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Reactor power monitoring using Cherenkov radiation transmitted through a small-bore metallic tube

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ABSTRACT

The use of a small-bore highly reflective metallic tube has been demonstrated at a pool-type nuclear reactor for transmitting Cherenkov radiation emitted from a quartz cylinder placed near the reactor core. The study revealed the promising prospect of using a metallic tube to remotely make localized measurements in order to independently monitor reactor power using Cherenkov light generated in the water pool or inside an attached radiator. This study confirmed qualitatively and quantitatively that commercially available stainless steel tubes with highly reflective inner surfaces can adequately transport Cherenkov light, produced in the proximity of a SLOWPOKE-2 reactor core operated at 20 kW, with acceptable transmission losses over significant distances. It was demonstrated that this Cherenkov-based instrument has a fast response, high fidelity, and the Cherenkov-induced output current varies linearly with the reactor power. Scans in the orthogonal directions showed the possibility of using the Cherenkov-based instrument for 3-D mapping of the general gamma field around the reactor core. Analytical and numerical models were developed and validated by experiments to predict the transmission efficiency of light in the highly polished small-bore light guides. This paper provides details of calculations and experimental validation under laboratory conditions and at a pool-type SLOWPOKE-2 reactor.

1. Introduction

Redundancy, accuracy, reliability, and diversity are of great importance in nuclear Instrumentation and Control (I&C) systems to monitor all aspects of a nuclear power plant's health (International Atomic Energy Agency, 1999). Following the development of optical fibres in the 1970's, the use of fibre-optic light guides to pipe Cherenkov light generated in the reactor core was proposed for use in nuclear core I&C systems as an additional method to the conventional in-core detectors, monitoring the reactor's global fission power and neutron flux. However, because of radiation-induced darkening in optical fibers, reliable and sustained performance in transmitting Cherenkov light from the reactor core has not been successful (Kakuta et al., 1999, Arkani and Gharib, 2009). All known transparent solid materials degrade over time, particularly in intense radiation environments such as inside a nuclear reactor core. Radiation darkening occurs more slowly in radiation resistant glass formulations but is still significant over a period of hours to days in typical reactor environments, such that it significantly impedes the ability to transmit light. Herein we show an instrument, made of small-bore highly-reflective metallic tubing, in which Cherenkov light generated at one end of the tube is directed onto a photomultiplier (PMT) located at the opposite end. Cherenkov light could be collected directly from the water pool or from a dielectric transparent object placed inside the metallic tube itself. In the present tests, latter approach was chosen for its simplicity and practicality.

1.1. Cherenkov light

Electromagnetic radiation known as Cherenkov light is emitted when a charged particle moves in a dielectric medium at a speed greater than the speed of light for that medium (Cherenkov and Akademii, 1934). A conspicuous example of that effect is the characteristic blue glow of a pool-type reactor. The light is mainly generated by high energy electrons produced by the Compton scattering of gamma rays and its intensity is linearly related to reactor fission power (Jordan, 1951), and can be transmitted from the source at the reactor core to a sensing device by means of a highly reflective metallic tube. The number of Cherenkov photons dN emitted at wavelength λ by one charged particle of charge number

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z traveling a distance dx in dielectric medium can be described by the Frank-Tamm formula (Frank et al., 1937):

$$\frac{dN}{dx}(\mathrm{cm}^{-1}) = 2\pi z^2 \sin^2\theta_c \int_{\lambda_1}^{\lambda_2} \frac{d\lambda}{\lambda^2} = 550\sin^2\theta_c \quad (1)$$

where θ_c is the Cherenkov angle which depends on the particle energy and index of refraction n of the dielectric medium (Hale and Querry, 1973). For electrons with energies higher than 1 MeV, $\sin^2\theta_c$ is estimated to be 0.4 (Brichard et al., 2007; Klein and Nishina, 1929; Johns et al., 1954; Sterbentz, 2008). Charged particles (electrons) are mainly generated by gamma rays through incoherent Compton scattering, and their number N_B is given by:

$$N_\beta = \rho\phi\sigma \quad (2)$$

where $\sigma = 0.5\ \mathrm{cm}^2/\mathrm{g}$ is the averaged total incoherent scattering cross section of gamma in quartz (Database, 2015), $\rho = 2.65\ \mathrm{g/cm}^3$ is quartz's density, ϕ is the gamma flux. For a cylindrical quartz of volume V and diameter D, the total number of Cherenkov photons generated by N_β Compton electrons can be approximated to:

$$N = \left(\frac{dN}{dx}\cdot D\right)\cdot(N_\beta V) \quad (3)$$

Eq. (3) uses the diameter D to represent the average distance traveled by electrons in the cylinder. Combing Eqs. (2) and (3) gives $\sim 10^{10}\ \mathrm{s}^{-1}$ photons in a cylindrical radiator measuring 1 cm in length and 0.5 cm in diameter under a gamma flux of $10^{10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. This value suggests that despite using a system of an optical transmission as low as$T \approx 10^{-7}$, which can be easily achieved using a typical highly-reflective metallic tubing, it remains possible to detect signals using a standard photomultiplier tube.

2. Experiments at a SLOWPOKE reactor

The reflective light-pipe Cherenkov instrument, called simply hereafter Cherenkov instrument, was demonstrated at the 20 kW SLOWPOKE (for Safe LOW POwer C(K)ritical Experiment) nuclear research reactor of the Royal Military College of Canada (RMCC) (Hilborn and Burbidge, 1983; Hungler et al., 2014). The reactor core has approximately ~200 fuel pins with low enriched uranium fuel (~19.9% U-235) arranged vertically inside a beryllium reflector assembly. The reactor core is suspended near the bottom of a pool inside an aluminum vessel; inside and outside the vessel is filled with de-ionized light water. To transport the Cherenkov light generated near the core, an approximately 6 m long metallic tube, corresponding to the pool depth, is required. Due to practical reasons, the Cherenkov instrument was made of 4 short stainless steel tubes of 6.4 mm O.D. × 4.6 mm I.D. connected by custom-made "push-to-connect" hubs. Each section was no longer than 1.8 m to allow for ease of transportation and installation into the pool. As shown in Fig. 1, a 3-section extension pole, and custom fabricated parts were used to hold the light-tubes together and keep the system stable and waterproof. The lower end of the stainless steel tube was fitted with a tube compression fitting which accepted an interchangeable insert made with a high-purity electrically-fused quartz rod http://www.heraeus-quarzglas.com. The tube has one bend to create an indirect path to the detector which prevents direct gamma radiation streaming while Cherenkov light is reflected multiple times by the inner polished surface of the small-bore tube and travels around the bend to the PMT.

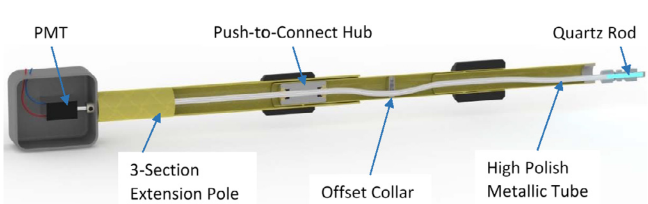

Fig. 1. Cross sectional view of the reflective light pipe Cherenkov instrument used at the Royal Military College of Canada (RMCC) SLOWPOKE reactor.

As shown in Fig. 2 one side of the Cherenkov instrument was mounted to the reactor's structure using a pair of magnetic-base holders attached to a horizontal steel I-beam, and the other side was attached to an elevator system in the reactor pool. The collected light was read by a Hamamatsu model R760 photomultiplier tube detector with a spectral response peaked at 420 nm https://www.hamamatsu.com/us/en/R760.html. The PMT detector was operated in current mode at a point well below saturation. The PMT current was averaged over 100 samplings by a Keithley model 6517B electrometer for each measurement https://www.tek.com/keithley.

2.1. Reactor power monitoring

To examine the response of the Cherenkov instrument with respect to the reactor power, the end tip containing the quartz radiator was placed near the outer surface of the reactor vessel and the reactor power was gradually raised from shut-down state to ~18 kW. Power was stabilized at selected levels within ±2% after which a PMT reading was taken for about 2 mins. Fig. 3 shows Cherenkov current output versus time. One can notice the fast response of the Cherenkov instrument when the reactor power is changed abruptly. The spikes before the plateaus are not an artifact, but rather the result of the reactor control system overshooting on the requested reactor power, before reducing power to the requested level. At stable power levels, the PMT current is steady within ± 3%. Fig. 4 shows Cherenkov current output versus reactor power derived from an in-core cadmium emitter Self-Powered Neutron Detector (SPND), which is formally taken as the true reactor power indicator (Hilborn and Burbidge, 1983). Over the entire power range (0–18 kW) a good linear correlation is observed between the PMT and the SPND readings, with a correlation factor approaching 0.9986 ± 6%.

Another important factor is the system fidelity which measures the response of the Cherenkov instrument when the reactor power is ramped up or down. A perfect system should show the same response whatever the power change direction is. As shown on Fig. 5 there is a relatively good fidelity within the linearity range. Hysteresis effects are mostly observed at high power and are caused by increased buildup of fission products which emit delayed neutrons and gamma-rays.

2.2. Reactor transient measurement

To measure a reactor transient with the Cherenkov instrument, the end with the quartz radiator was placed close to the reactor vessel with the reactor at maximum power; subsequently the control rod was rapidly inserted resulting in a reactor transient from full power to near zero. Results of this test are presented in Fig. 6. The Cherenkov current output follows very well with the expected power decay; a sudden decay due to the insertion of the control rod followed by the decay of fission products. Even at zero power, Cherenkov light continues to be generated in the quartz radiator from the gamma decay of fission products. Comparison with neutron flux given by the SPND system shows good correlation between the two measurements. The steadiness and stability of the Cherenkov instrument matches the existing SPND measurement. The behaviour difference between the two systems at zero (residual) power is due to the fact that the SPND system measures primarily neutron flux whereas the Cherenkov

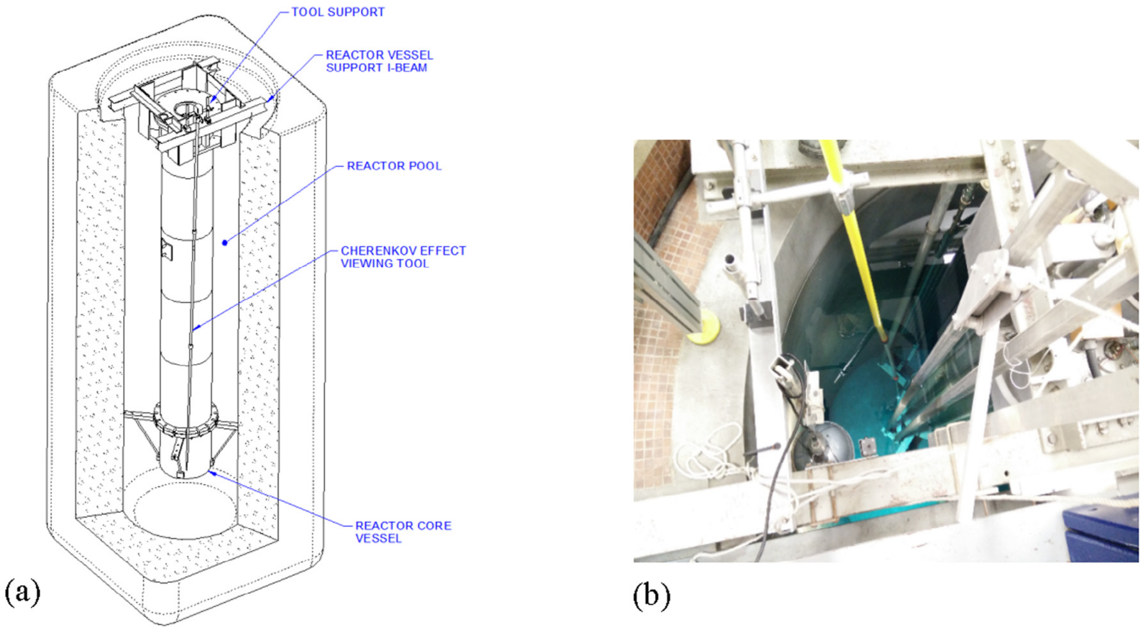

Fig. 2. (a) Schematic view of the Cherenkov instrument setup at the SLOWPOKE reactor. (b) View of the completed assembly in the reactor pool as seen from the top of the reactor.

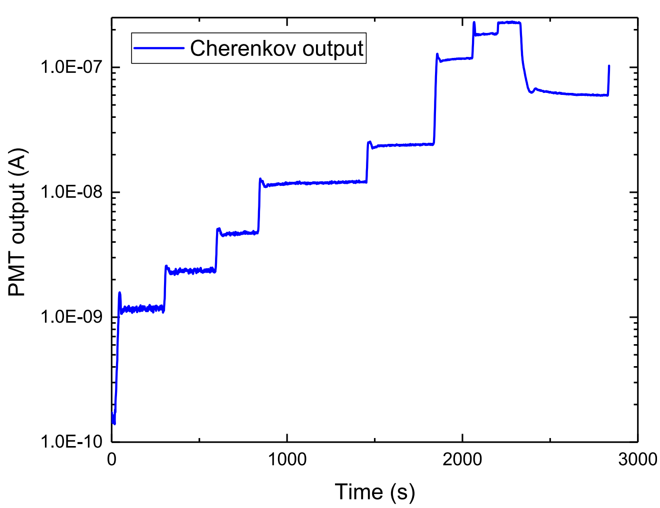

Fig. 3. Cherenkov instrument response over time as the SLOWPOKE reactor power is changed.

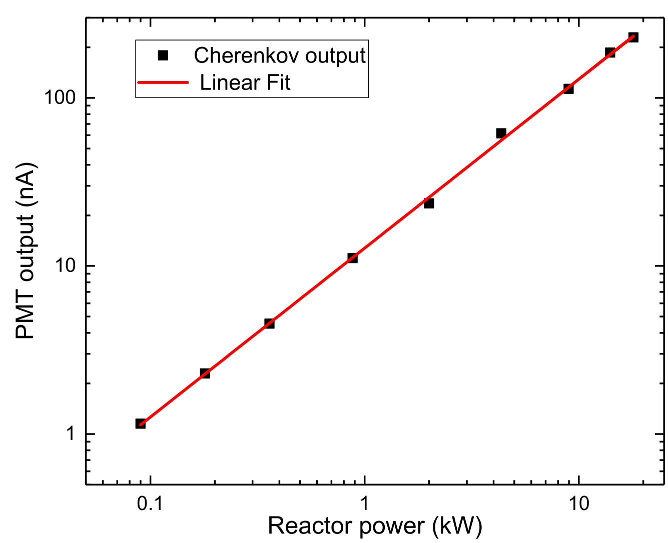

Fig. 4. Cherenkov light intensity versus SLOWPOKE reactor power.

instrument measures primarily the gamma flux. When the reactor is operating, the general gamma field inside the SLOWPOKE reactor is not well known but it is believed to be primarily proportional to the neutron flux (Jalali et al., 2013). As it can be seen in Fig. 6, this is still true when the neutron flux is above 10% of full reactor power. Thereafter the Cherenkov current persists longer than the SPND signal due to the long lived fission products emitting gamma radiation.

2.3. Local radiation measurement around the SLOWPOKE reactor core

The Cherenkov instrument was also used to scan the gamma field near the reactor core. Due to design limitations of the instrument, it was not possible to determine with precision the position of the end tip containing the quartz radiator. Despite these limitations one was able to scan the gamma field in the orthogonal direction, as shown in Table 1. Results confirm that the gamma field intensity decreases when the quartz radiator was moved away from the core which demonstrated that the Cherenkov instrument could be used for local gamma measurements and for 3-D mapping of gamma flux.

3. Light transmission in a highly reflective small-bore metallic tube

To better understand the SLOWPOKE results, experiments using a Carbon-14 (C-14) Cherenkov source were conducted in the laboratory. The C-14 source, sealed in a quartz radiator, provided a mixture of Cherenkov and scintillation light peaked at 300 nm. As shown in Fig. 7 the source was placed in front of ultra-high polished stainless steel tubing similar to the one that was used in the SLOWPOKE reactor experiments. According to the manufacturer specifications, the inner surface was polished to a roughness value

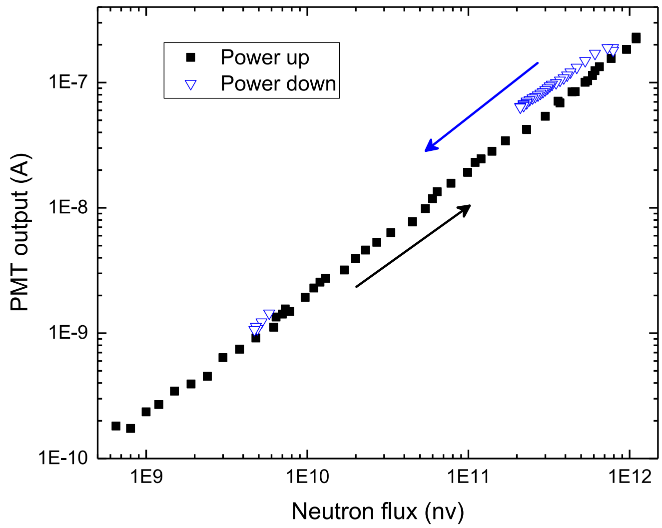

Fig. 5. Detector fidelity check in response to random SLOWPOKE reactor power increase and decrease.

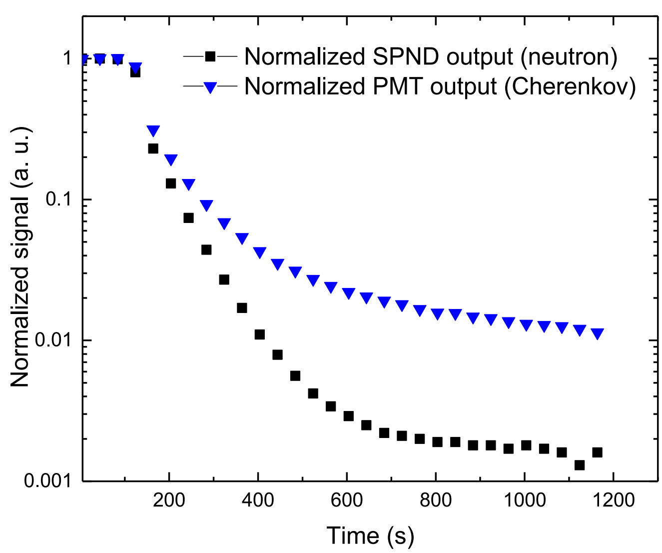

Fig. 6. Cherenkov light intensity and neutron flux variation during an induced SLOWPOKE reactor transient.

Table 1
Scan of the gamma field using the Cherenkov instrument.

Distance to the reactor vessel (cm)	PMT reading (nA)
~0	105
~30	60
~50	31
~70	15

of 0.25 μm. The other end of the tube was placed in front of a PMT to detect the transmitted light. Both ends of the tube, the source, and the PMT were enclosed in light-tight metal boxes to minimize the background from ambient light. There was essentially no detectable ambient light and the output signal due to dark condition was as low as 0.3 nA.

The transmission of Cherenkov light was measured with tubes of various lengths from 0.15 to 1.83 m. The dominant uncertainty was not the statistics of the signals; rather it was due to the uncertainty in positioning the source, tube and detector. This uncertainty was established by repeating the measurements after disassembly and reassembly of the whole setup: It was found that the results are reproducible within ±10%.

3.1. Calculation and simulations

The light transmission can be calculated analytically assuming a point isotropic light source located at distance *d* along the axis of a tube of pure specular reflection as shown in Fig. 8. Transmission *T* can be calculated as a function of the inner surface reflectivity *R*, and *L* the tube length as follows:

$$T = \frac{1}{4\pi}\int_0^{2\pi} d\varphi \int_0^{\theta_{max}} R^{\frac{L.\tan\theta}{D}} \sin\theta \; d\theta \tag{4}$$

where $\mathrm{L}.\tan(\theta)/D$ is the number of reflections required for a photon emitted at angle θ to be transmitted through the tube. The value of transmission *T* can be obtained by using, for example, the software Mathematica http://www.wolfram.com/ to evaluate the integral of all photons entering into the tube weighted by their probabilities to be transmitted through.

To include the diffuse reflection and account for the non-perfect finish of the optical surface, a Monte Carlo simulation was built using the unified model in the GEANT4 toolkit (Agostinelli et al., 2003). GEANT4 is a Monte Carlo toolkit capable of simulating a wide range of particle interactions and transport mechanisms. The non-perfect finish of the surface was approximated by assuming micro-facets with normal vectors that follow a Gaussian distribution with standard deviation σ_α around the average normal of the surface. Other parameters were specified in the simulation such as the specular spike constant C_{ss} which controls the specular reflections about the average normal of the surface, the specular lobe constant C_{sl} which controls the probability of specular reflections about the normal of a micro-facet, and the diffuse lobe constant C_{dl} which represents the Lambertian reflection (Agostinelli et al., 2003). Fits of the experimental data by both the calculation based on Eq. (4) and the GEANT4 simulation confirmed that the total reflectivity of the stainless steel is in the range 0.95–0.97. In fact, total optical reflectivity was found to be the most important parameter to fit the experimental data. Numerous combinations of the other parameters σ_α, C_{ss}, C_{sl} and C_{dl} showed no significant difference in the results and gave results close to the calculation predicted by Eq. (4). A comparison of the results of the GEANT-4 simulation, the calculation based on evaluating Eq. (4), and the experimental measurements are shown in Fig. 9.

The calculation and the simulation assumed an isotropic point source for Cherenkov source while in reality the Cherenkov radiator was volumetric with some angular distribution. This may account for the observed discrepancy when comparing calculation and simulation to the experimental data. An empirical power law of form $\mathrm{T} \propto \mathrm{L}^{-1.16}$ could well fit the experimental data, showing a significant advantage in light transmission efficiency using the reflective light pipe compared to the inverse square law.

4. Conclusions

This work demonstrated the feasibility of monitoring reactor power and mapping intense gamma radiation fields by the transmission of Cherenkov light through a small-bore highly-reflective metallic tube to a photon detector. The Cherenkov instrument can be localized to the position of interest inside a high radiation field environment, and the Cherenkov light can be transmitted to a low radiation field environment for detection. A slight curvature of the polished metallic tube prevented direct gamma radiation reaching the PMT, but allowed the transmission of Cherenkov light. These first tests confirmed qualitatively and quantitatively that

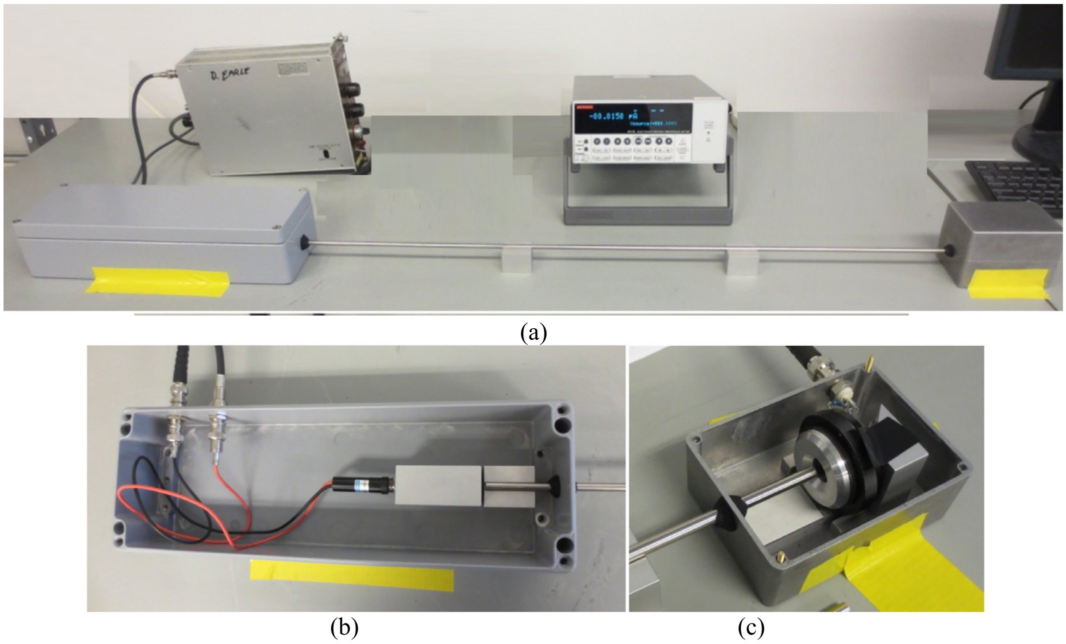

Fig. 7. Experimental setup (a) Overview of the experimental setup. PMT is enclosed in the box on the left side, and the source is enclosed in the box on the right side. (b) Opened PMT box. (c) Opened source box.

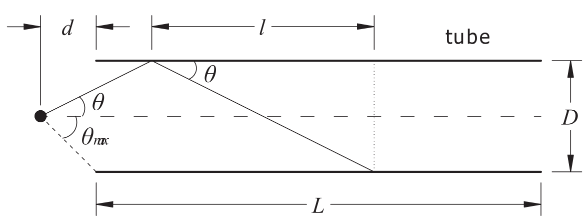

Fig. 8. Illustration of photon reflection in the tube. A point source is placed at the distance d in front of a tube with the length L and diameter D. A photon is emitted at angle θ.

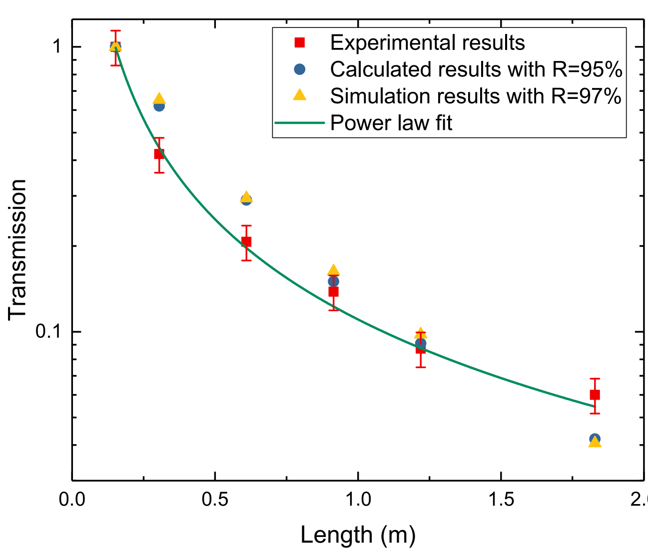

Fig. 9. Transmission of the Cherenkov light through the stainless steel tube. All data are normalized to the transmission through the 0.15 m tube. Experimental results are compared with calculation assuming total reflectivity, R, of 0.95, and with GEANT4 simulation assuming R of 0.97, $\sigma_\alpha = 10$, $C_{ss} = 0.9$, $C_{sl} = 0.1$, and $C_{dl} = 0$.

commercially available metal tubes with highly reflective inner surfaces can adequately transport light with acceptable transmission losses for distances that will allow access to points inside a high radiation field, typically in the 5 m to 15 m range. These tests demonstrated that the detected Cherenkov light intensity varied linearly with the reactor power and therefore could be used as an independent measurement of the reactor fission and decay power. It is expected, based on prior experience, that such a metallic light guide will function reliably and without degrading over time in a high radiation environment. An improved design could significantly reduce positioning uncertainties and other sources of signal error. The method described herein can be applied to other small diameter reflective metal tubes with good optical properties. The small-bore reflective light guide, as demonstrated in this work, can be used with an array of other passive and active sensor and interrogation systems to make measurements in high hazard environments, such as the vicinity of a reactor core, where the use of optical fiber light guides is not feasible. Work to demonstrate such measurement systems is in progress.

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