Design of Removable Shield Modules for Nuclear Plant Applications Using Monte Carlo Modeling - 16264

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ABSTRACT

A new modular shielding system has been designed and developed for nuclear plant applications as a replacement for traditional concrete blocks and plugs. The shield comprises interlocking modules that are custom designed using CAD and Monte Carlo modelling methods. The key benefit of these new modules is that they can be quickly removed and re-installed to allow temporary access to high radiation environments e.g. for maintenance and repair of plant equipment at nuclear power plants or waste handling facilities.

The traditional method for construction of these removable concrete blocks and plugs was to cast them in place. Within the aging fleet of commercial reactors, some plants are experiencing concrete degradation of these shield blocks and plugs as well as failure of lifting points. Additionally, the existing plugs are difficult to remove and re-install. The new modular system comprises a rigid steel enclosure filled with lead that can be installed in a fraction of the normal time. This approach can accelerate outage times leading to reduced dose uptake to operators and provide significant long term cost savings.

Use of Monte Carlo methods enables the shielding modules to be designed efficiently for neutron and gamma ray attenuation with the minimum necessary thickness of lead and steel. Furthermore, the modelling ensures the design is not compromised by streaming pathways, for example at the overlaps between modules or through internal structural components.

Shielding modules were supplied to the Brunswick Nuclear Power station (BNP), operated by Duke Energy, located in southeast United States. These modules have been installed to replace concrete shield plugs that are located on the roof above a Feed Water Heaters (FWH) bay. While specific in application, this project demonstrates that the shield module design concept could be expanded to address vertical block walls routinely found in personnel and equipment access hatches. This approach is applicable to a wide variety of new and existing nuclear facilities and will

lead to improved safety and reduced lifetime costs all the way through to future decommissioning and dismantling operations.

INTRODUCTION

Equipment access hatches are a common feature within commercial nuclear power plants, especially those of a Boiling Water Reactor (BWR) design. These hatches are located in both floors and roofs and are closed using removable concrete plugs that can provide both radiation and missile shield protection. These plugs periodically removed to gain system access for inspection and component replacement. The shield plugs are typically made of standard density concrete (2.4 g/cm^3) and are cast in place during plant construction. Access hatches may comprise single, or multiple plugs depending on size. A cross sectional view of a typical horizontal plug set is shown in Figure 1. They are tapered in design and incorporate overlapping, stepped seams to minimize radiation streaming effects. A viewpoint from the roof is shown in Figure 2.

Within the aging fleet of commercial reactors, some plants are experiencing concrete degradation of these shield blocks and plugs (Figure 3). Concrete spalling and falling concrete has been experienced during plug removal. Lifting points which consisted of “cast in place” lifting eyes, cannot be readily inspected for cracking, and in some cases have experienced failure; especially with roof mounted plugs that are more prone to weathering. Additionally, due to the tight tolerances used in their fabrications, the existing plugs can be difficult to remove and frequently require supplemental jacking. In some cases, the plugs could not be removed and had to be demolished in place.

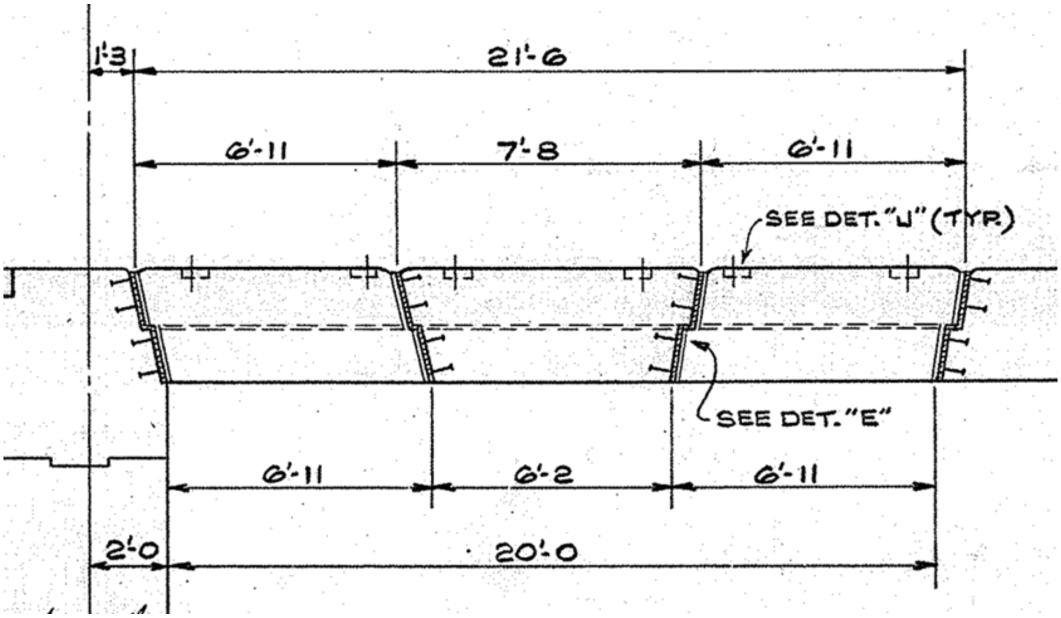

Fig. 1 Cross section view of typical access hatch a using three shield plugs.

Fig. 2 Typical roof mounted access hatch with multiple shield plugs.

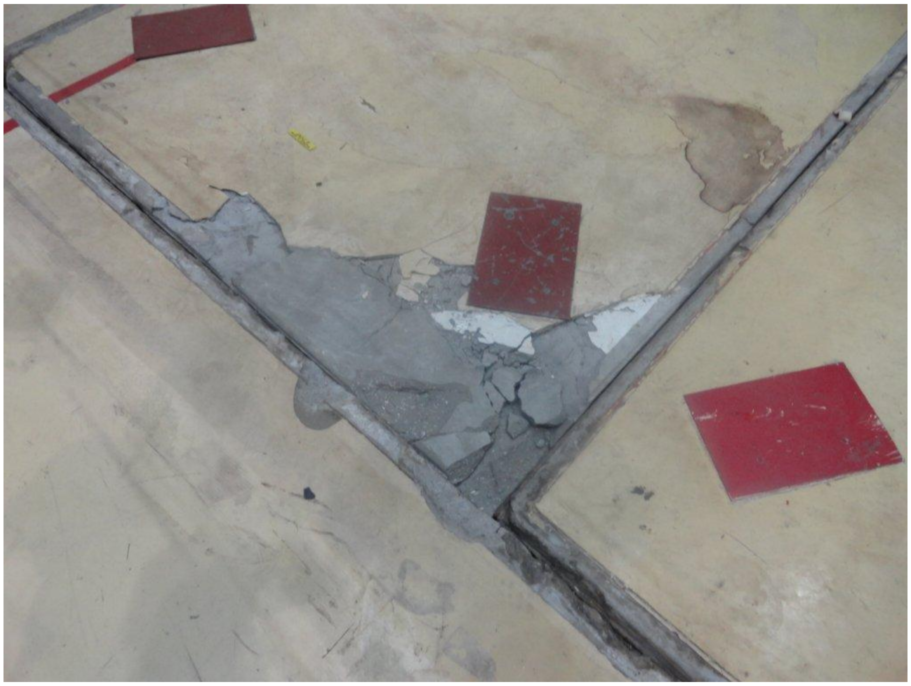

Fig. 3 – Typical concrete damage

A modular system has been designed and developed to replace these concrete plugs, which comprises a rigid steel enclosure filled with lead that can be removed and re-installed in a fraction of the normal time. Other shield designs are also possible where neutron shielding is required that incorporates layers of lead, virgin polyethylene and borated polyethylene. High-density materials other than lead can also be used in this design. This approach can accelerate outage times leading to reduced dose uptake to operators and provide significant long term cost savings.

Monte Carlo methods have been used to assist in the design of the shielding modules. A series of calculations were performed using MCNP6 [1] to ensure that the new plugs are designed efficiently for neutron and gamma ray attenuation with the minimum necessary thickness of material. Furthermore the modelling verified that the design is not compromised by streaming pathways, for example at the overlaps between modules or through internal structural components.

DESCRIPTION OF THE PROBLEM

Shielding modules were required to be supplied to the Brunswick Nuclear Power station (BNP), operated by Duke Energy. These modules replace concrete shield plugs that are located on the roof above a Feed Water Heaters (FWH) bay. The shield plugs needed to be replaced with a more durable, prefabricated, assembly. The approach taken for the FWH application, where N-16 is the primary source of radiation, is to build a self-supporting steel shell filled with lead shot. In this case, where the hatches are arranged horizontally, the frame can be laid to bear directly of the perimeter of the hatch. The new plugs feature overlapping joints so that they interlock in a manner to avoid streaming.

A second, separate problem has also been considered for a drywell equipment access hatch which uses removable, vertically stacked, concrete blocks to provide shielding for neutron and gamma radiation from the reactor. A replacement moveable shield was conceived to allow quicker access via the hatch during outages. The new design must address direct shielding and end scattering effects.

CHALLENGES PRESENTED

The retrofit of modular shielding in place of traditional concrete shield blocks present several challenges in both the shielding analysis and mechanical/structural design.

Design

One of the biggest mechanical design challenges for the modular shield is to ensure that they can accommodate the as-built tolerances inherent to poured-in-place concrete. Since the existing shield blocks were cast in place, they naturally conform to the opening’s size and any irregularities. Accurate as-built dimensions of the hatch openings are rarely available, and the ability to gather this data in an operating plant is extremely limited. The prefabricated replacement shield module must be designed with enough clearance to account for the variations in the hatch openings, and yet avoid potential streaming paths for gamma radiation. Similarly, by using higher attenuating materials (steel, lead) in the modular plug construction, the exact geometry of the existing concrete plugs will not be replicated since the overall thickness of the shield can be reduced. This requires careful consideration and reinforces the need for a detailed shielding analysis as the change in shield's shape and location relative to the hatch affects the angle of incident photons and the material thickness they will encounter as they traverse the shield. This can potentially lead to localized "hot spots" and unanticipated radiation streaming.

The design process must also result in a shield that can be easily analyzed and validated from a structural standpoint, as well as ensure ease of fabrication. It was recognized in the FWH shielding example that building a shield plug that would sit inside the access hole, as do the existing concrete plugs, would present both structural and fabrication challenges. Compromises were made which resulted in a shield plug design that is place over the access, rather than in it. This approach allows the plugs to be support by a bearing surface around the perimeter of the opening, resulting in a top mount design. This arrangement greatly simplified fabrication and avoids any potential for the plugs to become stuck in the access hole and better accommodated as-built tolerances. The obvious drawback is that it does result in a discontinuity in the floor/roof which may impact laydown area and equipment and personnel transit. A recessed, or flush mounted, plug arrangement has been developed to address these issues.

Various shielding materials were considered during the design process. Lead shot was ultimately selected for the FWH example based on several factors. Lead is an extremely effective, relatively inexpensive, gamma shielding material. Lead shot was selected as it is suitable for complex geometries and simplified fabrication and filling of the steel shells. Casting the lead (molten pour) was deemed logistically impractical due to the size of the plugs, and the effect of the shells preheating that would be required on the steel's material properties could not be readily quantified. Scaled studies were performed to select the optimum shot size and to ensure that a uniform pack density could be consistently achieved during the filling process. The quantity of shot used was controlled by mass and check by measuring the height of the shot poor. A means of stabilizing the shot after placement, to avoid shifting, was incorporated into the plug design.

Shielding analysis

Shielding high energy photon radiation (from N-16 in the FWH application, where the photon emission spectrum is dominated by 6-7 MeV photons) presents a major challenge for the designer of compact modular shielding. In addition, where neutron radiation is present, there can be problems arising from reflection, scattering and streaming. Furthermore, the neutron and photon energy spectra may not always be fully understood so the model has to evaluate energy sensitivity issues.

The new shielding modules must provide equivalent or better shielding than the concrete that they will replace. The shielding must allow for distributed source material so it is not always adequate to model the source as a simple point or plane source. In fact, it is likely that the process equipment, reactor component or vessels that is to be shielded will contain a complex source nuclide vector and/or a complex geometry. It is also possible that neighboring vessels can be a significant (sometimes dominant) source of dose for the replacement shield.

In Figure 4, a modular shield is shown placed over the top of a hatch that previously contained a concrete plug, which is representative of the FWH application. One challenge that must be addressed for this situation is the “corner clipping” effect where shine paths arise from radiation that passes through the corner of the surrounding concrete and not directly through the replacement shield. This is a direct consequence of the change in the shield’s geometry and orientation within the access hatch as previously mentioned. In this case the challenge can be solved by extending the shield to a sufficient overlap distance at the perimeter. The MCNP modelling allows the designers to determine the necessary overlap required to attain equivalent dose rate reduction as compared to the original concrete plug.

This example demonstrates the need to establish a detailed model of source activity where the source may arise from complex structure. Intuitively one might expect the process vessel immediately below the hatch to be the dominant source of dose on the shielded side. However, it can be seen that the clipping effect is most prominent for the neighboring vessel leading to a streaming effect that would not have been considered in a simple model.

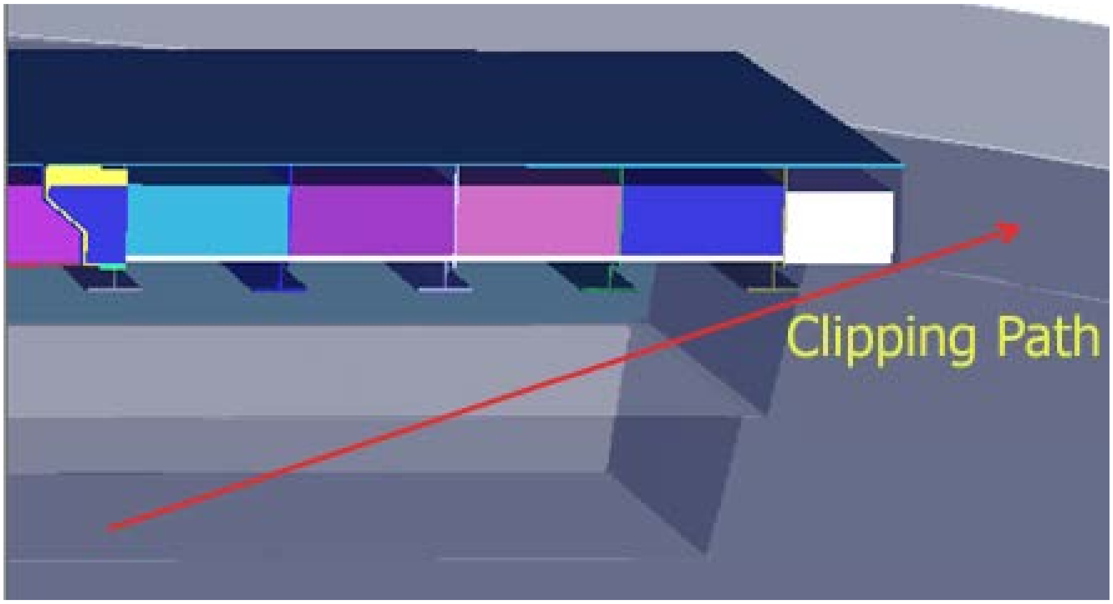

Fig. 4 Example of streaming effects in photon shielding problems (the “corner clipping” problem)

Figure 5 shows the results from the conceptual equipment access hatch application. In this case a combined photon / neutron shield (comprising layers of lead / polyethylene / borated polyethylene) was used to replace concrete blocks in a vertical hatch. As the new shield is to be mounted on a rail for easy removal, there are end gaps created by the standoff distance from the exterior wall and the inner surface of the shield. These gaps create a potential channeling / scattering path for neutrons that must be addressed by locating side panels at the ends.

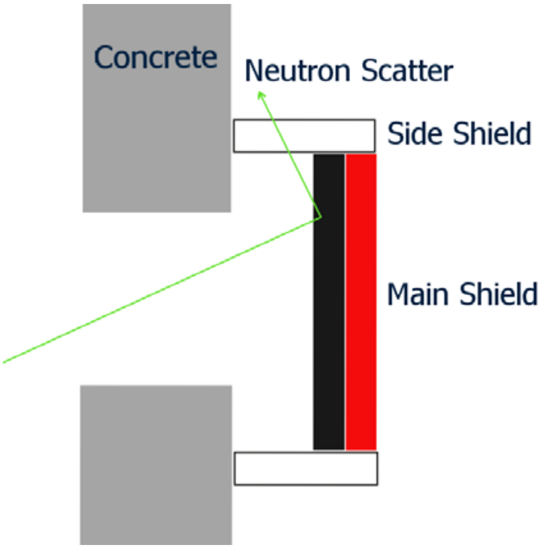

Fig. 5 Example of streaming / scattering effects in neutron shielding problems.

Traditional methods for dose assessment and shielding calculations such as MicroShield [2] are widely recognized industry standard tools for studying the shielding problems. Such tools use a fairly simple approach and have limited flexibility in terms of application for complex source and shield geometry situations. As a result, these tools provide a useful method for scoping studies but are not well suited to detailed design assessments and supporting calculations. For example, MicroShield does not address shine effects, is limited to simple planes and cylinders, and has no neutron dose rate calculation capability.

MCNP MODEL DESCRIPTION

Where the model is a highly complex large region that includes repeated modules, for the sake of simplicity (and improved calculation precision) the model can be divided into a “simple” region and a “detailed” region. The detailed region should attempt to simulate all significant internal features of the shield module, such as structural I-beams, panels, overlaps and so on. The simple region can have a more simplified representation of the primary shielding materials (lead shot, load bearing plates etc.). The primary analysis will proceed by focusing on the radiation emerging around the detailed region and applying symmetry arguments to extend the conclusions across the opening. The detailed region is usually located at the weakest point of the shield such as the overlap between the shield module and the perimeter of the hatch.

The simple/detailed approach reduces the time taken to develop the model and improves run times. Care must be taken to ensure that any simplification use is well understood and any symmetry argument is validated.

The purpose of the modelling is to characterize gamma and neutron dose rates above and around the modular shields and compare with the equivalent situation when the existing concrete plugs are in place. The model also evaluates streaming and end / edge effects as well as determination of the overlap end length and thickness of lead shot required.

The Monte Carlo N-Particle (MCNP6) [1] was selected for the calculations as it provides a general purpose code for radiation transport calculations that has been extensively verified and validated for nuclear shielding applications. Amongst the many benefits that MCNP6 provides is the ability to use advanced variance reduction methods (significantly reducing the run times required to achieve convergence) as well as a geometry and tally plotting that allows intuitive visualization of the results.

The MCNP Visual Editor [3] was also used extensively in this project in order to improve the model development process allowing engineers and physicists to closely collaborate in model development using CAD file conversion tools and 3D image plotting.

Two methods were used to determine the emergent dose:

1. Tally regions were created to calculate dose over large volumes around the exterior facets of the shield.
2. A mesh tally was created to encompass particular a region of interest in the model. The mesh was subdivided into voxels that are approximately 10-20 cm on each side. The mesh tally can be plotted in user-definable plot planes to get a contour plot of emergent radiation. This is particularly useful for evaluating streaming, reflection and ducting effects.

ICRP74 [4] flux to dose conversion was used for neutron and gamma problems. In the case of neutron problems, neutron-induced photon interactions were also modelled. The MCNP model was run using MCNP 6.1 with a target statistical precision of <1% Relative Standard Deviation at the tally (dose rate measurement) locations.

An example of photon dose rate contour plots created using the MCNP mesh tally method is given in Figure 6 and Figure 7 for the FWH project. In Figure 6 (a plan view on a plane located just above an example of an engineered plug at the facility) the sensitivity of the modelling is such that the structural I-beams in the plug can be seen. The I-beams create regions of slightly higher attenuation than the lead shot (the beam presents a longer path length). In this model the source is a FWH located directly below the engineered plug.

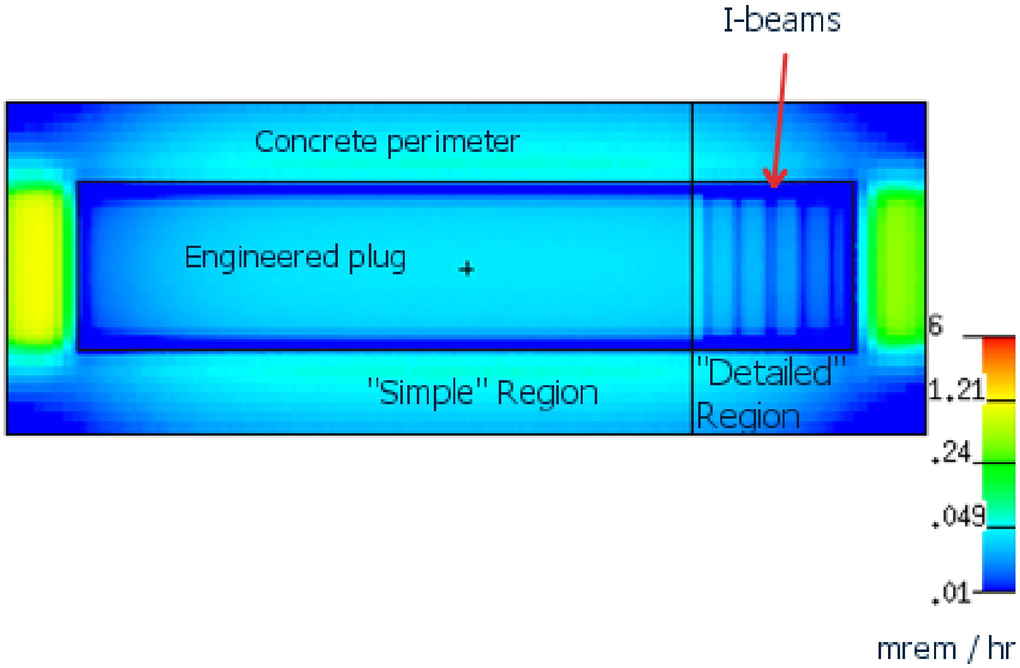

Fig. 6 Photon Dose Rate Contour Plot around Engineered Plug (Plan View)

Figure 7 shows a cross section view across the short side of the void with a source located at “Source 2” – a neighboring FWH. These results allowed the designers to quickly identify a streaming pathway due the clipping effect described above.

The plot shown is based on worst case assumptions where all of the activity in the source is located in a plane at the top of the vessel. Further modelling was performed to show that using a more realistic distribution of source in the vessel would reduce the dose rate in the streaming region to within acceptable levels. For this reason, it was decided that there was no need to increase the shield overlap length to provide additional shielding to address potential streaming. Minimizing the size of the shield has a significant effect on the weight of the shield modules and the total quantity of lead required.

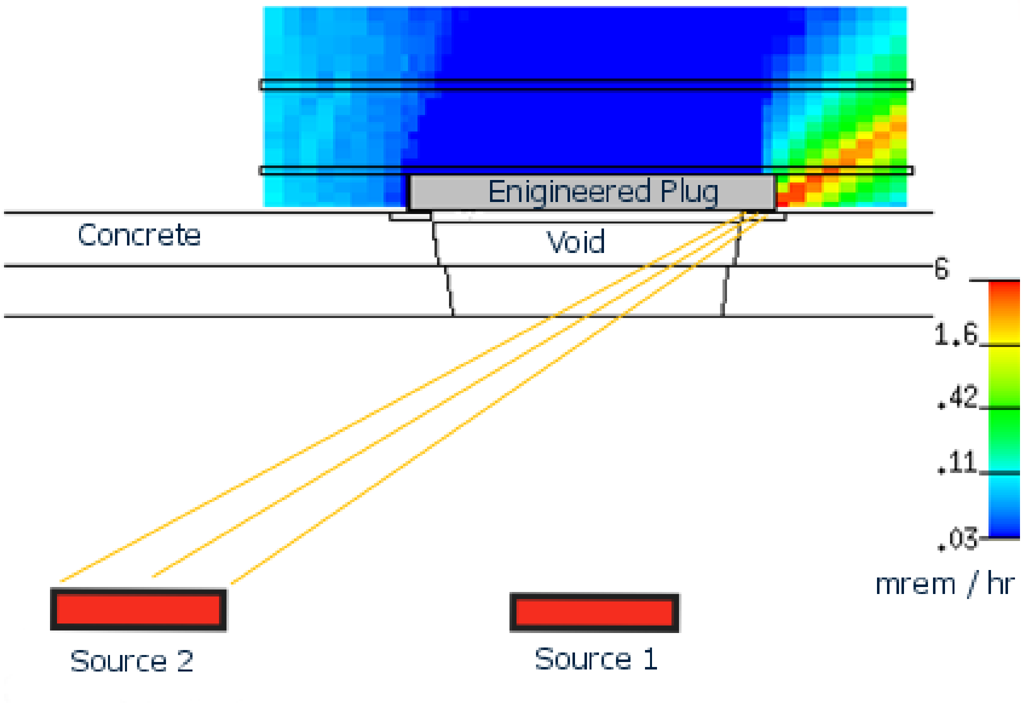

Fig. 7 Photon Dose Rate Contour Plot around Engineered Plug (Cross-Section View)

These modelling results were used to confirm the predicted shielding performance of the plugs. In particular, it was demonstrated that the overlaps between modules do not create a streaming path and the dose rates above the plug meet the site’s requirement of 1 mrem hr (10 µSv/hr). The modelling work allowed the design engineers to interact with the customer to find the optimum, most cost-effective shielding solution for this project.

SOLUTION DEVELOPED

A new modular system has been designed and developed to replace the traditional concrete plugs which is comprised of a rigid steel enclosure filled with lead. The new system can be removed and installed in a fraction of the normal time. This approach has been designed with the goal of accelerating outage times which in turn will lead to reduced dose uptake to operators providing significant long term cost savings.

This example has demonstrated the benefit of performing detailed modelling during the design phase to ensure the new shielding meets all of its performance requirements and gives the customer confidence in the effectiveness of the product. For operating reactors, shields must be normally installed during limited “outage” intervals which leaves very little margin for error in calculation of predicted performance.

The modular shielding system developed for Brunswick is shown in Figure 8.

Fig. 8 Modular Shielding System (horizontal plug, FWH example)

Neutron shielding calculations in MCNP are also particularly useful to design compact shields where space is limited and/or weight (lifting) restrictions apply. By modifying the thickness and location of the shielding layers, the designed can rapidly determine the optimum arrangement of virgin and borated polyethylene where the former has the optimum capability to reduce the energy of fast neutrons by moderation and the latter is very effective at absorbing the resulting thermal neutrons.

CONCLUSIONS

A new modular shielding system has been developed for use in nuclear facilities to replace traditional concrete blocks and plugs. One major advantage of these new modules is that they can be rapidly removed and replaced to allow temporary access to high radiation environments e.g. for maintenance access and repair/replacement of large items of plant equipment at nuclear power plants. The design is also applicable to waste handling and processing facilities where high dose environments are often encountered with limited man access.

One example of a new modular system comprises a rigid steel enclosure filled with lead that can be installed in a fraction of the time compared to the existing concrete blocks. This approach can accelerate outage times leading to reduced dose uptake to operators and provide significant long term cost savings.

This work has demonstrated that traditional methods for dose assessment and shielding calculations such as MicroShield provide a useful tool for scoping studies on shield thickness (for photon problems) but lack the capability to study complex problems, evaluate shine / scattering effects and are not applicable to neutron problems. Monte Carlo modelling methods can solve these issues and have been successfully applied in the design and development of such modular shields.

The power and flexibility of general purpose radiation transport codes such as MCNP6 enables the shielding modules to be designed efficiently for neutron and gamma-ray attenuation with the minimum thickness of lead and steel. Furthermore, the modelling ensures the design is not compromised by streaming pathways, for example at the overlaps between modules or through internal structural components.

The modules have been successfully deployed at nuclear power plants in the United States. The modules have been installed to replace concrete shield plugs that are located above Feed Water Heaters. This approach is applicable to a wide variety of new and existing nuclear facilities and will lead to reduced lifetime costs all the way through to future decommissioning and dismantling operations.

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