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Service Joining Strategy for the EU DEMO

Tristan Tremethick, Simon Kirk, Keelan Keogh, Alexander O'Hare, Emily Harford, Ben Quirk

United Kingdom Atomic Energy Authority, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK

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As part of the European Research Roadmap to the Realisation of Fusion Energy, the DEMO reactor aims to show the feasibility of a fusion power plant. Due to the loss of revenue created by downtime and the potential for a breakdown to render a reactor inoperable, maintenance is "mission critical" for a power plant. The harsh environment of a fusion reactor dictates that maintenance must be carried out remotely, which requires the development of new strategies and technologies. There are many challenges to be solved, one of which is how to manage service connections. Within DEMO, the plasma-facing, first-wall components will be the most challenging to connect services to, due to the number of connections and operational environment. High speed, highly reliable cutting and welding tools are required to minimise downtime and mitigate the danger of rendering the reactor inoperable. Uniquely, these tools are required to operate wholly in-bore to allow the current pipe density in the DEMO architecture, something that is not available from industry.

Here, the development of a Service Joining System to meet the DEMO scenario is presented. The joining strategy is discussed along with the substantiation of the design solution. The results of proof-of-principle trials to date are discussed and their implications for the strategy considered. Having discussed feasibility for DEMO, a roadmap is presented for the development of the Service Joining System to an appropriate Technology Readiness Level.

1. Introduction

The DEMO project is nearing the end of a pre-concept phase in which the technologies needed to enable a power producing fusion reactor have been investigated. Within the Remote Maintenance work package, one area of study has been the Service Joining technologies needed to meet the challenges of DEMO. This paper gives an overview of the strategy required, the resulting system concept, progress to date in substantiating the system and the future roadmap identified to ready the system for DEMO.

1.1. DEMO design drivers for Service Joining

The key drivers for DEMO design are given in the European Research Roadmap to the Realisation of Fusion Energy [1] and elaborated in terms of Remote Maintenance (RM) by Crofts et al. [2]. In summary, a Service Joining strategy must be:

Highly productive – Non-productive time on DEMO will be expensive. In terms of Service Joining, there are 752 pipes in the scenario RM is considering, accounting for ~40% of total upper port maintenance duration.

Reliable – Processes and equipment need to perform consistently. Cooling and breeding fluid transport are key to the function of DEMO and leaks are not tolerable.

Recoverable – Recovery options are limited, and RM equipment has the potential to write-off DEMO if it cannot be recovered or rescued.

1.2. DEMO design and use case for a Service Joining System

Service Joining activities in the current work have focused on connections to First Wall components. They are the most critical connections, requiring high integrity to protect the vacuum in the tokamak needed for operation, especially challenging if helium is used as a coolant. As these connections are the closest service connections to the plasma, they are subjected to the harshest operating conditions: high radiation (20-200 Gy/hr) and elevated temperature (550 °C). The pulsed operation of DEMO also means that the joint is subjected to cycling and thermal expansion of the first wall components, placing additional loads on the joint. The current configuration of DEMO relies on clustering several pipes in a small area to provide the necessary services to the First Wall components. Access to the worksite is also challenging. Fig. 1 shows a cross-section of DEMO.

E-mail address: tristan.tremethick@ukaea.uk (T. Tremethick).

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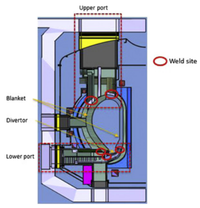

Fig. 1. First Wall Service Joining scenario.

2. A Service Joining System for DEMO

2.1. Strategy

Welding is the joining method chosen for First Wall components. Other forms of connection are not expected to provide the required performance in the harsh environment where leak tightness is key to protect the tokamak vacuum during operation. Other technologies may be possible further away from the plasma and Mechanical Pipe Connections are being pursued elsewhere in the Remote Maintenance work package but are not covered here.

Given the constraints imposed by the DEMO architecture, the welding system needs to be implemented in the following way:

- Operate in-bore – Due to pipe density and the limited access space in the port, it is necessary to conduct all the joining operations inside the pipe.
- Weld at any orientation – Driven by the routing of the pipework, the system needs to be able to access worksites and produce welds at any orientation.
- Align joints as pipework is installed - It is necessary to convert an initial misalignment of the pipes, expected to be a few mm, into a misalignment of fractions of mm for welding. To enable this, compliance must be provided in the pipes to allow manipulation of the pipe ends. Currently, it is planned to use expansion joints and alignment features built into the pipes so that they are self-aligning, as it has been found that it is not possible to provide large amounts of force via the in-bore welding tool.
- Enter the pipe in-line – Linear deployment into the pipes is needed to simplify operations.
- Place complex elements outside the port – Tools have been designed with minimal complexity in the high radiation environment to increase reliability. However, there are large, sensitive items such as the laser source and control system, as well as gas supplies, that need to be protected from the environment but sited near the tools.
- Separate tools for each function (inspection, welding etc.) – Limited functionality can be packaged inside the pipe. Separation of functions helps meet space restrictions but also reduces tool complexity to increase reliability. This also gives flexibility to run different operations in parallel.

2.2. Assumptions

Given the immaturity of the DEMO design, three assumptions have been necessary to allow the current Service Joining strategy:

1 Pipes to be welded will be in new condition or refurbished to ‘as-new’ condition outside of the tokamak – This is because the material will degrade over time in the harsh environment and the levels of helium absorbed in the material will prevent successful re-weld. Also, to prepare a pipe for rewelding would require cutting and finishing operations with a high level of accuracy, requiring complex tools in a high radiation area. Refinishing operations will create debris which will be hard to control.

2 Pipes to be cut will be drained of residual fluids and have a ‘clean’ interior – The expected pipe condition is unknown, especially if carrying a lithium-lead (LiPb) eutectic for tritium breeding. It is assumed that the cutting tool for pipe removal will not need to pass blockages or major damage as it traverses the pipe.

3 The Service Joining System (SJS) equipment will not position pipework – The system will manipulate the ends of the pipe as needed to make the joint, but pipe placement and support will be carried out by other RM systems.

2.3. Risks

As the concept for the Service Joining System is novel, it carries risk. The key technical risks carried are:

Inadequate and unvalidated weld material properties
Immaturity in NDT inspection techniques
Immaturity in welding /cutting technology
Unable to control pipe ends adequately
Control of debris
Uneconomical duration of operations

SJS development is driven by the need to mitigate these risks and verify the strategy will work for DEMO.

2.4. Technology Selection

Laser welding has been selected for the Service Joining System. One of the main advantages laser offers is in productivity, as welds can be completed in a single pass at a high welding speed. In terms of the weld produced, the laser produces a small Heat Affected Zone, minimizing the impact of welding on the parent material. Laser can minimise complexity as the process can be autogenous at smaller pipe sizes, removing complexity of filler wire addition. In addition, the welding power is scalable and controllable without adding complexity to the welding head. The process is non-contact which eliminates the failure mode of the tool becoming stuck to the workpiece and improves the potential reliability of the tool. Laser also allows extended deployment lengths without transmission losses. Laser can also be used for cutting, and there is potential to use it for pre- or post-weld heating processes as well.

2.5. SJS System overview

The Service Joining strategy is novel in that it is not usual to carry out all joining operations from inside the pipe. Such a system is not available from the marketplace, so RACE has had to substantiate novel solutions. A description of the concept tools that make up the Service Joining System is given below.

2.5.1. System container

The SJS system will be based in a container-like structure. This allows sensitive equipment to be shielded from radiation and makes the system self-contained with only an external power supply needed, minimising tokamak infrastructure. The container is delivered to a port entrance by ex-vessel equipment and then tools are delivered from the container to the pipe entrance by generic in-port equipment that is not part of the SJS.

2.5.2. In-bore Deployment System

The In-Bore Deployment System, shown on the right of Fig. 2, drives the tool from the pipe entrance to the weld site. There are two key challenges here: providing enough motive force inside the pipe and locating the tool accurately to the cut or weld site. Options to provide motive force from inside and outside the pipe are being considered.

2.5.3. Welding tool

The welding tool is shown on the left of Fig. 2 and fully described by Keogh et al. [3]. Briefly, the tool consists of the following major elements: rotating laser head, clamps to interface with a groove provided

Fig. 2. Welding tool and in-bore deployment system.

in the pipe and articulation to traverse bends.

The method of clamping to grooves in the pipe minimises disruption to fluid flow and ensure rigid location of the tool in the pipe for welding accuracy. The articulation feature has an actuator to pull the halves of the tool together. This acts against the clamps to locate the tool in the pipe but also achieves final alignment of the joint. A large amount of space is consumed in the tool by the articulation and pulling functions and alternative designs have been produced that omit this functionality if it can be proven unnecessary.

The tool has been designed to be as simple as possible to improve reliability, although the feature set may expand if needed to improve the quality of welding.

2.5.4. *Cutting tool*

The cutting tool has a very similar architecture to the welding tool except that the laser optics are focused to give a smaller spot size for cutting. The beam also exits the tool through a gas nozzle which gives a coaxial flow of nitrogen to clear material and help form the cut. Also, instead of pulling the pipes together, the tool pushes the pipes apart to aid separation during cutting. As with the welding tool, an alternative concept has been produced that omits this feature to give a more compact tool.

2.5.5. *Laser Bore Joint*

The Laser Bore Joint is key to the operation of the Service Joining System and several functions have been embedded into the joint. The joint is a feature that will need to be provided on DEMO pipework and components, but it reduces the tools that are needed for Service Joining and enables in-bore operation. The joint is shown in Fig. 3 and incorporates the following functions:

- Pipe alignment – Via a flexible element and the geometry of the cuff which guides the pipe to final alignment on insertion.
- Weld preparation protection – The cuff shrouds the preparation and protects it from damage during transport.
- Debris capture – When mated, the cuffs on the upper and lower sections create a cavity which retains debris during cutting and welding.
- Provision of backing gas – The cuff cavity also holds backing gas for the welding process and helium for leak testing.

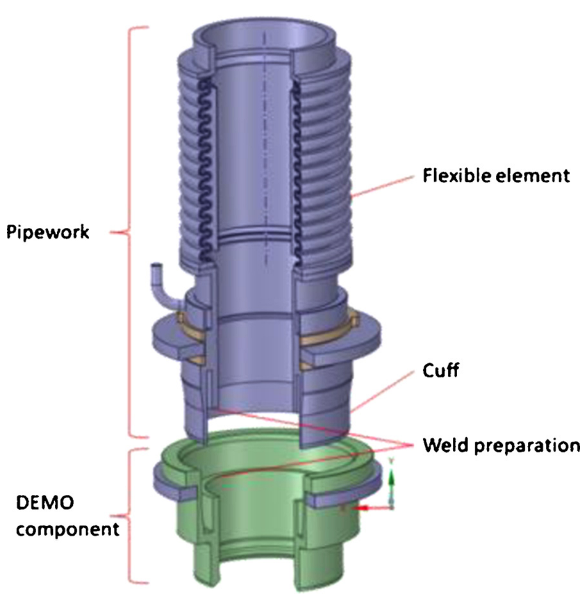

Fig. 3. Laser Bore Joint.

2.5.6. *Other elements*

The Service Joining System will also include Non-Destructive Testing and Post Weld Heat Treatment tools which will be stored in the container and deployed in the pipes on the In-Bore Deployment System.

3. Comparison to ITER solutions

ITER welding equipment for neutral beam water cooling pipes tested at RACE [4] has a space requirement, shown in Fig. 4, of 3x the diameter of the DN200 pipe (red zone in Fig. 4) with an additional access zone of 600 mm (Red hatched zone). In contrast, the in-bore design of DEMO requires 0.4x the diameter of the DN200 pipe. The DEMO strategy also allows different arrangements of the pipe because the external access zone is unnecessary. If such a system can be realised, it will enable the current DEMO architecture.

4. Substantiation of the design

4.1. *Proof of principle trials*

Proof-of-Principle (PoP) tools have been created, or are planned, for the elements of the system. They demonstrate the core functionality of the SJS tools and lower the risk that the current tokamak architecture is not valid. The trials carried out and planned to date are summarised below.

4.1.1. *Cutting PoP*

In trials continuing the work described by Keogh et al. [3], the cutting tool achieved cuts from inside the pipe through 5 mm 316 L and P91 (substituted for Eurofer 97) materials. Trials were carried out with a laser power of 1.9 kW, and the tool took 34 s to complete a cut. Debris was retained on the kerf of the cut which is advantageous for maintaining cleanliness in DEMO. The tool and cut samples are shown in Fig. 5.

Having completed testing of the PoP, the following work has been identified for further investigation:

- Remote operation needs to be demonstrated
- Optics redesign to increase power handling capability
- Investigation of cut quality vs retention of debris
- Cuts under compression/loads
- Cuts of pipes representing DEMO conditions with internal corrosion products or LiPb residue
- Radiation hardness testing is needed.

In-bore cutting has been achieved and appears to offer the speed required in DEMO relevant materials, achieving a Technology Readiness Level (TRL) level of 3-4.

4.1.2. *Welding*

In the most recent welding trials, in-bore welds have been achieved in P91 and 316 L in 3 mm thick pipes with a power level of 2.4 kW and weld time of 25 seconds. The tool and welded samples are shown in Fig. 6.

Several areas have been identified for future investigation:

- Remote operation to be demonstrated.

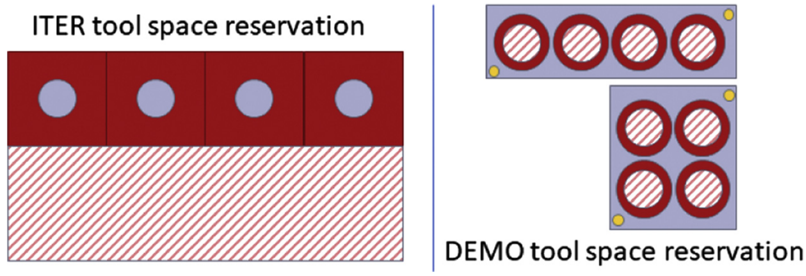

Fig. 4. ITER NB cutting and welding tool vs DEMO in-bore tool operating space.

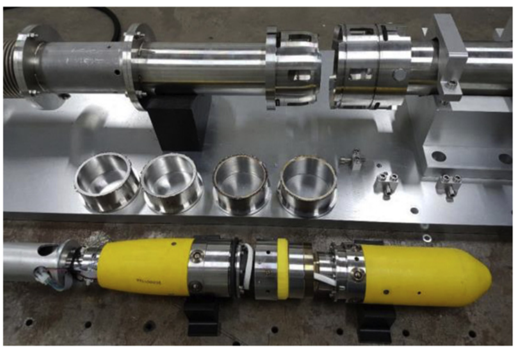

Fig. 5. PoP cutting tool and cut 316 L and P91 samples.

Fig. 6. Weld tool and welded P91 and 316 L samples.

- Power handling increase needed to achieve 5 mm thickness.
- Debris management on the tool.
- Clamping and alignment function - If the joint mechanism aligns with sufficient accuracy, it may be possible to omit these functions and simplify the tool.
- Develop control of weld during the main weld and in the overlapping start/stop region.
- Scaling to larger sizes.
- Weld process development followed by qualification for use on DEMO.

Welding in-bore has been achieved in DEMO relevant materials. The technique clearly needs further development, but it appears to have the potential to be feasible for DEMO and currently has a TRL of 3-4.

4.1.3. Laser Bore Joint

The Laser Bore Joint was tested under a range of misalignments. Weld preparations could be aligned from up to 2 mm initial radial misalignment. This required a force of 2 tonnes. The PoP is shown in Fig. 7.

Friction was found to be high between the components and high forces were required to align the weld preparations.

Future work identified from testing is:

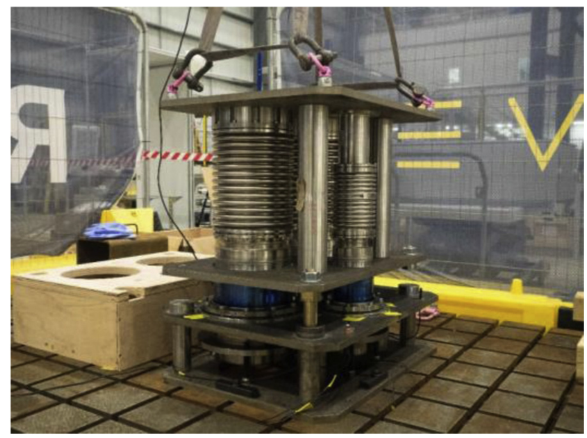

Fig. 7. LBJ Proof-of Principle testing.

- Flexible element development to qualify for fusion applications.
- Alignment geometry needs to be refined
- Research materials and coatings to reduce friction
- Combined testing with cutting and welding tools.

This testing demonstrated that weld faces could be aligned without external manipulation, achieving TRL 3.

4.1.4. Future work

PoPs still need to be completed for:

- In-bore Deployment – Testing planned for late 2019.
- NDT – Testing is not yet planned. The ability to remotely verify the quality of welds is critical and needs to be addressed as a matter of urgency
- PWHT – Testing planned for 2020

4.2. Weld materials

Early in the project, trials were carried out with Cranfield university on the weldability of Eurofer 97/ P91 [5]. It was found that the need for post-weld heat treatment to restore material properties could not be avoided. Welding Eurofer 97 therefore requires the welding strategy to include pre-heating and post-weld heat treatment. In contrast, 316 L does not require these processes. Removing them will reduce the number of tools in the system, making the joining process faster and more reliable. The disadvantage is that 316 L is not low activation and it is not so robust in operation at elevated temperature, so thicker pipes are required. However, it is strongly recommended that the 316 family of stainless steels is investigated for use in DEMO pipework.

5. Research and Development roadmap

Technology Readiness Levels [6] help to define the status of the SJS development and identify work that needs to be achieved in the future.

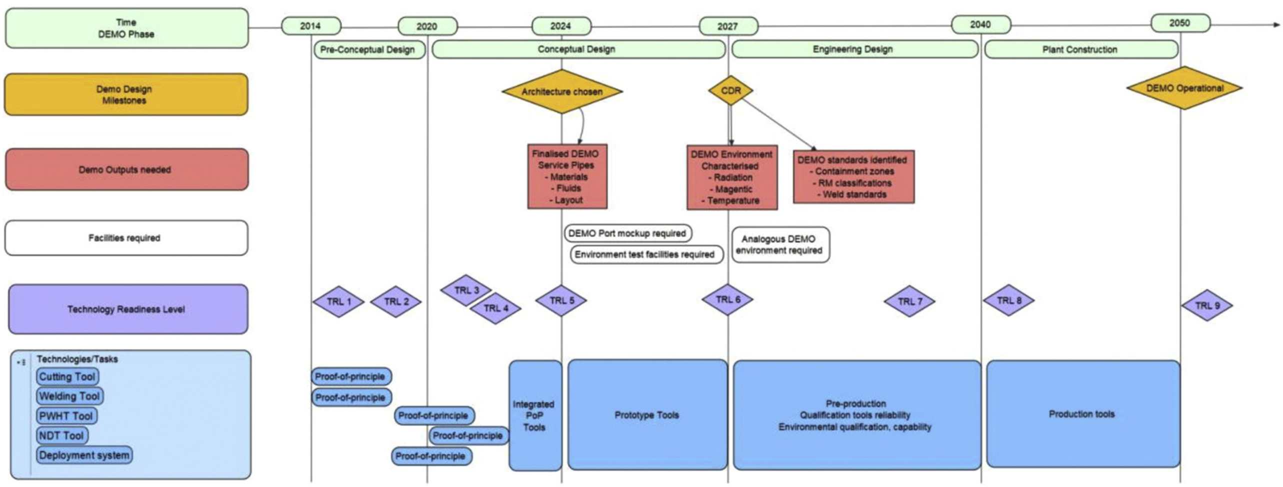

Fig. 8. Service Joining System Development roadmap.

The SJS development roadmap (Fig. 8) should:

- Keep pace with DEMO development.
- Engage industry with the development of the system.
- Mitigate technical risks so that the system is feasible.

DEMO will be entering the concept design phase in 2020. There are two significant dates in this period. For DEMO architecture definition in 2024, confidence is needed that the Service Joining strategy is correct, as in-bore joining operations enable the DEMO architecture. Confidence will be provided by completion of a proof-of-principle in each of the elements of the SJS, showing major technical risks can be overcome. As an output of the DEMO architecture definition, firm details of the joining scenarios will allow development of the SJS to meet the second significant date: DEMO concept design review. For this, the SJS should be demonstrably feasible, corresponding to TRL 6, requiring operation in port mock-ups and tests of components in radiation environments to be carried out. During the following DEMO engineering design period, development of the SJS in a representative operational environment needs to be carried out to allow the SJS to progress to TRL 7 and beyond, although such an environment is not currently available. One way to mitigate lack of facilities in the short-term is to exploit parallel industries and demonstrate elements of the system in those industries. In the engineering design phase, work should also focus on qualifying welds and improving the reliability of the system to production-ready levels. This will ensure a capable joining system is ready for the start of DEMO operations in 2050.

6. Conclusion

A system has been presented that meets many of the needs of DEMO. Early proof-of-principle work has substantiated the viability of the concept. A roadmap to bring the system to readiness for DEMO has been outlined so that the technical risks currently in the strategy can be reduced to an acceptable level.

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