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Verification and validation by eXtended Reality simulations of Test Blanket Modules replacement operations in Air-Fed Suits

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To study the feasibility of the **Test Blanket Modules (TBM)** replacement operations in **ITER Port Cells**, CEA develops a **mixed** (digital & physical) **validation by simulations** approach with immersive technology to verify hands-on operations. Main validation criteria concern operator accessibility, posture, detailed procedure sequence and time spent at workstations. Such complex replacement operations will assume series of hands on tasks for both normal and abnormal situations, sometimes with protection such as **Air-Fed Suit (AFS)**. After initial validation of key operation feasibility on digital mock-up, the goal is to optimize the process with minimization of occupational radiation exposure under the As Low As Reasonably Achievable (**ALARA**) requirement.

Virtual reality tools provide relevant means to develop a credible replacement scenario in a context of complex configurations. The process includes features such as **ergonomics assessment tool** coupled to **multi operators' collaboration**, tangible tools and integration of **advanced real time physics engine**. Lessons learnt from the field of existing CEA facilities enable identifying key parameters related to workstation Humans factors. This first set of observations would help to define methodology and criteria for qualification of operation in AFS.

The Digital simulation validation is deployed with a nuclear operator **avatar** in AFS to demonstrate **Nuclear Maintenance Operation feasibility** considering study of arduousness, accessibility and visibility thanks to **real time motion capture**. The recording of the whole simulation allows tracing and replaying for post-analysis data including body angulations, clash detection and operator field of view.

The integration of this approach at an **early phase of the design process** enables **validating technical options for replacement scenario**. This leads to promising and beneficial results concerning **design and integration of complex components in constraint working environments**.

This paper presents a review of the CEA studies regarding the extended virtual reality **capabilities and results** to support design **TBM integration and replacement scenario** within a nuclear environment framework.

Keywords: Air-Fed Suit, eXtended Reality, Virtual Reality, Mixed Reality, Nuclear Maintenance, ITER, Test Blanket Modules, Human Factors, ALARA

1 ITER Test Blanket Modules (TBM) replacement operation

In the ITER Tokamak building, two equatorial Port Cells (#16 and #18) aim at testing the Test Blanket Modules concepts (*Figure 1*). One of the ITER TBM Program objectives is to provide the first experimental data on the performance of Breeding Blankets [1] using the fusion of Deuterium & Tritium as a process to create energy.

The ITER Scientific Program schedules TBM replacement at each long term shutdown (every 2 years) since Tritium phase without impacting the ITER global program.

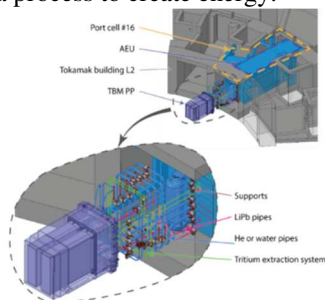


Figure 1 - TBM Port Cell overview

The TBM plant shall be designed so that **Occupational radiation exposure (ORE)** be **As Low As Reasonably Achievable (ALARA)** over the life of the plant [2].

Component replaceability is optimized by including human factors analysis and providing adequate space, illumination, platforms, lifting equipment, handling gear. Radiation exposure hazard is up to 100 μ S/h in the Port Cell [3]. (*Figure 2*)

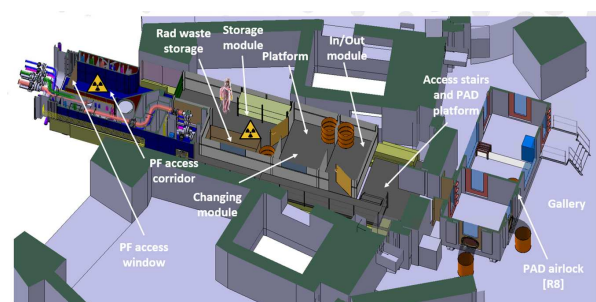


Figure 2 - Configuration for Pipe Forest removal operation

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2 Air Fed Suits

To prevent from contamination, the use of **Air Fed Suits (AFS)** shall be considered for maintenance operations. It includes additional requirements to take into account in the design process: (Figure 3)

- Impact on the activity (slower mobility, loss of dexterity, Quality of vision & posture) and collaboration with teammates
- Noise perturbation interfering with communications
- Hoses management (disconnect/reconnect, risk of falling)
- Operator mental workload & additional Stress
- Time management (2 hours shift maximum including dress/undress of 30 min)
- Standards for suits & Breathing Air
- Architecture of the cell : Airlocks for zone jump and in the port cell, limiting work at height
- Circulation routes width > 900 mm

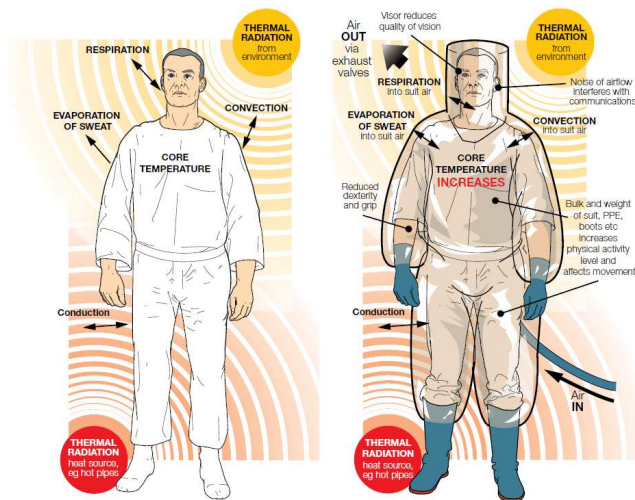


Figure 3 - additional constraints with Air Fed Suits [4]

3 eXtended Reality in the design process

To study the feasibility of the Test Blanket Modules replacement operations in Port Cells, a human-in-the-loop design method by means of Virtual and Augmented Reality is used at CEA IRFM. [5]

Although **scale 1 mock-up** will be mandatory for the ITER project, the need for training & optimization with the ALARA process leads up to consider prospective methods. For instance, using **digital mock-ups** (Figure 4) in the iterative process is an efficient tool in order to obtain time & cost reduction.



Figure 4 - Example of XR Digital Mock-Ups on Iter Site

The use of eXtended Reality is an asset all along the design process from feasibility to safe accessibility, maintainability and optimised design & methods. (Figure 5)



Figure 5 – eXtended Reality in the design process

It includes design by simulation and validation by simulation.

In the first step, **Overview & Exploration** helps in understanding the configuration and identifying the design drivers using immersive 3D models exploration during design reviews.

Then, a second step includes Component **Trajectory verification** including detection, mitigation of clashes and definition of space reservations based on the largest component and accessibility requirements.

Task Verification considers the adequacy between workplace configuration, volumes of workers with suits and utilities. It includes operator accessibility studies, tools accessibility and posture analysis.

Last, in **Sequence Verification** we study the adequacy of the surrounding with logistical aspects, contamination management & support services.

4 A structured approached including Human Factors

The methodology used at CEA involves two main points: design by simulation and validation by simulation.

Focusing on task verification and operators' activities, Human Factors aspects are crucial aspects, considering impaired dexterity and mobility of workers in AFS.

A preliminary study integrated the returns of experience and lessons learnt from the field of existing CEA facilities with nuclear suits use. As a result, the consideration of such equipment significantly modifies the activity and increases the percentage of additional execution time compared to a universal suit.

Additionally, a complimentary study has been initiated with the Ergonomie & Conception Company [6] in order to identify key parameters related to workstation human factors and to design a pre-grid & protocol rating of the work activity in AFS.

At last, the use of Mixed Reality allows to approach the future activities including their arduous side. This relies on the development of a suit prototype for simulation with the Matisec Company [7] that simulates the helm in digital environment but provides realistic interactions for the operator's body with a real AFS. (Figure 6)



Figure 6 – Air Fed Suit Mixed Reality prototype for simulation

This approach affords defining methodology & criteria for qualification of operation in AFS and validating by simulation the processes & interventions.

5 eXtended Reality Lab

The IRFM XR Lab is tuned to perform integration and operation configurations studies by means of VR and AR simulations for TBM Port Cell. It consists in a Mixed (Digital & Physical) validation by simulations approach with immersive technology, which is a potential powerful tool to support Human Factors design optimization studies. (Figure 7)

The scope of this lab is to perform simulations for feasibility studies of human operators in scale one conditions of representative Port Cell conditions & replacement operations. A scale one Free Roaming platform of 70m² provides a simulation of all workstations of the port cell for replacement operations within the bio-shield area, including the required airlock.

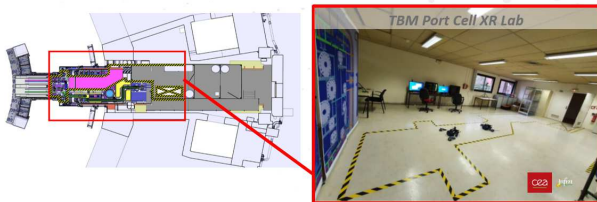


Figure 7 – eXtended Reality Lab overview

In order to quantify the activity of the operator equipped with Air-Fed suits and to identify unacceptable postures, it is necessary to capture the posture of the operator in combination with the handling loads the operator shall perform. (Figure 8)



Figure 8 – Avatar with nuclear suit & Motion Capture

Additional simulation features already included in the design process are listed below:

- Nuclear operator immersion with avatar in AFS (Figure 9)
- Integration of XDE advanced physic engine [8] [9]
- Real time Motion capture (optical & inertial tracking)
- Full Body Posture with RULA scores
- Distance Monitoring & Clash detection
- Swept volume analysis
- Tangible tools [10] & Mixed reality
- Pipe Forest digital twin with Realistic rendering according to pipe stress Analysis
- Visual cone to represent and analyze Operator Field of View
- Data/Time recording & replaying for post analysis
- Dose Management
- Multi operators' collaboration

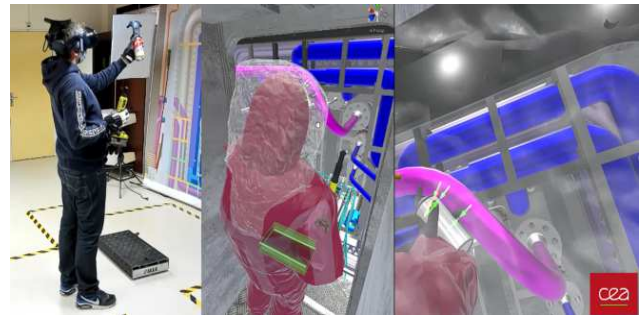


Figure 9 - XR lab immersive simulation

In addition, a PhD is ongoing at CEA IRFM studying “Methodology for validating the immersive simulation of complex gestures in a constrained environment”.

6 Capabilities & Results

A first step using the XR lab for design reviews led to the definition of a procedure for design verification. It enabled testing accessibility with one hand, two hands or tools for several Pipe Forest configurations.

This results in the definition of a protocol for engineering reports and the optimization of the Pipe Forest taking into account these ergonomic aspects.

The TBM replacement global scenario contains 275 task lines in the Model Based System Engineering definition with digital approach based on CEA LECSTAR nuclear basic installation procedures.

A notion of representativeness for each tasks is integrated according to a three levels basis (basic task, simple interaction, realistic).

A focus is considered on the task “A25-02-01 Tightening flanges or welding pipes at 2A interface” studying the accessibility of the bolts of the Pipe Forest flanges. (Figure 10) Automatic results analysis for the 172 bolts show an increase in accessibility from 25% to 85% between two design proposals.



Figure 10 – Bolts Accessibility Study with eXtended Reality

The Ability to replay the simulation from CSV files for Post Analysis including collisions, RULA scores & Visibility is an asset for ergonomics analysis.

The next step will be to couple all analysis files in the post analysis for more accurate and benefiting results.

Another way to use eXtended Reality in the design process is in the sequence verification. Indeed, the use of realistic simulations with immersive scenarios is an interesting tool for training purposes & skills transfer. It grants the ability to take into account normal, incidental and accidental phases.

It is also an asset during technical meetings with experts. As an example, a recent technical session allowed to validate and optimize solutions for the welding maintenance scenario of the TBM Pipe Forest. (Figure 11)



Figure 11 – Design Review for Welding Scenario Analysis

It resulted in the definition of points of vigilance, questioning and missing data in the sequence.

It also permitted identifying lack of visibility for the penetrant testing task and lack of space to pass in the corridor with the toolbox for evacuation scenario.

An effort is actually focused into optimizing engineering reports workflow in order to automatically integrate the conclusions from XR sessions.

7 Conclusion

Air Fed Suits are mandatory for human intervention in the ITER Port Cell. Based on lessons learnt from existing CEA nuclear facilities operations, activities are ongoing to validate the feasibility of the TBM maintenance/replacement scenario.

Virtual and Augmented Reality are extensively used taking into account a large set of constraints (ALARA, human factors, ergonomics, accessibility...).

Such studies led to improve designs (Pipe Forest) to enable the maintenance operations feasibility in Air Fed Suits and integrate complex components in constraint working environments at early stage of the design.

First results with digital mock-up also help to define Scale 1 physical mock-up and to reduce the number of iterations in the process.



Figure 12 – TBM Port Cell Digital Mock-Up

Note: at first plan we can see a WEST ICRH antenna and its auxiliaries systems. Additional holograms of the TBM Port Cell is placed virtually on the ground in order to compare the scale of the components. (Figure 12)

Next steps are to confirm the first positive results on the feasibility using increased representation of the simulation at a global level of the replacement scenario and to use physical mock-ups for specific tasks. One of the next challenge will be to qualify the simulation with extended reality in comparison with real reference operations in order to validate the accuracy of the results.

8 Disclaimer

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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