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ABSTRACT
The Joint European Torus (JET) Tokamak has been in use for experiments since 1983. In 1997 the first major use of DT resulted in an activation inside the torus to levels which restricted manual access and resulted in the need for many of the maintenance and modification tasks to be implemented by remote handling means.

Considerable experience has been accumulated in dealing with the preparation and operation of a remote maintenance facility for an operating Fusion device. The unique nature of the JET device presents many problems for remote handling which are peculiar to JET however it also presents many generic problems which are found in other application areas, for example:

- Provision of a remote handling system to undertake an extremely wide range of dextrous, and other tasks.
- Requirement to be able to handle high precision, high quality components without damage or positional error.
- Need to work anywhere inside a 200m^3 toroidal volume with entry available from just one 0.4m x 0.95m access port.
- Requirement to handle components ranging from delicate sensor heads weighing less than 100gm to handling large components up to 400kg.
- Requirement to ensure that all credible failures of the remote handling system do not result in damage to the torus and that all failed remote handling equipment can be recovered and repaired safely.
- Need to prepare the operating methodologies, procedures and operators in a timely way.
- Need to be able to deal with unexpected situations inside the torus in a timely and cost effective manner.
- Be responsive to late requests for unforseen operations.
- Provide a remote handling system which allows the operators to be effective and safe over a 10 hour operating day and a 2 shift operating pattern.

The experience gained from this work will be of interest to those engaged in a wide range of remote maintenance application areas.

1. INTRODUCTION

The Joint European Torus (JET) project is the world's largest experiment to study the physics and technology of energy generation using nuclear fusion. The experimental machine, a Tokamak, comprises a toroidal vacuum vessel of 3m major radius inside which a plasma is heated to temperatures of up to 450million degrees Kelvin.

The plasma is held in place by means of an arrangement of 32 toroidal field and 16 poloidal field magnetic coils and is heated by a combination of induction, particle beams and microwaves.

A future fusion reactor will use a mixture of Deuterium and Tritium (D-T) as its fuel. The JET Tokamak has been in operation since 1983 using primarily Hydrogen and Deuterium in order to avoid producing large amounts of fusion energy which would therein cause significant secondary activation of the torus and restrict manual access. This policy was adopted in order to ensure maximum flexibility for experimentation with the mechanical configuration and components.

During late 1997 a series of experiments were performed using D-T mixtures and this resulted in an activation of the machine which prohibited manual access to the inside of the torus for around one year and with the continued operation in D-D has restricted the access since. The continuing JET experimental programme continues to generate requirements to modify and maintain the inside of the Tokamak in the period since the D-T experiments. The activation levels dictate that the work must be done using remote handling methods where possible.

2. BACKGROUND

The derivation and implementation of the remote handling facility to meet JET requirement has been reported and discussed extensively in many earlier papers[1,2,3].

The Remote Handling Facility comprises the handling system and the management and operational systems.

The handling system has been developed around the man-in-the-loop philosophy in order to ensure the maximum operational flexibility. Remote work inside the torus is conducted by deployment of an advanced Master-Slave servo-manipulator with very sensitive force reflection and a comprehensive viewing system. The servo-manipulator is deployed on the end of a 10m long articulated boom which is able to enter the torus from the one available access port.

The aim of all task operational developments is to allow the operator to perform the tasks as if he were actually inside the torus i.e telepresence. In cases where the loads being handled exceed 20kg per hand then additional remotely controlled lifting equipment is provided.

Two major shutdowns have been successfully completed since 1997 using remote handling methods and over 3000 hrs of remote operations have been successfully completed.

The unique nature of the JET Tokamak as an experimental device has presented many problems to the team charged with preparing and implementing the remote operations and these are reported and discussed in this paper.

3. DEALING WITH A WIDE RANGE OF TASKS

3.1 Generic tasks

The JET remote handling facility is called upon to perform a wide range of tasks. The “telepresence” approach adopted at JET provides maximum use of the intelligence of the man in operations and simplifies the level of new remote handling equipment developments required when new operational tasks are requested. This minimizes both the equipment design and development life cycles and minimizes the operations preparations time and costs.

The types of remote task already successfully completed at JET include manipulation of components in the range 0.1kg-150kg, bolting and unbolting, sawing, welding, visual/camera inspections, radiation monitoring, 3-D photogrammetry and extensive vacuum cleaning.

3.2 At all locations

The remote handling operations have been performed at all positions inside the 200m^3 torus, including at the top and at the bottom. Working at the top of the torus with camera views which give no natural cues for direction of gravity requires the operators to be very aware and well trained. Remote operations have been performed with the articulated boom at full stretch from its entry port but also folded very tightly back on itself to allow work on or very close to its own entry port.

3.3 All types of components

The necessity for remote handling of components at JET has always been recognized and preparations have been made since the start of the project. Every component installed on the machine has been classified according to the likelihood of requiring remote handling as a result of its maintenance and failure probabilities. Those components which were likely to require remote maintenance were designed with features and characteristics suitable for remote handling. However, many components installed inside the torus were considered to never need remote maintenance and as such were not designed for remote compatibility. In practise however the experimental nature of the JET project has resulted in the requirement for significant modifications to the torus and the consequent necessity to remotely handle many non remote compatible components.

The JET remote handling facility has demonstrated its ability to be able to deal with both types of component. As an example in 1999 it was required to install a new system which required the temporary removal and replacement of one of the upper dump plates which had been designed only for manual installation and removal[4]. It was necessary to lower and temporarily support a 75kg section of Inconel structure which was attached to the torus with non captive bolts, washers and loose shims. A tool was designed to perform this function which was installed using one arm of the servo-manipulator leaving the other arm free to handle the supporting bolts. The tool interface accommodated the unquantified small degree of misalignment to allow for the installation tolerance of the Dump Plates. The bolt tab washers were removed by the manipulator using curved pointed pliers. To make the loose parts compatible with remote handling techniques, they were retained with “top hat” tools that were remotely attached to the Dump Plate. The removal of the Dump Plate was successfully accomplished as planned within a 13 hour period.

The complexity of the remote operations could have been simplified by the parallel use of a servo-manipulator on one articulated boom and a weight carrying device on a second articulated boom working in parallel. The cost benefit of building and using two booms for general JET remote handling has not been fully analysed but there is a clear technical advantage in the use of two booms for dealing with some classes of non remote handling components.

There is an increased cost of dealing with components not previously designed for remote handling both in terms of the need for extra equipment but also in terms of significantly longer preparations and operations duration.

3.4 Using a rationalized approach

The design of a component for JET remote handling compatibility is implemented by following a rational set of standards and guidelines. This results in a set of common elements and operational methods for handling. In contrast the JET components designed without remote handling in mind are constructed and installed in various and often unique ways optimised for the application, but which makes their subsequent remote maintenance very difficult and time consuming.

It has also been demonstrated that a rational design approach as implemented for remote handling components results, as a by-product, in designs which are also easier to install and handle manually thereby simplifying manual maintenance and minimizing costs.

In addition to the handling and manipulation operations there is a significant requirement for inspection and cleaning inside the torus. A similar argument to rationalize the component designs to suit inspection and cleaning can also be made. Considerable effort and tooling has been developed in order to inspect components in difficult access areas.

In retrospect, handling and inspection inside the JET torus would have been simplified if the design and handling of all components had been rationalized at an early stage. The selection of a common technique for attaching components to the torus wall and the provision of common type of inspection feature into components at the construction stage, saves considerable time and cost during subsequent shutdowns for modification of in-vessel components.

4. HANDLING DELICATE COMPONENTS IN A PRECISION ENVIRONMENT

4.1 Accurate installation

The JET Torus is an Ultra High Vacuum Vessel with internal components installed and aligned to extremely stringent dimensional tolerances. Many of the primary plasma facing components are aligned to +/- 0.1mm.

The remote handling facility is required to be able to remove and replace any of the internal components to these tolerances without damaging, blemishing or scratching any component.

The servo-manipulator is able to be used very accurately (<0.5mm) within a teach-repeat type mode but at present there is no similar performance from the boom deployment system and so the final positioning of components to such high tolerances is typically achieved by appropriate use of remote handling compatible alignment pins, slots and dowel holes.

4.2 Without damaging components

The installation of components without damage is achieved by the use of handling tools which incorporate features for rough alignment with respect to adjacent components and also provide alignment for the handling tools used for holding, bolting, unbolting, welding or cutting the component. An example of the type of problem is shown by the handling of the Divertor modules[5]. In this case it was required to remove 144 modules of c35kg each and to replace them with 192 new modules of similar size and weight. The modules comprise an inconel sub-structure onto which are mounted delicate carbon tiles. In situ the gaps between the adjacent tiles are nominally

3mm, but tolerance build up results in minimum clearances of only 1.4mm. The installation process requires the fastening of bolts with an 8mm allen key and which can only be reached through a gap between tiles of 10mm. The risk of damage from the allen key was eliminated by incorporation of key guides onto the module remote handling tool itself.

The physically large remote handling equipment, boom and manipulator, is prevented from damaging the internal components of the torus by use of a comprehensive command, control and monitoring system. The remote handling equipment continually provides real time information on its position to a computer which displays a 3 dimensional model of the torus and the remote handling equipment. The software systems provide safety overrides of the boom and manipulator motions to prevent any collision with the environment.

4.3 Measuring the “as installed” positions

The JET quality assurance process requires confirmation of the component final position in 3-Dimensions by direct measurement after installation. This has been achieved on a number of occasions at JET by use of a 3 dimensional survey system based on remote photogrammetry[6,7].

In addition to straightforward metrology the technique has also been used as part of the manufacturing process for new torus components when the JET configuration control data is not accurate or reliable enough to allow an exact fit of new components. In this type of application[4] the new features which are required to attach a component to the torus wall are first installed by remote welding. A 3-D photogrammetry survey is then undertaken to measure accurately the location and orientation of these attachment pads. The new components are then manufactured to suit. This process eliminates the use of shims and spacers and minimizes the installation duration.

5. BEING ABLE TO RESPOND TO CHANGING TASK REQUIREMENTS

5.1 Unexpected condition of the components

In addition to the planned tasks the remote handling facility has been designed to be able to deal with unexpected tasks. When it is operating the JET torus is an extremely hostile environment, UHV, 300°C ambient, plasma temperatures up to 450,000,000°K, cryogenically cooled panels throughout the lower part of the torus, up to 25MWatts of power being added to the plasma from microwave antennae and particle beam accelerators.

As a result, the condition of the components inside the torus at the start of remote operations is not always predictable and experience has shown on a number of occasions that planned operations have not been able to be completed as expected due to unusual torus physical conditions.

The JET remote handling facility has been able to accommodate many of the new tasks as requested with minimal additional lost time. As an example during operations in 1998 we were unable to release and remove a small copper waveguide as planned. Unfortunately the waveguide was trapped in a location very difficult to view and access and after an assessment of the situation it was decided to prepare a suite of mechanical levering tools, an inspection boroscope, an inspection lamp and a electric shear capable of cutting the waveguide into two. After three days the equipment was ready and taken into the torus for use by the servo-manipulator. The boroscope was used to confirm that the waveguide mounting bracket was distorted and thereby imposing a large strain on the waveguide. One of the mechanical levers was then used by the servo-manipulator to move the waveguide to relieve the strain. The bolt was then able to be unfastened and the waveguide was successfully removed.

A wide range of bolt sizes is used inside the JET torus and there is a real potential for seizure as a result of the hostile JET operating conditions. A number of tools and techniques have therefore been developed in order to satisfy both the normal and seized handling of these fasteners[8].

5.2 Last minute requests for essential tasks

The JET machine is an experimental device with an experimental programme that involves many hundred experimenters from around Europe. The results from an experimental campaign generate information and new ideas for more experiments. This work culture naturally results in requests for new experimental equipment and modifications to the existing components. Therefore, it is common for new task requests to be added at the last moment before remote operations start and also during remote operations. It is essential for the project that the modifications and enhancements can be achieved in a cost effective and timely way. The JET remote handling facility has proven itself capable of responding to last minute requests for new tasks. This is only possible because of the flexible man-in-the-loop approach to operations, the ability of the highly trained JET remote operations staff and the simplicity and re-usability of the remote operations procedures.

6. DEALING WITH FAILURES OF THE REMOTE HANDLING EQUIPMENT

6.1 Prevent faults before they happen

The cost of in service equipment failure in a remote application such as at JET is measured in terms of lost remote operations time and thereby lost operational time for the JET experiment. It is clearly vital to minimize the risk of such failures.

The major JET equipment has been subject to 1000hr operational soak tests and many years of operation. This experience has resulted in the derivation and implementation of preventative routine maintenance strategies. In the run up to an operational campaign the JET remote handling equipment is tested, maintained and re-commissioned. During the operational campaigns of 6 days/week and 20 hours per day a remote handling equipment maintenance day is planned for every other week. The maintenance day is used to test and monitor the condition of all major elements of the equipment and to identify when there are any quantitative diversions from its normal performance. This pre-failure indicators are then used to trigger a replacement of the abnormal elements and in so doing head off potential failures inside the torus.

A condition monitoring system using Neural Networks to provide a 24hour automatic measurement of the system performance and comparison to a normal operating signature is under development at JET.

6.2 Prepare the equipment in advance for remote recovery to a repair bay

It is well recognized that like all other equipment the JET remote handling system will fail. A significant failure of JET remote handling equipment when operating inside the torus can result in many weeks of delay whilst the equipment is extricated from the torus and repaired.

A fail safe, fail recoverable policy has been adopted, under which the JET equipment will halt in a safe condition when a failure occurs and has built in features to facilitate its recovery.

The effect of worst case system failures has been analysed in detail and methods for recovery to effect a repair have been derived. In many cases this has required specific elements to be introduced into the equipment design to facilitate its recovery.

The operational methods for recovery from worst case failure will require the introduction into the JET torus of a second manipulator system. This will enter through another port and will effect simple modifications to render the failed equipment recoverable.

The operational methods have been proven and the operators have been trained to implement the recovery operations.

In practice the JET remote handling system has proven itself very reliable and has suffered only two significant failures each of which could be recovered without recourse to deployment of the additional manipulator.

7. PREPARING FOR REMOTE OPERATIONS IN A TIMELY WAY

Major maintenance and modification of the JET torus occurs typically every 12-18 months. Since 1997 there have been two remote maintenance shutdown periods and a third major shutdown is planned for mid 2001.

Preparation of the remote handling facility for each shutdown comprises the following processes:-

- Task request
- Task definition
- JET component design and build
- Remote handling tooling design and build
- Remote operations task methodology derivation
- Task method proving using full scale mock-ups
- Remote operations procedures development and validation
- Remote operations staff training for planned operations
- Remote operations staff training for failure case operations
- Remote handling system preparation and qualification for operations
- Remote handling equipment maintenance staff training

The above processes must be fully completed before the shutdown operations start. The JET project management systems have been successful in timely preparation for the past shutdowns by application of classical project management, planning, identification and management of priorities.

The JET remote operations procedures are designed to facilitate the preparation process and the final operations[9]. The documentation is designed in a hierarchical structure to simplify the derivation and approval processes and to save time by maximizing the re-use of existing documents. The highest level operations document provides a description of the overall process and facilitates the logistical tracking of all JET component locations, RH equipment positions, procedures and other operations information.

8. WORKING SAFELY

The remote operations are performed inside the torus within an air atmosphere at normal temperature. The JET torus is activated and is contaminated with Tritium and Beryllium. These hazards need to be controlled and contained during remote operations.

A Safety Case has been prepared and approved for maintenance inside the torus. The activation exposure hazard to all personnel is controlled by use of the remote handling equipment which is able to withstand high total doses of gamma radiation. The tritium and beryllium contamination is contained by use of a depressed atmosphere inside the torus relative to the hall in which the torus is located. The hall atmosphere is also controlled at a depression relative to outside the building. The depression is maintained by housing the remote handling boom system within a contamination controlled enclosure which is physically sealed to the torus access port.

Different hazards to personnel exist during periods of mock-up trials. The remote handling equipment is of significant potential for damage that it is treated as a personal injury hazard and procedures are put in place to minimise the risks accordingly.

9. CONCLUSIONS

The JET remote maintenance facility has prepared for two major campaigns and has accumulated over 3000hrs of operational time.

The experimental nature of the JET machine has presented a number of difficult challenges for the preparation and operation of the JET remote handling facility.

A number of conclusions can be drawn from the experiences of the team involved in this work:

- Consider longer term modifications as well as maintenance when planning for RH compatibility.
- It is important to rationalise the handling and attachment of all components even if the first installation is by manual means.
- It is vital to design a remote handling system with inherent flexibility to deal with a wide range of expected and unexpected tasks in a cost effective and timely way.

- The remote handling system must have the capability to install delicate components in a safe and precise manner without any damage to other components.
- The overall remote handling facility must be able to respond quickly to changes in task requirements at short notice, either because of damage to components only discovered when confronted with the component inside the torus or as a result of last minute requests for essential work.
- The preparations must include provision for failure of remote handling equipment when operating inside the torus and the equipment must be designed to facilitate its rapid recovery and repair.
- The tasks must be proven and operators must be trained making use of full use of mock-ups. In future a wider use of Virtual Reality mock-ups is forseen.
- To maintain a responsive and flexible operations the procedures and other operations documentation must use a rational structure and facilitate the re-use of existing material.

10. ACKNOWLEDGEMENT

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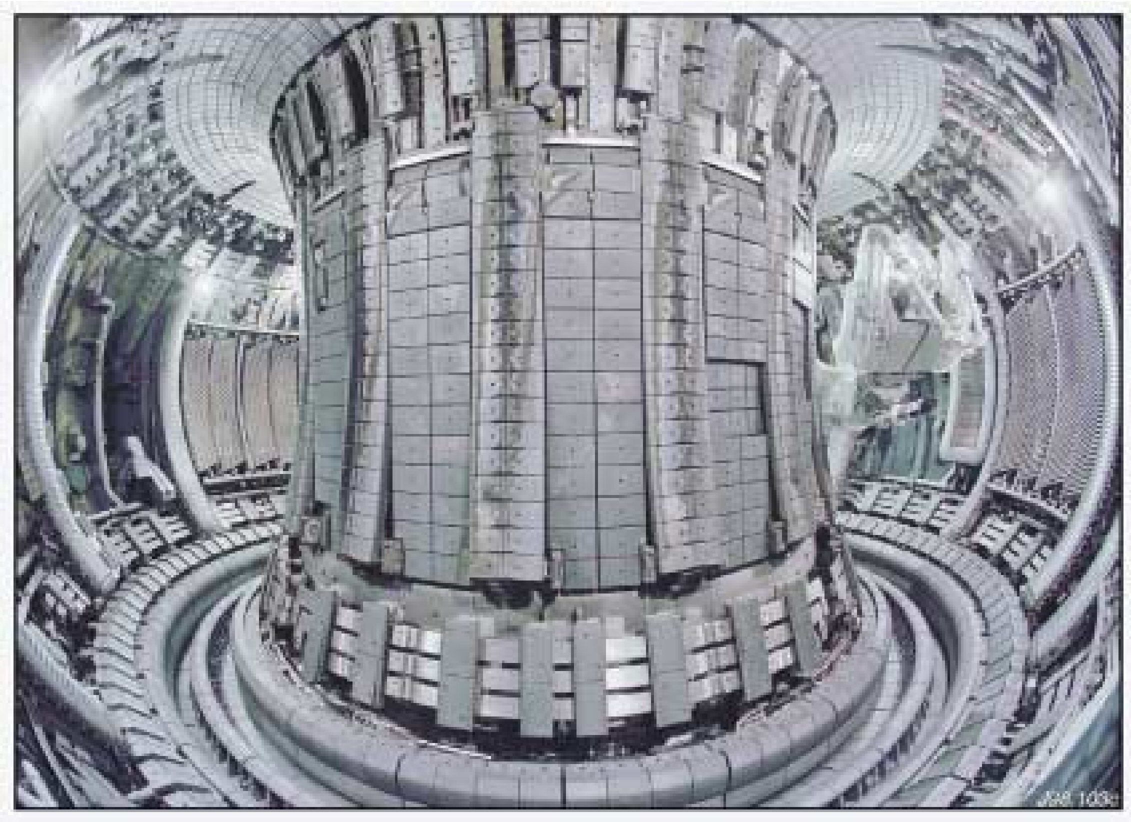

Fig.1: Remote handling manipulator positioned inside the JET Torus

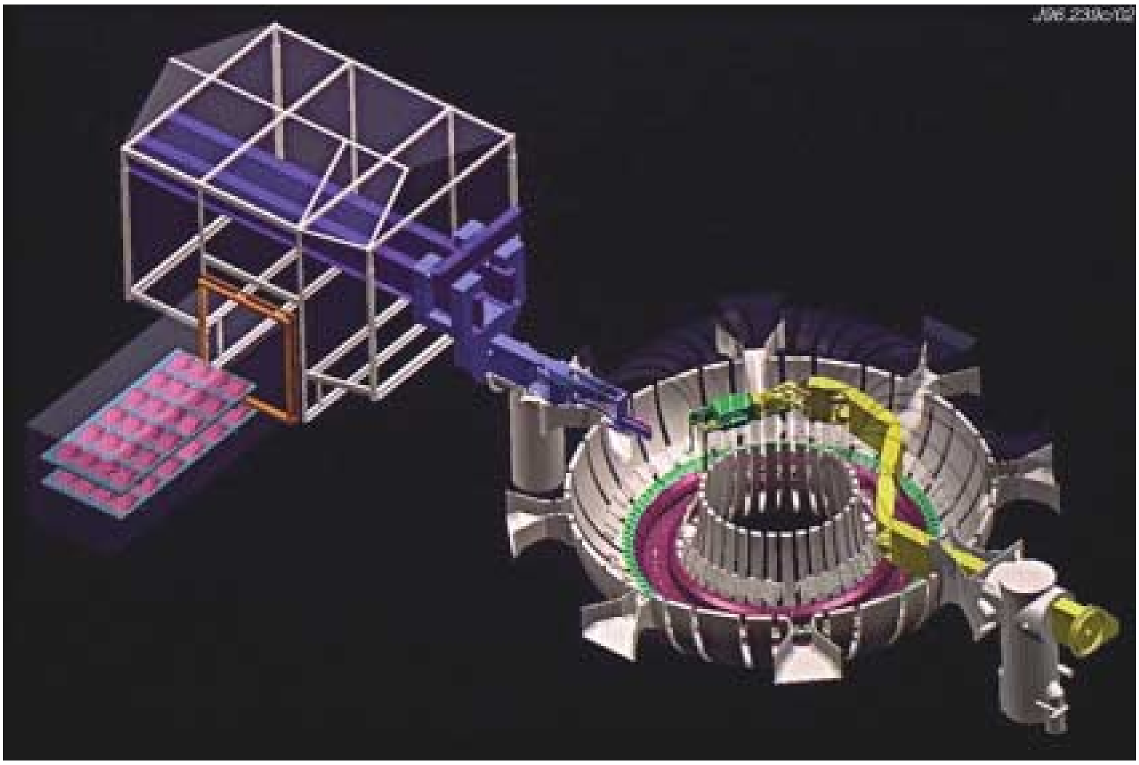

Fig.2: Overview of the JET Remote Handling System for work inside the Torus