Remote Gamma Ray Survey of Underground Ductwork at Y-12

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Abstract

Building 9206 opened at Y-12 in about 1944 for special chemical processing. For the first decade of its existence, a system of underground ducts provided the building's room ventilation and chemical process exhaust. The underground ductworks were removed from service and replaced with rooftop units when air conditioning became commercially available. The underground ducts were sealed and remained so until this year. No quantitative assessment of uranium holdup had been made. In the past few years, questions had been asked about the potential for a nuclear criticality accident that might occur because of the uranium holdup in the large underground ducts. No definitive statement could be made about nuclear criticality safety until a holdup survey had been performed. Such measurements are very difficult because access to the ductwork is limited, and because many measurement conditions are unknown and uncontrollable. A gamma ray detector and a miniature multi-channel analyzer were attached to a remote-controlled crawler, then driven up into the ductwork as far as possible. The crawler was equipped with lights and a video camera as well. Although a complete survey was not performed, six ducts were evaluated and about 800 feet of ductwork were scanned. Approximately 330 grams of uranium holdup was found throughout the ducts. This paper will outline the measurement conditions and assumptions required to calculate the holdup. Experimental difficulties are discussed, especially the factors that contribute to measurement uncertainty.

Introduction

An extensive system of underground ducts provided ventilation and process exhaust to Building 9206 when the building was first occupied. Several years later, the underground ductwork was removed from service and sealed. Many branch ducts served the process areas of the building, and these ducts were in turn connected to six main ducts that terminated in two (north and south) header pits. The north pit served four ducts, and the south pit served two ducts. The header pits have sump pumps to remove infiltrated ground water. The ducts are cylindrical, and are made of fired clay or cast concrete. Duct diameters range from 30” down to 6”, but it proved impossible to examine the smaller ducts.

Over the years, the ductwork may have accumulated deposits of process material. The mass and distribution of this holdup were unknown, and the situation created a concern about nuclear criticality safety. To resolve questions about potential criticality safety risk, video and radiometric surveys were performed to determine the amount of uranium held up in the ductwork.

A remotely controlled crawler was equipped with a video camera and gamma ray spectrometer, and this crawler traveled inside the ducts. The crawler was unable to negotiate sharp turns or climb steep slopes, so it was unable to explore any branch ducts. This report describes the survey of the main underground ducts only.

The visual inspection did not show any significant deposits on the inner walls of the ducts, but a ribbon of silt was visible in the bottom of each. The analytical approach to this project assumes that all uranium is in the silt at the bottom of the ducts. The silt was scanned with a collimated gamma ray detector, and the spectra were analyzed to calculate the amount of radiation emitted by U-235. The silt has been modeled as a two-dimensional area. The spectral data have been applied to this model to determine the amount of uranium present.

This paper describes the measurement technique, which is a departure from conventional holdup methodology. It also describes mathematical modeling of the likely source/detector interactions to develop suitable correction factors for variations in detector efficiency with respect to tilt angle. For logistical reasons, this modeling actually took place after the measurement campaign was completed. Uncertainties are discussed and their relative contributions are estimated. Calculations and quantitative results are detailed in another paper [1].

Experimental
Sludge samples were taken from the sumps in north and south pits. These samples were subjected to chemical analysis in the Plant Laboratory before the visual and radiometric scans were performed. The results allowed some initial estimate of the uranium holdup that might exist in the underground ductwork, and are included in this report for the record. Selected chemical analysis results are presented in Table 1.

Table 1: Uranium content of sludge samples taken from north and south pits. Uranium enrichment and concentration were both determined by isotope dilution mass spectrometry. The results shown are the averages of two determinations.

Sump ID	U (ppm)	U-235 enrichment
North pit	1173	13%
South pit	290	17%

Radiometric data were acquired using a portable, battery powered multichannel analyzer and a collimated, shielded NaI(Tl) detector. The detector and MCA were mounted on a remote-control crawler, with the detector looking forward and tilted about 60° off vertical (Figure 1). The collimator opening was about 13 cm off the floor of the ducts, but this varied because of the softness and varying thickness of the silt deposits. The detector and MCA were wrapped in heavy-gauge plastic film as protection from potentially contaminated silt. The MCA package was securely fastened to the crawler using plastic tape, and the detector was attached with a metal clamp (Figure 1). A video camera and lights were also attached to the crawler. Videotapes were made during the survey, and audio markers were made on the tapes that correspond to spectral filenames so that locations can be correlated with video images.

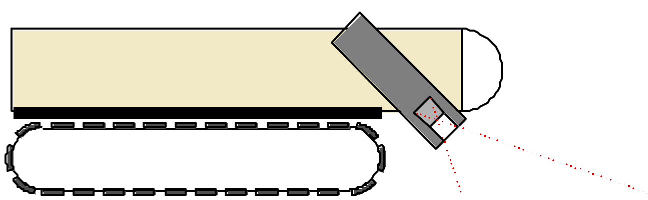

Figure 1: Diagram of remote-controlled crawler showing relative positions of horizontally mounted video camera and detector tilted from normal. Dotted lines represent the collimated detector's field of view.

The detector had an internal Am-241 source for spectrum stabilization and quality control. A signal cable connected the MCA to a computer. The long distance (up to 100 meters) between the MCA and computer made RS-232 communications unreliable. Communications were improved using RS-232/RS-485 converters at each end since the twisted-pair signals have better noise immunity. The converters required external power, so the crawler-mounted unit was equipped with a battery pack. Both the MCA and the battery pack were recharged every night. The communication wires had an unfortunate tendency to break at the converters.

The detector was initially calibrated using Los Alamos Generalized Geometry Holdup (GGH) methodology [2]. Approximately 180 spectra were acquired and analyzed for this project. Spectra were acquired for 150 seconds unless otherwise noted, and all spectra were 512 channels. Gain stability was checked frequently using the 60-keV peak from Am-241. The spectra were saved and analyzed after the survey was complete.

Two crawlers were used. The first crawler was a 4-wheeled vehicle with one motor. It could travel forward or reverse but could not be steered. It was only suitable for surveying straight ducts, and was only used in Duct N-1. The second crawler had independently operable caterpillar treads and could be steered. It was narrower than the first unit and top heavy, so it turned over once during the survey and had to be dragged out. The crawler was unable to negotiate turns sharper than 45^o, and unable to ascend steep slopes. For these reasons, only the main ducts were surveyed.

During the project, the crawler's lighting circuit developed electrical noise that interfered with MCA operation. To mitigate this, lights were switched off during measurements.

Data analysis and correction factors

Preliminary data reduction treated the silt deposits as generalized area deposits. The actual deposits were not ideal areas, since the detector field of view often extended beyond the margin of the silt ribbon. Some bias would be introduced by this problem.

Gamma ray attenuation is caused by the uranium in the deposit, and also by the deposit's inert constituents. A bias correction is necessary to compensate for this effect. Because the uranium concentration is quite low, the inert constituents of the silt will cause most of the attenuation. This attenuation depends on the density, thickness, and elemental composition of the inert constituents. Unfortunately, these parameters are not well known for the measured deposits. In some places, the silt deposits were on the order of several centimeters deep; in other places, they were barely evident. Except for sludge samples taken from the north and south sumps, no physical samples of the deposits were taken. The obvious assumption is that the sump samples are chemically similar to the silt in the ducts, except for variations in moisture content. Because these measurements were made for criticality safety purposes and not for nuclear materials accountability, the worst case was assumed - the uranium is deposited as a planar surface on the bottom of the duct under the silt, and further assumed that the silt is mostly clay. This assumption introduces a positive bias in the results. Calcium aluminosilicate was the assumed matrix for these attenuation calculations. Typical correction factors ranged from 1.2 to 1.5.

The measurement geometry was not ideal either, introducing more bias. Conventional GGH methodology uses a detector that is held normal to the surface of the holdup deposit. In this case, the detector was tilted off-normal for two reasons: to enlarge the detector field of view, and to reduce headroom requirements. The tilt angle significantly changed the detector response, introducing a bias in the GGH calibration. The magnitude and sign of the bias were unknown at the time of the measurements. Later, we learned that scientists at the Savannah River site had performed some Monte Carlo simulations that paralleled our measurement conditions, and their results indicated that the bias would be large and positive [3].

A series of experiments was performed at Y-12 to estimate the appropriate correction factors. In these experiments, uranium oxide was glued to cardboard and laid out on the laboratory floor to simulate a long, narrow silt deposit. The detector was held over the "deposit" and spectra were acquired over several tilt angles. These simple experiments indicated that, for a fixed deposit, the count rate increased roughly as the inverse cosine of the detector tilt angle. They also indicated that the finite width of the silt ribbon would not cause significant bias under prevailing conditions.

Table 2: Detector response vs. tilt angle. 9" X 18" Standard cards were used in this experiment. Each card contains 66 g of highly enriched U_3O_8. The cards were laid out in rectangular arrays (2 X 4 cards) and linear arrays (1 X 8 cards). The detector was positioned above the arrays at several elevations as indicated in the table, and the net detector response is noted. These data are displayed graphically in Figure 2.

	30^o		45^o		60^o		90^o	
	net cps	height (cm)	net cps	height (cm)	net cps	height (cm)	net cps	height (cm)
2X4 array								
Low	284	13	153	11	163	17	108	13
	265	13					77	13
							161	13
Medium	213	24	210	32	176	28	143	40
High	121	57	211	60	166	60	140	90
1X8 array								
Card 1	241	13					108	13
Card 2	216	13					77	13
							75	62
Card 3							161	13
							95	61

The uranium-bearing silt was deposited in the bottom of the duct. The width and thickness of the silt ribbon varied depending on the duct diameter and flow of infiltrated ground water. The moisture content of the silt was not uniform, either. These poorly characterized factors added uncertainty to the computed results; where possible, the video images were used to improve our estimates. Some twelve hours of videotape were screened for this purpose.

Monte Carlo simulation

To determine the effects of tilt angle on the detector response, Monte Carlo simulations were performed using MCNP [4]. The Monte Carlo calculations simulated interactions between the detector and the gamma ray source. The detector and source were modeled as follows:

<u>Detector</u>

In the simulations, the detector was modeled as a 2.54 cm X 2.54 cm cylindrical NaI(Tl) crystal covered with a thin cadmium foil. A collimated lead shield 1.27 cm thick surrounded the detector. The collimator extended 2.54 cm beyond the front of the detector. The detector was located 12.7 cm above the source. Fourteen simulations were carried out, one for each 5-degree increment of detector rotation. The detector was rotated from the normal position (vertical) to 65 degrees off normal with the axis of rotation at its front face.

<u>Source</u>

The source was modeled as a weightless plane emitting gamma rays only. Gamma ray energies were selected to represent the decay of ^{235}U. The discrete set of gamma rays is shown in Table 2. Since the source was weightless, no gamma ray self-attenuation effects were included in the model. The source extended 26 cm behind the detector, and 400 cm in front of the detector. The detector was tilted forward as shown in Figure 1.

Three different source widths were modeled. The three widths were 0 cm, 28 cm and 56 cm, each centered on the detector axis.

Table 3: Selected gamma rays from ^{235}U [5]

Energy (keV)	Branching Ratio (%)	Specific Emissions (s^{-1} gU^{-1})
105.00	2.69	2151
109.16	1.54	1232
143.76	10.96	8765
163.33	5.08	4063
185.72	57.20	45747
202.11	1.08	864
205.31	5.01	4007

Tally

Both the fluence in the detector volume (F4) and the pulses in the detector (F8) were tallied, but only the fluence tally was used for the results. The results shown in Figure 2 are the fluence tally from 161 keV to 211 keV. Because the source simulates only the emissions from ^{235}U, no background subtraction from the tally is necessary.

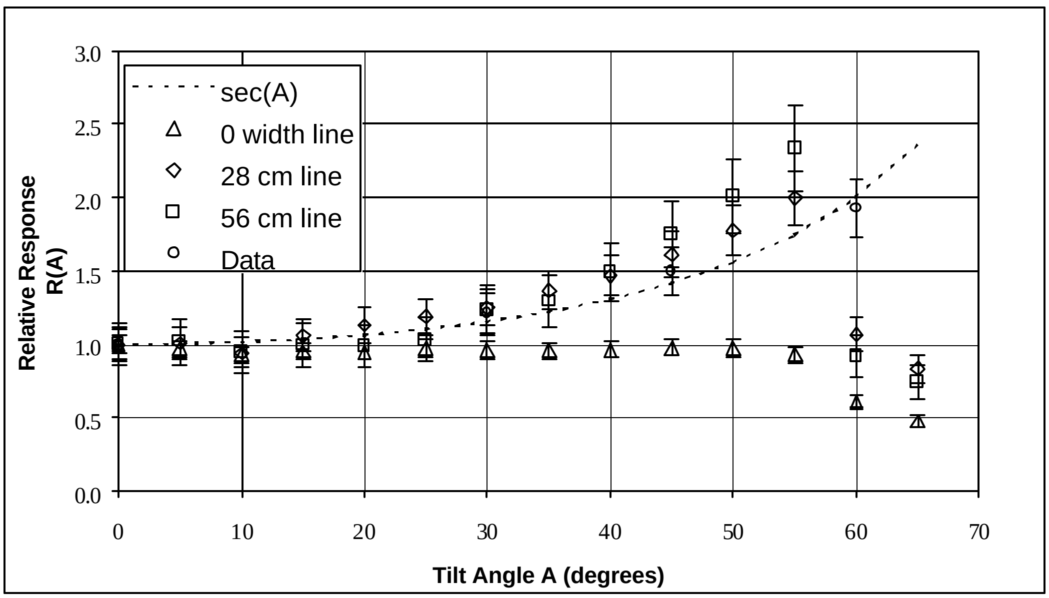

Figure 2: Relative detector response $R(A) = \Phi(A) / \Phi(0)$ **for 0, 28, and 56-cm line widths.**

The plot also shows experimental data acquired using a physical detector and area source similar to those described in the simulations. The same data are reproduced in Table 2.

MCNP Results

The results are shown in Figure 2. The angle-dependent fluence $\Phi(A)$ divided by the fluence normal to the source $\Phi(0)$ is shown. For a thin line source, the detector response is independent of the tilt angle A until the detector field of view extends beyond the end of the line. For non-zero width lines, the detector response increases as the tilt angle is increased. Figure 2 also shows experimental data acquired using a physical detector and area source similar to those described in the simulations. This data was previously observed to fit the secant of the tilt angle.

Error Analysis
Uncertainties include random and systematic errors, plus several unquantifiable uncertainties. For example:

Random errors are inherent in gamma counting and dimensional measurements.
Gamma counting errors follow Poisson statistics. Since all spectra were acquired for 150 s, measurements with the greatest uncertainty represented locations with the least amount of material. Typical counting uncertainties are in the 5 – 10% range for most measurements. Precise dimensional measurements were not possible, because the measurement locations were so inaccessible. The width and depth of the silt ribbon could only be estimated from the video images, and are probably only within 25% of the true values at best. The entire length of each duct was not analyzed, but measurements were made at approximately 5-foot intervals.

Systematic errors could result from inaccurate detector calibration, poorly-compensated gamma ray attenuation (either self- or matrix-induced), and tilt-angle corrections. Detector calibration errors are assumed to be minimal, and this assumption is supported by quality assurance measurements. Gamma ray interactions are complex and difficult to model, so some simplifications were made that probably introduce bias. All the silt was assumed to be calcium aluminosilicate, with the uranium deposited underneath the silt. The resulting attenuation correction factor was not adjusted for detector tilt, so the two resulting biases tend to cancel each other. Source-detector interactions were modeled as a function of tilt angle, and the observed count rate of a fixed source seems to increase approximately as the secant of the detector tilt angle. There is also some dependence on the width of the silt ribbon (see Figure 2). Rather than explicitly calculate a geometric correction for each location, the silt ribbon was assumed to be 11” wide everywhere and a geometric correction factor of 0.5 was universally applied.

Unquantifiable errors include variations in silt moisture content, ‘’sampling” errors, and unmeasured ductwork. Moisture content could only be roughly estimated as “damp” or “dry” from the video images. Where the silt appeared damp, a 20% gamma ray attenuation correction was applied corresponding to approximately ½” of water. Where the silt appeared dry, no moisture correction was applied. “Sampling” errors could arise because the silt was only spot-checked instead of scanning it in its entirety. Such errors would occur if hot spots were either over- or under-represented. No assumptions can be made about the magnitude or sign of such errors.
It is important to note that the entire length of each duct was not analyzed. The remote crawler could not turn corners sharper than 45°, and could not climb inclined surfaces. Only the larger-diameter ducts were accessible during this measurement campaign. No assumptions were made about the amount of uranium in the unsurveyed ductwork.

Discussion
Several assumptions were made during these underground ductwork measurements. The assumptions were based on observations made during the survey, and introduce uncertainties that affect the computed results.

All the uranium was assumed to be on the bottom of the ducts, buried under a ribbon of clay-like silt. There were no other significant deposits visible on the inner surfaces of the ducts. A gamma ray absorption correction factor was applied to all the measurements, and a further correction factor was applied if the silt appeared to be wet.

Gamma ray measurements were made at 5-foot intervals along each duct, everywhere the crawler could travel. The observed count rates were grouped together and averaged to calculate a result for each duct segment. It was assumed that the intervals were frequent enough to provide representative samples, since the detector's effective field of view extended about 3 feet in front of the detector.

Source-detector geometry for the underground ductwork measurements deviated significantly from the normal geometry specified in the generalized geometry holdup model. The detector was tilted about 60° off normal to decrease headspace requirements and to increase the detector field of view. After the measurements were completed, some additional physical experiments and mathematical modeling were done to determine the extent of bias introduced by this change. The MCNP results and the experiments both indicated that the observed count rate for a fixed source would increase roughly as the secant of the detector tilt angle increased. Based on this evidence, a correction factor of 0.5 was applied to compensate for the bias.

Several ductwork segments were inaccessible, so they were not surveyed. No inferences were made about the amount of uranium in them.

References

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[3] C.A. Hodge, R.D. Jeffcoat, S.D. Kahook, R.A. Dewberry, S.R. Salaymeh, and F.S. Moore, "^{239}Pu Holdup Measurements at Savannah River Site's FB-Line", in Proceedings of the Institute of Nuclear Materials Management 42nd Annual Meeting, Phoenix USA (July 2001)

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[5] INEEL Catalog of Isotope Spectral Data (based on ENSDF 8/5/99), data taken from the Worldwide Web at http://wastenot.inel.gov/gamma/actinide.html .