Transparent gamma radiation shielding, significantly better than lead glass, half the weight of lead

Attenuation of Gamma Radiation Using ClearView Radiation Shielding™ in Nuclear Power Plants, Hospitals and Radiopharmacies

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Abstract: *Radiation protection materials, such as lead (Pb), water, concrete, steel, and aluminum, have been successfully used for decades. Although they are effective shields, these materials do have limitations. For example, lead is heavy and toxic, and water and concrete must be thick to provide significant shielding, all of which renders these materials prohibitive for certain applications. For example, the half-value layer for water to shield against ^{60}Co is 30.48 cm (12″), which makes it an extremely bulky material. The development of ClearView Radiation Shielding™ addresses some of the limitations that are faced by traditional radiation protection shields. The product is a transparent liquid gamma radiation shield that can be fabricated in custom sizes and thicknesses. Here, we describe applications of ClearView Radiation Shielding in nuclear plants and hospitals. ClearView Radiation Shielding is used to shield nuclear power plant workers from ^{60}Co in critical path and high dose in refueling outages to observe automated operations inside the containment, and operations such as cylindrical frisking stations and benchtop sampling. ClearView Radiation Shielding is designed as rolling shields and radionuclide containments in hospitals to protect staff and families during unsealed radionuclide treatment such as MIBG and Lutetium therapies. For successful implementation in hospitals, the product was tested against various radioisotopes, also described in this work. Operational uses of ClearView Radiation Shielding in commercial nuclear and medical industries allows staff working in radioactive environments visibility, better communication and similar levels of radiation protection compared with traditional shielding materials. The product helps improve workflows and reduced total dose received by workers. Additionally, attenuation measurements using ClearView Radiation Shielding against multiple isotopes was performed. With 1.25 cm (0.5″) ClearView Radiation Shielding thickness, the shield attenuated 1) 65% of the effective dose from ^{131}I, 2) 35.15% of the effective dose from ^{137}Cs, and 3) 22.5% of the effective dose from ^{60}Co. Isotopes in the range of 35 keV to 1899 keV. 3.81 were attenuated greater than 90% with a ClearView Radiation Shielding shield thickness of 7.62 cm (3″). The half-value layer for ^{60}Co with a ClearView Radiation Shielding thickness of 3.81 cm (1.5″) attenuated the effective dose of ^{18}F gammas by 85.59%. With a density of 2.3 g cm^{-3}, ClearView Radiation Shielding was measured to be half the weight of lead for equal shielding. ClearView Radiation Shielding is transparent, lightweight, and an alternative material to conventional radiation shields to reduce radiation exposure. Health Phys. 119(00):000–000; 2020*

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INTRODUCTION

Attenuation, or shielding, of gamma radiation is a vital radiation protection principle. The ability to see through a radiation shield in high background radiation, or high gamma energy, environments is desirable for a several reasons. The weight, opacity, and toxicity of lead (Pb) are all drawbacks. Finding a comparable alternative to lead was the motivation to develop ClearView Radiation Shielding, which is documented in a prior publication (Bakshi, 2018). The results of initial testing of ClearView Radiation Shielding with ^{60}Co has shown that the half-value layer (HVL) is 3.81 cm (1.5″), half the weight of lead for equal shielding (Bakshi, 2018).

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Jayeesh Bakshi is affiliated with Radium Inc. who owns the patented ClearView Radiation Shielding product. Jayeesh Bakshi is also one of the inventors. The authors have no other conflicts of interest to declare.

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FIG. 1. Two ClearView Shields.

ClearView Radiation Shielding (Fig. 1) consists of a liquid shield with a density of 2.3 g cm^{-3} that is housed in a clear impact-resistant polycarbonate, allowing transparency while also providing gamma and x-ray shielding. ClearView Radiation Shielding was developed in 2016 and first used as a chemistry tabletop shield at LaSalle Nuclear Generating Station in early 2017 (Radium, Inc. 2017). The product was patented in April 2019 (Radium, Inc. 2019) and over the last few years has been used in nuclear power plants, hospitals, and radiopharmacies to improve operational workflows in radioactive environments.

Here, we describe the use of ClearView Radiation Shielding in nuclear power plants, hospitals, and radiopharmacies as well as the associated radiation exposure reduction data. To evaluate the shielding thickness needed, ClearView Radiation Shielding was tested against multiple gamma emitting radioisotopes ranging from 35 keV to 1899 keV photons. Table 1 shows the HVLs of different shielding materials compared with ClearView Radiation Shielding. In general, the greater the radiation intensity and energy, the thicker the shield needed to reduce the ionizing radiation to personnel. In line with the principles of as low as reasonably achievable (ALARA), shielding is used to reduce the cumulative dose exposure for personnel working in radiation environments.

Application of ClearView Radiation Shielding in nuclear power plants

Nuclear power plants use ClearView Radiation Shielding as an alternative shielding material to lead (Pb) in refueling outages, dry cask operations, frisking operations, refurbishments, chemistry benchtop sampling, and equipment maintenance, as described below.

Refueling outages

The main source of radiation exposure to plant workers during shutdown is from ^{60}Co with 99.9% gamma energies at 1173 keV and 1332 keV, a beta energy at 318 keV (Lubinski 2020), and initial measurements of ClearView Radiation Shielding showed that the HVL of ^{60}Co was 3.81 cm. During a nuclear plant refueling outage, the reactor head is removed for removing spent nuclear fuel and the addition of fresh fuel. Simultaneously, multiple maintenance activities are performed inside the containment, including inspections of the baffle bolts, core barrel movements, viewing lifting rigs, steam generator, pumps, feedwater heaters, and core barrel. To reduce scatter and shine from ^{60}Co during refueling and maintenance, lead blankets are used as a shadow shield for plant workers when possible to reduce exposure. Although the lead blankets provide protection against ^{60}Co, the major limitation is visibility. To compensate for the lack of visibility, video monitoring systems are installed, or plant workers peek around the lead blankets. As an alternative to lead, ClearView Radiation Shielding are designed to serve as observation windows on the refueling floor of a pressurized water reactor (PWR) plant as shown in Figs. 2 and 3.

Table 1. Comparison of half-value layers of shielding materials.

	Approximate half-value layers in cm (Rad Pro Calculator 2020; NDE Resource Center 2019)						
Isotope	Lead	Aluminum	Tungsten	Iron	Concrete	Water	ClearView Radiation Shielding
^{131}I	0.3	9.5	0.2	2.2	10.3	26.1	0.76
^{18}F	0.5	7	0.4	2.2	7.6	17.3	1.27
^{137}Cs	0.7	8.1	0.5	2.6	8.8	19.9	1.77
^{60}Co	1.8	10.9	1.1	3.7	11.8	26.4	3.81
^{124}I	0.7	7.2	0.5	2.3	7.8	17.9	0.47

Dry cask operations—spent fuel storage

Multiple nuclear plants use ClearView Radiation Shielding windows during dry cask operations, which transfer spent nuclear fuel into casks made from steel and concrete. Once the fuel transfer process is complete, the cask is sealed by a welding process. ClearView Radiation Shielding windows are used by several nuclear plants for observing the automated welding process for the transfer cask, shown in Figs. 4 and 5. The windows are 60.98 cm high × 30.48 cm (2′×1′) and 1.27 cm (0.5″) thick ClearView Radiation Shielding is used during dry cask operations. The survey data is discussed in later sections.

FIG. 3. Two ClearView Radiation Shielding shields used by a bed during MIBG therapy.

Frisking operations

Traditionally, frisker caves are made of thick water or lead bricks. Frisking operations are performed to measure contamination levels in various locations in a plant, which could include tool rooms, machine shops, and/or the refueling floor of a nuclear power plant. Before any valve is opened, or work is done during an outage, loose contamination is checked by a health physicist to certify that the radiation levels are safe for respirator use. The area measured for contamination is over 100 cm^2 with a disk, or smear, and then counted on a frisker to determine the amount of contamination present. Contamination on a surface is measured by rubbing a small cotton, or paper, disk on the surface where the contamination is to be measured then counted on a frisker, or similar instrument, to determine the amount of contamination that was on the smeared area of the material. Discrete particles are highly radioactive and cause the measuring probe to spike in counts rapidly because of a large surface area being measured. To perform accurate measurements, the background must be significantly low. As per users, desired count rate has been reported as less than 300 counts per minute. To achieve a low background in a high background environment, shielded caves are fabricated with an interior probe.

There are reports of nuclear power plants that use lead bricks (approximately 1,000 kg) as well as the necessity of using polar cranes on the refueling floor and reactor building to move the lead bricks during each outage. Handling and moving the heavy lead bricks pose a safety concern during each outage. In addition, the use of the opaque lead bricks to reduce background levels leads to contamination and inaccurate measurements. Another method to run the wipes in low background areas to yield accurate counts was having technicians go back and forth, but this resulted in additional lost time. The visible frisker cave fabricated from ClearView Radiation Shielding liquid is an alternative to the traditional lead bricks and has yielded accurate wipe results. The frisker cave tube is 30.48 cm long, with an inner diameter of 21.59 cm, and 3.81 cm thick. The cave is designed with a smear tray and a probe holder with a shielded back. A probe holder is attached 7.62 cm inside the cave. The frisker weighed 32.61 kg as opposed to

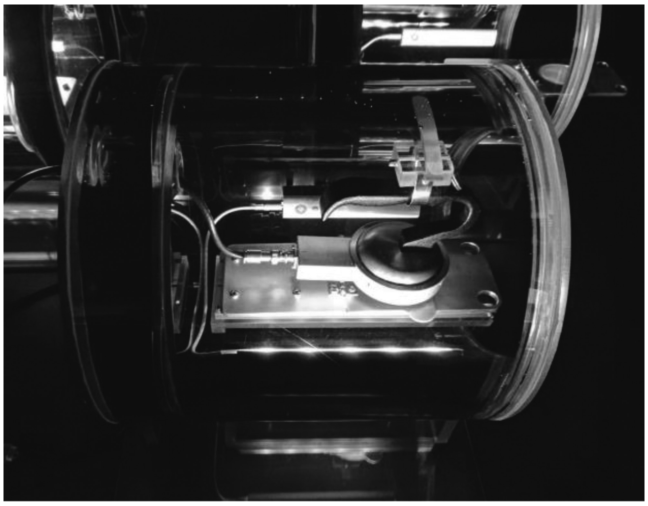

FIG. 2. ClearView Radiation Shielding frisker cave with smear tray.

FIG. 4. ClearView rolling shield used by a crib during MIBG therapy.

1,000 kg of lead. The ClearView Radiation Shielding frisker cave provides nuclear power plants the ability to perform frisking operations in a high background location, with visibility, background reduction, and ease of operation. The frisker cave is shown in Fig. 5, and survey data is discussed in later sections.

Chemistry benchtop sampling

Chemistry benchtop sampling of radioactive water at nuclear power plants uses either lead or no shielding because the line of sight is important. Benchtop shielding manufactured with ClearView Radiation Shielding liquid housed in polycarbonate panels is used in chemistry departments of nuclear plants. Chemistry technicians collect radioactive water samples from sample stations, which feed water from the reactor. The water sample is taken to the primary lab and connected to an apparatus that separates, or “strips,” the gas from liquid. The water samples are evaluated and tested for impurities, such as sulfates, fluorides, and chlorides, because excess of these contaminants can affect the structural integrity of different components in the plant. Primary water loop chemistry is studied because impurities in water chemistry can affect heat transfer properties of fuel rods. Chemistry personnel must be able to effectively view the sample preparation process. Sample preparation is a labor-intensive process that requires the technician performing the task to stand near a radioactive sample for 10 to 30 min. Some sampling is performed 3 to 4 times a week whereas some are outage related jobs that may require more frequent visits to the sample sink. Fig. 6 below shows how ClearView Radiation Shielding is installed and used in front of the sampling station in a PWR. Exposure data of the shield used for elevated water samples (where ^{60}Co was the primary source) during an outage is discussed in a later section.

Equipment maintenance

Angled ClearView Radiation Shielding shields are designed and used to inspect equipment. Nuclear power plant equipment is inspected during outages and are a significant source of radiation exposure for plant workers because the metallic alloys contain ^{60}Co. One such project is for baffle bolt inspection (Lubinski 2020; US NRC 2019). Baffles are vertical metallic plates that help direct water up through the nuclear fuel assemblies. Baffles assist in maintaining a high concentration of water flow in the core, and these plates are attached and secured with each other using edge bolts. The baffle edge bolts provide attachment along the seams between the plates and prevent any gaps from forming in the plates. Maintenance staff from nuclear plants who have conducted these inspections have shown that baffle bolts are damaged in regular operation because they are exposed to high thermal and mechanical stress and high radiation (Cobalt-60 2020). These bolts can show plastic deformation due to thermal expansion and potential for stress corrosion cracking. Although baffle bolts have not been required to maintain the structural integrity of the core nor considered safety equipment, their inspection is necessary (Lubinski 2020; US NRC 2019). A 58.42 cm wide $\times$ 35.56 cm high window is made from clear polycarbonate and filled with the ClearView Radiation Shielding liquid. The window is then mounted on an aluminum frame holding the window at an angle of 60°. The baffle bolts are placed behind the ClearView Radiation Shielding, which helps maintenance staff and plant workers cut threads in the bolts and lower internals. The shielding data of ClearView Radiation Shielding has

FIG. 5. Portable Foley bag shield.

been used in baffle bolt projects during two outages and are discussed in a later section.

Applications of ClearView Radiation Shielding in hospitals

The use of ClearView Radiation Shielding is designed into rolling shields and urine collection containment as an alternative shielding material to lead when treating high doses of radiopharmaceutical therapies.

Rolling shields

Rolling shields fabricated with ClearView Radiation Shielding in the hospital setting allows for the administration of high doses of radiopharmaceutical therapies without the use of dedicated lead-lined rooms. The design of the facility, designation of controlled areas, and radiation monitoring are important aspects that largely contribute to the radiation exposure of staff and members of the public. Radiation exposure can be managed using rolling lead shields that act as shielded walls, lead blankets to reduce the radiation emitted from the patient, and lead sheets placed under the patient's bed, which can be used to attenuate radiation levels from the patient. Traditionally, rolling lead shields have been used to reduce radiation levels but they did not provide any visual line of sight to the patient (Chu et al. 2016). Lead shields also have shown to be heavy and add structural loading constraints. Furthermore, some lead rolling shields weigh about 500 kilograms and have no handles for nurses or nuclear medicine technicians to move easily. The transparent, lightweight liquid in ClearView Radiation Shielding can attenuate radiation exposure and provide clear visual to the patient.

ClearView Radiation Shielding is fabricated and designed as rolling shields with different thickness for a lead-lined room and a non-lead-lined room. The rolling shield that has been used during dose reduction

FIG. 6. ClearView Shield for dose administration vial (20 mL).

to caregivers during 500 mCi ^{131}I meta-iodobenzylguanidine (^{131}I MIBG) (Chu et al. 2016; Barnes et al. 2018) therapies at a large cancer hospital in New York City fabricated a ClearView Radiation Shielding window measuring 121.92 cm (48″) high × 91.44 cm (36″) wide × 2.5″ thick (6.35 cm). The window begins approximately 25.4 cm (10″) from the ground and has 180° rolling wheels that are 20.32 cm (8″) high. The housing for liquid for the ClearView Radiation Shielding rolling shield is built within a 1.27 cm (0.5″) thick impact resistant polycarbonate (2.54 cm of the same material is considered bulletproof). The legs of the shield extend 34.29 cm (13.5″) on each side. The frame is constructed of lightweight and powder coated aluminum. The design is such that the leg of one shield could go under the other to make a large viewing window of 1.83 m (6′). Each of the rolling shield weighed 425 lbs. compared to the lightest rolling lead shield, approximately 700 lbs.

ClearView Radiation Shielding rolling shields have been similarly designed for non-lead lined rooms at a children's hospital in Ann Arbor, Michigan with a smaller window size. The window measures 30″ (76.20 cm) high and 24″ (60.96 cm) wide but with the same thickness of 2.5″ (6.35 cm) designed at a cancer hospital for MIBG therapies. The ClearView Radiation Shielding window is 24″ (60.96 cm) from the ground and designed to slide one shield under the other to provide a larger window. Prior to the use of the ClearView Radiation Shielding shields at the children's hospital in Michigan, ^{131}I-MIBG therapy for a neuroblastoma patient was canceled due to the high anxiety levels that resulted from the use of lead shields as a mock-up. The shields are shown in Fig. 7.

In another children's hospital in Boston, Massachusetts, rolling shields are designed for a pediatric crib. The ClearView Radiation Shielding windows measures 30″ (76.20 cm) high × 24″ (60 cm to 96 cm) wide, 24″ from the ground with a thickness of 1″ (2.54 cm), which is more than half the thickness compared to previous rolling shields. The design of the shields for the crib took into consideration the ability to manage a patient in the crib without hinderance or interference through the employment of swing doors as shown in Fig. 8.

Waste collection containment

ClearView Radiation Shielding shields are designed for urine collection containers of younger children who require Foley catheters. Much of the excess radiopharmaceutical is excreted through the urine, and urine held in the bladder can cause damage. Therefore, Foley catheters are placed before the start of radiopharmaceutical treatment to protect the patient's bladder. Although the bladder is protected with the Foley, there is possible internal and external radiation exposure to healthcare personnel. Traditionally, lead urine boxes were used to hold Foley catheter bags, but healthcare personnel could not see if the urine bags were full or when the bags needed to be changed. In some cases, pumps are used to remove the urine, but sometimes they also fail causing spillage. Lead containers being heavy and cumbersome had proven to be difficult for some nurses and nuclear medicine technician to transport from a storage area in a hospital to the therapy room. A 2.54-cm-thick ClearView Radiation Shielding cylindrical shielded container was fabricated for ^{177}Lu and ^{131}I therapies as shown in Fig. 6.

^{177}Lu decays via β- emission and low-energy gamma photons of Eγ 113 keV (6.6%) and 208 keV (11%), respectively. ^{133}I decays via gamma photos of Eγ 364 keV (81.7%) and 636.989 keV (7.17%), respectively. The housing of the container was constructed out of acrylic measuring 30.48 cm (12″) high with an inner diameter of 15.24 cm (6″), sufficient to fit standard (30 cm × 30 cm) Foley bags. The base of the urine container was composed of 0.635 cm (0.25″) steel, and the lid had a 2.54-cm thickness of ClearView Radiation Shielding liquid in a polycarbonate

FIG. 7. Contact testing of ClearView Radiation Shielding against radioisotopes.

housing. The lid was designed as a swing lid to open the container with holes for tubes for connecting the catheter to a Foley bag. For testing, both iodine and lutecium source vials were placed 13.5 cm above the base using foam pieces. Measurements were taken by placing the vial in the middle of the shield and on contact with the inner diameter of the shield. Measurements were performed using an Eberline R02 ionization chamber. Readings, discussed in a later section, were taken from the top and sides of the shield.

Shielding dose administration vials

^{177}Lu was approved by the FDA in 2018 to treat metastatic neuroendocrine cancers effecting the digestive tract [Treatment][12]. Conventionally, the ^{177}Lu is administered as a liquid in a 20-mL vial, which is stored in a lead pig. Inability to see through a lead pig led to cases of incomplete infusion of this radiopharmaceutical. ClearView Radiation Shielding liquid to radiopharmacies and nuclear medicine was investigated and developed in collaboration with nuclear medicine department in a hospital at Ann Arbor, MI. The shield measured 17.15 cm high, 12 cm outer diameter, and 2.54 cm thick. ClearView shielding liquid was housed in a 6-mm-thick acrylic housing and made fitting a 20-mL vial. The ClearView shield in use is discussed and readings are noted in a later section.

Application of ClearView Radiation Shielding in radiopharmaceuticals

Radiopharmaceuticals store, distribute, and dispose of a multitude of radionuclides. As an alternative to lead or tungsten, ClearView Radiation Shielding was analyzed with multiple isotopes. Initial testing of ClearView Radiation Shielding was performed with a known distance of 30.48 cm (12″) between the source, shield, and detector, respectively. The test shields used were 15.24 cm × 15.24 cm of multiple thicknesses, and the distance led to errors due to sky shine and scatter. For more accurate measurements, contact testing was performed. Multiple gamma photon energies (35 keV to 1899 keV) were investigated at a cancer hospital in New York City, with five different ClearView Radiation Shielding thicknesses to calculate the attenuation of the shield. The ClearView Radiation Shielding test shields used were 15.24 cm × 15.24 cm with thicknesses of 1.25 cm, 1.905 cm, 3.81 cm, 6.35 cm, and 7.62 cm. The radionuclides tested were ^{125}I, ^{133}Ba, ^{99m}Tc ^{131}I, ^{137}Cs, ^{89}Zr, ^{124}I to ascertain attenuation of the shield among a wide gamma energy range. A 451 B ion chamber (Fluke Biomedical, 2019) was the instrument used to take the radiation measurements with detection capabilities in the ionization region for alpha (> 7.5 MeV), beta (> 100 keV), and gamma (> 7 keV). The dose range

FIG. 8. ClearView Radiation Shielding shield being used for sampling radioactive chemistry samples.

operation of the meter was 0 mSv h^{-1} to 500 mSv h^{-1}, with a response time of 2 to 8 s. The radioisotope source was placed directly against the shield, and the radiation instrument was positioned directly against the opposite side of the shield to ensure that geometry with the measurements were consistent and to reduce any scatter, as shown in Fig. 7. The measurements allowed direct comparisons of attenuation capabilities depending on the thickness of the ClearView Radiation Shielding.

Results of operational dose savings in nuclear power plants

ClearView Radiation Shielding reduces personnel exposure while providing transparency to workflow during outages and in the special projects discussed below.

Dry cask operation measurements

ClearView Radiation Shielding observational windows [60.98 cm high × 30.48 cm (2′×1′) and 1.27 cm (0.5″) thickness ClearView Radiation Shielding] used during dry cask operations at two nuclear power plants showed a 22% reduction from ^{60}Co and more than 50% from lower energy gammas (Clearview Patent 2019). One nuclear power plant reported a dose savings of 50 μSv during the dry cask operation project whereas the other reported 40 μSv reduction attributed to the use of ClearView Radiation Shielding windows. A third power plant did not report a quantified dose savings but shared survey information with the observation windows. The unshielded dose rate was 1 μSv h^{-1} (gamma) and 2 μSv h^{-1} (neutron). With ClearView Radiation Shielding windows, the dose rates were < 0.2 μSv h^{-1} (gamma) and < 1 μSv h^{-1} (neutron).

Frisking operation measurements

Measurements were taken inside and outside of the frisker caves (30.48 cm long with an inner diameter of 21.59 cm and 3.81 cm thick) on refueling floors. The background was 2,000 cpm and < 250 cpm inside the frisker cave, a higher dose reduction than expected. The thickness used in the frisker was fabricated to the HVL for ^{60}Co; however, the background count rate was reduced by 90%. One reason for the higher dose reduction could be that the spectrum of photons is not a purely ^{60}Co spectrum but a mixed energy spectrum. Based on data testing, the spectrum would have an average energy of 400 keV to 500 keV. Although ^{60}Co photons would be present, the percent contribution could be lower than expected. Another reason for the higher dose reduction could be inaccurate background data measurement. Additionally, the background could have been closer to the reactor head whereas the frisker cave was placed further away from the reactor head. An important consideration is that the measurements performed were from background and scatter.

Shielding in chemistry sample sinks

Radiation reduction measurements of custom fabricated ClearView Radiation Shielding benchtop shields was accessed. A PWR used ClearView Radiation Shielding chemistry shields, 50.8 cm high × 27.94 cm wide beginning in 2017. Unshielded dose rates on contact for gas stripping were between 0.1 mSv h^{-1} and 0.15 mSv h^{-1}. Another boiling water reactor reported that weekly dose of an individual in the chemistry department was 0.28 mSv to 0.35 mSv at one visit per day unless additional sampling was needed to support the plant. If the job is performed by a single person, at one visit a day, the annual dose received would be 13 mSv to 16 mSv.

LaSalle Nuclear Plant used a 35.56-cm-wide × 58.42-cm-high × 3.81-cm(1 HVL)-thick ClearView Radiation Shielding shield in an aluminum frame at a 60° angle. Feedback from the ALARA analyst is confirmed the 50% shielding from ^{60}Co (Bakshi 2018; Radium, Inc. 2017) and is shown in Fig. 8.

Equipment maintenance measurements

The dose rates with the ClearView Radiation Shielding shielded window ranged from 8 mSv h^{-1} to 15 mSv h^{-1} on contact and 3-7 mSv h^{-1} at 30 cm. Without the shield, the dose rates ranged from 30 μSv h^{-1} to 70 μSv h^{-1} on contact. With the angled ClearView Radiation Shielding flat shield, the dose rate readings ranged from 4 μSv h^{-1} to 12 μSv h^{-1}. The tools for the baffle bolt inspection projects were approximately 6 inches from the shield. The highest dose received on a single entry was 25 μSv in 2018 after ClearView Radiation Shielding windows were used compared to 49 μSv in a 2016 when they were not used. The overall dose was calculated per machined location, averaged out by 6 to 8 machine hours. In 2016, when the ClearView Radiation Shielding shields were not used for 210 machined locations, the dose was 63.4 μSv $bolt^{-1}$. In 2017 and 2018, when the ClearView Radiation Shielding was installed and used, the dose dropped to 32.2 μSv $bolt^{-1}$ for 206 machined locations and 30.41 μSv $bolt^{-1}$ for 213 machined locations, respectively.

Results of radiopharmaceutical measurements

Multiple isotope testing results. Table 2 summarizes the attenuation of gamma sources ^{125}I, ^{133}Ba, ^{99m}Tc, ^{131}I, ^{18}F, ^{137}Cs, ^{89}Zr, ^{124}I with increasing thickness of ClearView Radiation Shielding test shields.

The ClearView Radiation Shielding shields between 1.905 cm and 3.81 cm provided 10th value layer dose reduction for low energy isotopes such as ^{125}I, ^{133}Ba, and ^{99m}Tc. The shielding factor was reduced from ^{131}I (361 keV) to ^{137}Cs (661 keV). There was an increase in shielding factor with ^{89}Zr (909 keV) to ^{124}I (1899 keV). Further investigation is needed, but one potential reason for the increase is the absorption-edge effect. Photon

Table 2. Attenuation of radioisotopes with increasing thickness of ClearView Radiation shielding.

Isotope	Energy (keV)	1.25 cm % Attenuation	1.905 cm % Attenuation	3.81 cm % Attenuation	6.35 cm % Attenuation	7.62 cm % Attenuation
^{125}I	35	99.83	99.83	99.95	99.95	99.83
^{133}Ba	80, 356	71.88	87.27	93.1	96.1	98.14
^{99m}Tc	140	99.79	97.69	99.63	99.75	99.79
^{131}I	361	65.9	79.3	88.8	95.9	97.6
^{18}F	511	49.20	70.56	85.59	90.74	94.50
^{137}Cs	661	35.15	53.38	71.8	83.83	90.9
^{89}Zr	909	46.34	58.54	73.17	87.8	90.24
^{124}I	1691	52.69	67.45	78.52	90.55	91.31

attenuation is a function of cross sections. The photoelectric cross-section depends on the energy of the incident photon and atomic number Z of the atom. If energy of the incoming photon is higher than the binding energy of the K-shell electrons, the resultant absorption will be photoelectric absorption of the photons. The photoelectric cross-section rises to large values, which are interpreted as discontinuities. The incident photon does not have sufficient energy to eject an electron from a lower shell, so it will eject an electron from the next most tightly bound electrons, leading to a sudden increase attenuation coefficient of the incoming photons. A photon with an energy just above the binding energy of the electron is hence more likely to be absorbed than a photon with an energy just below this binding energy. Similar sudden increases in attenuation may also be seen in other shells than the K shell.

Results of operational dose savings in hospitals

Rolling shield measurements. During a Neuroblastoma treatment (200 mCi ^{131}I infusion), the dose rate without the shield was 2 mSv h^{-1} and reduced to 0.015 mSv h^{-1} with the ClearView Radiation Shielding rolling shields. During a 980 mCi infusion for a ^{131}I MIBG therapy, the dose rate after 18 h without the shield was 0.6 mSv h^{-1} and with the 2.54 cm (1″) shield was reduced to 0.06 mSv h^{-1}. All measurements were taken 6 feet from the patient.

Waste collection containment measurements. The 2.54 cm thick ClearView Radiation Shielding cylindrical urine container that was fabricated for ^{177}Lu and ^{131}I therapies, and dose rate measurements, were taken for both radionuclides and are summarized in Table 3.

The application of the ClearView Radiation Shielding containers reduced the radiation exposure and provided visibility of urine output volume to healthcare personnel without opening the container.

Dose administration shield measurements. Survey was performed at a hospital in Ann Arbor, MI, with a 2.54-cm-thick ClearView shield during a 7.4 × 10^{12} Bq (200 mCi) ^{177}Lu infusion (Clinical Trials Arena, 2020) Without any shielding, on contact with the ^{177}Lu vial, the dose rate noted was 8.5 μSv h^{-1}. The ion chamber measured 0.31 μSv h^{-1} directly on the other side when the vial was inside and up against the shielding. ClearView shield was used to shield the gammas and the acrylic container was the beta shield.

Another hospital in Stanford, CA, used the shield with same doses and noted the dose rate measured 0.05 μSv h^{-1} outside the shield when a 7.4 × 10^{12} Bq (200 mCi) ^{177}Lu vial was placed inside a 2.54-cm ClearView shield. In both cases, greater than 99.95% shielding was seen without any exposure when the ion chamber was kept at 30 cm.

DISCUSSION AND FUTURE WORK

Lead-free ClearView Radiation Shielding shields have been designed and implemented in the nuclear power and medical industries. Applications have developed in areas where visibility is highly critical to perform critical jobs with radiation protection. The three general guidelines for controlling exposure to radiation are minimizing exposure time, maximizing distance from the radiation source, and shielding yourself from the radiation source. Transparent ClearView Radiation Shielding shields have provided the ability to optimize exposure time and distance from radioactive sources, which in turn have resulted in lowering cumulative dose exposure for technicians and staff working in radioactive environments.

For equivalent shielding, ClearView Radiation Shielding shields may be two to three times thicker than lead but lighter in weight, which has made handling, working with, and storage of the shields much easier than lead. For example, in frisker operations, the transparent ClearView Radiation Shielding

Table 3. Attenuation of ^{131}I and ^{177}Lu with 2.54 cm ClearView Radiation Shielding cylindrical container.

Location of source	Location of detector	^{131}I, 2.53 GBq	Dose reduction	^{177}Lu GBq	Dose reduction
On contact		20 mSv h^{-1}		4 mSv h^{-1}	
13.5 cm from the base and 7.62 cm from the edge	Shield Top	1.2 mSv h^{-1}	94%	0.07 mSv h^{-1}	98.2%
	Shield Edge	2.8 mSv h^{-1}	86%	0.11 mSv h^{-1}	97.25%
13.5 cm from base and in contact with shield inner surface	Shield Top	1.2 mSv h^{-1}	94%	0.06 mSv h^{-1}	98.5%
	Shield Edge	3.90 mSv h^{-1}	80.5%	0.19 mSv h^{-1}	97.29%

shield design with a fixed probe allows for accurate and repeatable geometrical measurements in a lower background environment inside the cave. Nuclear plant staff now roll 72 pounds of a frisker cave in a pelican case as compared to 1,000 kg of lead bricks. Hospital staff now roll in ClearView Radiation Shielding shields, which are 40% lighter in weight than lead for some inpatient radiotherapies. Transparent ClearView Radiation Shielding Foley bag shields allow visual monitoring of the catheter connection and allow hospital staff to see if a pump will fail.

ClearView Radiation Shielding shields have been used during outages for several high dose jobs in nuclear plants such as shielding the foreign material exclusion monitor in a nuclear plant, viewing the reactor vessel head removal, and installation and frisking operations in the fuel handling building.

Nuclear medicine technicians have expressed need for shielding 20-mL and 30-mL syringe shields to administer ^{18}F. The options to shield hand doses is limited and ClearView Radiation Shielding could be used. Cyclotrons are particle accelerators that produce radioactive isotopes and often require timely maintenance. However, the targets in cyclotrons are hot sources of radiation and result in high background radiation. These targets must be shielded for multiple maintenance activities, and visual access is highly desirable. Hot cell windows in some locations are made of zinc bromide, which is extremely hard to handle and eats away the housing. In nuclear plants, the refuel bridge is a location of high background radiation, and refuelers need more protection than a plastic jumpsuit provides. In some spent fuel handling facilities in Idaho and the Pacific Northwest, multiple jobs expose personnel to ^{137}Cs and ^{60}Co during waste handling. Researchers in all these fields are investigating how the application of ClearView Radiation Shielding can be fabricated and used to provide workflow solutions as well as radiation dose reduction.

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