Novel Radiometry for In-Pipe Robotic Inspection of Holdup Deposits in Gaseous Diffusion Piping – 19503

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ABSTRACT

Summary: This paper details the first complete, DOE approved, deployed and operational radiometry for robotic nondestructive assay (NDA) of holdup deposits in gaseous diffusion piping. Some features, like peak-finding, Compton correction, detector efficiency, and material properties are characteristic of typical manual methods. Most features are specific to in-pipe robotic deployment. These include in-motion radiometry, self-determined location, geometric modeling of thick deposits, bounding of self-attenuation thickness and auto-checking of replicate measurements. Significant are the means for determining all the properties, equations, and constants for automatically computing and displaying all the quantities, uncertainties and information needed for NDA reporting, analysis, and review.

Earlier work by this team demonstrated rudimentary but convincing robotic in-pipe NDA of holdup deposits in pipes. Cold testing with high-enrichment mat sources and hot tests with low U-235 loadings together succeeded to exhibit convincing proof-of-principle. This research-grade radiometry implementation lacked accurate odometry, efficiency calibration, high-fidelity detector modeling, attenuation modeling, forward geometric modeling, auto-segmenting, uncertainty modeling, replicate checking, deconvolution and much more.

This work explains the technical basis behind robotic in-pipe NDA. It includes discussion of a new method for modeling of self-attenuation using in-pipe deposit geometry information, detail of the method's total measurement uncertainty, and explanation of calibration methods and results.

Beyond development of automation-specific radiometric elements, the paper highlights analyses, testing, and technical bases specific to and supportive of the methodology. Examples include collimation characterization, detector efficiency determination, auto-calibration methodology, and odometric replicate-checking.

Results of this methodology are formalized in a DOE EM Technical Basis Document, implemented in software, formally verified in review and acceptance testing and proceduralized as a means for D&D NDA at the Portsmouth enrichment facility.

Application/benefit to others: Measurement of U-235 quantity is a well-known cost and schedule driver in D&D of every defunct gaseous diffusion enrichment facility in the world. The radiometry methodologies and results detailed in this paper were the high hurdles. Having established the technical basis for this automated NDA, the opportunity is to apply this to many sizes and robot forms for addressing holdup deposit NDA throughout the D&D community.

INTRODUCTION

A significant challenge in achieving "criticality incredible (CI)" status for D&D of gaseous diffusion facilities is characterization of every pipe and component to ensure that the amount of U-235 in holdup deposits is below the CI threshold. Any piping that exceeds the criterion incurs costly removal, handling, and management before disposal. Pipes below the criterion are candidates for economical demolishing in place without severing, lowering, handling, or cleaning.

The current method of assay involves manually positioning radiation detectors on pipe exteriors for miles of pipe [1]. This requires extended work at elevation and removal of enclosure panels and other obstructions. What follows is lengthy transcription, analysis, reporting, and archiving, which are largely manual and often lengthy processes. These manually-deployed assays and their analysis/reporting processes are significant and well-known cost drivers and schedule bottlenecks within DOE D&D.

Chartered by DOE at the Portsmouth Gas Diffusion Plant in 2017, the Pipe Crawling Activity Measurement System (PCAMS) is an in-pipe robotic and auto-analysis package for automatic NDA of defunct gas diffusion piping. Deployment of the system has demonstrated faster, more certain NDA results while minimizing risk to personnel and need for human intervention. Deployed in research form in late 2017 [2,3], PCAMS is now a production prototype delivery successfully hot tested in July 2018 and slated to begin operations in January 2019. Initial deployment of 30- and 42-inch pipe inspection is projected to cover 50,000 feet of piping and with huge positive beneficial cost and schedule impacts in two process buildings at the Portsmouth site alone. Advancements in method, analysis, and robotic technology, proceduralization and operations are currently being applied to development of smaller-size pipe inspection (3- and 10- inch) for other potential facilities including the sister diffusion plant in Paducah, Kentucky.

The enabling advantage of the PCAMS method is traversal along and direct observation of contaminated pipe wall interiors (Fig. 1). Interior inspection allows the "RadPiper" robot to travel unobstructed while carrying a novel disc-collimated detector which exploits the axisymmetry of piping to speed assay and simplify calibration, analysis, and qualification of method. This automation is in contrast to manual methods' need to deploy personnel in full PPE at elevation to remove miles of protective paneling and directly access the exterior of each foot of process piping over which to dwell detectors. These methods require extensive plant disassembly and dwell time, up to fifteen minutes per five feet of pipe. RadPiper instead automatically traverses piping at 10 feet (for 30-inch pipe) or 6 feet (for 42-inch) per minute and autonomously reaches its safe endpoint before reversing to its origin, collecting replicate data on reverse.

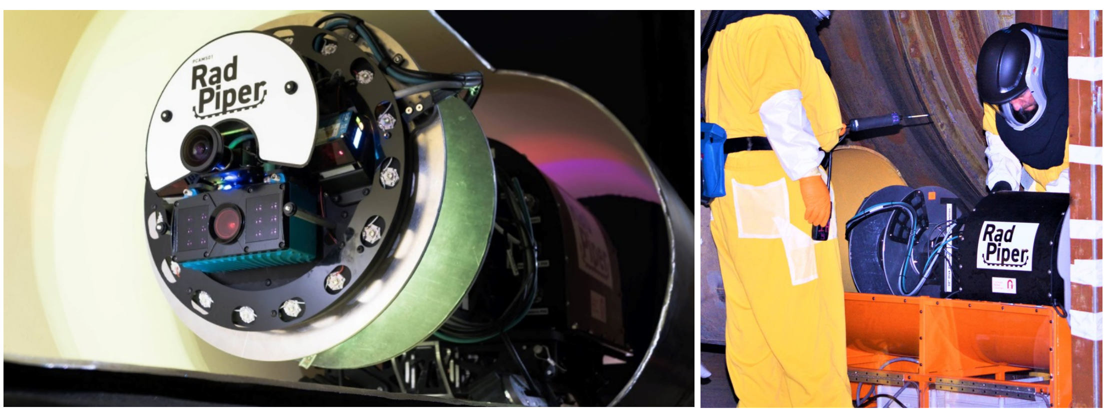


Fig. 1. (Left) PCAMS RadPiper traversing a cutaway pipe and (right) deploying into a process pipe.

Fifty thousand feet of the pipe immediately assayable by PCAMS at DOE Portsmouth is contained within two large process buildings, the challenge of which is two-fold. First, the initial set of pipes to inspect are large diameter: 30- and 42-inch. These large diameters mean that even small percentages of pipe wall can include large amounts of holdup deposit. Second, this section of the cascade handled low-enriched uranium, meaning that deposits of the same U-235 content are much thicker and much more highly self-attenuated than at higher enrichments. The initial RadPiper robot and PCAMS method are designed to handle these particular challenges, with extensive self-attenuation modeling and geometric inspection of pipe surfaces. Compliance with DOE EM standards [4,5] is discussed further in [6].

The full PCAMS radiometric method is summarized in Eq. 1, which reports mass of U-235 per length of pipe. Reading left to right, the 186 keV count rate term is conservatively adjusted based on the characteristic smoothing of disc-collimated detector assay . The self-attenuation factor further adjusts this result based on PCAMS novel calculation method, which takes advantage of direct geometric profiling of deposit thickness. The 186 keV activity of U-235 combines with the calibration efficiency to determine a characteristic count rate per gram-per-foot conversion factor. The final term conservatively adjusts the reporting from a per-field-of-view to per-foot basis for NDA and CI determination .

Eq. 1

An overview of this data collection, analysis, and, reporting is provided in the next section, followed by details of the collimated detector count rate and adjustment. PCAMS modeling assumptions and deviation flagging are the next novel topic, followed be details specific to the self-attenuation method. This final attenuation-adjusted loading is reported per NDA requirements, and additional information regarding the minimum detectable amount (MDA) and total measurement uncertainty (TMU) is also automatically calculated as described. The final section covers specific calibration procedures that incorporate detector assembly specifics into the method. Practical implementation of the method in analysis software is detailed in [7], the overall system and commissioning operations are related in [6], and robot and sensing details are included in [8]. This work is based on the 2017 research prototype method in [2,3].

ANALYSIS OVERVIEW

The PCAMS RadPiper robot deploys autonomously into process piping and digitally logs spectroscopic, geometric, odometric, and other inspection and status data while continuously traversing a pipe. Upon autonomously detecting an impassable obstacle (e.g. closed valve), the robot pauses to assay its final segment of pipe and then commences its reverse traversal, continuously re-inspecting all pipe covered in the forward traverse. Before and after each run, RadPiper automatically conducts a quality control (QC) and contamination check, verifying efficiency and peak location of its integrated Am-241 check source and comparing 186 keV counts to detect any acquired U-235 contamination. Results are displayed live to the technician on a wireless tablet and written directly to a USB jump drive in a sealed compartment, which is transferred to a desktop for upload to the PCAMS Post-Processing Software (PPS) Server.

PCAMS PPS automatically localizes gamma spectra based on correlating their timestamps to fused laser rangefinder measurements and encoder odometry at an interval of 5 mm. These spectra are then averaged over the length of the detector's field of view based on the robot's continuous motion in the pipe. A straight-line fit [9] of the Compton continuum is subtracted and propagated through total measurement uncertainty to yield a moving average of net count rate along the pipe. These count rates are then conservatively adjusted to compensate for PCAMS characteristic smoothing sharp deposit discontinuities, which though less common in process pipes are typical in testing regimes.

Initial U-235 content, unadjusted for self-attenuation, is computed from the net count rate based on each robot's individually-tracked detector and collimator calibrations. The attenuated estimate is then run through the PCAMS self-attenuation model, and segments that deviate from this model are automatically flagged based on radiometric and other robot sensor data. Quality assurance is also conducted to officially document the robot's pre- and post-run QC checks and verify the pipe's total and maximum segment loadings match on the forward and reverse runs (replicate checking). Details of these quality control measures are included in [7].

Final radiometric reporting involves averaging forward and reverse runs, segmenting the pipe into one-foot intervals, and conservatively reporting the maximum loading in each segment to NDA and Nuclear Criticality Safety (NCS) measurement requirements. These per-foot loadings along with original spectra, geometric heat maps, and camera images are displayed on the PCAMS desktop Analyst Interface. This interface allows analysts to examine and approve/reject flagged segments and add other annotations, as well as view automatically formatted NDA and NCS reports. Once approved, reports are officially archived in the PCAMS system and uploaded back to the main Portsmouth database.

A simplified workflow is provided in Fig. 2, wherein the blue sections (spectra to detected loadings) is covered in the following Disc Collimation section. Model assumptions and flagging (purple) and the self-attenuation models (teal) are explained in the subsequent two sections. TMU and MDA calculations (gray) follow next, and detector calibration (green) finishes this paper's method. Experimental results and future developments are also included herein. Orange blocks (data, pipe, and robot information) are covered primarily in this series' robotics and sensing paper [8]. Yellow items are parts of the broader post-processing analysis system, covered in much greater detail in [7].

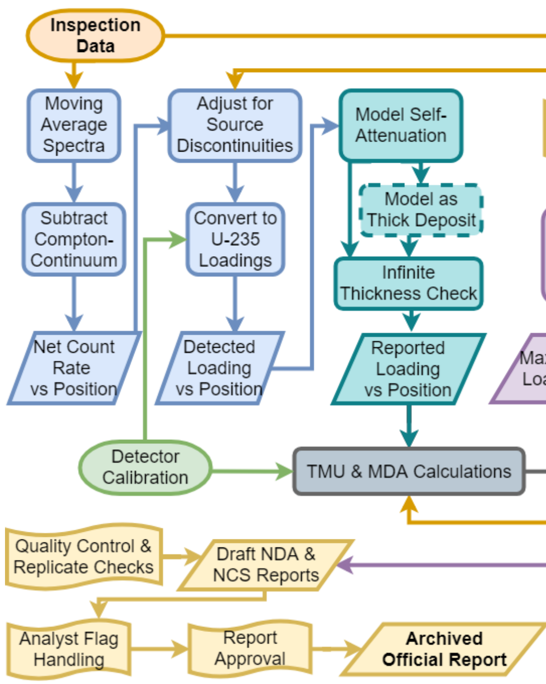


Fig. 2. PCAMS radiometry workflow, starting with inspection data and moving through net counts, detect loadings, attenuation adjustment, TMU and MDA, and by-segment reporting and flagging.

The method described hereinbelow is under final review by DOE EM for deployment in January 2019. Mathematical bias limits are -30% (underestimate) and +100% (overestimate) in 30-inch pipe with a maximum of +200% in 42-inch pipe. Total measurement uncertainty is limited to 15% in 30-inch standard modeling and 13% in 42-inch (though approaches 55% when reaching infinite thickness for self-attenuation). The system fulfills a customer requested minimum detectable amount (MDA) of 5 g/ft with an *a priori* MDA of 0.25 g/ft.

DISC-COLLIMATED DETECTOR

The heart of the PCAMS RadPiper robot and method is a novel disc-collimated detector [10] comprised of a 2x2 NAIS Sodium Iodide Scintillation Detector (5 cm long, 5 cm diameter) centered between two lead collimating discs, revealing a defined axisymmetric annulus of pipe wall to a robot traversing along the interior axis of a pipe. RadPiper mechanically transforms to center this detector assembly in 30- and 42-inch pipe to provide axisymmetric modeling of piping interiors.

The PCAMS collimator itself is a complex and precisely-dimensioned 27 kg (60 lb) assembly surrounding the scintillation crystal and accommodating its photomultiplier and high-voltage base. It also incorporates an onboard Am-241 check source for in-situ quality checking. All of these are contained within a precision machined aluminum tube that maintains a structural but minimally attenuating 0.3 cm wall in the field of view. Mounted to each end of the tube are anodized flanges that hold 46 cm, 6 kg aluminum-backed lead discs orthogonal to the tube at a spacing of 15.75 cm. These discs attenuate over 99% of gamma radiation outside the field of view, and the bolt holes mounting these discs are further shielded with lead-aluminum mask rings.

On the front side of the collimator is an adapter plate that allows modular removal of the front sensing assembly, which contains an infrared mapper for robot safeguarding and a fisheye camera for technician and analyst situational awareness in addition to other critical devices. Wires for these devices are routed on a plastic wire bridge over the collimator at a constant radius to the detector crystal and a varying clocking angle in order to minimize their attenuation effect. On the rear of the collimator is its carriage, which allows manual centering of the assembly in either 30- or 42-inch pipe, and the detector cap, which simplifies changeout of the detector if necessary. These components are labeled in Fig. 4.

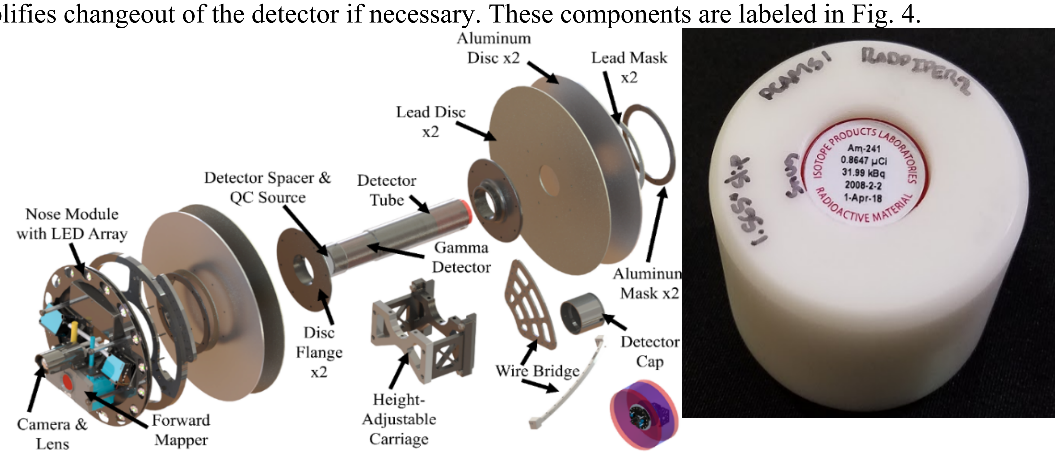


Fig. 4. (Left) exploded view of the RadPiper collimator assembly and (right) closeup of its check source.

This collimator assembly described above is designed to yield a large but less than one-foot field of view: the former for maximum count rate and traversal speed and the latter for precision in reporting g/ft measurement. The fields of view in 30- and 42-inch pipe as displayed in Fig. 5 and calibrated per the calibration section below.

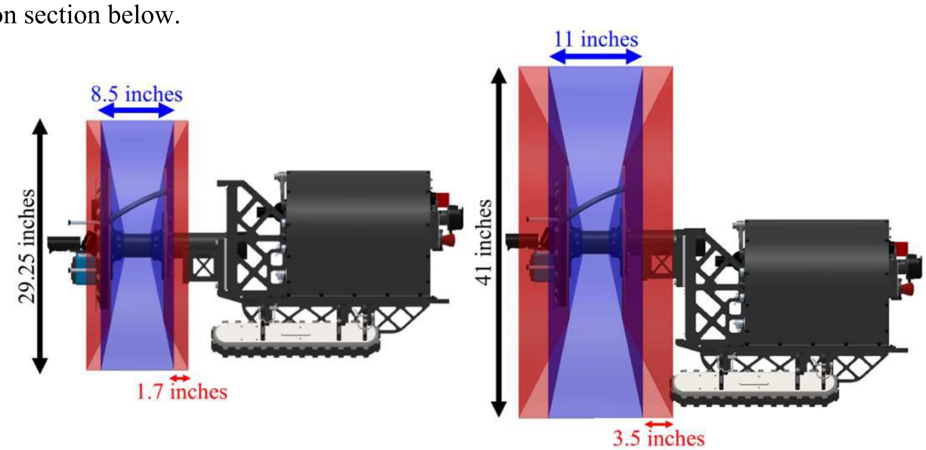


Fig. 5. Fields of view for the RadPiper collimator in 30- and 42-inch pipe.

The finite size of RadPiper's detector and collimating discs create a shadowing effect over the short (red in Figs. 5-7) sections of pipe wall as the robot traverses, as illustrated in three dimensions in Fig. 6. This creates an overcounting effect of 15% in 30-inch pipe and 22% in 42-inch pipe, as visible in the red regions of Fig. 7's plot for normalized efficiency versus position in the field of view.

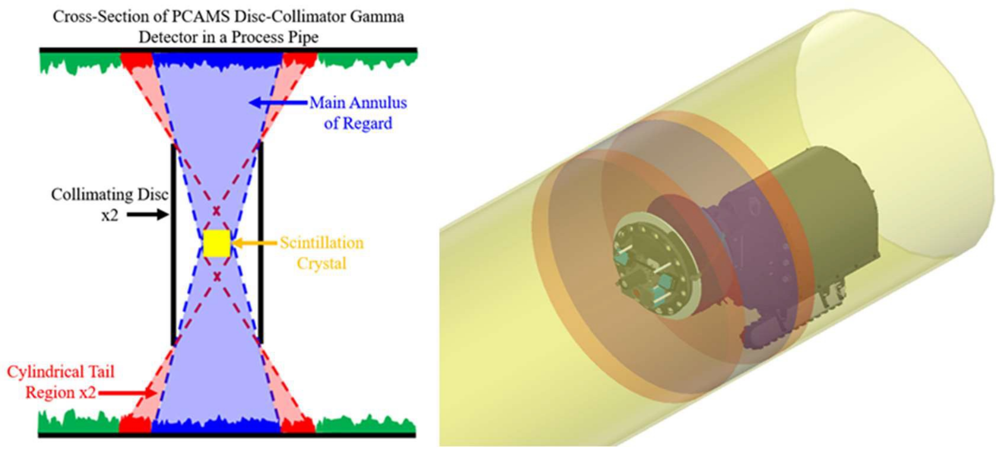


Fig. 6. (Left) schematic view and (right) isometric rendering of RadPiper's disc collimator in a gas diffusion pipe, showing the gamma detector's primary annulus of regard in blue and its tail regions in red.

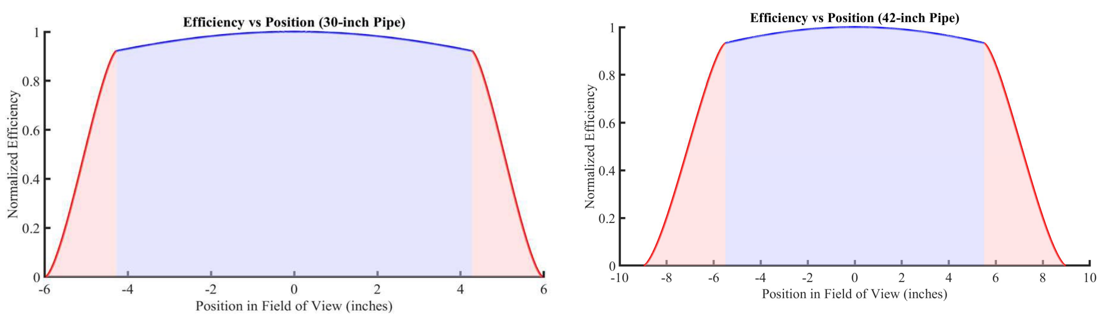


Fig. 7. Plots of normalized efficiency versus position 30- and 42-inch pipe for the gamma detector's disc- collimated field of view, with the main field shown in blue and the shadowed tail regions in red.

The practical effect of this overcount is minimal in typical process piping with long, continuously variable holdup deposits, e.g. created by leaks at a weld seam. In the event of sharp discontinuities in loading, however, as in many test regimes, the overcount region and continuous moving average effects require correction to prevent underestimation of U-235 loadings within a segment. Note that this underestimation is only a smearing effect (lower peak and wider base); the total reported loading remains consistent. The phenomenon is illustrated in Fig. 8, wherein the straight black curves represent actual U-235 loadings in a simulated pipe, the orange represents RadPiper's measurement if the robot were static at each infinitesimal location (i.e. the effect of the collimator's tail shadowing), and the blue represents the additional effect of the robot's motion and moving average. The plot shows a series of deposits increasing from 1 in (2.5 cm) to 27 inches (68.5 cm) with the worst-case underestimate case of exactly 1 foot (30.5 cm) circled in red. The underestimate is visible in the gap between black and blue peaks and the slightly wider bases of the blue curves. This effect is worst in 42-inch pipe, which the illustrated case.

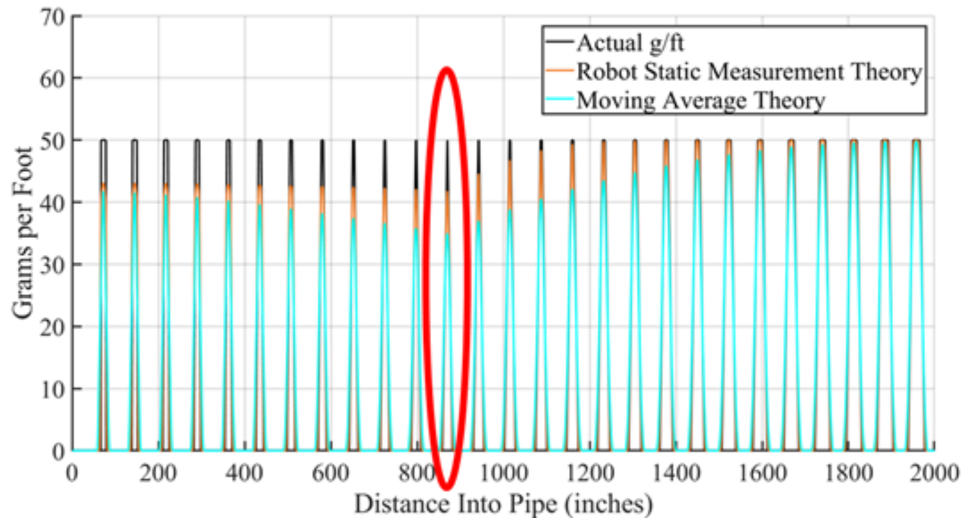


Fig. 8. Simulation of PCAMS static measurement (orange) and in-motion assay (blue) of 50-gram sources in 42-inch pipe at 1- to 27-inch lengths, showing the undercount effect at short sources.

PCAMS applies a discontinuity adjustment factor such that , which is optimized to ensure PCAMS stays within specified positive and negative bias limits. The current factors are 1.14 in 30-inch pipe (the worst case 12-inch deposit is 1.16) and 1.39 in 42-inch pipe (worst-case 1.40). The factors combined with bias from the PCAMS self-attenuation method result in the mathematical limits of -30% to +100% in 30-inch pipe and -30% to +200% in 42-inch pipe. Actual 50-gram (CI limit) loadings are typically reported with +50% and +110% biases, respectively.

STANDARD PIPE MODEL AND DEVIATION FLAGGING

PCAMS uses automated modeling checks and multi-sensor feedback to enforce two key assumptions underlying the axisymmetry and self-attenuation approaches for the method. First, the RadPiper robot is expected to center the collimated detector collinearly with the instantaneous center of the steel pipe wall. Segments in which the robot may exceed its pitch and/or yaw threshold are flagged based on launch conditions and inertial measurement unit readings (Fig. 9 left). These flags can be manually and (with authorization) automatically cleared at low U-235 loadings. An additional flag detects holes in pipe walls, such as those created by vacuum ports, based on RadPiper's geometric laser scanner (Fig. 9 right). Such ports and fittings are flagged for additional separate NDA.

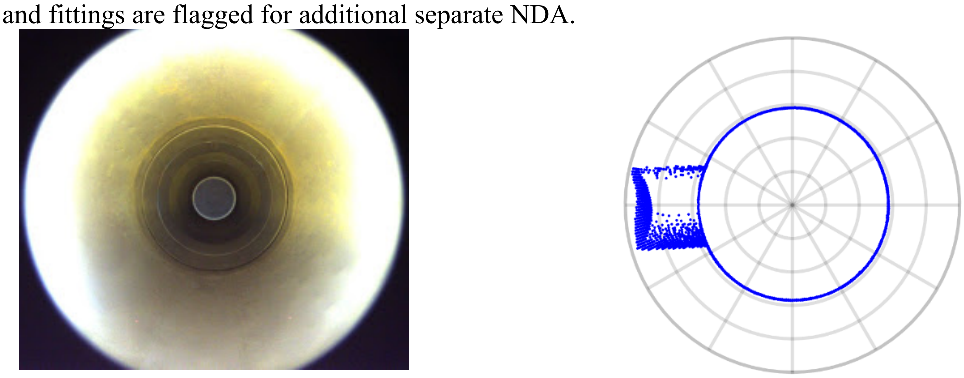


Fig. 9. (Left) RadPiper approaches a reducer fitting that will cause it to pitch upward and reverse as well as flag radiometric results for this different pipe geometry. (Right) Geometric heat map and image of a vacuum port flagged by RadPiper for separate NDA.

The second key modeling assumption is that holdup is expected to be less than the assumed thickness used in the PCAMS self-attenuation Eq. 2 [11]. These thicknesses are 0.22 cm in 30-inch and 0.35 cm in 42-inch pipe. Note that use of this method requires use of an assumed density, taken as 4.72 g/cm^2 representing UO_2F_2-H_2O [12,13]. This introduces another source of bias when test sources are of other materials. The bias limits quoted herein are designed for both uranyl fluoride dihydrate and triuranium octoxide as found in Hybrid Tacky Mats (HTMs) at between 0.5% and 17% enrichment.

Eq. 2

PCAMS enforces this assumption by flagging segments that have a 95th percentile sampled thickness that would create more than a -30% underestimate in overall reported loading: 0.37 cm and 0.53 cm thick, respectively. This sampling also uses RadPiper's geometric laser profiler data (Fig. 10).

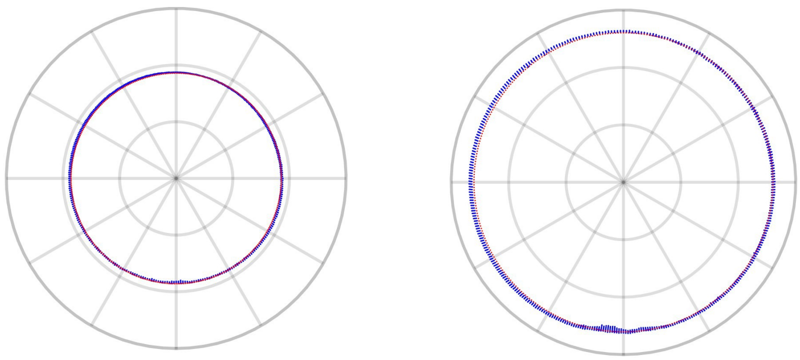


Fig. 10. Geometric profiles of thickness-flagged segments in (left) 30- and (right) 42-inch process piping, showing geometric buildup on the bottom of each pipe.

These laser profiles are converted into pools of diameter measurements (which are more robust to off-centering than radii) for each segment and then sampled one thousand times, taking the mean of three random diameters each time. The resulting histogram is Gaussian, and its 95th percentile diameter is compared to the diameter that would yield flagging thickness in an ideal pipe (Fig. 11). Note that the effect of this sampling is to center the histogram on the mean diameter of the pipe segment, which is useful both to remove noise and to handle clean process pipe dimensions, which are found to be elliptical. It also detects robot traversal over thick deposits that may not trigger inertial measurement pitch sensing. An additional flagging condition captures sharp source lumps of high thickness but lower coverage.

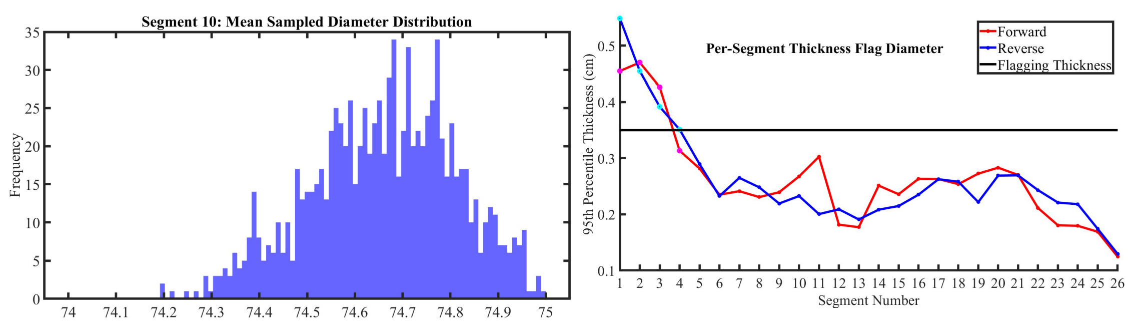


Fig. 11. (Left) Histogram of sampled diameters denoting the 95_{th} percentile thickness and (right) a plot of 95_{th} percentile segment thicknesses versus flagging thickness (black), which flagged segments circled.

SELF-ATTENUATION MODELING

With flagging of detector off-centering, pipe holes, and deposit thicknesses enforced, the PCAMS method can assume all detected 186 keV counts in a pipe segment emanate from attenuated UO_2F_2-$2H_2O$ holdup deposit. Conservatism in nuclear criticality determination dictates a worst-case assumption that all counts originate from within the segment and that all deposit is at the maximum assumed thickness. This gives standard PCAMS modeling a constant attenuation factor of 0.60 in 30-inch and 0.47 in 42-inch pipe.

Because RadPiper collimates a full annulus of pipe wall, PCAMS does not distinguish gamma counts by clocking angle in the pipe. As such, the resulting worst-case deposit geometry is a segment of uniform assumed thickness that varies in coverage () to match the detected (count rate based) loading (Fig. 12) per Eq. 3.

Eq. 3

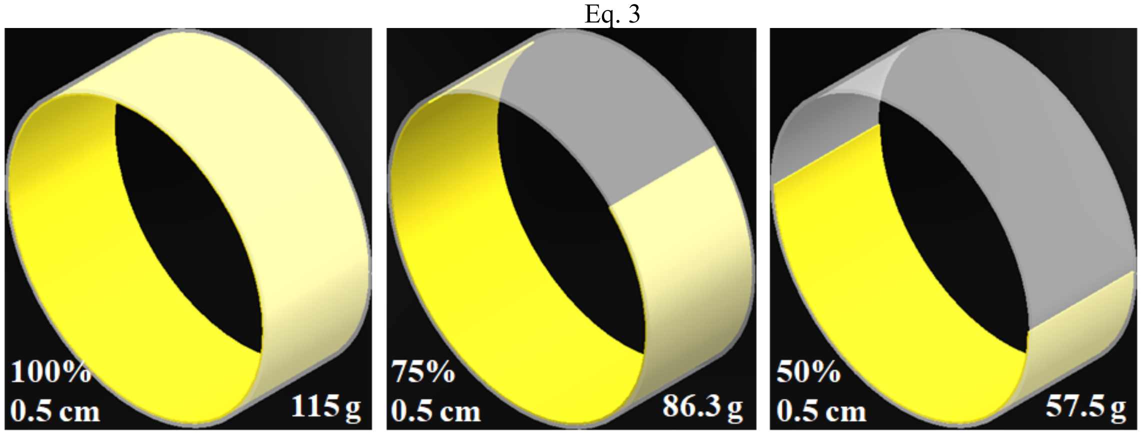
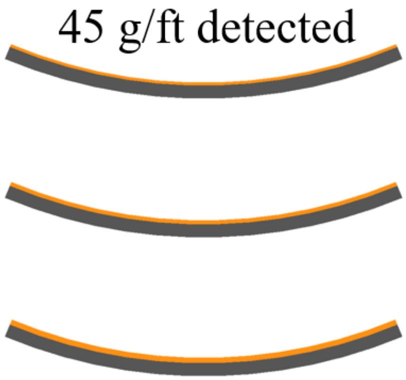


Fig. 12. Varying coverage in a model pipe segment showing changing loading at constant thickness.

While calculating this coverage does not affect the reporting loading in standard modeling cases, it is an important step due to the possibility of calculated coverages exceeding 100%. In such cases, the deposit material is actually thicker than the assumed thickness (but less than the flagging thickness). PCAMS executes another attenuation model to handle these cases.

Iterative Model for Above-Thickness Deposit

In cases where the detected count rate must originate from deposit larger than the assumed thickness, PCAMS attempts to provide analysts with a re-estimation of deposit content. This method involves iteratively increasing the *thickness* variable in Eq. 2 and recalculating the coverage until the modeled coverage is 100%, as illustrated in Fig. 13. (While 100% coverage could cause underestimates on some large lumps, the PCAMS source discontinuity and assumed thickness parameters are set to limit this bias to a standard approved -30%.)



$$0.22\text{cm}: \frac{66\text{ g/ft unattenuated}}{51\text{ g/ft by volume}} = 129\%\text{ coverage}$$

$$0.30\text{cm}: \frac{77\text{ g/ft unattenuated}}{69\text{ g/ft by volume}} = 112\%\text{ coverage}$$

$$0.4\text{cm}: \frac{92\text{ g/ft unattenuated}}{92\text{ g/ft by volume}} = 100\%\text{ coverage}$$

Fig. 13. Example of iteratively increasing the PCAMS model thickness until it yields a physically possible deposit case. Note that the pipe cross-sections on the left are 45° slices in order to show such small deposit thicknesses (orange), but the method is applied to the full 360° (100% coverage) cross-section.

The PCAMS self-attenuation program also does an automatic check for loadings within three sigma (total measurement uncertainty) of infinite thickness. Upon completion of all modeling, checks, and final attenuation adjustment to the detected U-235 loading, the PCAMS method finds the maximum loading reported within each segment. This is used as the reported NDA loading as it is the basis on which the discontinuity adjust is calculated and its bias is minimized (recall Fig. 5).

In order to determine the NCS measurement, the *a posteriori* MDA must also be computed as a minimum reporting value. For NDA loadings above MDA, NCS normally adds two-sigma of the total measurement uncertainty to the NDA value and compares it to the CI criterion.

MINIMUM DETECTABLE AMOUNT

PCAMS computes its *a priori* lower limit of detection (LLD) and subsequent MDA based on the 15-minute background spectrum taken in a clean test pipe preceding its detector efficiency calibration. The experimental *a priori* MDA of the first robot is 0.25 g/ft (30-inch pipe), an order of magnitude below the customer requested MDA. This is computed using Eq. 4 and converting the resulting LLD count rate to U-235 mass without regard for attenuation [14]. The experimental ratio of count rate to U-235 mass is 35 counts per second per gram-per-foot in 30-inch pipe and 19 of the same in 42-inch pipe, based on a calibrated detector efficiency of 44%.

Eq. 4

A posteriori LLD is computed similarly to its clean-pipe *a priori* counterpart but incorporates the 196 keV peak of RadPiper's pre-inspection QC check as a background spectrum. Because this spectrum is collected outside of the contaminated process pipe, it is computationally attenuated through a pipe wall per Eq. 5, wherein *contin* indicates the continuum spectrum for the given segment or the *QC* check. Thus, characteristic *a posteriori* MDAs for segments under this limit are also approximately 0.25 g/ft.

Eq. 5

TOTAL MEASUREMENT UNCERTAINTY

PCAMS 15% (30-inc pipe) and 13% (42-inch pipe) total measurement uncertainty (TMU) propagates potential error from five sources: detector calibration, current detector orientation, current pipe conditions, and current spectroscopy. Calibration uncertainty derives from the tests' counting and source uncertainty as well as from the PCAMS model, as discussed in the next section, and carries a total characteristic value of 3% for both pipe sizes. This is minimized due to RadPiper's automated calibration procedures which limit error in source location.

The robot's detector orientation can differ from calibration conditions due to RadPiper's skew angle or radial offset while traversing a pipe. This is characterized based on robot steering activity and enforced to these limits using pitch and geometric profiling flagging. The result is a characteristic 12.6% TMU effect in 30-inch and a 9.4% effect in 42-inch pipes.

Current pipe condition effects on uncertainty are two-fold. This first is the manufacturing tolerance of the pipe, taken as a 1.5% effect [15]. The second is the potential longitudinal discontinuity of the source deposit. This phenomenon results in a method bias of 14% and 39% (30- and 42-inch) as described above in the collimation section but also carries some uncertainty, 2% and 3.5%, respectively, due to the assumptions underlying these models as discussed below in the calibration section.

Though not present with the PCAMS standard model's single assumed thickness, PCAMS also accrues additional self-attenuation uncertainty in the thicker deposit model as deposit approaches infinite thickness (which occurs at 54% TMU). Uncertainty is propagated through the PCAMS self-attenuation model by inputting the detected gram loading plus one-sigma pre-attenuation TMU for computation at the one-sigma range of enrichment uncertainties (e.g. 0.96 wt% and 1.04 wt% for a 4% one-sigma on a 1 wt% nominal enrichment). PCAMS takes the worst-case difference in reported loading as its final one-sigma TMU.

The per-segment two-sigma total measurement uncertainty bounds for PCAMS unofficial performance demonstration testing are shown in Fig. 14.

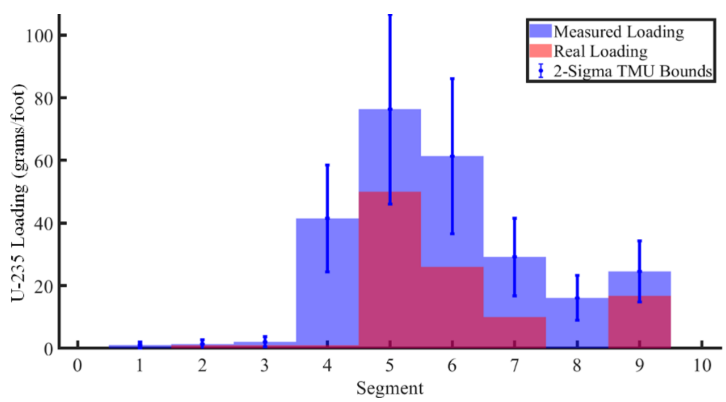


Fig. 14. Sample PCAMS reported loadings (blue) and ground truth (red, purple showing overlap) with 2-sigma TMU error bars.

The modeling uncertainty contribution to detector pose and pipe tolerance are taken as the root mean square error (RMSE) of the detector model calibration, as described below.

DETECTOR MODEL CALIBRATIONS

The PCAMS disc-collimated detector requires two calibrations: one for overall detector efficiency and another for efficiency versus position along the pipe axis in the detector's field of view. (These calibrations can be computed from a single test but are separated in order to increase the types of useable reference sources). The first calibration involves simply driving the robot slowly over a source with a known total loading, which RadPiper conducts autonomously when commanded via its wireless interface. This test yields a time series of spectra showing an increase in the 186 keV peak as the robot approaches the source, and then a mirrored decrease as it passes it (Fig. 15 left). The total loading reported by PCAMS is set equal to the true loading and can be visualized in the scale difference between the actual and idealized moving average result (Fig. 15 right).

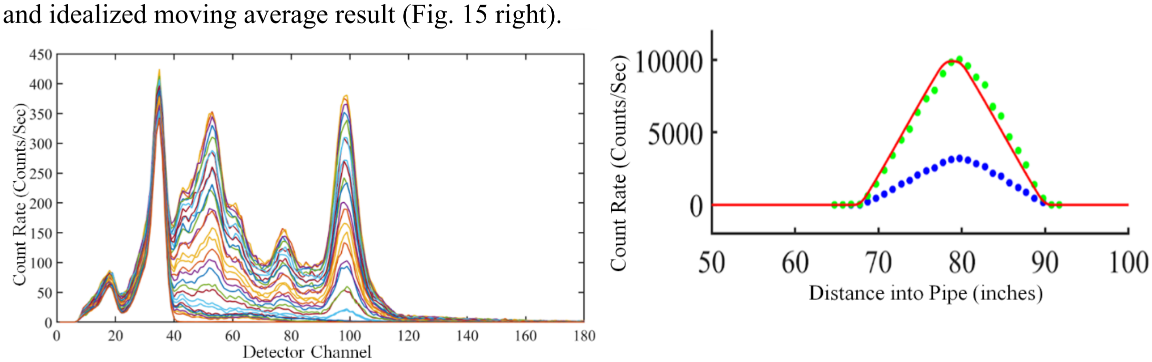


Fig. 15. (Left) Spectra sampled as RadPiper drove over a calibration source in a 30-inch pipe. (Right) Net 196 keV count rate for each spectrum localized to its position in the pipe (blue) as compared to the idealized robot model (red) and the subsequently efficiency-adjusted experimental curve (green).

The efficiency versus position in the field of view calibration is more complex and can be understood as experimentally determining the detector's true effective field of view dimension. Experimentally, it involves RadPiper automatically driving over a known point source (herein Co-57 due to unavailability of high-loading U-235 point sources) at known distance and time intervals, illustrated schematically in Fig. 16 (left). The result is a point source characterization of the detector's response throughout its entire field of view. This raw data is shown in dark blue in Fig. 16 (right). The curve is then scaled by the overall detector efficiency, taken as the area under the experimental and theoretical model (red) curves, to generate the light blue curve. The final step automatically finds the most likely field of view length by minimizing the RMSE (i.e. area) between the scaled experimental and model theoretical curves, adjusting the theoretical curve for this field of view. This entire process is automated after similarly automatic robotic positioning and data collection.

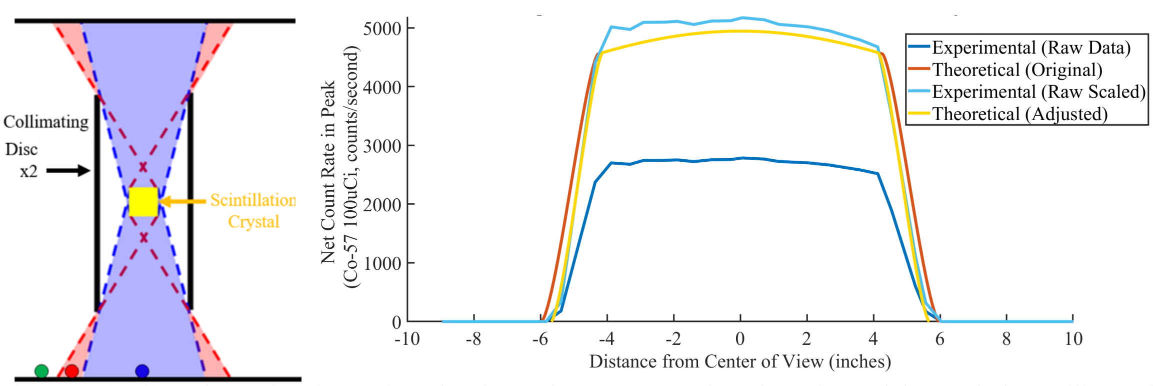


Fig. 16. (Left) Schematic view of a circular point source at locations in and beyond the collimated detector's field of view. (Right) Experimental 30-inch calibration showing raw (dark blue) and efficiency-scaled (light blue) data and the original (yellow) and RMSE-minimized (red) theoretical model.

The resulting field of view measurement is incorporated into PCAMS auto-analysis as the specific robot's field of view length, and the resulting minimized RMSE is taken as the model error in TMU. This use of RMSE represents a larger effect than the calibration uncertainty actually causes because counting uncertainty in calibration affects the RMSE more than the length of the field of view (the latter being the parameter on which the model actually depends).

KNOWN SOURCE COMMISSIONING TESTS

NDA technicians and analysts at DOE Portsmouth in collaboration with Carnegie Mellon University developers conducted over 200 known-source U-235 test runs for two RadPiper robots in PCAMS test pipes. The culmination of this commissioning test plan was a set of six unofficial Performance Demonstration Program (PDP) for each robot. A sample 30-inch PDP test is plotted in Fig. 9; a sample 42-inch test is included below in Fig. 17.

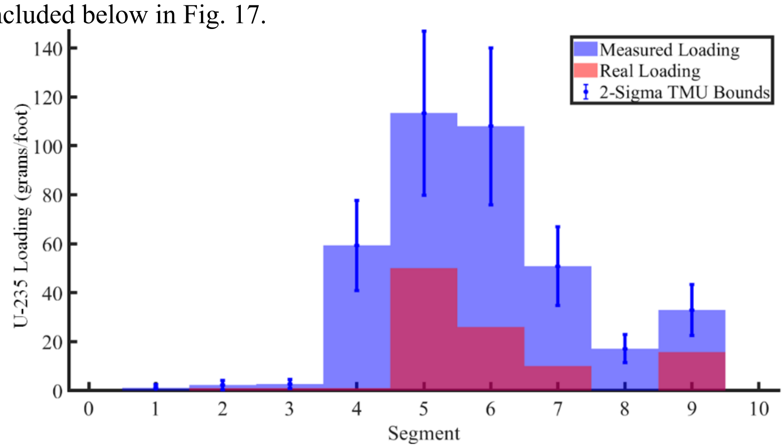


Fig. 17. Sample results from an unofficial PCAMS PDP test in 42-inch test piping.

PCAMS exhibited a six-run average bias of under 80% for peak segments in 30-inch pipe and under 200% in 42-inch pipe. This drops to under 60% and 125% above customer MDA (5 g/ft). Non-peak segments can have a maximum loading equal to that of its adjacent segment, due to the conservative selection of the maximum loading in each segment (which may occur near a segment line) as its reported value. Fig. 18 below shows the average bias plotted against the raw detected grams in each case. Note that this is the detected rather than corrected loading due to the bias limits lines (green and red) dependency on the former. Data points are labeled with their true loading. Another commissioning study at 100 grams is also included to show results above CI (though this test as fewer repetitions).

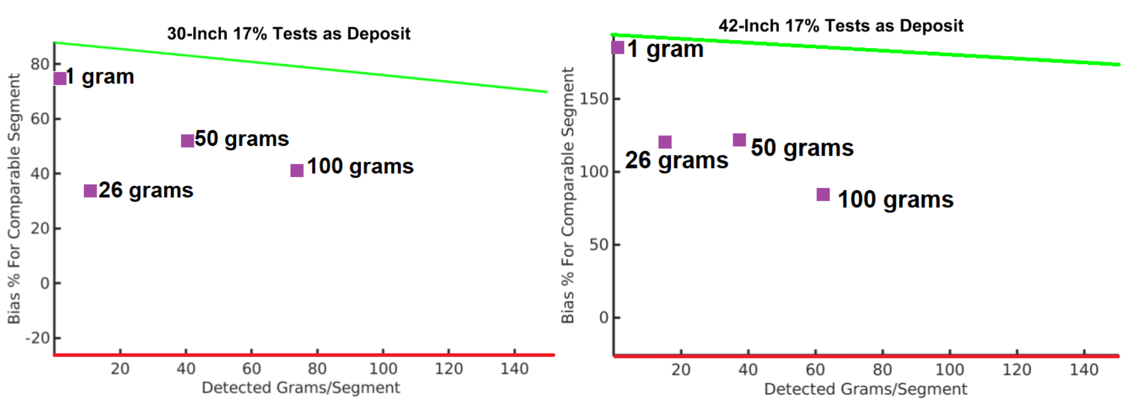


Fig. 18. Average bias vs detected grams at 17% enrichment treated as UO_2F_2-$2H_2O$.

Between runs, the robot and method exhibited a relative 1-sigma standard deviation of 1.73% on 50 grams, 8.47% on 26 grams, and 20.14% on 1-gram peak segments. Fig. 19 shows the smooth curve of reported grams (before segmenting) and the per-segment reports along with their 2-sigma TMU bounds. Note that repeatability for all segments lies well within 2-sigma and is in fact within 1-sigma.

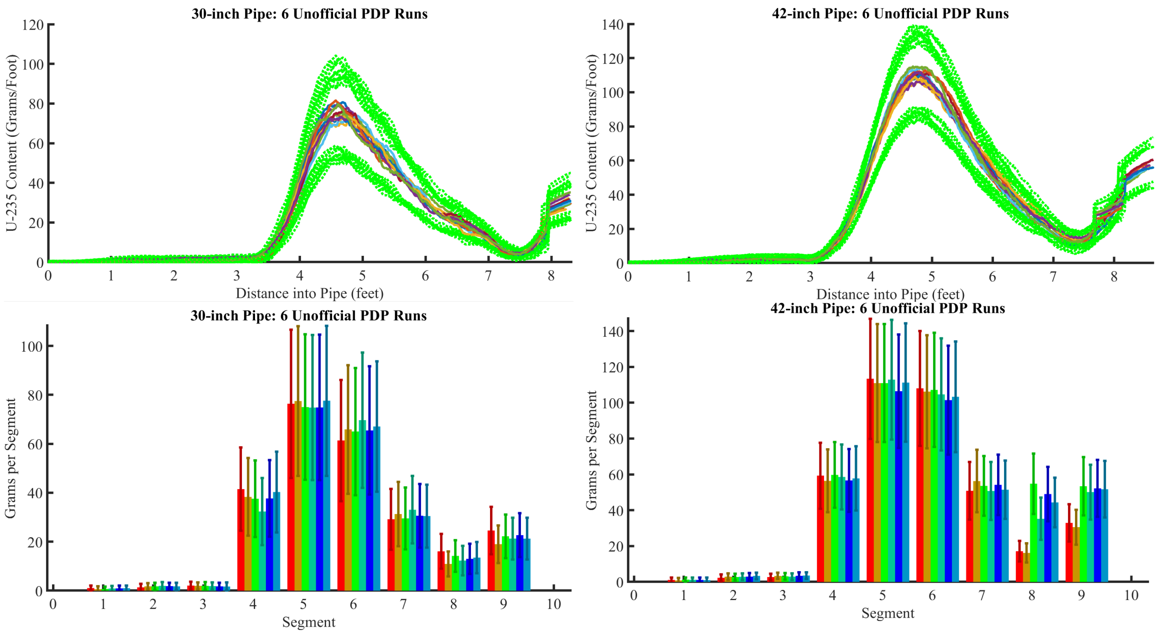


Fig. 19. PCAMS repeatability over 6 runs in 30- (left) and 42-inch (right), with 2-sigma TMU bounds.

CONCLUSION

This paper documents the key novel developments of the PCAMS radiometric method that formalizes the modeling for and leverages the unique advantages of robotic in-pipe nondestructive assay of U-235 holdup deposit. The key feature is a novel disc-collimated gamma detector that the PCAMS RadPiper robot continuously moves along the axis of 30- and 42-inch pipes. The robot also carries localization, geometric, and orientation sensors that are used to inform computation of U-235 loadings in each foot of inspected pipe and to flag out-of-model geometry, radiometry, and/or orientation for subjective analyst review.

The radiometric methodology described herein exhibits an *a priori* MDA of 0.25 g/ft, a characteristic TMU of 13-15%. Bias limits have been bounded mathematically based on isotropic standards and will be refined in further operational applications. The system has been shown in controlled test and process pipe inspection to correctly flag conditions that violate its model assumptions: under-defined or out-of-tolerance detector pose as well as in-pipe geometric building and holes. Calibration procedures for two RadPiper robots have been executed with near-identical results of 44% efficiency and 21.6 cm (30-inch pipe) and 28.0 cm (42-inch pipe) fields of view.

The current PCAMS method is submitted for final review to DOE EM as codified in a method Technical Basis Document and accompanying memoranda and sample reports. The entire PCAMS pipeline and methodology is code, verified, documented, and delivered to the Portsmouth Gaseous Diffusion Plant where it is incorporated into the PCAMS server in its information technology infrastructure. The system has been successfully hot tested by Carnegie Mellon-trained NDA technicians and analysts.

After official approval, future work in the PCAMS method includes removal of some flags and enhanced automatic flag clearing at low-loadings per requests from Portsmouth NDA. After July 2018 hot testing that provided geometries or real process piping, an improved geometric model based on the spatial relationship of deposit in elliptical pipes is being developed. An updated localization method [16] is also being integrated to decrease localization uncertainty to sub-centimeter. Improvements to the key sources of model bias, the discontinuity adjustment and self-attenuation, are being vetted.

More broadly, PCAMS methodology is being applied to the development of 10-inch and 3-inch pipe inspection, the latter using a miniature cubic cadmium zinc telluride detector. Approval and deployment of the current method are scheduled to save hundreds of thousands of person-hours and millions of dollars at DOE Portsmouth alone, and expansion to additional facilities and pipe sizes will save countless more hours of hazardous and lengthy manual NDA that poses a bottleneck to D&D around the world.

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