ABSTRACT

This research exploits in-pipe access to develop robotically deployed, high-cadence, accurate, certain, paperless assay of U-235 in holdup deposits within process piping. Prior radiometric assay from outside the pipes suffered from manual deployment challenges, attenuation of detection through pipe walls, long counting times, approximate modeling, and shortfalls associated with transcription and human interpretation. These downsides limited the speed, quality, and economy of assay resulting in vast cost and budget consequences to D&D. D&D of outdated facilities cuts into these pipes as part of the demolition process, creating the unique, previously unexploited possibility of robotic in-pipe assay. The assay collimates radiation emanating from all but a short segment of pipe wall from reaching a gamma detector. Hence, the detector only views and measures source from a short segment of pipe at a given time. This is achieved by an innovative pair of collimating discs that are coaxial with the pipe and positioned fore and aft of the detector.

The detector assembly is translated through pipes by an autonomous mobile robot. Beyond radiometric assay of U-235, the robot images and geometrically models the pipe interior and deposit appearance. The robot is recovered from the same pipe opening from which it is launched, hence it drives the same distance out and back, measuring the same deposits twice. This achieves redundant radiometric and odometric measurements which adds further to statistical significance of the method.

INTRODUCTION

There are compelling motivations for robotic characterization of enriched uranium holdup in piping (Figure 1). Segments of piping in gaseous diffusion enrichment facilities have to be removed and cleaned at great expense when their wall deposits contain large amounts of residual UF₆ decomposition products (e.g. UO₂F₂, UF₅, UF₆). Other segments deemed clean enough by assay can be left in place to be economically demolished and landfilled with the facility. Current manually-deployed non-destructive assay (NDA) techniques are used to view segments of pipe externally through pipe walls. An assay method and robot are developed herein to perform a high-cadence, robotically deployed NDA technique that surveys process piping internally with detector and sensors that directly view the holdup deposits.

In Situ Object Counting System (ISOCS) and Holdup Measurement System 4 (HMS4) are examples of existing manually deployed radiometric assay techniques [1,2]. Their upsides are that they are developed and certified. Their disadvantages include manual deployment, attenuation by passing through pipe walls, long counting time, approximate modeling, and shortfalls associated with transcription and human interpretation. These downsides limit the quality, speed, pragmatics and economy of their application. That has an immense cost and schedule consequence to D&D. Alternately, an in-pipe methodology has the overwhelming advantages of precluding through-wall attenuation, experiencing high count rates for
accuracy and certainty, and transiting full pipe length from a single point of launch and recovery. The need is to develop, certify and robotically integrate a radiometric assay method that exploits the advantages of in-pipe deployment.

This research innovates disc collimation that exposes only the radiation emanating from a cylindrical segment of pipe wall and excludes radiation emanating upstream and downstream from that segment of pipe wall [3]. This is achieved by an innovative pair of collimating discs that are coaxial with the pipe and positioned symmetrically fore and aft of the detector (see Figure 2). The detector collimated in this way views an incremental circular belt of deposit at known radius from which simple, accurate U-235 assay is quantified.

![Fig. 1. Process piping with yellow holdup deposit (left). Side view of robot for holdup deposit measurement (right).](image)

An autonomous robotic crawler is innovated to carry the disc-collimated detector assembly through pipes and acquire requisite radiometric, visual and geometric data (Figure 1). The robotic crawler maintains velocity as required by the method. Odometry correlates radiation readings with location along the pipe. A triangulation range sensor rotates to create a model of deposit thickness that could be used to correct gamma measurements for self-attenuation by thick deposits. Robotic pipe inspection methods have been implemented for water, sewer, natural gas, and other applications [4,5,6]. The goal of these systems is to characterize the structural integrity of the pipe instead of deposit material inside the pipe.

The robot developed herein is autonomous and untethered. Analogous robots in nuclear applications [7,8,9] have been tethered. A tether provides sustained power for lengthy operations, mechanical recovery, and straightforward means of teleoperation. Downsides of tethering include tether management, tether contamination, and implications of tether handling by operators. The preponderance of historical tethering also reflects prior inability to exhibit robust operational autonomy in practice [10]. The upside motivations typically prevail in nuclear servicing, but tethering is not embraced in this development. The robot shuttles quickly through pipe lengths that apply in D&D of enrichment facilities. That precludes the need for sustained tether power and avoids the associated liabilities. Constant velocity, consistent operation, and uninterrupted driving are important to the method, and further motivate automation. D&D piping must regularly be cut and removed for other purposes, so extrication is uniquely possible in D&D by cutting a pipe. The ultimate motivation for autonomy is the guarantee of accurate, certain, high-cadence assay unaffected by vagaries of teleoperation.

This paper develops a new method for NDA of holdup deposits in gaseous diffusion piping by integrating disc-collimated gamma detection and untethered autonomous robot operation. The platform, dubbed
“RadPiper”, was successfully hot tested at the Portsmouth Gaseous Diffusion Enrichment Facility in Piketon, Ohio, in late 2017. Results of this testing appear in the sister publication to this paper, “Results of Robotic Evaluation of Uranium-235 in Gaseous Diffusion Piping Holdup Deposits” [11]. Robotic disc-collimated measurement could transform NDA of U-235 in piping with substantial savings of cost, time, and personnel exposure during D&D of gaseous diffusion enrichment facilities.

RADIOMETRIC METHOD
The disc-collimated radiometric method developed herein is a first-of-kind system for in-pipe robotic assay of holdup deposits. By observing deposits from within pipes the method exploits the known cylindrical geometry to simplify collimation, calibration, and analysis. It achieves high count rate due to preclusion of attenuation through pipe wall, proximity of detector to deposit, high emission of U-235 at 186 keV, and high efficiency of NaI detector counting at the 186 keV energy. Radiation at that low energy is efficiently attenuated by thin material, minimizing weight of the required collimators and facilitating robotic deployment. The sensing requires no moving parts enabling a mechanically robust system. By viewing the entire surface of interest with high energetic efficiency, the method exhibits high count rates and reliable statistics while operating at high rates of speed relative to all other techniques.

![Diagram of RadPiper's collimated detector assembly in a gaseous diffusion pipe](image)

Fig. 2. Illustration RadPiper’s collimated detector assembly in a gaseous diffusion pipe, highlighting the sections of deposit that are fully viewed, partially viewed, and fully shielded from the detector crystal.

Disc-collimated detection exposes to a detector only the radiation emanating from a cylindrical segment of pipe wall and excludes radiation emanating upstream and downstream from that segment of pipe wall [3]. This is achieved by an innovative pair of collimating discs that are coaxial with the pipe and positioned symmetrically fore and aft of the detector (see Figure 2). Within that figure blue connotes the belt of deposit impinging on the entire crystal. Red connotes narrow rings of deposit impinging only partially on the crystal. Green connotes deposit in the remainder of the pipe that is excluded from the crystal by the collimating discs. The detector collimated in this way views a circular belt of deposit at known radius and large area. The known geometry of pipe, discs and detector make the U-235 assay calculations straightforward. The significant deposit within the field of regard and direct view of deposit without attenuation results in very high count rates relative to deposit source strength versus prior
methods. This achieves accurate, confident measurement at high robot driving speed.

Figure 3 illustrates the favorable geometric implications of disc collimation as it pertains to correlating detector count with amount of source in a cylindrical belt of deposit (the cross-section of which is seen in Figure 2). This shows normalized count rate for a source of uniform strength located throughout the collimator’s field of regard. The color scheme of Figure 3 correlates with the color scheme of Figure 2 in that blue is the region of deposit that impinges on the entire crystal and red is the region of deposit that impinges only partially on the crystal. Beyond the red region nothing impinges on the crystal except an amount less than 1% that leaks through the collimators. The illustrated graphic depicts an 18-inch (0.46-m) collimator in a 42-inch (1.1-m) pipe. The arc of the blue central region is primarily due to inverse-square relationship of source nearby the crystal and falloff with axial distance from the crystal. The slope of the red boundary region is primarily related to falloff due to shadowing from full visibility down to no visibility of deposit onto the crystal. Figure 3 shows the excellent correlation of experimental data and analytic modeling of the collimator, crystal, and pipe geometries.

![Fig. 3. Plot of normalized detector counts versus position for RadPiper’s 18-inch (0.46-m) collimated detector assembly in a 42-inch (1.1-m) pipe. Position is measured as the axial distance between the center of the detector crystal and the position of the point source, with blue being within the 12-inch (0.3-m) field of regard and red being in the region of excess detection. Experimental data points are plotted over the top of the theoretical curve. Points outside the theoretical curve are caused by minimal shine through the collimating discs.

The robustness of the method is unaffected by the inclusion of the sloped regions beyond full crystal visibility. That region is included for practical inspection purposes, since preclusion of that region would require either discs of full pipe diameter or a point detector crystal of dimension zero. Neither is realistic. Pipe-diameter discs would preclude mobility. Point detectors do not exist and could never achieve the high count rate which enables high-speed assay. Practical measurement is instead enabled by smaller discs separated so as to count the complete source within the 1-foot (0.3-m) annulus and admit only a small overage of source beyond the one-foot (0.3-m) length. The field of regard that views the complete source is made symmetrical about the midplane of the detector crystal. The region of overcount is thus asymmetrical due to inherent asymmetries in scintillation crystal-photomultiplier tube detectors. This asymmetry is irrelevant as the total overage is calculable and correctable by the method or can be retained.
as a conservatism factor. The excess detection region generated by the use of smaller collimating discs is illustrated in red in Figure 2. Use of the 186 keV peak to quantify U-235 has the serendipitous effect of a lightweight collimator solution. Thin (¼-inch or 3.18-mm) lead nearly completely attenuates the 186 keV peak. Hence discs can be large enough for geometric collimation and light enough for robotic deployment. The detector selected for this method uses a 50-mm long by 50-mm diameter (2-inch x 2-inch) Thallium-doped Sodium Iodide (NaI(Tl)) scintillator mated to a 50-mm (2-inch) photomultiplier tube and tube-base multichannel analyzer. The components chosen were a temperature-stabilized detector and a multi-channel analyzer base from Canberra (NAIS-2x2 and Osprey base, respectively). NaI detectors exhibit high efficiency in measuring U-235’s 186 keV gamma photons and are site-approved for use at the robot’s DOE testing facility.

The factors involved in computing the grams of U-235 in the detector’s field of regard (including the aforementioned geometric considerations and given reported counts from the detector) are summarized in Equation 1, where \( M_{\text{isotope}} \) is the mass in grams of U-235 contained in deposit on a length of pipe centered around the disc-collimated detector. The theoretical values of these factors in 30- and 42-inch (0.76- and 1.1-m) pipes are tabulated in Table 1.

\[
\frac{M_{\text{isotope}}}{c_{\text{rep}}} = \frac{1}{c_{pg} + c_{pgoT} + c_{pg∞}} \frac{1}{c_{\text{CrsEf}}} \frac{1}{c_{\text{AlTb}}} \frac{1}{\gamma_{1g}} \frac{1}{r_{\text{self}}} \tag{Eq. 1}
\]

The variables in this equation account for the following phenomena:

- \( c_{\text{rep}} \) Counts reported by detector
- \( \gamma_{1g} \) Gamma emission per second from a single gram of isotope
- \( c_{pg} \) Fraction of gamma rays reaching the detector that emanate from deposit on the collimated length of pipe. This term is primarily dependent on the relative diameters of the pipe and detector crystal.
- \( c_{pgoT} \) Excess detection due to finite dimensions of detector combined with clearance between collimation discs and the pipe. No excess detection occurs for an idealized point detector having zero dimension. No excess detection occurs for collimation discs with diameter matching the internal diameter of the pipe. For detectors with finite dimension and collimating discs with diameter less than that of pipe, some excess detection occurs beyond the field of regard due to visibility of source to partial volume of the detector.
- \( c_{pg∞} \) Excess detection due to incoming signal from the infinite pipe, which permeates a collimator of finite thickness and material of finite mass attenuation
- \( c_{\text{AlTb}} \) Attenuation due to the structural cylinder surrounding the detector
- \( c_{\text{CrsEf}} \) Crystal efficiency. A predicted value for this parameter can be used, as described in Table 1, or the parameter can be determined during efficiency calibration.
- \( r_{\text{self}} \) Decreased detection due to self-attenuation of deposit, most relevant for thick deposits

### Table 1. Radiometric method constants

<table>
<thead>
<tr>
<th>Quantity</th>
<th>30-Inch Pipe</th>
<th>42-Inch Pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma_{1g} )</td>
<td>43000</td>
<td>43000</td>
</tr>
<tr>
<td>( c_{pg} )</td>
<td>0.0013</td>
<td>0.00067</td>
</tr>
<tr>
<td>( c_{pgoT} )</td>
<td>0.00024</td>
<td>0.00023</td>
</tr>
<tr>
<td>( c_{pg∞} )</td>
<td>0.000041</td>
<td>0.000032</td>
</tr>
</tbody>
</table>
In addition to the theoretical model, testing utilized surface mats and vial sources of uranium of varying enrichment and other gamma sources. These diverse sources were positioned at various locations on a moveable mount system. Data from these tests were used to perform energy and efficiency calibrations and characterize the performance of this detector/collimator assembly. Figure 3 displays the experimental data points of normalized count rate for a Co-57 source versus position overlaid on the theoretical curve for the 18-inch (0.46-m) detector assembly in a 42-inch (1.1-m) pipe with a separation of 6.62 inches (0.168 m).

This method is scalable for assessing uranium deposits in pipes of any diameter sufficient for a detector and robot locomotion. Scaling determines collimation disc diameter, separation, and driving speed. For larger pipes, fewer emitted gamma rays impact the detector due to the reduced view factor. This leads to slower drive speeds to acquire statistically significant data on larger pipes. For 30-inch (0.76-m) pipes and U-235 quantities of typical interest, driving speed for measurement can exceed 30 feet per minute (9 meters per minute).

ROBOT

The robotic NDA method presented here is propelled through pipes with a robot dubbed “RadPiper”. An exploded view labeling the robot’s various components is shown in Figure 4. The full robot is 1 meter long by 0.4 meters wide and 0.5 meters tall (45 x 17 x 21 in) and weighs approximately 80 kg (180 lb).
**Structure and Mechanisms**
RadPiper moves through pipes on a track-driven platform that maintains the axial centering of its disc-collimated detector and auxiliary sensors. These tracks incorporate encoders (for odometry) and respond to onboard computer commands based on IMU (inertial measurement unit) and spinning laser rangefinder information to keep the robot upright and safeguarded.

RadPiper’s disc-collimated detector assembly is constructed of aluminum-plated ⅛-inch (3.18-mm) lead discs 16 inches (0.41 m) in diameter. The detector’s scintillation crystal is positioned between the discs using experimental geometric characterization to ensure symmetry. The entire disc-collimated detector assembly is then cantilevered from the front of the robot chassis as a single modular unit. This design ensures no robot components impinge on the full field of regard and excess detection region of the detector assembly.

The collimator module also supports two of RadPiper’s auxiliary sensors. The robot’s forward-most spinning laser rangefinder is mounted on the back of the rear collimating disc. Centered on the front of the collimator module is the robot’s camera and array of light-emitting diodes (LEDs) for imaging of inspected pipes. Both of these sensors are discussed further below.

**Computing, Power, and Electronics**
RadPiper operates as a tetherless autonomous robot with fully contained onboard power, safeguarding, and data logging. The robot’s main computer is a fanless embedded Intel quad core i7 system (Adlink MXE-5501). The radiation detector electronics (Canberra Osprey) are powered at 48 volts via power-over-Ethernet and communicate with the main computer via Ethernet.

Power during operations is provided by a pair of onboard 24-volt 20-amp-hour lithium iron magnesium phosphate battery modules with integrated battery management (Valence type U1-24RT) connected in parallel. These provide sufficient energy for all expected robot missions and conditions, with a maximum total round trip of 600 feet (183 meters) or five hours duration. Operators charge the robot via a port on the rear user interface using an off-board charging system that runs on standard 120-volt single-phase power. Charging time is typically two hours allowing for rapid turnaround of robot service.

Power to the various internal buses of RadPiper (48, 24, 12, and 5 volts) are generated via commercial converters (Vicor VI-200, XP DTE and CUI PYB types). Motor drives are powered directly from the main battery bus as is a shunt regulator that prevents excessive bus voltage during motor backdriving. Batteries and inputs to the converters, drives and shunt are protected with ordinary automotive thermal fuses.

White and ultraviolet (UV) LEDs for imaging are driven by a custom buck converter board, which enables control of light intensity and pulsing synchronous with camera frame acquisition via the acquisition board. LEDs are mounted using adhesive thermal pads to an aluminum heatsink. Pulsed operation reduces heat load and prevents thermal damage to the LEDs.

The two track modules (Inuktun Minitrack 6000 Extended) are driven by a pair of Copley digital drives (Accelnet Micro Panel type ACJ) configured for brushed motor operation and networked via Controller Area Network bus (CANbus). A Copley CANbus to USB serial converter provides a network gateway for
the main computer. Track encoder feedback is converted from single-ended to differential and provided to the motor drives to close the control loop. Track position is returned from the motor drives to the main computer through the CANbus gateway. A data acquisition board (Labjack T7) enables digital sensor and operator interface switch input and digital output from the main computer. Figure 5 presents this computing architecture.

![Computing architecture diagram](image)

**Fig. 5.** Computing architecture

**Operator Interface**

An operator interacts with the robot primarily through the switches, buttons, and indicators on the rear panel, as pictured in Figure 6. This panel is designed to provide a simple interface that is easy for operators in personal protective equipment to use without extensive training. A USB data drive is used to store data from each run and transfer data to a post-processing computer. A capsule protects the USB data drive from contamination during robot operation. The main power button connects the robot power, and on/off status is displayed by the red LED indicator. Battery status is separately displayed for each battery on a set of LEDs on the rear panel.

For safety while moving, storing, and handling the robot, a motion stop button inhibits driving. There is also a second motion stop button on the front of the robot body, which can be seen in Figure 4. The calibrate switch initiates 3 minutes of stationary radiation data collection. This is used for collecting radiation background and energy calibration gamma spectra. The forward/reverse and turn jog switches are used to drive the robot from its launch rig into a pipe. The start switch initiates a data run in a pipe. The run status indicator LED shows when the robot is warming up, executing a calibration data collection, or executing a data run. This indicator changes color from flashing green to flashing red to indicate whether the robot is proceeding forward or reversing out of a pipe.

A VGA monitor connection is provided for debugging purposes. The spinning triangulation sensor is discussed in the next section. Not visible in Figure 6, an Ethernet port and a USB port are provided on the top of the robot for debugging purposes.
Safeguard and Auxiliary Sensing

In addition to a radiation detector, the robot carries a number of sensors to collect other modes of data inside pipes and to safeguard the robot. A fisheye camera captures images looking forward down a pipe. Illumination for imaging is provided by onboard LEDs (see Figure 7). There are eight white LEDs that illuminate full-color imaging and eight ultraviolet LEDs for UV fluorescence imaging. The holdup deposit material, uranyl fluoride, fluoresces green under UV illumination, although the intensity of fluorescence varies with hydration. The green channel of an image taken under UV illumination is used as a measure of fluorescence.

Two spinning 2-dimensional triangulation laser rangefinders (RPLIDAR A2) are mounted on the robot. One, centered on the back, gets a full 360-degree slice of a pipe. Another, mounted on the aft side of the radiation sensing assembly, gets a partial view due to obstructions from robot structure. This sensor’s main purpose is safeguarding in front of the robot’s tracks to prevent driving out of open pipe ends.
An inertial measurement unit (IMU, Xsens MTi-20) is mounted inside the robot body. Relevant IMU safeguards include RadPiper driving into a reducer fitting, in which case the robot will automatically reverse after pitching beyond a maximum angle threshold. Two optical time-of-flight proximity sensors (SICK DS35-B15521) mounted on either side of the robot in front of the main body look forward and detect closed or obstructed pipe ends, triggering a reverse.

**Software**
The robot software is based on the Robot Operating System (ROS) framework. ROS provides message passing tools, data logging tools, debugging tools, and a community of developers that have released open source software packages.

The core component in the software system is the system executive. The system executive monitors the buttons on the operator panel to process the commands. For example, the calibrate switch triggers a predefined series of steps to log data from the radiation detector for three minutes without moving. The start switch triggers the robot to drive forward and collect data until either a system fault is detected or a terminating condition is met. The current executive has three predefined terminating conditions:

1. Forward mission duration more than a specified length of time.
2. The robot had a pitch of magnitude greater than 3°.
3. An obstruction was detected using the forward-looking proximity sensors.

Upon detecting a fault or terminating condition, RadPiper reverses until it senses that its rearmost spinning triangulation sensor has exited the pipe. At this point the robot stops driving, and a change in status light indicates run completion.

The multi-channel analyzer for the radiation detector operates in continuous collection mode and polls for the current accumulation of counts approximately every 0.1 seconds. These and other sensors’ data are recorded to a ROS log file, referred to as a bag file.

**OPERATIONS AND DATA PROCESSING**
Nominal operation for pipe inspection includes collection of a background spectrum, collection of an energy calibration spectrum, a pipe inspection run during which data are collected as the robot travels forward and as it reverses back out of the pipe, and a final background spectrum collection. Comparison of background data before and after a pipe run can determine if radioactive contamination that would interfere with valid measurement was picked up on the robot during a run. A uranium source was used for energy calibration in this work.

After a pipe inspection run, data are transferred to a post-processing computer and processed to determine localized values for grams per unit distance. While accumulated gamma spectra data are stored every 0.1 second, these data are re-processed to a user-specified collection and reporting time. Incremental spectra for each 0.1 seconds are obtained by subtracting the previous spectrum from the current spectrum. Counts in the selected collection time are obtained by summing \([\text{collection time}]/0.1\) of these incremental spectra. Reporting time specifies how frequently the collection should be re-started. Reporting time can be equal or less than to collection time. Nominally the collection time is 3 seconds and the reporting time is 1 second. Each spectrum is considered to be localized at the position where the detector was in the middle of the collection time.
For a given localized spectrum, a grams per unit length measurement can be computed from the number of counts in the 186 keV peak. Counts in peak for a given spectrum are given in the equation below, with \( \chi \) indicating channels of the pipe data, \( \beta \) indicating channels of the background data, \( p_s \) and \( p_f \) representing the start and end channels of the peak region of interest, and \( q_s \) and \( q_f \) representing the start and end channels of a Compton subtraction region of interest. For this work channel \( p_s \) corresponds to an energy of 172 keV, \( p_f \) to 201 keV, \( q_s \) to 225 keV, and \( q_f \) to 254 keV [12].

\[
c_{Re} = \left[ \sum_{i=p_s}^{p_f} \chi_i - \beta_i \right] - \left[ \sum_{i=q_s}^{q_f} \chi_i - \beta_i \right]
\]

(Eq. 2)

This work uses the energy calibration spectrum (3 minute collection) and automatically computes a linear calibration using three uranium peaks: 186 keV, 766 keV, and 1001 keV. A prior calibration is used to predict the approximate peak locations, and a window around an expected peak location is extracted. Within this window, Gaussian smoothing is applied, and then the second derivative is computed. The peak channel is located using the second derivative data. Slope (\( m \)) and offset (\( b \)) parameters for a linear calibration are then computed from the locations of the three peaks using the equation below, with \( e \) indicating energies, \( \chi \) indicating channels, and \( \mu \) indicating a mean.

\[
m = \frac{\sum_{i=1}^{n} [(\chi_i - \mu_e)(e_i - \mu_e)]}{\sum_{i=1}^{n} [(\chi_i - \mu_e)^2]}, b = \mu_e - m \mu_e
\]

(Eq. 3)

Since background spectra are collected outside of a pipe and inspection data are collected inside a pipe, it is important to account for attenuation through the steel pipe walls before doing background subtraction. Since the steel used is primarily iron, a table of attenuation data for iron [13] is interpolated to find an appropriate attenuation multiplier for each spectrum channel, given the specified pipe thickness. This attenuation is applied before background subtraction is done.

The crystal efficiency, \( c_{CrsEf} \), can be determined by doing an efficiency calibration. This is done by exposing the detector assembly to a source of known quantity (\( M_{\text{isotope}} \)) with known self-attenuation (\( r_{\text{self}} \)). Equation 1 is then back-solved for \( c_{CrsEf} \). The calibrated \( c_{CrsEf} \) value used for the results in the following section is 0.96.

The method integrates sources (even with sharp discontinuities) within its one-foot field of view. For example, imagine a source that is 1.5 feet (0.46 m) long and averages 25 g/ft (85 g/m) of U-235. The actual g/ft over a one-foot field of view does not reach 25 until the entire field of view is over the source, or about 6 inches (0.15 m) in. Likewise, the actual g/ft drops below 25 within about 6 inches (0.15 m) of the far side of the source. This is illustrated in Figure 8. Also, since the robot is moving, it reports the moving average of the actual g/ft number. At the nominal speed, the moving average is over a 6 inch (0.15 m) distance (this is shown as ‘Theoretical Robot’ in Figure 8). For a one-foot wide source that would push the g/ft value just slightly above a leave/cut threshold surrounded by bare pipe, the moving average can miss the peak. However, conservatism can be built into other parts of the method, (for example, using an overly conservative assumption on self-attenuation), such that the method always
overestimates. Deposits in actual piping are also expected to vary much more smoothly.

Fig. 8. Illustration of how the robot measures a 1.5-foot (0.46 m) long, 25 g/ft (85 g/m) source.

Figure 9 shows the graphical user interface developed to view post-processed data. Grams per unit distance data is shown localized relative to distance into the pipe, and imagery and gamma spectrum data are also shown for a user-selected location. The user interface also enables the user to set the collection and reporting times and the leave/cut threshold. The interface highlights when the measured value crosses this threshold by changing the color of the plot background in those regions. Parameters of the radiometric processing can also be viewed and adjusted using menu options within the interface.
Fig. 9. The post-processing user interface showing g/ft data plotted with respect to distance into the pipe. A robot image and the recorded gamma spectrum from the selected location are also displayed.

**CHARACTERISTIC RESULTS**

A test of the method was conducted with a series of flexible uranium mats with known quantities of U-235 laid end to end down a pipe. The robot’s view of the test setup is shown in Figure 10. The lengths, the actual gram/ft values, and the robot measured gram/ft values for each of the four mats are provided in Table 2. Figure 11 shows the predicted and measured data as a function of distance into the pipe. The difference in magnitude between the actual/predicted values and the measured values is primarily due to a conservative value for the self-attenuation ($r_{self}$) of the uranium source. Further results for testing with this and other source configurations are described in a companion paper [11].

![Robot's view of test setup for uranium mat testing](image)

**TABLE 2.** Lengths and g/ft of U-235 in each mat compared to RadPiper’s g/ft measurements. Measurements are calculated as the maximum or minimum point for short mats or average of the plateau values, within <0.75 g/ft (2.5 g/m) step change, for long mats.

<table>
<thead>
<tr>
<th>Mat Number</th>
<th>Total Length of Each Mat (in)</th>
<th>Actual g/ft U-235 per Mat</th>
<th>Measured g/ft U-235 per Mat</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Run 1 Forward</td>
</tr>
<tr>
<td>1</td>
<td>17</td>
<td>17.65</td>
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<td>4</td>
<td>35.5</td>
<td>1.69</td>
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CONCLUSIONS

A new method is developed for NDA of U-235 in holdup deposits within gaseous diffusion piping by innovating disc-collimated gamma detection with a pipe crawling robot under untethered, autonomous operation. This method achieves high quantitative accuracy, high speed and auto-analysis with quality and economy unachievable by prior or competing approaches. The enabling capability is the advantage of robotically observing from the inside looking directly at the deposits on pipe walls versus manually measuring from the outside with detection attenuated through pipe walls. All other advantages derive from this. Internal detection exploits the axisymmetry of piping that simplifies collimation, calibration, analysis, and qualification of the method.

Geometric characterization of a constructed collimator assembly showed excellent alignment with theoretical predictions for normalized count rate given a range of source positions relative to the detector. Integrated robot testing with a series of known sources showed the expected pattern in g/ft data, albeit with an intentionally conservative overestimate of uranium quantity. The robot achieves consistent results when comparing data from its forward and reverse pipe traversals.

The first-of-kind prototype RadPiper robot and radiometric method were hot tested at the Portsmouth Gaseous Diffusion Enrichment Facility in Piketon, Ohio in September and October 2017. These results are presented in a companion paper at this conference [11]. Additional streamlining of operational features, refining the methodologies, and development of implementation planning documentation will support near-term deployment of a production prototype at the DOE Portsmouth site in fiscal year 2018. Later follow-on goals include scaling the robot for the range of pipe sizes at the Portsmouth facility and developing internal robotic assay for other gaseous diffusion cascade components such as compressors and valves.

Immediate refinement, extension, maturation and application of this holdup measurement system are underway. The ambition is to achieve vast, near-term savings of budget, schedule, and manpower in the D&D of Portsmouth enrichment facilities. Greater savings are possible at the Paducah facility. Since in-pipe holdup measurement is broadly applicable to other isotopes and types of deposits, the impact will ultimately be much greater in variety, facility, nation and world.
REFERENCES

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