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The Remote Handling Systems for ITER[1]

Isabel Ribeiro[a], Carlo Damiani[b], Alessandro Tesini[c], Satoshi Kakudate[d], Mikko Siuko[e], Carlo Neri[f]

[a] Institute for Systems and Robotics /Instituto Superior Técnico, Lisboa, PORTUGAL
[b]Fusion for Energy, Barcelona, SPAIN
[c]ITER Organization, Cadarache, FRANCE
[d] ITER Tokamak Device Group, Japan Atomic Energy Agency, Ibaraki, JAPAN
[e] VTT Systems Engineering, Tampere, FINLAND
[f] Associazione EURATOM ENEA, Frascati, ITALY

The ITER Remote Handling (RH) Maintenance System is a key component in ITER operation both for scheduled maintenance and for unexpected situations. It is a complex collection and integration of numerous systems, each one at its turn being the integration of diverse technologies into a coherent, space constrained, nuclearised design. This paper presents an integrated view and recent results related to the Blanket RH System, the Divertor RH System, the Transfer Cask System (TCS), the In-Vessel Viewing System, the Neutral Beam Cell RH System, the Hot Cell RH and the Multi-Purpose Deployment System.

Keywords: Remote Handling, ITER, F4E, JADA

1. Introduction

During ITER lifetime all components that provide the base functions of the machine must be inspected and maintained. Because of the level of radioactivity, soon after the start of the Deuterium-Tritium pulses, these operations will be carried out by means of Remote Handling (RH) procedures using the ITER Remote Maintenance System (IRMS). The novelty and complexity of the RH requirements, and the need for timely, safe and effective remote operations in such a nuclear environment constitute a major challenge of the overall project, making the IRMS a key component in ITER's design and operation. RH operations in ITER are required inside the Vacuum Vessel (VV), the Cryostat, the Neutral Beam Cell, and the Hot Cell. Blanket modules, port plugs and divertor cassettes are the main in-vessel components that have to be remotely handled and transported from the Tokamak Building (TB) to the Hot Cell Building (HCB) for maintenance and refurbishment. This requires special robotic vehicles and manipulators to take them from the VV to inside a sealed cask to transport them to the HCB, where these components are refurbished or prepared for disposal. Due to the contaminated nature of the environment, all the RH systems have to be radiation tolerant. This paper gives an integrated view of the ITER remote maintenance requirements, [1], of the RH systems' design, and presents the recent results on the development of their various components, namely: the Blanket RH System under development in Japan, the Divertor RH System, the Transfer Cask System (TCS), the In-Vessel Viewing System and the Neutral Beam Cell RH System allocated to European teams, the Hot Cell RH System and Multi-Purpose Deployment system under study by the ITER Organization. The paper concludes by presenting the main developments and actions still needed to move from the current situation to the delivery to the ITER site and integration of the IRMS.

2. The Blanket Remote Handling

2.1 General

Blanket modules (BSM) provide shielding from the high thermal loads within the Vacuum Vessel (VV) and the 14-MeV neutrons produced by the fusion reactions. Blanket maintenance requires the remote manipulation of the 440 modules that are exchanged via an In-Vessel Transporter (IVT) running on a passive rail self-deployed around the equatorial region. This process implies the use of multiple pairs of IVT TCSs (main and intermediate IVT casks) operating in VV port cells 3, 8, 12 and 17, for the support of the IVT rail, the deployment of the IVT vehicle/manipulator system, the system services and the BSM exchange system. The IVT provides also complementary functionalities during installation and removal of each blanket module, namely bolting/unbolting, cooling pipes cutting, welding and inspection, and sensing/viewing. Up to 4 BSM can be transferred in one go of the TCS from VV to HCB for refurbishment (First Wall (FW) exchange) or disposal as radwaste. The BSM (indicative size 1.5x1x0.5 m, weight up to 4.5 tons) are equipped with a FW panel in direct view of the plasma, therefore the alignment of the various panels must be performed with millimetric accuracy. During the ITER nuclear phase, the decay gamma dose rates during in-vessel maintenance is up to several hundreds of Gy/h,

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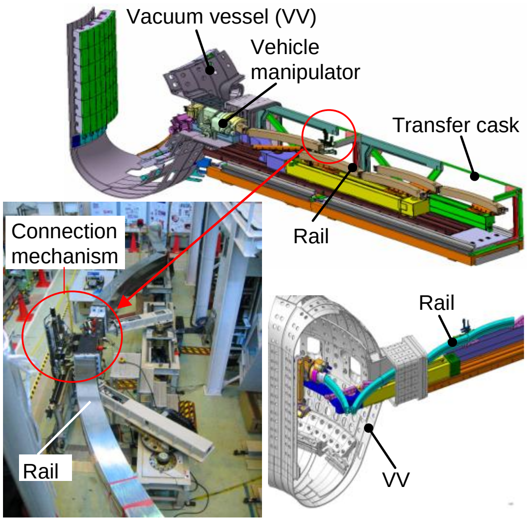
Corresponding author: Tel: +351 218418059, fax: + 351 218418291
E-mail address: mir@isr.ist.utl.pt (I.Ribeiro)

therefore all RH systems must be tolerant to such level of radioactivity.

2.2 Current R&D activities and results

Connection and disconnection of the rail joint for rail deployment/storage in the TCS is a crucial operation. A demonstration of connecting the rail joint was carried out to verify the design of the blanket In-Vessel Transporter (IVT) as shown in Figure 1, [2].



(a) Connection of rail joint (b) Rail deployment into VV

Fig.1. Demonstration of the rail joint connection.

The position accuracy between each blanket module and its two supports keys in the VV is specified to be within 0.5mm. Sensor-based control through monocular vision has been developed to measure the relative position between the key and the blanket. Variations in positioning accuracy are about 10 mm, 8 mm and 3 mm in the x, y and z-axes, respectively. To avoid key jamming, torque control is used to reduce excessive loads which may damage the end-effector. Final installation to within 0.5 mm between the module and the two keys has been demonstrated using the above approach as shown in Figure 2, [3].

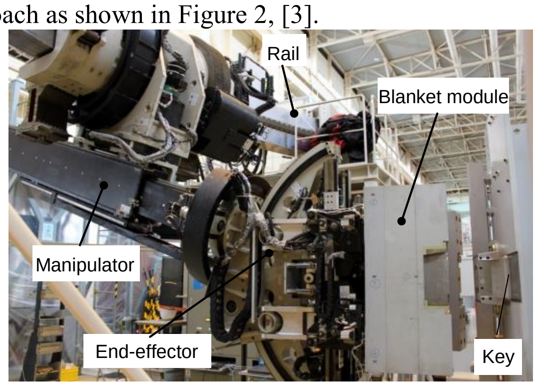


Fig.2. Installation of a blanket module.

3. The Divertor Remote Handling

3.1 General

The lower part of the ITER vessel is fitted with the divertor, segmented in 54 cassettes (indicative dimensions 3.4x1.2x0.6 m, weight up to almost 10 tons), which have to sustain heat loads coming from the diverted plasma in the range of several MW/m^2. It is expected that the erosion of the plasma facing components (PFC) will require the exchange of the whole divertor three times during the first 20 years of ITER operation. From a TCS docked in each of the 3 RH ports (2, 8, 14) at the divertor level the cassette movers are introduced in the port. They are composed by the cassette multifunctional mover (CMM), i.e., a tractor moving radially along the port and equipped with various end-effectors for cassette transportation, and a Cassette Toroidal Mover (CTM), delivered into the VV by the CMM, able to move in toroidal direction in order to transport the cassettes from the entry port to its location (Figure 3). Like for the blanket, the divertor installation and removal – again to be performed with millimetric accuracy between the PFCs – require other functionalities of the movers, i.e., manipulation, locking/unlocking, pipe cutting / welding / inspection, sensing/viewing, and possibly dust cleaning. The TCS transfers each cassette to the HCB where it can be refurbished (the eroded/damaged PFCs are replaced) or disposed as radwaste.

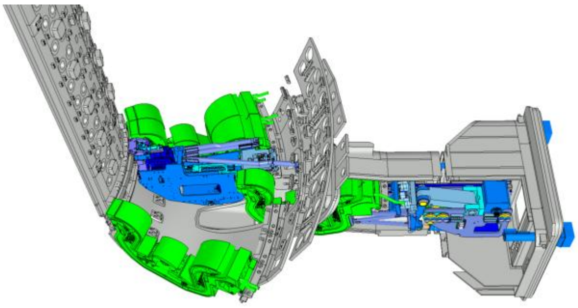


Fig.3. Sketch of the Divertor RH System in operation.

3.2 Current R&D activities and results

Divertor maintenance is a RH Class 1 operation (class 1 = scheduled maintenance during ITER lifetime; class 2 and 3 likely and unlikely maintenance, respectively) which means that the design of the divertor RH system must be complemented and validated by proof-of-principles and full scale mock-ups/prototypes. A R&D programme is ongoing based on the development and operation of a full scale test facility, the Divertor Test Platform 2 (DTP2), where the in-vessel divertor maintenance principles and equipment are tested. The DTP2 consists of a full-scale mock-up of the lower section of the ITER VV, a CMM prototype, various tools used for the cassette connecting and disconnecting, a water hydraulic manipulator arm handling the tools, the mover control hardware and the operator control room (Figure 4). Besides testing the divertor maintenance cycle and developing the related operational tasks, the DTP2 facility is used to verify/improve the design of the divertor components, and of the related interfaces.

One essential element for the RH systems is the equipment control and its human-machine interface. The DTP2 supervisory system is a combination of virtual techniques and camera viewing system, and integrates many technologies from simple sensor information to camera view and image processing. Virtual technologies are used to combine the information and to provide operator necessary information to control the tasks being performed. The control system also takes care that the process instructions are followed, the equipment is behaving as expected and all the necessary data is stored, [4].

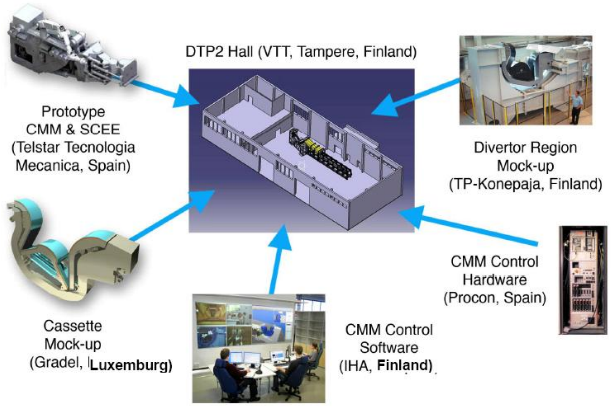


Fig.4. Initial set-up of the DTP2 facility.

The DTP2 installation and set-up took a considerable effort. After a careful initial integration, calibration and control tuning process, the mover and the control system were initially operated and the cassette handling trials were performed with close eye contact. During that phase, the cassette manipulation trajectory was defined and the routines for the cassette loading/unloading by the CMM end-effector were developed. Also a virtual model used to control the real device was calibrated including real-life deflections. After that, the mover remote trials from control room started. Camera images from the field were limited to simulate real conditions and the cassette manipulation was controlled mainly based on the virtual model. The operation was successful and the cassette searching, picking, placing and manoeuvring were done within few millimetres accuracy. Measured from the tip of the cassette, the position accuracy and repeatability for the CMM are about 2 mm; when adding the SCEE, 1 mm more accuracy error and 5 mm more repeatability error are observed, [4, 5]. These figures can be improved by modifying the end-effector joint mechanics and tuning the controller further. The result obtained so far indicate that the cassette handling can be done within the planned way with the existing equipment, [4].

The DTP2 facility will be in the near future extended toroidally to allow the testing of the in-vessel mover CTM, to be prototyped together with other CMM end-effectors. The control system development will continue to provide a more ITER-like environment with intensive integrated use of virtual reality.

4. The Transfer Cask System

4.1 General

The Transfer Cask System, (TCS), is devoted to the transportation of heavy (up to 45 tons) and activated loads between the TB and the HC. The TCS, whilst ensuring confinement of radioactive dust contamination inside the cask itself, has no radiation shielding capabilities and therefore must be operated remotely without hands-on assistance. The TCS is composed of a cask envelope confining the load to be transported and equipped with specific in-cask devices, a pallet that holds the cask, and an Air Transfer System (ATS) that acts as a mobile robot (Figure 5). The ATS, when positioned underneath the pallet, can transport the entire TCS, but it can also be removed and travel alone, enhancing its operational flexibility. The ATS is based on air-cushion technology complemented by driving/steering wheels that is compatible, unlike a full wheeled vehicle, with the payload and floor specifications. Depending on the size, layout and type of transported components (blanket, divertor, plugs, etc.) there are different TCS configurations, as described in [6] with the largest dimensions being 8.5x2.62x3.62 m (length x width x height) and a maximum weight of about 100 tons (~ double of its payload).

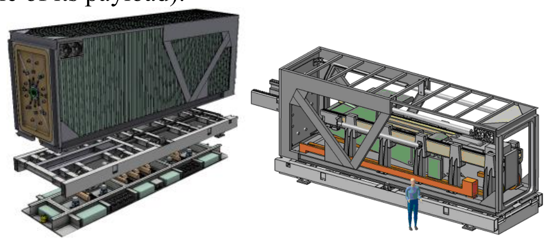


Fig.5. Two representations of the TCS.

During ITER maintenance operations, the TCS moves autonomously or semi-autonomously (powered by on-board batteries) between each level of the TB and the HCB. In the TB, TCS's pre-planned trajectories are executed between the VV port cells and the lift that connects to the various levels of TB and HCB. Collisions with adjacent systems and structures are avoided by ensuring a safety margin of about 300 mm. Similar trajectories are generated for the TCS docking and parking locations in the HCB. Once docked to a VV port and connected to the service lines, the TCS double door system is operated in order to gain access inside the vessel without loosing confinement. The in-cask devices are therefore operated in order to perform the maintenance tasks, like unblocking and removal of a port plug, deployment of the cassette movers or of the IVT monorail system.

4.2 Current design, R&D activities and results

4.2.1 TCS trajectories

A TCS motion planning algorithm, yielding TCS smooth trajectories that maximize the clearance to the closest obstacles and that incorporate manoeuvres whenever necessary was developed, [7, 8]. A specific software tool to evaluate the optimum trajectory between any two locations, for scheduled and unexpected operations, was developed. It provides the required flexibility on TCS's trajectory definition to accommodate future changes in the buildings, to study motion strategies associated with TCS parking logistics and to define the motion of rescue vehicles that may intervene in unexpected situations.

For the nominal TCS operation, a total of 63 trajectories were calculated from/to the lift to/from the VV ports in all levels of TB and to/from the docking positions in HCB. Given the need to preserve a safety margin between the TCS and the closest obstacles, recommendations were made to modify the building design, in particular the position and aperture angle of the VV port doors that represent narrow access to the ports. The area spanned by the TCS along the trajectories between the lift and all VV port cells in the divertor level of TB is represented in Figure 6. For each path, the distance to the closest obstacle along the TCS motion is calculated, together with a proposed TCS velocity profile.

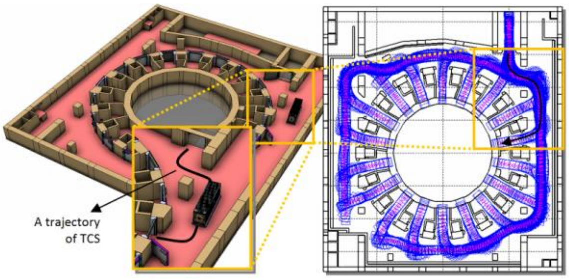


Fig.6. Trajectories of the TCS in the divertor level of TB.

Future improvements will focus on TCS path following, in particular driving the ATS from beneath the pallet, and on the motion to implement parking logistics, and those involved in rescue and recover situations.

4.2.2 TCS virtual model

A 3D Virtual Reality (VR) model of the TCS, the TB and the HCB was implemented, [9]. The VR environment, where those referred above and any other trajectories are simulated, is complemented by a Human Machine Interface (HMI). The HMI functionalities allow for the choice of four different virtual viewing cameras, either in the TCS or in the building, and of the TCS driving mode (automatic, semi-automatic, manual). Figure 7 displays a HMI snapshot with camera images and a general view of the scenario. This 3D VR system is an important step on supporting the TCS design and possible building changes.

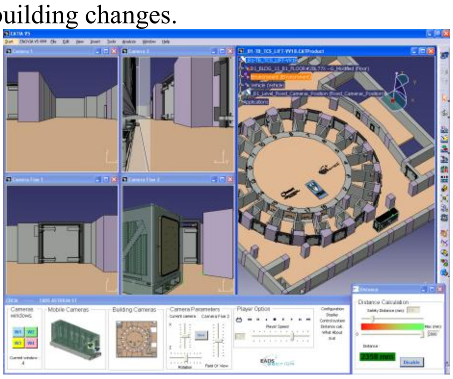


Fig.7. HMI for TCS operation.

4.2.3 TCS test facility

As the operation of a cask can be associated to a RH class 1 or 2 operation, the maintenance and the design of the TCS require a full scale prototyping. The requirements of a TCS test facility were identified, in terms of building and equipment characteristics. Besides the appropriate spaces for offices, control room and equipment storage, the proposed test facility, with $\approx 1200 m^2$, contains three main areas: a) TCS trajectory testing area, to test TCS motion performance, in particular path following and velocity control, acceleration and deceleration, motion under floor gap sealing and floor irregularities, manoeuvres, ATS motion to/from underneath the pallet; b) Docking testing area, to test the complete procedures of the TCS approach to a VV port cell, connection of the service connector and alignment of the cask envelope; c) Transfer testing area, to test the transfer of the port plug from/to the TCS.

4.2.4 TCS design

The current TCS design has to be reviewed and further developed, in order to reach the degree of consistency and maturity needed for the industrial procurement of such nuclear-grade system. Therefore, the present activities include the study of the existing design, the identification of the critical areas, the conceptual development of the most important subsystems, the identification of the various cask typologies, the failure and recovery/rescue scenarios, and the derived key aspects of prototyping (linked to the test facility), [10]. As a complement to this, a gamma irradiation analysis is being implemented: the TCS is modelled with 4 blanket modules inside the cask envelope acting as gamma source and the resulting dose rates into the various regions of the TCS is calculated. These results can be used to optimise the TCS layout especially in terms of TCS's components localisation and maintenance strategy of motors, sensors and electronics. Another analysis is also being run with a divertor cassette on board the CMM.

5. The In-Vessel Viewing System

5.1 General

The In-Vessel Viewing System (IVVS) is a fundamental tool to perform in vessel inspections between plasma pulses or during a shutdown. It consists of six identical IVVS-GDC plug units (see Figure 8) mounted in penetrations located at the lower level of the VV (ports 3, 5, 9, 11, 15, 17), where two different systems will share the in-vessel access from behind the blanket shield modules: the in-vessel viewing and metrology system proper (IVVS), and the glow discharge cleaning system (GDC).

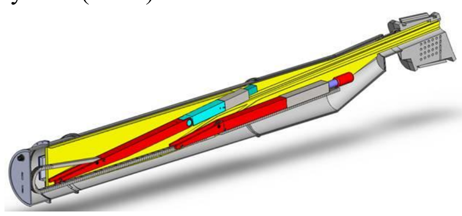


Fig.8. Schematic view of the IVVS-GDC plug (IVVS grey-blue probe in upper position, VV entrance on the right.

The IVVS will be used to perform scheduled and on-demand inspections inside the VV to survey the status of the blanket first wall and divertor plasma facing components. A laser-based scan where the image of the surfaces and their distances from the scanning head are acquired is used. Because of the operational requirements and constraints the design of the IVVS-GDC plug poses many challenges with regard to: a) lay-out and integration of the various plug components into the geometrically constrained environment; b) resistance to the design loads like those coming from plasma transients and seismic events; c) compatibility with the ITER environmental conditions (within the primary vacuum boundaries): neutron fluence up to 5 10^{13} n/cm^2, activation, gamma dose rates and doses up to 5 KGy/h and 5 MGy, ultra high vacuum, baking temperature 200°C, magnetic field up to 8 Tesla; d) fail-safeness and recoverability, reliability, availability, maintainability, inspect-ability; e) system lifecycle from first assembly and installation, operation, transportation via TCS to the Hot Cell for repair/replacement of components.

The specifications for the IVVS system are: a) metrology accuracy: 0.5 mm at 5 m distance on ITER relevant materials and surfaces; b) viewing spatial resolution: ≤1mm at target distances of 0.5m-4m and ≤3mm at target distances up to 10m; c) inspection time: ≤ 8h for an overnight inspection of the whole VV; d) self-illumination, i.e., no need of external light source.

5.2 The IVVS probe mock-up

The heart of the IVVS is the viewing-metrology probe itself. A proof-of-principle mock-up is already available and operational in ENEA, [11], which developed and tested a Viewing and Ranging System (Figure 9). It uses the amplitude modulated laser radar concept, which intrinsically guarantees radiation resistance, being the probe's sensing parts essentially made of silica. Starting from its design and construction in 2001, in two successive development phases, its performances were upgraded and, at present, the IVVS mock-up already approaches the target specification requested for ITER, although it does not withstand with all the ITER environmental conditions. Current tasks are the evaluation of the potential of a system based on the IVVS mock-up and the conceptual design of an IVVS probe fully compliant with the ITER requirements. The work has been divided in three main tasks: 1-laboratory tests with the ENEA IVVS mock-up to verify that its performances are matching those required for the final application in ITER; 2-assessment of the expected viewing/metrology capability of the IVVS in the ITER conditions; 3-conceptual designs of an IVVS probe prototype and related test bed, in preparation for the future procurement and testing activities.

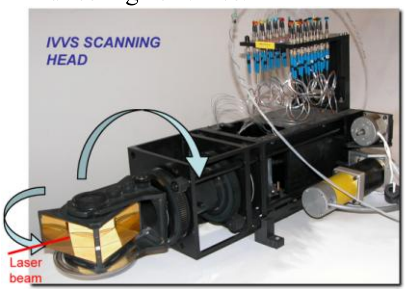
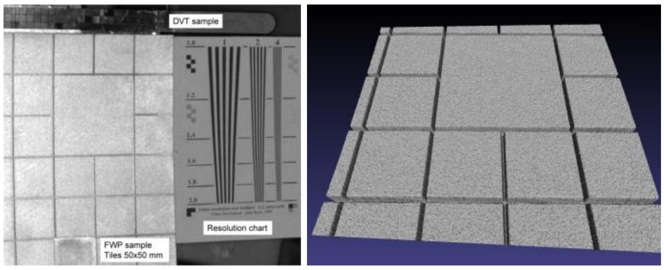


Fig.9. ENEA IVVS mock-up.

As example of the current activities, [11], Figure 10-a) shows a viewing image obtained by the IVVS on ITER-like targets (PFC and FW like material) taken at ≈4 m distance. Also a resolution chart was added to the scene to better evaluate the resolution capability of the system, which is better than 1 mm. Figure 10-b) shows a 3D STL image produced with IVVS data on a first wall panel (FWP) mock-up. The size of the smaller tiles is 50x50mm and the global accuracy obtained was better than 0.5 mm.



a) b)

Fig.10. a) Viewing image taken by the IVVS; b) 3D image, in STL format, produced by the IVVS.

5.3 The IVVS-GDP plug design

In addition to design and R&D of the probe, other on-going activities - tackling the main IVVS-GDC plug design issues mentioned in section 5.1 - are: a) identification of a conceptual lay-out of the plug respecting the various geometrical, environmental and operational conditions; b) validation of the concept by performing electromagnetic and mechanical analyses; c) nuclear analysis, to identify the level of neutron fluence and gamma activation in the various parts of the 8-meter long plug; d) studies on motors compatible with the ITER vacuum, temperature and magnetic field.

6. The Neutral Beam Cell RH

6.1 General

The Neutral Beam Cell (Figure 11) hosts one Diagnostic Neutral Beam injector, two Heating and Current Drive Neutral Beam injectors and, at the upper level, three diagnostic plugs. Since the start of the ITER D-T phase, due to neutron activation and to contamination with Tritium and activated dust, the components belonging to all these systems will require remote maintenance.

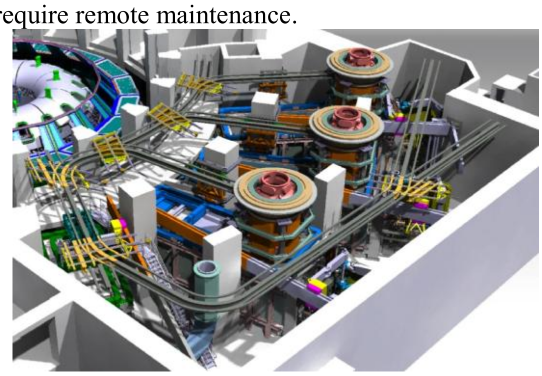


Fig.11. NB cell RH layout.

The NB Cell RH system is the combination of various devices: a) 50-tons monorail crane, equipped with special lifting interfaces, able to transport the various components from their original location to a specific transfer area (to get out of the NB cell towards the HCB); b) transport cradle specifically designed for the 26-tons NB source/accelerator; c) force feedback manipulator arm and various tooling; d) special end-effectors/devices for the installation and removal of the diagnostic tubes located in the upper level; e) auxiliary devices for temporary storage and transportation.

6.2 The NB RH design

A first series of studies had already defined, in broad terms, the NB cell RH layout, and currently the conceptual design of the whole system is ongoing with the aim of identifying and validating all the functional specifications, before starting the real industrial procurement phase, [12].

7. The Multi-Purpose Deployment System

The described in-vessel maintenance systems are designed to perform dedicated tasks, but for the "non baseline" in-vessel operations the Multi-Purpose Deployer (MPD) will be used. These are: dust accumulation monitoring and removal, tritium inventory monitoring, vacuum vessel inspection, vacuum vessel leak detection, in-vessel diagnostics maintenance, assistive and contingent RH operations, and recovery from failure. The core of the concept is an articulated transporter, which can move and supply a dexterous manipulator with dedicated end-effectors from the equatorial ports to any locations inside the VV. The MPD transporter and manipulator are stowed in a standard equatorial cask, and the service packs providing the tool services are stowed in the service cask which is shorter than the standard equatorial cask. The MPD main cask is docked to the VV port, and the service cask is docked at the rear of the main cask which gives flexibility such as the exchange of the tools and providing required services that are needed for the in-vessel tasks.

8. The Hot Cell RH System

The HC will be equipped with a set of general purpose equipment and specific RH tools to allow two main functions: a) the repair/refurbishment/testing of machine components which must be returned to service; b) the processing of machine components which must be discarded as radwaste. General purpose equipment needed for the correct execution of RH tasks on the machine components and on the HC systems (e.g., lights, connectors, cables) consists of overhead and gantry cranes carrying telescopic masts and manipulators. Viewing cameras for general RH operations surveillance and close up monitoring of RH processes will also be needed.

Equipment will be required to carry out the cleaning of the components prior to the start of the repair /refurbishment/ testing operations. This will help reduce the radioactive dust inventory inside the HC and keep the HC RH tooling contamination as low as possible. The same equipment will be used for the decontamination of the IRMS, to allow subsequent hands-on maintenance and inspection prior to its returning to service. General purpose RH workstations will be provided to support the repair/refurbishment and radwaste processing operations. They will consist of adjustable support structures to place the machine component in the most favourable way relative to the RH tooling. The latter will be deployed by gantry cranes fitted with telescopic masts and manipulator(s). All HC RH systems will be designed to be RH compatible, i.e., capable to be rescued if necessary and repaired when required.

9. Future Developments

The previous sections have shown that the IRMS is the collection and integration of numerous systems, each one being the combination of diverse technologies (e.g., moving machinery, cranes, force feedback manipulators, special tooling/end effectors, umbilicals, rad-hard viewing/sensing components, etc) into a coherent, space constrained, design, exceeding by far in complexity any similar experience (e.g., the JET RH). There is still a massive amount of design and R&D required in order to move from the present status (conceptual design ongoing, supported by some R&D actions) to the final design, procurement and delivery to site.

Some key elements of the implementation scenario are: a) the completion of the conceptual design and functional specification for all the IRMS subsystems and the identification of the related R&D actions (e.g., the pre-qualification of radiation tolerant components), including the needs in terms of prototyping and testing in facilities; b) the identification of industrial integrators able to produce the final design and manufacture the IRMS using qualified technologies; c) the manufacturing and test of full scale, ITER-relevant IRMS prototypes, to be tested in ad-hoc facilities, to validate the design and to start the preparation of the ITER remote handling team and operations; d) the manufacturing of the final IRMS taking into account the results of the prototyping; e) the delivery to site and final integration and commissioning.

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