Commissioning of Robotic Inspection and Automated Analysis System for Assay of Gas Diffusion Piping – 19500

Siri Maley*, Heather Jones*, Warren Whittaker*, David Kohanbash*, Josh Spisak*, Ralph Boirum*, Andrew Zhang*, J. David Yesso**, Russell Riddle**, William Whittaker*
* Carnegie Mellon University
** Subcontractor to Fluor-BWXT Portsmouth LLC

ABSTRACT

Robotic, in-pipe, nondestructive assay (NDA) is a revolutionary and important means for measuring, analyzing, and reporting radioactive holdup deposits in enrichment piping. This innovation promises vast advantages for efficiency, safety, and cost savings. Payoff, however, lies in utilization much more than innovation. Crossing that threshold from a technical capability to an everyday tool occurs only after rigorous commissioning, adoption, and infusion. This must meet the highest standard, and there can be no compromise. Certification of a new NDA technology must meet the highest standards for quality, safety, and efficacy. Prior to this work, there was no precedent of procedure and method for certification of a robotic methodology for this purpose. The best of robotics had not certified NDA. The best of NDA had not certified robotics. Hence, a great deal of discovery, resourcefulness, and collaboration contributed to this success. This paper chronicles the first-of-kind chartering, co-development, testing, documentation, and site integration that certified this trailblazing in-pipe, robotic NDA.

Commissioning had to demonstrate and certify end-to-end NDA automation from robot traversal to computer analysis to report generation of contaminated process piping at the Portsmouth, Ohio gaseous diffusion facility. This was a rigorous campaign of tests, evaluations, and documentation. Highlights included multiple tests in four elevated pipes exercised the gamut of NDA and robotic capabilities. Each of the four test pipes presented a unique loading of U-235. The tests demonstrated operations in both 30-inch and 42-inch diameter pipes with varying lengths and terminated by a variety of valves and fittings. Tests in a fifth pipe at floor level demonstrated deployment and applicability for pipes at this ground height and robot recognition of another fitting type. All operations, calibration, deployment, auto-reporting, and analysis were handled by Portsmouth site personnel. These tests concluded a series of component-level acceptance tests which certified all constituent technologies and operational features. Test metrics included comparison of reported to ground truth results and assessment of data quality from quality assurance and replicate measurement comparison.

Beyond the radiometry associated with any NDA method, this unique commissioning path exercised and evaluated all the robotic features that are intrinsic to automation. These include odometry, geometric modeling, autonomy, remote launch and recovery, and end-to-end data flow. Each of these required verification and certification. These evaluations were first-of-kind for the decommissioning community, requiring innovation and resourcefulness in their own right.

INTRODUCTION

Characterization (especially as related to criticality incredible declarations) is a well-known cost and schedule driver in decontamination and decommissioning (D&D) process of every defunct gaseous diffusion enrichment facility in the world. Each gaseous diffusion facility contains hundreds of miles of piping that must be characterized, inspected, and certified as being below the criticality incredible (CI) threshold for U-235 content to facilitate D&D activities. Pipes containing material above the CI threshold normally require time-consuming and costly removal and management in hazardous conditions by personnel at elevation.

Pipes containing less U-235 than the CI threshold are candidates to be economically demolished in place, though decommissioning supervisors still require understanding of the total U-235 content.

The Pipe Crawling Activity Measurement System (PCAMS) and "RadPiper" robot were hot tested at Portsmouth in July 2018 with intention for infusion into regular operations beginning November 2018 (Fig. 1). Previous work on this program included hot testing of two research prototypes in 2017 [1,2,3].

Fig. 1. Technicians prepare to deploy PCAMS RadPiper into a contaminated process pipe.

In the DOE Portsmouth facility alone, RadPiper is anticipated to save months of critical-path schedule, associated person-hours, and significant costs across hundreds of meters of assayable pipe. Carnegie Mellon's charter included reducing hazards and increasing throughput for technicians, requiring remote deployment at elevation with minimal disruption to the existing facility structure. This requires robust automatic safeguarding by the robotic pipe crawler to avoid entering any elbows, valves, or pipe intersections it cannot safely traverse.

This paper presents the overall PCAMS system as deployed for nondestructive assay (NDA) at the Portsmouth, Ohio plant along with the results of initial operations. It specifically covers the technician and analyst workflow as well as the supporting equipment, documentation, and integration processes required for DOE certification. This paper will be of interest to any stakeholder looking to deploy a similar automated robotic system in their facility, beginning with discussion of the system's overall concept of operations and compliance with relevant NDA standards and continuing into details of system and user workflow, quality assurance, hardware operations, and NDA reporting with hot testing results.

CONCEPT OF OPERATIONS

The preexisting non-destructive assay (NDA) method at Portsmouth employs radiometric measurement from the pipe exterior to quantify the U-235 content of pipe [4]. This technique requires spectroscopy through the attenuating steel pipe wall with no direct observation of the pipe interior. It also requires human presence at the pipe wall, entailing costly, hazardous, and time-consuming activities to provide access to the piping and lengthy work in confined and elevated areas by personnel in restrictive personal protective equipment (PPE).

Both the preparation and inspection processes are slow, labor-intensive, and error-prone, with some inspection methods requiring multiple technicians and 15 minute dwell times for every five-foot section of pipe. In addition, the data collection system is manual in nature, with opportunities for both cost and schedule improvements.

PCAMS precludes many of the hazards and bottlenecks of existing NDA practices by conducting robotic inspection, digital data logging, automated analysis, reporting, and archiving of pipe runs. The PCAMS RadPiper robot travels along the interior of process pipes (Fig. 2). Cladding, structure, and insulation that surrounds the piping need not be removed as is necessary for externally deployed manual methods. The robot carries a novel disc-collimated gamma detector [5] along the center axis of the pipe. This acquires gamma spectra relating to a continuously moving annulus of pipe wall without the attenuation experienced by sensing through the pipe wall. A camera and geometric profiler directly observe the interior deposit geometry to inform automatic radiometric analysis. Visual and geometric models are provided to analysts as supplementary exhibits in cases where interpretation of radiometry benefits from this other information.

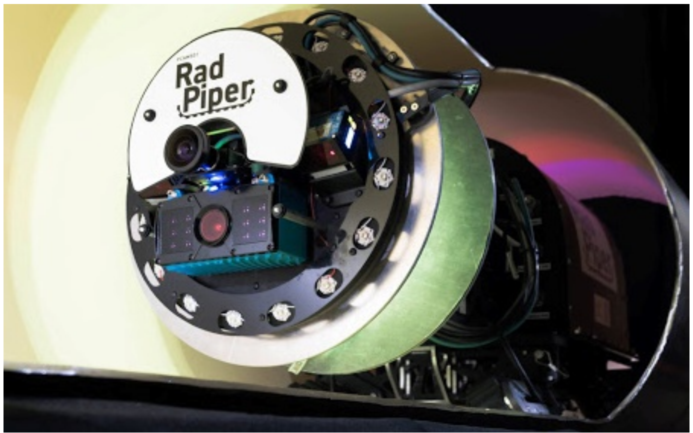
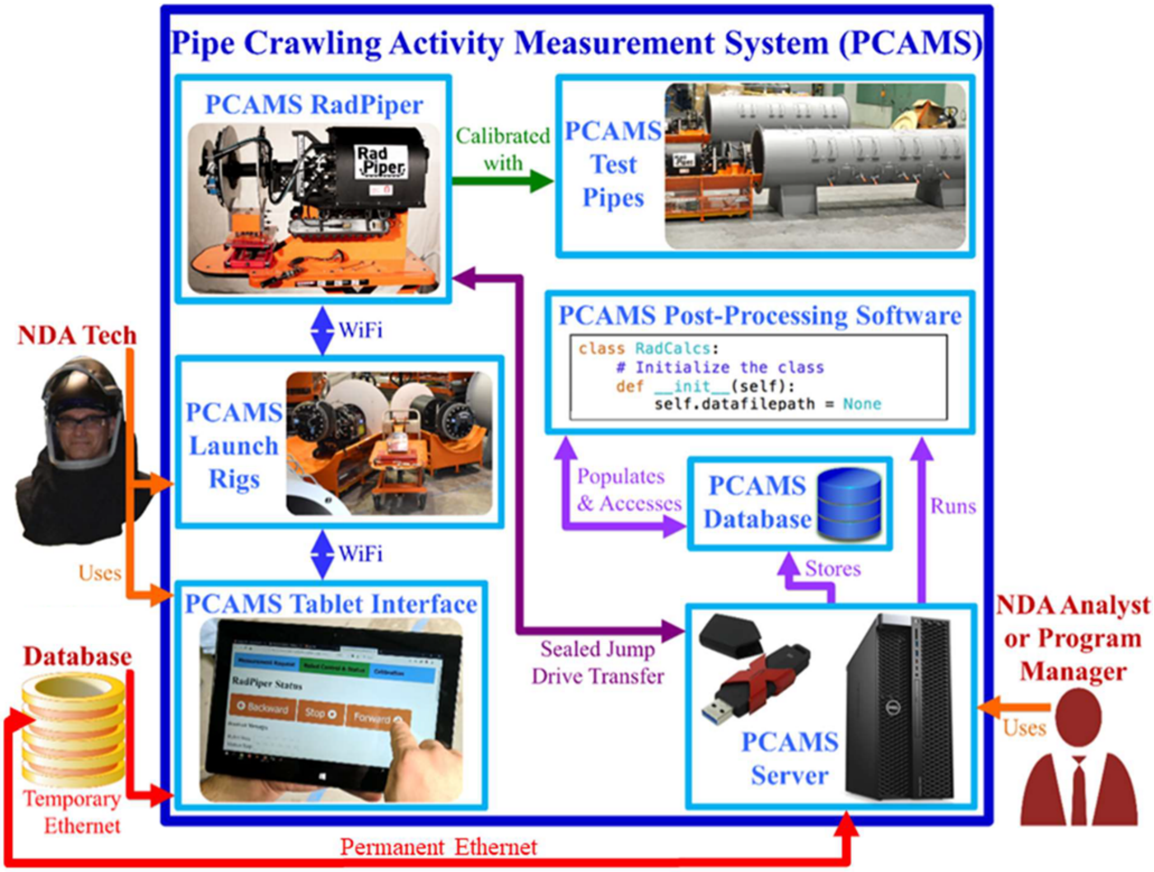


Fig. 2. PCAMS RadPiper shown inspecting the wall of a cutaway pipe. The large discs in front bracket a gamma detector, which views a disc-collimated annulus of holdup deposit on the pipe wall.

The RadPiper robot autonomously traverses and returns to the open pipe end from which it was deployed, having stored all radiometric, visual, geometric, localization, and other data onboard a removable jump drive located in a sealed and uncontaminated compartment. Technicians then remove this jump drive and transfer it to a PCAMS post-processing server, which automatically generates preliminary results for analysts to review. Analysts use the custom user interface to view any results flagged as questionable by the automated processing, and they can use supplemental visual, geometric, and spectroscopic exhibits collected by RadPiper to accept or reject specific results. The final results are then auto-collated into a Portable Document Format (PDF) report and permanently archived in the PCAMS database, which is integrated into the existing Portsmouth IT infrastructure. The PCAMS server also contains the ability to generate files for automatic integration of results into a site-specific repository.

In addition to handling inspection requests, robotic inspection, automated analysis, and report generation, the RadPiper PCAMS system includes everything necessary to automatically calibrate and confirm the quality of NDA results for 30- and 42-inch pipes. The key additional component is a set of test pipes in these diameters with removable cutouts for holding various known-content Working Reference Materials (WRMs) in order to test the robot with certified U-235 sources. PCAMS technical documents and procedures include the method and processes for automatically calibrating and routinely verifying the robot gamma detector.

Data collection for these procedures is fully automated by the robot and technician interface, the latter of which is a wireless touch-screen tablet designed for personnel in PPE. Fig. 3 illustrates the PCAMS workflow.



```
class RadCalcs:
    # Initialize the class
    def __init__(self):
        self.datafilepath = None
```

Fig. 3. PCAMS system overview. NDA technicians remotely deploy the pre-calibrated robot on its launch rig via a wireless tablet request loaded from the site database. Data collected by the robot is transferred via jump drive to the PCAMS server that databases the information, runs auto-analysis and reporting software, and allows NDA analysts and managers to edit and approve the report. Upon approval, PCAMS NDA results are directly exported to the site database.

STANDARDS AND REQUIREMENTS

The PCAMS system is hot tested and slated for initial deployment in Portsmouth's X-333 building, a two-story Category II nuclear facility with almost 8 kilometers (5 miles) of standard 30- and 42-inch straight horizontal piping in its enrichment cascade. The PCAMS team was chartered with creation of two complete production prototype systems to ASME Nuclear Quality Assurance (NQA)-1 Quality Level 3 (QL3) standard as implemented in Portsmouth-Paducah Project Office standards for general and information technology quality assurance. The Post-Processing Software (PPS) analysis, in particular, is certified as safety-related software for use in criticality safety determinations. Certification requires maintenance of and adherence to the program's Software Quality Assurance (SQA) Implementation Plan, and Method Verification and Validation (V&V) Report. The initial report includes independent verification of all PCAMS PPS data handling, calculations, modeling, and error checking for radiometric, localization, and geometric methodology and reporting. This included independent Monte Carlo N-Particle Transport Code by Savannah River National Laboratory that yielded a 5.9% difference from the PCAMS model.

Additional V&V of the analyst user interface ensures that all final results and radiometric, geometric, visual, robot status, and batch information data displayed are correct per PCAMS, SQA, and quality standards.

Integrated into the PCAMS method of six different automatic quality controls checks (detailed in [6]):

1. Automatic checks by RadPiper of its onboard Am-241 source before and after each run.
2. Simultaneous contamination checks for U-235 at 185.7 keV that occur during Am-241 checks.
3. Checks of spectra from each segment of inspected pipe for the Am-241 source in the presence of high or low U-235 loadings.
4. Check of the full pipe spectrum (spectra summed over entire run) to confirm U-235 peak location.
5. The first of two (2) replicate checks of each batch, based on the total measured grams of U-235.
6. The second of two (2) replicate checks of each pipe batch, based on the segment with the highest reported U-235 loading.

These PCAMS method checks and software V&V reports are a key to PCAMS current and continued compliance with the PPPO quality assurance program. Additional requirements are compliance with Fluor's D&D Independent Technical Review (ITR) process and Batch Process Verification (BPV) Checklists, which PCAMS conducts automatically and displays in its Data Review Report Table of auto-generated NDA reports. Checklist items include certification that approved calibration, calibration confirmation, and calibration verification tests for the specific robot are within required time windows. PPS also verifies that RadPiper's functional checks were acceptable and that two NDA technicians present for robot deployment independently entered and digitally signed off the correct pipe identification information.

Many other ITR and BPV items are inherent in PCAMS automation, including lack of transcription errors, appropriate units and constants, and correct report formatting and content. Final reports cannot be generated for Project Manager approval until all issues flagged for subjective analyst review are either accepted (e.g. rejecting an uninspectable segment) or cleared (accepting the data with a comment detailing the appropriate reason). For instance, PCAMS will automatically flag segments in which it passed a vacuum port (which cannot be assayed by RadPiper while it the main piping run), allowing analysts to accept the measurement for the pipe itself and request separate NDA measurement(s) of the vacuum fitting.

For the robot itself, PCAMS ensures compliance with NQA-1 QL3 through delivery of a Requirements, Integration and Test Report detailing compliance with all technical and functional requirements for safety, operations, data logging, and management, robot performance and sensing, mobility and electromechanics, testing, training, certification, and delivery. The PCAMS team also delivered an in-person training course and an Operations Manual with handling, deployment, and maintenance procedures, as well as official drawings, original manufacturer documentation (e.g. for PCAMS-modified scissor lifts).

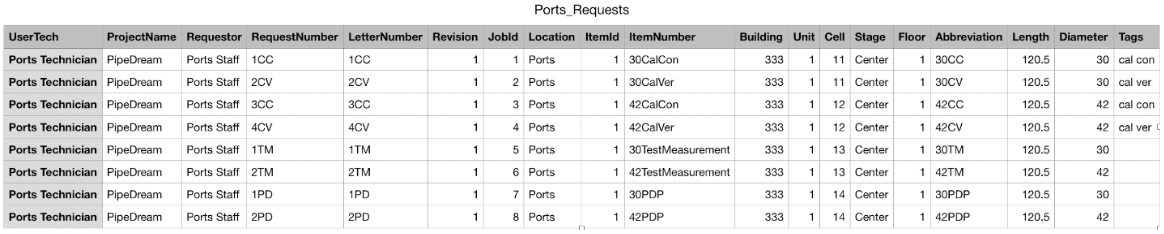
Details of method requirements, assumptions, limitations, modeling, and calculations are included in a comprehensive Technical Basis Document authored by the Carnegie Mellon team. Three hundred pages of additional documentation, four design reviews, an acceptance test, calibration and commissioning test week, and hot testing week were also executed during fiscal year 2018 in order to ensure the system's current streamlined integration into site operations and analysis processes, safety and administrative protocols, and information technology infrastructure. The following sections detail the resulting system in terms of technician, analyst, and automated PCAMS operational workflows, quality assurance, and testing, robot handling and maintenance, and NDA reporting, the last including results from hot testing in contaminated process piping. Other papers on the PCAMS system cover the RadPiper robot specifically [7], the automated analysis system [6], and the radiometric [8] and localization [9] methods.

AUTOMATED DATA FLOW

Pre-Populated Measurement Requests

The PCAMS automated data flow begins and ends with the DOE site. First, the database exports a measurement request to the PCAMS tablet interface. An NDA technician operates the pipe crawling robot which surveys the requested pipe and stores results to a USB jump drive. The results are transferred to a post-processing server which provides analysis to the NDA analyst and program manager. Once the measurement request has been fulfilled via PCAMS, all results are directly imported back to the site database.

The detailed flow of data begins when the wireless tablet interface receives a series of measurement request files from the site database via temporary ethernet connection. On each of the Portsmouth tablets is a PCAMS browser that acts as a live gateway to a RadPiper robot. The browser automatically parses the job and pipe identification, requested run length, expected pipe diameter, and any additional tags provided manually by the requestor or automatically by the site database. Tags include requests for a specific run distance (as opposed to the full length of traversable pipe) and notes about pipe segments that differ from the standard pipe model, e.g. expansion joints. Request files are a simple spreadsheet format and can also be created or edited manually on a desktop or the tablet for supplementary or checkout runs (Fig. 4). The final measurement request information is passed directly to RadPiper and later onto the post-processing server for data quality assurance.

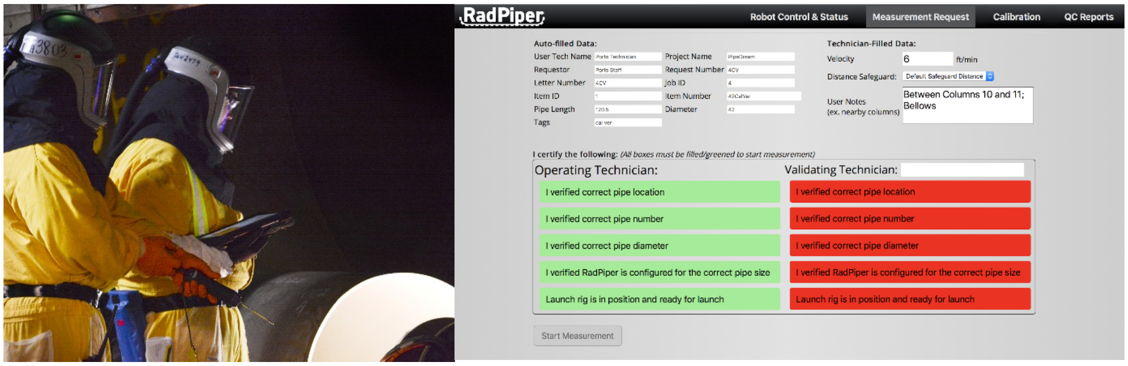


Ports_Requests

UserTech	ProjectName	Requestor	RequestNumber	LetterNumber	Revision	JobId	Location	ItemId	ItemNumber	Building	Unit	Cell	Stage	Floor	Abbreviation	Length	Diameter	Tags
Ports Technician	PipeDream	Ports Staff	1CC	1CC	1	1	Ports	1	30CalCon	333	1	11	Center	1	30CC	120.5	30	cal con
Ports Technician	PipeDream	Ports Staff	2CV	2CV	1	2	Ports	1	30CalVer	333	1	11	Center	1	30CV	120.5	30	cal ver
Ports Technician	PipeDream	Ports Staff	3CC	3CC	1	3	Ports	1	42CalCon	333	1	12	Center	1	42CC	120.5	42	cal con
Ports Technician	PipeDream	Ports Staff	4CV	4CV	1	4	Ports	1	42CalVer	333	1	12	Center	1	42CV	120.5	42	cal ver
Ports Technician	PipeDream	Ports Staff	1TM	1TM	1	5	Ports	1	30TestMeasurement	333	1	13	Center	1	30TM	120.5	30	
Ports Technician	PipeDream	Ports Staff	2TM	2TM	1	6	Ports	1	42TestMeasurement	333	1	13	Center	1	42TM	120.5	42	
Ports Technician	PipeDream	Ports Staff	1PD	1PD	1	7	Ports	1	30PDP	333	1	14	Center	1	30PDP	120.5	30	
Ports Technician	PipeDream	Ports Staff	2PD	2PD	1	8	Ports	1	42PDP	333	1	14	Center	1	42PDP	120.5	42	

Fig. 4. A measurement request as displayed by RadPiper's wireless tablet interface.

When an NDA technician is ready to begin inspecting a particular pipe, they need only select the measurement request matching the pipe from a dropdown list. The screen then auto-populates as shown in Fig. 5. The principal technician and a validating technician then independently complete five safety checks to ensure RadPiper is ready to drive and is located in the correct pipe. Additional options include entering comments that populate into the final NDA report and setting a fixed distance to inspect a particular section of pipe. After entering their names and confirming their selections, the technician presses the start button to begin RadPiper's automated deployment procedure. This is the only time two technicians are required to operate a single robot, but multiple robots can be deployed simultaneously via different tablets.



Auto-filled Data:
User Tech Name: Ports Technician
Requestor: Ports Staff
Letter Number: 4CV
Item ID: 1
Pipe Length: 120.5
Tags: cal ver
Project Name: PipeDream
Request Number: 4CV
Job ID: 4
Item Number: 42CalVer
Diameter: 42

Technician-Filled Data:
Velocity: 6 ft/min
Distance Safeguard: Default Safeguard Distance
User Notes (ex. nearby columns): Between Columns 10 and 11; Bellows

I certify the following: *(All boxes must be filled/greened to start measurement)*

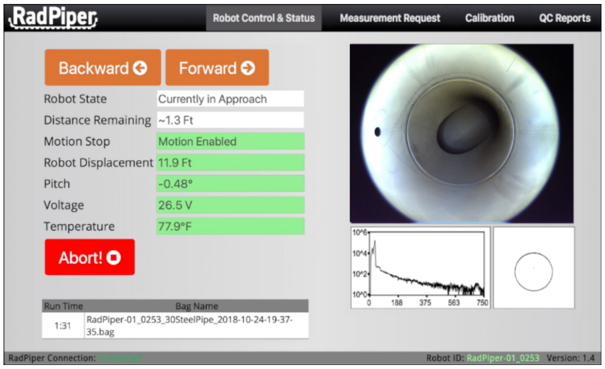
Operating Technician:	Validating Technician:
🟩 I verified correct pipe location	🟥 I verified correct pipe location
🟩 I verified correct pipe number	🟥 I verified correct pipe number
🟩 I verified correct pipe diameter	🟥 I verified correct pipe diameter
🟩 I verified RadPiper is configured for the correct pipe size	🟥 I verified RadPiper is configured for the correct pipe size
🟩 Launch rig is in position and ready for launch	🟥 Launch rig is in position and ready for launch

Fig. 5. (Left) NDA technicians deploying RadPiper into a process pipe. (Right) Start screen of the PCAMS RadPiper wireless tablet showing information populated from the measurement request (top left), technician input (top right), and the deployment safety checks for both operators (incomplete information is highlighted in red).

Remote Monitoring of Autonomous Robotic Inspection

Upon receiving the wireless start command from an NDA technician's tablet, RadPiper begins a three-minute quality control check which includes spectroscopy of its onboard americium-241 check source and benchmarking of background radiation levels outside the pipe. After successfully completing this check, the robot automatically displays the results and enters the pipe to begin inspection. If the check fails (e.g. failure record the check source spectra), the robot halts and alerts the NDA technician's tablet of the failure.

The live display and immediate feedback to the NDA technician continue throughout the pipe traversal for as long as the robot is within wireless range (tested to over 30 m). The tablet displays live imagery from the robot's forward fisheye camera as well as the current gamma spectrum and geometric profile of the pipe interior. Additional information about the robot's position, orientation, battery voltage, internal temperature, and other status and health checks are also displayed with alerts in the event of errors or safety conditions (Fig. 6). Note that despite the wealth of information RadPiper provides to the user, it requires no operator intervention during pipe inspection. It automatically traverses forward until detecting the end of its requested run, an impassable obstacle (e.g. closed valve), or an irrecoverable robot error (e.g. low battery). Once a reversal condition is met, RadPiper alerts the technician and reverses to its starting position in the launch rig. The technician retains the ability to take manual control of RadPiper at any time.



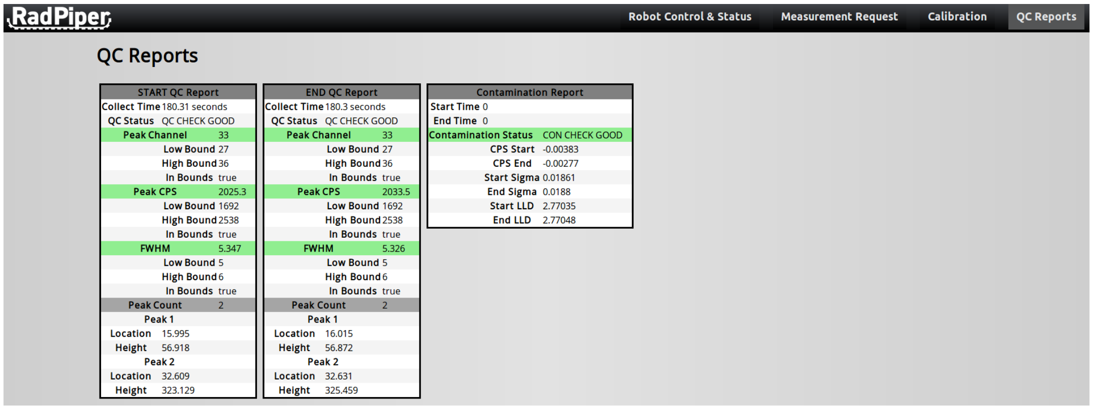
Robot State: Currently in Approach
Distance Remaining: ~1.3 Ft
Motion Stop: Motion Enabled
Robot Displacement: 11.9 Ft
Pitch: -0.48°
Voltage: 26.5 V
Temperature: 77.9°F

Run Time	Bag Name
1:31	RadPiper-01_0253_30SteelPipe_2018-10-24-19-37-35.bag

RadPiper Connection: Connected
Robot ID: RadPiper-01_0253 Version: 1.4

Fig. 6. Technician's view as RadPiper approaches a swept tee requiring it to end its forward traversal and return to the launch rig.

Upon returning to its start position, RadPiper automatically begins its post-run quality control check. After successful completion of this check, the results are again displayed to the technician on the tablet (Fig. 7). A failed check alerts the technician to implement corrective action or rerun the check (the latter only in cases of an efficiency failure within three standard deviations). In the latter case, the check can be rerun immediately through the tablet interface. If RadPiper passes the technician can continue to inspect additional pipes without interruption.



QC Reports

START QC Report	
Collect Time	180.31 seconds
QC Status	QC CHECK GOOD
Peak Channel	33
Low Bound	27
High Bound	36
In Bounds	true
Peak CPS	2025.3
Low Bound	1692
High Bound	2538
In Bounds	true
FWHM	5.347
Low Bound	5
High Bound	6
In Bounds	true
Peak Count	2
Peak 1	
Location	15.995
Height	56.918
Peak 2	
Location	32.609
Height	323.129

END QC Report	
Collect Time	180.3 seconds
QC Status	QC CHECK GOOD
Peak Channel	33
Low Bound	27
High Bound	36
In Bounds	true
Peak CPS	2033.5
Low Bound	1692
High Bound	2538
In Bounds	true
FWHM	5.326
Low Bound	5
High Bound	6
In Bounds	true
Peak Count	2
Peak 1	
Location	16.015
Height	56.872
Peak 2	
Location	32.631
Height	325.459

Contamination Report	
Start Time	0
End Time	0
Contamination Status	CON CHECK GOOD
CPS Start	-0.00383
CPS End	-0.00277
Start Sigma	0.01861
End Sigma	0.0188
Start LLD	2.77035
End LLD	2.77048

Fig. 7. Technician’s view of the quality control and contamination check at the end of a run.

Automatic Data Analysis and Reporting

After completion of one or multiple (one jump drive can hold up to several dozen) inspection runs, RadPiper’s NDA technician can remove the USB jump drive from its sealed uncontaminated compartment (using one glove to unscrew the cover and a clean glove to remove and bag the drive). This jump drive is then brought to a separate desktop for uploading to the PCAMS post-processing server (Fig. 8). This upload passes all site database measurement request, request edits, technician input and comments, and robot inspection data to the server for analysis.

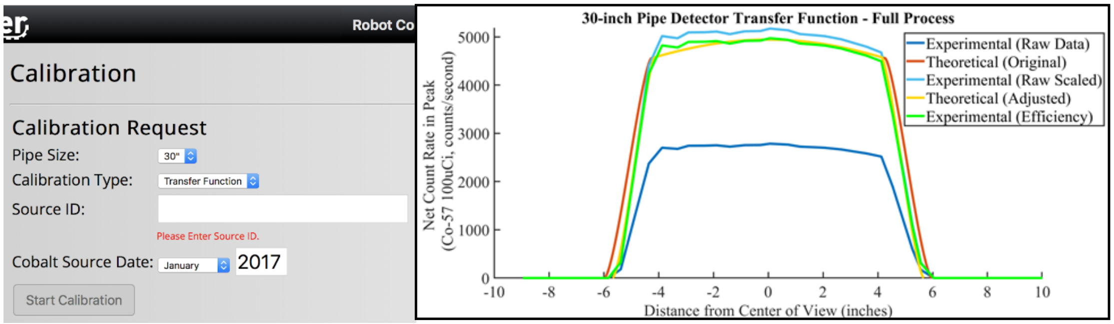
Fig. 8. (Right) sealed USB jump drive compartment on RadPiper and (left) jump drive inserted for upload to the PCAMS Post-Processing Server.

The server passes all relevant data to the analysis and reporting software and independently archives the raw data for integrity assurance purposes. After final approval of an NDA report, official results can be exported directly from PCAMS back to the Portsmouth site database.

INTEGRATED QUALITY ASSURANCE AND TESTING

In addition to the official inspection runs and integrated quality control source checks described above, the PCAMS system includes automatic data collection, test analysis, and compliance tracking of calibration parameters, annual confirmation of recalibration, and weekly calibration verification tests for each robot.

PCAMS has two radiometric calibration procedures, one for overall detector assembly efficiency and one for determining efficiency versus position along the disc-collimated field of view. Both only need to be conducted once for each robot (excluding major maintenance or detector replacement) and involve traversal over known gamma sources at specific distance and time increments. The technician selects which calibration and pipe size to run and identifies the test source. The tablet provides prompts regarding source placement, and the robot conducts all motion and data collection autonomously. The calibration itself is computed automatically by a software package which will be fully integrated into the on-site post-processing server in 2019 (Fig. 9).



Calibration

Calibration Request

Pipe Size: 30"

Calibration Type: Transfer Function

Source ID:

Please Enter Source ID.

Cobalt Source Date: January 2017

Fig. 9. (Left) technician's screen for calibration and (right) automatic longitudinal distance vs. detector efficiency calibration plot.

Calibration confirmations and verifications are processed as standard inspection runs but are tracked separately on the PCAMS server in order to automatically report if the robot and detector are within their required annual and weekly test ranges. These known-source tests are conducted in PCAMS 30- and 42-inch test pipes (approximately 76 and 107 cm), which have a series of removable panels to position sources at different distances and angles (Fig. 10). Inclusion of the calibration pipes in the PCAMS system allows technicians to verify procedures and run practice tests outside of real process pipes.

Fig. 10. (Left) RadPiper deploying into 30- and 42-inch PCAMS test pipes. (Right) Technician securing a known U-235 source in a removable test pipe panel.

ROBOT TRANSFORMATION AND DEPLOYMENT

PCAMS RadPiper robots can inspect both 30- and 42-inch process pipes by transforming to position its collimated detector on the center axis of either pipe size. In order to do adapt the robot, technicians use a custom cart to raise and lower the collimated detector assembly and adjust the robot treads. The cart includes an integrated scissor jack for adjusting the collimator height and suspends the treads freely in the air to enable safe, ergonomic adjustment (Fig. 11). The robot is fully rigid in either configuration, facilitating absolute sensor registration and axisymmetric radiometric modeling.

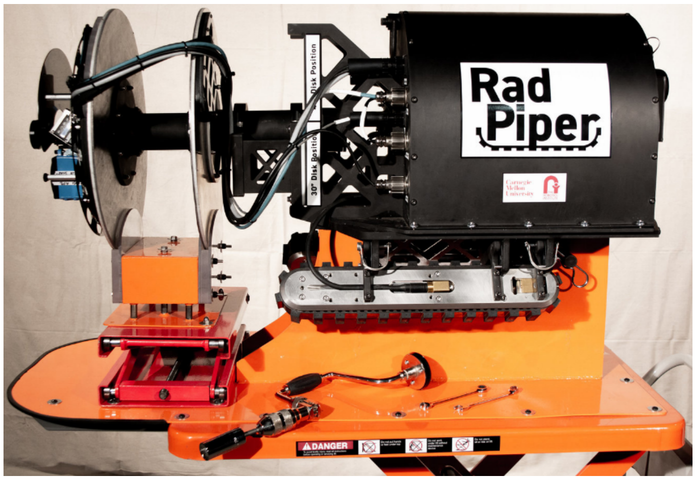


Fig. 11. RadPiper in 30-inch configuration on its cart, with reconfiguration tools in the foreground.

Transport between the robot reconfiguration stand and the launch rig is performed using a hoist attachment mounted on the robot's front bulkhead directly above its center of mass such that RadPiper hangs exactly level during transport.

After configuration for the correct pipe size and placement on the launch rig, technicians position the launch rig in front of the entrance to a pre-cut pipe. For low pipes, this is done by steering a pallet jack and braking it in place. For high pipes, the launch rig is locked to a modified scissor lift and is remotely driven (no personnel onboard at height) to align with the pipe opening (Fig. 12).

Fig. 12. RadPiper deploying into a (left) at-grade process pipe and (right) an elevated pipe.

Both launch rigs include a directional antenna for robot communication and magnetic-mount omnidirectional antennas for tablet communication as well as onboard power and storage space for the robot charger. A leash mechanism connects the launch rig to the robot towbar for safe transport, and a punch-out section in the rear panel physically contains the robot and triggers the robot's emergency stop without damage if it ever fails to stop upon exiting the pipe. The white panel on the back of the rig (Fig. 12 left) is the reflective target for RadPiper's laser rangefinder.

MANUAL HANDLING AND MAINTENANCE

When not deploying remotely at elevation, technicians can make use of RadPiper's rear bulkhead interfaces (Fig. 13). These interfaces, including the main power switch and charging power switch, are mounted for ergonomic use by technicians wearing full PPE. A physical motion stop button is wired directly into the track motor controllers and is automatically pressed if RadPiper drives into the back of its launch rig. A manual forward/reverse jog switch is included for positioning the robot in its designated launch rig perimeter or rotating the tracks during decontamination.

Two sets of indicator lights are visible on the back of the robot as it traverses a pipe: a pair of battery gauges and three LED lights display the robot's power status (red or off), travel direction (flashing green for forward and flashing red for reverse), and wireless connectivity (yellow or off). Next to these interfaces are various robot sensors, including a rear-pointing laser rangefinder (which reflects off the white target of the launch rig), a wireless antenna (directed toward the launch rig's matching antenna), and a spinning laser triangulation sensor, which geometrically profiles the pipe interior. A tow bar is mounted directly to the track platform for securing the robot and recovering it in the event of an in-pipe mobility failure.

RadPiper also has multiple sensor connections of its front bulkhead that quickly detach to allow removal of the collimator and front sensing modules. On the opposite side of the front surface is the user data interface, which includes a series of debugging ports and the sealed compartment containing the removable USB jump drive to which RadPiper logs its inspection data.

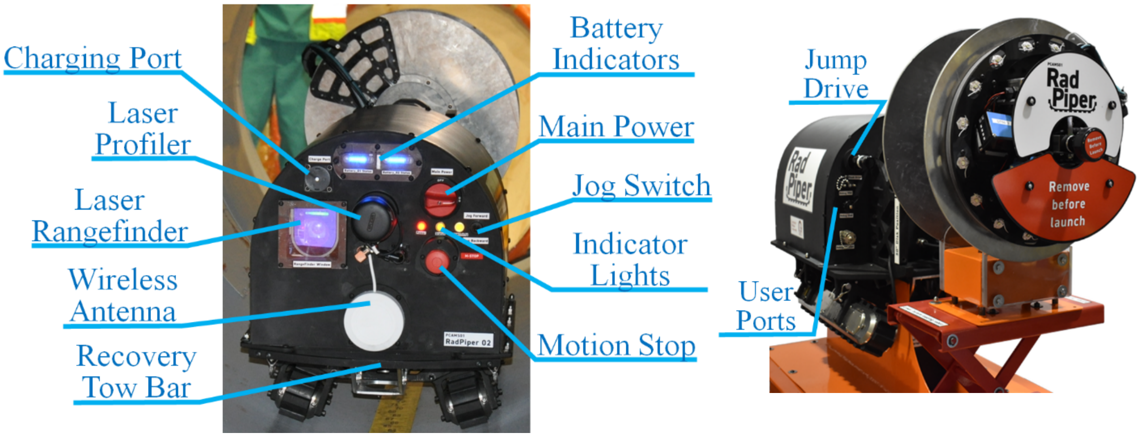


Fig. 13. (Left) RadPiper in a test pipe with its rear interfaces and sensors labeled. (Right) RadPiper on its cart with its front-mounted debugging ports and USB jump drive labeled.

If more invasive operations are required, technicians can disassemble and replace all key RadPiper modules (Fig. 14). The collimator detector, check source, and support brace remove with four bolts each (the last enables future inclusion of additional pipe sizes, e.g. 24- and 36-inch, approximately 61 and 91 cm). The bottom mobility platform is removable for decontamination or to adapt to different pipe sizes. The front sensing module is fully removable to provide easier replacement of the camera, safeguarding laser mapper, and point laser sensors.
On the rear bulkhead, the laser profiler, antenna, and sensor windows are externally removable.

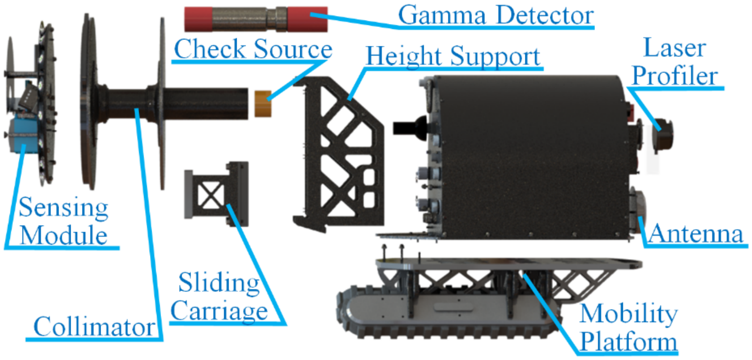


Fig. 14. Replaceable modules comprising RadPiper.

NDA RESULTS AND REPORTING

Portsmouth technicians and analysts successfully tested RadPiper and its automated analysis and reporting software in over 60 meters (200 feet) of contaminated pipe and over 300 runs in test pipes during Summer 2018. RadPiper consistently identified and retreated from multiple impassable conditions autonomously: closed valves, pipe reducers, and swept tees in both 30- and 42-inch pipes (Fig. 15).

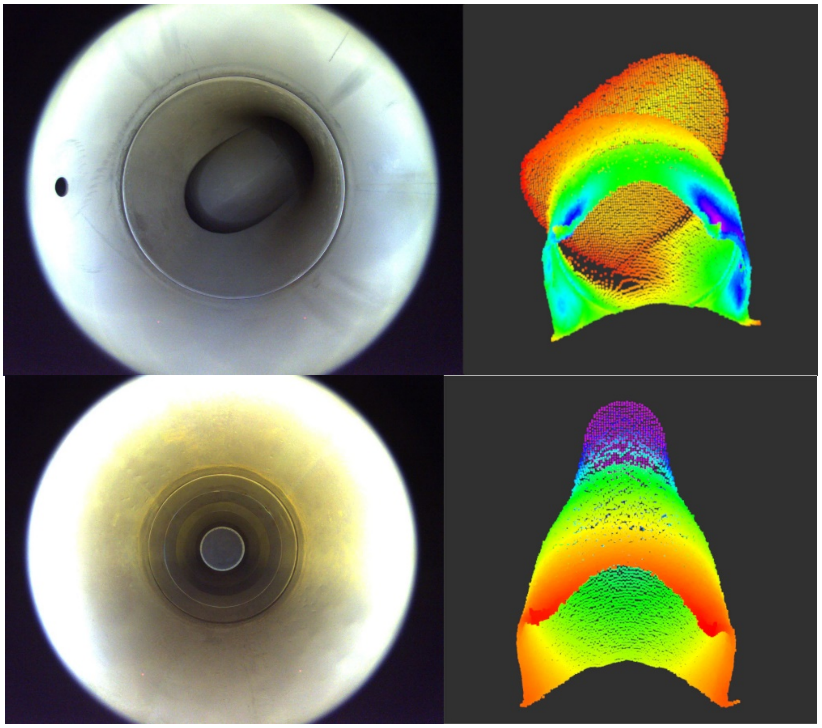


Fig. 15. Camera images (Top and bottom left) and safeguarding models of (top right) a swept tee and (bottom right) a reducer.

Robot data and post-processing localization software exhibited a standard deviation of 0.88 cm regarding the distance to a flange weld joint it traversed six times (three forward/reverse runs).

Building drawings also provide dimensions between two sets of weld seams: PCAMS measured the first to within 2.5 cm and the second to within 1.3 cm (examples in Fig. 16).

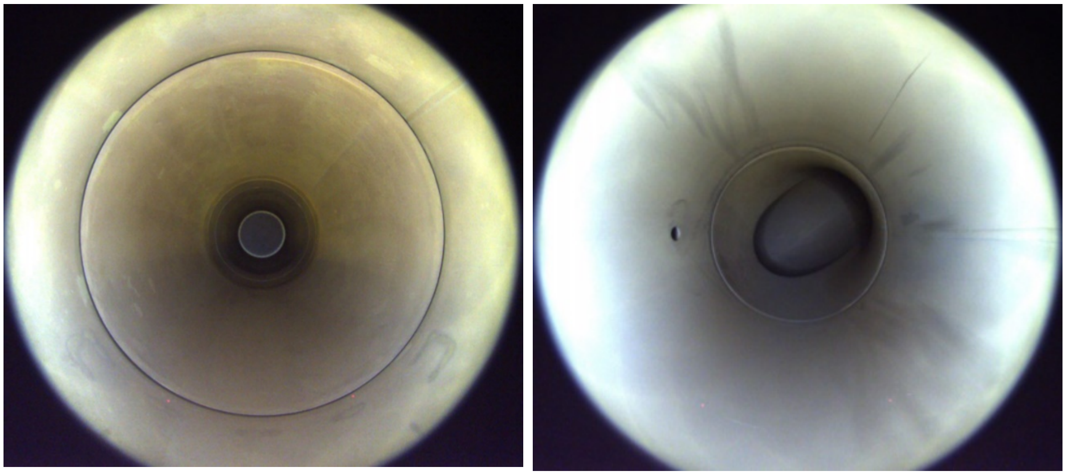


Fig. 16. Pipe features localized in PCAMS in process piping runs.

All process pipes inspected thus far have exhibited very low U-235 loadings (Fig. 12), so the full range of PCAMS capability has not yet been experienced. Radiometry results also include geometric profiles of the pipe interior, which are used to inform self-attenuation determinations (Fig. 17).

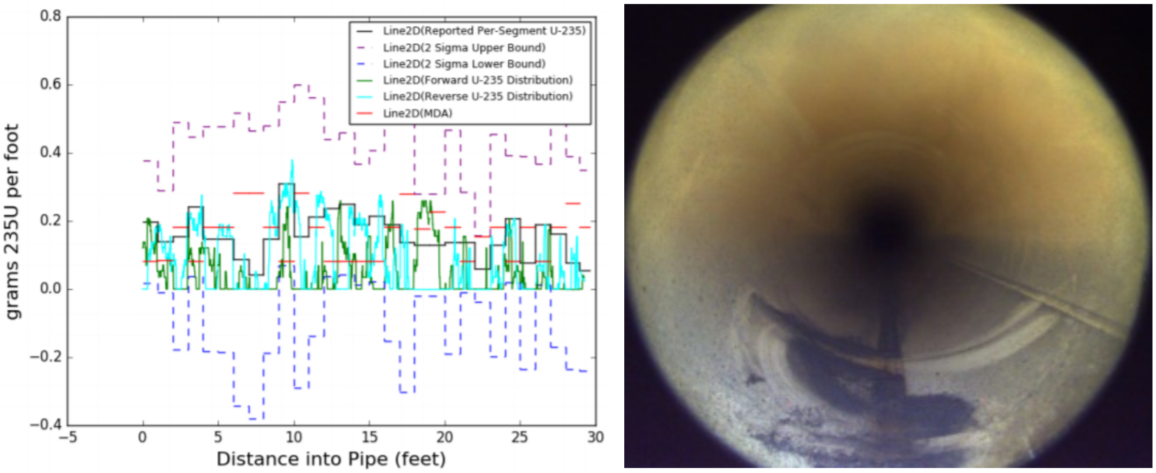
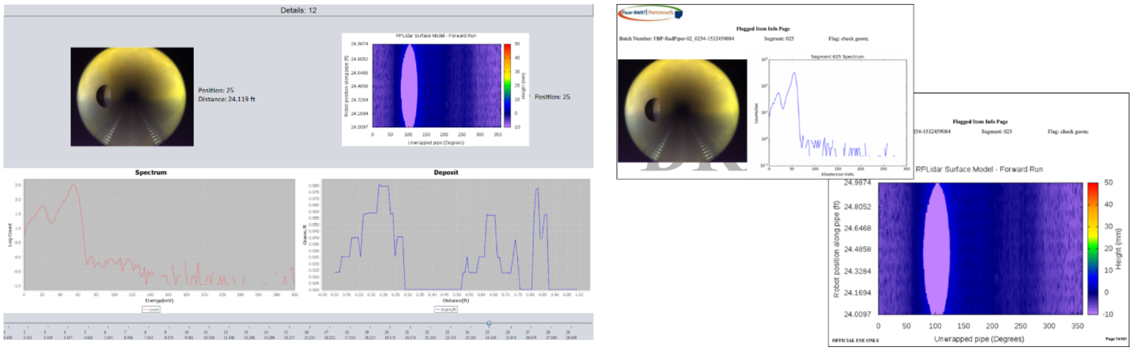


Fig. 17. (Left) U-235 content of a PORTS process pipe and (right) geometric model of its interior.

All NDA results are automatically analyzed and displayed in the analyst interface in PCAMS post-processing (Fig. 18). Portsmouth analysts independently navigated the interface to review and annotate reports, clear automatic flags, and reject uninspectable segments. PCAMS correctly threw flags to alert analysts of thick geometric buildup (debris from pipe cutting) and holes in the pipe surface (vacuum ports). The former were cleared as non-deposit, and the latter were identified as requiring separate assay.


Details: 12

Position: 25

Distance: 24.119 ft

Position: 25

Flagged Item Info Page

Batch Number: FBP-RadPiper-02_0254-1532459084

Segment: 025

Flag: check geom;

Fig. 18. (Left) Flagged segment display in the analyst interface showing an alert to geometric buildup on the bottom of the pipe. (Right) Excerpt from an auto-generated report showing details of a flagged vacuum port.

Measurement requests for all inspected pipes were generated by Portsmouth’s site database, except one that proved technicians can manually update requests via the tablet while in PPE on the cell floor. Upon final approval of PCAMS procedures, official reports for these pipes will be imported back to the site database, completing the full circle of automated inspection, analysis, reporting, and archiving.

PATH TO COMMISSIONING

Development of the PCAMS method, robot, and analysis system have moved at what some have called “Manhattan Project-like” pace through many stages of CMU, Portsmouth, and DOE development and acceptance. Interactions included four design reviews, an acceptance review, an on-site calibration week, a hot testing and verification week, and sessions for technician and analyst training. Uncounted are the tens of thousands of person-hours required to adapt to the unforeseen needs of commissioning and deploying a novel robotic system. The end count is thousands of design decisions, fabrication of hundreds of parts, coding and verification of twelve thousand lines of software, and delivery of over seven hundred pages of manuals and thousands of NDA report pages fulfilling over one hundred official requirements. Official documents include an Operations Manual, Fabricated Drawings and Equipment Lists, Purchased Hardware Documentation; Analysis Manual, Verification and Validation Report, Server and Software Guide, and Test and Requirements Reports. Equipment includes two test pipes, a lifting hoist, two scissor lifts, four launch rigs, two pallet jacks, a transformation cart, two RadPiper robots, four electronics modules, fifteen jump drives, and two official servers with PCAMS Post-Processing Software (Fig. 19).

Fig. 19. Support equipment in the production PCAMS system (for two robots).

CONCLUSION

The Pipe Crawling Assay Measurement System is the first commissioned and operating automated DOE-approved NDA of holdup deposits in enrichment piping. The system certification achieved here is a very high bar beyond the many elements of robotics, radiometry, auto-analysis, auto-reporting, site integration, and deployment challenges when taken individually.

PCAMS is the first DOE approved automated means for NDA CI measurements of any kind. Hitherto NDA measurement was the exclusive domain of manual methodology and human interpretation.

PCAMS is a pioneering game-changer that shifts NDA CI measurements from a paper-heavy human-centric process towards a formalized, standardized, efficient hands-off enterprise.

The RadPiper robot is tetherless and autonomous. This breaks the cultural and technical mold of nuclear robotics that are commonly tethered and teleoperated for many reasons. The autonomy accomplishes the precision driving, safeguarding and automated data-logging that are beyond human capability and essential to achieving the high standard of NDA quality and certainty that PCAMS exhibits.

PCAMS is the forebear of many future variations and refinements that will evolve to address the vast agenda for NDA of radioactively contaminated facilities, piping, and processing equipment around the world. The procedures for commissioning those many evolutions were pioneered in this work. These procedures and methods will apply to all evolutions of this class of NDA automation that are yet to come.

REFERENCES

1. “Robotic NDA of Holdup Deposits in Gaseous Diffusion Piping by Gamma Assay of Uranium-235”, H. Jones, W. Whittaker, O. Sapunkov, T. Wilson, D. Kohanbash, S. Maley, J. Teza, E. Fang, M. McHugh, I. Holst, C. Ng, R. Riddle, WM 18331.
2. “Robotic Measurement of Holdup Deposit Volume in Gaseous Diffusion Piping to Quantify U-235 Content”, L. Papincak, H. Jones, M. Hanczor, W. Whittaker, J. Teza, D. Kohanbash, S. Maley, D. Arnett, A. Tallaksen, A. Duncan, I. Cordova Lantadilla, R. O’Keefe, J. Ford, W. Whittaker,WM 18375.
3. “Results of Robotic Evaluation of Uranium-235 in Gaseous Diffusion Piping Holdup Deposits”, H. Jones, S. Maley, T. Wilson, R. Riddle, M. Reibold, W. Whittaker, D. Kohanbash, L. Papincak, W. Whittaker, WM 18303.
4. Smith, S.E. et al., “Holdup Measurement System 4 (HMS4) - Automation & Improved Accuracy,” Institute of Nuclear Materials Management Meeting 2004.
5. “System and Method for Passive Assay of Holdup Deposits in Nuclear Piping”, W. Whittaker, S. Maley, H. Jones, O. Sapunkov, PCT/US18/52245.
6. “Automated Analysis, Reporting, and Archiving for Robotic Nondestructive Assay of Holdup Deposits”, H. Jones, S. Maley, K. Yonekawa, D. Kohanbash, M. Mousaei, W. Whittaker, WM 19508.
7. “A Robot for Nondestructive Assay of Holdup Deposits in Gaseous Diffusion Piping”, H. Jones, S. Maley, D. Kohanbash, W. Whittaker, M. Mousaei, J. Teza, A. Zhang, N. Jog, W. Whittaker, WM 19504.
8. “Novel Radiometry for In-Pipe Robotic Inspection of Holdup Deposits in Gaseous Diffusion Piping”, S. Maley, H. Jones, W. Whittaker, WM 19503.
9. “High Precision Localization Using Reciprocal Sensor Fusion for In-Pipe Nuclear Robot NDA”, D. Zhao, W. Whittaker, WM 19516.

ACKNOWLEDGEMENTS

Commissioning of this pioneering system required committed and intentional collaboration by DOE, DOE’s PPPO, the Portsmouth site contractor. The real acknowledgement is to their many great people. This degree of co-development and collaboration is completely unprecedented in the experience of the authors. The accomplishment owes high appreciation to the many evangelists, technologists, implementers, operators, analysts, managers and leaders who contributed so immensely. They leave their mark of high impact for generations to come.

Funding for this work was provided by the US Department of Energy under cooperative agreements DE-EM0004383 and DE-EM0004478.