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Virtual Reality-based Simulation System for Nuclear and Radiation SafetySuperMC/RVIS

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Abstract

The suggested work scenarios in radiation environment need to be iterative optimized according to the ALARA principle. Based on Virtual Reality (VR) technology and high-precision whole-body computational voxel phantom, a virtual reality-based simulation system for nuclear and radiation safety named SuperMC/RVIS has been developed for organdose assessment and ALARA evaluation of work scenarios in radiation environment. The system architecture, ALARA evaluation strategy, advanced visualization methods and virtual reality technology used in SuperMC/RVIS are described. A case is presented to show its dose assessment and interactive simulation capabilities.

Key Words: Radiation protection; Virtual reality; Organ dose assessment, Voxel phantom, SuperMC/RVIS

1. INTRODUCTION

For as low as reasonably achievable (ALARA) evaluation of an operation in radiation environment[1], the optimal scenario should be found to prevent the operators being too much exposed and integrating too much dose. However, due to the involved risks, the work scenario is always designed based on experts' or past experiences, without considering faults in plant design, human wrong operation by unskillful handing, risks associated with unpredictable situation, the suggested work scenarios are always not the optimal scenarios according to ALARA principle.

Virtual reality (VR) technology[2], in turn, has been appliedin many diverse areas, with the possibility of performing virtual simulations of real environments, with high degrees of realism. Then, it is possible to simulate these risk situations, considering hypothetical scenarios, as the presence of radioactive areas, for example. Virtual reality may thus be used for training of personnel, avoiding the inherent risks in the real scenarios or environments. The immersive characteristic of virtual simulations improves training effect, as users feel as they were navigating within the environment, involved and interacting with it.

To date, significant efforts have been made for simulation of nuclear and radiation safety by using VR technology. Several studies have developed the virtual-reality based simulation system for predicting the dose and ALARA study in order to better design the planning[3-6]. A number of studies have used virtual environment for training of personnel in operation and maintenance procedures[7-8]. Some authors have dedicated the key technology study, including the dose calculation method [9-10], path-planning method[11], radiation map visualization method[12-13], etc. Most of studies are focused on the virtual simulation for dose assessment without considering the radiation sensitive of different organs.

Based on virtual reality (VR)technology and high-precision whole-body computational phantom named Rad-HUMAN[14], a virtual reality-based simulation system for nuclear and radiation safety named SuperMC/RVIS has been developed for organdose assessment of interventions in nuclear or radiation working sites. The latest version is SuperMC/RVIS2.3. It isdeveloped by FDS Team [15-21], which is devoted to the research and development of advanced nuclear energy systems in China. Open source development toolkits areused for low cost. The improved features of our system are accurate evaluation of organdose rates, which considered with the radiosensitive level of different organs, and advanced visualization of radiation on a graphical user interface (GUI).

In this paper, the system architecture, dose assessment methods, advanced visualization methods and virtual reality technology used in SuperMC/RVIS are described. A case, which is virtual reality-based simulation for dose assessment during CLEAR-I[22] spallation target maintenance, is shown to validatethe capabilities and feasibility of the system.

2. OBJECTIVE AND ARCHITECTURE

SuperMC/RVIS is designed to be an integrated virtual reality-based simulation system for organdose assessment of interventions in nuclear or radiation working sites. The goal is to bring the user a complete software tool, taking into account all relevant components of the missions: working site, workers, tools and equipments, dedicated procedures involved, time management, and so on. SuperMC/RVIS will allow the operators to prepare and repeat, in a safe virtual world, the whole operations they will have to perform, before achieving the real interventions inside the hazardous facilities. The user interface is shown in Figure 1.

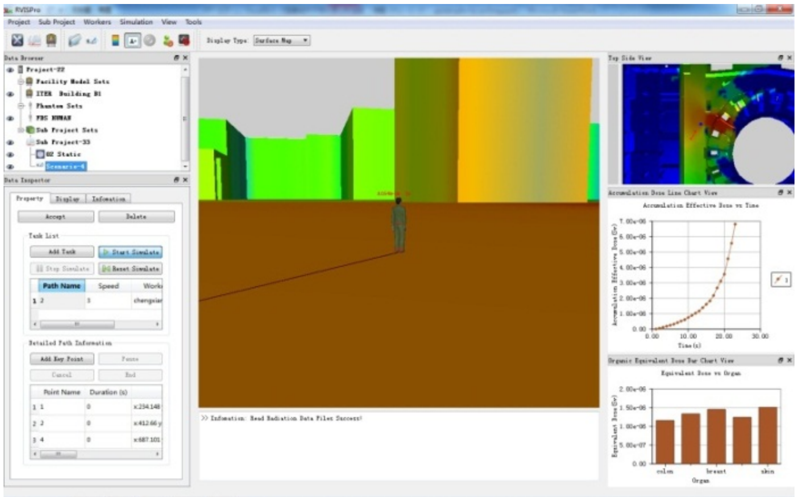

Figure 1. User Interface of SuperMC/RVIS2.3

2.1. Hierarchical Modular Architecture

The hierarchical and modular system architecture was used in SuperMC/RVIS and the architecture was divided into resource layer, core layer, service layer and application layer. Upper layers were developed based on the below one and the details of function model were encapsulated by using the component technology. The detailed information of each layer is introduced as follows.

Resource Layer: The software, hardware and supporting data resource is assigned in this layer including computing resource, storage memory, commerce software resource, avatar, computational phantom, dose limitation regulation, virtual reality hardware, and so on. The software resource, for example, included not only the CAD software, but also the radiation transport simulation software, such as MCNP, TORT.

Core Layer: Independent function model, which can work independently or bethe specific technical model, is assigned in this layer. The combinations of these function models can be used to provide the solution related nuclear and radiation safety. This layer includes virtual modeling, parallel rendering, organdose evaluation, planning path optimization, and so on.

Service Layer: The solution related nuclear and radiation safety provided by SuperMC/RVIS2.3 is assigned in this layer including scenario interactive design and evaluation, roaming simulation and real-time organ dose evaluation according to the planning path, maintenance routine optimization, and visual analysis of calculation result and so on.

User Interface layer: Terminal environment for specific application requirements through the combination of solution from the service layer is assigned in this layer, include Laptop, Immersive environment and Web browser. Plan analyst will be able to design a scenario on a laptop, while an operator will be trained inside an immersive environment, and worker manager will be able to see/study historical dose of workers who ever involved in the mission through Web site.

2.2. Open source toolkits and immersive environment

SuperMC/RVIS2.3 takes OGRE[23], which is an Open Source 3D Graphics Engine, as a tool to create and navigate in virtual environment, VTK[24] as visualization algorithms supported library, QT [25] as GUI toolkit and RakNet[26] as network communication toolkit. These open source toolkits are selected as they are free for non-commercial and education purposes, important application such as the one treated in this work can be implemented with no costs for research or educational institutions.

Nuclear and Radiation Safety Simulation Laboratory, at INEST • FDS Team, contains a projection room, where the user can have an immersive experience in a virtual environment, due to stereo vision. Figure 2 shows the composition of virtual reality simulation environment in INEST • FDS Team. It was constructed with active stereo projector, data helmet, data glove, advance real-time motion capture system, etc. It can provide multi-wall high-fidelity immersive 3D environment and interactive simulation experience for operating training and disassembly simulation.

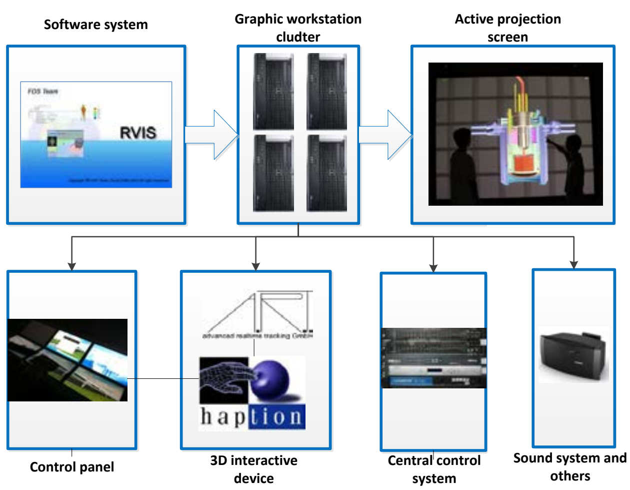

Figure 2.System components of 3D stereoscopic virtual reality simulation platform

2.3. Radiation transport calculation

The CAD-based Monte Carlo program for integrated simulation of nuclear system named Super Monte Carlo Calculation Program for Nuclear and Radiation Process[27], developed by FDS Team in China, has been used for radiation transport calculation in SuperMC/RVIS. Super Monte Carlo Calculation Program for Nuclear and Radiation Process is developed bases on hybrid MC -deterministic method and advanced computer technology.SuperMC intends to perform the radiation transport calculation as the core.The calculation result, neutron or gamma flux field, is used as the input of SuperMC/RIVS for organ dose assessment.

In addition, other state-of-art radiation transport codes, such as MCNP/TROT, can also use to for the radiation transport core of SueprMC/RVIS.

2.4. Result and process visualization

The output data can be automatically and intelligently visualized andmixed with the input models according to users' interests so that it can extremely simplify the information extraction from massive data. The calculation results can be visually analyzed with various styles such as mixed visualization with geometries, iso-surface, color map and volume rendering. Calculation geometry can be converted to CAD model for visualization. The trajectories of particles are visualized to help users to set cell importance in using variance reduction technique. Besides, some normal visualization functions, such as curve plot, 2D map plot, mesh plot, geometry-coupled visualization and geometry-based data cutting, several new advanced visualization functions are supported, such as unified color mapping for various data maps, dynamical visualization in space. Now SuperMC/RVIS has directly supported of data post-processing for multiple codes, such as SuperMC, MCNP and TORT. Figure 3 shows the visualization functions of SuperMC/RVIS.

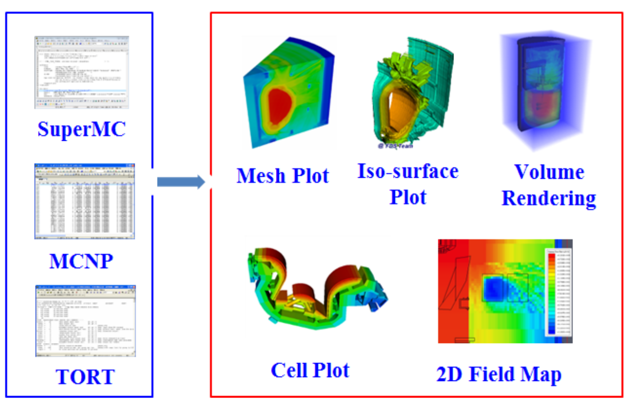

Figure 3. The visualization functions of SuperMC/RVIS

2.5. Virtual modeling and interactive simulation

Virtual scene objects can be made by CAD software, and then imported into Autodesk 3ds Max to generate all core OGRE mesh/material files plus .scene files by using OgreMax Scene Exporter. We can add texture obtained from photos of the real environment in 3dmax. In response to the issue of OGRE only supports its unique geometric model format MESH and can't directly import other common CAD model format, SuperMC/RVIS has also developed many format conversion method which could convert the STL/3DS/STP into OGRE MESH format.

SuperMC/RVIS provides three-dimensional virtual interactive simulation function for nuclear complex facilities based on virtual reality hardware, which is shown in figure 4. It can achieve accurate collision detectionto parts' virtual assembly and disassembly, evaluation and optimization to assembly scenarios, and then it can verify the reasonability of nuclear facility model design to assembly's perspective, evaluate the assembly scenarios, and train the assembly workers and so on.

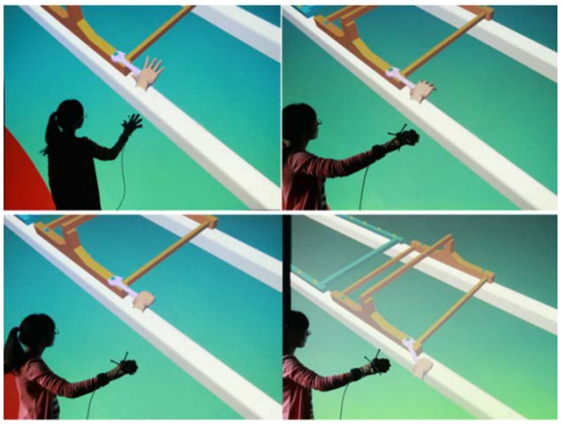

Figure4. Slide rails installation interactive simulation

2.6. Virtual roaming for organ dose assessment

After the modeling stage, paths can be defined, taking into account that the avatar can walk or stand at some locations for some time, during typical operations. Various doses vs. time have been calculated, for example, accumulated whole-body dose, effective dose rate, and equivalent dose rate of sensitive organs. The movement speed of a worker inside the nuclear working site can be assigned by users, taking account the realities of different tasks. Real-time dose assessment wasdisplayed with the dose rate distribution with refresh rate of 50 Hz, which is shown in Figure 5.

The simulations allow for immersion by users, it is proportioned by the perspective or stereo views and the userswill sharein the virtual environment. Operational and maintenance tasks could be tested and evaluated firstlyin such a safe environment, before people entered the real environment. Based on the simulation results, SuperMC/RVIS could perform better planning of working activities. Thus, unnecessary radiation dose was avoided in the first training stage, fulfilling As Low As Reasonably Achievable (ALARA) principle, which means radiation dose for operators must be reduced to the minimum amount.

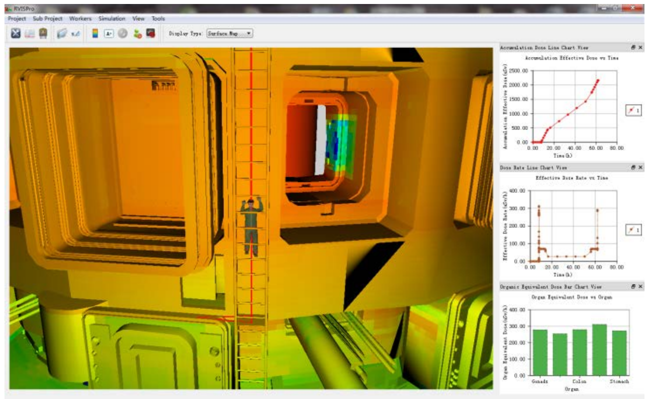

Figure 5. Real-time dose assessment and visualization of dose rate distribution in nuclear working site

3. METHODOLOGY

3.1. CAD-based Point Kernel Integral Method for Real-time transport calculation

It is necessary to estimate radiation exposure precisely to improvethe maintenance work efficiency while decreasing radiation exposure. For this, a large-scale calculation throughout the room or work area is required to estimate the change of dose rate in detail according to work progress, namely to decompose and remove the components and pipes, and install the radiation shield.

A CAD-based point-kernel integral method for real-time radiation dose assessment was proposed and implemented in SuperMC/RVIS. CAD models represented by Boundary Representation method can be automatic converted without human effort to further calculation model which is represented by Constructive Solid Geometry (CSG) method and organized in hierarchical tree structure. Sources distribution is also converted from CAD models and assigned in user interface. Materials distribution can be assigned in the geometry model.

Then according to the ray-trace method, range of the ray between source point and detecting point can be calculated based on the CAD model made last step, as well the shielding materials it passed. With the appropriate build-up factor, the dose rate contributed by the point source can be calculated, using the point-kernel method[15]:

$$D(E,Ld,r) = F(E) \cdot B(E,Ld) \cdot exp(-Ld(E))/4\pi R^2 \quad (1)$$

F(E) is the flux density-radiation dose conversion factor, B(Ld, E) is the buildup factor, Ld(E) is the optical distance(in the units of mfp) between the source point and detecting point. Taylor fitting function is used to calculate the buildup factor B(Ld, E) in our work:

$$B(E, Ld) = A_1 e^{-\alpha_1 Ld} + (1 - A_{1)} e^{-\alpha_2 Ld} \quad (2)$$

The parameter A1, α1, α2 is determined by the energy and materials. The optical distance:

$$Ld = \sum_{i=1}^{n} \mu_i(E) t_i \quad (3)$$

$\mu_i(E)$is the linear attenuation factor for material in No. i zone. Total dose rate of detecting point is the integral for the source volume and energy:

$$D(r) = \int_E \iiint_V D(E, Ld, r) \quad (4)$$

For the integral of source volume, Monte Carlo integration algorithm based on statistical error is used. With a given statistical error, adaptive Monte Carlo sampling of point source in the source volume is carried out, until the error is below the specified value.

3.2. Intelligent data analysis and visualization method

Several visualization methods have been employed to make huge and complex simulation result intelligibly[29]. As the simulation result is in essence volume data, several most usual volume data visualization methods have been developed [30-31]: slice, iso-surface and direct volume rendering (DVR) based visualization.

To support mixed visual display of dynamic volume data result and geometry, a 3D-texture mapping method has been developed. The radioactivity of radiation data is shown using colour in a semi-translucent manner, and as a 3D-texture mapped to geometry model. To get the data of interest inside some components, a geometry model based on data clipping method has been developed. Thus, analyst can analysis the data of interest part, such as the maximum result location and tallied zones. In addition, parallel acceleration method etc. has been developed to speed up the rendering of time-varying 3D radiation data.

The mixed visualization method of dynamical 3D radiation dose field and geometry model was developed, including 2D map coupled with geometry wire-frame and mapping result data onto geometry surface. The method adopts a streamline technique, and uses a time engine to drive the dynamic visualization. The basic idea of the mixed visualization method is to take both geometry models and volume data as transparent objects and render them in the same scene. The key problem of mixed visualization is transparency rendering, which is one of the classic difficult problems in computer graphic community. The basic principle of depth peeling technique is to sequently render a series of images of the scene along an indicated view direction, and to synthesize a result image by blending technique. Based on depth peeling technique, SuperMC/RVIS implements transparency rendering on programmable graphic process unit (abbreviated as GPU) by CG programming, thereby realizes the time-varying mixed rendering of geometry models and 3D volume data with common visualization algorithms.

3.3. Real-time organ dose assessment method

In order to quantitatively describe the radiation hazards suffered by the staff in nuclear working site, a whole-body computational phantom of Chinese adult called Rad-HUMAN was used, which contained 46 organs and tissues and created by using Multi-Physics Coupling Analysis Modeling Program named SuperMC/MCAM [32-38] from sectioned images of a Chinese visible human dataset.

Dose calculation accuracy of voxel model lies in that absorbed doses of the human organs are calculated for each voxel, with the average absorbed dose treated as the organ dose, which is shown in formula (5).

$$D_T = \frac{1}{N}\sum_{j=1}^{N} D_{T,j} = \frac{1}{N}\sum_{j=1}^{N} \emptyset_j * CF \qquad (5)$$

Among them, D_T is the absorbed dose to tissue or organ $D_{T,j}$ is organ absorbed dose for the voxel j and $\emptyset_j$ is the flux of the voxel j, CF is dose conversion factor for the flux, N is for the amount of voxels organ.

The above equation indicates, organ absorbed dose is the mean flux composition of each voxel. Therefore, organ absorbed dose calculation is transformed to get each voxel flux. The radiation field calculation can be previous calculated by SuperMC/MCNP/TORT.

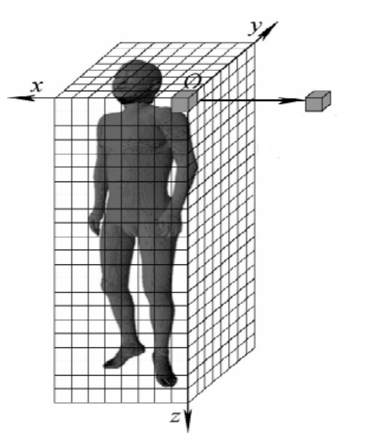

Figure 6. Rad-HUMAN voxel phantom

For Rad-HUMAN voxel model, the following illustrates how to calculate the equivalent dose of an organ. In Figure 6, the coordinate system is right-handed Z-axis downward. Repeating the sequence of the first voxel is filled X-axis, then Y-axis and finally the Z-axis. So as to fill the order for all voxels numbered sequentially traversing voxels, each voxel corresponds to a U number of organs, which means that it is composed of voxels of the organ. Traversal rule: first X-axis direction, then traverse the Y-axis direction， and at last traverse the Z-axis direction. Calculation flow chart of organ equivalent is shown in Figure 7.

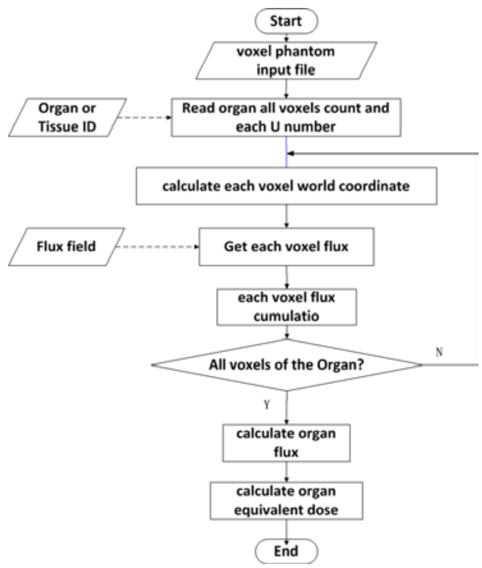

Figure7. Flow chart of organ equivalent dose calculation

3.4. ALARA Evaluation strategy

A good ALARA pre-job study must therefore be performed and should contain the predicted doses for the different suggested work scenarios and provide a quantitative basis to select between various alternative work scenarios for a specific operation.

The ALARA analysis of a work scenario is under the data structure “Project”. A “Project” is a fixed geometry, a fixed radiation dose, which is calculated by other radiation transport simulation codes, a set of scenarios based on the same intervention requirement, a set of paths and a set of workers. In a scenario data structure, several tasks are defined and a roaming path is implemented by a worker.

Users can virtually design and simulate an intervention scenario for selecting the suitable roaming paths by considering the limited individual dose level. The result of different scenarios can be compared for selecting a suggested work scenario. The workflow of assessment of an intervention scenario is shown in figure 8.

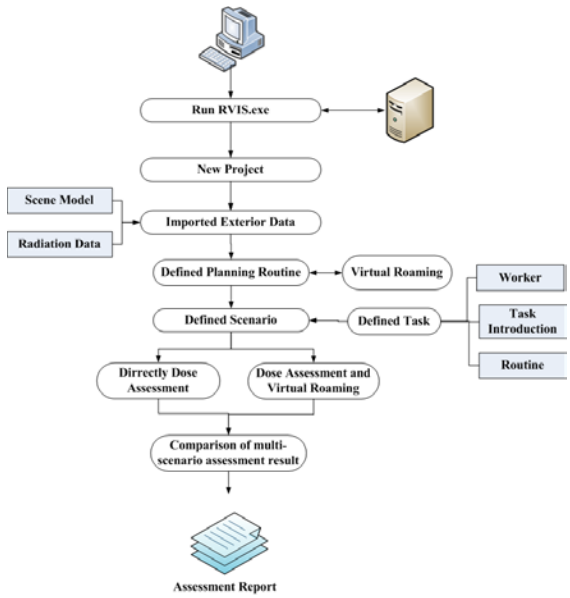

Figure 8.Workflow of assessment of an intervention scenario

4. VIRTUAL REALITY-BASED SIMULATION FOR DOSE ASSESSMENT DURING CLEAR-I SPALLATION TARGET MAINTENANCE

The case study chosen to validate the proposed development for dose assessment in nuclear and radiation environment was the modeling and simulation of ChinaLEAd-based Research reactor CLEAR-I spallation target maintenance. CLEAR-I is a strategic priority research program of Chinese Academy of Sciences--the future of advanced nuclear fission energy-ADS transmutation system. Spallation target is a key component to connect the accelerator and subcritical reactors in CLEAR- I. Spallation reactions produce neutrons for subcritical neutron source reactor to provide high-energy protons. Due to the high energy intensity proton bombardment and intense neutron irradiation, while a large number of nuclear heat deposition also need to be cooled, and thus generally shorten life of the target window. Target window is designed to replace once a year and should be carried out by manual.

4.1. Real-time Organic dose assessment

The shutdown dose rate distribution was calculated based on Rigorous 2 Step Method by using VisualBUS[37], which is a CAD-Based Multi-Functional 4D Neutronics Simulation System developed by FDS Team. Virtual scene can be modeled in SuperMC/RVIS2.3 by imported the geometry model and radiation dose rate distribution.

After the modeling stage, planning path can be defined, taking into account that the avatar can walk or stand at some locations for some time, during typical operations. The movement speed of a maintenance person was assumed as 5km/h and real-time dose assessment were displayed with the dose rate distribution with refresh rate of 50 Hz, but the simulation time can be accelerated by any times. The location of room wall in reactor top wall(-710， -744, 633) was selected to test the calculation time. The test result is shown in Table 1.We have found that the calculation time is less than 40ms, which means the proposed method meets the real-time calculation requirements.

Table 1 Test Result of Organic Dose Calculation Time

Test No.	Calculation Time(ms)	Test No.	Calculation Time(ms)
1	14	6	14
2	15	7	13
3	13	8	14
4	14	9	15
5	14	10	14

Various exposed doses and working time could be on-line calculated and shown on the screen, which is shown in Figure 9, for example, accumulated dose, effective dose rate, and equivalent dose rate of sensitive organs. Various organ dose Rate result in Location(-710， -744, 633) is shown in Table2.The maximum dose rate duringthis maintenance activity was 0.914μSv/hr. The accumulated dose of a maintenance person was 0.213 mSv.

Table 2 Various Organ Dose Rate in Location (-710，-744，630)

No.	**Organ**	**Voxel Number**	**Dose Rate(μSv/hr)**
1	Red Marrow	7781	3.10E-03
2	Salivary Glands	5780	3.42E-03
3	Extrathoracrc Region	1048	3.19E-03
4	Oesophagus	1063	3.32E-03

5	Heart	8601	3.22E-03
6	Lung	75243	3.45E-03
7	Thymus	664	3.22E-03
8	Stomach	3947	3.57E-03
9	Muscle	755833	3.22E-03
10	Kidneys	46917	3.24E-03
11	Breast	268	4.17E-03
12	Thyroid	526	4.30E-03
13	Prostate/Uterus	452	3.22E-03
14	Gall Bladder	1807	3.22E-03
15	Spleen	3947	3.22E-03
16	Adrenals	372	3.22E-03
17	Oral Mucosa	2036	3.22E-03
18	Pancreas	3649	3.22E-03
19	Small Intestine	17105	3.22E-03
20	Colon	8157	3.56E-03
21	Urinary Bladder	1316	3.75E-03
22	Gonads	921	4.08E-03
23	Kidneys	8081	3.22E-03

24	Lymphatic Nodes	3666	3.22E-03
25	Brain	8601	2.62E-03
26	Skin	93604	3.13E-03
27	Endosteum	65697	3.28E-03
Total		1127082	3.50E-03

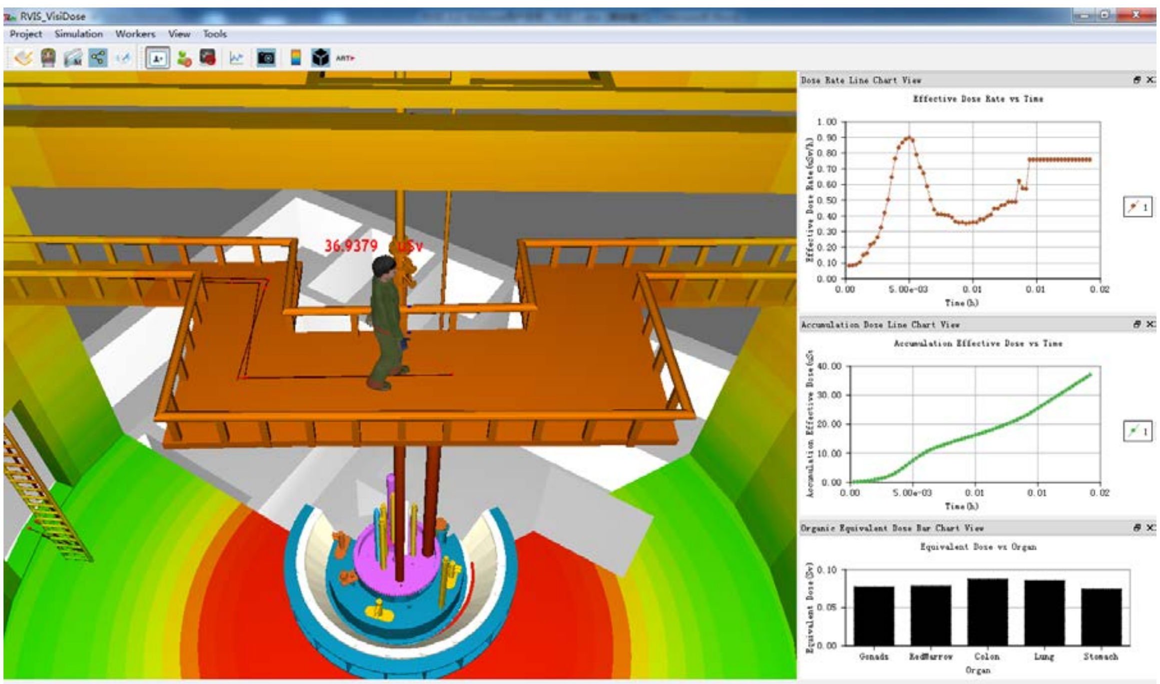

Figure 9. Virtual roaming and various dose calculated on-line along the planned path during the change of spallation target

4.2. Virtual training for manual inspection and repair

A virtual environment for CLEAR- I Spallation target maintenance had been established based on RVIS and VR hardwares in FDS Team for operator training. The virtual environment for CLEAR- I Spallation target maintenance was shown in Fig.10. The simulation allowed an immersive experience. Users could navigate the virtual environment by controlling an avatar to walk the way they wanted, visualizing the reactor rooms and radiation field, and experiencing the repair procedure. The dose information was computed in real-time and displayed, allowing them to evaluate the dose received by the avatars while walking.

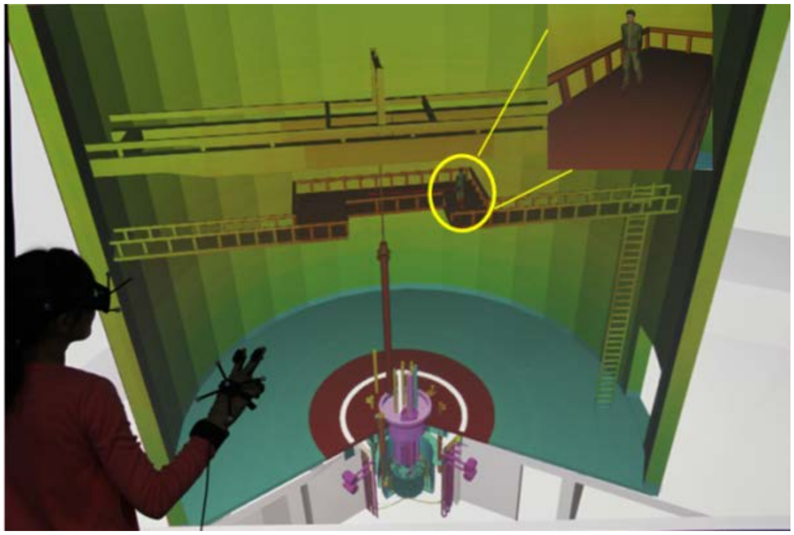

Fig.10 Virtual environment for CLEAR- I Spallation target maintenance

Operational and maintenance tasks could be tested and evaluated first in such a safe environment, before people entered the real environment. Based on the simulation results, supervisors could perform better planning of working activities. Thus, unnecessary radiation dose was avoided in the first training stages, fulfilling As Low As Reasonably Achievable (ALARA) principle, which means radiation dose for operators must be minimised.

5. CONCLUSIONS AND FUTURE WORK

Based on virtual reality (VR) technology and high-precision whole-body computational phantom named Rad-HUMAN, a virtual reality-based simulation system for nuclear and radiation safety named SuperMC/RVIS has been developed for organic dose assessment and ALARA evaluation of work scenarios in radiation environment. In this paper, the system architecture, ALARA evaluation strategy, advanced visualization methods and virtual reality technology used in SuperMC/RVIS are described. Virtual reality-based simulation during CLEAR-I spallation target maintenance has been demonstrated to validatethe feasibility and effectiveness of the system. SuperMC/RVIS makes it possible to safely perform the designs and optimization of work scenario in the risky areas taking into account the radiosensitive level of different organs.

In the future, reverse engineering modeling technique, like point cloud data obtained by laser scanning, map and image recognition technology, etc., will be used to get the CAD model and work scenario in complicated conditions, such as some old plants with general overhaul and large scale scenarios outside the nuclear plants. Besides, Monte Carlo method coupled with Point Kernel method will developed for the real-time dose assessment in the changing radiation environment, which the radiation source is changing.

6. ACKNOWLEDGMENTS

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