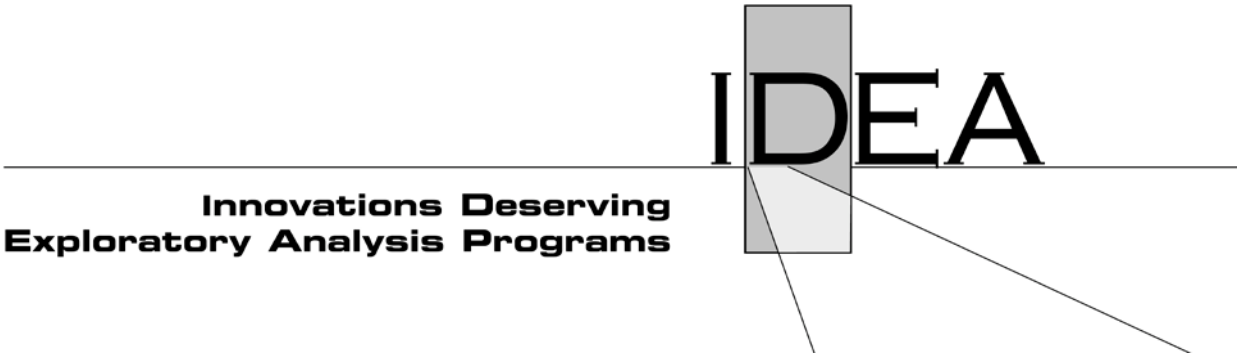

Highway IDEA Program

Development of a 2nd Generation Neutron-Based Detector for Chloride in Concrete

Final Report for
Highway IDEA Project 136

Prepared by:
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Richard A. Livingston

July 2014

TRANSPORTATION RESEARCH BOARD
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Development of a 2nd Generation Neutron-Based Detector for Chloride in Concrete

IDEA Program Final Report

Contract Number: NCHRP 136

Prepared for the IDEA Program

Transportation Research Board

The National Academies

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July 16, 2014

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Executive Summary

• *IDEA Product:* The outcome of this research will be an advanced nondestructive test instrument for measuring chlorides in concrete using a prompt gamma neutron activation (PGNA) system with electronic collimation. The current method of chloride analysis in concrete is destructive and time-consuming, and consequently is not done frequently in the field. The proposed system will permit regular nondestructive inspection of structures for possible risk of chloride-promoted rebar corrosion with improved spatial resolution. This information in turn would be used to develop a strategic approach to bridge maintenance and repair for chloride deterioration which would be more cost-effective and minimize traffic congestion due to these activities.

• *Concept and Innovation:* The nondestructive test method is based on prompt gamma neutron activation. In this technique neutrons from a portable source are used to irradiate the concrete structure. The neutrons are captured by atoms in the material, and in this process gamma rays are emitted with characteristic energies. The gamma rays travel out of the concrete and are then counted by detectors. The size of each gamma-ray peak in the spectrum is proportional to concentration of the element in the concrete. This technique is especially sensitive for measuring chlorides because of the very large capture cross-section of chlorine. The FHWA has supported research on PGNA chloride detector systems for several years. However, the current system is omni-directional, and consequently the sampled volume in the concrete is relatively large ~100,000 cm^3 so that the spatial resolution is relatively coarse.

This research introduces two major innovations. One is the use of electronic collimation to make the system directional. In this approach, a very thin planar detector would be mounted in front of the existing coaxial detector. The two detectors would operate in coincidence mode, so that only gamma rays passing through both would be counted, and hence gamma rays from other directions would be rejected. Consequently this arrangement would detect a cylindrically shaped volume within the concrete with a radius of 1–2 cm. In addition to the improved spatial resolution of the detector, background would be significantly reduced, thereby improving the counting statistics. Finally, by eliminating the hydrogen signal from the moderator, it would also be possible to measure the water/cement ratio in the concrete.

The second major innovation is the replacement of the ^{252}Cf radioisotope source by a portable neutron generator. This produces a more intense neutron flux while at the same time

reducing radiation safety issues. Since the generator can also be operated in a pulsed mode, this raises the possibility of time of flight measurements for estimating the chloride depth profile.

• *Investigation:* The original work plan, as initially conceived, had three stages: 1. Numerical modeling and simulations to optimize the design of the system; 2. Instrument assembly and calibration in the laboratory on test specimens with known chloride concentrations; and 3. Field testing on actual concrete bridges. Stage 1, which concerned design calculations, has largely been completed. This consisted of specifying the dimensions of the planar gamma-ray detector, selecting the type of neutron generator and modeling the moderator using the MCNP software.

However, a major obstacle to the completion of Stages 2 and 3 was the lack of a thermal neutron source in the timeframe of this project due to a combination of factors. The nuclear reactor at the University of Maryland was not operable because of the failure of an essential neutron monitor, which took nearly a year to replace. Simultaneously, the nuclear reactor at the National Institute of Standards and Technology (NIST) was down for a year to install additional beam lines. Finally, a portable neutron generator was obtained by the University of Maryland under an equipment grant from the Department of Energy, but it was not possible to operate it on campus because of radiation safety licensing issues. Consequently, most of the work proposed in Stage 2 of the original work plan, which involved calibration of the system in the laboratory, could not be accomplished. Nevertheless, some experimental investigations were carried out using radioisotope gamma-ray sources. This work confirmed the principle of electronic collimation and verified the improved directionality of the system. In addition, experiments using the cold neutron PGNA station at NIST provided data on calibration that can be used to estimate the performance of a portable field PGNA system. Finally, concrete test specimens were cast with known amounts of chloride in them. These specimens can be used for calibration of the system when a portable neutron source becomes available. The field tests proposed for Stage 3 also could not be carried because of a lack of a portable neutron source.

Recommendations for future research primarily concern increasing the data acquisition rate through several hardware and software improvements. These include increasing the gamma-ray detector response by switching to a more efficient scintillator type detector and using a digital pulse processing subsystem to reduce dead time. Software improvements involve post-processing of the spectrum to recover scattered photons by spectrum deconvolution. Finally, the neutron fluence rate can be increased by adapting a more advanced design of the moderator.

• *Plans for Implementation:* A number of state departments of transportation have expressed interest in using the PGNA system when it becomes available. Also, several private sector companies have expressed interest. Current plans are to continue the research on laboratory testing of the system using the portable neutron generator at a special facility at NIST.

I. Introduction

The objective of this research was to design, build, and evaluate an advanced nondestructive test instrument for detecting chlorides in concrete with high spatial resolution using a prompt gamma neutron activation (PGNA) system in a Compton telescope configuration. This was in response to the NCHRP Focus Area: "Maintenance and Renewal of Service Life—Advanced diagnostic technologies to enhance early detection of deterioration and repair technologies that reduce the time between repair and resumption of service."

I.1 Chloride damage in concrete

A major cause of the deterioration of reinforced concrete structures is corrosion that is promoted by chlorides (Bentur et al. 1997). The sources of the chlorides include road deicing salts, concrete setting accelerants, or seawater, either in the concrete mix water itself or as airborne droplets from ocean spray. Corrosion of reinforced concrete is a major component of the estimated $8.3 billion annual direct cost of corrosion in highway bridges reported in a 2002 publication of the Federal Highway Administration (FHWA) (Koch et al. 2002).

The urgency of the problem arises from the current state of the highway infrastructure. Most of the bridges on the interstate system are at least 40 years old. At a typical rate of diffusion of chloride of 5×10^{-12} m^2/s and given the typical thickness of concrete on the order of 50 mm, the time to initiation of corrosion is about 35 years (Thomas 2001). Hence, greatly increased corrosion is imminent.

The current method for measuring chloride content of concrete is a destructive method based on drilling out a core of the concrete. This is then crushed and treated with acid to dissolve the chloride, which is analyzed by either wet chemistry or ion selective electrode (Khan 1997). With either analytical technique the total time for analyzing a sample, including drilling is determined. An accurate and nondestructive way to assess the chloride content of concrete in order to

estimate the probability of corrosion is urgently needed. Therefore it is proposed to develop such a nondestructive method using prompt gamma neutron activation that would provide a measurement in significantly less time.

I.2 Prompt gamma neutron activation

Prompt gamma neutron activation (PGNA, or alternatively, PGAA or PGNAA) is an elemental analysis technique based on the radiative capture of a neutron by the nucleus of an atom in the target material (Lindstrom and Paul 2000). The basic principle of PGNA is illustrated by the schematic diagram in Figure 1 with the ^{35}Cl (n, γ) ^{36}Cl reaction as an example. Immediately after the capture of the neutron the ^{36}Cl nucleus is an excited state. In order to reach the stable ground state, it promptly emits several gamma rays of specific energies.

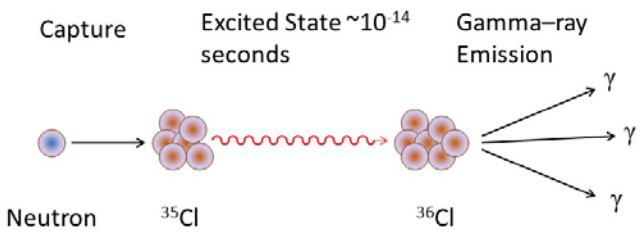

Figure 1 Schematic diagram of prompt gamma neutron activation.

The governing equation of PGNA, which for a point in the target material is given by:

$$r = n\sigma_{\gamma}^{Z}\phi_{th}\varepsilon(E) \tag{1}$$

where: n = number of density of atoms of the element of interest; σ^{Z}_{γ} = product of neutron capture cross section, abundance, and yield of the target element; ϕ_{th} = thermal neutron fluence rate, cm$^{-2}\cdot$ s^{-1}; and $\varepsilon(E)$ is the detector response function for the energy of the photon of interest (Lindstrom and Paul 2000). The total count rate is the integral of r, weighted by the attenuation of the emitted gamma ray in the material, over the sample volume. Of the four factors in Eq. 2, the number density, n, is the unknown variable to be measured, and σ^{Z}_{γ} is constant for a given isotope. The σ^{Z}_{γ} of the ^{35}Cl (n, γ) ^{36}Cl reaction is 33.1 x 10^{-24} cm^2, which is among the highest of

all the elements. Thus PGNA would be a very suitable candidate for measuring chlorides in concrete.

The major gamma rays produced in this reaction are shown in the decay scheme in Figure 2 (Dewey and Kessler 2000). The nucleus is initially excited to the 8579.1 keV level. The major decay step of 6.111 MeV occurs 20% of the time. This is the most favorable gamma ray for PGNA of chloride in concrete because its attenuation factor is low, meaning that it can travel through tens of cm of concrete. Also, it occupies a position in the energy spectrum where there

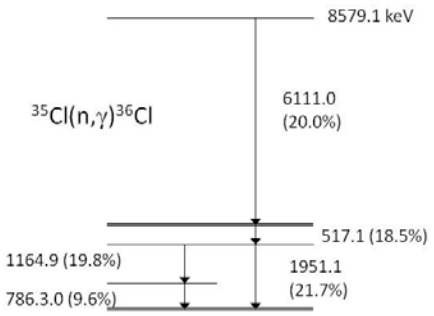

Figure 2 Decay scheme for the excited ^{36}Cl nucleus (Dewey and Kessler 2000).

are a very few other lines. Two other possible lines are at 1.164 and 1.951 MeV, although their attenuation factors would be higher. The remaining two lines at 0.517 and 0.786 MeV have even higher attenuation and fall in a part of the spectrum that is crowded with other gamma-ray lines.

I.3 Neutron activation applications for concrete

There is a significant literature on the analysis of concrete by neutron activation, but not all of it is directly relevant to the measurement of chlorides in the field. First of all, there are two different types of neutron activation. The PGNA method measures the gamma rays that are emitted simultaneously with the capture of the neutron. The other type measures the gamma rays emitted at some later time after capture; this is often referred to simply as neutron activation analysis (NAA) or instrumental neutron analysis activation (INAA). Since the delays can range from seconds to years, delayed neutron analysis typically involves a much longer measurement time, and it usually requires a much more intensive neutron source such as a nuclear fission reactor to activate the material in the first place. However, for some elements that do not emit detectable prompt gamma rays, INAA may be the only alternative.

In the specific case of chlorine, both prompt and delayed gamma rays are emitted. The prompt gammas come from the ^{35}Cl (n, γ) ^{36}Cl reaction discussed above, and the delayed gammas (1.64 and 2.17 MeV) from the ^{37}Cl (n, γ) ^{38}Cl reaction with a half-life of 37.2 minutes. In the first project on neutron-based chloride detection supported by FHWA, Rhodes et al. (1980) used both types of activation. This dual activation approach was necessary because of the limited resolution of the sodium iodide detectors available at the time, which could detect only the 6.111 MeV line in the PGNA spectrum. However, one objective of the research was to develop a method of estimating the chloride depth profile by differential attenuation. This requires the counting of gamma rays of two different energies, and hence range, in concrete. The second gamma ray was thus produced by INAA. To achieve reasonable counting statistics, a very intense 400 μg ^{252}Cf neutron source had to be used, which required massive truck-mounted shielding. Two sodium iodide detectors were involved, but these were not operated simultaneously, but rather sequentially. One was used for PGNA, and then the other for INAA.

Subsequent FHWA research in neutron-based chloride detection, described below, used HP germanium detectors in place of sodium iodide (Livingstone and Saleh 1998, 2000). The significantly better energy resolution of this type compared to NaI, 2 keV vs. 100 keV, combined with the use of a multichannel analyzer with an order of magnitude increase in digital channels, 16 K vs 1024, made it possible to detect several chlorine lines simultaneously, thus eliminating the need for INAA. It also permitted the use of a much less intense ^{252} Cf source, thereby reducing radiation safety issues. Computer simulations were carried out with the MCNP software of this omni-directional system to better understand its performance (Mohamed et al. 2008). Hardware improvements also included encapsulation of the ^{252} Cf source in zirconium rather than stainless steel to reduce background gamma rays.

Other research specifically concerning the detection of Cl with PGNA includes the work of Collico et al. (1995), who used a very intense (3 Ci) AmBe neutron source to measure Cl, among other elements, in hardened concrete. Naqvi et al. (2004) used a pulsed neutron beam to measure the Cl content of portland cement powder. Both of these approaches are limited to the laboratory.

More broadly, PGNA has a long history of use in characterizing cement and concrete, but not explicitly for Cl. The analysis of cement raw materials at cement kilns by PGNA using ^{252} Cf is well established commercially (Foster and Bond 2006) and over 300 systems have been installed.

For the characterization of concrete, as opposed to portland cement, PGNA has been applied in a number of studies (Duffy 1972; Iddings 1975; Howdyshell 1977; Anderson et al. 1983; Rowbottom et al. 1997).

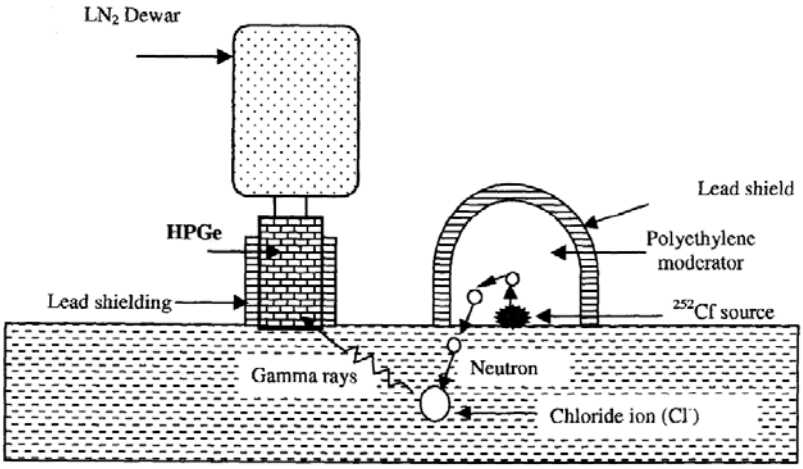

Figure 3 Schematic diagram of the original omni-directional PGNA.

I.4 First generation PGNA omni-directional chloride measurement system

A schematic diagram of the existing chloride detection system is given in Figure 3. The ^{252}Cf radioisotope neutron source generates fast neutrons with typical energies in the 1–5 MeV range, while PGNA requires thermal neutrons (2.57 x 10-8 MeV). Therefore it is necessary to use a moderator to slow down the neutrons to thermal energies

The moderator design currently used was developed with MCNP simulations. It consists of a solid cylinder of polyethylene 15 cm in radius with a hemispherical end cap.

The system was calibrated in two stages. First, the detector itself was calibrated using the PGNA setup at the NIST Center for Neutron Research. Very pure samples of sodium chloride were placed in the reactor-generated cold neutron beam, and the detector was used to measure the resulting gamma-ray spectrum. In the second stage, the complete system including the ^{252}Cf neutron source was used to measure the chloride in mortar test slabs prepared at TFHRC. As shown in Figure 4, both stages yielded a very linear calibration function and both had a detectable signal at the threshold for corrosion. However, the count rates are very different, reflecting the differences in neutron sources and the geometry of the experiment.

However this single detector omni-directional approach leaves some room for improvements:

1. The sampled volume in the concrete is relatively large ~100,000 cm^3 so that the spatial resolution is relatively coarse.
2. The chloride signal is averaged over depth, so it is not possible to measure the depth profile which is important to assessing possible corrosion hazards.
3. The detector is sensitive to gamma rays generated by the hydrogen content of the moderator around the source, which makes it impossible to measure water within the concrete itself, which is an important parameter.
4. The detector is also sensitive to the gamma rays produced by PGNA of other elements in the moderator which adds significant background.

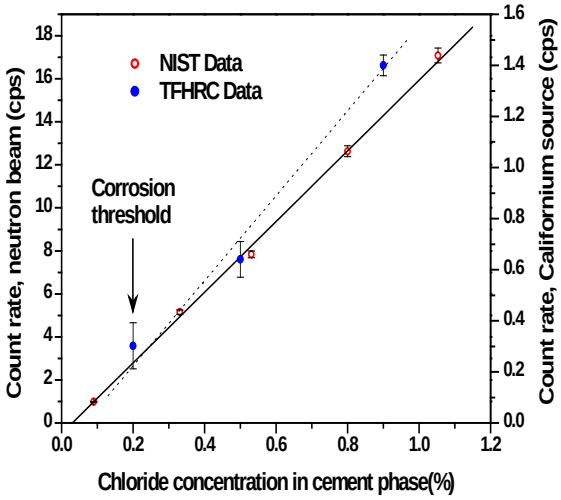

Figure 4 Results of calibrations with neutron beam and ^{252}Cf source for the omni-directional.

To overcome these difficulties, it is therefore proposed to develop and evaluate a second generation PGNA chloride detector based on the use of a Compton telescope configuration using two detectors.

I.5 Conceptual design of 2nd generation system

As discussed above, the current 1st generation system is omni-directional and thus samples a very large volume. In order to improve the spatial resolution, it is necessary to make the detector more directional by introducing a collimator to constrain the solid angle in which the gamma rays are detected. In the laboratory this is usually done by a physical collimator, which consists

of a shield of dense material such as lead around the detector, with an opening that defines the direction. However, the thickness of lead required to attenuate a 6.111 MeV gamma ray coming in the wrong direction by a factor of 100 would be about 10 cm. Consequently, the mass of the entire collimator would be about 250 lbs, which would be impractical for a system intended to be portable. An alternative approach employed here uses an electronic collimator based on the Compton telescope configuration.

The significant features of this system are shown in Figure 5. In this system, a gamma ray emitted from the concrete first passes through the electronic collimator. If it is travelling in the right direction; i.e., from the concrete, it is counted. In the process, the gamma ray gives up a

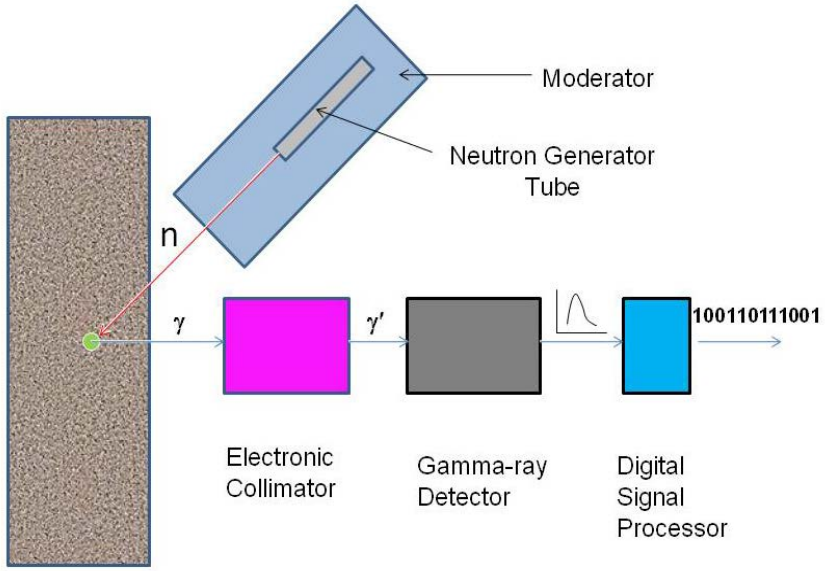

Figure 5 Conceptual design of 2nd generation chloride measurement system.

small amount of energy through Compton scattering. The gamma ray leaving the collimator then enters a conventional HPGe detector where its remaining energy is measured. The output of the HPGe detector is an analog voltage pulse, as shown in Figure 5. In conventional counting electronics, this pulse is integrated to give a total charge, which is then digitized for assignment to a specific counting bin or channel. In the 2nd generation system, another innovation is the introduction of a digital signal processor which digitizes the actual shape of the analog pulse. This enables more precise determination of the gamma-ray particle's energy.

The third innovation is the replacement of the ^{252}Cf radioisotope source by a neutron generator. This is motivated by the fact, as discussed below, that introducing the electronic

collimator reduces the overall count rate. Commercially available portable neutron generators use the deuterium-deuterium (D-D) or deuterium-tritium (D-T) fusion reaction to generate the neutrons and can produce neutron currents as high as 3×10^8 n/s, which is about 30 times greater than the maximum from the ^{252}Cf radioisotope source. In addition to providing a higher neutron flux, the use of the neutron generator would minimize the need for shielding requirements during transport.

In addition to the improved spatial resolution of the detector, background would be significantly reduced, thereby improving the counting statistics and reducing the time required to make a scan of an area. Although the main emphasis here is on the detection of Cl, the system will also simultaneously measure the other elements in concrete. By eliminating the hydrogen signal from the moderator, it would also be possible to measure the water/cement ratio in the concrete. Other elements such as Ca, Si, Al, Mg, Na, and K can also be measured, which can be used to reverse engineer the original mix design (Anderson et al. 1983). Therefore the proposed technology may have other markets beyond the inspection of concrete structures for chlorides.
Also, the neutron generator can be operated in a pulsed mode. This makes it possible to measure additional elements by fast neutron activation and also to make time-of-flight measurements for depth profile measurement.

I.6 Operating principle of electronic collimation

As noted above, the current system is omni-directional and thus samples a very large volume. In order to improve the spatial resolution, it is necessary to make the detector more directional by introducing a collimator to constrain the solid angle in which the gamma rays are detected. In the laboratory this is usually done by a physical collimator, which consists of a shield of dense material around the detector, with an opening that defines the direction. However, the thickness of lead required to attenuate a 6.111 MeV gamma ray coming in the wrong direction by a factor of 100 would be about 10 cm. Consequently, the mass of the entire collimator would be about 250 lbs, which would be impractical for a system intended to be portable. An alternative approach proposed here would be an electronic collimator using the Compton telescope configuration.

The term “Compton telescope” is short for an x-ray or gamma-ray telescope based on Compton scattering. This was developed for astronomy at X-ray or gamma-ray wavelengths

where optical methods involving lenses or mirrors are not effective (Schonfelder 2004). The astronomical Compton telescope is a very complicated system involving arrays of detectors to collect images. In the application to PGNA chloride detection, the Compton telescope would consist simply of a single very thin planar detector mounted in front of the existing coaxial HPGe

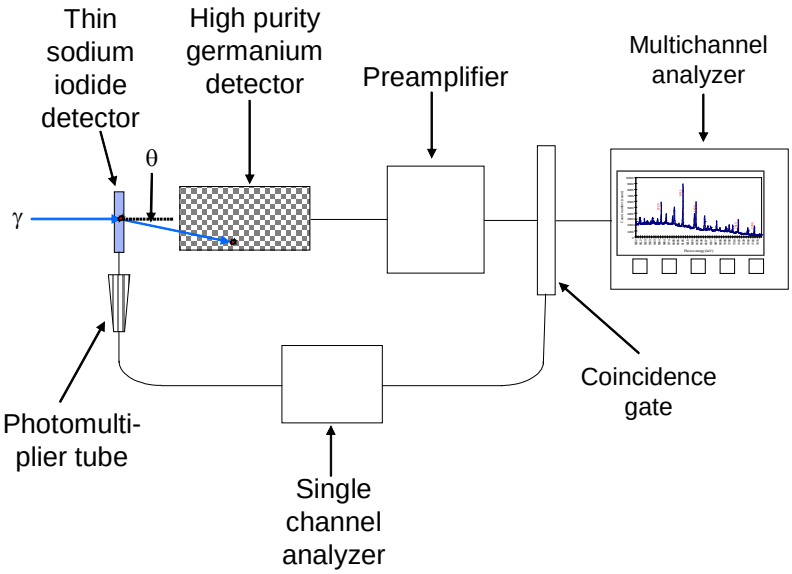

Figure 6 Schematic diagram of the electronic collimation system.

detector as shown in Figure 6. It would thus be more accurate to refer to it as an electronic collimator. A gamma ray traveling in the preferred direction enters this planar detector. Its detection starts the timing. The photon then exits the first detector and enters the HPGe detector where its energy is measured. The two detectors operate in coincidence mode, so that only the photons passing through both within a specified time window would be counted, and those from other directions would be rejected.

The electronic collimator thus detects only those photons coming from a roughly cylindrically shaped volume within the concrete. The diameter of this volume is essentially determined by the area of the first detector. The depth of the volume is determined by the processes of neutron and gamma-ray transport within the material. These processed cannot be calculated analytically, and hence numerical simulations have to be used.

Finally, the literature review did not uncover any other efforts to use a Compton telescope configuration for PGNA to measure Cl in concrete in the field. Therefore, the proposed system is innovative.

II. Proposed Work Plan

The scope of work of the project as originally proposed consisted of three stages:

Stage 1: Numerical Simulations

In order to optimize the design of the system, it is necessary to carry out numerical simulations of the neutron and gamma ray transport from the ^{252}Cf neutron source to the gamma ray detectors. This done using the computer code MCNP combined with optical ray tracing (Mohamed et al. 2007). The optimization would concern the shape and composition of the neutron moderator and also the configuration of the two detectors in the telescope. The numerical simulations would also investigate the influence of concrete composition on the operating parameters of the instrument.

Stage 2: Instrument Assembly and Calibration

Once the design has been finalized, the instrument would be assembled. Initial testing may involve absolute calibration of the instrument at the Cold Prompt Neutron Gamma Activation facility at NIST's Center for Neutron Research under the cooperative agreement between NIST and the University of Maryland. This would involve the use of both radioisotopes and PGNA on pure chloride and nitrogen standards to cover the full 1–-10 MeV energy range of interest (Saleh and Livingston 2000; Molnar et al. 2002) to determine the shifts in the gamma-ray peaks created by the Compton telescope configuration.

To evaluate the directionality of the detector, ^{137}Cs or ^{60}Co gamma ray radioisotope sources would be placed around the detector at various angles from the axis. The area of these sources is so small ~5 mm^2 that they approximate point sources. To verify the performance of the moderator, the neutron flux at the moderator/concrete interface would be imaged using a neutron-sensitive single phosphor image plate.

Calibration of the system for chloride analysis in concrete would be performed in the laboratory on slabs of concrete made with known of amounts of chlorides which would be

prepared by the Civil Engineering Department at the University of Maryland. Two types of test specimens would be made. One type would be whole slabs of concrete with uniform chloride distribution made by adding known amounts of chloride to the mix water. The second type would simulate the chloride diffusion profile typical of de-icing application to the surface. The test specimen would be built up by stacking smaller tiles of concrete or mortar containing varying quantities of chloride. A similar approach would be used to create horizontal chloride variation in order to test the detector's spatial resolution.

Stage 3: Field Testing

Upon completion of calibration in the laboratory, the instrument would be tested in the field on bridges in the Maryland State highway system. Specific bridges would be selected from the Maryland State Highway Administration bridge inventory using a sampling methodology similar to one previously developed for delayed ettringite formation. The selected bridges would provide a variety of chloride environments from Tidewater to the Appalachian Mountains and also to allow evaluation of different types of concrete bridge design. Performance evaluation metrics include counting statistics, background and operator friendliness. For comparison, some cores would be drilled from the concrete and tested for chloride content by conventional chemical methods.

III. Design Calculations

III.1 Electronic collimator

As discussed above, the electronic collimator consists of a very thin planar detector mounted

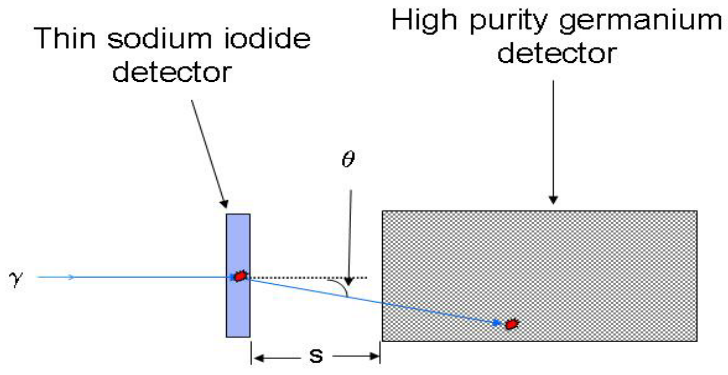

Figure 7 Geometry of Compton scattering.

in front of the existing coaxial HPGE detector as shown in Figure 7. A gamma-ray photon traveling in the preferred direction enters the front of the first detector and gives up a very small amount of energy by Compton scattering, which involves knocking loose an electron. This event is detected and starts the timing circuit. The photon then exits the first detector and enters the HPGe detector where the rest of its energy is deposited. The two detectors would operate in coincidence mode, so that only the gamma rays passing through both within a specified time window would be counted, and those from other directions would be rejected.

As shown in Figure 7, the Compton-scattered photon moves off in a direction that is at an angle θ to the incident direction. If this angle is too large the photon will miss the HPGe detector entirely and thus not be counted. The limiting value of the angle is clearly:

$$tan(\theta_{\max}) = r / s \tag{2}$$

where: r is the radius of the HPGe detector and s is the separation between the two detectors. The radius is fixed at 3.8 cm by the geometry of the detector, but s is adjustable. A larger value of s means a smaller value of θ_{max}. Thus the field of view of the system can be adjusted by changing the distance s. However, specifying a larger s in order to narrow the field of view also means that more of the photons of interest will miss the second detector, thus reducing the count rate.

The Compton angle θ can be calculated from the Compton scattering energy relationship which is simply the conservation of energy modified to take into account relativistic effects:

$$\Delta E = h\nu \left(\frac{\left(h\nu / m_o c^2\right)\left(1-\cos\theta\right)}{1+\left(h\nu / m_o c^2\right)\left(1-\cos\theta\right)} \right) \tag{3}$$

where: ν is the wavelength of the incident gamma ray, h is Planck's constant and $m_o c^2$ is the rest mass energy of the electron (0.511 MeV). The maximum detectable energy loss occurs when $\theta \approx 90^o$, since at higher angles the photon is backscattered and does not enter the HPGe detector. For the 6.111 MeV chloride photon, this maximum energy loss would be 5.639 MeV or about 92%. The scattered photon would thus have a minimum energy of 0.472 MeV.

However, the scattering is not isotropic. The angular differential scattering cross section, or the probability of scattering into a specific differential element of θ, is given by the Klein-Nishina formula:

$$\frac{d\sigma}{d\theta} = \frac{Zr_o^2}{2\pi}\left(\frac{1}{1+\alpha(1-\cos\theta)}\right)^2\left(\frac{1+\cos^2\theta}{2}\right)\left(1+\frac{\alpha^2(1-\cos\theta)^2}{(1+\cos^2\theta)[1+\alpha(1-\cos\theta)]}\right) \quad (4)$$

where: Z is the atomic weight of the detector material, $\alpha \equiv h\nu/m_o c^2$ and r_o is the classical electron radius. The resulting computed angular distribution of scattered photons is plotted for several incident gamma-ray energies in Figure 8. This indicates that at 6.111MeV, the distribution would be highly peaked in the forward direction and hence the typical value of θ would be very low. Hence, by Eq. (2) the energy of the scattered photon would be close to the incident energy.

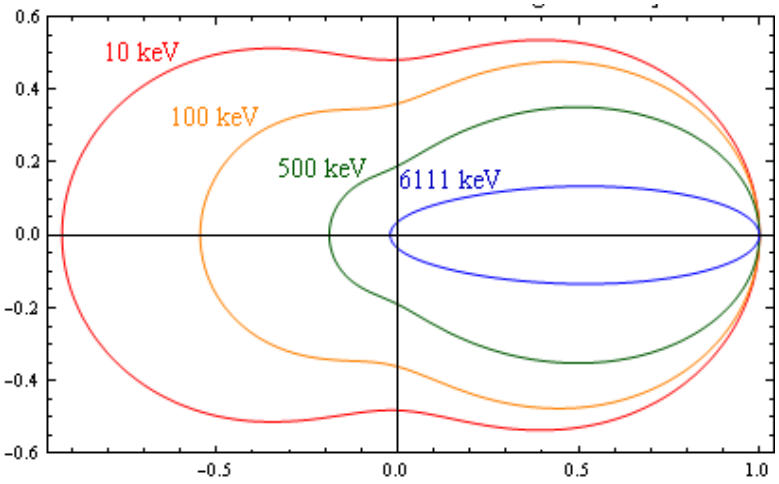

Figure 8 Angular distribution of scattering photons resulting from the Klein-Nishina model of Compton scattering in NaI.

III.2 Planar detector design

The planar NaI detector is a critical element of the collimator subsystem. In turn the most important parameter in the design of the detector is its thickness. Ideally it should be as thin as possible to minimize loss of photons by total absorption through the photoelectric process. Moreover, as the detector becomes thicker, the probability increases of a photon entering it from the side instead of the front and thus triggering a false count by chance coincidence. On the other hand, the incident photon has to deposit a certain amount of energy above the minimum detectable in the first detector for it to be detected. If it is not detected then the time window will

not be opened. Consequently, the incident photon has to have at least one scattering event in the detector in order to start the counting process. Thus the probability of such an event, p_{scat}, should be as large as possible. This is given by:

$$p_{scat} = 1 - \frac{I}{I_o} = 1 - e^{-x/\lambda} \tag{5}$$

where: I_o is the incident beam intensity, I is the intensity at the distance x into the material, and λ is the mean free path; i.e., the average distance a photon travels before a scattering (or absorption) event. This implies that the ratio x/λ should be as large as possible. The mean free path is a property of the material, and is thus fixed. Consequently, the only way to increase the ratio is to increase x, the thickness of the NaI detector.

The mean free path is a function of the photon energy and the material density:

$$\lambda(E) = \mu/\rho(E) \cdot \rho \tag{6}$$

where: $\mu/\rho(E)$ is the energy dependent mass attenuation coefficient and ρ is the material density. The result is that for a 6.111 MeV photon in NaI, $\lambda = 7.81$ cm. Consequently, for a 2 cm thick detector the probability of a triggering event is about 0.23. Thus, inserting this second detector would reduce the count rate in the HPGe detector by a factor of roughly 5. If this is unacceptable, it is possible to compensate for this reduction in several ways described below in Section VI.

The resulting design of the NaI detector is presented in the drawing in Figure 9. This configuration with the photomultiplier tube (PMT) co-planar with the NaI disk is known as a "banjo" detector. Eventually for use in the field, it may be desirable to rotate the PMT by 90º; i.e., parallel to the axis of the disk, to make the overall chloride measurement system more compact. This can be done by inserting a prism at the window between the NaI disk and the PMT. However, this would result in some loss of signal.

III.3 Neutron generator selection

As discussed above, the introduction of the NaI detector reduces the counting rate. To compensate for this, the ^{252}Cf radioisotope source would be replaced by a neutron generator which can give a higher neutron flux. The main components of the neutron generator are illustrated in Figure 9 (Chichester and Simpson 2004). It is actually a compact linear accelerator. The ion source can be either deuterium or a mixture of deuterium and tritium gases. The atoms are stripped of electrons, which gives them a positive charge. They are then accelerated by the large voltage difference between the ion source and the target. When the accelerated ions hit the target, fusion happens with the production of a helium isotope atom and a neutron. This appears

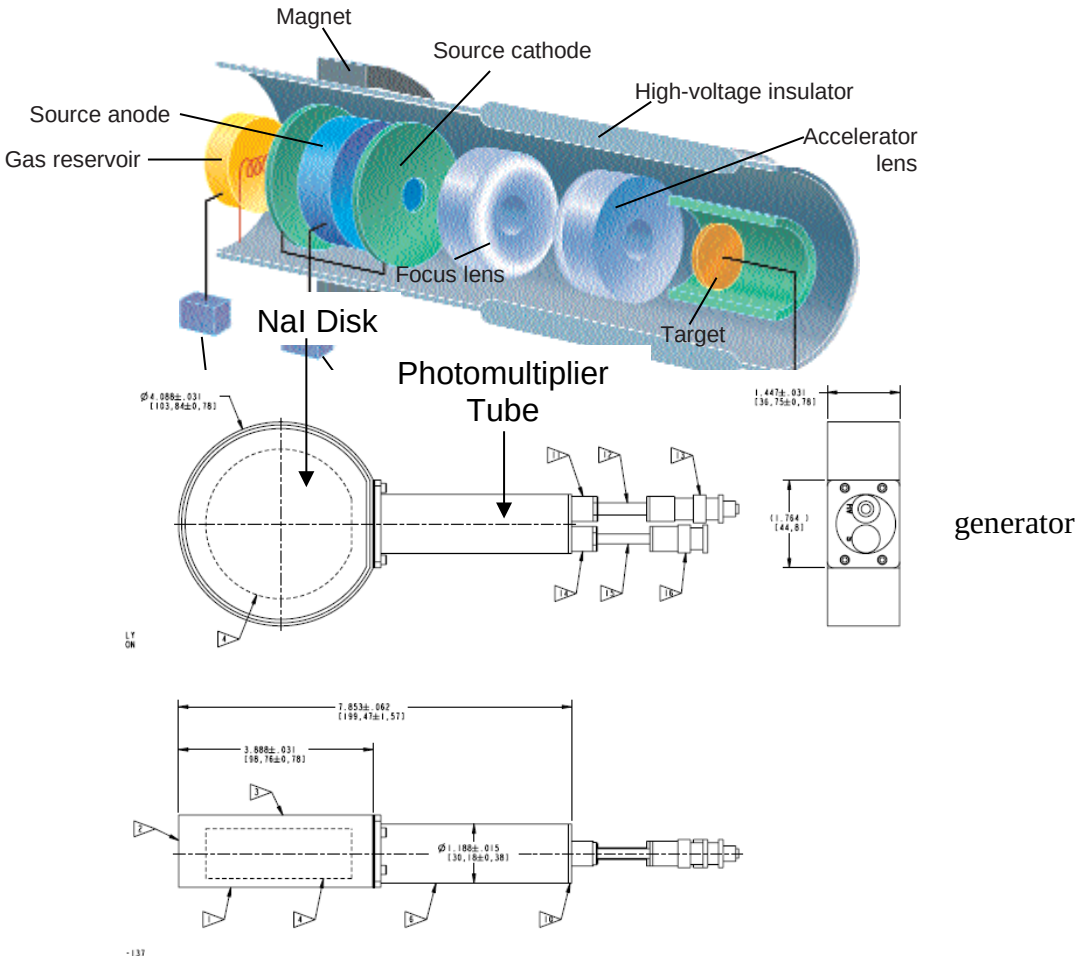

Figure 9 Design of the NaI detector. Dimensions are in cm.

to be a highly complicated system that would be difficult to operate in the field, but in fact, commercial systems based on sealed tube design have been developed. These are simple to use

generator

and reliable. Consequently, they are now used in a number of applications in the field, such as petroleum detection and explosives detection (Chichester and Simpson 2004).

The main issue for the specification of the neutron generator is the selection of the type (D-D or D-T) of neutron generator tube. One consideration is the energy of the neutrons. The D-T fusion reaction produces a 14.1 MeV neutron. The D-D reaction produces a lower energy neutron with 2.45 MeV. In comparison, ^{252}Cf emits neutrons with a range of energies with the most probable value being about 2 MeV. Thus a larger volume of moderator than currently used may be required to slow the neutrons down to thermal energies. This would increase the bulk and weight of the overall system. On the basis of neutron energies it would appear that D-D type would be preferable since the neutron energies are relatively close to that of ^{252}Cf. However, the neutron source strength must also be considered. The D-D nominal yield is 2.5 x 10^6 n/s while the D-T yield is 3.0 x10^8 n/s. Thus the D-D system would produce fewer neutrons than the existing ^{252}Cf source. Therefore the choice is the D-T system.

III.4 Moderator design

The replacement of the ^{252}Cf radioisotope neutron source with the D-T neutron generator requires a re-consideration of the design of the moderator for two reasons. One is the difference in geometry between the two sources. The ^{252}Cf comes in a cylindrical capsule 0.5 cm in diameter by 2.5 cm length, while the D-T tube is 20 cm in diameter and 70 cm in length. The other is the difference in the energy of the emitted neutron, ~2 MeV for the ^{252}Cf source vs 14.1 MeV for the D-T tube, which implies that the moderator for the latter would need more volume to slow the fast neutrons down to thermal velocity.

Moderator design for field applications is not yet an exact science. Ideally, the moderator should maximize the delivery of thermal neutrons to the target while minimizing losses due to capture in the moderator material, while at the same time minimizing the radiation exposure to the operators.

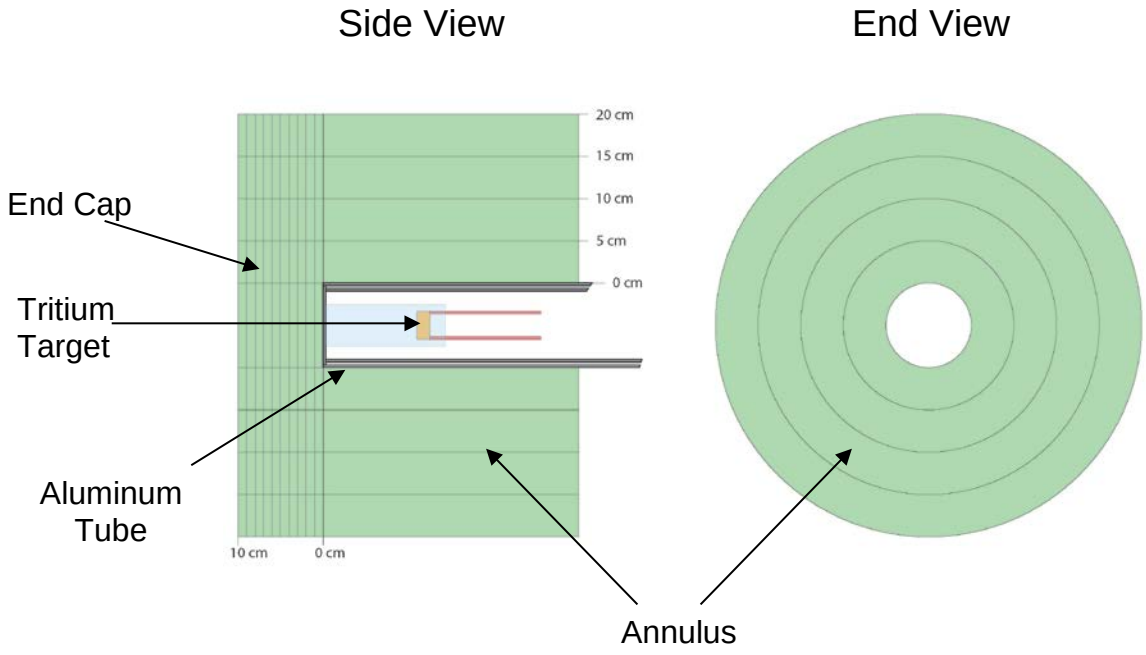

Figure 10 Schematic diagram of the initial moderator geometry for the D-T tube.

The moderator design used in the first generation PGNA system consisted of a solid cylinder of polyethylene 15 cm in radius with a hemispherical end cap (see Figure 3). The preliminary design for moderator for the D-T tube (Figure 10) consists of a cylindrical annulus into which the tube fits and an end cap between the face of the tube. The material chosen for the moderator is polyethylene. This contains a significant amount of hydrogen, which is the most efficient element for neutron scattering and thus the most effective at slowing down the neutrons. However, it also has a large cross-section for absorption. Consequently, the thermal neutron flux in the moderator is the balance between two competing processes: slowing down of fast neutrons, which increases the thermal neutron population, and absorption, which removes them. This problem can't be solved analytically. Therefore, it has to be modeled by numerical simulations using the computer software MCNP (Team 2003).

The effect of varying the dimensions of the moderator shown in Figure 10 was thus investigated by MCNP computer simulations. Five different values for the annulus wall thickness ranging 0–20 cm were chosen. For each of these thicknesses, the thickness of the end cap was varied systematically from 0 to 10 cm in 1 cm increments. The results are presented in

the plots in Figure 11. The thermal neutron flux for the point at center of end face is plotted against the end cap thickness. It can be seen that for the end cap by itself without an annulus, the flux peaks at a value of 615 n/cm^{2}s. Any additional thickness tends to act slightly more as an absorber than a moderator.

Adding an annulus significantly increases the thermal neutron flux by nearly an order of magnitude. One reason for this is that neutrons that initially travel in the radial direction, and would otherwise be lost, are scattered into the axial direction. It can be seen there is no significant increase in the neutron flux going from a wall thickness of 15 cm to 20 cm. This increment of thickness would increase the overall weight of the moderator by 38%. This suggests that the optimum wall thickness would be 10–15 cm.

Finally, for any wall thickness, adding a thin end cap causes an actual decrease in neutron flux. It then reaches a local maximum for an end cap thickness around 3 cm.

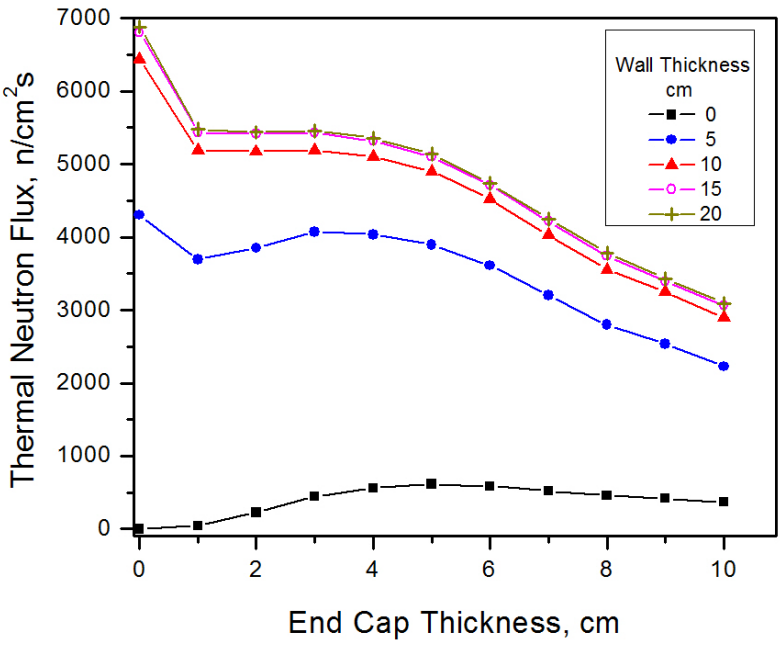

Figure 11 Thermal neutron flux at center of moderator end face.

IV. Experimental Investigations

IV.1 Proof of principal of electronic collimation

Since there were no neutron sources available at the time of experiment, it was necessary to use a radioactive source of gamma rays, ^{137}Cs. The energy of the gamma ray, 0.661 MeV, was considerably below that of the H and Cl lines of interest, 2.224 and 6.111 MeV, but the results are still qualitatively valid.

The first experiment concerned the effectiveness of the background rejection. As shown in Figure 12, the source was placed alongside the HPGe detector to represent gamma rays that would not originate in the target material. Spectra were then taken with the coincidence circuit off and then with it on. The counting time for both cases was 100 s.

The graph also presented in Figure 12 shows the results. In the case with the coincidence circuit off, all the typical features of the ^{137}Cs spectrum are present including the 0.661 MeV gamma photopeak and the 32 keV X-ray peak. With the coincidence circuit on, there are essentially no counts. The inset in Figure 5 shows the region of interest around the photopeak. There are only three counts compared to the 4,442 counts with the coincidence off. This is a reduction in count rate of 6.75 x 10^{-4}. To achieve the same attenuation with a physical collimator

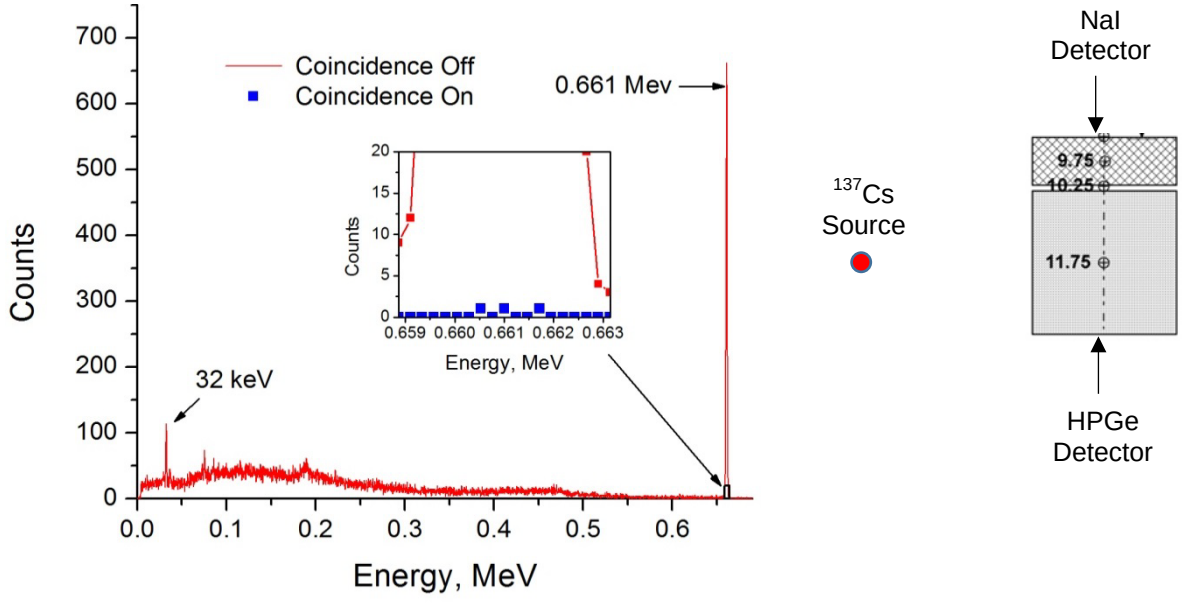

Figure 12 Gamma ray spectra of ^{137}Cs source placed alongside the HPGe detector as shown in the diagram on the right. Both the coincidence off and the coincidence on spectra are plotted. The inset shows the counts in the main peak with coincidence on.

would require a cylindrical lead shield around the HPGe detector 6.4 cm thick which would weigh 32 kg or 71 lbs. For the higher energy gamma ray of 2.223 MeV emitted by neutron capture on hydrogen, the same attenuation factor would require 111 kg of lead or 245 lbs.

IV.2 Detector angular response

The second experiment investigated the angular dependence of the electronic collimator, which determines the field of view. The source was placed in front of the NaI detector at a distance of 9.25 in along the center axis of the pair of detectors. The source was then systematically moved transversely from the center line as shown in the diagram in Figure 13.

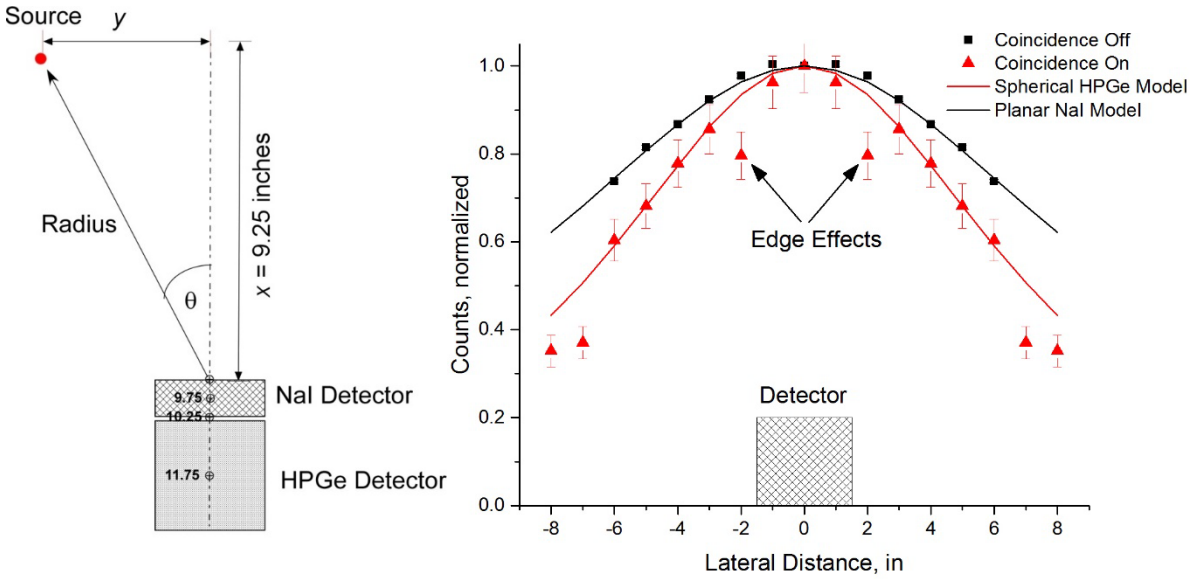

Figure 13 Diagram and data for mapping of electronic collimator angular resolution.

The area under the ^{137}Cs 0.661 MeV peak is plotted as a function of transverse distance for both coincidence off and on in Figure 14. It can be seen that there is a significant difference in between the two conditions. With the coincidence circuit on, the counts decrease more rapidly with distance from the center axis. There is a dip in the data around ± 2 in., which may be due to edge effects with the NaI detector, which extends to only ± 1.5 in.

As also shown in Figure 13, the data have been fitted to a pair of models, which are simply functions of the solid angle subtended by the detector and the incidence angle of the photon to the detector's surface (Knoll 2000). The solid angle depends on the source-detector distance and the detector shape. In the coincidence off condition, the detector array has an angular dependence that is best approximated by a spherically shaped detector, which is the effective

shape of the HPGe detector. For the coincidence on condition the best fit is to a planar detector. This indicates that the NaI detector is in fact controlling the count rate, which is the stated objective of the electronic collimator.

IV.3 Concrete test slabs

In order to evaluate the performance of the system, it is necessary to have test specimens with known chloride contents. Therefore, specimens were cast with calcium chloride added to the mix water of the concrete batches in specified amounts (Livingston et al. 2010). These will be used to determine the calibration function relating the detected Cl gamma-ray counts to the actual Cl concentration in the concrete. They will also be used to determine the data quality parameters of sensitivity, precision and minimum level of detection.

Two shapes of specimens were cast. One is a thick slab with dimensions of 3 ft by 3 ft by 5 in. (90 x 90 x 12.7 cm). These dimensions are larger in lateral area and depth than the volume detected by the PGNA system. Thus each specimen is effectively a semi-infinite slab. Five of these slabs will be cast with Cl concentrations as shown in Table 1.

Table 1
Thick Slabs Cl Content

Slab No.	Cl Concentration % Cl by wt Concrete
1	0.6
2	0.5
3	0.3
4	0.025
Control	~0

The chloride concentrations are selected to span the range of values typically found in the field down to the concentration that has been identified as the threshold for promoting corrosion: 0.025% by weight of concrete. These thick slabs thus have spatially uniform concentrations of Cl, which would be representative of a concrete mix that had calcium chloride added as an accelerator or as anti-freeze for low temperature emplacement.

However, the chloride content of concrete bridge decks in North America is more often the result of de-icing salts applied to the surface. This produces a non-uniform Cl depth profile which can typically be modeled as a Fick's Law-type diffusion gradient as shown in Figure 14a (Livingston et al. 2010). This profile can take many years to develop, and thus it is difficult to

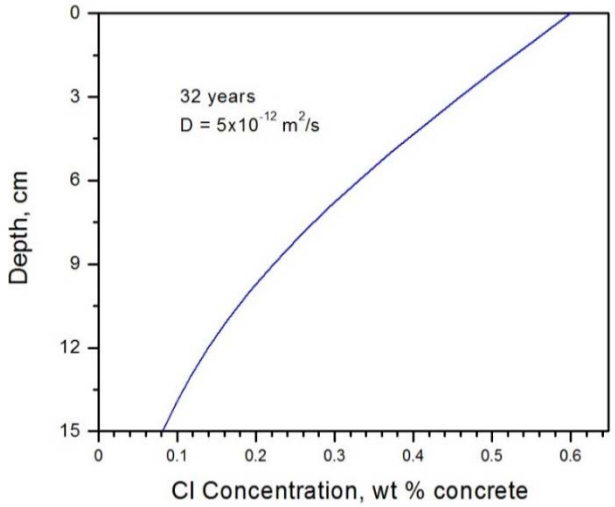

Figure 14a Typical Cl gradient in concrete.

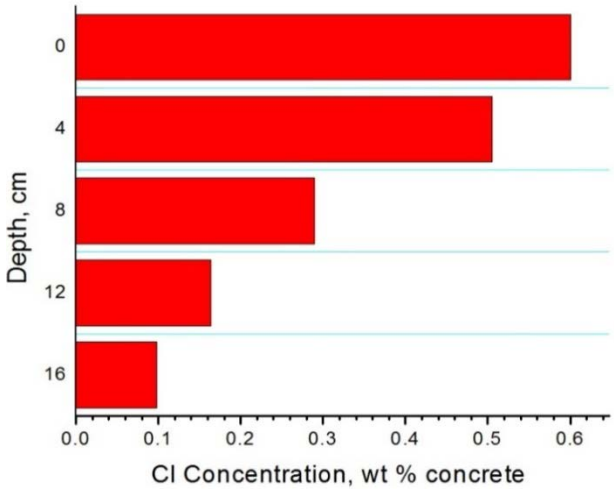

Figure 14b: Thin concrete slab approximation to the Cl gradient in Fig. 14a.

prepare laboratory specimens by the ponding technique. Therefore, to approximate this profile, a series of 5 thin concrete slabs each 3 ft by 3 ft by 1 in. (90 x 90 x 2.54 cm) were prepared. The chloride content thus is uniform within an individual thin slab, but it varied from slab to slab as shown in Figure 14b.

The concrete was mixed in five batches. As shown in Table 2, the proportions of the concrete constituents were held constant except for the calcium chloride, which was dissolved in the mix water. Both thick and thin slabs of a given chloride content were cast from the same batch. Figure 15 is an image of a typical thin slab being cast in its wooden mold. The slabs are left in the molds for ease of handling and to protect the edges from chipping. The concrete slabs are currently in storage at the Maryland University Training Reactor.

Table 2

Mix Designs for Concrete Slabs (lbs)

Constituent	Control	Batch No.			
		1	2	3	4
Water	65.67	65.67	65.67	65.67	65.67
Cement	131.35	131.35	131.35	131.35	131.35
Coarse aggregate	301.00	301.00	301.00	301.00	301.00
Fine aggregate	268.00	268.00	268.00	268.00	268.00
Calcium chloride	—	4.05	3.38	2.03	0.19

Figure 15 Casting of a typical thin slab concrete test specimen.

IV.4 Cold neutron PGNA results

As described in Section V, no neutron sources were available during the course of this research. Nevertheless, it is possible to make an estimate of the feasibility of an NDT method using PGNA for measuring chloride based on the results from a related project concerning the feasibility of using PGNA for measuring hydrogen as an indication of moisture in building

stones (Livingston et al. 2014). This research was funded by a collaboration between the University of Maryland and the Smithsonian Institution.

This research included a systematic characterization of the lithology and physical properties of seven building stones and one brick type used in the buildings of the Smithsonian Institution in Washington, D.C. In particular, cold neutron PGNA was also used to determine chemically bound water (CBW) content using the nuclear reactor at NIST's Center for Neutron Research (NCNR). Cold neutrons have the temperature of liquid hydrogen ~20 K (Paul et al. 2008) compared to 293 K for thermal neutrons that would be produced in the field PGNA system. This makes the capture cross-sections for cold neutrons considerably higher than for thermal neutrons and thus the production rate of PGNA gamma rays would be proportionately higher. However, the two rates can be compared using the $1/v$ relationship of the capture cross section to the neutron velocity v.

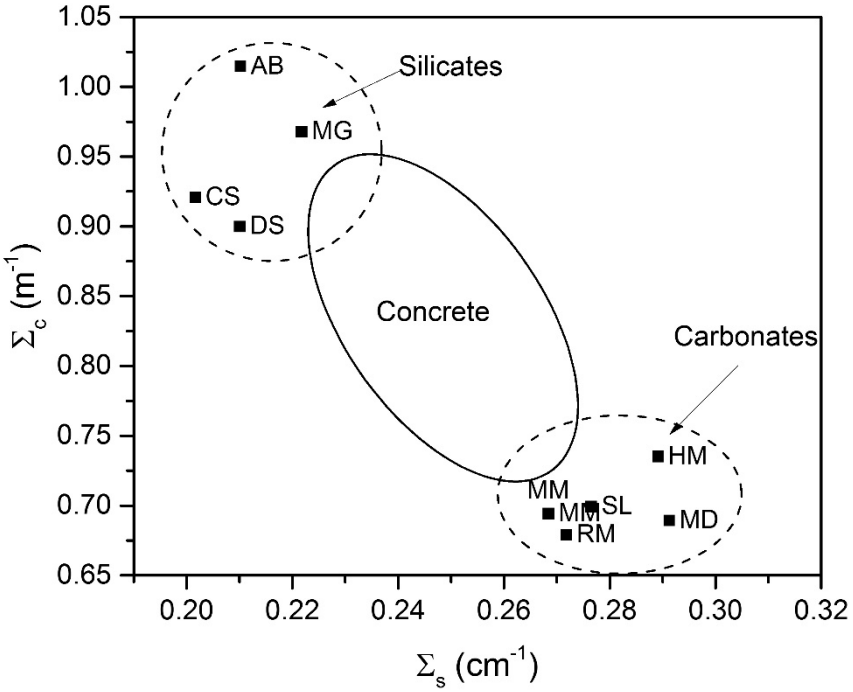

Figure 16 Comparison of stone and concrete neutron transport parameters (after Livingston et al. 2014).

The stones' chemical composition ranged from silicate (Mt. Airy granite) to carbonate (Holston marble). Portland cement itself is a calcium silicate and concrete is a mixture of

cement and stone aggregates, either silicate or carbonate. Consequently, the neutron transport properties of concrete span the range between the two types of stone, as shown in Figure 16. This makes it possible to apply the results of the Smithsonian stones study to concrete.

Samples of each stone were ground into powder which was then pressed into a pellet. Each pellet was irradiated with cold neutrons. The thermal neutron equivalent flux was approximately 8×10^8 cm^{-2} s^{-1}. In all 27 samples of stone, eight standards and two background samples were analyzed, generating a total of 37 spectra.

The results of the NIST PGNA measurement of the CBW in the Smithsonian stones provide some data points that can be used to project the performance of a portable PGNA system for use in the field. Table 1 presents some PGNA parameters for the NCNR measurements compared to those for a field system based on a neutron generator. The H_2O concentration, 0.4%, is taken from the Salem limestone CBW. This would be the minimum value that would have to be detected in the field. It is the same for both cases, because it is a property of the stone, not the measurement system. On the other hand, the sample volumes differ significantly. For the NCNR measurements, this was fixed by the pellet size. In the case of the field system, the volume is a function of the electronic collimator design and the details of the neutron and gamma ray transport in the material, which cannot be determined analytically. However, 1000 cm^3 is a reasonable order of magnitude, based on previous work using Monte Carlo numerical simulations, which found a sample volume of 10^5 cm^3 for an uncollimated system (13). The neutron flux also differs significantly, in the other direction. This reflects the fact that neutron sources for use in the field are limited to strengths less than about 10^9 s^{-1} to avoid the need for bulky and heavy shielding. The reactor-based value of 8×10^8 $n/cm^2 \cdot sec$ is the thermal equivalent of the actual cold neutron flux. The gamma-ray detector efficiencies are the same, assuming that both measurement systems use the same design of HPGe detector. Then the observed H count rate of 35 cps for the reactor case, the equivalent count rate for the field system would be on the order of 1 cps. This is a reasonable rate for field measurement because it implies a data acquisition time of about 15 minutes to achieve 3% uncertainty. It should also be noted that it is for the lowest expected H value.

Table 3
Comparison of PGNA parameters

Parameter	Reactor, Measured	Field, Projected
H_2O concentration, %	0.4	0.4
Sample volume, cm^3	0.5	1000
Neutron flux, $cm^{-2} \cdot s^{-1}$	8×10^8	5×10^3
Detector absolute efficiency, %	0.0268	0.0268
H Count rate, cps	35	~1

The H count rates were roughly 1–3 cps. Taking into account differences in neutron energies and fluxes and sample volume between cold PGNA and a portable PGNA instrument, it appears that it is feasible to apply PGNA in the field for H measurement. For applying these results to chloride detection, it should be noted that the major difference between the two elements is the partial capture cross-section, σ^Z_γ. For the H capture reaction ^1H (n, γ) ^2H, the σ^Z_γ is 0.333×10^{-24} cm^2 compared to 33.1×10^{-24} cm^2 for the ^{35}Cl (n, γ) ^{36}Cl reaction. This implies that the count rate for chlorides would be about two orders of magnitude greater, which would make PGNA very practical for chloride measurement in the field.

This estimate of the projected field performance does not take into account two hardware-based factors that would reduce the effective count rate. One is the gamma-ray background. The other is the loss of detector efficiency due to the introduction of the electronic collimator. However, these can only be determined by actual measurement on a prototype PGNA system.

V. Summary of Progress

The original work plan, as presented in Section II, had three stages. Stage 1, which concerned design calculations, has largely been completed. This consisted of specifying the dimensions of the planar gamma-ray detector, selecting the type of neutron generator and modeling the moderator using the MCNP software.

However, a major obstacle to the completion of Stages 2 and 3 was the lack of a thermal neutron source in the timeframe of this project due to a combination of factors. The nuclear reactor at the University of Maryland was not operable because of the failure of an essential

neutron monitor, which took nearly a year to replace. Simultaneously, the nuclear reactor at NIST was down for a year to install additional beam lines. Finally, a portable neutron generator had been obtained by the University of Maryland under an equipment grant from the Department of Energy, but it was not possible to operate it on campus because of radiation safety licensing issues. Consequently, most of the work proposed in Stage 2 of the original work plan, which involved calibration of the system in the laboratory, could not be accomplished. Nevertheless, some experimental investigations were carried out using radioisotope gamma-ray sources. This work confirmed the principle of electronic collimation and verified the improved directionality of the system. In addition, experiments using the cold neutron PGNA station at NIST provided data that can be used to estimate the performance of a portable field PGNA system. Finally, concrete test specimens were cast with known amounts of chloride in them. These specimens can be used for calibration of the system when a portable neutron source becomes available. The field tests proposed for Stage 3 also could not be carried out because of a lack of a portable neutron source.

VI. Future Research

VI.1 Motivation

A critical factor that determines the feasibility of an NDT system to be used in the field is the data acquisition rate. This depends upon the amount of time required to collect a complete set of data at a given location on a structure. For techniques based on radiation measurement, this time is set by the count rate and the specified uncertainty. The fractional uncertainty, based on counting statistics, is $\sqrt{N}/N$, where N is the total number of counts collected at a peak of interest such as the 6.111 MeV for Cl. Thus for an uncertainty of 10%, n = 100 counts and for 1%, N = 10,000 counts. The time to acquire a gamma-ray spectrum, τ, is given by:

$$\tau = N/R \tag{7}$$

where: R is the count rate of the photon of interest. This is the total rate, which is the integral of this function over all points in the sample volume.

In field applications of PGNA, a compromise value of 1,000 counts for N is typically used, giving an uncertainty of 3%. In previous work on chloride measurement with the single omni-directional detector, a count rate on the order of 1 count per second (cps) was achieved. Thus τ =

16 minutes. This compares favorably with the hour or more required for the standard chloride measurement method, which involves destructive sampling and wet chemistry analysis (Khan 1997).

However, adding the NaI detector to make the electronic collimator will inevitably reduce the count rate for several reasons. One is that by intention the sample volume is reduced. Second, as discussed above, this detector has to be limited to about 2 cm thickness. However, this means a certain number of photons will pass through the detector without being detected at all and hence won't trigger the coincidence circuit. It is estimated that only 20% of the incident photons will be detected. Finally, timing considerations in the coincidence circuit itself will mean that a certain number of photons which should be counted will be missed.

Therefore, a major objective of future research would be to compensate for this loss in data acquisition rate caused by the electronic collimator through improvements in both hardware and software. This strategy is based on consideration of the governing equation of PGNA, given above as Eq. 1, which for a point in the target material is given by the product: $n\sigma_{\gamma}^{Z}\phi_{th}\varepsilon(E)$. Of the four factors involved, the number density, *n*, is the unknown variable to be measured, and σ^{Z}_{γ} is constant for a given isotope. Therefore, the options for increasing the data acquisition rate are to increase either the detector response function $\varepsilon(E)$ or the thermal neutron fluence rate ϕ_{th}, or preferably both.

VI.2 Increased detector response

The effective detector response function involves the intrinsic detector efficiency as well as the electronic circuitry for electronic pulse height analysis.

a. Intrinsic detector efficiency—The HPGe detector normally used for PGNA has a relatively low efficiency compared to scintillator detectors such as NaI, however, it has been preferred because of its significantly better energy resolution, ~3 keV vs NaI, at 47 keV (Knoll 2000). Recently, a new type of scintillator, lanthanum bromide ($LaBr_3$) has become commercially available with a resolution ~20 keV. Although still not as good as HPGe, Favalli et al. (2010) found that it is adequate for PGNA work. It also had an efficiency approximately 10 times better than HPGe. Other advantages include a much faster response time, discussed below, and room temperature operation, which avoids the liquid nitrogen cooling system required for HPGe. Therefore, it is proposed to replace the HPGe detector in the PGNA system with a $LaBr_3$ one.

b. Dead time reduction—The pulse height electronics can analyze the energy of only one photon at a time. Thus the count rate is limited by the amount of time required to analyze the electronic pulse of a single photon. Any other photons entering the detector during this period will not be counted. The pulse width of an HPGe detector is roughly 6 μs, while the pulse width of a scintillator detector like NaI is about 700 ns and for $LaBr_3$ ~100 ns. This implies a theoretical improvement in count rate by a factor of 60. This is another justification for switching detectors.

However, this higher count rate will be difficult to achieve without also upgrading the electronics. Historically, analog pulse shaping circuitry (i.e., pulse shaping amplifiers, delay line circuits and discriminators) has been used to analyze the output of radiation detectors. However, direct digitization of the detector output followed by digital pulse analysis techniques offers much higher speed. This is because more complex signal conditioning and 'optimal' filtering functions can be implemented (Scoullar et al. 2011). Another advantage of digital pulse processing (DPP) is stable operation across a wider range of temperatures and noise environments, which is important for systems to be used in the field. Therefore, it is proposed to replace the conventional analog electronics with a DPP system.

VI.3 Spectrum post-processing

In the conventional approach to PGNA radiation detection, only the photons that deposit all their energy in the detector at the photopeak position in the spectrum are included in the count rate. However, many of the photons passing through the detector deposit only part of their energy, because of Compton scattering out of the detector or electron-positron pair production, and thus go uncounted (Knoll 2000). If these photons were also included, the effective count rate would go up significantly for a given flux of photons on the detector. The photons reduced by pair production can be recognized because they have characteristic energies of either 0.511 or 1.022 MeV below the photopeak energy. However, the Compton-scattered photons can have a wide range of energies and appear as part of the overall Compton background of the spectrum. Nevertheless, the contribution of a given energy photon to this background can be recovered by a process known as spectrum deconvolution or unfolding (Knoll 2000). In the case of concrete, this process is simplified because it is a manmade material in which the major elements are limited to the set of Ca, Si Al, K, Na, Mg, and Ca, and their proportions can be calculated from the mix design.

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### VI.4 Increased thermal neutron fluence rate

For PGNA, the 14 MeV neutrons produced by the neutron generator must be slowed down to thermal energies by scattering in the moderator. In the process, many of the neutrons are lost by capture in the hydrogenous material of the moderator. Numerical simulations by the investigators of the thermal neutron fluence rate yield from a simple cylindrical polyethylene moderator found a maximum value of 5,500 $cm^{-2} \cdot s^{-1}$ for a neutron source strength of $10^9$ fast neutrons per second. Consequently, there is considerable room for improvement by the advanced design of the moderator. This includes a more complex geometrical shape. Another option is the addition of a reflector. A third option is to replace the hydrogenous material with another with a higher neutron scattering to capture ratio (moderator ratio) such as graphite or heavy water. Finally, it may not be desirable to completely thermalize the neutron fluence rate in the moderator. The concrete itself contains about 8% water, as discussed above. It would be more effective to allow some fast neutrons to thermalize in the concrete. It would be necessary to perform numerical simulations of neutron and gamma-ray transport using MCNP to determine the optimum moderator design.

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Appendix A
Information Dissemination

Publications

Livingston, R.A., M. Al-Sheikhly, C. Grissom, E. Aloiz, and R. Paul (2014). "Feasibility Study of Prompt Gamma Neutron Activation for NDT Measurement of Moisture in Stone and Brick," *40th Annual Review of Progress in Quantitative NDE*, D.E. Chiment, L.J. Bond, and D.O. Thompson, Eds., AIP, Vol. 1581, pp. 828–835.

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Presentations

Oral

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Poster

Livingston, R.A., M. Al-Sheikhly, and A.M. Amde (2011). *Development of a Second Generation Neutron-Based Detector for Chloride in Concrete*, NCHRP IDEA Project 136, Transportation Research Board Annual Meeting, Washington, D.C.