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** See annex of M.L. Watkins et al, "Overview of JET Results ",*
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ABSTRACT

During the EP2 (Enhanced Performance 2) shutdown, planned to start in summer 2009 and to last for over 1 year, the JET tokamak will be upgraded to incorporate an ITER-like all-metal wall. Operating experience with this type of wall will aid ITER in their design choice for plasma facing components in divertor and plasma heating systems.

It is essential that this extensive in-vessel refurbishment be completed in the shortest possible time and this has necessitated the implementation of a significant enhancement of the remote handling system.

A new deployment method for RH tools and components has been devised comprising an extension to the articulated Boom, which enters the JET Vessel through the Octant 1 port. In the EP2 shutdown this will transport a multi-drawer task module to the workplace of the MASCOT (the JET servo-manipulator), which itself is deployed by the existing Octant 5 Boom. The new Octant 1 Boom can remotely exchange its task module inside the Octant 1 Boom Facility.

This new Boom system will save time by eliminating the need for the existing Octant 5 Boom to frequently move around the torus in order to fetch new tools and components. It also reduces the dependence on manned entries in pressurised suits into the Octant 1 Boom facility to load the tool and component racks.

In addition, the very large number of remote handling tasks demanded by the JET EP2 upgrade has required the design and development of an extensive range of new remote handling tools, examples of which will be described.

This paper will discuss the design, control and operation of all the new remote handling equipment being developed at JET in preparation of the EP2 shutdown. It will also discuss the advances being implemented in management and presentation of operational data within the command, control and HMI (Human Machine Interface) system.

1. INTRODUCTION

During the EP2 (Enhanced Performance 2) shutdown, planned to start in summer 2009 and to last for over 1 year, the JET tokamak will be upgraded to incorporate an ITER-like all-metal wall [1]. Operating experience with this type of wall will aid ITER in their design choice for plasma facing components in divertor and plasma heating systems.

It is essential that this extensive in-vessel refurbishment be completed in the shortest possible time. A time and motion study resulted in the introduction of significant enhancements of the remote handling system at JET in order to achieve productivity gains.

The following chapters will describe the new remote handling equipment designed to streamline the remote handling operations, as well as all the new tools for the servo-manipulator, which are needed to interface with the myriad of new vessel components which will have to be installed remotely during the EP2 shutdown.

2. THE JET EP2 SHUTDOWN

The JET EP2 refurbishment shutdown requires the removal of over 4000 CFC tiles from the vacuum vessel and their replacement with an ITER-Like Wall (ILW) of solid beryllium, beryllium coated inconel, solid tungsten and tungsten-coated Carbon Fibre Composite (CFC) tiles. Tasks also include a major upgrade of diagnostic equipment and the replacement of Divertor components, including a toroidal row of tiles in the ‘load bearing septum replacement plate’, which will become solid tungsten tiles. This work will be done using the JET remote handling system. In order to complete this extensive programme in a timely fashion it is necessary to maximise the operational efficiency of the remote handling facility.

3. THE OCTANT 1 BOOM

The JET remote handling system comprises two articulated Booms that access the vessel through diametrically opposite ports. The Octant 1 Boom is used to transfer components and equipment. The Octant 5 Boom transports and positions the Mascot force reflecting manipulator. The original configuration of this Octant 1 Boom could only just reach into the vessel at Octant 1. Hence, the Octant 5 Boom was required to travel to Octant 1 to collect and deliver tools and components. It was recognised that a significant benefit can be achieved by the Octant 1 Boom delivering components and equipment to the point of use in-vessel [*figure 1*].

3.1 THE BOOM UPGRADE STRATEGY

A concept of using Task Modules [*figure 2*] to deliver in-vessel components and tools to the point of use for Mascot was devised. The Task Module is a Stainless Steel fabricated framework. Its external bounding dimensions are 875mm high, 1050mm long and 380mm wide which is the maximum size that can be passed through the vessel port and manoeuvred around the torus. Within the framework are 6 drawers that can be independently extended from either side. The drawers are each capable of carrying a distributed load of 100kg. Components are located in the drawers on trays or in open boxes to present them conveniently to the Mascot. A tray, located between the upper longitudinal side members, is used for the storage of small tools.

In order to transport a Task Module in vessel, the existing Octant 1 Boom has been upgraded. This involves the replacement of the Boom Addition and End-Effector with a Boom section comprising 5 new links totalling over 8m in length [*figure 3*]. Each link has a yaw axis with a motion of $\pm 120^o$ and a rotation speed of up to 3.0^o/sec. The translation trolley and Rail system which provides 7.8m of linear travel is retained from the original Oct 1 Boom. Hence the Boom can now reach 75% of the in-vessel region. It should be noted that it is unnecessary for the Octant 1 Boom to reach 100% of the vessel as the Octant 5 Boom and Mascot require an adequate working envelope within the remaining space.

The Task Module is attached to the end of the Boom by means of an end-effector known as the Vertical Traverse Section (VTS) [*figure 4*]. The VTS has a hooked docking interface which engages in the end of the Task Module. It has a vertical motion of 400mm and is able to raise a fully loaded Task Module at 20mm/s. This allows the remote collection of Task Modules from within the Octant 1 Boom Facility Enclosure and an ISO container that is docked onto it. A load cell within the VTS provides feedback to the operator to control the load transfer during the pick and place operations. The docking operation is also assisted by cameras and limit switches that indicate correct alignment and engagement.

Once a Task Module is correctly hooked onto the VTS, a latch is actuated to prevent inadvertent uncoupling. There is also an electrical services connection which engages to provide the Task Module with power for additional LED lighting.

Electric, pneumatic and water hydraulic tools services are provided by interface connections on the top and side of the VTS. These services are for tool functions such as vacuum cleaning, video inspections, welding, cutting, and bolting. Having these services close to the task site optimises the connection times and reduces the lengths of the service looms.

There are 4 Task Module parking locations in the ISO Container and a further 3 within the Enclosure. This enables the use of 6 Task Modules with a spare parking location for logistical organisation. The ability to randomly access the Task Modules provides versatility for the in-vessel tasks being performed. By pre-loading these Task Modules with components and their associated tooling, it is possible to complete many shifts of operation without the need for manned access to the Oct 1 Boom Enclosure. Previously, manned access was required for every shift of remote operation. The Task Module parking positions within the Octant 1 Enclosure provide the capability to continue RH operations whilst the ISO Container is undocked for reloading.

3.2 ADDITIONAL BOOM END-EFFECTORS

There are planned EP2 tasks for which the use of the Task Module is not practical. These tasks include the handling of many long sections of wiring loom conduit that are to be installed for diagnostics within the ILW. These conduits measure up to 2m in length and will not fit into a Task Module. There are also many EP2 tasks that will utilise existing tooling that it is not cost-effective to replace or upgrade. Examples of this are the Divertor handling tools which have been used since 1997 and the Dump Plate removal tools previously used in 1999.

For these tasks an alternative End-Effector, known as the Roll End-Effector (REE) [*figure 5*], can be docked onto the VTS in place of a Task Module. This End-Effector utilises a proprietary pneumatic fail safe tool changer to pick and place subframes loaded with components. It is also able to interface with the existing tine (an end-effector to pick up tools) that has been used with the previous Octant 1 Boom End-Effector since 1997. Hence, none of the previous capabilities of the JET RH system have been compromised by the upgrade. The REE also enables larger components to be rotated to allow them to pass through the narrow Octant 1 port.

The REE has cameras to assist the pick and place docking function. It also incorporates status switches and pressure transducers to indicate the payload has been docked safely.

3.3 BOOM DESIGN AND MANUFACTURE

The technology of the Octant 1 Boom upgraded design and the end-effectors is founded on the 20 years of JET operational experience developed with the existing Octant 5 Boom. As an example the design of the Boom axis drive units is identical to that used on the Octant 5 Boom. Thus the project risk was minimised whilst enabling the JET RH team to meet demanding timescales.

The design of the Boom links was based on the original JET Octant 5 Boom designed in 1983. However, during manufacture the design concept was reviewed in liaison with the supplier, resulting in a reduction of the complexity of the fabrications whilst maintaining the weight and stiffness constraints specified by JET. More of the sections were machined from billets rather than fabricated as previously. This ensured better control of the distortion due to welding and minimising the amount of “green” material necessary for the final machining operations. The completed Boom links were assembled and tested by the contractor and delivery was achieved ahead of schedule.

The End-Effectors and Task Modules are all entirely new designs. The engineering schemes were produced by the RH team working with the JET drawing office. They were produced using Catia V5 to a high level of detail which included the selection of all major components. This helped the selected contractor to gain a clear understanding of the requirements. Subsequently, there were no major design changes, and hence no delays occurred during the preparation of manufacturing drawings and the assembled End-Effectors were delivered to JET site in early March 2008 having met the specified operating parameters.

The integration of the new parts with the existing JET systems is progressing. A major part of this work is the installation of all of the wiring looms. The JET RH team has found that undertaking this work on site provides the high level of equipment reliability with which the system must operate. The commissioning work will commence upon completion of the assembly work in September 2008. The system is due to be ready for mock-up proving trails, procedure development and training by the end of 2008.

3.4 BOOM CONTROL FEATURES

In order to make the simultaneous operation of two BOOMs inside the vessel as safe (for the plant) and easy to use as possible, the individual control systems for each of the two BOOMS are now linked. In particular the ‘Virtual Rail’ motions, which drive the BOOMs on a virtual circular rail around the vessel, are now correlated, so as to ease the approach of one BOOM to the other, with an automated sequence allowing the servo-manipulator, which is mounted on the Octant 5 BOOM, access to the tools and equipment stored on the Octant 1 BOOM task module or other end-effectors. Furthermore, collision avoidance checks and safety constraints have been introduced.

4. TOOL DESIGN

The very large number of remote handling tasks demanded by the JET EP2 upgrade has required the design and development of an extensive range of new remote handling tools, examples of which are introduced in the following chapters.

4.1 THE 100KG WINCH

In order to enable the Mascot servo-manipulator to handle large loads, there has always been a small winch mounted onto the chest plate between the two mascot slave arms.

The new tungsten divertor, which is to be installed during the EP2 shutdown, exceeds the weight of the previous modules by a factor of more than two. Therefore it was necessary to design a new winch [*figure 6*], capable of lifting 100kg (twice the max. load of the previously used winch).

Special design features of the winch include pinch rollers to ensure the cable is always taut even if paying out the cable under no-load conditions. Furthermore a traversing drum was designed to ensure that the cable is always fed directly into the grove on the drum itself.

4.2 TILE HANDLING TOOLS

Approximately 300 different types of tiles will be installed remotely during the EP2 shutdown, almost every type necessitating a different tool to be designed.

The design of tiles for the ILW differs greatly from any that have previously been installed at JET. Most of the currently installed CFC tiles are secured by a single bolt accessed through a hole in the front of the tile. This provides a relatively simple remote handling operation. However, the bulk Beryllium of the ILW is unable to withstand the localised heat load caused by such a bolt access hole. Hence, a new system of tile fixing has been devised. The tiles, which must be bolted to the existing in-vessel attachment points, have been designed so that each tile covers the fixing bolts of its previously fitted neighbour. The development of this solution has required a complete new suite of tools to be designed and tested. A small sample of these tile tool designs is given in the following chapters.

4.2.1 A2 Antenna Protection tile tool

The A2 Antenna protection tile tool [*figure 7*] is to be used during the EP2 shutdown as part of the process to replace existing tiles in the JET vacuum vessel. It is used by the remote manipulator. Specifically it is to be used to install the new design of A2 Antenna Protection Tiles which attach to the A2 support structure. A 4:1 gearbox inside an aluminium body provides the mechanical advantage for the Mascot to open the tile pairs.

4.2.2 Direct tile handling

As an alternative to using specialised tooling, a new method has been devised to pick up tools directly with the grippers of the servo-manipulator. This is referred to as direct tile handling. A suite of finger adapters was designed, which can be fixed to the mascot gripper using a standard clip-on interface, which in turn have specially shaped outer gripping features to interface with various different tile types [*figure 8*].

Special new features within the control system of the Mascot servo-manipulator allow the calibration of the maximum limits of travel and the gripping force for each set of direct tile handling finger adapters.

4.3 conduit installation tools

Another system requiring the design and manufacture of an extensive new range of tooling is the wiring for the embedded diagnostic for the ILW [*figure 9*]. 22 sections of trunking and conduit are to be installed on the walls of the vessel amongst the pre-existing components. The routing is complex as it goes behind and between the upper dump plates and saddle coils. It is attached in places to welded supports that will be installed remotely using a process first used in 1999. Tools have been designed for the installation of long sections of conduit, some of which are up to 2m in length, and for the installation of wiring looms of up to 7m in length into their pre-placed trunking. Devising assembly methods that are amenable to the two armed, albeit dextrous, Mascot manipulator has been extremely demanding and required the close liaison between the teams designing the wiring and the tooling.

CONCLUSIONS

The adaptability of the JET remote handling system has allowed a significant upgrade to create a facility that can provide the needs for the EP2 Shutdown. The system originally conceived to repair JET machine breakdowns is now used for major refurbishment of the in-vessel components, undertaken in a highly efficient manner and with a new approach towards optimisation of productivity.

Project risk has been minimised by using tried and tested technology. It has been possible to schedule the manufacturing, assembly and commissioning with precision as a result of the JET team's previous experience.

ACKNOWLEDGEMENT

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REFERENCES

[1]. J Pamela, Journal of Nuclear Materials, Vol.363-365 (2007), p.1-11.

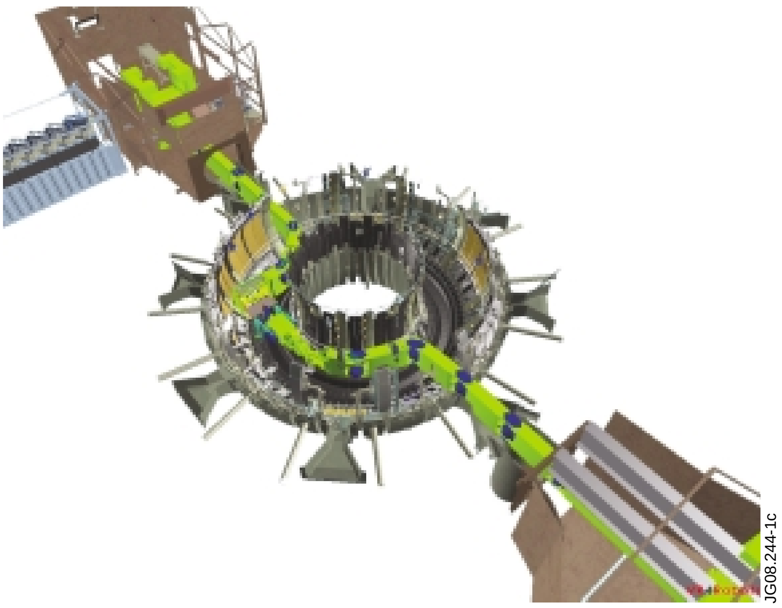

Figure 1: The new Octant 1 BOOM and Octant 5 BOOM inside the vessel.

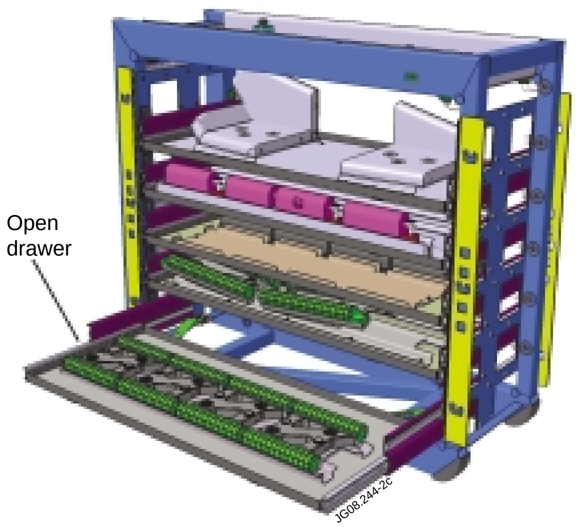

Figure 2: Task Module for Octant 1 BOOM.

Figure 3: Octant 1 BOOM.

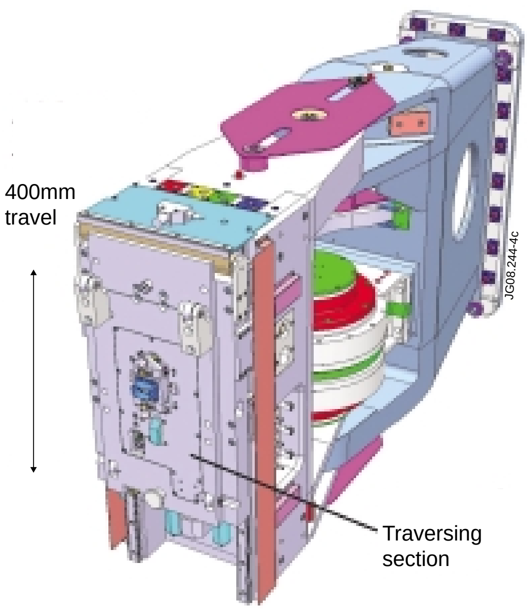

Figure 4: Vertical Traverse Section of Octant 1 BOOM.

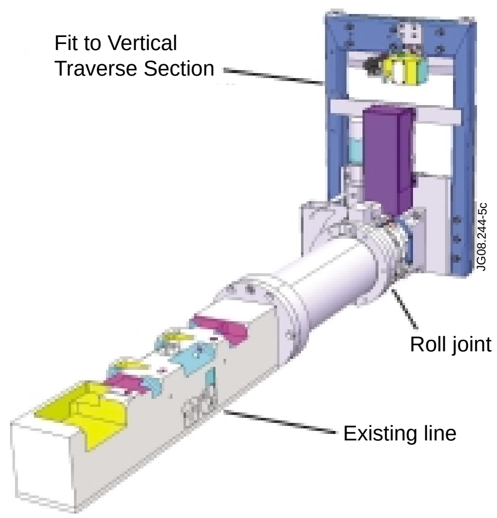

Figure 5: Roll End-Effector for Octant 1 BOOM.

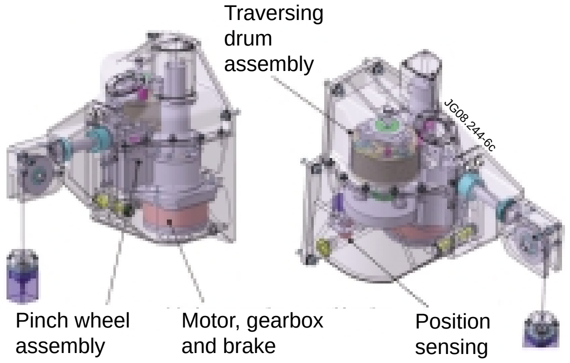

Figure 6: The 100kg winch.

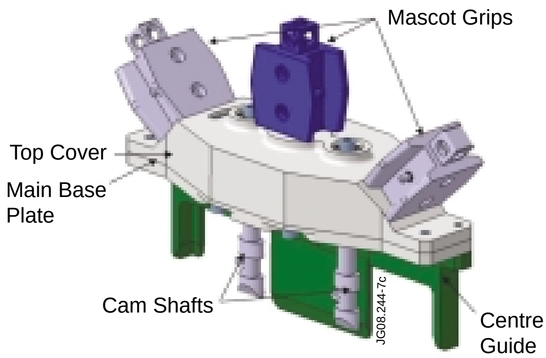

Figure 7: The A2 Antenna protection tile tool.

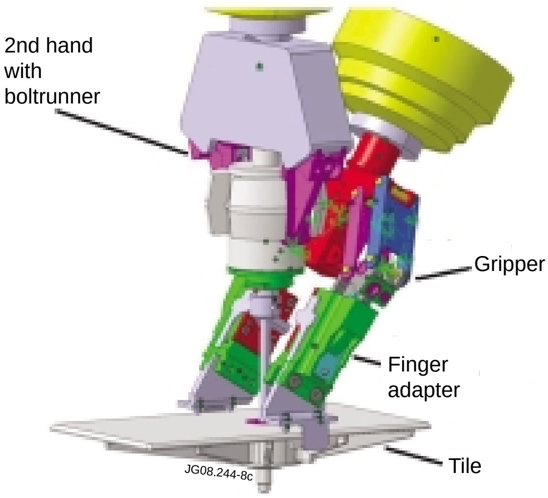

Figure 8: Direct tile handling with finger adapters.

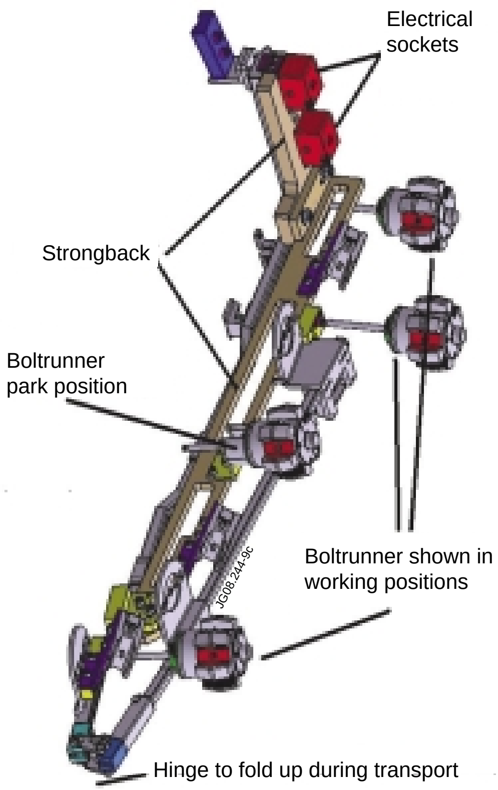

Figure 9: Inner Wall Guard Limiter conduit at OCT 3Z (folded up during vessel entry).