EUROPEAN FUSION DEVELOPMENT AGREEMENT

JET

EFDA–JET–CP(04)06-13

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** See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2002 (Proc. 19th IAEA Fusion Energy Conference, Lyon (2002)).*

Preprint of Paper to be submitted for publication in Proceedings of the
23rd SOFT Conference,
(Venice, Italy 20-24 September 2004)

ABSTRACT

JET is the only operating platform within fusion where Remote Handling (RH) techniques have been developed to a stage that allows in-vessel maintenance work to be carried out fully remotely. JET's in-house team developed the methodology and a rational approach that allowed them to succeed in this task. This work clearly shows that the gap between developing the first prototypes and having an RH system ready for operational use, has a time and manpower costs which can easily be under-estimated.

After a presentation of the context of this study this paper summarises some of the main lessons learned by JET RH team during the development and operation of their RH equipment. Starting from the JET example, the paper then tries to give ITER some references for the identification of areas of improvement and for evaluation of the amount of work and manpower costs that are really needed for a complete RH system to become fully operational and reliable.

INTRODUCTION

In ITER, Remote Handling (RH) was defined by the designers at the beginning of the project as the nominal solution for the maintenance of the reactor.

Due to the introduction of a significant amount of Tritium in the JET torus in 1997 and application of ALARA considerations JET has today the only operating platform within fusion where RH techniques have been developed, tested, and improved to a stage that allows in-vessel maintenance work to be carried out fully remotely.

Even if the RH systems used in both reactors will be different, there is no doubt that ITER will have to go through the same development steps as those followed by JET before saying that its RH equipment is safe and reliable. Compared to JET, ITER has the advantage of taking RH into account in the early design of the machine. It becomes therefore interesting to take advantage of this situation and try to introduce recent operational feedback from JET into the ITER design process. EFDA, through the fusion technology task JW0-FT-5.2, asked an external party (CEA/LIST) with knowledge in RH, fusion and ITER to gather useful lessons learned by JET in the RH field which could be relevant to the ITER case. Discussions and meetings between the JET RH team, EFDA and CEA/LIST were held. Recommendations were reported in a final document [1] and are summarized in the following sections.

1. RH PHILOSOPHY

Experimental reactors like JET, are subject to changes in their configuration in order to test new components and systems. In general, this affects the RH tasks by:

- increasing the level of difficulty
- increasing the level of detail of the task
- increasing the number of tasks (less modularity)

To cope with this, from the beginning JET adopted a generic "man in the loop" RH strategy [2], which maximised its adaptability to the environment and minimised the need for re-configuration of the equipment from one shutdown to the next. This is not to say that all operations are controlled using a “man in the loop”. In fact, the RH system is operated in an automatic (or robotic) way when there is a need for time optimisation and/or accuracy of motion and is open to manual intervention when a high level of human supervision and/or adaptability is required.

This “man in the loop” approach also lends itself well to RH tasks relating to unexpected events. What is important here is not speed or degree of automation of the task, but the adaptability of the RH equipment and procedural approach. The experience at JET is that the ability to reconfigure the RH task procedure and tooling during RH operations is an important key to its success.

2. SIMPLIFYING INTERFACES

In order for the development of RH equipment to be effective, the JET team found it essential to simplify the interface between the torus and the RH equipment because:

- the impact of modifications to the torus does not lead to significant changes to either the RH equipment or the RH operations Safety Case.
- only the end-effector has to be adapted to account for new operations
- changes to tools and equipment between successive shutdowns are minimised.

In fact, at JET the only interface between the torus and the RH equipment is the size of the access port through which the RH equipment enters the vacuum vessel.

In contrast, a large proportion of the planned ITER RH equipment, in particular for divertor replacement is (arguably by necessity) heavily dependent on the machine design. The disadvantage of this has already been illustrated by the knock-on effect of the new ITER 2001 design which has resulted in a significant reconfiguration of the divertor handling equipment.

Although this situation was probably unavoidable for the case of divertor handling, the lessons learned from the JET experience should be kept in mind for other less constrained situations e.g. use of the In-vessel transporter, port plug maintenance and hot cell work.

3. ADDITIONAL MAINTENANCE WORK FOR FUSION REACTORS

According to JET’s experience, the nominal maintenance of a fusion reactor is not only related simply to component replacement. During the course of the various remote handling shutdowns a number of supplementary tasks have become part of the nominal maintenance scheme and have often required the development of specific RH equipment: e.g. Inspection for leaks, cleaning, erosion measurement, as built metrology, electrical connector replacement and checking, sampling, de-tritiation, checking and re-tightening bolts.

Installation of In-vessel services (electrical power, lighting for viewing systems…) should not be underestimated in both terms of design and installation time and should be considered as part of any shutdown.

4. EQUIPMENT DEVELOPMENT LIFE CYCLE:

The RH tool (or RH equipment) is of prototypical nature and after manufacture its reliability needs to be proven in order to be ready for RH operations. The general scheme used in the development of a new piece of RH equipment or tool at JET is defined by the so-called "life-cycle" of the product:

This life-cycle can be divided into the following phases:

- Phase 1: Definition of the requirements & Design of the system
- Phase 2: First version system
- Phase 3: Development to maturity
- Phase 4: RH operations

The experience at JET was that this evolution can only be efficient if:

- interfaces between the RH equipment and the machine are frozen
- R&D work is completed

As an example, for the JET boom and Mascot the first reflections and designs started in 1982 and commissioning of the first system was made during 1985. In 1993, the JET RH team decided to make a global reliability test of this equipment, known as the "1000 hours test". The first shutdown, known as the "Remote Tile Exchange" or RTE, in which this equipment performed completely remotely occurred in 1998. Analysis shows that regarding preparations specifically required for execution of the RTE shutdown, roughly:

- 120 man-years were invested in the development of the first version systems
- 140 man-years were required to develop this equipment "to maturity"
- 100 man-years were invested in RH operational preparations prior to the shutdown.

So, based on the JET experience, it can be said that following its original design and manufacture, the effort required to properly prepare the RH equipment for real operations involved as much work as creating the equipment in the first place.

The message for ITER contained in this experience is clear. Even having developed and successfully tested the first prototypes of a RH system, the greater proportion of the effort still lays ahead.

5. RELIABILITY / AVAILABILITY ASSESSMENT

A piece of equipment has to be designed to satisfy both the performance and functionality required. But due to the one off nature of the RH equipment, its reliability and its availability has to be evaluated with special care[3].

Estimations of the reliability of the JET RH systems using standard methods (based on the prediction of "Mean Time Before Failure", MTBF) proved difficult because of the prototypical nature of the equipment. Instead the reliability of the RH systems was assessed and improved during long-term endurance test campaigns using purpose built scale one mock-ups or test facilities.

JET's experience showed that the reliability of a system is linked to decisions taken during its design phase and in order to minimise the risks:

- Use of tried, tested and simple engineering techniques is recommended.
- Quality control during design, construction and maintenance is necessary.
- Use of complex onboard electronic components in the irradiated zone should be avoided.
- All control systems should be provided with failsafe watchdogs.
- All in-vessel systems should be provided with a means of rescue.

According to JET's experience it seems that for prototypical components of this type, it is the build quality that has the greatest influence on the MTBF.

6. RECOVERY FROM FAILURE

At JET, measures were put in place to be able to remotely recover RH equipment from all in-vessel failures which were considered credible. Nevertheless, it is important to note that, even at the highest levels of in-vessel activation, there was always the backup possibility for manual intervention in case remote recovery of failed equipment proved impossible.

For ITER, because at some point man-access will be completely impossible, the definition of the frontier between credible and non-credible failures will need to be more extreme. However, it does appear that during the first 7 years of operation, the fusion power will be gradually increased and in-vessel radiation levels will remain low enough to allow man access. From an RH operational standpoint, it is important that this time is used to the full with regard to the development and tuning of the RH equipment before the machine becomes fully activated.

7. CONTROL SYSTEM DEVELOPMENT

JET RH team realised [4) that although the RH equipment was unique to JET, at a low level, the control functions required were similar to those in industrial applications. In the early years of JET RH development, final design and manufacture of control systems was left to external companies after a definition of the functional requirements. This lead to the undesirable situation of having almost as many different control system architectures as pieces of RH equipment.

More recent experience at JET has shown that control system standardisation can provide huge benefits in terms of quick response to failures and reduction of spares. Therefore JET now chooses to use widely commercial products configured 'in-house' by a local team. This has been found to greatly accelerate the development of a system and helps to maintain homogeneity. The latter is far more difficult if the task relies on the use of several sub-contractors and underlines the importance of having a local team on which you can rely on to quickly solve problems and develop new applications.

It is interesting to note that over recent years, similar problems have been reported in relation to the RH equipment prototypes developed for the ITER L7 project [5,6]. It therefore appears that, as well as being a topic for future consideration for ITER construction, there could be more immediate benefits in considering such an approach for the ITER prototype development program currently underway.

8. TOOLING ISSUES

Designing tools to be remotely operable means providing them with specific features which reduce the level of risk in performing the task [7]. At JET, where possible the responsibility for high-skilled operation is transferred from the operator to the tool itself, thus leaving the operator to concentrate on the global activity. However, at the same time the skill of the operator allows reduction in the complexity of the tooling itself. Therefore for any given task a good balance must be met.

A common feature of this technique is that remote tooling requires more space than would have been needed for manual tooling. This is, unfortunately, a necessity, often not appreciated by machine designers.

Although the number of tools can be minimised by standardisation, the large number of tools required during each shutdown at JET has created a significant overhead for tool repair, storage and contamination control. This aspect should not be overlooked for ITER.

9. TEST FACILITY

Final tuning of RH procedures in training facilities is essential to succeed during real operations. JET's experience showed that considerable time could have been saved if personnel had been trained previously to perform the in-vessel work. The way followed by JET is to use a full size mock-up [8] of the in-vessel environment. A similar approach is planned for ITER through the construction of an on-site "RH Test Stand". Based on the JET experience the importance of such a facility cannot be understated.

10. VIEWING SYSTEMS

The viewing needs for Remote Handling activities are correlated to the level of automation of the tasks. A simple task with a high level of automation will only require a low level of visual control and a final check of the situation is probably sufficient. For highly skilled operations where men are heavily involved in the loop, a real-time high quality viewing system is essential to guarantee the success of the operation.

For ITER, the topic of real-time viewing for RH operations seems not to be well defined, although recent predictions for radiation levels in the plasma chamber during maintenance [10] suggest that the use of standard radiation hard cameras should be possible.

11. USE OF VIRTUAL REALITY

With progress in computer-science, the introduction of Virtual Reality to augment the real-time viewing systems seems an attractive approach. Recent developments at JET [9] show that real improvements for operations can be achieved by exploiting these techniques. As such, Virtual Reality is today used extensively at JET during operational preparation and final task execution. It has been found that performing a task in a 3D world can really help the operator to memorise the task.

But because VR is unable to cope with unpredictable situations like machine damage, real-time camera views still remain central to the RH strategy employed at JET.

12. SUPPORT FOR RH OPERATIONS

It is easy to forget that the RH equipment operating inside an area needs a huge amount of external backup (e.g. cubicles, wiring, storage areas, maintenance and decommissioning areas) and this takes up a large amount of space outside the working zone. When RH is a necessity, it is not only essential to provide a RH-friendly design for the machine and its components, but also to provide the necessary support (access space, building space and management procedures) to allow for RH operation to be carried out in a safe and reliable way. This appears to be an over-riding message when talking to JET RH staff about their experiences and should clearly be taken on board in the preparations made for ITER.

CONCLUSIONS

JET has the unique experience of creating the only operational system for tokamak maintenance which has already successfully carried out long-term maintenance campaigns under fully remote conditions. Based on the topics discussed above, although a number of differences exist between the ITER and JET RH environments, it is believed that ITER could surely take advantage of the lessons learned over many years at JET for the development of its own RH equipment and strategies.

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