Development, dose reduction, and applications of an innovative, non-toxic transparent gamma radiation shield designed to reduce body dose exposure.

Radiation Attenuation and Stability of ClearView Radiation Shielding ™—A Transparent Liquid High Radiation Shield

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Abstract: *Radiation exposure is a limiting factor to work in sensitive environments seen in nuclear power and test reactors, medical isotope production facilities, spent fuel handling, etc. The established choice for high radiation shielding is lead (Pb), which is toxic, heavy, and abidance by RoHS. Concrete, leaded (Pb) bricks are used as construction materials in nuclear facilities, vaults, and hot cells for radioisotope production. Existing transparent shielding such as leaded glass provides minimal shielding attenuation in radiotherapy procedures, which in some cases is not sufficient. To make working in radioactive environments more practicable while resolving the lead (Pb) issue, a transparent, lightweight, liquid, and lead-free high radiation shield—ClearView Radiation Shielding—(Radium Incorporated, 463 Dinwiddie Ave, Waynesboro, VA). was developed. This paper presents the motivation for developing ClearView, characterization of certain aspects of its use and performance, and its specific attenuation testing. Gamma attenuation testing was done using a 1.11 × 10^{14} Bq ^{60}Co source and ANSI/HPS-N 13.11 standard. Transparency with increasing thickness, time stability of liquid state, measurements of physical properties, and performance in freezing temperatures are reported. This paper also presents a comparison of ClearView with existing radiation shields. Excerpts from LaSalle nuclear power plant are included, giving additional validation. Results demonstrated and strengthened the expected performance of ClearView as a radiation shield. Due to the proprietary nature of the work, some information is withheld. Health Phys. 114(4):467–475; 2018*

Key words: *operational topics; accelerators, decommissioned; accidents, handling; Fukushima*

INTRODUCTION

Background

- ANSI—American National Standards Institute;
- HPS—Health Physics Society;
- AAPM—American Association of Physicists in Medicine;
- UWRCL—University of Wisconsin Radiation Calibration Laboratory;
- ^{60}Co—Cobalt-60;
- CVRS—ClearView Radiation Shielding;
- ICP–OES—Inductively Coupled Plasma–Optical Emission Spectroscopy;
- Pb—Lead;
- Fe—Iron;
- Sb—Antimony;
- kGy—Kilogray;
- PCT—Polycarbonate;
- PMMA—Polymethyl Methacrylate;
- R^2—coefficient of determination;
- RoHS—Restriction of Hazardous Substances;
- cm—centimeter;
- Sv—Sievert;
- HVL—Half Value Layer; which is thickness of a material reducing the intensity of radiation by absorption and scattering by half (definition from the European Nuclear Society 2017); and
- TVL—Tenth Value Layer, which is average amount of material needed to absorb 90% of all radiation, i.e., to reduce it to one-tenth of the original intensity.

Motivation

The inability for prolonged working in a radioactive environment has limited radiologists, technicians, doctors, nuclear power plant personnel, engineering support and maintenance, in some cases biologists and chemists to perform tasks efficiently. Existing

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The author declares no conflicts of interest.

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shielding materials like Pb, Pb-Sb, Fe, etc., come with their drawbacks of being heavy and with the potential of creating internal sources of radiation or becoming activated. Moreover, they are opaque solids limiting visibility, workability and feasibility. To overcome this, instrumentation such as cameras are needed with no direct visibility. Increasing costs and radiation damage to electronics is another factor that becomes a consideration. When opaque materials are being used as shields, it is often found that workers need to work around them without any viewing capability. Occasionally workers receive doses on the face and body to overcome this limitation.

Current transparent shielding like lead glass may be suitable for their transparency but some of them provide low attenuation. Additionally, some lead glasses and acrylics deteriorate in transparency over time and are heavy. Identifying sources of leaded glasses and acrylics has shown that with limited suppliers, users compromise either in quality or purchase expensive material with long lead times, sometimes from overseas. Some facilities use zinc bromide as shielding which is difficult to handle is not compatible with many structural materials. Table 1 shows attenuation capabilities of a few transparent shields with their Pb equivalencies.

Shielding of hot cells and radioisotope manufacturing uses heavy lead lined cabinets. Leaded glass for higher performance has a density ranging between 4.0 g cm^{-3} and 5.9 g cm^{-3} making them heavy. Rolling panels and mobile carts using lead shielding are a hazard because of their weight and restrict viewing capability. Other conventional shields either are not as effective as Pb or have the same limitations. Radiation protection today is applied in a way that represents a trade-off between dose received and workability. It is highly unlikely to see both co-exist at the same time. Motivated by industry concerns on current radiation shields being heavy and toxic with limited options in available shapes, the aim was to innovate and develop a radiation shield for worker protection that increases access and stay time without inhibiting performance or efficiency.

Table 1. Conventional transparent shields with leaded equivalences. (Direct Scientific 2017; Amerope 2017; Raybar 2017; Biodex 2017; Radiation Products 2017).

Conventional transparent shield (thickness, mm)	Pb. equivalent, (mm)
Direct Scientific Lead Acrylic (8 mm)	0.3
Direct Scientific Lead Acrylic (12 mm)	0.5
Biodex Lead Glass (8 mm)	0.3
Biodex Lead Glass (12 mm)	0.5
Biodex Lead Glass (22 mm)	1.0
Biodex Lead Glass (35 mm)	1.5
Leaded Glass - Ray Bar (7.0 mm – 8.5 mm)	1.8 – 2.4
Radiation Products Leaded Acrylic (8 mm)	0.3
Radiation Products Leaded Acrylic (12 mm)	0.5
Radiation Products Leaded Acrylic (22 mm)	1.0
Radiation Products Leaded Acrylic (35 mm)	1.5
Marshield LX -57 b (9 mm)	2.0
Marshield LX -57 b (14 mm)	3.0
Marshield LX -57 b (17 mm)	3.3
Marshield Lead Free Glass (12 mm)	0.5

There are several occasions in the chemistry departments of nuclear power plants where personnel have to handle QC samples and work with minimal or no protection. Decommissioning of nuclear power plants and material handling areas such as core refueling floor and spent nuclear fuel storage in concrete bunkers also entails a large potential exposure to radiation where today lead or concrete is used. Weight, thickness, maneuverability, and visibility are all important considerations in the use of shielding to ensure dose reduction to workers. During outages, personnel have to work in challenging conditions of radiation and shield themselves using heavy lead. Equipment like the steam generator shield door uses lead in the manway making the equipment extremely difficult to work with. The motivation of perfecting and testing CVRS with a national standard was to ensure measurement results were acceptable so as to ensure proper characterization of CVRS's performance and provide confidence in its use in occupational radiation environments.

Methodology

A manufacturing process was to create a stable solution of CVRS. The process flow from the initial batches was replicated and adjustments were made within the process flow to ensure that chemical structures and relative quantities of the attenuation species in CVRS remain at constant values over time. This exercise was additionally done to ensure that CVRS maintained its structural integrity, ensuring longevity and continued performance. The final mass fractions were validated performing ICP–OES testing and reviewing the mass specifications of raw materials. Bond formation as expected and predicted by theory was validated by performing Raman Spectroscopy. The aim of testing reported in this paper was to validate the preliminary testing (done by a radiographer) with a recognized national standard in order to establish testing conditions which are consistent with acceptable practices, which is further explained below. The final product was a high-density liquid—ClearView Radiation Shielding, which was encased in a PCT housing. Some initial shields are shown in Fig. 1a and b.

The effect of changing temperature on the attenuation capability of CVRS was also studied. This paper studies the attenuation of CVRS when used in frozen and

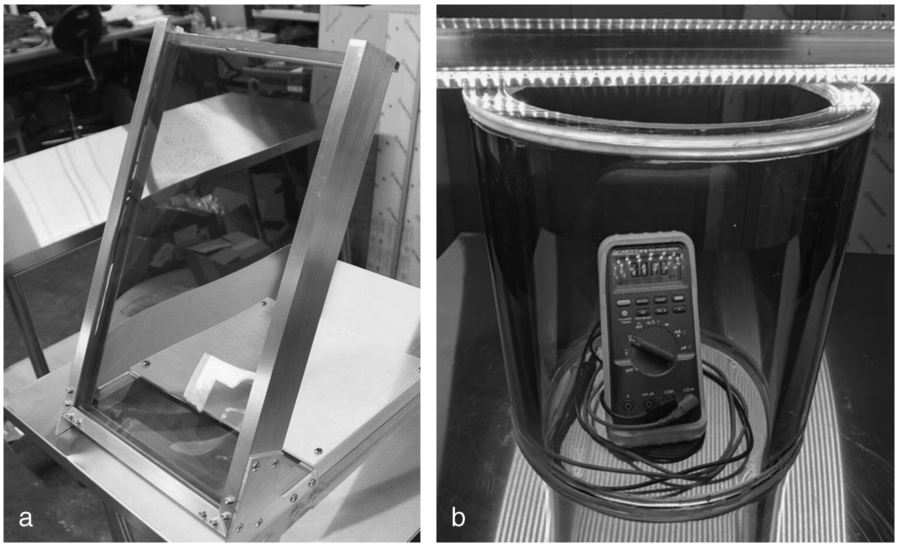

FIG. 1. ClearView Radiation Shielding (a) Table top with work bench and (b) Cylinder.

partially frozen conditions to establish a range of working conditions. The shield was placed in a deep freezer overnight and tested for attenuation the next day. Effects of larger gamma radiation dose on PCT have been reviewed and discussed. The aim of developing CVRS was to reduce dose exposure to personnel working. Hence, personnel dosimetry testing was adopted for evaluating the shielding capability of CVRS.

Personnel dosimetry testing is used to determine dose equivalent for occupational conditions and absorbed dose for accident conditions. In general, these tests are conducted under controlled conditions and include irradiation with photons, electrons (beta particles), neutrons, and selected mixtures of these radiations. The range of delivered absorbed doses or personal dose equivalents and tolerance levels are based on considerations of radiation protection expressed in current publications of the National Council on Radiation Protection and Measurements (NCRP), the International Commission on Radiation Units and Measurements (ICRU), and the International Commission on Radiological Protection (ICRP) (ANSI/HPS 2009).

DESIGN OF EXPERIMENT

Testing for CVRS

The attenuation testing was done at The University of Wisconsin's Radiation Calibration Laboratory, which is an Accredited Dosimetry Calibration Laboratory by the AAPM. UWRCL is accredited through the American Association for Laboratory Accreditation for meeting the performance criteria of the internationally accepted ISO/IEC 17025. The test setup was according to the (ANSI/HPS 2009) standard using a 3000 Curie ^{60}Co irradiator and PMMA (ICRU 1992) phantom effectively mimicking the scattering of human body tissue. The same standard is also used to calibrate dosimeters and survey meters. The un-attenuated dose was chosen for the testing. Attenuating the incident beam would have added uncertainties, and the ^{60}Co photon energies would not be consistent but a spectrum. Measurements were done for shallow dose equivalent (D_p 0.07 mm) and deep dose equivalent (D_p10 mm). The source strength was calibrated 2 d before the experiment and measurements were taken to ensure the perpendicular incidence of the beam. Conversion factors of air kerma to shallow and deep dose equivalent were referenced from the NIST Beam Code ^{60}Co as shown in figure 2 (ANSI/HPS 2009). First the dose was measured without any obstruction and then with test containers; these were 15.24 cm in diameter and increasing thicknesses of 1.27, 1.905, 2.54, 3.175, 3.81, 4.445, and 5.715 cm. The beam field was the size of the TLD holder, a 10 cm by 10 cm field, which is shown in Fig. 2. The ^{60}Co beam was incident

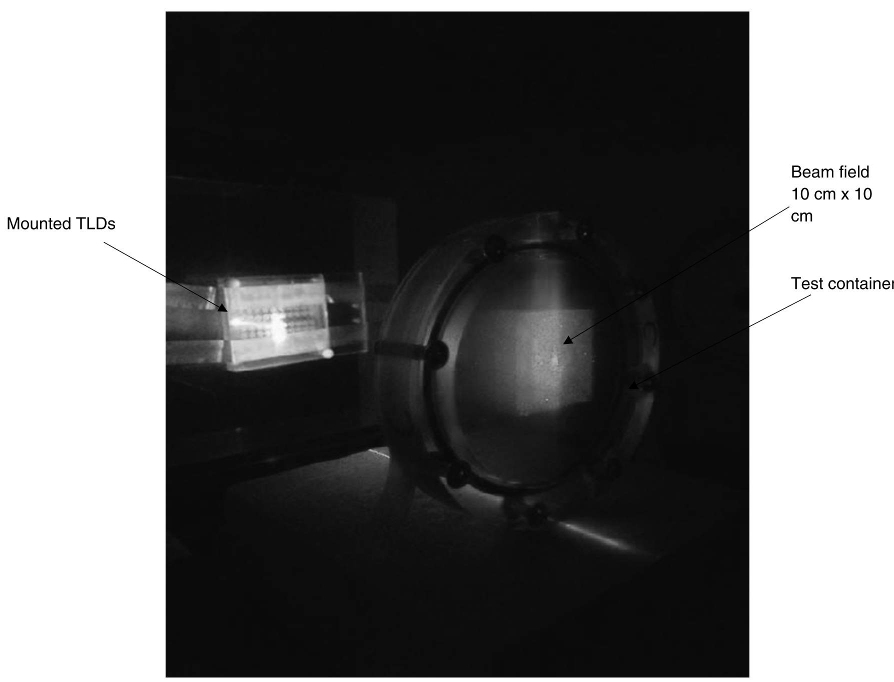

FIG. 2. Attenuation testing setup of CVRS.

Table 2. Comparison of lead equivalence between CVRS and other transparent shields with same thickness.

Thickness (cm)	^{60}Co attenuation	Lead equivalence (cm)
1.27	22 %	0.4
1.91	29 %	0.6
2.54	37 %	0.7
3.17	44 %	1.3
3.81	51 %	1.8
5.71	64 %	2.3

on the shield and the transmitted dose was measured by the TLDs. Results from this experiment are shown in Table 2 in the following section.

Attenuation of ^{60}Co gammas with frozen CVRS

This experiment was done a few months later. Cold ambient temperature motivated us to evaluate the attenuation of CVRS under winter conditions. The test containers were kept in a freezer overnight and tested at the UWRCL. Testing was performed using the ^{60}Co irradiator, the ANSI N.13.11 testing standard and TLDs (ANSI/HPS 2009). The solution did partially melt back to liquid state while transporting to UWRCL. The test containers were 20.32 cm diameter and with increasing thicknesses of 1.27, 1.905, and 2.54 cm; the TLDs were mounted on a holder attached with tape on the PMMA phantom. The distances between ^{60}Co irradiator samples and between the test samples and PMMA phantom (with TLDs) were both 30 cm. To maintain consistency, the incident dose was measured similarly as in the section titled "Testing for CVRS" at a distance of 60 cm by TLDs mounted on the PMMA phantom without the test containers. Horizontal and vertical lasers were used to assure perpendicular incidence of the ^{60}Co beam. With increasing thickness the attenuation was measured and the setup is shown in Figs. 3 and 4, with results below. Each brown dot represents a TLD, and the red color is not the color of the shield but a laser that was used to center the shield and TLDs mounted on the PMMA phantom.

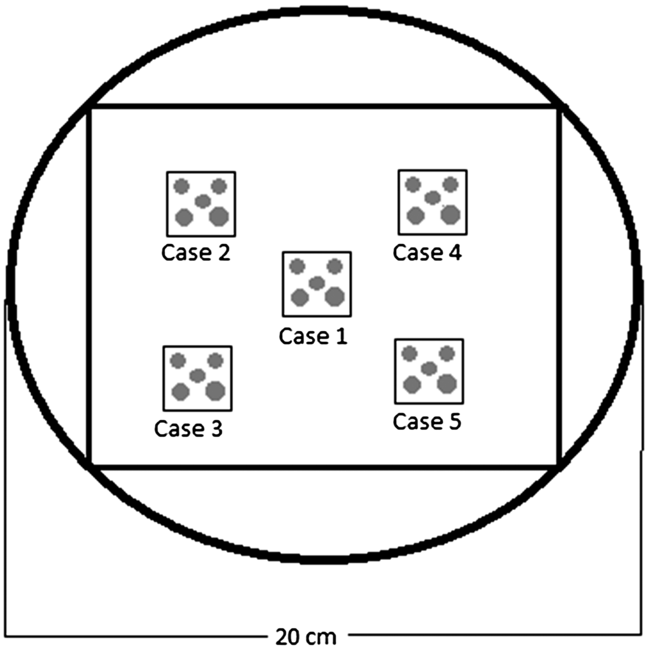

FIG. 3. Setup of TLDs for freezing experiment.

Time stability

The states of CVRS batches manufactured in between last week of June 2016 and the last week of August 2016 were investigated. Their states are also reported as of 31 October, 2017.

DATA ANALYSIS AND RESULT OF EXPERIMENTS

Attenuation of ^{60}Co gamma radiation with CVRS

Transmitted fraction of ^{60}Co gamma radiation with increasing CVRS thickness was plotted in Fig. 5, and the attenuation results are shown in Table 2. The delivered dose of 1 Sv in 100 s is reasonable for this testing since a radiation shield would likely see such a cumulative dose in its usage. The results show that the curve follows an expected exponential and, with an R^2 of 0.9987, the fit looks reasonable. We can see that approximately half of the dose was attenuated around a thickness of 3.81 cm (Fig. 5).

We can see that half of the dose was attenuated by a thickness of 3.81 cm. Results from TLDs used in measuring attenuation with 3.81 cm CVRS are shown in Table 3.

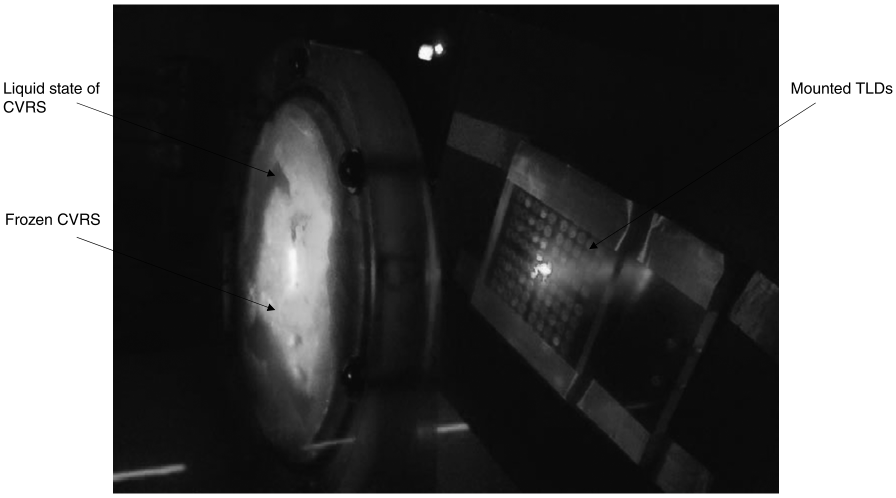

FIG. 4. Attenuation testing of frozen CVRS.

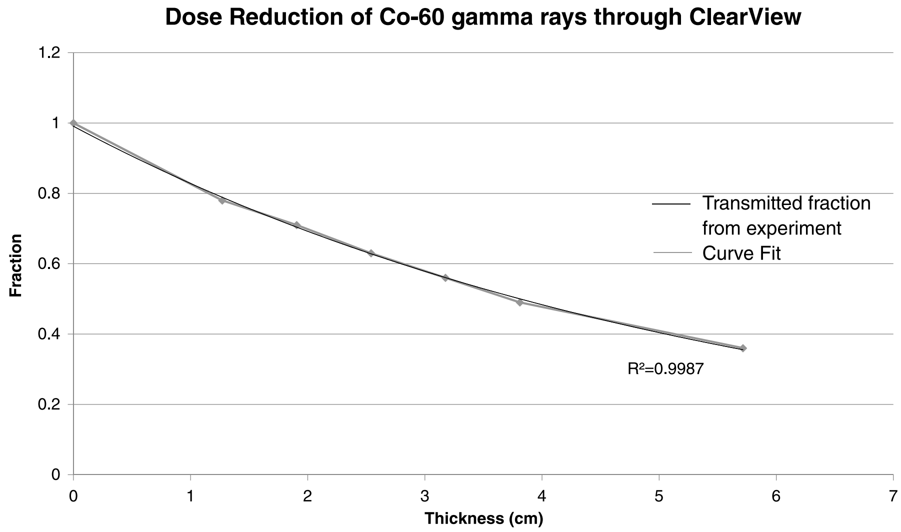

FIG. 5. Dose reduction testing of CVRS.

Freezing performance stability of CVRS

It was important to establish a consistency in CVRS's performance in different temperature conditions. CVRS shields of 1.905 cm and 2.54 cm thickness were tested. The setup of the experiment was the same as above. The results are tabulated in Tables 4 and 5.

Comparisons of CVRS's attenuation with existing radiation shields

More than 50 batches of 100 mL each were used for measuring the density of CVRS. The batches were stored in 100-mL beakers and weighed. The density of CVRS was calculated to be 2.3 g cm^{-3} (Figs. 6 and 7).

Without accounting for the buildup factor, 1.25 cm of Pb would attenuate 50% of ^{60}Co gammas. However, 3.81 cm of CVRS attenuates over 50% ^{60}Co gammas, and this includes the buildup. Comparing CVRS and Pb, for a comparable attenuation, CVRS would be 37.56% lighter for attenuation of 1 HVL of ^{60}Co. Accounting for buildup in Pb, this weight difference would be close to 50%. An intermediate value of 42% is displayed in Fig. 7. Dose and attenuation are functions of gamma energies; hence, these HVL numbers are true only for a ^{60}Co source. An isotope with lower gamma energy would have a lesser HVL. CVRS has a density of 2.3 g cm^{-3}, which is very close to the density of concrete, 2.4 g cm^{-3}. But the HVL of concrete is 6.05 cm (NDT Resource Center 2017) and that of CVRS is 3.81 cm. The density of CVRS is 2.3 g cm^{-3} and leaded glass ranges from 4–5.9 g cm^{-3} depending on the lead equivalences. Reviewing this and Table 1, we can say that CVRS provides a higher radiation attenuation per unit density thickness; CVRS is lighter and more effective per unit radiation attenuation compared to the other known transparent shields. Comparisons from Table 1 have been made with CVRS in Table 6.

Thermal expansion and boiling of CVRS

The volumetric expansion coefficient of CVRS was calculated. Seven mL of CVRS was heated in graduated cylinder made of borosilicate glass. The volume was seen to increase by 0.02 mL with when the temperature was raised from 70° C to 80 °C. The change in volume, temperature and expansion coefficient of borosilicate glass (LD Didactic 2017) were used to calculate the volumetric expansion coefficient (Expansion 2017) and seem to be 0.000289 1/°C. The volumetric expansion coefficient of water and oil at 90 °C are reported as 0.000695 1/°C and 0.00070 1/°C, respectively (Expansion 2017). Heat was further applied to initiate boiling of CVRS; this was seen to occur at 107 °C.

Housing clearview

ClearView's housing will be application based. Some applications will have PCT housing constructed with varying wall thicknesses of 0.3175 cm to 2.54 cm, based on the volume and thicknesses of CVRS required. For large shields, thicker-walled PCT will be used with addition of structural bolsters or bracket supports in a way that transparency will not be affected. Because the HVL of CVRS is better than concrete, it may be used as a construction alternate where transparency is not vital. In such cases, a wall filled with CVRS can

Table 3. Attenuation with 3.81 cm CVRS.

Incident dose (Sv)	Transmitted dose (Sv)	% ^{60}Co gamma attenuation
1.01	0.49	51.4
1.02	0.49	52.0
1.06	0.50	50.1
0.98	0.47	51.7

Table 4. Attenuation with 1.905 cm CVRS" and move up where it is called out.

Position of measuring TLD	Attenuation freeze	Attenuation liq (ref. table 2)	State of CVRS
Center — Case 1	0.28	0.29	Liquid
Top left — Case 2	0.3	0.29	Liquid
Bottom left — Case 3	0.3	0.29	Solid(frozen)
Top right — Case 4	0.28	0.29	Liquid
Bottom right — Case 5	0.27	0.29	Solid(frozen)

Table 5. Attenuation with 2.54 cm CVRS.

Position of measuring TLD	Attenuation freeze	Attenuation liq (ref. table 2)	State of shield
Center — Case 1	0.35	0.37	Liquid
Top left — Case2	0.35	0.37	Liquid
Bottom left — Case 3	0.33	0.37	Solid(frozen)
Top right — Case 4	0.34	0.37	Solid(frozen)
Bottom right — Case 5	0.33	0.37	Solid(frozen)

be made with suitable housing. In applications where PCT is used, increasing dose may start producing a yellowish tint. Literature review shows that PCT discoloration may begin after a total dose of 25–50 kGy (De Melo et al. 2006; Weber and Miguez 2006). Assuming a quality factor of 1, this would yield a cumulative dose of 2.5×10^7 mSv − 5×10^7 mSv. High locked radiation areas such as the steam generator have dose rates ranging from 5 mSv h^{-2} from the entry to 25 mSv h^{-1} as you rise up towards the tube sheet region. This gives PCT a minimum working time in the range of 10^6 h. Mechanical properties of PCT before and after irradiation up to 50 kGy have are the same and radiation resistance of irradiated PCT is similar to an un-irradiated sample (De Melo et al. 2006). In a high dose environment where cumulative reaches hundreds of Gy, CVRS shielding can be in toughened glass housings and the PCT yellowing can be circumvented.

For applications with PCT housing, different adhesives were studied and methacrylate-based structural adhesive was suitable with recommended operating temperatures between −55° C and 121.11° C with tensile shear strength of 4,000 psi. Additionally, PCT starts softening at temperatures greater than 130° C. For higher temperature and heavy loading considerations (larger shields), appropriate modeling is considered using ANSYS and COMSOL to ensure integrity and design to ensure a solid framework. The shield structure engineering will account for expansion of CVRS liquid under higher temperatures.

OPERATIONAL USE OF CLEARVIEW

Nuclear power plant

ClearView's transparency can be used in accordance with ALARA during outages and daily work, preventing whole body dose and limiting radiation to extremities while saving sensitive body parts such as heart, lungs, etc. Some examples are:

- Dry cask storage campaigns as observation windows;
- Rolling shields and low level refueling floor shielding while operating a manipulator crane where Pb shielding causing a loss of view;
- Steam generator shield door gamma shield (replacing Pb) which prevents whole body dose protection while cleaning the steam generator during an outage;
- Construction of frisking stations and booths to enable seeing the probes and operating without damaging any equipment;
- Sampling of reactor water, purge gases and other radioactive sample preparations; and
- Baffle bold refurbishment, installing thermocouples and dosimeters.

LaSalle nuclear generating station located in Ottawa, IL, operated by Exelon Corporation, used a 35.56 cm × 58.42 cm × 3.81 cm (1 HVL) thick CVRS shield set in an aluminum frame at a 60° angle (Fig. 7) in their Unit 2 L2R16 refueling spring 2017 outage. This was done to prepare Chem-Decon and elevated reactor water samples where ^{60}Co was the primary dose source in the samples collected [see Fig. 8].

The feedback from a Sr. ALARA Analyst is as follows:

"The ClearView RS shield (1.5" thickness) produced a true 50% reduction on dose rate and allowed chemistry personnel to clearly view their sample preparation and other work. Dose rates were tested from multiple distances and dose rates were taken unshielded and shielded with the same geometry. A total exposure reduction of 30% was seen for the entire Chem Decon sample preparation process for the Chemistry Technicians over the course of the outage compared to previous sample preparation

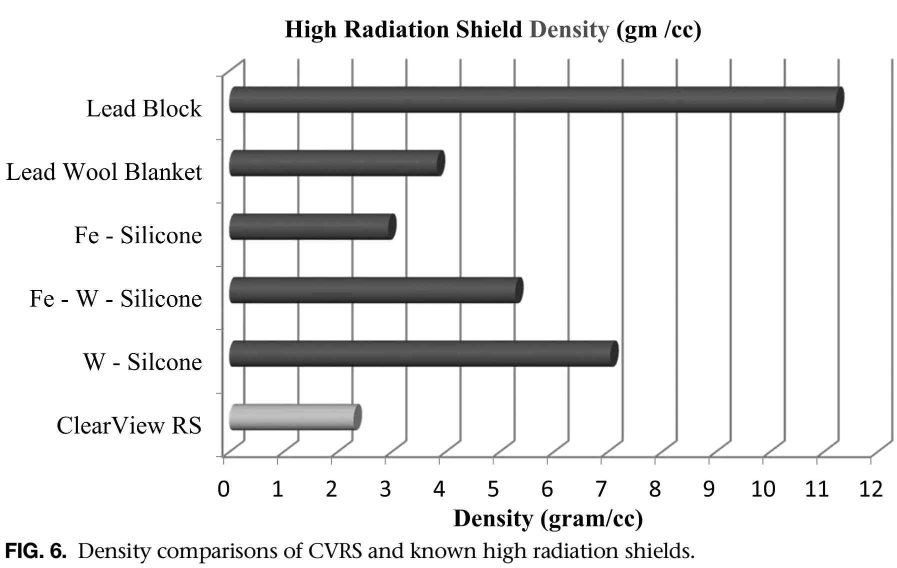

FIG. 6. Density comparisons of CVRS and known high radiation shields.

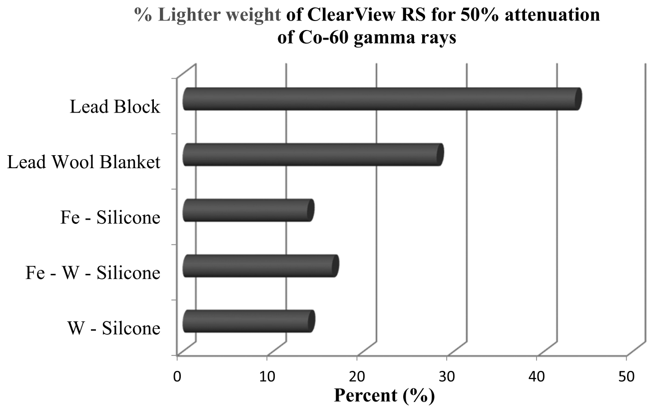

FIG. 7. Weight percent by which CVRS is lighter compared to existing high radiation shields for 1 HVL.

evolutions without the ClearView RS shield. The ClearView RS shield was also used in a fume hood and as a table top sample preparation station and the shield was easily moved around the lab where it was needed." [Cruise 2017] *The dose rates were ranging between 0.25 mSv/hr to 3 mSv/hr mainly. An estimate of 3 mSv/hr dose was averted over the course of the outage, and the shield is in use till date. The findings were presented in the Boiling Water Reactor Owners Group ALARA meeting and Exelon's internal innovation expo.*

Idaho, Argonne, and Lawrence Berkeley National Laboratories have expressed interest in using ClearView as windows in their hot cells where presently zinc bromide and mineral-oil-like substances are used, which have proven to be a challenge in handling and disposal.

Some medical applications

- Rolling shields in fluoroscopy and interventional radiology;
- Shielding in high dose radiotherapy such as brachytherapy;
- Viewing window or construction material for radio-nuclear instrumentation;
- Shielding in hot cells and cyclotron facilities;
- Shielding in PET Labs and transporting radioisotopes;
- Shielding in nuclear medicine manufacturing, QA and QC stages;
- Transparent pigs to store vials and syringes; and
- Windows in rooms for procedures such as Metaiodobenzylguanidine (MIBG) Therapy for neuroblastoma where visibility into a room is needed.

SUMMARY AND CONCLUSION

Material characterization

ICP-OES and Raman spectroscopy testing along with reviewing the mass specifications help in concluding that the elemental composition of CVRS is environmentally safe, non-toxic, nonflammable and would not become an additional source of radiation. In case it has to be drained, CVRS is safe to be disposed down a regular residential or industrial drainage system and requires no special treatment.

Gamma attenuation

CVRS's attenuation demonstrated that the Half Value Layer is a little less than 3.81 cm. From Tables 2 and 3, we can see that the attenuation with 3.81 cm CVRS is greater than 50%. Being conservative, we can report that the HVL of CVRS is 3.81 cm and TVL is 12.65 cm. These were calculated by using the mass attenuation coefficients obtained by the values.

Freezing

Attenuation of CVRS when frozen or crystallized was compared to a complete liquid state.

Table 6. Comparison of lead equivalence between CVRS and other transparent shields with same thickness *Pb equivalence reported by supplier".

Conventional transparent shield (thickness, mm)	Pb. equivalent, (mm)	Thickness CVRS (mm)	Pb. Equivalence CVRS (mm)
Direct Scientific Lead Acrylic (8 mm)	0.3	8	3.2
Direct Scientific Lead Acrylic (12 mm)	0.5	12	4.8
Biodex Lead Glass (8 mm)	0.3	8	3.2
Biodex Lead Glass (12 mm)	0.5	12	4.8
Biodex Lead Glass (22 mm)	1	22	8.8
Biodex Lead Glass (35 mm)	1.5	35	14
Leaded Glass - Ray Bar (7.0 mm – 8.5 mm)	1.8 – 2.4	7–8.5	2.8–3.4
Radiation Products Leaded Acrylic (8 mm)	0.3	8	3.2
Radiation Products Leaded Acrylic (12 mm)	0.5	12	4.8
Radiation Products Leaded Acrylic (22 mm)	1	22	8.8
Radiation Products Leaded Acrylic (35 mm)	1.5	35	14
Marshield LX -57 b (9 mm)	2	9	3.6
Marshield LX -57 b (14 mm)	3	14	5.6
Marshield LX -57 b (17 mm)	3.3	17	6.8
Marshield Lead Free Glass (12 mm)	0.5	12	4.8

FIG. 8. Table top shield used at LaSalle Nuclear Power Plant (reproduced with permission from Exelon).

At a thickness of 1.905 cm, the attenuation seen was to be 28.6% for the frozen area as compared to 29% for a pure liquid. For 2.54 cm of CVRS, attenuation for frozen portions was seen to be 34% as compared to 37% for a pure liquid. The reduction in attenuation can be attributed to many reasons. The angle of incidence for the gamma beam might not be perfectly 90°. Another reason may be the difference in state of the shield causing a slight change in the contribution from scattering radiation. It was concluded that there was not a substantial difference between the shielding whether it was in a liquid or solid state. The freezing temperature of CVRS was reported as 14°C. Upon returning to liquid state, the transparency was seen to maintain and CVRS's optical performance was seen to maintain.

Stability

CVRS was seen to be stable since the day on which the first successful batch was manufactured; this is a period of a little over 16 months and no changes were noted or seen. Parameters subject to possible change were known, and they remained constant. These cannot be shared due to the proprietary nature of work. It can be concluded that CVRS is a stable liquid over time, and remains in its original state without any change in color or appearance. The thermal expansion of the CVRS does not seem significant. Being in a polycarbonate housing and PCT being an insulator also prevents much heat being transferred to the shield. Based on the boiling point of the shield, it is recommended that the shield not be used at temperatures above 90°C. For higher temperatures, the housing should be made with another material such as toughened glass. The air kerma rate for the ^{60}Co irradiator was 0.008 Gy s^{-1} and, based purely on the irradiation times, CVRS has been exposed to a cumulative dose of 4 Gy.

Visibility and transparency

Semiconductor laser beams of red and green color, wavelengths 650 nm and 532 nm, were incident on CVRS with a thickness of 16.24 cm. It was seen that green and red colors transmitted well. CVRS also maintains its transparency with increasing thickness. The shield does tend to become a little dark, which can be taken care by placing LED lighting to illuminate the shield, but testing with 30-cm-thick shield has shown that CVRS does not become translucent or opaque. Assuming the housing clarity is maintained, CVRS maintains its transparency for large thicknesses.

FUTURE WORK

Our future work is to test the physical properties of CVRS, namely thermal conductivity, viscosity, angle of refraction or light bending in viewing on increasing thickness, and freezing temperature. Using CVRS has validated that it attenuates high energy gamma rays effectively; however, extended usage of the shield for high cumulative doses going into hundreds to thousands of Grays will be experimentally tested. Based on the contents of CVRS, we can expect that the shield performance and attenuation of the shield would not change at high doses. Certain aspects not evaluated by the current experiments, such as structural damage or degradation of PCT and adhesive, will be done in the future; however, literature shows that PCT and acrylate based adhesive should hold well in high doses (NASA SP-8053 1970]. We also think that CVRS would be an effective neutron shield and plan to present results from conducting a neutron attenuation experiment along with studying effects of high doses on CVRS. Future work will also consist of researching applications, preparing custom solutions, and evaluating body dose saving for personnel in the nuclear power and medical industries. Small-scale testing has been done to prepare a gel form of CVRS which is also shape assuming. Smaller batches have shown that the density and volume has not changed significantly to change the HVL, but this will be validated by testing. This form will be particularly useful for jobs that require shielding be placed around or draped over an object.

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