The Exchange of JET Divertor Modules using Remote Handling Techniques

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ABSTRACT

The Joint European Torus (JET) project was set up under the auspices of 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 September and October 1997 a series of experiments was performed in the JET machine using a Deuterium-Tritium (D-T) mixture, the fuel to be used in future fusion reactors. This has resulted in an activation of the torus to a level which prevents extended manual interventions for about one year.

The JET remote handling equipment was originally specified, designed, built and commissioned to satisfy a general repair and maintenance function. 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 has been implemented.

In 1994 a new requirement for a major modification to the JET torus using only remote handling methods was defined and, although a significant departure from the original requirements, the adaptability of the original Remote Handling system has allowed it to be applied to this new task with minimum modification.

This paper describes the preparations for this first fully remote handling shutdown for JET.

I. 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 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.

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 thereby 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.
However, during September and October 1997 a series of D-T experiments were performed in the JET machine and these have resulted in a significant increase in the vacuum vessel radioactivity to a level which renders the torus inaccessible to personnel for anything other than the most brief tasks for around one year.
Figure.2 shows the inside of the torus in 1996. 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.

The JET divertor study programme requires that in early 1998 the divertor must be replaced with an alternative configuration and the activation levels dictate that this modification must be done using only remote handling methods.

A suite of remote handling equipment was originally specified, designed, built and commissioned to satisfy a general repair and maintenance function for JET during a final operational phase when significant amounts of D-T were to be used. 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 include a major modification to the JET torus but the inherent adaptability of the teleoperation philosophy has allowed its application with little modification.

II REMOTE HANDLING REQUIREMENTS AND CONSTRAINTS

The present, MkIIa, divertor comprises a ‘U’ shaped water cooled mechanical structure onto which are bolted 144 MkIIa divertor modules, fig.3. These are to be removed and replaced with 192 MkIIgb divertor modules of similar size but different shape. In addition to this primary task it is required to clean four Beryllium evaporators, vacuum clean the divertor region, replace a number of small diagnostic components, inspect the torus protective tiles and undertake a 3-dimensional survey of the divertor support structure using videogrammetry techniques.

The D-T operations have made use of a 20gm site tritium inventory and have resulted in an activation of the torus giving an in-vessel dose rate of 4000µSv/hr at the start of the remote handling shutdown. Extensive use is made within the torus of Beryllium presenting a toxicity hazard when gaining access to the torus.
III. OVERVIEW OF THE OPERATIONAL SCENARIO

All in-vessel work will be 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], fig.4. All other equipment required inside the torus will be transferred through a second port using a special end-effector mounted on a short articulated boom [3]. After removal the activated MkIIa divertor modules will be stored on trolleys within removable ISO cabins.

Figure 4 Overall Remote Operations Scenario

The dose rates expected to prevail in areas outside the torus fall rapidly to levels which allow 95% of all ex-vessel work to be performed manually. The only exception to this is the handling and storage of activated MkIIa modules removed from the torus which require the use of fully remote handling transfer to shielded storage cabins.

During the entire shutdown period the torus and the attached operational areas will be purged with air and maintained at a depression relative to the surrounding Torus Hall.

Each MkIIa module will be removed following a sequence of handling tool attachment, untorquing, unbolting and transfer. The operation on each module requires 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 moved around the torus in sequence with the module removal. Each module will be 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 is adopted for the MkIIgb installation sequence.
IV. DIVERTOR DESIGN

The MkII divertor, fig.3, was designed to facilitate an exchange in an activated environment by remote handling.

The ‘U’ shaped divertor support structure incorporates dowel slots to ensure the precise alignment of divertor modules as well as serving to cool the target tiles by radiation. It also incorporates pre-wired electrical sockets into which diagnostics attached to the divertor modules can be remotely plugged.

The Mark IIa divertor modules are 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 is dependent only on the accuracy of the tile machining (±0.05mm).

The divertor target tiles are 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 will 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 is designed for remote handling.

The divertor modules have features incorporated which make them compatible with the remote handling tools.

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.

V. REMOTE HANDLING EQUIPMENT DESIGN

As far as possible the operational scenario has been developed with a view to using the already developed JET Remote Handling equipment. In this way both the costs and the development risks associated with new equipment have been minimised. The general philosophy for remote handling at JET has been to develop a flexible system based on a man-in-the-loop control strategy able to be deployed to undertake any one of a large number of potential remote repair type tasks [4].

General equipment

The Articulated Boom is a 10m long, 18 degree of freedom, robotic transporter with a control system capable of providing single joint, multiple joint and resolved motion operation. It can be pre-programmed with motion sequences for any number of degrees of freedom contemporaneously. It has built-in low level and high level safety features to prevent uncommanded motions,
position, velocity and motor current limits and collision warning. It has one camera mounted on a 1 m long robotic arm attached at the front of the boom. The Boom is housed within a contamination control enclosure which will be sealed to the torus.

The Mascot servomanipulator is a bi-lateral, force-reflecting servo-manipulator with 20kg capacity and 100gm tactile sensitivity per arm. The Mascot operates in Master-Slave configuration with additional features for force scaling, gravity compensation and teach-repeat provided by the digital control system. At JET the Mascot slave is configured with a miniature camera attached to each forearm on a passive mount and also has and one pan/tilt camera and a 50kg winch mounted between the shoulders.

General purpose viewing in-vessel is by means of four fixed pan/tilt camera units and two miniature cameras on pan/tilt heads which can be remotely positioned anywhere using the Mascot.

The Tile Carrier Transfer Facility (TCTF) comprises a short version of the articulated boom with a special end-effector designed to facilitate component transfer between the torus and special trolleys located in storage cabins. The short boom and trolleys are housed in the TCTF contamination control enclosure which itself is sealed to the torus during operations. The storage cabins are sealed to the TCTF enclosure by means of a 2m x 2m double door system designed and developed at JET.

**Divertor Module Handling Tools**

A concept for handling of the divertor modules was derived to satisfy the objectives of minimising the complexity of the tasks whilst maximising the safety and speed of operation [5]. This was achieved by designing handling tools which deskilled the repetitive tasks by transferring the difficult divertor module alignment control to the tools themselves.

The gaps between the adjacent tiles are nominally 4mm, but tolerance build ups can result in minimum clearances of only 1.4mm. Installation has to be achieved without damage to the sharp tile edges which are critical to the divertor performance.

The handling tools form the interface between the Mascot and the divertor modules and their primary function is to support the weight of the divertor modules and transport them within the torus. They also provide a means of handling that prevents damage to the critical edges of the tiles and guidance for the hexagonal keys which must pass between the divertor tiles to reach the module fixing bolts.

The interlocking design of the MkIIa divertor requires the installation of modules between two previously installed modules. This is conveniently achieved by leaving the module handling tools attached to the two already installed modules during the fitting of the third module which enables them to be used to provide accurate guide features for the handling tool on the
third module. Once these guide features are interlocked it is impossible for the modules to collide fig.5.

The same handling concept is used during both module installation and removal.

**Bolting Tools**

Divertor module fixing bolts are driven with hexagonal keys which locate in guides on the handling tools. Bolting operations are performed with tools directly operated using Mascot.

A ratchet driver is used to run the bolts in “finger tight”. Using alternate grasping features it can also be used for unbolting. It employs virtually friction free roller clutches so that it works even when the bolt is very loose.

The bolts are torqued to 35Nm using a pre-set slipping torque wrench with a multiplier and an indicator lamp. A double ended wrench is available for use up to 90Nm if required for releasing of tight bolts.

**VI. PREPARATION OF EQUIPMENT FOR OPERATIONS**

**Reliability and Response to Faults**

The success of any significant remote handling operation is dependant on the good reliability and repairability of the remote handling equipment. A programme of work was initiated in 1995 to assess and improve all aspects of the JET remote handling equipment Availability [6]. Fault reporting and fault isolation procedures are vital to the maximisation of overall Availability and a formal Fault Recording and Corrective Action System has been in operation at JET since 1994 [6]. The system provides operators with facilities to record details and actions taken for each fault. The completed reports are reviewed weekly by the equipment support personnel and any consequent design or operations actions are included in the forward programmes. This process has resulted in an environment of continuous development and reliability improvement.

The Mean Time To Repair is significantly affected by the component spares available at short notice. It is not economic to retain a full stock of all items as spares and so a strategy based on component availability and probability of failure has been implemented.
Equipment Recovery from Failure

A fail safe and fail recoverable policy has been applied to all aspects of JET remote handling equipment design.

In the case of a failure of parts of the remote handling equipment that will operate within the torus, methods have been devised to withdraw the equipment from the torus for repair. In the worst case it may be necessary to deploy ex-vessel remote handling equipment into the torus through a second port to render the equipment into a recoverable state.

Contingencies for Unplanned Events

Considerable effort and resources have been invested in making contingency provisions for dealing with unplanned events due either to torus component or Remote Handling equipment failures during the shutdown.

All of the divertor modules have been designed to enable their handling even if the tiles are cracked or broken, if the bolts fixing the module to the support structure are seized or if the primary attachment points for the handling tools to the modules is obstructed.

In the event that it is required to undertake tasks as a result of failures for which no specific preparations have been made the problem will be assessed and tackled in an incident response type of situation making use of the adaptability of the teleoperational approach by using operators to undertake tasks to a large extent as if they were being done manually.

Inclusion of new tasks

The adaptability of the JET Remote Handling system can facilitate the preparation of new tasks at relatively short notice. This is an essential feature for remote handling of an experimental device such as JET and new tasks which require the minimum of tooling development and new Boom manoeuvres can be accommodated with only a week or two of preparation. Two new tasks were added to the divertor shutdown after requests were made only 4 weeks before the start of the shutdown. The first involved the collection of dust from tile surfaces inside the torus and the second required the positioning of a mirror system inside the torus to facilitate a measurement of the light transmission through diagnostic windows.

VII. OPERATIONAL TRIALS

Operator Training

The in-vessel tasks require highly skilled operators who are both fully familiar with the remote handling equipment and also with the tasks required to be performed. A comprehensive training programme for all tasks has been implemented including methods for dealing with both normal and failure situations [4].
Training and re-familiarisation will continue in parallel to the shutdown operations to ensure that operators are fully prepared immediately prior to doing the real task.

Mock-up Programme

Many years of manual shutdown experience at JET has shown that to ensure efficient work it is essential to comprehensively prepare procedures and train operators using full scale mock-ups. This is even more relevant for remote handling tasks where unexpected procedural problems can cause severe delays. This has been achieved by constructing a full size mock-up [7] using dimensional information taken from the tokamak as-built metrological surveys and by deploying the real remote handling equipment for mock-up trials.

Extensive mock-up operations have already taken place and all required tasks have been proven to be feasible. The final shutdown preparations have made extensive use of the mock-up facility for procedural validation, operator training and rehearsal.

JET Torus Trials

In order to prove that preparations made by use of the full scale mock-up facility are valid when transferred to the actual torus, the opportunity was taken during the MkIIa Divertor first installation shutdown to install 33 divertor modules by fully remote handling inside the real torus, fig.6.

VIII CONCLUSIONS

The JET experiment requires that a major torus system be replaced using only Remote Handling methods during early 1998.

The JET remote handling system originally envisaged for one-off repair and maintenance type tasks adopted the philosophy of man-in-the-loop teleoperation in order to ensure maximum flexibility of approach for a task definition which could not be accurately predicted at the beginning of the Fusion experiment. It has been this teleoperation type of approach which has facilitated the preparation for the new modification type task with minimum cost and time.

Preparations for the fully remote replacement of the JET divertor system are now complete and a system comprising equipment, procedures and staff is ready for this first remote
handling shutdown at JET. The preparations have included contingencies for the possibility of remote handling equipment or JET component failures during the shutdown and the equipment necessary to ensure recovery from the worst case situations envisaged are in place.

The adaptability of the JET Remote Handling system has been demonstrated by the preparation and incorporation into the shutdown plan of two additional tasks identified as late as only one month before the start of the shutdown.

IX. REFERENCES