4 JET OPERATIONS

4.1 JET OPERATIONS IN CAMPAIGNS C15-C19

UKAEA has had the responsibility for the operation and safety of the JET facilities since January 2000 under the European Fusion Development Agreement (EFDA). The legal and financial provisions are defined by the JET Operation Contract between the European Commission (that confers the contractual management to the EFDA Associate Leader for JET) and UKAEA. The JET research programme is carried out by Task Forces of visiting European scientists from fusion laboratories associated to EFDA, including UKAEA Culham (see Chapter 3), under the responsibility of the EFDA Associate Leader for JET.

At the beginning of the reporting year, the re-commissioning ('Restart') of JET systems following the 2004/05 Shutdown, which had proved to be difficult and lengthy because of a number of technical failures, had just been completed. A two-week period of "High Level Commissioning" of diagnostic and heating systems in preparation for the experimental campaigns was carried out during April 2006. Campaign C15 started on 24 April 2006. The reliability and availability of the JET systems remained low during this period and the campaign ended early on 25 May due to a water leak on the Octant 4 Neutral Beam (NB) Injection system (see Section 4.2.2). During the campaign nitrogen contamination of the plasma was detected indicating a possible nitrogen or air leak.

Operations resumed on 12 June with a period of reconditioning to recover from the water leak and Campaign C16 started on 5 July. On 6 July a thunderstorm led to loss of electrical power to the Culham site, which resulted in the cryopanels of the pumped divertor warming up and the vacuum vessel becoming de-conditioned. With the vacuum vessel at ambient temperature and with the cryopanels warm it became clear that there was an air leak into the vacuum and so significant time was invested in leak testing (see Section 4.2.6). After identification and repair of several leaks, very good vacuum conditions were achieved. First plasma was achieved on 18 August 2006, after which a full Restart was carried out in the period up to 22 September 2006. During this Restart all heating systems reached their milestones.

Following these problems with JET operations, the EFDA Associate Leader for JET decided to carry out a review of the reliability of JET systems, which took place in September 2006. All JET systems were reviewed and all the main equipment failures that had affected JET operation during the last few years were discussed. A number of actions, both technical and managerial, were raised and are presently being implemented.

Campaign C16 recommenced at the end of September and was immediately followed by Campaign C17. System availability and performance were generally very good during this period and some systems worked exceptionally well. For example during C16 and C17 the number of discharges with NB power in excess of 20MW was about twice the number of pulses with similar performance since the installation of the pumped divertor in 1993 and records for neutral beam heating on JET were broken (see Section 4.2.2). In addition, more than 30MW of combined NB, Ion Cyclotron Resonance Heating (ICRH) and Lower Hybrid (LH) heating power was achieved in a few pulses.

Campaign C18 started on 8 January 2007 and finished on 9 February. This was immediately followed by Campaign C19 which ran from 12 February to 4 April. These campaigns included periods of operation that exploited the unique capability on JET to vary the degree of toroidal variation ("ripple") of the toroidal magnetic field. These experiments were performed to assess whether the plasma behaviour changed as the value of the toroidal field ripple was increased from the normally very low values on JET to the higher values that will be present in ITER (see Section 3.2.3 for a discussion of the experimental results). The performance of JET during C18 and C19 was generally good but two water leaks and an air leak on the Octant 8 NB system (see Section 4.2.2) and the failure of the Octant 8 Rotary High Vacuum Valve (RHVV) (see Section 4.2.6) meant that the planned scientific programme was seriously affected and had to be changed to suit the lower neutral beam heating power available.

4.2 Performance of JET Systems

4.2.1 Power Supplies

A Flywheel Generator Converters

In March 2006 a failure of a transformer in the braking circuit of the Toroidal Field (TF) Flywheel Generator Converter (FGC) occurred. The failure caused one of the transformer windings to move and completely destroyed the mountings and connections of the transformer. There was little disruption to operations since the experimental programme could continue using the TF static units only. Fortunately a spare winding was available and the time to make the repairs was minimised. The transformer was re-instated in early May 2006. The most likely cause of the failure was an inter-turn short within the transformer.

Some time was also lost because of indications of increased levels of vibration on the Poloidal Field (PF) FGC. After extensive investigations to rule out a genuine increase in the level of vibration, the cause of the excessive vibration readings was found to be due to the monitor mounting bracket possessing a natural frequency close to the 100Hz excitation frequency and this was corrected by remounting the bracket. As part of these investigations, an imbalance was identified in the rotor currents of the PF FGC pony motor due to failure of a connecting bracket that moves an adjustable electrode in the variable liquid resistor. The bracket was replaced and there have been no further problems.

B PF Power Supplies

There has been a continuing problem on the Fast Radial Field Amplifier (FRFA) with an increasing failure rate of driver modules for the GTO Thyristors that has resulted in all of the spares being used up; replacements are on order from the manufacturer. In February 2007 one of the four sub-units had to be taken off line due to another GTO driver failure. A serious fault on FRFA occurred in mid-March 2007 resulting in the shorting of the main transformer secondary on sub-unit 11 and a consequential blowing of eight GTO fuses. Even though the transformer is designed to survive a small number of shorts the sub-unit was immediately put off line for investigation.

C Preparation for TF Ripple Experiments

The capability of JET to run with different currents in the odd and even sets of TF coils, which allows the toroidal variation (‘ripple’) of the TF magnetic field to be varied, had not been used since the mid 1990s and hence the systems had to be re-commissioned. The work involved reinstating some equipment, modifying some systems that had been replaced since the last ripple experiments and a full re-commissioning of the TF local controller and Coil Protection System (after making some additions to the software). Following concerns regarding the risk of damaging the TF coils if one of the FGC protection systems failed to operate when a TF trip occurred while the average TF current was above 43kA, an additional, independent trip system was installed to give assurance that the current delivered from the TF FGC would be reduced sufficiently quickly when required. Operations with varying values of TF ripple have been very successful but no operation above 43kA was carried out because the beam power required for these experiments was not available following the failures on the Octant 8 NB system.

D Additional Heating Power Supplies

The performance of the NB power supplies has been generally good, and for some periods very good, and has permitted very high NB power levels being delivered to the plasma (see next Section). However, there have been a number of persistent faults, including: voltage ripple on the Module 6 arc power supply which limits the operating voltage on this injector to 70kV; a calibration error on Module 5 HV power supply which limits the operating voltage to 118kV; spurious trips on Modules 10 and 11, and spurious Pulse Inhibits on Module 9.

4.2.2 JET NEUTRAL BEAM SYSTEM PERFORMANCE IN 2006

Over the last year a large number of operational difficulties were experienced with the two Neutral Beam Injector (NBI) systems on JET. As reported in last year's annual report there were a number of problems encountered with the neutral beam systems in the latter part of the Restart in the first quarter of 2006 but they were working well by the beginning of April 2006. A good period of beam operation followed in which 18 JET pulses had a neutral beam power in excess of 20MW.

Campaign C15 was curtailed when a significant water leak occurred in PINI 2 on the Octant 4 Neutral Injection box (NIB) on 26 May. The vacuum vessel was cooled and vented together with the NIB. PINI 2 and two other PINIs that had collected water in them from the leak were removed. A total of 630 litres of lightly tritiated water was safely removed from the NIB. PINI 2 had been little used since PINI 1, which serves the MSE (Motional Stark Effect) diagnostic, had been upgraded in 2002 because use of PINI 1 at the optimum energy for the MSE diagnostic required PINI 2 not to be used. In view of the low usage of PINI 2 and the small increase in total power (0.65MW) it could contribute when MSE was not required, it was decided to take it off, replace it with a blank and continue with the remaining 15 PINIs.

Over the summer there was very little operation due to torus vacuum problems. Full operation resumed at the end of August and another good period of operation followed until the end of October. During this time the neutral beam performance was slightly lower than in Spring with a number of power supply issues limiting operation to just less than 20MW, although the average power and energy, 10.1MW and 50.2MJ respectively, were as good as any other JET operational period with the exception of 2003.

On 30 October 2006, a water leak on PINI 7 of the Octant 8 NIB stopped operation. Following removal of the PINI, it was found that the back-plate of the ion source had failed. Although inconvenient, only six operational days were lost to remove the PINI, replace the back-plate, re-install the PINI and commission the system back to full operation. It was established by sectioning the back-plate that this failure was simply due to age-related corrosion/erosion in a region of high flow velocity and turbulence within the internal cooling channel manifold (see Figure 4.1). The investigations were helped by the fact that the site of the leak had not been subject to melting from back-streaming electron beams that had occurred with previous similar failures. It is now known that the cause of all of the other, hitherto unexplained, ion-source back-plate failures since 2002 were similarly age-related and not due to increased service duty (power, pulse length). A complete set of new replacement back-plates built to the original design is therefore being procured.

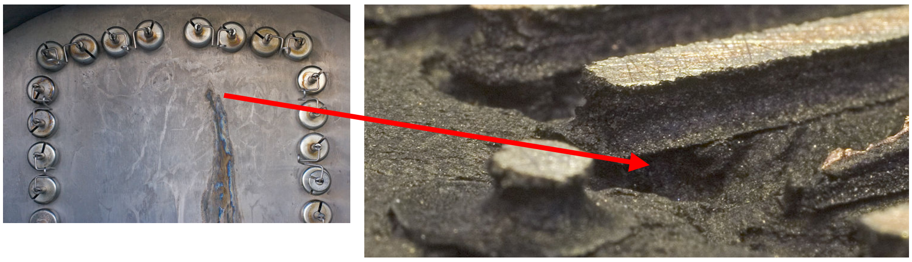

Figure 4.1: *View of ion source backplate failure showing (left) the site of the leak on the filament side of the backplate and (right) an enlarged internal view of the water channel of the backplate*

With just 15 PINIs the performance in the period through to the end of the year was unprecedented with many new records being set, most notably:

- The maximum injected energy in a single pulse - 186MJ (previous record 170MJ);
- The maximum power in a single pulse - 23MW (previous record 22.8MW);
- The average power per pulse - 13.8MW (previous record 12.8MW).

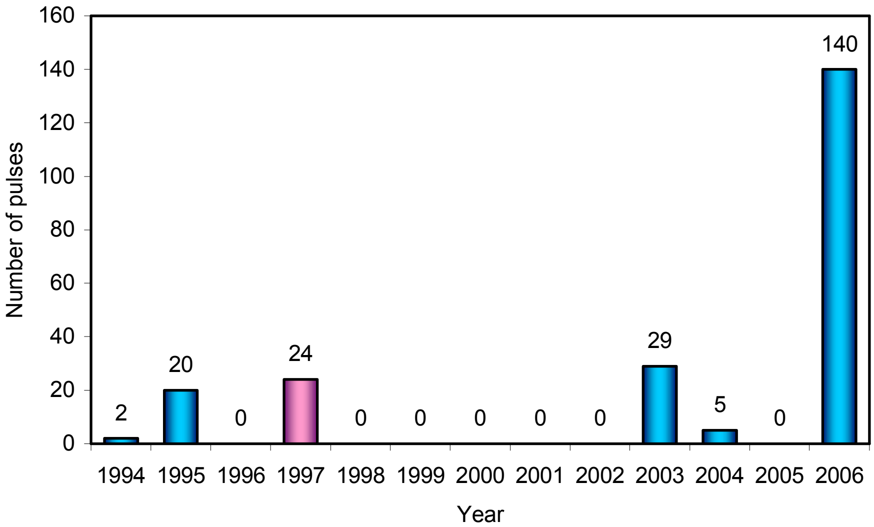

Figure 4.2: *Number of JET pulses with neutral beam power in excess of 20MW*

Figure 4.2 shows the number of pulses with an injected power in excess of 20MW as a function of year. The large number of high power NB pulses is probably the most outstanding feature of this period of operation, as it demonstrates not only the outstanding level of performance but also the reliability of the NB and associated power supply and other systems.

The final period of neutral beam operation through to 4 April 2007 was affected by three significant problems on the Octant 8 Neutral Injection Box (NIB). On 5 March a small water leak in the NIB vacuum was detected which was found to be on the Central Support Column water circuit and seemed to be associated with the quadrant serving PINIs 7 and 8. Locating precisely and repairing this leak could only be done in the Shutdown so operations continued with very limited use of PINIs 7 and 8. Subsequently a larger water leak occurred on 15 March when the back-plate of PINI 8 failed. The source of the leak was rapidly identified and the leaking water circuit was clamped off to allow operations to continue. On 20 March, during a period when the NIB cryopanels were regenerated due to an interruption in the supply of cryogens, an air leak was observed which was traced to a leaking seal on the ion source of PINI 6.

4.2.3 Ion Cyclotron Resonance Heating Operations

The highlight of this year's ICRH operations has been the success in implementing the 3dB splitters to release Module A to drive the ITER-Like Antenna. These splitters have shown the expected good power waveforms and ELM tolerance after some optimisation of the Voltage Standing Wave Ratio (VSWR) arc detection system and debugging of the control system. Unfortunately, it has become increasingly clear during the year that when operating at 37MHz and 42MHz the present antenna geometry can result in arcs being initiated at voltage nodes that cannot be detected by the normal VSWR system. This prevents the use of the ELM tolerance provided by the 3dB splitters at these frequencies until arcs at voltage node can be detected safely by other means (sub-harmonic, optical and acoustic techniques are presently being explored).

The project to install an externally-mounted conjugate-T ELM tolerant matching system to some of the existing JET antennas during the 2007 shutdown is progressing well. Another potential arc-detection weakness has been identified and a new protection system designed to suit.

Significant sidebands on the RF spectrum, discovered during earlier second harmonic studies, were removed when linear power supplies replaced switch-mode units in the phase control circuits. Phase jitter was causing amplitude modulation by "detection" in the high-Q matching circuits. This modification will be installed on all modules during the 2007 shutdown.

4.2.4 Lower Hybrid Operations

The Lower Hybrid (LH) plant was in operation for most of 2006, either for commissioning the various systems and conditioning the LH launcher, or for providing LH power for plasma experiments.

In parallel to operation, the first phase of the Klystron Fast Protection System (KFPS) refurbishment took place. This system, which comprises the fast logic electronics that control and protect the klystrons and auxiliaries, was failing because of ageing components. The first of seven modules has been installed and fully commissioned.

4.2.5 Cryogenic Plant

Cryoplant availability was very good throughout the year; apart from a 7.5 hour loss of service in March 2007 caused by a faulty valve on the main K160 compressor, there was almost no lost time. Operationally, the main challenges have been ice and particle blockages of the cold ejector in the pumped divertor (PD) loop. These were remedied by flushing out the ejector (0.8mm throat) and instituting a pure helium flush after regenerations of the PD cryopumps.

4.2.6 Vacuum Systems

On 6 July a thunderstorm led to a loss of site power, one consequence of which was the regeneration of the machine cryo-panels to ambient temperature. In the absence of the pumping normally provided by the cryo-panels it became apparent that a new air leak, which had previously been suspected, was not only present but was sufficiently large ($5x10^{-3}$mbar l s^{-1}) to prevent further useful plasma operations. Therefore it was decided to carry out a period of leak testing. Two significant leaks were found, one on a valve on the KS1 diagnostic beam line, which was replaced, and one on the Octant 4 Main Port Adapter lip weld, which was repaired. Several smaller leaks were also identified and fixed. Additional work was carried out in parallel with the leak testing including the repair of failed PINI filaments and the replacement of the Torus turbo pump TT01 which was exhibiting signs of imminent failure. The machine was pumped down on 10 August, followed by a six week re-commissioning phase.

As part of the work to repair the water leak that occurred on 30 October on PINI 7 on the Octant 8 NIB it was decided to trial a novel procedure that permitted the venting of only the Octant 8 NIB, leaving the Torus and Octant 4 NIB at vacuum. The fact that the Torus was not vented saved approximately two weeks of operational time because the vacuum vessel did not require reconditioning. The procedure had a series of hold points throughout the venting process to ensure that the vent proceeded in a controlled manner and a detailed risk assessment addressed the safety issues regarding the exchange of the PINI with some of the machine under vacuum. The PINI exchange was successfully completed on 1 November and JET operations recommenced on 2 November.

When the water leak on PINI 8 of the Octant 8 NIB occurred on 15 March 2007, the Octant 8 Rotary High Vacuum Valve (RHVV) was closed but there were some problems sealing it. Later it was found that the RHVV had become jammed in the closed position; it is not yet clear whether the problems with the RHVV are associated with the water leak on PINI 8 or it is a coincidence that it happened at the same time.

4.2.7 DIAGNOSTICS

A large number of plasma diagnostics are operated by UKAEA under the JET facilities Operation Contract (JOC). The period April 2006 to March 2007 was a period of almost continuous operation for diagnostics either for the scientific campaigns C15-C19 or for the two Restart periods. During the year there was a large involvement of the diagnostic teams assisting in the commissioning and bringing into use of new diagnostic enhancements (see Section 4.3.1). In addition there have been some developments under JOC of existing diagnostics.

The JET multichannel, far infrared interferometer, which is the standard tool for line-integrated plasma density measurements, has been improved by installing a new high-frequency data acquisition system (up to 2MHz). This has proved to be an extremely sensitive tool, through the use of Fourier spectrograms of the raw data, for the detection of a range of MHD modes in the plasma core. Measurement of the effect of the plasma on the probing beam polarisation also now allows an independent measurement of the plasma density using the Cotton-Mouton effect. This measurement will allow the performance of the interferometer to be improved by providing a signal which can be used to remove discontinuities or “fringe jumps” in the density waveform from the interferometer.

Operation of the two LIDAR profile diagnostics was maintained despite interactions with the installation of the new High Resolution Thomson Scattering system (see Section 4.3.1). Some damage occurred to shared optics during the initial commissioning of the HRTS laser but LIDAR operation was re-established for most of the campaigns.

4.2.8 CODAS

In May 2006 the Culham site connection to the Internet was switched to a direct connection to the Thames Valley Network (TVN). This is a multi-gigabit fibre ring connecting Reading University, Rutherford-Appleton Laboratory, Culham Science Centre and Oxford University which provides a 1-Gigabit Ethernet connection onto TVN. The full bandwidth is not required for the present level of Internet usage so initially the existing 34Mb/s connection to the SuperJANET research network was continued but this was upgraded to 100Mb/s in February 2007.

Fusion scientists now have access to the EGEE (Enabling Grids in e-SciencE) grid, the largest grid infrastructure in the world. The EGEE grid is a very large computing resource shared by 200 sites around the world. Consisting of over 30,000 computer processors, and 50 Petabytes (50 million Gigabytes) of data storage, the EGEE grid allows scientists access to more computing power than is available at a single university or laboratory. Originally designed to analyse data from the Large Hadron Collider (LHC) experiment, due to come on-line at CERN in 2007, the EGEE grid now supports a wide range of other "Big Science" disciplines including protein folding and drug discovery in addition to fusion. A cluster consisting of 74 processors and 1.5 Terabytes of disk storage has been installed in the JET computer room and integrated into the Grid. Although configured to prefer fusion applications, it also provides resources to other scientific disciplines, including particle physics and biomedicine. It was recently used in a campaign to discover anti-malarial drugs.

4.3 Support to the JET Enhancement Programme

4.3.1 Bringing the JET EP1 Diagnostics into Full Operation

The first phase of the JET Enhanced Performance Programme (known as JET EP1) included 13 separate diagnostic enhancement projects. These projects were each managed by one or more fusion Associations and UKAEA was involved in the management of several of these. Following installation the new diagnostics were commissioned by Association staff with help from UKAEA as JET Operator and were progressively brought into full operation during the Restart periods and operational campaigns. Several of the new diagnostics have already made significant contributions to the scientific campaigns. In addition some of them have proved to be valuable for machine protection purposes. For example, the new wide-angle infra-red camera developed by CEA (France) was very useful in validating the models of where fast particles would hit the JET plasma-facing components during the experiments with enhanced TF ripple (see Figure 4.3).

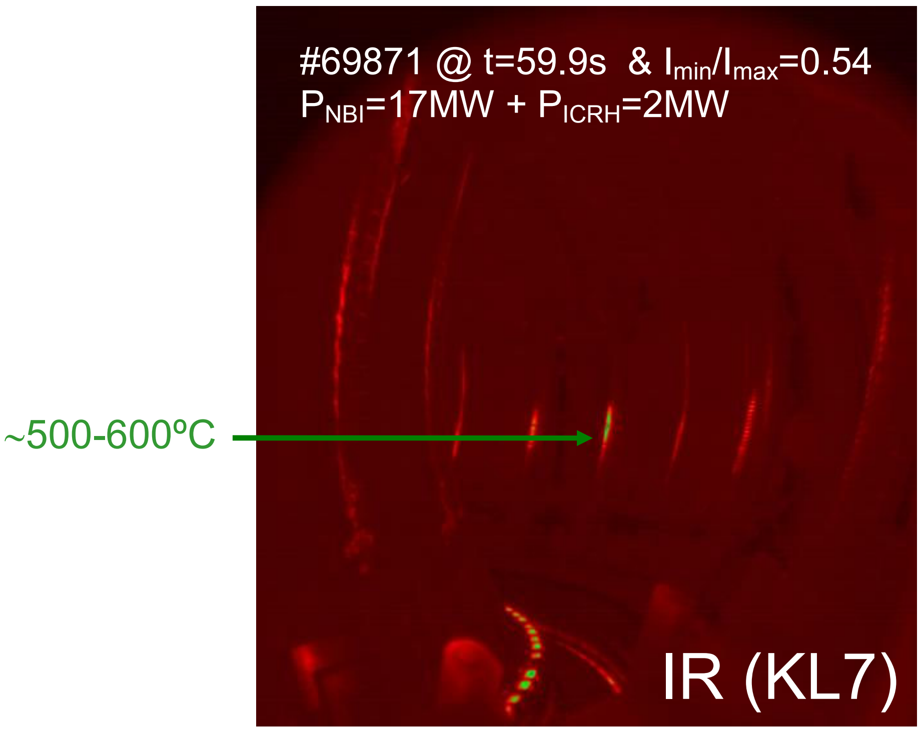

Figure 4.3: *A view of the JET limiters during a TF ripple experiment from the new wide-angle infra-red camera (KL7)*

Several in-vessel diagnostics have been improved including a refurbishment of faulty Langmuir probes in the divertor region and two divertor modules each containing entirely new magnetic pick up coils. Halo detector coils have been built by ENEA (Italy) and four arrays of these detectors were installed in the top of the vacuum vessel to measure halo currents flowing in the vessel structures during plasma disruptions.

Horizontal and vertical viewing Bolometer cameras and new divertor bolometers have been developed by IPP Garching (Germany) to replace bolometer cameras displaced by the new ITER-like ICRH antenna and the old divertor bolometer cameras which had a large number of non operational channels.

Figure 4.4: *One of the two KB5 bolometer cameras*

A High Resolution Thomson Scattering (HRTS) diagnostic has been installed to improve the resolution of steep gradients of electron temperature and density at the plasma edge and at the Internal Transport Barrier. This system, which has been designed and built by ENEA, had to be commissioned on JET through a close collaboration between ENEA staff and the JOC LIDAR team because it shares some of the optics of the LIDAR system. The commissioning of the system proved to be challenging because problems with the HRTS laser resulted in damage to some of the optics. Following extensive investigations by the ENEA and JOC teams, the cause of the problem has been identified and additional protection systems have been installed by the manufacturer of the laser. The HRTS system is still under commissioning, but the first preliminary results are very promising and it is already providing valuable data.

4.3.2 Other Diagnostic Enhancements

In addition to the JET EP1 and EP2 programmes, there is a "small enhancement programme". This permits developments which improve the quality of experimental data that can be implemented between Associations and the Operator without needing significant resources. A number of such projects have been completed this year including one with Ecole Royale Militaire (Belgium) to develop an activation probe. Figure 4.5 shows a picture of the new probe after exposure in the irradiation experiment. Note the area covered by particle dust as a result of plasma exposure. Analysis of the probe samples was carried out in Belgium.

Figure 4.5: *New activation probe*

4.3.3 Preparation for the 2007 Shutdown

It was not possible to install the ITER-like ICRH antenna, which is one of the projects in the JET EP1 programme, during the 2004/05 Shutdown because it was still under development. The late delivery of a diagnostic feed-through meant that some of the pick-up coils which were part of a magnetic measurement upgrade were also not installed. A knock on effect of this was that one of the two new Toroidal Alfven Eigenmodes (TAE) antenna structures was not installed. These items will be installed in 2007 by remote handling in a Shutdown that will complete the EP1 programme, undertake some preparatory work for the 2008/09 Shutdown and install some of the components being procured via the JET EP2 programme. In addition, work will be done to repair several components that failed during operations, most notably the Rotary High Vacuum Valve and the Central Support Column of the Octant 8 Neutral Injector Box.

The original planned duration of the 2007 Shutdown, based on its expected content at the end of 2005, was 20 weeks. Subsequently extra tasks were added which increased its duration to 26.5 weeks. The late addition of further tasks because of the failure of the Octant 8 Rotary High Vacuum Valve and the water leak on the Central Support Column of the Octant 8 Neutral Injection Box means that the plan is still being revised but it is expected that the Shutdown duration will not need to be extended by more than two weeks.

The JET EP1 tasks planned to be completed include:

- The installation of an additional in-vessel antenna for the excitation and detection of TAE modes;
- The upgrade of the first wall magnetic diagnostics to enhance real time control of the plasma;
- The installation of the ITER-like ICRH antenna.

The JET EP2 tasks consist of:

- The installation of a new High Field Pellet Injector (HFPI) for ELM mitigation and deep fuelling studies;
- High voltage power supply infrastructure work and PINI modifications as part of the Neutral Beam Enhancement Project;
- First wall metrology surveys for the ITER-like Wall Project;
- Surveys and cable installations for a number of diagnostic projects.

Important Operator remedial work will be undertaken on:

- The vessel bake out plant;
- A leaking diagnostic window;
- The water leak on Octant 8 NIB system;
- The Rotary High Vacuum Valves;
- Extensive refurbishment of bus-bars, circuit breakers and switch gear.

During the reporting period extensive enhancements have been completed within the Assembly Hall in support of future Shutdown logistics, including:

- Increasing the capacity and enhancement of the Active Ventilation System;
- Dismantling of the redundant Torus Access Cabin;
- Long term storage of the Pellet Injector Box;
- Adding an ISO container docking feature on the Remote Handling maintenance facility;
- New maintenance and development area for the suite of semi automatic cutting and welding tools;
- New Posting Facility with critical EP2 features for the In-vessel Access facilities;
- New Bonded Store facility for the ITER-like Wall component logistics;
- New “goods in” inspection facility.

4.3.4 ITER-LIKE WALL PROJECT

The ITER-like Wall (ILW) project is part of the second programme of JET enhancements (EP2). The project is led by UKAEA as JET Operator with core engineering and installation related activities based at JET including secondees from other EURATOM Fusion Associations. The R&D tasks have been managed by other Associations but under the overall management of the JOC ILW team.

ITER reference materials have been tested in isolation in tokamaks, plasma simulators, ion beams and high heat flux test beds. However, an integrated test demonstrating both acceptable tritium retention and an ability to operate a large high power tokamak within the limits set by these materials has not yet been carried out. The current objective of the ILW project is to install in JET a beryllium wall and an all tungsten divertor (the favoured back-up materials solution for ITER). This choice is technically more demanding than the ITER-reference combination which has CFC tiles at the strike point. The design leaves open the option to replace remotely specific rows of divertor tiles with carbon fibre composite (CFC) at a future date. The ILW will provide a test bed for integrated scenarios with ITER relevant edge conditions and compatibility with the wall, thus speeding up the early phases of ITER.

The most urgent contracts for the beryllium and CFC materials were placed in 2005 by the European Commission. During the period of this report, all of the CFC material was delivered to JET. The majority of the beryllium, which was recycled from components previously used in JET but no longer required, has also been delivered well ahead of when it is required for the manufacture phase.

In September 2006, CCE-FU (the senior European fusion committee) approved the €33M budget for the manufacture of all the main hardware components for ILW and the first key contracts in the chain have now been started. Prototype tiles made from aluminium rather than beryllium have recently been delivered (see Figure 4.6) as part of the design validation process.

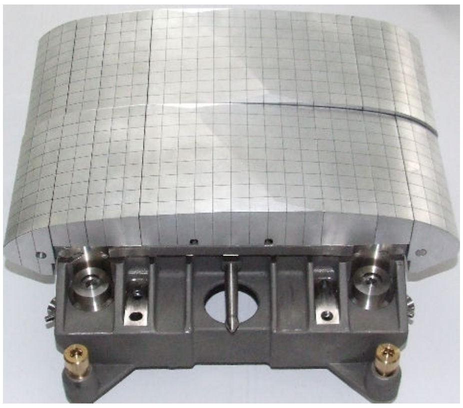

Figure 4.6: *Two prototype outer poloidal limiter tiles showing part of the carrier in the foreground. Tiles on the adjacent carriers stack together to hide the carriers and fixing bolts from the plasma*

In addition to the new wall tiles, a key objective of the project is to install all the components within a 46 week period during the 2008/09 Shutdown. This will be achieved by a major enhancement to the Remote Handling system to allow co-operative working with two booms. To make this possible the existing short boom is being extended by adding additional links which will allow it to carry complete packages of components and tools to the point where they are required. The new boom links and all the new remote handling tools which will be required are being procured under UKAEA/JOC contracts.

To ensure that the shutdown goes according to plan, a high level of design validation is required both for the remote handling tooling and the interfaces with the components themselves. "Mock-up" trials which have started this year are an essential part of this process. Figure 4.7 shows an inner wall guard limiter mock-up tile being installed by the MASCOT remote handling system on a jig representing the in-vessel beam.

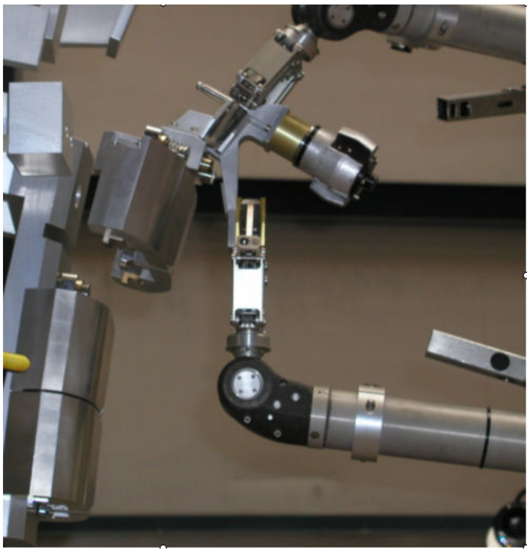

Figure 4.7: *Remote handling mock-up trials of the installation of a limiter tile assembly*