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ABSTRACT

The Joint European Torus (JET) project was set up by EURATOM in the late 1970's in order to study the feasibility of controlled Nuclear Fusion. The experimental device has been operating since 1983 and comprises a toroidal shaped vacuum vessel in which high temperature plasma is created and controlled.

During late 1997 a series of experiments using deuterium and tritium fuel mixtures were performed which resulted in the torus becoming radioactive to a level which prohibited personnel access for around one year. Almost immediately after the experiments a major modification to the JET torus was required using remote handling methods alone.

This paper describes the practical implementation of this first fully remote handling shutdown for JET.

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, figure.1.

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.

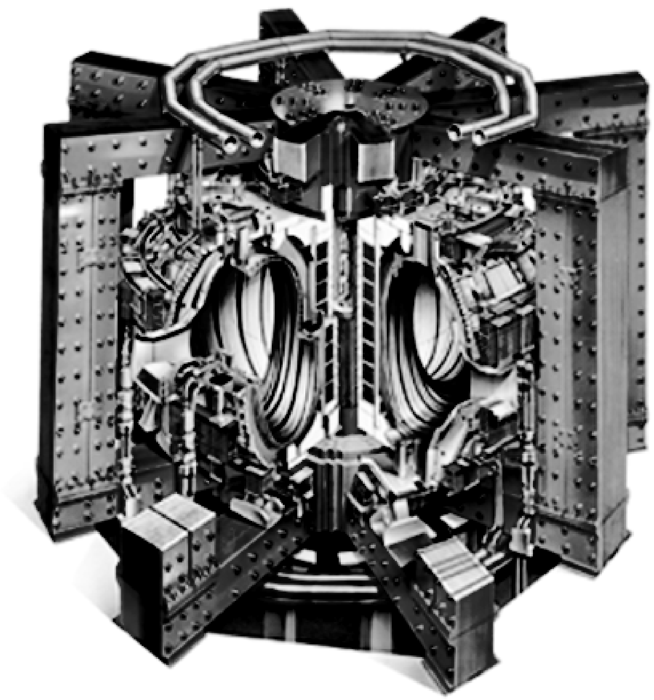

Figure 1 JET Tokamak

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 1984 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 a loss of manual access. This policy was adopted in order to ensure maximum flexibility for experimentation with the Tokamak mechanical configuration and components.

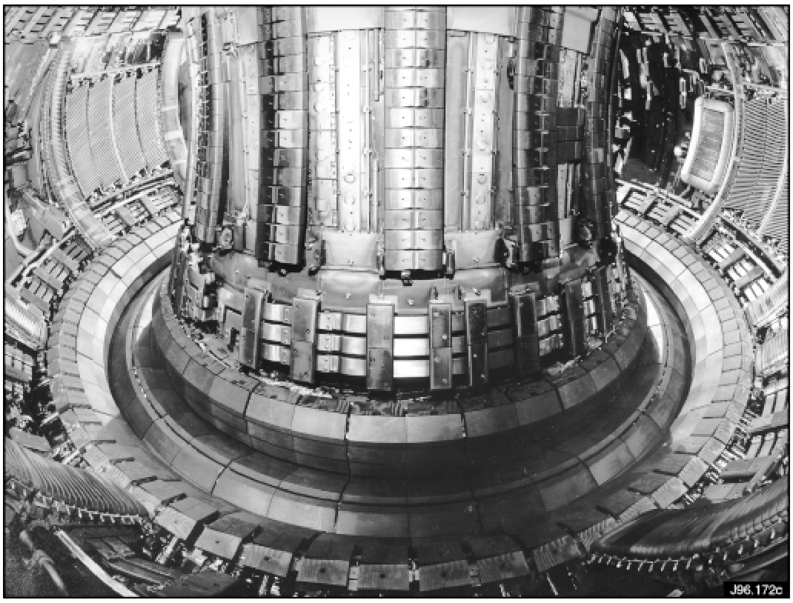

Figure 2 Inside the JET Torus before remote modification

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. The JET experimental programme required that in early 1998 the divertor had to be replaced with an alternative configuration and the activation levels dictated that this modification must be done using only remote handling methods. The inside of the torus before the remote modification is shown in figure.2.

The divertor is a key system for controlling plasma impurity and can be seen as a continuous channel formed by tile surfaces in the lower part of the photograph. It was required to remove all 144 modules which form the divertor and to replace them with 192 new modules to create a new configuration as shown in figure.3.

A suite of remote handling equipment was originally specified, designed and built to satisfy a general repair and maintenance function for JET. The experimental nature of the JET machine and its progressive modification and development demanded that the remote handling system be as adaptable as possible and be able to undertake repair and maintenance tasks at short notice. To meet this requirement a fully teleoperational methodology was adopted and a system based on man-in-the-loop control using bi-lateral, anthropomorphic, force reflecting servomanipulators was implemented.

The original remote handling system requirements did not envisage a major modification to the JET torus, such as replacement of the divertor, but the inherent adaptability of the teleoperation philosophy allowed its application to this task with little modification.

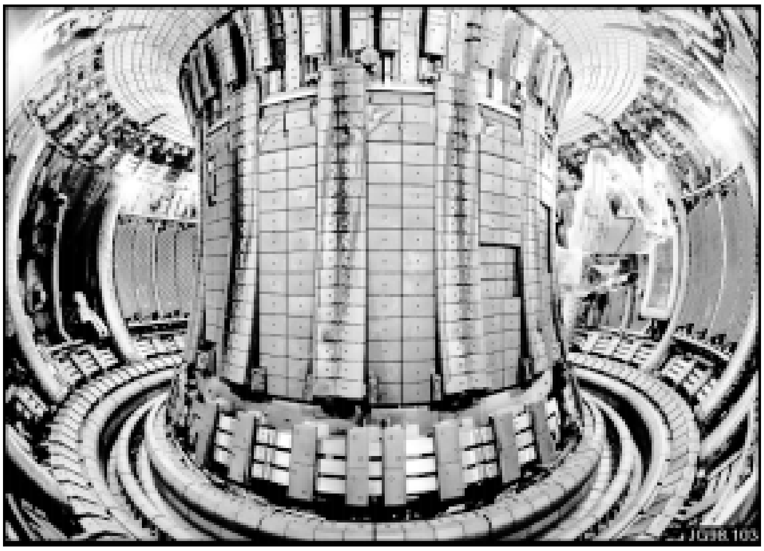

Figure 3 Inside of JET Torus after modification - May 1998

2. REMOTE HANDLING REQUIREMENTS AND CONSTRAINTS

The original, MkIIa, divertor comprised a ‘U shaped water cooled mechanical structure onto which are bolted the 144 MkIIa divertor modules, figure.4. It was required to remove these and replace them with 192 MkIIgb divertor modules of similar size but different shape. In addition to this primary task it was required to clean four Beryllium evaporators, vacuum clean dust and flakes from the divertor region, replace a number of small diagnostic components, inspect the torus protective tiles and undertake a full 3-dimensional survey of the divertor support structure to an accuracy of less than 1mm using digital videogrammetry techniques.

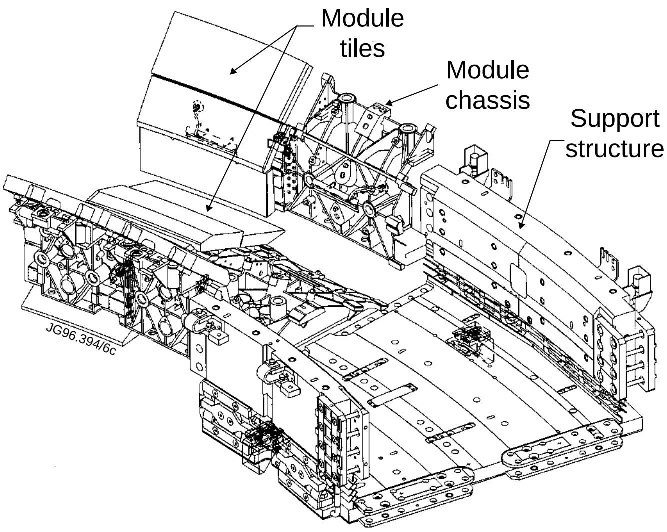

Figure 4 JET MkIIa Divertor construction

The D-T operations made use of a 10gm site tritium inventory and resulted in an activation of the torus giving a background in-vessel dose rate of 4.5 mSv/hr at the start of the remote handling shutdown. Personnel working in this level of radiation would receive their entire JET annual allowed exposure within 1 hour.

3. DIVERTOR DESIGN

The JET divertor is a key system inside the torus and is designed to remove impurities from the plasma. The energy contained in the plasma is large and the MkII divertor has been designed to be able to absorb 20MW of power for 10 seconds duration. The divertor tile surfaces exposed to the plasma must be very accurately aligned in order to avoid creating hot spots during the energy transfer. For the same reason the tile surfaces and edges must not be damaged during installation.

The MkII divertor, figure.4, has been designed for remote handling and comprises a 'U' shaped divertor support structure onto which are bolted modules whose tiled surfaces form the divertor shape. The support structure incorporates dowel slots to ensure the precise alignment of divertor modules and also incorporates pre-wired electrical sockets into which diagnostics attached to the divertor modules can be remotely plugged.

The Mark IIa divertor modules were designed with large carbon fibre reinforced carbon composite (CFC) tiles supported by accurately machined Inconel modules with the tile corner supports shared between adjacent modules. The precise tile alignment thus achievable was dependent only on the accuracy of the tile machining (±0.05mm). The modules were arranged one each on the inner, outer and base surfaces of the divertor structure, figure.5.

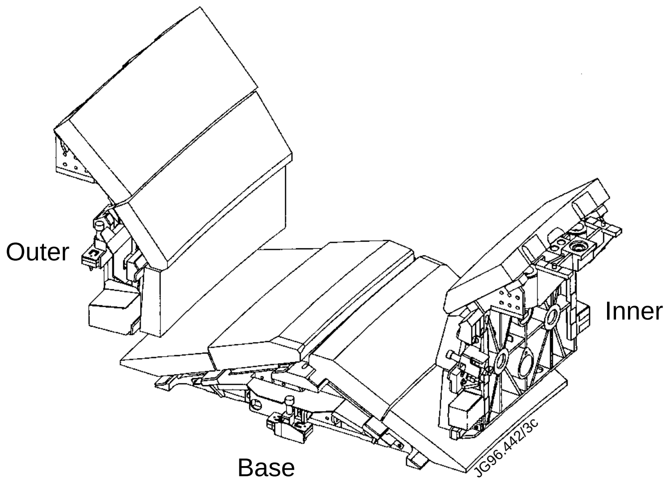

Figure 5 MKIIa Divertor Modules

The MkIIa divertor target tiles were fixed to the module structure by locating dowels and spring loaded bolts. The material strength across the fibre direction is enhanced with tie rods in tension to avoid crack initiation also to ensure that in the very rare circumstance of a tile cracking no parts could fall off the modules.

Diagnostic sensors are attached either on to the modules themselves or directly to a remote handling plug. In both cases the insertion and retraction of a plug into and from a socket attached to the support structure was designed for remote handling.

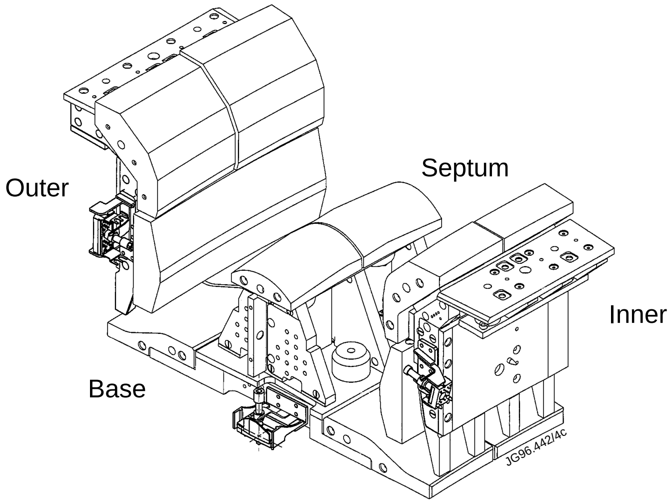

Figure 6 MkII Gas Box Divertor Modules

The captive bolt assemblies float within the modules to prevent side loads on the bolts and thereby minimise the risk of seizure during operation. In the unlikely event that they become damaged both the bolts and the aluminium bronze nuts to which they attach are remotely replaceable.

The MkII gas box divertor modules differ in configuration and design from the MkIIa. The gas box divertor has four modules one each on the inner, outer and base surfaces of the divertor structure and an additional so-called Septum module which is bolted onto the base module, figure.6. The MkIIgb modules comprise CFC tiles mounted on a pre-fabricated CFC module structure. The modules are aligned and bolted to the divertor structure in a similar way to the MkIIa.

4.OVERVIEW OF THE OPERATIONAL SCENARIO

All in-vessel work was done fully remotely by means of the Mascot servo-manipulator (1) transported into the torus through a rectangular access port by the JET Articulated Boom (2), figure.7. All other equipment required inside the torus was transferred through a second port using a special end-effector mounted on a short articulated boom (3). After removal the activated divertor modules were stored on trolleys within removable ISO cabins, figure.7.

The radiation dose rates in areas outside the torus vacuum vessel were low enough to allow 95% of all ex-vessel work to be performed manually. The only exception to this was the handling and storage of activated MkIIa modules removed from the torus which required the use of fully remote handling transfer to shielded storage cabins.

To prevent contamination spread the torus and the attached operational areas were purged with air and maintained at a depression relative to the surrounding Torus Hall.

Each MkIIa module was removed following a sequence of handling tool attachment, untorquing, unbolting and transfer. The operation on each module required a module handling tool and an associated set of wrenches and temporary protective covers. The complete suite of tools and covers for handling one module are integrated together and were moved around the torus in sequence with the module removal. Each module was removed from in-situ with the Boom in a single and fixed location with all tools within arms reach for the Mascot thereby minimising the number of boom movements.

The reverse approach was adopted for the MkIIgb installation sequence.

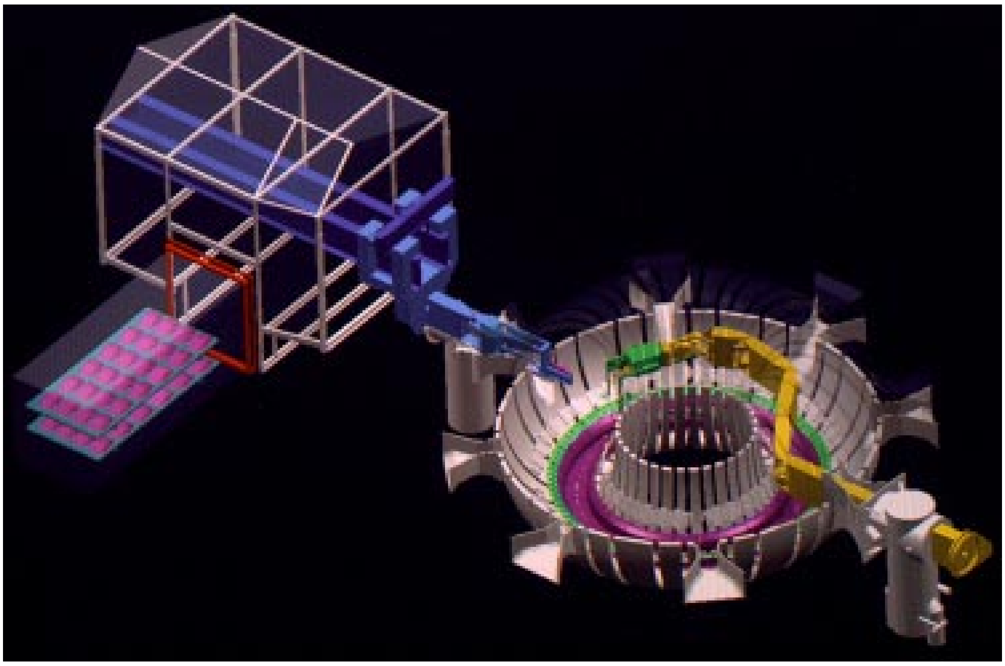

Figure 7 Overall remote operations scenario

5. EXECUTION OF THE PLANNED TASKS

5.1 Removal of the MkIIa Divertor

The removal of the MkIIa modules was planned to be done by first removing the 48 inner ring of modules followed sequentially by the Outers and the Bases. The design of the components required that this removal sequence be interrupted at two points for removal of three small radio frequency waveguides and the replacement of the diagnostic connector sockets on the divertor structure. Also, in order to remove the 48 Outer modules it was first necessary to remove and temporarily store inside the torus 96 rectangular carbon tiles spaced equally all around the torus.

The removal of all 144 MkIIa divertor modules was successfully achieved using the pre-planned techniques. The 480 attachment bolts were successfully released with the unfastening torque found to be typically within 20% of the installation fastening torque. The worst case was one bolt which required a torque 90% greater than the fastening torque. One unexpected aspect was the partial sticking of some of the inconel modules to the inconel divertor structure. Post removal inspection suggests this to be caused by partial diffusion bonding. Not all of the modules suffered from this effect but those that did were more difficult to remove and required the Mascot operator to impart a twist or shearing motion on the module at the same time as lifting with the winch. A problem was experienced during the removal of one of the small rf waveguides which required a change to both the method of removal of the waveguide and also to the overall operations sequence. This unplanned event and its solution is discussed fully later in section 8.1.

After removal of the MkIIa modules it was necessary to clean the four Beryllium evaporator heads and the divertor support structure using a remote handling compatible vacuum cleaner and then to undertake a full 3-dimensional digital photogrammetry survey of the divertor structure and other selected in-vessel components (10). These operations were implemented as planned with no problems.

5.2 Installation of the MkIIgb Divertor

The installation of the MkII gas box divertor modules was planned as a sequential operation starting with the Bases followed by the Outers the Inners and finally the 48 Septum modules. A new set of radio frequency waveguides were to be installed at the appropriate point in this sequence. All of these operations were implemented as planned with minor changes to the order in which modules were installed which was necessary to accommodate some unexpected tasks as discussed later.

5.3 Other tasks

The remote handling operations were facilitated by the installation into the torus of an eight camera viewing system and a range of temporary storage trays. These systems were installed and connected in the torus as soon as possible after gaining access and then were removed at the end of the operations with no problem.

The remote handling operations were carefully planned to ensure the safety of both the JET in-vessel components and the remote handling equipment itself. Accordingly it was necessary to temporarily remove a small number of vulnerable carbon tiles from the torus and to install temporary protection covers over other vulnerable components. These operations were also successfully completed with no problems.

Planned visual and radiological surveys were conducted using the remote handling cameras and Mascot to deploy a Gamma monitor. The video survey was designed to be an automatic sweep of every visible part of the torus internal elements but interrupted at various locations to enable manual control of the camera to be used to perform detailed close up inspections. The video survey was recorded and subsequent inspection using the video revealed further regions of the torus where a revisit for close up inspection was required. These operations were successfully completed over a 3 day period at the start of the shutdown and repeated at the end of the shutdown. The gamma radiation monitoring was successfully achieved using a hand-held monitor in the Mascot gripper and with the dial reading visible from the remote handling cameras. To obtain the maximum sensitivity of readings at various locations in the torus it was necessary for the Mascot operator to change the dial readout scale setting by rotating a plastic knob on the meter.

All of the above tasks and operations were defined, planned and prepared well in advance. However, as with all JET shutdowns, a number of essential tasks were only requested at the last moments before the start of the shutdown. The first involved the systematic sampling of dust from the surfaces of the divertor modules and surrounding areas. This required the design and implementation of a vacuum cleaning system with special nozzle and an exchangeable cyclone filter to facilitate the subsequent sample analysis. The second task was to be able to measure the transmissibility of four diagnostic visible spectrum windows using a laser source outside the torus and a reflector positioned inside the torus. The flexibility of the JET remote handling system allowed the tools and procedures for these tasks to be prepared within a short time and mock-up validation was able to be completed before the shutdown started. No unexpected problems were encountered during the actual operations.

5.4 Task Analysis

During the shutdown the time taken for every operation was logged. Many of the tasks had previously been performed inside the torus by manual means during other shutdowns and table.1 compares task operations rates using remote handling methods with the manual rates.

Task	Remote	Manual	Rate	Notes
Installation of MkIIa Divertor modules (c1996)	-	0.38	units/hr	Manual rate is for one team. Two teams are usual.
Removal of MkIIa Divertor modules	0.43	-	units/hr	
Installation of MkIIgb divertor modules	0.55	-	units/hr	
Full torus inspection	16	8	hrs	Remote Inspection provides a full video record.
Divertor 3-D Videogrammetry	32	20(E)	hrs	Manual implementation would include remote camera deployment.
Replacement of small diagnostic electrical sockets	4	8(E)	units/hr	Manual rate is for one team. Two teams are usual.
Inner wall Tiles	2.1	5	units/hr	Manual rate is for one team. Two teams are usual.

NB. (E) - Estimate

Table.1 Comparison of operations performance rates for Remote and Manual implementation of tasks

6.EXECUTION OF THE UNPLANNED TASKS

A number of unexpected events occurred during the shutdown which required immediate assessment and new operations to be implemented. In each case whilst the necessary tooling, procedures, Boom teach files and Mascot moves could be created and visually checked off-line no practical mock-up trials or operator training was feasible before the actual task was performed inside the torus.

6.1 Removal of a damaged waveguide

The first major alteration to the planned operations occurred when it was discovered that the Outer waveguide of a microwave diagnostic was unable to be unbolted even at a torque close to its expected yield. Unfortunately the waveguide mechanically trapped one of the MkIIa Outer modules in situ and after an assessment of the situation and a further unsuccessful attempt to dislodge the waveguide by rocking the divertor module it was decided to prepare two mechanical levering tools, an inspection boroscope, an inspection lamp and a electric shear capable, if necessary, of cutting the waveguide into two. After three days the equipment was ready and taken into the torus. The waveguide fixing bolt is some 200mm below the visible surface of the divertor structure and so 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 with Mascot to move the waveguide to relieve the strain. The bolt was then able to be unfastened and the waveguide was successfully removed using the second lever device and Mascot fingers. The operations inside the torus during analysis and final removal of the waveguide resulted in a loss of 1 day.

6.2 In-situ cleaning of Divertor modules

The second major unexpected task was the requirement to vacuum clean the MkIIa divertor Base modules before they were removed from the torus. A system had been prepared to clean the divertor structure after all of the modules had been removed and this relied on being able to place the vacuum cleaner onto the previously cleaned part of the divertor structure. In order to implement the new task it was necessary to prepare a temporary platform which was deployed above the Base modules onto which the vacuum cleaner was placed. This operation was successfully implemented within one week of its request with only 1 day interruption to the shutdown.

6.3 Tritium sampling

Half way through the shutdown it was requested to sample tritium in the atmosphere overnight during the remote handling operations quiet period from 0200-0600hrs by deployment of a tritium bubbler within the torus. A bubbler was packaged into a receptacle which could be handled with the Mascot and could be serviced during the daytime by Health Physics personnel.

This system was prepared and successfully deployed for 5 nights with no loss of shutdown operations time.

6.4 Removal of newly installed MkIIgb modules

During the installation of the MkII gas box modules it was necessary to manually check the electrical continuity of all divertor diagnostic systems which had been connected through the remote handling plug and socket using Mascot. None of the connections made remotely was found to be faulty, however one of the Base modules was found to have been wired incorrectly resulting in the loss of a vital halo current detection coil. It was decided that this should be rectified by removal of the Base module and by manual modification of the connector outside the torus. The removal of a Base module containing a diagnostic connector requires the additional removal of its two adjacent modules, consequently three modules were removed, the repair was effected and all three were successfully re-installed.

6.5 Cleaning of quartz windows

The final major interruption to the planned operations involved an unscheduled requirement to clean two 90mm dia. quartz windows at the bottom of one of the main vertical ports. These windows had become obstructed by some of the dust and flakes falling from the divertor region. The windows are 1750mm below the surface of the divertor structure with a line of site access through a slot in the divertor of 12mm x 35mm. Experience from previous manual cleaning of the windows indicated that this was a task of the highest level of difficulty with an inherent risk of damage to the windows. In view of the short time available for preparation it was decided to adopt a vacuum cleaning approach and a 2500mm long 11mm dia nozzle was designed and tested. The equipment, task plan, procedure and teach files were created and made ready within 9 days of the task request and the task was successfully completed within a single $10^1/_2$ hour shift inside the torus. As the work inside the torus required the removal of three Outer modules previously installed the total interruption to the shutdown was 1 full day.

6.6 Housekeeping

In addition to the major unexpected tasks described above there were a number of other unplanned events which were able to be overcome with insignificant interruption to the shutdown program. A number of small items of debris were found inside the torus which had to be either picked up and disposed of using Mascot fingers or as in the case of displaced fibrous packing material and fixing clips had to be pushed back into place using Mascot. Two of the MkII gas box modules could not be installed as planned. One module interfered with the housing of a fixed bolometer and in the second case the handling tool clashed with a gas shield. In each of these cases the interference was with sheet metal items made to suit by hand in previous shutdowns. In both cases the solution was to remove the module and tool from the torus and to manually cut off material to relieve the interference.

Of vital importance to finding a solution for all of the unexpected events described above and in many other cases was the ability of the JET remote handling system to be used as if a man were inside the torus thereby providing the Operations engineers with the tools for ad-hoc manipulation, inspection and diagnosis. For example the analyis of the mechanical interference problems was only possible because we were able to test various hypotheses by offering up the components in a free form way and at the same time inspecting the module and the infrastructure. Similarly the decisions to proceed with new tasks was taken only after detailed inspection and analysis of the relevant parts of the torus.

7. PERFORMANCE OF THE REMOTE HANDLING EQUIPMENT

The JET remote handling equipment has been developed over many years and was prepared using formal methods to ensure its suitability for the tasks and its reliability (11)(12). The equipment was utilised for 16hrs per day and 6 days per week with Sundays being used for systematic inspection and testing.

The articulated boom was used throughout the shutdown with just two failures requiring a significant interruption to operations. In both cases an open circuit fault developed on one of the 1000 cores and 15000 connections comprising the Boom wiring system. A motor wire on the boom camera arm failed with the arm in a position which made it impossible to remove the boom from the torus. The inability to electrically drive the camera arm motor made it impossible to stow the arm without external assistance and in the limit it would have been necessary to insert a recovery Mascot into the torus through the port opposite Boom entry to effect a recovery. However,the Mascot on the end of the main Boom was manouvred into position and used to backdrive the actuator and push the camera arm back to its stowage position. There were no other significant failures of the Boom system during the shutdown and no adverse indications were detected in the characteristics of the servos, sensors or actuators during the weekly inspections and tests.

The Mascot performed flawlessly during the entire shutdown period.

Over 100 remote handling tools were prepared and used during the shutdown. With the exception of a seizure of one radio frequency waveguide handling tool and the divertor module handling tool interference discussed earlier there were no problems with the tooling.

The camera systems inside the torus were crucial to the safety and efficacy of the operations. There were no failures of any camera inside the torus and with the excellent illumination provided by lighting from the JET In-Vessel Inspection System the quality of the camera images was excellent.

There were no significant faults or interruptions due to problems with any of the remote handling system electrical power, communications or pneumatic service systems.

The JET remote handling Fault Reporting and Corrective Action System (6) was in use during the shutdown and an average of 7.2 faults were reported per week. Of these only the two discussed above caused a delay in the shutdown of more than 30mins. The general level of equipment Availability was consistent with that experienced during mock-up operations with Boom and Mascot both operating at or above 98%.

8. OPERATIONS ORGANISATION AND MANAGEMENT EXPERIENCE

The shutdown plan was implemented on a 2 shift operation providing 16 hours of in-vessel work each day. Each shift was staffed by an operating team comprising a Boom operator, a Mascot operator an Operations Engineer and a deputy Operations Engineer. Three complete teams were trained for the shutdown in order to provide a rest period and cover for sickness. Hand-over between shifts was managed with a daily meeting.

The shutdown operations were planned and prepared in advance with formal operations documentation and comprehensive operator training (8).

The operations personnel were provided with training for normal operations and also provided with instructions on what to do in the event of equipment failure situations. 45 task plans and 390 detailed operating procedures were used during the shutdown.

The operations were implemented by three operations teams each comprising an Operations Engineer, a deputy and two operators. Over the 15 week shutdown period the two shift operation meant that one team was always available for use in the event of sickness. Each $10^1/_2$ hour shift comprised two 4 hour operating periods with lunch break and an interface meeting between the teams. The organisation worked very well, operations were implemented safely, communication was efficient and personnel remained motivated and effective throughout. Whilst sickness did occur there were no interruptions due to either operator error or sickness.

Equipment faults and failure rectification were dealt with by a team of on-call support engineers. The on-call engineers were trained to be able to diagnose faults down to a Line Replaceable Unit and a set of spares was prepared in advance of the shutdown. The on-call engineers were required on an average of 1 occasion per week.

9. CONCLUSIONS

The JET experimental programme required that a major torus system be replaced using only Remote Handling methods during the first half of 1998.

The JET remote handling system originally envisaged to satisfy one-off repair and maintenance type tasks adopted the philosophy of man-in-the-loop teleoperation in order to ensure maximum flexibility of approach. It was this flexibility that facilitated the preparation for the new major modification type task with minimum cost and time.

The remote handling shutdown was successfully concluded on time at the end of May 1998.

Over 450 individual components were remotely handled within the JET torus during a 15 week period operating 20 hrs per day, 6 days per week.

The 38 pre-planned tasks were implemented with minimal operational problems or procedural variations.

The time taken to achieve many of the tasks was comparable to the time which would have been taken to perform the same work manually.

The successful conclusion of the pre-planned shutdown tasks was the result of the flexibility of operation provided by the man-in-the-loop approach and the detailed and rigorous preparation of the equipment, procedures and training.

The JET remote handling equipment functioned almost flawlessly throughout the shutdown with only 2 significant faults occurring over the entire period. The total operational time lost due to equipment problems was less than 3 days.

As found in many previous manual JET shutdowns a number of new tasks had to be included in the operations at short notice. Ten unplanned tasks were identified only after operations in the torus had started. All of the unplanned tasks were successfully completed and whilst they took longer to implement inside the torus than if they had been fully prepared using the mock-up the total interruption to the shutdown was insignificant due to time saving in other well rehearsed tasks.

The successful completion of the un-planned tasks was due to the adaptability of the man-in-the-loop based JET remote handling system. The telepresence capability provided by the system coupled with the skill of experienced operations staff allowed the work to be implemented as if it were being done manually inside the torus. Without this capability many of the unplanned tasks would not have been possible to perform without significant delays to the shutdown program.

10. REFERENCES

(1) L.Galbiati, T.Raimondi, “Control and Operational Aspects of the Mascot 4 force feedback servomanipulator of JET”, 14th Symposium of Fusion Engineering, San Diego, 1991

(2) T.Raimondi, “ The JET Remote Maintenance System”, Proc IAEA Technical Meeting IAEA-TECDOC-495, Karlsruhe, 1988

(3) L.Jones, et al, “Design and development of a new transporter facility for JET”, 19th Symposium on Fusion Technology, Sept 1996, Lisbon

(4) A.Rolfe, “Remote Handling on Fusion Experiments”, 19th Symposium on Fusion Technology, Sept 1996, Lisbon

(5) S.Mills, A.Loving, “Design and development of RH tools for the JET divertor exchange”, 19th Symposium on Fusion Technology, Sept 1996, Lisbon

(6) A.Rolfe, et al, “The assessment and improvement of JET remote handling equipment availability”, 19th Symposium on Fusion Technology, Sept 1996, Lisbon

(7) R.Cusack, et al, “The implementation of a full size mock-up facility in preparation for remote handling of JET divertor modules”, 19th Symposium on Fusion Technology, Sept 1996, Lisbon

(8) R.Cusack, et al, “Operational experience from the JET remote handling tile exchange”, 20th Symposium on Fusion Technology, Sept 1998, Marseille

(9) S.Mills, A.Loving, “Remote bolting tools for the JET divertor exchange”, 20th Symposium on Fusion Technology, Sept 1998, Marseille

(10) B.Macklin, et al, “The remote photogrammetric survey and engineering analysis of the divertor structure during JET’s remote tile exchange”, 20th Symposium on Fusion Technology, Sept 1998, Marseille

(11) L.Galbiati, et al, “Experience from remote handling equipment support during the Remote Tile Exchange”, 20th Symposium on Fusion Technology, Sept 1998, Marseille

(12) A.C.Rolfe et al, “Preparations for the fully remote exchange of JET divertor modules”, 17th Symposium on Fusion Energy, San-Diego, Oct 1997