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ABSTRACT

In 1997 a series of experiments were performed in the JET machine using deuterium-tritium (D-T) mixtures and resulting in discharges with record breaking fusion power and fusion energy. The experiments demonstrated a key technology required for fusion, namely the on-line operation of a tritium fuel re-processing plant.

These experiments left the inside of the JET vessel inaccessible to manned access for approximately one year. During this time, the complete Mark IIA divertor, a major system within the torus, was successfully removed and replaced with a new divertor design, the Mark II Gas Box divertor, using only remote handling techniques. This was the first application of the JET remote handling system and a demonstration of a further key ITER technology.

The paper explains the methodology and operational approach taken to achieve the results using the remote handling system developed at JET. It describes the remote handling equipment including the force-reflecting servo-manipulator, the specialised tools designed, the facilities needed, and the trials, planning and training carried out to ensure the safe, reliable and rapid completion of the remote handling tasks. The planned tasks are outlined including the execution of the novel procedure for a remote, sub-millimetre precision, dimensional survey of the divertor support structure using digital photogrammetry. Furthermore the paper shows how the adaptability of the system was used to successfully undertake a large number of unplanned tasks including the removal of damaged tiles, a damaged diagnostic system and the vacuum cleaning of diagnostic windows.

I. INTRODUCTION

At the Joint European Torus (JET), the world's largest tokamak, set up under the auspices of EURATOM, a series of experiments were performed in 1997 using deuterium-tritium mixtures: the fuel to be used in future fusion reactors. These successful experiments resulted in discharges with record breaking fusion power and fusion energy [1]. In addition the experiments demonstrated one of the key technologies required for fusion, namely the on-line operation of a tritium re-processing plant [2].

As a consequence of the D-T experiments the inside of the JET machine was activated to approximately 4.3mS/hr and will not be accessible to manned access until the middle of 1999. The radiation level on the outside of the machine remains at a low level which does not affect ex-vessel work. Directly after the D-T experiments and using only remote handling techniques, the complete JET Mark IIA divertor has been removed and replaced with a new divertor design, the Mark II Gas Box divertor. This has been the first application of the JET remote handling system and a powerful demonstration of another key technology required for fusion.

A. The Operational Approach to the Remote Handling Shutdown

The remote handling approach taken was designed to maximise the safety, reliability and speed of the operations. The in-vessel work was done fully remotely from the Remote Handling Control Room using the Mascot servo-manipulator transported around the torus on the 10m long Articulated Boom housed in the Boom Enclosure, entering the vessel through one of the main horizontal port openings, Fig.1. A short second boom, identical to the main boom but with only one articulation, housed in the Tile Carrier Transfer Facility (TCTF) and entering the vessel from the opposite side, was used to transport equipment in and out of the vessel. The activated Mark IIA divertor modules were unbolted and detached from the structure by the manipulator on the boom, then transferred onto a special end-effector attached to the second boom. The tile carriers were then removed from the vessel, transferred to the TCTF and placed fully remotely onto a trolley which was later rolled into the attached but removable ISO container for storage. The new Mark II Gas Box Divertor modules were installed in the vessel using the reverse procedure. Tools and other components required during the shutdown were transferred into the TCTF via a posting port located in the floor of the enclosure and leading to a controlled storage area beneath.

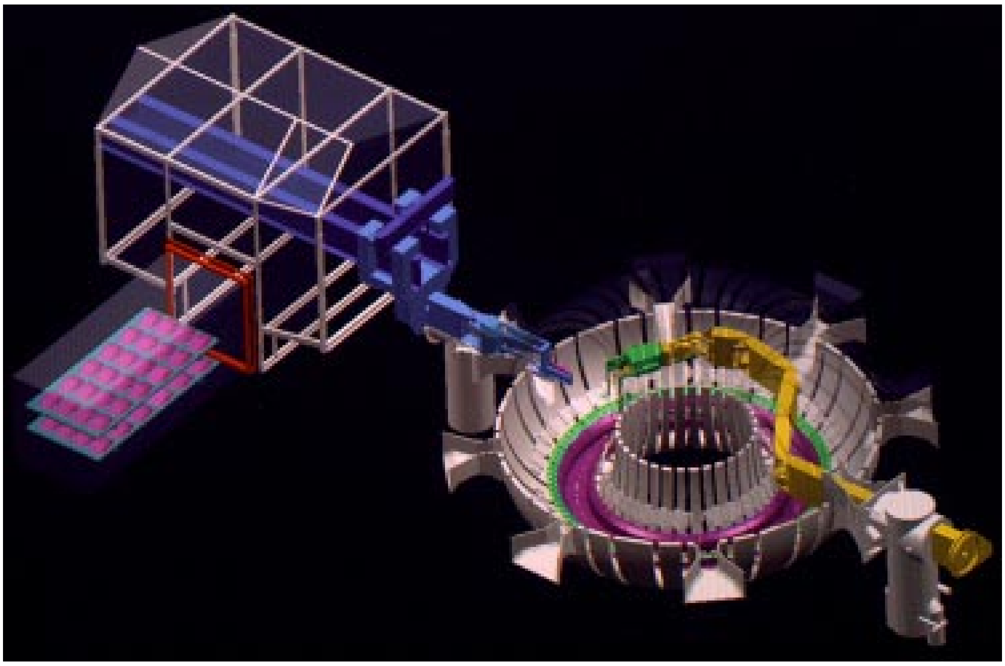

Fig. 1 Tile Carrier Transfer Facility Vessel and Boom

Special emphasis was placed on the safety aspects of the work. The equipment and the operating procedures were carefully designed to deal with tritium gas emanating from the vessel and in-vessel components and with the containment of tritium and beryllium containing dust and particulates present in the vessel. The pressures in the JET vessel and all the attached enclosures and facilities were carefully controlled at a level below atmospheric pressure. The atmosphere from these areas was pumped either to the Exhaust Detritiation System (EDS) of the JET

Active Gas Handling System [3] where the tritium was removed and stored or to the HEPA filtered and monitored stack. The contamination levels were constantly monitored in all areas of the plant by the use of radiation monitors and the frequent use of smearing with swabs and on-site analysis.

II. REMOTE HANDLING COMPATIBLE DESIGN

The JET tokamak was designed for operations with deuterium/tritium as fuel and therefore took the requirements for remote maintenance into account from the start.

The Mark IIA and Mark II Gas Box divertor modules[4] the support structure and the associated diagnostics were designed to enable the remote exchange in a short time. This is exemplified by the concept of tiles attached to tile carriers which are installed and exchanged in one piece. This has the added advantage that alignment of the tiles is achieved automatically by the correct installation of the carriers. Special attention was paid to the design, the clearances and tolerances, the lifting features and camera viewing, the possibilities for jamming and seizing, the materials used and the possibility for removal if damaged.

An in-depth study was made of the optimum design of the remote handling fixing bolts and threads including the exchange of seized bolts/threads.

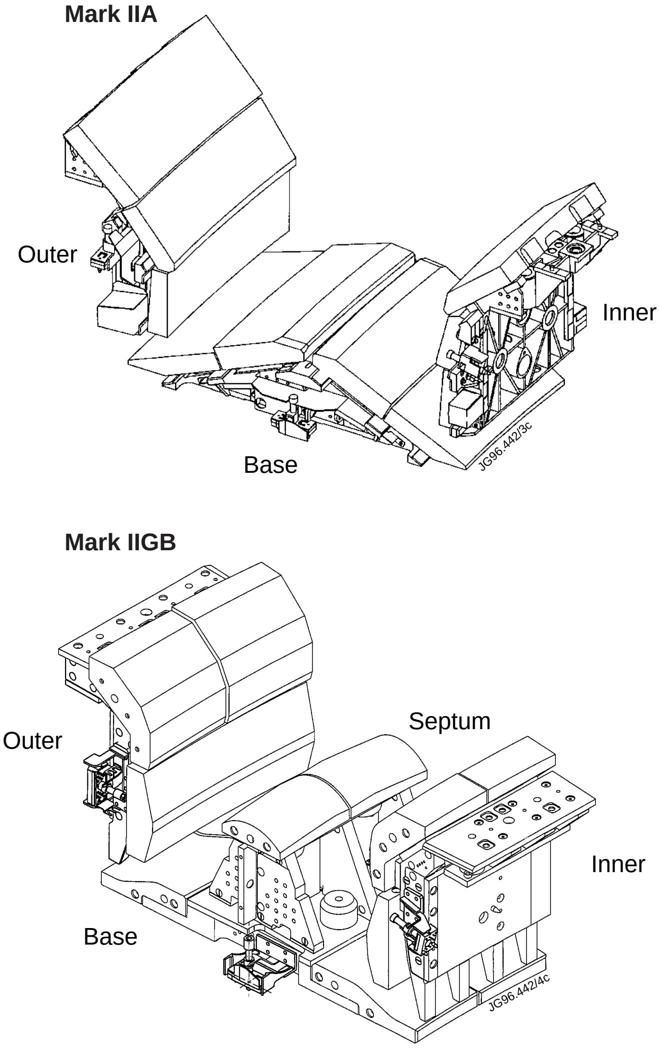

Fig. 2 Mark II and Gas Box Divertor Modules

III. REMOTE HANDLING EQUIPMENT

The remote handling equipment was originally developed in parallel with the design of the JET machine in order to establish the tools for a general repair and maintenance function. The experimental nature of the JET machine dictated that it would be progressively modified. Therefore, the remote handling equipment was designed to be adaptable to modifications and able to respond quickly to unforeseen circumstances. The remote handling methodology chosen was based on a fully tele-operational system involving the man-in-the-loop control of a two armed, force reflecting servo-manipulator [5]. Having visual, acoustic and tactile feedback gives the operator a distinct sense of presence in the vessel.

A Manipulator

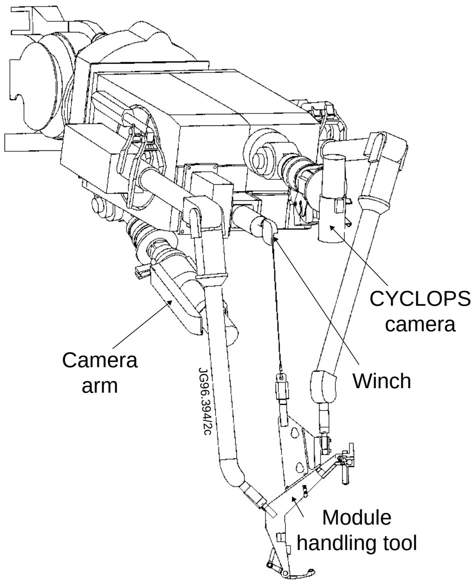

Fig. 3 Mascot Servo-Manipulator

The Mascot manipulator [6], a bi-lateral, anthropo-morphic, force reflecting servo-manipulator, has a 20 kg handling capacity, a 100gm tactile sensitivity per arm and a winch which allows it to lift and lower components up to 50 kg, Fig.3. Mascot operates in master-slave configuration i.e. it duplicates the movements of the master unit being manipulated by the operator in the Remote Handling Control Room distanced from the JET vessel. It has additional features for force scaling, gravity compensation and a teach/repeat capability all provided by the digital control system. The mascot slave is configured with four cameras; one attached above the arms in the middle of the shoulder, one on a separate moveable “Camera Arm”, and one attached to each wrist on a passive mount which can be directed wherever required by using the gripper on the other arm.

B Articulated Boom

The JET Articulated Boom [7] is a 10m long transporter consisting of up to six sections flexibly joined together. It has 18 degrees of freedom and can carry up to 600kg. It can reach any point within the vessel to within better than 10mm. The boom can be pre-programmed to automatically execute any number of motions at the same time and to approach a pre-determined point.

C Tools

The nature of the Mascot manipulator is such that in principle it can, with minor adaptations, use any tool including power tools designed for manual operation. This facility is particularly useful when required to deal with unplanned situations.

A set of special tools were designed [8] to minimise the complexity of the tasks whilst maximising the speed and safety of the remote operations. The tools attached to each of the tile carriers had features to guide the adjacent tools thereby eliminating the danger of damage to the tile edges when installing or removing tile carriers, Fig.4. As the in-vessel tasks consist in large part in bolting and unbolting operations performed directly using the manipulator, a specially designed ratchet driver was used to run-in the bolts. The same tool could also be used for unbolting by simply using alternate gripping features on the tool. Additional tools were designed for other tasks such as: the removal/installation of the inner wall, poloidal limiter and divertor entrance tiles; the cleaning of the beryllium evaporators heads; the vacuum cleaning etc.

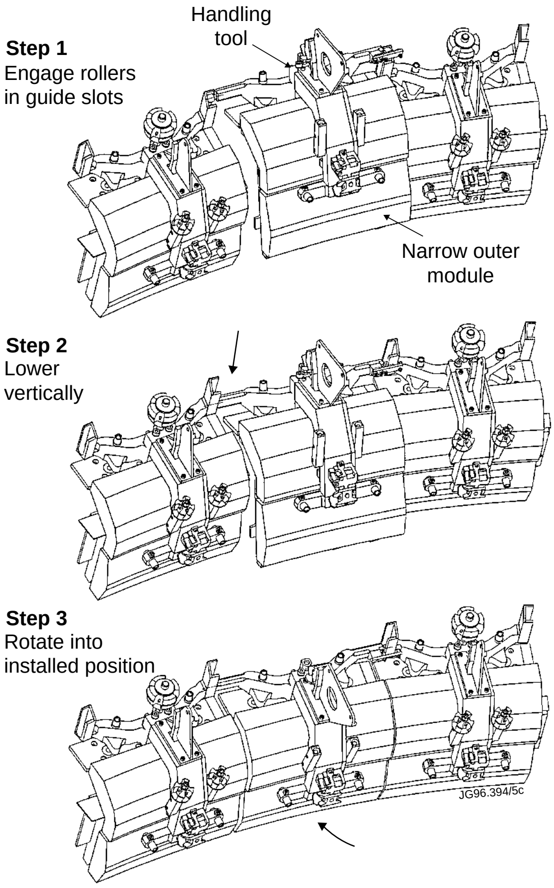

Fig. 4 Installation Sequence for Narrow Outer Modules

IV. REMOTE HANDLING FACILITIES

A number of special facilities were designed and implemented for the shutdown. The contamination control aspects of the shutdown were addressed by the design and use of contamination control enclosures for the boom and the tile carrier transfer facility and a dedicated ventilation system capable of handling the tritium out-gassing from the vessel and the components.

A Remote Handling Control Room

The Remote Handling Control Room is the centre from which all the in- and ex-vessel remote tasks are executed, controlled and monitored. It contains the Mascot master manipulators and the Control Stations for the transporter systems. The operators operate the master manipulators using the video screens and the combination of tactile and sound feedback. The Man-Machine-Interfaces (MMI), developed at JET, provide an optimised graphical interface for the operator which is both easy to use and to update [9].

B Boom Enclosure

This boom was housed in a complete contamination enclosure which was ventilated into a monitored stack and which had, attached to it, a Controller/Dresser Unit (CDU). This unit contained all the equipment needed to allow operators to dress and enter the boom enclosure in full pressurised suits for maintenance and repair work. The CDU housed the controller/dresser and the equipment required to view, communicate and supervise the operators in the enclosure as well as that required to decontaminate the operators (shower etc.) exiting the enclosure.

C Tile Carrier Transfer Facility and ISO Containers

The short boom and end-effector were housed in the Tile Carrier Transfer Facility (TCTF), Fig.1, [10] which had a separate ventilation system connected to the monitored stack and an attached CDU. Attached to the TCTF was the ISO container used to store the divertor modules and vented directly into the torus and thus the EDS system. The double door connecting the ISO container to the TCTF, one half of which was attached to the TCTF and ISO containers respectively, allowed the safe contamination free exchange of ISO containers.

D In-Vessel Training Facility

The In-Vessel Training Facility (IVTF) represents a full-scale mock-up of the inside of the JET vessel [11]. It has a number of different objectives but during the preparation for remote handling shutdown it was used extensively to establish the procedures; to train the staff; to prove the articulated boom teach files and to provide the opportunity to create photographs and documentation to support the operations. The implementation of the remote handling equipment and in particular the use of the servo-manipulator require highly skilled operators who are familiar with the equipment as well as the tasks to be performed.

V. PLANNING, PREPARATION AND TRAINING OF REMOTE HANDLING OPERATIONS

The success of a remote handling operation is critically dependent upon the reliability of the equipment used, the ability to recover quickly and effectively from failures and to deal with unexpected or unplanned events.

The program for testing and monitoring the reliability of the remote handling system was initiated in 1995. Fault reporting and fault isolation procedures were formalised. This led to a continuous improvement of the equipment reliability and a good understanding of weak points and their elimination [12]. It also led to an economically viable strategy for spares based on component availability and failure probability.

A very comprehensive trial and training program was implemented in the IVTF in order to establish the best procedures for each of the planned tasks as well as the unplanned recovery tasks and to familiarise and train several teams of operators with all the tasks to ensure that they are fully prepared.

The shutdown itself was planned in detail for two shift operation using the experience gained in the trials. The whole shutdown was programmed to last four months from the end of operations to the closure and pump down of the vessel.

A Execution of Planned Procedures

All the planned procedures were executed as predicted and on time with no significant problems. The planned work included the following successfully completed tasks:

A detailed initial radiation survey of the vessel carried out using a portable ion-chamber monitor transported by the manipulator. The average mid-vessel radiation level was found to be 4.3 mS/hr with higher levels in contact with components.

A pre-programmed procedure was used to inspect the complete vessel using a video camera. The recording of the results was used to identify areas for a subsequent closer examination. The machine was shown to have suffered no major damage by the preceding high power operational period. The only damage found was hairline cracks in a small number of poloidal limiter tiles.

The removal of all 144 Mark IIA divertor modules using the prepared tools and procedures went exactly as planned with no unexpected problems. This included the un-torqueing and removal of on the order of 1500 bolts not one of which seized on removal. The foreseen procedure to drill out seized bolts and install new thread inserts was not needed to be implemented. Similarly the transfer of the modules onto the short boom, onto the stands and into the ISO containers, as well as the exchange of the ISO containers themselves went exactly as planned. The installation of the new Gas Box Divertor modules was equally successful and went as planned. All of the bolts were remotely installed and torqued without problems.

The removal and re-installation of a number of diagnostic systems and electrical plugs attached to the modules was completed successfully.

The shutdown plans required the vacuum cleaning of the in-vessel components at different stages including the cleaning of the divertor support structure prior to the installation of the new divertor. As the dust and carbon flakes contained a large amount of tritium which outgassed continuously, they were collected in a small container which was remotely sealed within the vessel before being removed. The cleaning of the four beryllium evaporator heads using a special tool attached to the vacuum cleaner was also completed successfully.

1. Digital photogrammetry. The divertor support structure was surveyed remotely to confirm its integrity prior to the remote installation of the new Gas Box divertor.

Digital photogrammetry with newly developed coded targets and in conjunction with novel ‘targetless’ software was the technique used for the remote survey [13]. The 6.3 million

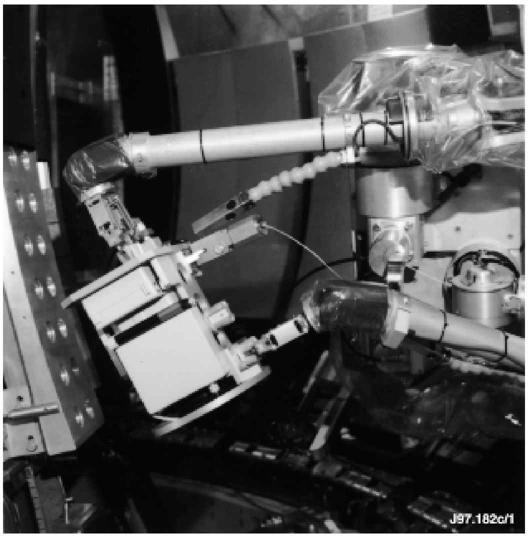

Fig. 5 Digital Photogrammetry Camera held by Servo-Manipulator in Training Facility

pixel digital camera with built-in processor and the ability to download data via an ethernet connection to the Remote Handling Control Room, was deployed on the servo-manipulator, Fig.5. The coded target technology allowed almost completely automatic processing of the survey data.

The survey involved positioning eight target frames fitted with retro-reflective targets on the divertor support structure after the removal of the tile carriers. When processed, these allowed accurate (±0.06mm) determination of the camera positions. The now accurately known camera positions were subsequently used as the basis for triangulation measurements to untargeted or 'natural' features of the divertor structure. Using this technique, a measuring accuracy for natural points of about ±0.3mm was achieved. It was confirmed that the diameter, roundness, concentricity and level of the divertor support structure were virtually unchanged compared to those during the original installation.

B Execution of Unplanned Procedures

A large number of unplanned tasks were performed during the shutdown. The following is a description of some of the more involved additional tasks.

Seven pairs of poloidal limiter tiles previously identified as showing indications of damage were removed and replaced by remote handling. They were removed in order to confirm the findings of the inspection and also to provide tile samples for further study and analysis. The remote handling procedure to exchange these tiles had been developed and practised prior to the shutdown in anticipation of the findings.

A diagnostic wave guide was found to be displaced by 40mm from the expected position and could not be removed by the established procedure. The captivated diagnostic obstructed the removal of the adjacent tile carriers. The manipulator was used to inspect the damage by inserting a video scope into the inaccessible areas in the neighbourhood of the support of the diagnostic. It was verified that the wave guide support structure had been displaced (caused by "halo" currents) but not damaged. Tools were adapted to aid in the removal of the wave guide and, if required, to cut it out. Using these tools it was possible to deflect the wave guide, free the remote handling bolt and remove the diagnostic. The displaced wave guide support was surveyed using digital photogrammetry and the results used to manufacture a new wave guide which was later installed.

Two diagnostic windows used by a laser diagnostic were covered in carbon flakes and dust and required cleaning. To circumvent contamination control problems associated with opening windows, the debris removal was done by remote handling from inside the vessel. Using the servo-manipulator a 2.5m long 11mm diameter stainless steel tube was passed through the 12mm wide slot in the divertor support structure. A vacuum cleaner was attached with the tube 5mm above the window and moving the tube with the manipulator all the debris was removed successfully.

VI. CONCLUSIONS

The highly successful conclusion of the first fully remote JET shutdown is a clear demonstration of the viability of remote handling as a method of maintenance, repair and upgrading of fusion devices, a key technology required for the eventual realisation of fusion power. The work shows the strength of the methodology chosen for the remote handling work. All the planned tasks were completed in a safe, rapid and efficient yet flexible way. The ability to deal with unexpected and unplanned situations and new tasks was often required and successfully demonstrated. A more robotics based approach would have rendered many of the planned tasks impossible to complete in a timely and cost effective way and most of the unplanned tasks could not even have been contemplated.

The shutdown represents a model for future remote handling tasks in terms of preparation and implementation, i.e. definition of tasks, mock-up requirements, preparation of hardware, anticipation of problems, design of tools, reliability studies, development of procedures, trials and training of operators, and documentation needed. The experience gained in the execution is directly transferable to future shutdowns as well as the application to larger machines.

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