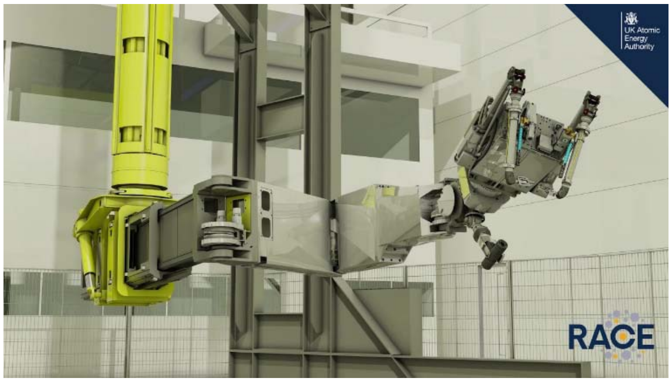

Fig. 3. Render of TARM supporting "MASCOT" end-effector.

world capable of deuterium–tritium fusion experiments [3], being in operation since the 1980s. It is located in the Culham Centre for Fusion Energy (CCFE) and operated by the UK Atomic Energy Authority (UKAEA). JET is currently fitted out with an "ITER-like" inner wall that consists of many components containing Beryllium, which is toxic to humans making the environment hazardous even without the introduction of activated materials.

Remote handling was developed for JET in anticipation of high radiation levels during fusion experimentation, with the boom systems developed in 1984 to be utilized as a basis for remote handling in subsequent systems. Since then, there has been more than 50 000 h of remote operations experience using the booms as a deployment system. This system now consists of carriage-on-rail insertion of boom-type deployers into vessel, as shown in Fig. 2. The structure of these deployers mostly consists of articulated links with yaw joints followed by final positioning joints for end-effectors. Each of the full assemblies of these booms has eight DOFs with each arm of the "MASCOT" servo-manipulator end-effector adding a further six DOFs [4]. There was an emphasis on maintainability and recoverability of the system from in-vessel due to the unpredictable nature of systems containing electronics in radiation environments.

B. Joint European Torus Telescopic Articulated Remote Mast

The telescopic articulated remote mast (TARM) was developed to support ex-vessel maintenance of JET, originally deployed from a large gantry crane in the JET containment hall. However, it was never utilized for this purpose due to lower-than-expected radiation levels in the hall. The primary joint structure consists of a supporting vertical "mast" that can rotate around the central axis of its body and provide linear translational vertical movement. This then supports a boom-type deployer "arm" similar in structure to the JET booms. This boom-arm is connected to the mast by a horizontal telescopic joint that may extend and retract the remaining rotational joints that support an end-effector, as shown in Fig. 3. This system positions the end-effector with nine DOFs. Now, the TARM is being used by Remote Applications in Challenging Environments (RACE) as a test rig for various systems such as JET boom components and an adaptive position controller for DEMO remote maintenance systems.

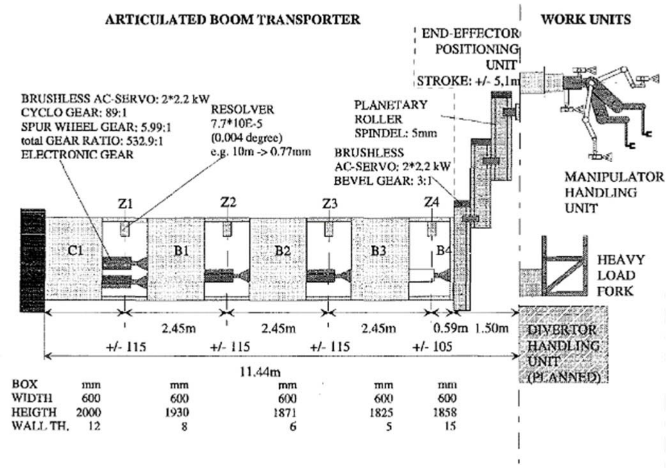

Fig. 4. EDITH system components.

C. Next European Torus Experimental Device for In-Torus Handling

The experimental device for in-torus handling (EDITH) was in development in the 1990s as a maintenance deployment system that would support maintenance on the since-shelved Next European Torus (NET) project. This project consisted of a double-null tokamak that was to be the successor to JET. There was a full prototype built that consisted of a boom-type deployer with a further end-effector positioning unit that was similar to a fork-lift mechanism that provided translational vertical movement in order to handle divertors in the top of the vessel as well as possibly the bottom of the vessel. The full structure of the system is shown in Fig. 4. It was also to be used for other more precise maintenance and inspection tasks. This system could provide six DOFs and up to 1-ton payload capacity for an end-effector [5].

D. TFTR Maintenance Manipulator

The Tokamak Fusion Test Reactor (TFTR) was developed by the Princeton Plasma Physics Laboratory in the 1980s as the U.S. flagship fusion device. Its target was to achieve the fusion "breakeven" value of $Q = 1$ input–output power ratio using a deuterium/tritium fuel mix, to then be used as a design basis for successive reactors. It unfortunately never reached

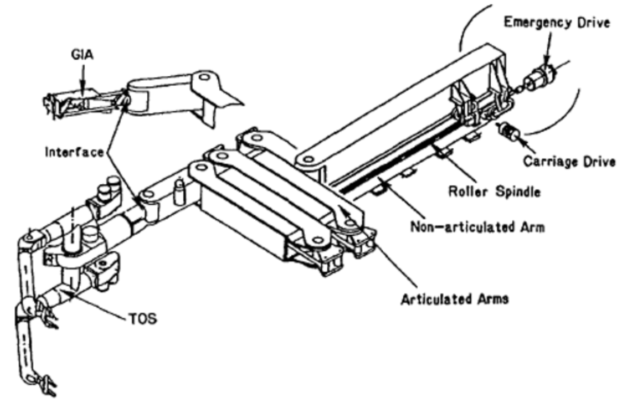

Fig. 5. TFTR maintenance manipulator in folded configuration.

this value but continued to be used for experiments until the late 1990s [6]. The maintenance manipulator was developed by Kern-Forschungzentrum Karlsruhe, a predecessor to the Karlsruhe Institute of Technology. This boom-type deployer differed from the previous systems in that it could be deployed in vacuum conditions with temperatures up to 150 °C. This boom structure also contained yaw joints that had their axes of rotation offset from the centrelines of the links bodies in an alternating fashion in order to allow the links to fold in on themselves in the horizontal plane. This folded configuration is shown in Fig. 5. The yaw joints of the systems also differed in that they were driven by linear acting drive units contained within the length of the link bodies. This system provided eight DOF, but most of these were acting in the horizontal plane.

E. Snake-Like Deployers

The snake-like deployers typically consist of motor-tendon and/or pulley-tendon driven systems through rigid links. This reduces the amount of radiation-sensitive electronics required in the highest radiation environments and eliminates the need for volume and weight constraining gear systems. The main systems looked at were.

1) The Super Dragon, developed for high- and long-reach inspection in Fukushima Daiichi [7].
2) The articulated inspection arm (AIA), used for inspection in the Tungsten (chemical symbol “W”) Environment in Steady-state Tokamak (WEST), formerly known as Tore Supra, shown in Fig. 6 [8].
3) Articulated maintenance arm (AMA), that could be used for inspection and small maintenance activities in the Experimental Advanced Superconducting Tokamak (EAST) [9].

The slender and lightweight design of these systems means that they had a low payload capacity and also positioning issues due to cable stretching and possible high torques on motors in some configurations.

Fig. 6. WEST AIA in mock-up test.

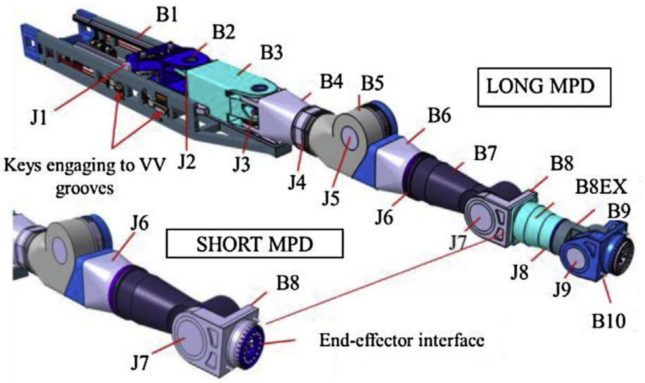

Fig. 7. ITER MPD long and short configuration joints (J indicates a joint and B indicates a structural body).

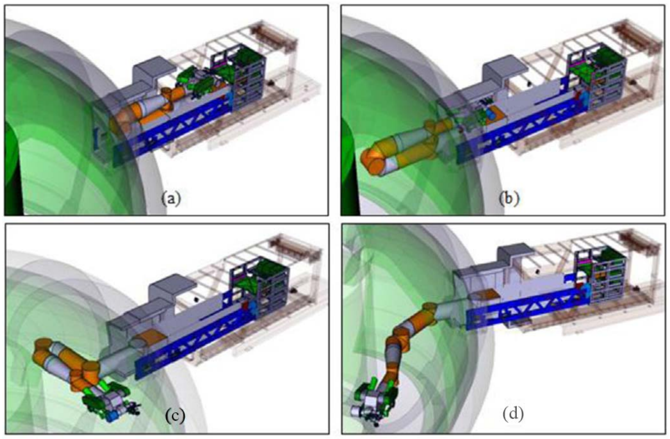

Fig. 8. Initial and final steps of ITER MPD deploying into vessel. (a) Folded system about to enter vessel. (b) System “elbow” deployed into vessel. (c) Final system folded configuration. (d) System fully deployed around torus.

III. PROSPECTIVE DEPLOYER SYSTEMS

A. ITER Multipurpose Deployer

The ITER tokamak reactor currently being built in Saint-Paul-lès-Durance will perform fusion experiments and prove the feasibility of fusion reactors with a target Q value of 10 [10]. Due to the high amounts of neutron radiation produced from the fusion reactions, many of the plasma facing components will become activated and will subsequently give off high levels of gamma radiation. This radiation is expected to give a high dose rate of up to 500 Gy/hr after a four-week cool-down period to any structure entering the vacuum vessel, which could be hugely detrimental to any electronic or polymer components.

The current ITER MPD design structure consists of a wide variety of rotational joint types after fewer initial planar joints. The ITER MPD will be used for unplanned maintenance and inspection activities within the ITER vessel. For the

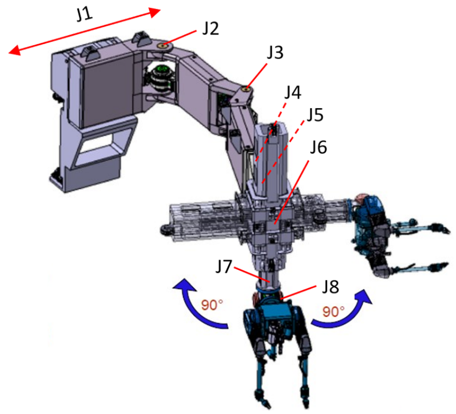

Fig. 9. ITER BLT joint structure.

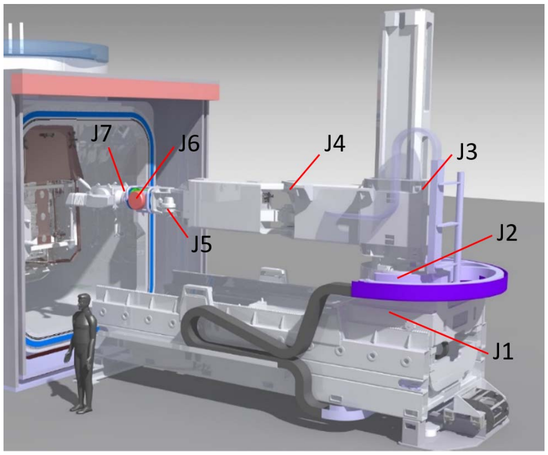

Fig. 10. ITER BSRHE joint structure.

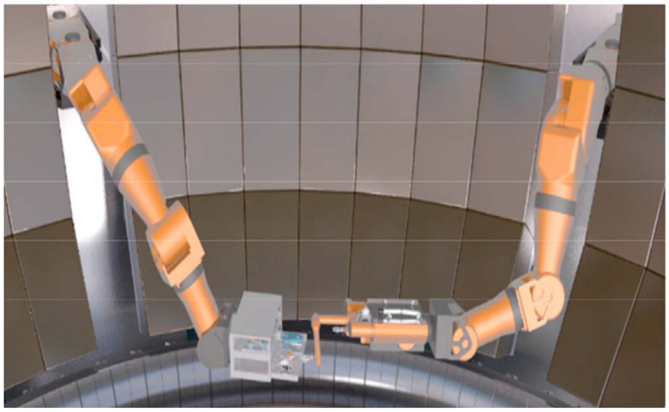

Fig. 11. Dual collaborative CMOR system deployed with manipulator and support system.

purposes of this report, its structure will be referred to as an "anaconda-type" deployer that can fold itself along the vertical plane. It does this in order to stow itself into a transport cask that is restricted in size due to building facility constraints. It deploys "elbow first" from the cask into the vessel and then uses the series of alternating rotational joints to "unfold" itself in-vessel.

The main design of the ITER MPD (shown in Figs. 7 and 8) has an estimated 2-ton payload, but an alternate "heavy" design has been proposed that is suggested to support up to a 5.8-ton payload [11], but this configuration requires access from two equatorial ports. The full extended configuration of the main ITER MPD design provides up to nine DOFs.

B. ITER Ex-Vessel Systems

ITER also utilizes boom-type deployers in ex-vessel maintenance, such as the systems used in the neutral beam cell. The main structures of these systems are referred to as the beam line transporter (BLT) and the beam source remote handling equipment (BSRHE). These systems also consist of offset-alternating yaw joints that allow the systems to fold in on themselves in order to reduce stowed volume.

The BLT, shown in Fig. 9 [12], has eight DOFs, including a telescopic joint that provides lowering vertical movement to the end-effector. It is initially supported by a linear translational joint that may travel the neutral beam cell radially toward the tokamak.

The BSRHE, shown in Fig. 10, is similar in structure to the BLT. The supporting base structure of the system also acts as a carriage on rail, labeled as J1, that allows for linear insertion of the system into a neutral beam injector.

The neutral beam cell has a significantly lower dose rate of 1 Gy/hr when compared to the ITER vessel, but this is not a negligible value as it still rules out human access to the cell as the radiation would have deterministic effects on any personnel present within minutes.

C. Chinese Fusion Engineering Test Reactor Multipurpose Deployer and CMOR

The Chinese Fusion Engineering Test Reactor (CFETR) is a project that will have a DEMO-like tokamak similar in scale to ITER and expects to produce similar dose rates to ITER of around 500 Gy/hr during its planned maintenance period. This reactor also had an MPD design, which has changed design slightly in recent years and was re-envisioned as the CFETR multipurpose overload robot, or CMOR, shown in Fig. 11 [13]. The structure of this system takes the form of an "anaconda style" deployer similar to the ITER MPD and again deploys "elbow first" into the vessel even without the limiting factor of predetermined building facility constraints.

In contrast to previous systems, CMOR is integral to planned maintenance operations and procedures and would be expected to be in the vessel for prolonged periods of time, likely to receive large doses of radiation in its operational lifetime. The structure of joints and drive units with large planetary gearing within this system may cause cabling being routed through the structure of the deployer to be mechanically constrained as well as added constraints to access of the joints and drive units for recovery and maintenance purposes. The proposed design for CMOR is expected to give nine DOFs with an expected 2000-kg payload capacity.

IV. SYSTEM COMPARISONS

The current DEMO MPD design is based on the straight planar boom-type deployer, which provides the controllability of an inherent robust mechanical load path as shown in many of the previously built systems. Upcoming designs appear

TABLE I
DEPLOYER STYLE COMPARISON TABLE

Deployer Type	"Straight" Boom	"Alternating" Boom	Snake	Anaconda
Payload	3	3	1	2
Stiffness	3	3	1	3
Controllability	3	2	1	1
Volume	1	2	2	3
Port Deployement	3	1	3	2
Storage Transfer	1	2	3	2
Maintenance Ease	3	2	2	1
Recoverability	3	2	1	1
Total	**20**	**17**	**14**	**15**

to favor the anaconda style configuration, and although this design may reduce the stowed volume of the system, it then increases the complexity of the vessel deployment procedure and increases the difficulty of maintenance and recovery of the system, especially considering that these systems are expected to be in use over several decades. These systems would also have significantly lower possible total lengths and payloads when compared to boom systems. This is due to the anaconda style systems only being able to utilize roughly half of the port height within their structural height due to deploying in a folded configuration. The offset-alternating joint booms may be another solution to reduce stowed volume and limit transporting to vessel issues, but deployment into vessel would have to be carefully monitored due to the tight tolerances encountered when passing through the equatorial port.

The different criteria for determining the optimal suitability for a system have been derived from the DEMO MPD requirements. These criteria (shown in Table I) are: payload, stiffness, controllability, stowed volume, port deployment, storage transfer, maintenance ease, recoverability, and reliability. Due to the limited data available (both calculated and empirical) for some of the systems looked at, the scoring for these categories is generalized and relative for each system. This is done on a scale of 1–3, with 3 being the best performance within a specific category and 1 being the poorest performance.

Due to current conceptual design phase of DEMO and therefore the DEMO MPD, the current system requirements have few specific technical values to adhere to such as stowed volume and other geometric constraints. This makes it difficult to apply weighting to the specified categories or rule out any design in favor of another due to noncompliance of certain necessary requirements. Some top-level comparisons could also be made between the systems and related back to the stated required tasks for the DEMO MPD. The tasks of inspection, measurements, and dust monitoring have been shown to be performed by all existing systems, with the prospective systems being designed to be also as capable for such. The other required tasks of small maintenance and removal/rescue operations require systems with sufficient payload, accuracy, and repeatability. The snake-like deployment systems above would not be likely to achieve these tasks. Although the straight boom systems tend to be the most favorable of the systems in terms of performance, the required space needed to accommodate them would need to be carefully and specifically integrated into the surrounding plants and systems with consideration that this may not be feasible, as is believed to have been the case with the ITER MPD which led to the development of the anaconda style design.

Another factor used to compare these systems would be their technology readiness levels (TRLs) [14]. From a mechanical perspective in their own relevant requirements, "straight" booms, "alternating" booms, and snake-like deployment systems have all been shown to be successfully deployed within nuclear environment applications. From this, it could be assumed that these types of systems when applied to the requirements of a DEMO MPD are at least TRL-6—technology demonstrated in a relevant environment. Due to the little empirical evidence for anaconda systems, these would likely be at most TRL-4 due to their lack of DEMO or validation within nuclear environments. However, as the radiation dose rate of the DEMO in-vessel environment is estimated to be several orders of magnitude above any of the empirical systems discussed within this report, none of these systems could be said to be demonstrated or even validated within a similar comparable environment. Thus, the highest current TRL that each of these system types could be when applied to a DEMO MPD environment is TRL-4—technology validated in laboratory. An important note to make is that as the ITER and CFETR in-vessel maintenance dose rates are estimated to be within an order of magnitude with that of DEMO, they could be considered comparable relevant environments. Once the ITER MPD and CFETR CMOR have been developed further and empirically demonstrated within their reactor maintenance environment, the anaconda-type system would then be TRL-6 for a DEMO MPD environment, while the other systems would still be TRL-4 provided no significant advancement occurs within the other system types.

V. CONCLUSION

From the options studied, the driving design parameters can be determined back to the specific constraints and requirements that the systems must adhere to. There were common constraints across many of the systems, like port size/access, and also more specific constraints like the anaconda style suiting a requirement that an ITER MPD must be stowed in a cask. The straight boom style system would be the most suitable design for the current tasks that a DEMO MPD is expected to perform. However, there is no particularly strong candidate without first fully defining the requirements and constraints that a DEMO MPD must adhere to.

VI. FURTHER WORK

Further work on MPD development would include reviewing the MPD design options in light of the experience from other deployment systems. In particular, the empirical data gained from the upcoming anaconda style systems would provide a great deal of design input, especially in having full live testing of entire deployment systems in the extremely high-fusion radiation dose-rate environment, but data from this may not be available for a number of years. For current design iterations of a DEMO MPD, integration studies need to be performed with corridor transfer space required for system transfer to vessel, the deployment connections, the removing of port door and limiters, and the time taken for system transfer from storage to full in-vessel deployment. The maximum moment loads with every possible configuration of the system in-vessel will be needed as well as the optimum materials and geometry for structure links in order to determine the most feasible mechanical characteristics of any iteration of a final system design. Another important design factor for the DEMO MPD would be seismic mitigation studies as they will be important as cantilever system designs would be particularly susceptible to seismic events.

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