REMOTE HANDLING MAINTENANCE OF ITER*

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Abstract

The remote maintenance strategy and the associated component design of the International Thermonuclear Experimental Reactor (ITER) have reached a high degree of completeness, especially with respect to those components that are expected to require frequent or occasional remote maintenance. Large-scale test stands, to demonstrate the principle feasibility of the remote maintenance procedures and to develop the required equipment and tools, were operational at the end of the Engineering Design Activities (EDA) phase. The initial results are highly encouraging: major remote equipment deployment and component replacement operations have been successfully demonstrated.

1. INTRODUCTION

ITER is described in detail in the Final Design Report [1]. The in-vessel components must be maintained and handled remotely because of neutron activation. Due to plasma interactions, the divertor high heat flux components are expected to erode to such an extent that they will require replacement several times during the lifetime of the machine. Blanket modules are expected to require replacement only in case of damage due to unexpected events. Furthermore, all blanket shield modules will be replaced with tritium breeding modules at the end of the Basic Performance Phase (BPP) in preparation for the Extended Performance Phase (EPP).

The ITER vacuum vessel is shielded from direct plasma interactions and is not expected to require any maintenance throughout the life of the machine. Equally, all components outside the vacuum vessel but inside the cryostat (which provides the vacuum environment for the superconducting coils), are designed to last the lifetime of ITER without requiring maintenance. However, it can not be fully ruled out that unexpected failure occurs that requires repair. Calculations have shown that the nuclear shielding provided by in-vessel components and the vacuum vessel itself is such that the build-up of neutron-induced activation inside the cryostat is slow and that time-limited hands-on access into the cryostat may be feasible up to the end of the BPP [2]. Hands-on repair is therefore considered the primary approach should, in the unlikely event of a failure, access into the cryostat be necessary. However, components that may require remote handling will be constructed to be remote handling compatible.

In-vessel maintenance requires access of remote handling equipment through ports. Access is gained after removing the inserts that are normally located inside the dedicated remote maintenance ports. To remove these inserts, not only have the relevant plug and closure plates in the bioshield and cryostat to be removed, but also a number of services, including coolant lines, vacuum connections, signal cables etc. As the predicted radiation level in these port areas is relatively low, the strategy is to use hands-on assisted operations to reduce the number of complex remote operations.

While it is considered desirable to carry out maintenance and repair in-situ, the present state of the art limits these operations to inspections and a few adjustment operations. Remote repair and refurbishment will normally be carried out in a dedicated hot cell facility, requiring removal and reinstallation or replacement of the relevant components. Extraction and reinstallation, as well as the transfer of active components, have to be carried out such that activated dust and tritium remain fully confined, and exposure of personnel or sensitive components to gamma radiation is avoided. The strategy that has been adopted involves sealed transfer casks that are docked to the vessel and hot cell via double-sealed door arrangements. The casks do not provide gamma shielding because of size and weight constraints. Therefore, personnel will be evacuated from the tokamak pit area during transfer operations, and any sensitive components along the pathway have

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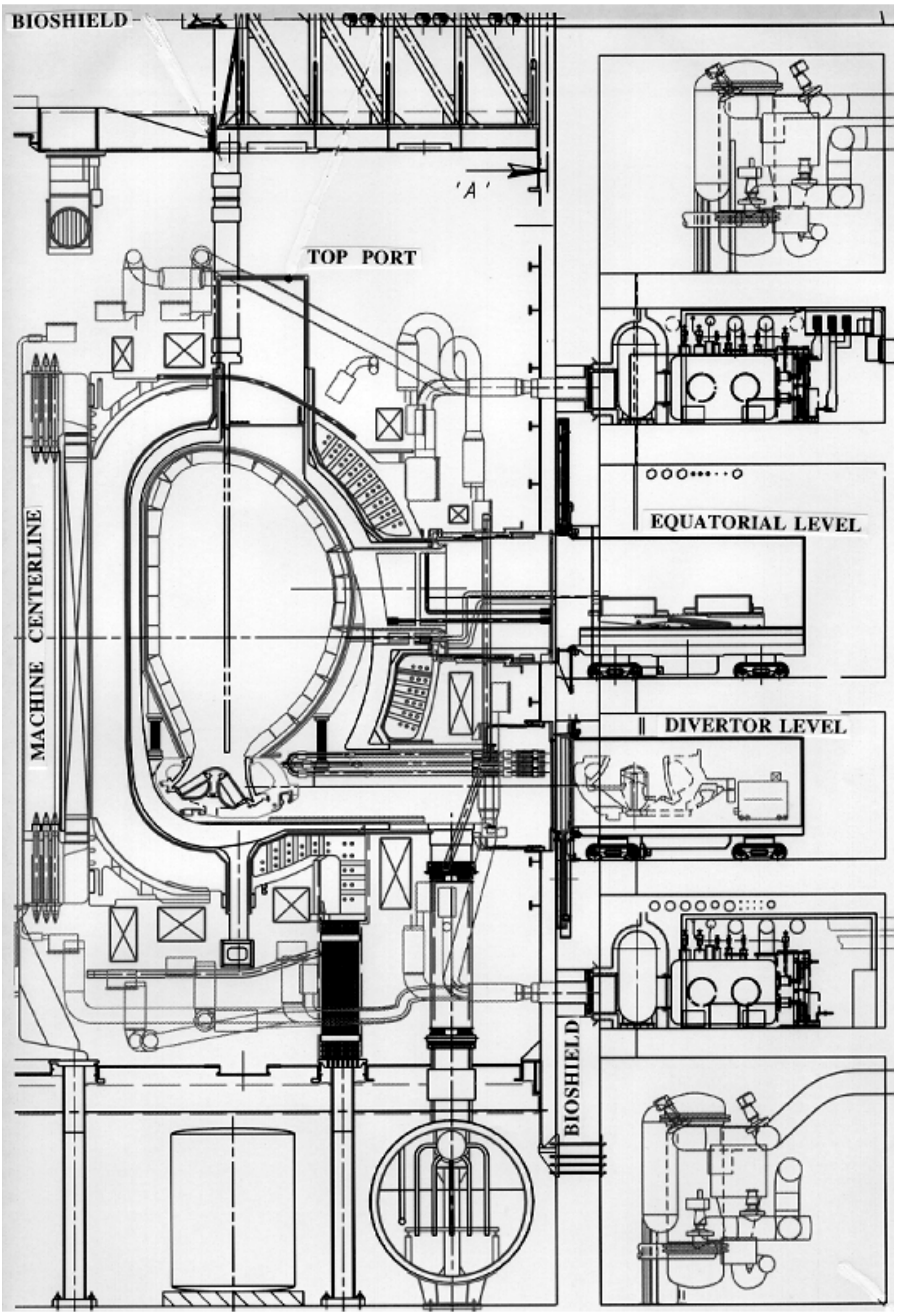

FIG. 1. ITER Machine Elevation

to be shielded. Figure 1 depicts an elevation of the ITER tokamak depicting the access ports and maintenance casks at the various levels around the bioshield.

The aim of this paper is to give an overview of the ITER remote maintenance as well as to describe the rationale for the strategies adopted for the in-vessel and ex-vessel component maintenance.

2. APPROACH FOR IN-VESSEL MAINTENANCE

Procedures for in-vessel maintenance have been developed taking into account the following constraints:

(i) maintaining confinement of activated materials and tritium at all times,
(ii) application of as low as reasonably achievable (ALARA) principles for radiation exposure of personnel,
(iii) impact on machine operation.
(iv) cost.

During machine operation, the radioactive inventory in the vacuum vessel is confined by two barriers: the vacuum vessel and the cryostat vessel. For component replacement or repair requiring introduction of large-scale remote maintenance equipment, it is impractical to maintain two barriers at all times. It has therefore been decided that the connection to ports of maintenance and components transfer casks will be such that one barrier is maintained at this location. As a prerequisite, however, the amount of releasable radioactivity is strongly reduced by certain activities prior to cask docking; lowering the temperature of in-vessel components and vacuum vessel to near ambient temperature, venting the vessel with dry nitrogen and maintaining a purge flow through a detritiation system. Furthermore, if required, maintenance activities may begin with the removal of in-vessel dust.

These activities lower the stored energy inside the heat transfer loops and the releasable activity inside the vessel such that one confinement barrier suffices during maintenance operations. It is clear that these activities take time and hence are not appropriate for frequent in-vessel inspections that may be necessary to investigate plasma-facing components after strong disruptions or expected component damage. The in-vessel inspection systems design requirement is therefore based on maintaining at all times two confinement barriers during deployment and on operating with the in-vessel components at interpulse temperature. In this way, frequent inspections can be carried out without significantly degrading machine availability, and maintenance interventions can be preceded by quick inspections revealing the extent of damage, so that repair or replacement preparations can already be targeted prior to opening the vacuum vessel.

The in-vessel viewing (IVV) systems will provide direct high resolution imaging, to millimeter resolution, or detailed metrology, to 0.1 millimeter resolution, depending on which system is in use. The direct views will be used to routinely inspect all the plasma-facing components, from the vertically deployed IVV mast, which will be held under operational vacuum conditions for deployment between plasma discharges. The metrology data is used to create an electronic representation of the current condition of the in-vessel components, for the planning of future maintenance activities.

In-vessel maintenance is done remotely, hence fully satisfying ALARA considerations. The opening of ports does, however, involve hands-on assisted operations. These involve not only the deployment of personnel outside the bioshield, but also hands-on operations when the bioshield plug in front of a port has been removed. In the latter case personnel will be exposed to certain dose rates and the procedures are subject to strict ALARA guidelines, whereby the exposure has not only to be limited as much as practical and below statutory levels, but personnel exposure should also be justified against the drawback of having to develop and deploy otherwise complex and costly equipment.

To limit the impact of maintenance and repair operations on machine availability, the following approach has been adopted:

(i) expected frequent, routine maintenance activities, e.g. divertor replacement, must be accomplished in a short time;
(ii) components that are expected to require infrequent, but occasional, maintenance must be designed to allow remote maintenance in a reasonable time.
(iii) components that are designed to require no maintenance, but should they fail, must be repaired or replaced remotely, must be designed to allow remote maintenance, but the maintenance time is generally of much less importance than functional design considerations.

Table I lists the main components inside the vacuum vessel and their main characteristics for maintenance. As shown in Table I, the divertor is expected to require replacement several times during the lifetime of the ITER machine. Therefore, the design of the divertor is driven not only by functional requirements, but also largely by remote maintenance requirements. These considerations have led to a divertor design involving its segmentation into cassettes. The design allows draining and coolant pipe cutting (and welding) operations to be carried out by hands-on-assisted activities external to the bioshield, in parallel with other preparatory activities. The number of cassettes is given by the available port width for transfer into and out of the vessel. The in-vessel operations to be carried out by handling equipment is mainly limited to the radial and toroidal

TABLE I. IN-VESSEL COMPONENTS* REQUIRING REMOTE MAINTENANCE

Component	Dimensions H x W x L (~ m)	Weight (t)	No of Units (-)	Expected Maintenance Frequency During Lifetime (-)	Maximum Duration of Replacement (months)
Divertor Cassettes	2 x 1 x 6	26	60	3 - 8 few	6 (all cassettes) 2 (single cassette)
Blanket Modules	1.3 x 2 x 0.5	< 4.3	740	1 (all mod's) few (single module)	24 2 (single module) 3 (toroidal row)

*Excluding components located in ports.

transport of cassettes and locking activities, whereas coolant pipe welding, cutting and leak testing can be carried out from outside the bioshield. Accurate alignment of all plasma-facing components is crucial. A remote metrology system may be introduced to survey, with submillimetre accuracy, the rails to which cassettes are attached prior to (re)installation, as well as the high heat flux surfaces of cassettes after (re)installation.

After the BPP all 740 blanket shield will be replaced with breeding blanket modules prior to the start of EPP operations. To limit the impact on machine availability, single modules must be replaced within 8 weeks, whereas the complete module change must be accomplished within 2 years. Modules are attached to a backplate, which also includes the coolant manifolds. The backplate is horse-shoe shaped in elevation section with modules attached in poloidal and toroidal arrays. To allow quick, accurate installation and withdrawal of modules, the in-vessel module handling transporter is designed to have its main axes of transportation oriented in the toroidal and poloidal directions. The equipment is based on a segmented, toroidal rail and a vehicle with telescopic arm and end-effector. The vehicle rides on the rail in the toroidal direction and can turn around the rail to provide the telescopic arm and end effector with poloidal movement. The backplate attachment positions (before module assembly), as well as the modules themselves (after assembly), can be surveyed by the same metrology system as used for the divertor cassettes.

Small holes in the front face of the modules allow access for mechanical attachment, coolant and electrical connections. The rather complex mechanical design of the modules and the modularization is optimized with respect to the payload capacity of the handling system which is determined by the maximum size of the equipment and limited by the port opening and available space for handling inside the vessel. Both port opening and in-vessel space are fully utilized when inserting the vehicle or transferring modules and by the kinematic trajectories of the handling equipment with modules attached inside the vessel, respectively. The dedicated remote handling ports are constrained in width and height by the toroidal field (TF) coils and required space for intercoil structures between ports respectively. To maximize the port width, the number of ITER TF coils was reduced from 24 to 20 early in the design phase.

The cost of equipment and maintenance features is generally minimized by maximum standardization. This is only partially achieved for in-vessel components, by the use of the same inspection and metrology equipment, but different transporters and end-effectors have been developed for the divertor and blanket modules. The advantage of this approach is, however, that both components can be maintained fully independently of each other. Further standardization improvements, especially regarding the standardization of all remote cask docking interfaces would have been beneficial and were considered at the end of the EDA.

Port insert assemblies are also in-vessel components. Those at equatorial and divertor levels generally consist of a shield plug filling the opening in the blanket, backplate and vacuum vessel shield, as well as additional equipment, including plasma measurement equipment (diagnostics). In some instances, e.g., ion cyclotron heating and current drive, test blanket modules, and diagnostics are integrated with the shield plug. For maintenance or withdrawal of the insert, the latter is withdrawn into a transfer cask, followed by repair in the hot cell and reinstallation of the refurbished insert or a new one. At the divertor level, 16 out of 20 ports contain cryopumps. In that case the shielding is provided partially by divertor cassettes.

To allow rapid replacement and to minimize the number of remote operations on components exposed to the vacuum inside the vessel, the inserts, including shield plug and vacuum vessel closure plate, will be handled as one integrated unit. The merits of this approach are that fully tested units can be inserted without requiring additional remote work on the in-vessel components and that this lends itself to a high degree of standardisation as the vessel port interfaces are the same for all ports at equatorial level. Moreover, as the number of remote operations is minimized, relatively quick replacement is achievable. The demerit is that this requires cantilevered handling of large and heavy loads (2.6 x 1.6 x 4m, approx. 50-70 t).

In addition to horizontal vacuum vessel ports at the divertor and equatorial levels, there are vertical upper ports penetrating the vacuum vessel shell in between the 20 toroidal field coils. Ten of those ports are dedicated to the routing of coolant pipes to and from the backplate and from the vacuum vessel itself, whereas the other ten are allocated to diagnostics. Due to neutron activation and tritium contamination, those diagnostic components that are exposed to the plasma require remote handling. Access for maintenance is via vertical port extensions that connect with the upper lid of the cryostat. For standardization reasons, the diagnostic probes are, to as large an extent as practical, arranged in a modular way on cylindrical plugs that can be replaced remotely, if necessary.

3 STATUS OF IN-VESSEL MAINTENANCE

The feasibility of the two main in-vessel remote replacement procedures, for divertor cassettes and blanket modules, had, at the end of the EDA, been demonstrated in large test stands. While the simulated remote operations are still far from complete, the chief handling procedures and transportation from installation position to and from transfer port positions were clearly demonstrated on dummy components at 1:1 scale in size and weight. Parts of the transfer operations were already carried out in automatic mode. Welding and cutting operations, although not yet integrated in the test stands, had been qualified to varying degrees in bench tests using prototypical equipment. Port handling concepts are described in more detail in [1] and [3].

Based on the use of four dedicated remote handling ports at both equatorial and divertor levels, a seven day working week and two shifts a day for in-vessel operations, a number of independent analyses concluded that the stipulated maximum component replacement times for both blanket modules and divertor cassettes can be achieved. Verification will, however, only be obtained when the detailed procedures are fully carried out in the test stands. The blanket handling and divertor handling test stands will continue to operate in the post-EDA period to develop in further detail the handling procedures, and the equipment. Special emphasis will be placed on the development of equipment recovery procedures from any credible malfunction or accident.

Details of the blanket handling equipment and test demonstrations are given in [4], whereas the detailed status of the development of divertor remote handling is given in [5]. The in-vessel viewing and metrology systems are described in [6].

The diagnostic systems inside the vertical port that require remote maintenance, can be accessed after placing a cask onto the port extension penetration in the cryostat lid. A double-seal door system is used to allow passage of components and insertion of handling tools from that cask. At the end of the EDA, conceptual designs had been generated. Details of the designs are described in [7].

With the exception of inspection, in-vessel maintenance will be carried out with the vessel vented with dry nitrogen and the vessel and in-vessel components cooled to near ambient temperature. Components to be replaced will be drained and, depending on configuration and level of decay heat, will slowly rise in temperature to a somewhat higher level. The in-vessel gamma radiation dose rate 24 hours after the last plasma pulse is expected to be around 3×10^4 Gy/h decreasing to approximately 1×10^4 Gy/h after 10 days and to roughly 3×10^3 Gy/h one year after the last pulse. Remote handling equipment, even when introduced into the vacuum vessel for only a short time, must be designed to be "radiation hard". To achieve this, a broad based radiation hardening development programme, that was already initiated prior to the EDA, has been continued throughout the EDA. Very good results have been obtained for many constituent components of the large scale remote handling equipment to be used in-vessel. The aim of having available equipment that is radiation hard up to at least 10^8 Gy under a gamma dose rate of 3 x 10^4 Gy/h has been approached or exceeded for many constituent parts and components.

It is intended to have available, at the start of machine assembly, a complete set of remote handling equipment and tools - if feasible, already fitted out with radiation hard parts and components - to be used for initial machine assembly, albeit not always in a fully remote mode. It is expected that together with the tests carried out in the large test stands, this would demonstrate and verify the procedures and equipment.

4. APPROACH FOR EX-VESSEL MAINTENANCE

The ITER cryostat is a very large cylindical vacuum vessel with many penetrations in the cylindrical shell. Side penetrations are either for cryostat ports that connect via bellows to ports in the vacuum vessel at the divertor and equatorial levels, or for water or cryogenic coolant lines. Additionally, four side penetrations in the lower part of the cylindrical shell, as well as four penetrations in the lower flat lid and 25 penetrations in the upper lid are for access into the cryostat itself.

Although the cryostat is a very large vessel (36.5 m diameter x 31 m high), the interspace between vacuum vessel and cryostat shell is filled with port ducts, and service lines. Moreover, all coils and cold structures are shielded from direct line of sight to warm surfaces by 80K thermal shields. Access into the cryostat and to the cold components is therefore blocked by thermal shields and movement inside the cryostat is severely impeded by service lines and ducts. To gain human access, the cold structures have to be warmed to room temperature and the cryostat has to be vented with air. This takes approximately one month. Following an intervention, evacuation and cooldown, takes another month. The long time span and the difficulty of gaining access for inspection and maintenance due to congestion and thermal shields, has led to the requirement that there must not be any components inside the cryostat that require maintenance. All components must be designed to last the lifetime of ITER without needing maintenance or replacement. However, it is clear that even with the application of conservative design criteria and tough quality control procedures, failure of components inside the cryostat cannot be fully ruled out which would then require access for repair.

Such a repair intervention is a very unlikely event and occupational radiation exposure analyses predict that time-limited human access into the cryostat remains a feasibility up to the end of the BPP, Therefore, the adopted strategy for repair inside the cryostat is based on hands-on operations with human access into the cryostat, at room temperature. Such access will be strictly time-limited and the approach outlined below will be followed:

- (i) hands-on repair is the reference scenario, with remote repair as a back-up, should dose rates preclude hands-on repair;
- (ii) to reduce the duration of in-cryostat operations, permanent walkways and platforms will be available inside the cryostat to gain quick access to strategic locations. These include lifting points and other special features;
- (iii) back-up provisions for in-cryostat remote operations will be provided and, where practical, will use the special features introduced for hands-on operation.

Worker's exposure is subject to legal dose limits and to ALARA considerations. It is assumed that for ITER a 20 mSv/y regulatory dose limit will be imposed. To ensure that regulatory limits are not exceeded, reduced administrative limits are set for individual exposure control. Additionally, scenarios are reviewed to ensure that occupational radiation exposure is reduced to levels as low as reasonably achievable. Therefore hands-on operations are normally considered only in areas where the dose rate is below 750 µSv/h. The dominant factor for the radiation shielding of the ITER shield blanket and vacuum vessel was to keep the dose rates low in the cryostat to allow human access. This turned out to be more restrictive than the avoidance of excessive nuclear heating or irradiation damage to coils. It is expected that towards the end to the BPP the dose rate 10^6 s after a plasma pulse will be around 100 µSv/h at the cryostat inner wall.

The following in-cryostat repair operations have been considered during the EDA:

- repair of electrical insulation breaks of cryogenic pipes inside the magnet break boxes;
- repair of electrical insulation breaks on other cryogenic lines;
- bolt tensioning of intercoil structures;
- leak checking to find vacuum or cryogenic leaks.

As a typical example, access to the magnet break boxes and the repair of electrical insulation breaks have been studied in more detail for both hands-on and remote repair [8]. In addition to local repair operations, the replacement of any of the coils has to be considered. The design of the Central Solenoid (CS) is such that, after accessing the top and bottom connections, it can be withdrawn from the top after opening an inner cover in the upper lid out of the cryostat. As it is located in a very well shielded position, the dose rate is expected to be sufficiently low for short-term access. The upper Poloidal Field Coils (PF1 and 2) can be similarly lifted out of the cryostat by removing the central cover of the cryostat lid together with the upper thermal shield. For coil PF 3 all upper coolant lines and their guard pipes have to be removed. Coils PF 4 to PF 7 are “trapped” either between ports or underneath the machine. Replacement of these coils, although ultimately possible, will not only take a very long time but also involve removal and installation of many other systems. It has therefore been decided that these coils should have redundant winding packs (modules). They are composed of four modules each. Each superconducting coil can develop its full ampere turns with only three modules in case one of four modules malfunctions, albeit at a lower operation temperature. Should, however, more than one module fail, the coil would have to be replaced. For such an event, annular rings have been included in the bottom lid of the cryostat that can be removed to provide an opening for the corresponding coil to be lowered through. The space underneath the cryostat can be fitted out to cut the faulty coils in pieces for removal and for rewinding a new replacement coil. Redundant windings could not be included in the Toroidal Field Coils (TF). Should they develop unrecoverable faults, they will have to be replaced. Such a major operation has been studied [1] and is, in principle, feasible, although it will require installation of substantial radiation shielding structures above the cryostat and in the Tokamak Hall.

Features are included in the design of the vacuum vessel and thermal shields that would, in principle, allow their cutting, rewelding and handling by remote means. However, this is considered such an unlikely event, that the remote equipment and procedures would be fully developed and tested only when required.

5. STATUS OF EX-VESSEL MAINTENANCE

As ex-vessel repair operations are very unlikely to be required, the studies undertaken in the EDA have been restricted mainly to showing the feasibility of repair work and to provide input to the design of components and additional features to facilitate repair work when necessary. Conceptual designs are available for permanent walkways, platforms and structures and fixtures inside the cryostat. Access hatches have been incorporated in the design of the thermal shields. Moreover, access openings are provided in the cryostat shell to allow quick access to all areas that may need human or remote equipment access for postulated repair operations. The design of the cryostat, thermal shield, vacuum vessel, the layout of service lines inside the cryostat, as well as the position of the magnet break boxes have been driven, to a considerable extent, by the requirement to facilitate remote or hands-on replacement and repair of components inside the cryostat.

Remote back-up procedures have been studied to a limited extent. This focused mainly on kinematic studies with manipulator and transporters to gain access to strategic positions, e.g. magnet break boxes inside the cryostat. Preliminary bench tests involving remote replacement of an insulation break inside a break box showed very encouraging results so that it is believed that this can indeed be developed as a credible back-up scenario. Studies devoted to coil replacement scenarios, have also mainly focused on ensuring that this is, in principle, feasible. These studies determined the space requirement underneath the cryostat for coil rewinding, the requirement and geometries for the annular rings in the bottom lid and the covers in the upper lid of the cryostat. The many steps involved in coil replacement scenarios were investigated and proposals were made for the shielding of the cryostat opening when the upper lid and bioshield are removed and for the shielding of large, activated components withdrawn from the cryostat. Furthermore, initial evaluations show that the skyshine dose rates accompanying operations, that involve removal of the cryostat lid (and top shielding), must be kept of sufficiently short duration (approximately one shift) so that the allowable dose limit at the site boundary (100 μSv/y assumed) is not exceeded.

6. TRANSFER OF ACTIVATED COMPONENTS TO AND FROM THE HOT CELL BUILDING

As mentioned above, repair or refurbishment of in-vessel components, especially divertor cassettes, will generally occur in dedicated cells in the hot cell building [9]. During maintenance periods, biological shielding will be in place to allow man access into the areas around the cryostat while in-vessel maintenance operations are in progress.

Transfer of activated components to and from the hot cell building can be initiated only after evacuation of all personnel from the pit and pathway. The route from the divertor and equatorial levels is via circumferential galleries, through the lift shaft to the -12.7 m level of the building (hot cell building entry level). From here the casks travel approximately 150 m to the hot cell building. Docking ports are provided for unloading and loading of components. During a 24 hour day, two shifts are devoted to maintenance operations and one, the night shift, is devoted to transport operations. In-vessel maintenance could, in principle, go on in parallel with transport operations.

Casks are designed to be leak tight so that tritium and in-vessel dust is fully confined during transport. Due to decay heat, a slight overpressure may be generated. Casks will be designed to be tight for the expected rise in pressure. However, in the very unlikely event that a loaded cask is stuck during transport for a prolonged time, some form of passive overpressure relief, without escape of dust or tritium, has to be provided. The intention is to develop a filtered relief valve and rupture disk assembly connected to a low temperature catalytic convertor and absorber that would retain all dust and ~ 99% of the released tritium.

The original transportation system was based on railway tracks and included turntables in areas were sudden changes of direction were required. Due to the impact of rails on the building design, an alternative system based on air cushion flotation was studied and a conceptual design of an air cushion transporter for ~ 100 t payload was developed. The reference transportation vehicle is now based on air flotation with onboard batteries and compressors, guided by tapes buried in the floors [10]. The time to transfer a cask from a vessel port to a hot cell has been estimated at 45 minutes.

7. CONCLUSIONS

At the end of the EDA, the remote maintenance strategy for ITER had been fully defined.

Remote maintainability has had a major impact on the layout of the machine and design of components. Major in-vessel remote handling operations have been demonstrated on large-scale test stands. Testing will continue after the EDA to develop (in detail) procedures and equipment. This will include rescue of equipment from any credible event.

The main maintenance strategy adopted involves in-situ inspection followed, if necessary, by component replacement and repair/refurbishment of components in a hot cell.

Hands-on and/or hands-on-assisted maintenance are/is used in areas of low radiation background and where a very unlikely repair operation could be required. In this case, special features are included in the design to limit, as much as practical, the workers' exposure times in the radiation field.

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