DEVELOPMENT OF KEY FUSION TECHNOLOGIES AT JET

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Abstract

The recent operational phase in JET in which Deuterium-Tritium fuel was used (DTE1) resulted in record breaking fusion performance. In addition to important contributions in plasma physics, the JET Team has also made major advances in demonstrating the viability of some of the key technologies required for the realisation of future fusion power. Two of the most important technological areas which have been successfully demonstrated in JET are the ITER scale tritium processing plant and the exchange of the divertor and maintenance of the interior of JET by totally remote means. The experiment also provided the first data on tritium retention and co-deposition in a diverted tokamak. Of the 35g of tritium injected into the JET torus, about 6g remained in the tokamak. The amount resides mainly on cool surfaces at the inboard divertor side. The precise, safe and timely execution of the remote handling shutdown proved that the design, function, performance and operational methodology of the RH equipment prepared over the years at JET are appropriate for the successful and rapid replacement of components in an activated tokamak environment.

1. INTRODUCTION

The clear long term objective of the European Fusion Programme is to develop a fusion power source based on magnetic confinement. This objective, formulated for the first time 25 years ago, has recently been reconfirmed [1]. The European fusion programme, in a concerted effort of the European Fusion Associations, European industry and JET, the flagship of European fusion research, has consistently followed the path of fusion reactor relevant plasma physics research and the development of the technologies aimed at a demonstration reactor.

JET, the world's largest Tokamak, is closest in scale and operating conditions to ITER, the design for the Next Step, and has both the plasma and divertor configuration foreseen for the Next Step. From the very beginning, and in recognition of the long term objectives of the fusion programme, JET included the development of reactor relevant technical capabilities required to study fusion physics and power production using deuterium-tritium fuel and to perform maintenance and repair work through the use of remote handling techniques [2].

The recent operational phase of JET, DTE1, in which deuterium-tritium fuel was used, resulted in record breaking fusion performance and a set of definitive experiments enabling the threshold for H-mode transitions and the confinement in ELMy H-mode discharges to be scaled to ITER using direct evidence from D-T plasmas [3]. In addition to these important contributions in the area of plasma physics, the JET Team has also made major advances in demonstrating the viability of some of the key technologies required for the realisation of future safe fusion power reactors. Two of the key technologies successfully demonstrated are the ITER scale tritium processing plant and the totally remote exchange of the divertor and maintenance of the interior of JET.

2. THE JET ACTIVE GAS HANDLING SYSTEM (AGHS)

The JET Active Gas Handling System (AGHS) demonstrated the first safe, reliable and routine operation of a closed loop tritium-deuterium fusion fuel supply and re-processing plant. The site inventory of 20g of tritium was circulated and reprocessed five times by the AGHS to provide over 64g of tritium for neutral beam injection and 35g of tritium for gas introduction into the JET machine. The

[1] See Appendix to IAEA-CN-69/OV1/2, The JET Team (presented by M.L Watkins)

AGHS has been used continuously during torus operation since May 1997 to pump the exhaust stream from the torus and to handle batches of mixed gases from the regeneration of the torus and neutral beam injection cryopumps, separating these gases into hydrogen isotopes, helium, and impurities. Over 13 m^3 of mixed gas at atmospheric pressure has been processed.

The AGHS was designed to [4]:

- pump gases from the torus and to separate these gases into helium, hydrogen and impurities,
- isotopically separate the hydrogen into tritium, deuterium and protium and to re-inject purified tritium and deuterium into the torus,
- de-tritiate impurity gases to recover the tritium for re-use,
- remove and purify air from, and provide ventilation to, enclosures where tritiated air is likely to arise.

a) Pumping of the exhaust gas from the torus and during regeneration of the neutral beam injection cryo pumps is carried out by the use of a JET designed cryogenic forevacuum system. The cryogenic forevacuum system consists of a set of units containing an Accumulation Panel (ACP), a Cryo-Transfer Pump (CTP) and a gas reservoir. The ACP is an advanced cryopump able to pump hydrogen isotopes and impurity gases and a section with helium cooled activated carbon to pump helium. By heating the activated carbon section separately the helium can be released and conducted to the Impurity Processing System (IP). Hydrogen is separated from impurity gases by the CTP and transferred to uranium beds which absorb hydrogen at room temperature and release it at higher temperatures. The impurity gases are also conducted to IP. The re-cycling time of the pump for the removal of hydrogen and helium is in the order of several minutes.

b) Two isotope separation systems, a gas chromatography and a cryo-distillation system, are used in combination. The typical tritium purity achieved is 99.88%, well above that required for neutral injection and better than the purity of the original tritium supplied to the JET site. Deuterium and impurities are de-tritiated in order to recover the tritium for re-use and to permit excess deuterium to be discharged to the atmosphere.

c) The Impurity Processing system consists of a mechanical pump section where all the impurity gases from the torus and within the AGHS are collected and compressed. This is followed by either one of two systems; a system of chemical modules in which the impurity gases are cracked on hot U-beds followed by cold U-beds to absorb the hydrogen isotopes; or a recombiner in which the impurity gases are oxidised to water and carbon-oxides. The water is trapped on a cold trap and then cracked on a hot U-bed followed by a cold U-bed to absorb the liberated hydrogen isotopes. Work is underway to eliminate the U-beds and to use catalysts instead.

d) The Exhaust Detritiation System (EDS) was designed to de-tritiate gas contaminated with low levels of tritium prior to discharge into the atmosphere and to provide ventilation to the torus and other major components in the event of a breach of the vacuum containment, either unplanned or for maintenance and repair purposes. The system is a conventional tritium removal system based on catalytic oxidation of hydrogen and hydrocarbons to water and the subsequent trapping of the water vapour on molecular sieve.

Valuable experience was gained during the experiment in the practical aspects of safely operating, maintaining and repairing a tritium contaminated fusion device. In particular, an intervention to repair a small water leak in the tritium neutral beam injector featured manned access inside the injector in full pressurised suits [5]. The EDS was used throughout the 56 day intervention to ventilate the injector box and detritiate the exhaust stream. The ventilation kept the tritium concentration at levels where pressurised suits are able to provide the protection factor necessary to keep workers' accumulated dose well below routine exposure limits. The de-tritiation factor of >1000 available from the EDS kept environmental discharges to around 1% of JET's authorised limits. The EDS ventilated the torus and other enclosures during the subsequent remote handling shutdown phase [6].

A sophisticated system of tritium accounting was developed at JET which indicated the following distribution of tritium at this point in time [4]:

Total amount of tritium (corrected for radioactive decay to August 1998)	**19.10 g**
Tritium in water stored at JET	2.13 g
Tritium in U-beds	13.11 g
Tritium in torus, co-deposited layers, flakes, and tiles (partly removed from the vessel during the remote handling shutdown)	3.86 g

The exhaust of tritium from the torus is now about 10 mg /week.

3. THE FULLY REMOTE EXCHANGE OF THE JET DIVERTOR

The limited operation using D-T fuel in JET resulted in an activation level in the machine of the order of 4 mSv/h at the end of the operation period. 1998 saw the successful completion of the first fully remote shutdown at JET directly after the tritium operations [7,8]. Manned intervention in the machine, prevented after the D-T operations phase, will become progressively possible only after about one year. During the remote handling shutdown the complete Mark IIA divertor (144 modules) was removed and replaced with the Gas Box Divertor (192 modules). All the planned tasks as well as a number of unplanned tasks were accomplished successfully. These included: the detailed visual inspection and video recording of the inside of the vessel; the remote vacuum cleaning of in-vessel components including the collection of co-deposited flakes of carbon and hydrogen isotopes; the removal and installation of a number of diagnostic systems including the disconnection and reconnection of numerous RH electrical connectors; the remote removal and replacement of a number of limiter and first wall protection tiles; the remote removal of an oxide layer and cleaning of four beryllium evaporators; the first ever fully remote dimensional survey using videogrammetry techniques, to confirm the position, shape and integrity of the divertor structure with a point precision of $< \pm 0.1$ mm (targeted) or ± 0.3 mm (targetless) [9]; and the inspection, removal and precise dimensional survey, repair and re-installation of a damaged diagnostic system.

The work was based upon the implementation of the remote handling philosophy and the use of tools developed from the start of the JET project. The work was executed by means of the force-reflecting Mascot servo-manipulator [10], transported into the vessel on the 10m long JET articulated boom [11] Fig.1.

The boom, housed within a contamination control enclosure sealed from the torus, entered the torus at octant 5 main horizontal port. The in-vessel work was executed by the operator of the servo-manipulator from the Remote Handling Control Room located at a distance from the torus, *Fig.2*. The sensation of touch transmitted by the manipulator, combined with the view provided by the video cameras, and the audio signal, give the operator a distinct sense of presence within the vessel [8].

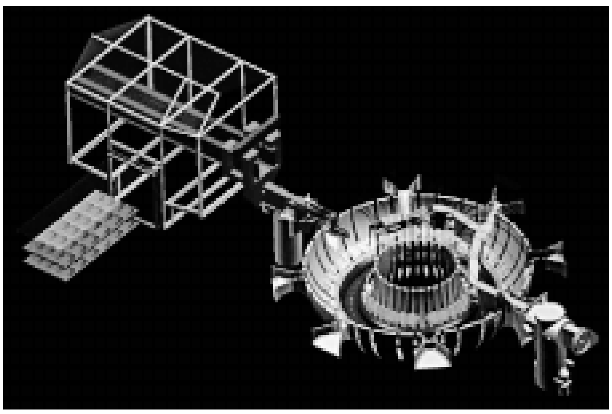

Fig.1. Overall remote handling operation scenario

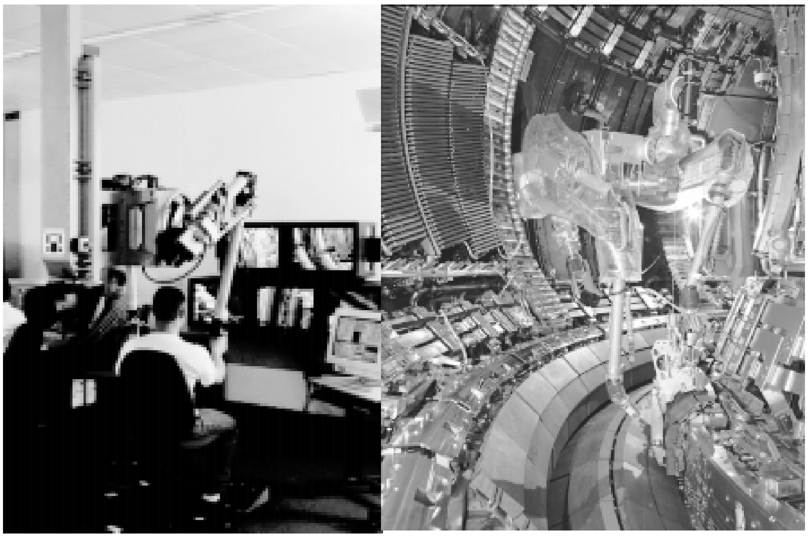
Fig.2. Mascot operator and in-vessel slave

The components of the Mark IIA divertor were removed and transported by the boom to octant 1 where they were transferred to an end effector attached to a second shorter boom (of otherwise identical design to the main boom) which removed the components from the vessel and manoeuvred them, without manual intervention, onto trolleys for storage in a removable ISO container attached to the Tile Carrier Transfer Facility (TCTF), a contamination control enclosure located at octant 1 which housed the short boom [12]. The same techniques, in opposite sequence, were then used to install the 192 modules of the Mark II Gas Box divertor, Fig.3. The contamination control enclosures, the JET vessel, as well as the ISO containers were kept at a depression relative to the surrounding Torus Hall and ventilated at a rate of 10-20 air changes per hour. The enclosures were ventilated either directly to an external exhaust stack or by the Exhaust De-tritiation System of the AGHS [6].

4. EXAMPLES OF TECHNICAL EXPERIENCE

The decision to apply systems and technologies which had never yet been tried and tested on fusion devices, or which were totally new developments, has provided JET with invaluable experience and knowledge in many areas essential for the design of any next step device. The solution of numerous very detailed engineering and design problems are themselves just as important as the solution of overall concepts and strategies. This knowledge and experience, whilst solving many outstanding questions, also points towards the areas where further work is needed. The following is a short list, by no means comprehensive, of items associated with tritium and remote handling, which exemplify the breadth of essential experience and knowledge gained and residing at JET.

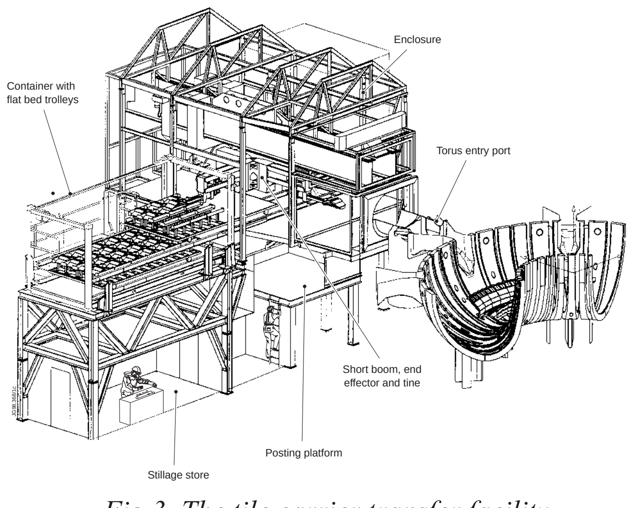

Fig.3. The tile carrier transfer facility

4.1 Tritium Technology

4.1.1 Tritium Handling and Ventilation

Although it was expected that, after the D/T experiments, the torus and the enclosures attached to it would require to be ventilated through a tritium removal system such as the EDS, it is only the JET experiments which have provided the information on the extent of the tritium out-gassing from the exposed vessel and components. This information is essential when considering the radiation protection and ventilation systems and other facilities required for future projects. At the end of deuterium tritium operations and after the completion of the tritium clean-up exercise the amount of tritium remaining in the vessel amounted to approximately 6g or 17% of the tritium introduced into the vessel during the campaign [14]. Most of this tritium was bound up in co-deposited layers of carbon and hydrogen isotopes. These layers were found mainly adhering to the cooler surfaces on the inner side of the divertor or had become detached in the form of 40-50 μm thick flakes. During the shutdown much of the co-deposited tritium was removed from the vessel either by the brushing and vacuum cleaning exercise or with the carriers themselves as they were transferred out of the vessel. The co-deposited layers and flakes de-gas in the presence of humid air being drawn through the enclosures (off-gassing rates on the order of 0.6 GBq/hr were measured for one divertor module after removal from the vessel [12]).

4.1.2 Tritium Contamination

The boom, Mascot and tools which were used in the vessel during the shutdown were found to have absorbed tritium into their surfaces from where it subsequently emanated at a relatively constant rate. This required that all tools and components used in the vessel during the shutdown had to subsequently be stored in radiation controlled and ventilated areas. The In-Vessel Training Facility, in which all the trials for in-vessel procedures and the training of staff for both manual and remote shutdowns is performed was required to be enclosed and ventilated. The introduction of the boom into the training facility will require that this enclosure be classified as a Radiation Controlled Area with all the resulting consequences. Removal of tritium is only possible through prolonged heating in vacuum; a procedure which can only be applied in a minimum of cases. Surface cleaning is able to temporarily reduce the level of radiation from the surface of components but this returns after a short interval due to tritium diffusing back towards the surface.

4.1.3 Tritiated Water

The EDS system, used to extract tritium from gases and air, produces relatively large amounts of tritiated water. It is clear that this method of tritium extraction needs to be supplemented by a reliable and inexpensive method of tritium extraction from water. Such a system does not, at present, exist at JET.

4.1.4 Pumping, Purification and Separation of Isotopes

The new methods developed at JET to integrate the pumping of the exhaust gases and the separation of the pumped gases into hydrogen isotopes, helium and impurity gases have been shown to be both effective and efficient. The AGHS, the first integrated system developed to perform the required functions, worked safely, reliably and efficiently. It certainly forms the basis for a future closed cycle fusion fuel re-processing plant [15].

4.1.5 Uranium Beds for Storage of Hydrogen Isotopes

The storage of hydrogen in the form of metal hydrides and in particular the storage of tritium in Uranium has long been known to be a very safe and compact method. The uranium beds developed at JET and used successfully in the recent campaign, permit the storage of up to 100 g of tritium and the precise in-situ measurement of the tritium inventory using calorimetry with an accuracy of ± 0.6 g [16].

4.2 Remote Handling

4.2.1 The Remote Handling Philosophy

The remote handling philosophy developed at JET to facilitate the maintenance, repair and up-grading of the JET machine by remote techniques has been shown to be a full success. Based on the man-in-the-loop it allows the operators to perform work in the vessel as if they themselves were in the vessel. This method obviously relies heavily on the ability to "see" in the radiation environment using radiation proof cameras or otherwise. These technologies, which include the remote surveying methods developed at JET, are considered to be essential for remote handling in future fusion devices with higher radiation levels and must be developed further [7, 8].

4.2.2 Fasteners for Remote Handling

The design of a bolt connection for the divertor can serve as a good example of the approach taken at JET to address the detailed design problems associated with the use of remote handling technology in the environment of a fusion device. The bolt is designed to join, using remote handling tools for connection and disconnection, two components in the vessel, in this case the divertor modules to the water cooled divertor support structure, and conform to the following requirements:

The bolt connection must withstand the mechanical forces. This requires a good understanding of the electrical currents ("halo" currents) and forces that flow in the individual parts and components of the device. The direction (into the plasma or onto the vessel) and amplitude of these forces are strongly dependent upon the shape, detailed design and alignment of the in-vessel components and the location of their points of attachment to the vessel. A general design criterium is also to separate, as far as possible, mechanical connections and current paths.

The bolt connection must not seize during installation, operation or removal. It must resist high vacuum, high temperatures, differential temperatures, ionised hydrogen impingement, forces both radial and transversal (large transverse forces on bolts must be eliminated in the design), and electric currents. The influence of the various parameters on the un-bolting torque is not known and could benefit from further study. The JET experience has led to design criteria including specially selected, different materials to be used for the bolt and female thread insert; specified dimensional tolerances, hardness and manufacturing methods; close quality control; guided bolt insertion for remote handling and bolt assemblies which "float" to allow for thermal expansion. Location is provided separately by dowels.

The bolt connection must not open during operation. During installation the bolt must be correctly pre-loaded by the applied torque (the design must ensure that torque is transferred to the pre-load) and any locking mechanism must be remote handling compatible. The un-bolting torque must be within specified limits.

The bolt must be "trapped" for remote handling, i.e. must not drop out. The design must hold the bolt captive.

The bolt must fully retract so that, un-bolted, it does not impede the relative movement of the two components. The JET design features a "pop-up" mechanism using a spring which retracts the bolt once undone.

If seized or damaged, both bolt and female thread inserts must be removable and replaceable. The design features a pilot hole in each bolt which facilitates the remote drilling of the bolt (using vector movement constraints of the manipulator). The female threaded insert can also be removed and replaced and fixed in position by remote handling [17].

Figure 4 shows the implemented design solutions for the remote handling bolt assembly. Figure 5 shows the un-fastening torque of the bolts after extended plasma operations. The 1996 data were taken before the tritium campaign when the bolts were undone and re-torqued. The 1998 data were taken during the remote divertor exchange. The results show that the steps taken were successful in maintaining the torque within the design limits. During the remote removal and installation of the JET divertors not one of the ≈ 1000 bolts seized or cross threaded. It was therefore not necessary to implement any of the procedures or tools available to recover failed bolting connections [17].

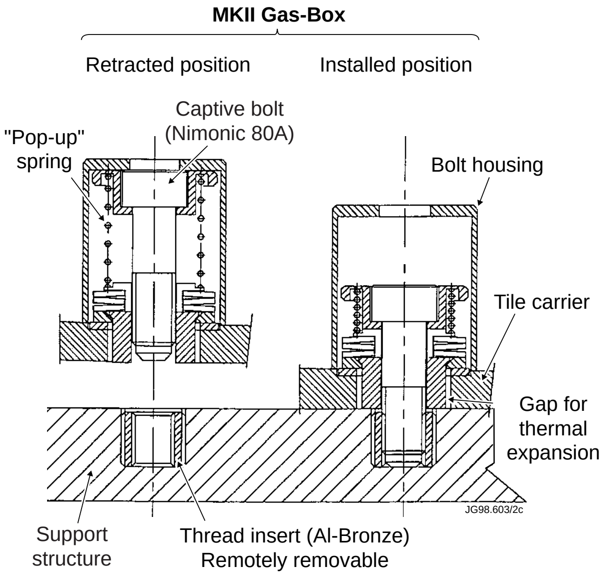

Fig.4. The remote handling bolt assembly

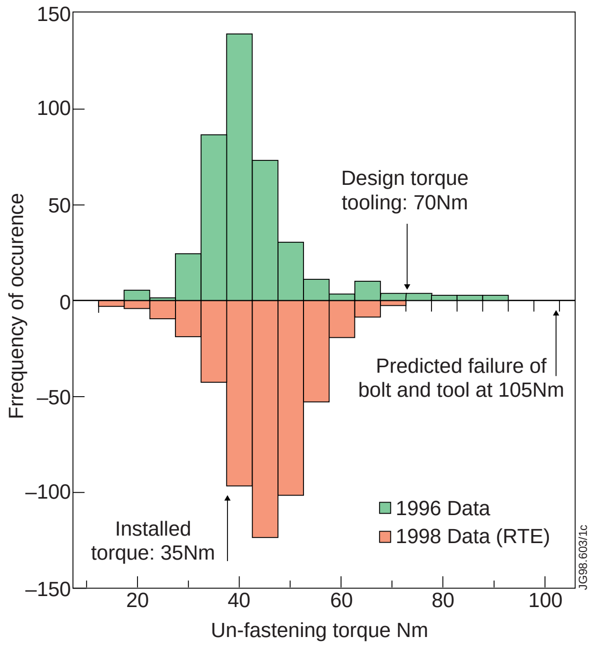

Fig.5. Un-fastening torque of divertor bolts

The design solutions, although effective in JET, would still benefit from additional studies before they can be safely implemented in the Next Step device.

5. CONCLUSIONS

Remote handling and tritium processing are two of the key technologies which need to be well established before routine operation, repair and maintenance of fusion power reactors can be envisaged. JET is the only fusion device world-wide which was devised with remote handling and tritium operation in mind. JET has successfully carried out a campaign with deuterium-tritium fuel and has subsequently carried out major in-vessel work using the remote handling equipment developed over the years. The experience gained at JET is invaluable for the conceptual design and realisation of the next step. It extends from the basic design philosophy through to the detailed design requirements of each and every component. It extends to the important areas of the organisation and management of a project to successfully integrate the engineering aspects, including the remote handling requirements, into the physics and operational requirements of the machine. These include not only the hardware but also the operational procedures; the standardisation and documentation, the software and the mock-up requirements and facilities required for the training of personnel; the methodology for failure recovery; the control of hardware and software reliability; the spares policy; the planning and management of shutdowns; the facilities and procedures to ensure safety, the control of radiation exposure and contamination; etc.

It is clear that the most efficient way to continue on the path to fusion reactors is through the continued research into reactor relevant technologies whilst making the most use of the presently available experience, expertise and facilties.

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