EUROPEAN JOINT PROGRAMME
FOR THE INTEGRATION OF
RADIATION PROTECTION RESEARCH
CONCERT

This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 662287.

PODIUM
Personal Online DosImetry
Using computational Methods

EJP-CONCERT

European Joint Programme for the Integration of Radiation Protection Research

H2020 – 662287

D9.106 – Guidelines for implementing the workplace geometry and the radiation field map in the dosimetry application Part 1: Workplace geometry

Lead Authors: Martin Andersson, Maria A. Duch, Jonathan Eakins, Jan Janssen, Pasquale Lombardo, Olivier van Hoey

Reviewer(s): Filip Vanhavere, Mercè Ginjaume

and CONCERT coordination team

Work package / Task	**WP1**	**T9.6**	**SST 9.6.1.2**
Deliverable nature:	**Report**		
Dissemination level: (Confidentiality)	**PU**		
Contractual delivery date:	**2018-12-31 (M43)**		
Actual delivery date:	**M43**		
Version:	**1**		
Total number of pages:	**17**		
Keywords:	**Workplace geometry**		
Approved by the coordinator:	**M43**		
Submitted to EC by the coordinator:	**M43**		

Content

1 Introduction

The objective of the PODIUM project is to develop a user-friendly online application to calculate workers' doses in real time. Instead of measuring individual doses with a physical dosemeter, doses will be calculated. This will be done by using a combination of (i) monitoring of the position of workers in real time and (ii) the simulation of the spatial radiation field, including its energy and angular distribution.

For this methodology, the geometry of the workplace is important since the accuracy of the position monitoring system of the workers will depend on how the system is implemented in each specific workplace; in particular, the placement of the tracking sensors is of great importance. In addition, some of the simulation modules would need a description of the workplaces (dimensions, construction materials...). This workplace description can be done once before the work starts, but it might need to be repeated if relevant elements of the workplace (like the shielding) are subject to change.

Another key aspect is the definition of the radiation field. To be able to simulate the staff doses many different parameters that allow to characterize its spatial, angular and energy distribution should be collected. The application of the proposed methodology for the radiation field mapping will be done in two fields that could most benefit of the advantages of it: interventional radiology and workplaces with mixed neutron/photon fields. Thus, the complexity of this task is different depending on the specific problem to simulate. In interventional radiology, the radiation field changes several times during a procedure of several hours in such a way a continuous calculation of the radiation field is required, whilst radiation fields for mixed neutron/photon workplaces are not that much time dependent. But even in this case the radiation field can vary, if the inventory or spatial positioning of radioactive sources in the workplace change over time. Therefore, the methodology for implementing the workplace geometry and the radiation field map in the dosimetry application are both of great importance.

The present document entitled "Guidelines for implementing the workplace geometry and the radiation field map in the dosimetry application. Part 1: Workplace geometry" describes the definition of the most important elements characterizing the workplaces geometry. The second part, which will be released later on during the development of PODIUM, will include the additional elements that will further improve the radiation field definition.

2 Interventional radiology workplaces

Interventional radiology and image-guided treatments are areas of the medical sector that could benefit from applying the PODIUM online dosimetry system. In these fields of application, it is foreseen to provide fast dose calculations by using two approaches. The first approach will use a library of pre-calculated dose conversion coefficients, while the second one will be based on the use of fast MC simulations with the MC-GPU code and calculations with standard codes such as PENELOPE.

The full description of the workplace geometry involves considering several elements present in the operating rooms, since the radiation field that reaches the worker position is mainly composed by scattered radiation produced when the radiation beam generated by the X-ray equipment impinges on the patient's body.

Therefore, information on different components is needed:

- Elements related to the generation of the X-ray beam:
    - Anode (angle and material) of the X-ray tube.
    - Inherent filtration of the X-ray tube (thickness and material).
    - C-arm radius of the installed equipment (isocenter location).
- Elements that can influence the scattered radiation that reaches the worker' position:
    - Anatomy of the patient (sex, height, weight), modelled by using anthropomorphic phantoms, as the main scattering body. Anatomical region examined (chest, abdomen, …).
    - Patient table (material, thickness, position).
    - Characteristics and position of movable protective elements (table shields, ceiling-mounted or wall-mounted shields…).
    - Focal spot position.
    - Shape and size of the radiation field.
    - Source to image intensifier distance.
    - Source rotation angles.
    - Image intensifier components.
    - Source to walls/ceiling distance.
    - Walls material.

Among these elements, the characteristics of the X-ray equipment installed in an operating room (X-ray tube, patient table, table shields…) could be considered as part of the workplace description, but in an interventional radiology procedure the operating conditions of this equipment will vary many times during the procedure. For instance, in a typical procedure the same X-ray tube will operate with different kilovoltages and added filtration, and the movable shields will be located at different places. This is why the geometrical description of all of these elements will be included in the future document "Guidelines for implementing the workplace geometry and the radiation field map in the dosimetry application. Part 2: Radiation field mapping" devoted on how to characterize the radiation field. In this section only the static elements of the room (walls, ceiling, shelves…) are considered for the workplace geometry definition in an interventional radiology room, since they will affect the placement of the tracking sensors. On the other hand, the materials and dimensions of the room walls have a very little impact on the staff doses and are not going to be included in the MC simulations.

The studied medical procedures are carried out in operating rooms that could have variable dimensions depending on the specific site, thus, in section II.1.1 it is proposed a method to model the operating room by using specific sensors in such a way that a CAD file is generated. This file could be used to easily visualize the geometry of the workplace with standard computer-aided design tools such as AutoCAD, and to define the relative positions of the most relevant elements in the room such as C-Arm, bed and shields. In section II.1.2 are included the guidelines on how to set-up the IPS system (see deliverable D9.105), specifically how to set the single camera system.

2.1 Modelling the operating room

The proposed method to model the operating room is to use Structure sensors (Occipital Inc.), i.e., a 3D camera attached on an iPad. The camera uses the RAM-memory to create a 3D mesh of the filmed geometry. The created 3D mesh environment was generated using the app Canvas. The 3D mesh is then post-processed by the additional "Scan To CAD" service ($29.00 per scan) in the Canvas app, which converts the generated 3D mesh into an editable CAD file.

Figure 1. Print screen of the generated 3D mesh of the operating room using Structure sensors and the app Canvas.

To show the final outcome of the system, the process was applied to the operating room number 105 of the Malmö Hospital. The generated 3D mesh by the Canvas app and the post-process CAD file of the room are presented in Figure 1 and Figure 2.

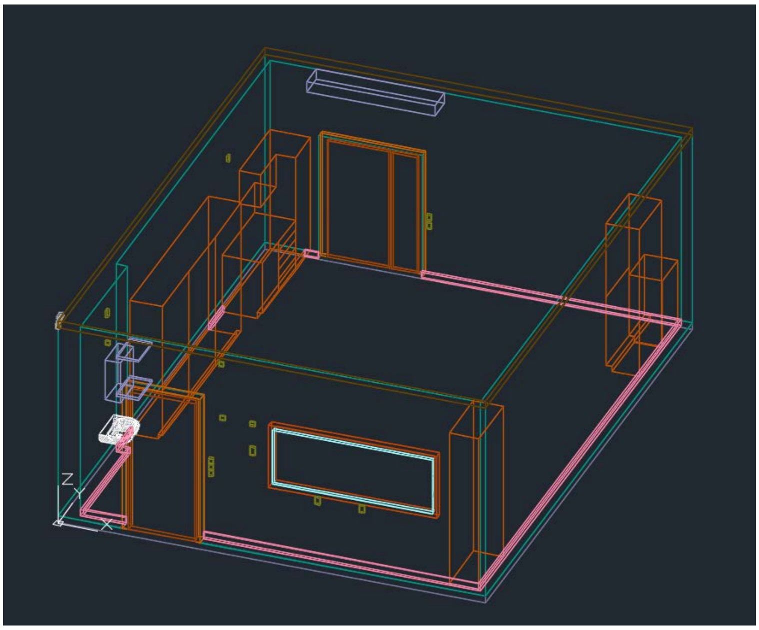

Figure 2: Post-processing CAD file of the operating room using the "Scan To CAD" service and shown in the computer software AutoCAD.

2.2 Guidelines on how to set-up the IPS System

The placement of the IPS camera is highly dependent on the features of the IR room where it is installed. For achieving an optimal tracking accuracy, the IPS camera should be placed following a series of ideal criteria, which are described in this paragraph. However, in some cases it could become necessary to compromise some criteria to reduce both the intrusiveness and the possibility of obstructions. The first priority in the placement must be the discreteness of the IPS, i.e. we must assure that the work of the staff is not hindered during the course of any procedure. All the components of the IPS, including the Kinect, the cables and the acquisition PC controlling the IPS, must be placed safely and out of highly trafficked areas. This applies not only to the areas where doctor and nurses walk, but also to the areas where the C-Arm can be moved. Especially in the case of ceiling mounted C-Arms, it is necessary to take into account of the lateral excursion of the device when it is moved along its mounting rail.

Assuming that these requirements are met, the first condition for an optimal positioning is that the Kinect should have a front facing view of the staff. With a front facing view, the IPS will deliver the most accurate tracking of chest, head, and of both arms and both hands. To ensure that the tracking is continuous even when the doctor and the medical staff move around the patient, the Field Of View (FOV) must allow for coverage of a sufficiently large area (5-10 m^2) surrounding the patient bed.

Considering the horizontal and vertical apertures of the RGB and depth sensors of the Kinect v.2, the ideal position should allow for a final distance between the Kinect and the doctor of about 2 to 4 meters. A distance of about 2.5/3 meters will deliver the highest tracking accuracy. Considering this constraint, the distance components along the longitudinal, lateral and vertical axes needs to be adjusted so that they respect some additional conditions. The vertical distance depends mostly on the height of the Kinect, and it has an obvious implication on the vertical inclination of the camera. The larger the vertical distance, the more downwards the Kinect will have to be rotated, so that the FOV reaches the doctor height. However, due to the inner limitation of the Kinect v.2 recognition algorithm, hard rotations about the horizontal axis (tilt angle) could lead to inaccuracies in the estimation of the joint's position. Above 25°, there is a high chance that bodies will not be recognized at all. In practical terms, the camera should not be placed above 2.5 meters of height. Similarly, also the horizontal rotation of the camera should not be too high. Hard rotations about the vertical axis of the camera can compromise the view of the doctor. The higher the horizontal rotation, the more lateral the view turns out to be. Lateral views can lead to self-occlusions, i.e. one side of the doctor's body hides the other side from the camera. In such cases, the Kinect recognition algorithm will try to infer the most probable position of the hidden joints. However, the joint inference algorithm can lead to negative effects on both precision and accuracy, and it can cause high frequency jittering to the hidden hand joint. Furthermore, high horizontal rotation angles will lead to difficulties in the calibration of the IPS. The calibration is a process through which we transform the local coordinates produced by the Kinect into Real-World coordinates, which are necessary for the calculation of the relative positions of source, patient, shields and doctor/nurse. For calibrating our IPS we make use of some reference patterns (checkered boards) that are placed on the room walls. The patterns should lie perpendicularly to the camera view to deliver the best accuracy in the calibration. Ideally, to reduce the chance of self-occlusions and to ease the calibration process, the horizontal rotation angle should lie in the range of (-20°, +20°).

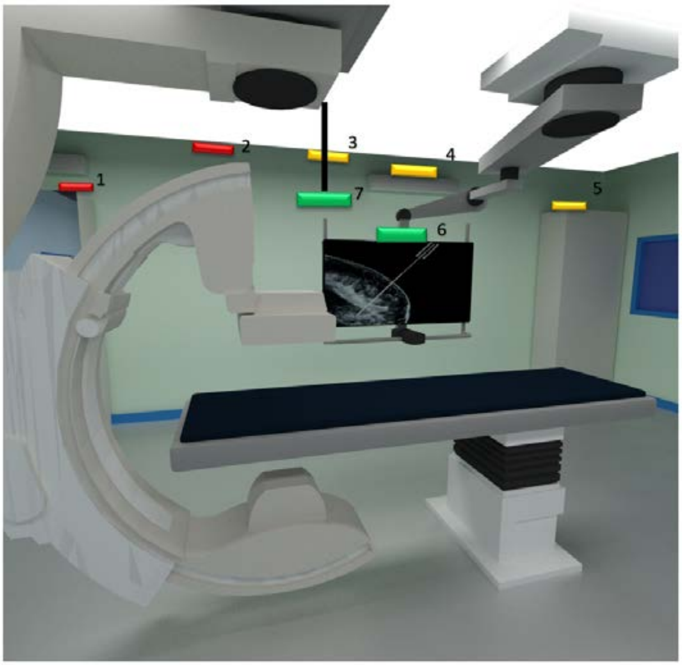

Figure 3: Potential Kinect locations within the Malmo test room. The most ideal positions are shown in green, while less favorable ones are indicated in orange and red.

Figure 3 shows some possible locations for the Kinect. The room geometry is taken from the Malmo Hospital test room number 105 (serving as reference in PODIUM), which has a ceiling mounted C-Arm from Siemens. In this figure, seven possible locations are shown. The green color code indicates the locations corresponding to the most ideal positions, while the red indicates the least favorable ones. The red locations would either deliver less accurate tracking data (increasing errors of about 1-2 cm), lead to frequent occlusions, or require a more complex calibration. Nevertheless, all these positions could be used in case the room geometry does not allow for placing the Kinect in the more ideal locations. Table 1 shows qualitative remarks with the respective advantages/drawbacks of each location.

Position	FOV	Distance Kinect-Doctor	Tilt angle	Horizontal angle	Occlusions	Calibration
1: Kinect mounted on a closet on the side of the C-Arm.	Good. It covers the whole region of interest.	Not good. The camera is far from the monitored area.	Good. The vertical position at about 2.1 m of height implies a tilt angle smaller than 20°.	Not good. The horizontal position requires angle of rotations larger than 20°.	High probability of occlusions with the C-Arm when rotated.	Complex due to large distances and relatively hard tilt and horizontal angles.
2: Kinect hanging right below the ceiling on the same side of the C-Arm	Good. It covers the whole region of interest.	Not good. The camera is far from the monitored area.	Not good. The vertical position at about 2.7 m of height implies a tilt angle higher than 25°.	Ideal. The Kinect has a front facing view of the doctor.	Medium probability of occlusion with C-Arm when rotated	Complex due to large distances and relatively hard vertical and horizontal angles.
3: Kinect hanging right below the ceiling at the center of the bed	Good. It covers the whole region of interest.	Good. The camera is not too far from the monitored area.	Not good. The vertical position at about 2.7 m of height implies a tilt angle higher than 25°.	Ideal. The Kinect has a front facing view of the doctor.	Low probability of occlusion from tv screen and C-Arm when rotated.	Easy, thanks to the ideal distances and to the relatively good vertical and horizontal angles.
4: Kinect mounted on a wall light at about 2.3 meters of height	Good. It covers the whole region of interest.	Not ideal. The camera is far from the monitored area.	Mediocre. The vertical position at about 2.3 m of height implies a tilt angle of about 20°.	Ideal. The Kinect has a front facing view of the doctor.	Medium probability of occlusion from tv screen and C-Arm when rotated.	Easy, thanks to the ideal distances and to the good vertical and horizontal angles.
5: Kinect placed above the closet on the right side of the room	Good. It covers the whole region of interest.	Not good. The camera is far from the monitored area.	Good. The vertical position at about 2.1 m of height implies a tilt angle smaller than 20°.	Not good. The horizontal position requires angle of rotations larger than 20°.	Medium probability of occlusion from tv screen if rotated.	Complex due to large distances and relatively hard vertical and horizontal angles.
6: Kinect mounted on the imaging screen	Excellent, doctor during procedure always look screen so even if moved it will always track doctor.	Excellent. The camera is at ideal distance to allow high accuracy and good view of the scene.	Good. The vertical position at about 2 m of height implies a tilt angle smaller than 20°.	Ideal. The Kinect has a front facing view of the doctor.	Very low risk of occlusions.	Complex. If the monitor is moved frequently, it will require an automated calibration procedure
7: Kinect hanging on the ceiling thought a mounting rack	Good. It covers the whole region of interest.	Excellent. The camera is at ideal distance to allow high accuracy and good view of the scene	Mediocre. The vertical position at about 2.2 m of height implies a tilt angle of about 20°.	Ideal. The Kinect has a front facing view of the doctor.	Very low risk of occlusions.	Easy, thanks to the ideal distances and relatively hard vertical and horizontal angles.

Table 1: Comparison of advantages/drawbacks of the proposed locations for the placement of the camera in room 105 of Malmo Hospital

To summarize:

1. Among all, locations 1 and 2 are the worst. Besides the hard angles (vertical and horizontal) and the high distances to the doctor, these positions are likely to lead partial occlusions when the C-Arm is rotated around the patient body. In this sense, position 5 is already a better option, but it can also lead to partial body occlusions because of the image monitor. However, in this case the camera is far from the monitored area, thus, reducing the useful tracking range and the accuracy of the depth measurement.
2. In principle, locations 6 and 7 deliver the best combinations of distances, FOV, rotation angles and occlusions risk-free. With such positions, in fact, the distances are maintained within 2 to 3 meters and the risk of self-occlusions and occlusions with objects is very low. However, the implementation of these setups presents some difficulties, reason for which we have not been able yet to place the Kinect in the Malmo test room. In the case of location 6, the problem is that the calibration will be invalidated when the doctor moves the monitor. This issue could be solved by means of an automatic calibration software re-calculating the transformation matrices when a change of position is detected. Within WP1, we will try to study the feasibility of developing an automated calibration software. On the other hand, by adopting the setup number 7 we would solve the issue of the calibration by means of a fixed holder hanging from the ceiling. In this case, we would have to leave an opportune clearance space between the C-Arm and the mounting rack, so that the camera will never interfere with the movements of the C-Arm. Therefore, in case the automatic calibration software reveals to be too difficult to be implemented for the setup number 6, we will consider the use of a fixed holder.
3. Overall, the locations 3 and 4 are the easiest to implement. The Kinect is far enough from the C-Arm, and the central position allows a frontal view of the doctor. So, even if the distances Kinect-doctor are relatively large, these Kinect locations still lead to a good tracking accuracy. The most concerning issues for these setups are the high tilt angle (especially in position 3, which can lead to a complex calibration) and to the risk of occlusions when the C-Arm is rotated towards the center of the bed.

3 Mixed neutron-gamma workplace fields

The PODIUM system is intended to be used in workplace fields that contain neutrons. However, due to the physical nature of neutron generation and of neutron-matter interactions, such fields will inevitably also contain photons. So, the system must in fact be suitable for dosimetry in mixed neutron-gamma fields, or at least it must be able to discriminate between neutron and gamma dose contribution.

Example scenarios where such fields can exist include, but need not be limited to:

a. nuclear power stations and their associated support facilities, such as fuel processing, transport, and de-commissioning industries;
b. accelerator facilities that have beam types and energies capable of producing neutrons as either primary or generated particles, such as might occur within high-energy research accelerators or around medical accelerators;
c. engineering applications that utilize neutrons, such as for geological analyses of samples.

Within the scope of the PODIUM project, suitability of the system in the above types of field will be tested at two sites. The first is within the Radiation Metrology laboratory facility at PHE’s Centre for Radiation, Chemical and Environmental Hazards (CRCE) in Chilton, UK. At this site, the low-scatter environment routinely used to perform Secondary Standards certified exposures to an ^{241}Am-Be source has been modified by the inclusion of water tanks to produce a location- and angle-dependent field that has been shown to be similar in energy distribution to the types of workplace fields that can exist at a nuclear power station.

The second is within a nuclear facility hosted at the SCK•CEN site in Mol, Belgium. At this facility, a transport container with spent MOX fuel will be placed in a large room. This setup represents a realistic mixed neutron/gamma workplace field in which workers can receive significant neutron dose.

3.1 Modelling of the geometry

In mixed neutron/photon workplace fields, the geometry and the radiation field are often coupled because the sources are often movable (e.g. transport containers with spent fuel, portable neutron sources …). Therefore, in this first part of the deliverable both geometry and radiation field will be discussed. However, more details on the radiation field will be included in the second part of the deliverable.

The geometry of mixed neutron/photon workplace fields needs to include objects/materials that emit radiation or that can significantly influence the staff doses. For complex fixed radiation sources such as nuclear reactors or accelerators, usually simulations of the radiation field are already available for locations with significant dose rates. The data from these simulations can then be used to characterize the radiation field (e.g. as a phase space file) and the complex geometry of these sources need not to be included in the workplace geometry. For more simple portable radiation sources such as transport containers with spent fuel or portable neutron sources, a (simplified) model of the source should be included in the geometry and it should be possible to easily adapt the position of such sources and assessing the effect on the radiation field. Different objects/materials in the workplace can affect the radiation field by shielding or scattering. We will need to assess which objects/materials significantly affect the radiation field. The most important objects/materials need then to be included in the workplace geometry. For simple geometries this can be done by using simple macro-bodies. For more complex geometries, it might be necessary to use a CAD model. If a CAD model is not yet available it might be generated for instance by using the technique described in II.1.

In principle, the model of the facility needs to be sufficiently detailed to provide an accurate estimate of the dose rate at every location at which an individual might conceivably be located within it. The transient nature of the field would also need to be considered in environments in which that is relevant, such as fuel storage facilities, for example, where the inventory and spatial positioning of radioactive sources in the area might change over time. The model also needs to be robust to the inevitable uncertainty in accounting for every factor that could contribute to perturbations in the dose rate as a function of location, noting that some of these might conceivably be unknown or unknowable to the individual performing the modelling.

In practice, the above requirements would be impossible to fulfil completely. It is therefore clearly not realistic to provide precise and universal guidelines that are true in general on how to model a facility; instead, different requirements would necessarily be adopted and adapted on a case-by-case basis. However, several overall approaches may be adopted to mitigate against the problems caused by imprecise or incomplete knowledge of the input required for the model, and standard good practice will help to optimize the reliability of the results obtained:

Simulation code: The simulation code used to generate the dose rate data can be either deterministic or Monte Carlo, general-purpose or user-specific. The only condition is that it needs to be fit for purpose, and hence able to output accurate data that is reliable for both neutrons and photons. This requirement may be demonstrated via independent testing and benchmarking. FLUKA, GEANT, MCNP and PHITS are examples of general-purpose Monte Carlo codes that fulfil these requirements, and can be considered sufficiently consistent for the needs of the PODIUM system. It is not envisaged that advanced IT facilities, such as computer clusters, would be required to perform the simulations; the Monte Carlo codes listed above can easily all be run on standard PCs, though computational times would scale with the physical size and complexity of the site being modelled. It is necessary to run Monte Carlo calculations in coupled neutron-photon mode, with kerma conditions generally assumed such that electron transport may be neglected.

Modeller: The accuracy of the dose rate map will clearly depend on the ability of the individual performing the modelling: it is obvious that they must be sufficiently familiar with mathematical modelling techniques to not only be able to construct a reliable model of the facility but also understand the uncertainties and limitations associated with their approach. This would include an awareness of parameter-sensitivity analyses, and an ability to determine which factors (e.g. objects, materials, physical parameters etc.) within their facility would be most key to obtaining accurate results. Whilst official accreditation of this discipline does not currently exist, competency could potentially be verified by a CV-based approach: demonstrably significant experience in mathematical modelling using the code to be employed, potentially alongside successful participation in intercomparison exercises, such as those organized periodically by the EURADOS WG6 consortium.

Parameter variation: Even if a modeller could reproduce the geometry of their room with apparent high fidelity, there is still the possibility that 'hidden' aspects within it could impact dose rates. Examples here could be the unknown presence of neutron absorbing material behind a wall panel, which could significantly affect scatter, or imprecise knowledge of the material compositions or densities that they input into the model. It is therefore necessary to perform parameter sensitivity analyses of the modelled environment, to ascertain which factors are most and least significant. Furthermore, it is then necessary to benchmark the results against measured data. Estimates of ambient dose equivalent rates are suggested for this, because survey instruments are typically readily available within workplace fields. The recommended approach would be for the RPA to perform measurements at those locations that are judged to be the most susceptible to environmental factors, and also at those locations where individuals are most likely to be positioned during routine use of the facility, and compare their results with analogous data generated within the model; agreement between the measured and modelled results would support and confirm (or otherwise) the accuracy of the overall dose rate map. Given the energy-dependence of response of typical survey instruments, only broad confirmation may be possible.

Time dependencies: It is possible that the geometry of the modelled room may be time-dependent, leading to a time-dependent dose rate map. It may therefore be necessary to produce a set of 'contingency' dose-rate maps for a given environment, each for a different anticipated configuration of objects within it, with the choice of which map is most appropriate to use made in real-time. The use of installed area monitoring equipment could also be employed to provide real-time dose assessments and correction factors

The above headings provide discussion on the general approach to modelling the geometry of a given neutron facility of interest. To illustrate the overall methodology, however, it is instructive to consider a case study that relates to the modelling of a real facility. This is provided below for the example of the PHE Radiation Metrology neutron laboratory, which contains an ^{241}Am-Be source moderated by tanks of water as a simple simulation of a realistic workplace field within the nuclear industry (see next section). The second test with the transport container at SCK•CEN must still be started. In this case a simplified model of the room will be implemented in MCNP again by using macro-bodies. Also a simplified model of the transport container and the fuel will need to be implemented. Important in this case will be that the position and orientation of the transport container can easily be modified. In MCNP this can be done for instance by specifying translations and rotations for the set of cells corresponding to the transport container. The simulations of the radiation field will then in principle need to be performed for a discrete set of possible positions of the transport container. If it is found that the radiation field is not influenced significantly by the materials in the room, the simulated radiation field can simply be translated and rotated together with the transport container and no additional simulations for different positions need to be performed. In that case it will also be easier to implement the presence of multiple transport containers.

3.1.1 PHE Neutron Facility

An image of the PHE neutron facility is shown in Figure 4. Cross-sectional and plan views of the PHE neutron facility are shown in Figure 5. The figure is schematic, being generated as output from a Monte Carlo model using the VISED package of MCNP. The laboratory is essentially a rectangular room, approximately 8 m long, 5 m wide, and 2.5 m high, with the source and exposure platform positioned on the central long-axis. When not in use, the ^{241}Am-Be source is stored below ground, but is raised to a height of ~1.25 m above the floor during exposures.

Figure 4: The PHE Neutron Laboratory in routine use. The ^{241}Am-Be source is contained within a steel tube, itself partially encased within a lead shield (painted yellow). A moveable platform allows objects to be placed as different distances (and heights) along a central axis away from the source.

In order to build the model, measurements were made of the physical dimensions of every aspect of relevance within the real laboratory (Figure 4). Of course, 'of relevance' here is subjective, and is inevitably based on the judgement of the modeller. Nevertheless, it is evident (Figure 5) that aspects of the facility that were considered unlikely to affect the dose at a given location have not been included in the model; typical examples of this are small objects that may be judged not to induce significant neutron scatter, such as wall-fixtures, control panels, a monitor screen, and the wooden desk placed against the wall.

With all dimensions recorded, a scale diagram was produced that could subsequently be translated into the MCNP model. This translation proceeded according to standard methodologies used for Monte Carlo modelling projects: the geometry was deconstructed into a set of quadratic surfaces defined and located according to an agreed coordinate system, with Boolean logic applied to then combine those surfaces into representations of the real-world shapes. In this case, the origin of the co-ordinate axes was identified with the 'standard' point-of-test used in routine measurements at PHE, which is 1 m from the source and 1.25 m above the floor, with the X-axis associated with the width of the room (left-right in Figure 5c), the Y-axis associated with the length of the room (left-right in Figure 5a, up-down in Figure 5c), and the Z-axis associated with the height of the room (up-down in Figure 5a). Pragmatically, the modelling was achieved using a text editor to create an MCNP-readable input file describing the geometry, with the VISED programme utilized to provide a visual double-check.

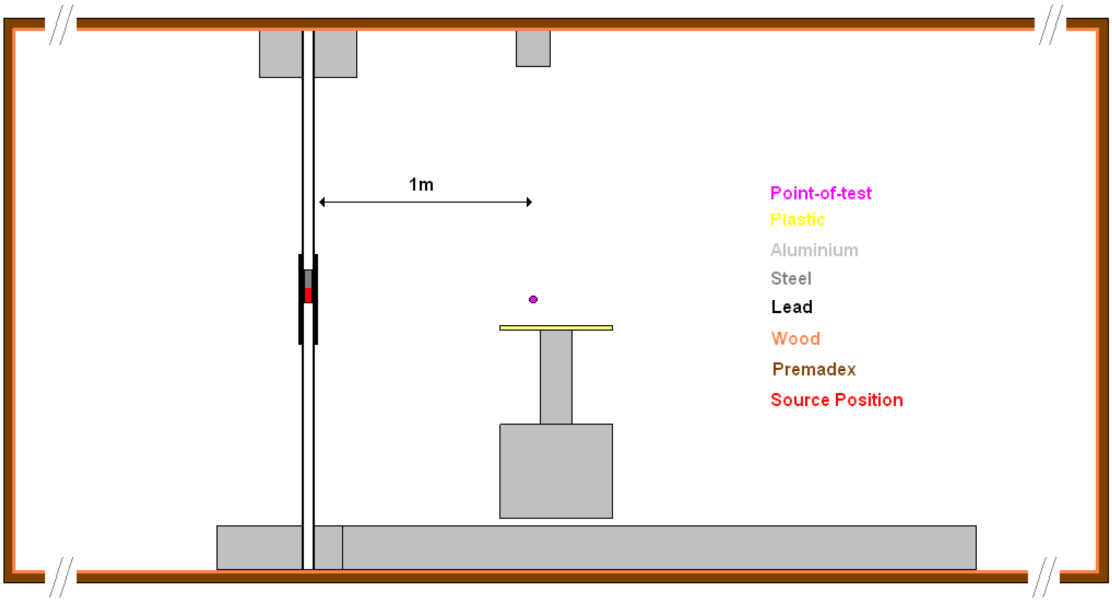

Figure 5a: Cross-sectional view of the PHE Neutron Laboratory in ‘normal use’. The figure is truncated in the left-right direction: the actual laboratory is ~8m long (Y-axis) and ~2.5m high (Z-axis).

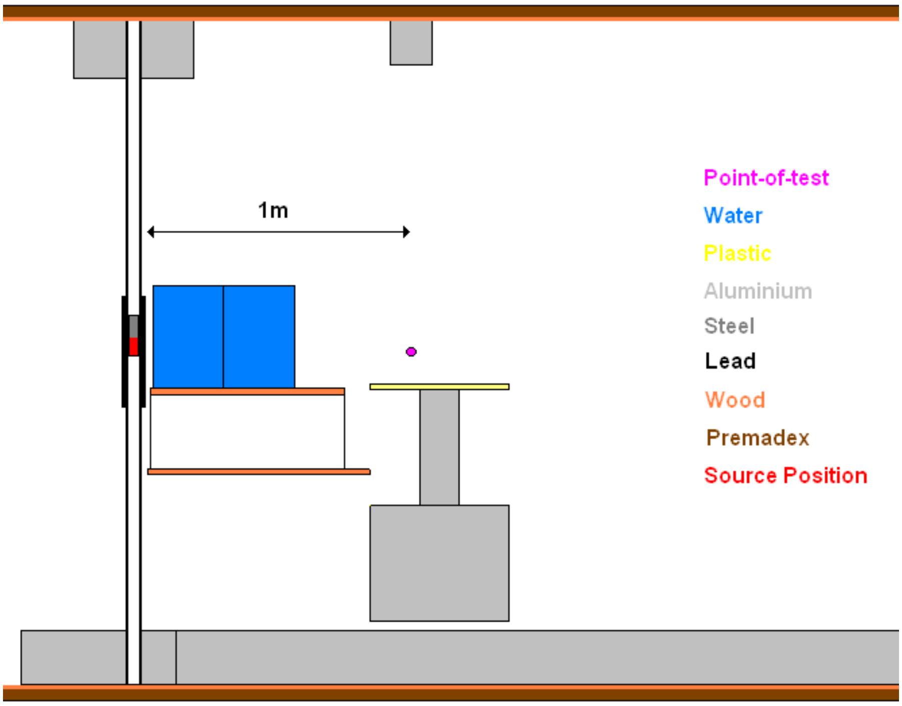

Figure 5b: Cross-sectional view of the PHE Neutron Laboratory including water tanks adjacent to the source.

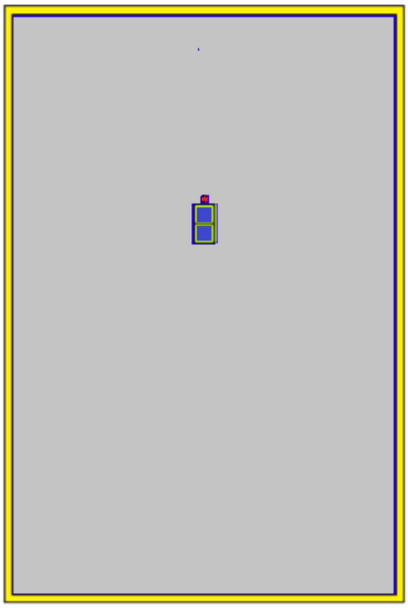

Figure 5c: Plan view of the PHE Neutron Laboratory. The water tanks are shown in blue, with the ^{241}Am-Be source (red) positioned adjacently. The walls (yellow) incorporate wood panels placed in front of Premadex neutron-absorbing material. The laboratory is ~8m long (Y-axis) and ~5m wide (X-axis).

Once the spatial arrangements of objects had been defined, these shapes were 'filled' with the correct materials within the MCNP input file, in accordance with the physical objects present in the actual laboratory. MCNP considers matter as a 'dense gas', i.e. a mixture of isotopes (or atoms, for photon-only problems) in user-defined proportions. Essentially, a given material is therefore specified according to two main parameters: its physical density, given either as mass per volume or atoms per volume; and the ratio of its composite isotopes, given either as a mass-fraction or an atom-fraction. However, for neutron problems, a specification of the chemical bonding of light nuclei is also recommended, to correctly account for neutron-nucleus thermal scattering effects (i.e. the so-called $S(\alpha,\beta)$ 'thermal treatment'). For this third parameter for each material, the most up-to-date $S(\alpha,\beta)$ data provided in MCNP were used, with the most appropriate next-best choice made where data were absent for a given material, such as using light water O-H data for tissue, or assuming polyethylene-like C-H bonds for wood, polymethyl methacrylate (PMMA), and Premadex (^{6}Li-loaded wax).

Of course, the accuracy of the model will depend on the accuracy with which the materials can be defined, which may be complicated if the precise chemical composition of a given object in a geometry is unknown. In such cases, best guesses and compromises would be inevitable. For the PHE laboratory, however, most of the materials used in its construction can be assumed to be fairly commonplace, such as the aluminium, stainless steel, lead, polymethyl methacrylate, wood and Premadex used to build the facility, and the water of the moderator. Typically, it was fairly easy to obtain physical density data from reliable and referenceable online sources for most common materials.

The chemical composition of common materials is also relatively easy to obtain. Of course, one complication to this for neutron exposures compared to photon-only problems is that the correct isotopic compositions of the individual elements in a given material need to be provided, alongside simply the ratio of elements in its chemical formula. For the most part, natural isotopic compositions were assumed for each element, freely obtainable from resources such as the "I*sotopic compositions of the elements*" [1]. Where non-standard isotopic compositions are relevant, such as for the Premadex neutron-absorbing material that is enriched with lithium-6 rather than natural lithium (~10% ^{6}Li + ~90% ^{7}Li), appropriate isotopic breakdown data provided by the manufacturers were used.

Once the shapes comprising the physical objects have been 'filled' with materials within the MCNP model, the specification of the geometry is essentially complete. However, the source term needs also to be defined within the model. For most workplace facilities where neutrons may be present, such as within the nuclear sector, the neutrons originate from a radioactive source of physical dimensions, density and material composition. Thus, source and geometry are effectively 'coupled' within Monte Carlo models containing neutrons, so the physical parameters of the source need to be incorporated into the specification of the input geometry. For the PHE source, this was relatively easy: the neutrons are emitted from a small cylinder of aluminium (~few cm^3), inside of which the ^{241}Am-Be is distributed

In addition to the physical specifications of the source, the energy distribution of the emitted neutrons needs to be defined within the model. Again, this is a relatively easy for the PHE ^{241}Am-Be source, which is a well-defined calibration source that emits according to ISO 8529 [2] specifications. Moreover, MCNP normalizes all output results to 'per-source-particle'. In order to link that output to the real world, the activity of the source needs also to be considered, such that a multiplication factor may be introduced. As before, this is relatively easy for the PHE source, which is well-benchmarked and is calibrated to secondary standards criteria.

Similarly, to the specification of the material data, the accuracy of the model will depend on the accuracy with which the source term can be defined. For the PHE neutron facility model, the accuracy may therefore be assumed fairly high: the energy distribution of emitted neutrons and the composition of the source pellet are both well-known and well-characterized, with the dose rates at the point of test typically determined to better than 10 % uncertainty. In a general workplace environment, however, this may not be the case: the compositions and contents of fuel flasks, for example, may be known only to a limited extent, and the presence of short-lived radionuclides could lead to a transient emission characteristic. These limitations will lead to two related problems: firstly, the energy distributions of the neutrons and photons may be poorly known and time dependent; secondly, if the materials surrounding and shielding the source are poorly defined, the degree to which the neutrons are attenuated and secondary particles are generated may be simulated inaccurately by the model. The extent to which ignorance of the source term and its immediate environment will impact the dose rate at a given location will obviously vary on a case-by-case basis, but could be significant and again emphasizes the need for corroborative measurements and a cautionary approach to the modelling. This type of uncertainty will be investigated and discussed in later work, where application on the PODIUM system in an actual workplace field will be tested.

The MCNP simulation is run in coupled neutron-photon mode, with detailed physics options chosen by default. Of course, for the simulation to be useful, it is necessary to be able to extract results and output from it. The methodology applied to achieve this will be described in a later report, alongside discussions of attempts to mitigate for inaccuracy and uncertainty within the model.

3.2 Guidelines on how to set-up the IPS System

The main difficulties for mixed neutron/photon workplace fields arise from the fact that such workplaces can be very large and many workers can be present in one workplace. Therefore, often the use of two or even more tracking cameras will be required and the tracking algorithms need to be able to track all the workers present in the workplace.

Inevitably, use of the tracking cameras within a facility will vary on a case-by-case basis, with their number, locations and orientations fully dependent on the geography of the room and the objects within it, noting that these latter may potentially be variable. The objective would be for the cameras to be able to determine, at all times and for all anticipated configurations of the geography, the position and orientation of each individual within it. The minimum number and configuration of cameras is therefore that needed to achieve this aim in the environment in which the PODIUM system is to be employed. Essentially, this means that wherever an individual is and whatever might be around them (including other workers), there must always be a clear line-of-sight between him/her and at least one of the cameras. Depending on the tracking system used, additional cameras may also be required in very large environments, in the circumstance where individuals can move too far away from a given camera for his/her position or orientation to be accurately determined due to its finite range.

For a static environment, the camera configuration may be relatively straightforward: easily determinable given accurate scale-drawings and the stated field-of-view of the camera, and readily testable post-installation. For transient environments, in which additional objects might be introduced or removed, the engineers and RPAs tasked with establishing the PODIUM system would need to carefully consider every conceivable permutation of objects within the room to ensure that line-of-sight is always possible. Again, annotatable scale-drawings of the environment, and thorough understanding of its intended operation, would be essential to guide this aim.

In all cases, safety systems must be put in place to ensure that any modifications from the set of configurations considered at the set-up stage would trigger a re-evaluation of the camera requirements. Obvious examples of this could be introducing new equipment into an environment, or re-purposing it so that it is no longer static. As always, the focus would be on the RPAs at such facilities to ensure that their dosimetry system is at all times fit for purpose.

For the case-study of the PHE Neutron laboratory, choosing the number and positioning of cameras may be relatively straight-forwards. This is because the laboratory is an approximately 5×8 m^2 rectangular room, with the neutron source, water moderating tanks, and calibration platform all located along the central axis, and no other significantly sized objects are present. Occlusions of individuals within the field-of-view can therefore only be caused by these central components or by the presence of other workers (if any) in the laboratory. The number of cameras in the room will likely scale with the number of workers, to ensure that there are no individual-individual occlusions. However if only one individual is likely to be present, which is the envisaged scenario in the PHE neutron facility, use of two tracking cameras may hypothetically be sufficient, because the only potential occlusion of that individual is by the moderating tanks.

The natural positioning of the two cameras would be in diagonally opposite corners of the room, assuming that each camera can track to a range of at least ~6 m and has a field of view of at least 90°. The door to the laboratory is at the bottom-right of Figure 5c, so the obvious locations of the cameras would therefore be in the bottom-left and top-right corners of Figure 5c. The suitability of these suggestions for the needs of the PODIUM system will be tested in due course.

4 Conclusions and future works

This document provides guidelines on how to model the workplaces according to the foreseen applications. These guidelines will be complemented with a future document “Guidelines for implementing the workplace geometry and the radiation field map in the dosimetry application.

Part 2: Radiation field mapping” devoted on how to characterize the radiation field. In the medical field the use of radiation shielding and operating conditions of the X-ray tube vary many times during an intervention, and this can have a big influence on staff doses. For mixed neutron-gamma workplaces the radiation field will be more easily described, but anyway should be calculated for each specific site every time it changes.

This work is ongoing and it will include both the methods to calculate the radiation field mapping and the description of the modelling of moving objects, for either interventional radiology workplaces: C-arm, protective shields; and mixed gamma-neutron workplaces: transport containers…

5 References

[1] Commission on atomic weights and isotopic abundances, International Union of Pure and Applied Chemistry (IUPAC).

[2] ISO 8529-1:2001. Reference neutron radiations - Part 1: Characteristics and methods of production.