Results and Perspectives from Testing at Portsmouth

Robotic Measurement of $^{235}\text{U}$ in Pipe Holdup Deposits

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Introduction

A team from Carnegie Mellon University and University of Nevada, Reno developed two robots for evaluation of holdup deposits in deactivated gaseous diffusion piping. The effort was supported by DOE EM. Facility expertise throughout development, as well as robot operation at the DOE Portsmouth site, was provided by Fluor-BWXT.

The RadPiper robot conducts radiation-based assay. The PipeDream robot conducts volumetric deposit characterization. Both robots were demonstrated in tests conducted at the DOE Portsmouth site on 19 and 20 September 2017. An additional test of the RadPiper robot was conducted on 17 October 2017. Results from these tests are presented below, with RadPiper discussed first, followed by PipeDream.

Figure 1: Portsmouth operators in PPE with PipeDream (left) and RadPiper (right).
Figure 2: Carnegie Mellon, DOE, and Fluor-BWXT group photograph with RadPiper and PipeDream.

Figure 3: Rod Rimando of DOE EM and Marty Reibold of Fluor-BWXT with PipeDream.
RadPiper: Radiation-based Assay

Executive Summary

RadPiper is a pipe-crawling robotic NDA platform for D&D of gaseous diffusion process piping. This initial proof-of-application prototype was successfully hot tested by operators at the DOE Portsmouth facility on 18-21 September and 17 October 2017. The testing achieved all goals of traversing pipe, measuring $^{235}$U, deployment by facility personnel, and displaying analyzed radiation, visual, and geometric information. The success was a Kitty Hawk moment. The RadPiper tests demonstrated robotic in-pipe measurement of holdup deposit to a resolution, accuracy, and speed unachievable by alternate methods. Key highlights include:

1. Pipe traversal at the unprecedented speed (for accurate holdup assay) of 10 ft/min.
3. Accurate measurements with tight error bounds of source strengths that varied from <1g/ft to 17.65 g/ft.
4. Output of industry-standard g/ft $^{235}$U measurements at 2-inch intervals, or 3-6 times more frequently than the external manual NDA practice of every 6-12 inches or more.
5. Deployment by Portsmouth operators wearing appropriate PPE into process pipes at multiple heights and locations.
6. Display of visual deposit appearance and internal pipe features in fully lit, full coverage high definition and correlated to pipe location.
7. Reporting of precise geometry for pipe interiors as mapped by the robot’s spinning laser rangefinder.
8. Mapping of the shape, dimension, and location of the hot pipe openings and contaminated vacuum fittings that the robot passed.
9. Sensing of deposit fluorescence in high definition and full coverage with intense ultraviolet light. This sensing mode returned no observable fluorescence.

These goals did not address broader system capabilities for auto-analysis, auto-reporting, auto-archiving, and integration with full-scale site operations for screening pipe. These are all addressable in the future and secondary in scope and difficulty to the fundamentals of physics, robotics, and method as demonstrated in this testing.
Training of Portsmouth operators for the deployment, operation, and recovery of RadPiper (Figure 5) was done using a clean pipe and took less than two hours. Operators then conducted numerous cold, warm, and hot test runs in four different pipes (Figure 6 and Figure 7). The following sections report radiation, imagery, geometric, and operational results, discussions, and findings from these tests.

Figure 5: The RadPiper prototype and its launch rig by the cold pipe as CMU and Portsmouth operators review the procedure.
Figure 6: Portsmouth operators in PPE deploying RadPiper in the warm pipe.

Figure 7: Operators in full airborne PPE launch RadPiper from its launch cart into the first hot pipe.
Cold Pipe Hybrid Tacky Mat Testing

RadPiper completed three forward and three reverse runs in a 15’ cold (clean) 30” pipe over a series of four Hybrid Tacky Mats (HTMs). These silicone mats contain evenly-distributed known quantities of $^{235}$U and were arranged end-to-end on a tarp inside the pipe (Figure 8 and Figure 9). Their actual contents, provided ex post facto by Portsmouth operators, and the g/ft measured by RadPiper are displayed in Figure 10.

Figure 8: Close-up of hybrid tacky mats (HTMs) used in cold pipe testing.

Figure 9: Hybrid tacky mats as deployed in cold pipe for testing, photographed by RadPiper.
As Figure 10 indicates, RadPiper consistently and conservatively overestimated the g/ft of $^{235}\text{U}$ along the pipe. The solid gray line is the actual g/ft of $^{235}\text{U}$ in the pipe. The black line shown is a prediction of the $^{235}\text{U}$ g/ft an idealized robot would measure with RadPiper’s 12” field of regard. This is identical to the actual g/ft except for slight rounding due to a 3-second moving average. The colored curves are RadPiper’s results. Note the uncanny match. This is quality measurement of grams/ft $^{235}\text{U}$ every 2” along the pipe. The magnitude of each peak, each valley, and each plateau on the true g/ft curve matches the RadPiper measurement. The slopes transitioning between the plateaus, created as the 12” field of view covers less of the previous mat and more of the next, also match. Table 1 presents the measured g/ft of each mat averaged across all runs. These values also reflect the method’s overestimation, which is a function of a conservative self-attenuation multiplier.

<table>
<thead>
<tr>
<th>Mat Number</th>
<th>$^{235}\text{U}$ per Mat (g)</th>
<th>Total Length of Each Mat (in)</th>
<th>Actual g/ft $^{235}\text{U}$ per Mat</th>
<th>Measured g/ft $^{235}\text{U}$ per Mat</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25</td>
<td>17</td>
<td>17.65</td>
<td>19.9</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>17</td>
<td>3.53</td>
<td>5.6</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>35.5</td>
<td>8.45</td>
<td>9.5</td>
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<tr>
<td>4</td>
<td>5</td>
<td>35.5</td>
<td>1.69</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Table 1: Contents, lengths, and g/ft of $^{235}\text{U}$ in each tacky mat compared to RadPiper’s g/ft measurements. Measurements are calculated as the critical point for short mats or average of the plateau values (within $<$0.75 g/ft step change) for long mats and are averaged across all runs.

Potential Use of Visual Odometry

The one failure of RadPiper’s prototype radiation measurement in this testing occurred in Run 2, when the robot slipped on the tarp supporting the tacky mats (Figure 11). This slip is visible in robot camera imagery and thus may later be correctable using visual odometry in future evolution. The slipping caused an offset in RadPiper’s localization of its forward run of
approximately 6”. This is visible in Figure 12. Figure 13 illustrates a notional correction that might be later implemented using visual odometry. The robot also slipped 12” on the reverse run; however, post-processing corrects this automatically by indexing off when RadPiper detects its return to the open end of the pipe.

Figure 11: Image of cold pipe taken by RadPiper during Run 3 Forward showing three mats misaligned due to RadPiper slipping in Run 2.

Figure 12: Comparison of theoretical output to the worst RadPiper forward run. This run failed due to RadPiper’s tracks slipping on the mat tarp, which is visible from RadPiper’s visual imagery. Visual odometry could help correct for this in future evolution. The robot also slipped on the reverse run, which is auto-corrected in post-processing by indexing off of when RadPiper detects its return to the open end of the pipe.
Figure 13: A notional correction to Run 2 Forward (Figure 12) that might be provided by visual odometry in future evolution. This is a basic single-value adjustment that could be further refined to account for slip at other locations throughout the run.

Ability to Tag Sections Above CI

None of the tacky mats used in cold testing had g/ft above the CI criterion set in RadPiper’s analysis software. Figure 14 illustrates the area RadPiper (solid red) and an ideal g/ft measurement (dotted red) would tag as above a hypothetical CI threshold of 15 g/ft. The boxes highlight the entire section of pipe in the 12” field of view that is above CI. The RadPiper box is conservatively wider and contains the idealized CI section. Further conservatism and localization can be incorporated in future evolution, as desired.

Figure 14: Chart of one tacky may run highlighting a pipe section that the RadPiper analysis system (dotted red) and an ideal g/ft measurement (red) would tag as “above CI” for a hypothetical threshold of 15 g/ft.
Cold Pipe Line Source Testing

RadPiper conducted 5 forward and 5 reverse runs over known-quantity line sources during cold pipe testing. These line sources (Figure 15 and Figure 16) are concatenated “straws” of known $^{235}\text{U}$ content. All sources in these tests were 0.75 g/ft. Table 2 and Figure 17 show RadPiper’s radiation measurements versus the known source content.

Figure 15: Close-up of line sources used in cold pipe testing. Individual line sources were tied into a chain to stretch down the pipe.

Figure 16: Line sources as deployed in cold pipe for testing as photographed by RadPiper.
<table>
<thead>
<tr>
<th>Run Number</th>
<th>Measured Mean g/ft $^{235}$U Forward</th>
<th>Measured Mean g/ft $^{235}$U Reverse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Content</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>1</td>
<td>0.77</td>
<td>0.72</td>
</tr>
<tr>
<td>2</td>
<td>0.74</td>
<td>0.73</td>
</tr>
<tr>
<td>3</td>
<td>0.74</td>
<td>0.72</td>
</tr>
<tr>
<td>4</td>
<td>0.74</td>
<td>0.75</td>
</tr>
<tr>
<td>5</td>
<td>0.79</td>
<td>0.76</td>
</tr>
<tr>
<td>Mean for Direction</td>
<td>0.75</td>
<td>0.74</td>
</tr>
<tr>
<td>Overall Mean</td>
<td>0.75</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: RadPiper’s mean g/ft measurements for each run in each direction compared to the known 0.75 g/ft content.

These line sources were used for RadPiper efficiency calibration, and there were good estimates available for the material content ($U_3O_8$ mixed with 19% silicon powder), density, and geometry, which enabled computation of the expected self-attenuation of the material. (CMU researchers did not have all these details on the tacky mats.) Thus, measurements of the line sources using these values are expected to be accurate as opposed to overestimates. In addition, measurements <1 g/ft are subject to signal/noise considerations when the robot gathers data at 10 ft/min. (Slower traversal can provide better counting statistics.) As with the tacky mat analysis, additional conservatism can be built into this post-processing as desired in future evolution. Figure 18 displays the 3-sigma bounds of these data, which, despite the noise, almost entirely bracket the known source value. Figure 19 displays 3-sigma bounds for 30-second or 0.3 m (1 ft) averaging for the data, which is the smallest reporting interval for Portsmouth NDA in this piping. These sigma bounds completely bracket the known source at all points on all runs.
Across all cold pipe mat and line source testing, RadPiper measured $^{235}$U sources from 0.75 g/ft up to 17.65 g/ft with quality and speed across the order of magnitude of interest to screening holdup deposits in production pipes. The initial hot test deposits discussed elsewhere in this report were a further order of magnitude lower with characteristic <0.1 g/ft.

**Warm Pipe Testing**

“Warm pipe” testing was conducted in a short section of process piping that had been cleaned of any deposit material but was still considered contaminated due to potential $^{235}$U embedded in
the grain. Portsmouth operators wore PPE (suits and gloves) for the testing with CMU members outside the control zone. This pipe included an upward bend at the far end, which allowed a test of RadPiper’s maximum pitch safeguard.

Operations started with 3 minutes each of background collection and energy calibration with a uranium vial source. RadPiper then conducted 3 forward-and-reverse tethered runs at 10 ft/min. In the first run, operators triggered reverse by obstructing the robot’s forward-looking closed valve sensors. On the second and third runs, reverse was triggered by the robot detecting that its threshold for maximum safe pitch had been exceeded as it drove up into the curve of the elbow at the end of the pipe. This safeguard worked as intended.

The maximum $^{235}\text{U}$ g/ft was estimated at estimated 0.1 g/ft. This number, as expected, is very low and well below both CI interest for holdup screening and RadPiper’s intended radiation measurement range while moving 10 ft/min. The exact g/ft number thus has very low certainty, though RadPiper can conduct slower NDA runs if higher certainty at such low $^{235}\text{U}$ content is desired.

Images under both ultraviolet (UV) and white light were collected in the warm pipe. Given the short length, there was too much external illumination to distinguish UV fluorescence, if any. Figure 20 displays a white-lit visual image.

Figure 20: Robot camera image from inside the warm pipe as the robot approaches the elbow.
Initial Hot Pipe Testing

The initial “hot pipe” where testing was conducted on 20 September 2017 was the 30-inch B-line of diffusion cell X-33-4-1 that runs from the B-inlet Block Valve to the Stage 8 Compressor. Three main runs of 6 minutes (3 minutes or 30’ one-way) were conducted by Portsmouth operators in suits, gloves, and airborne protection (Figure 7, Figure 22). Additional system checkout, detector stabilization, energy calibration, and background collection, were also conducted. CMU operators coordinated these operations from outside the airborne control zone at a distance of approximately 50’ from the open end of the pipe.

Hot testing began with robot power-up and checkout, detector stabilization, background radiation data collection, and energy calibration with a 9” uranium vial source handled by the rad con operator. The robot was then programmed and deployed on several pre-runs before the three main hot test runs were conducted. Each of the latter runs was 6 minutes long, with the robot traveling 3 minutes down the pipe before reversing. These runs were conducted autonomously. Separate background data were collected between each run and after the last run in order to detect any potential radiation contamination on the robot itself. The following is a nominal timeline of these three main RadPiper hot test runs and important pre-run steps.

1. 15min Detector Warmup
2. Systems Checkout
3. Pre-run trials in pipe
4. 3min Background Collection
5. 3min Energy Calibration
6. Reversal time set to 3min
7. Robot inserted in pipe
8. 6min Autonomous Run 1
9. Robot removed from pipe
10. 3min Background Collection
11. Robot inserted in pipe
12. 6min Autonomous Run 2
13. Robot removed from pipe
14. 3min Background Collection
15. Robot inserted in pipe
16. 6min Autonomous Run 3
17. 3min Background Collection
18. Remove memory stick

Each autonomous run in the hot pipe involved operators in PPE (Figure 22) successfully rolling, raising, and aligning RadPiper’s launch cart at the pipe opening, jogging the robot into the piping, and initiating data collection. RadPiper then autonomously traversed to its return point (based on time), reversed direction, and auto-stopped upon reaching the open end of the pipe. The three runs and pre-run steps took approximately 1.5 hours.
Preliminary results were reported in a post-operations meeting. These included $^{235}$U measurements of <1 g/ft, with many readings so low as to be affected by signal-to-noise. Visual imagery showed visible deposit along the pipe wall, including faint “texture” in the deposit. Internal pipe joints and vacuum fitting were also imaged and geometrically mapped as discussed below. UV fluorescence imagery detected essentially nothing.

Figure 22: Portsmouth operators in PPE discuss the job with CMU operators outside of the contamination control area.

Radiation Results

The initial grams/foot $^{235}$U results for the first hot pipe are shown in Figure 23. Results are localized using single-track robot odometry zeroed by when the rear spinning laser rangefinder enters and exits the pipe (Figure 26). The grams/foot $^{235}$U results are based on reading the scintillation detector counts (for a 12” field of regard) every 0.1 seconds, computing a 3-second moving average and reporting that average every 1 second. (This same procedure is used in cold and warm testing.) The self-attenuation multiplier used in this initial analysis is 0.75 based on expected deposit enrichment and density. With significantly less than 1 g/ft and RadPiper traveling at 10 ft/min, the counts received by the detector are so low as to be subject to signal-to-noise limitations. Figure 23 shows RadPiper’s $^{235}$U g/ft results and Figure 24 shows the 2σ bounds of these results compared to Portsmouth’s external NDA measurements. For this pipe, all preliminary external NDA measurements in the region that RadPiper scanned were below the minimum detectable amount (MDA). The RadPiper data serve as an upper bound for the traditional NDA data.

RadPiper collected a median of 88 counts in the peak region of interest (2.93 counts/second) using 30-second or 5’ averaging. This compares to Portsmouth’s external NDA measurements, which reported a median of 127.3 counts in peak (or 0.14 counts/second) over a 900-second dwell time for 5’ sections.
Figure 23: Initial $^{235}$U g/ft results for RadPiper's three main runs in the first hot pipe.

Figure 24: Preliminary comparison of RadPiper’s and Portsmouth’s 2σ bounds for the first hot pipe. RadPiper’s upper bounds (solid lines) and lower bounds (dotted lines) for its three main 10 ft/min runs are shown using a running average of g/ft over 5’, reported for each foot of pipe. Portsmouth’s preliminary external NDA data are given for 5’ sections. Most of these readings were below the minimum detectable limit (shown in magenta). For the one reported value, the g/ft is in blue and the two-sigma upper bound is in green (the lower bound would go below zero). Note that RadPiper’s results are an upper bound over the preliminary Portsmouth NDA result.

Geometric Results
The initial hot pipe used in testing is 43’ 6.5” long from the open end to a closed gate valve. Centered at 24’ 4” in is a 12” vacuum spool attached to the left-side pipe wall and parallel to the ground plane. At 39’ 5” in, there is a 30” to 24” reducer fitting that RadPiper cannot traverse.
The robot was programmed to stop and reverse after traversing the first 30’ of pipe. RadPiper’s main spinning laser rangefinder, mounted on the rear of the robot (Figure 26), mapped this section of the pipe. The results, along with a computer model of the pipe using dimensions externally measured by Portsmouth operators, are shown in Figure 25.

Figure 25: (Left) Computer model generated using hot pipe dimensions externally measured by Portsmouth operators. (This shows approximately 13’ 6.5” of piping that RadPiper did not traverse.) (Center) RadPiper’s 3D geometric map of the same pipe, with some structure and personnel visible at the pipe entry. (Right) Cross-sectional detail of the vacuum fitting that extends from the side of the hot pipe. (Bottom) Top view of the same hot pipe.
The point clouds shown in Figure 25 can be used to measure specific distances, such as the position of the vacuum fitting relative to the cut pipe end. Portsmouth operators externally measured this distance as 23’ 10”, though this is subject to some uncertainty. (For instance, laser rangefinder data show that the cut edge of the pipe is nonorthogonal.) Measurement differences were still much less than 1% (mean of 0.16% forward and 0.54% reverse). Future evolution will more precisely characterize RadPiper’s odometry to reduce measurement bias.

<table>
<thead>
<tr>
<th>Run Number</th>
<th>Portsmouth (Externally Measured)</th>
<th>Measured Distance to Vacuum Fitting (ft)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>23’ 10”</td>
<td></td>
</tr>
<tr>
<td>1 Forward</td>
<td>23’ 10.4”</td>
<td></td>
</tr>
<tr>
<td>1 Reverse</td>
<td>23’ 11.5”</td>
<td></td>
</tr>
<tr>
<td>2 Forward</td>
<td>23’ 10.5”</td>
<td></td>
</tr>
<tr>
<td>2 Reverse</td>
<td>23’ 11.6”</td>
<td></td>
</tr>
<tr>
<td>3 Forward</td>
<td>23’ 10.5”</td>
<td></td>
</tr>
<tr>
<td>3 Reverse</td>
<td>23’ 11.5”</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Distance measured by Portsmouth operators (externally) and RadPiper from the cut edge of the hot pipe to the close edge of the vacuum fitting. Measurements exhibit differences significantly less than 1% despite uncertainty in the external measurement.

Imagery Results

RadPiper took 2216 camera images during its three main runs in the first hot pipe, including 1107 visual images illuminated by white LEDs and 1109 illuminated by ultraviolet (Figure 27) in an attempt to view ultraviolet fluorescence of deposit material. No ultraviolet fluorescence was visible; however, a thin coating of light yellow deposit material along the pipe wall was visible from the open end (Figure 7). Figure 28 and Figure 29 show detail of fittings and deposit in this hot pipe.
Figure 27: RadPiper with its centered fisheye camera illuminated by white LEDs (left) and ultraviolet LEDs (right).

Figure 28: Visual image taken by the initial RadPiper robot inside contaminated process piping at DOE Portsmouth. This image is taken after the robot has reversed. A vacuum spool intrudes from the left, and the robot’s tracks are visible along the pipe floor in a thin yellow layer of holdup deposit.
Second Hot Pipe Testing

RadPiper was tested in a second hot pipe on 20 September 2017. This pipe was the 30-inch B-line of diffusion cell X-33-3-3 that runs from the B-inlet Block Valve to the Stage 8 Compressor. Three main runs of 6 minutes (3 minutes or 30 feet one-way) were again conducted by Portsmouth operators in suits, gloves, and airborne protection. Testing concluded with a slower run of 12 minutes (6 minutes or 6 feet one-way) at 1 ft/min. A similar procedure of system checkout, detector stabilization, energy calibration, background collection, were also conducted. CMU operators again coordinated these operations from outside the airborne control zone at a distance of approximately 50' from the open end of the pipe.

Hot testing began with robot power-up and checkout, detector stabilization, background radiation data collection, and energy calibration with a 9” uranium vial source handled by the rad con operator. The robot was then programmed and deployed on several pre-runs before the three main hot test runs were conducted. Each of the latter runs was 6 minutes long, with the robot traveling 3 minutes down the pipe before reversing. A final slower run at 1 ft/min for 12 minutes (6 minutes or 6 feet one-way) was conducted in order to acquire better counting statistics for the deposit, which is significantly below Cl. All runs were conducted autonomously. Background data were collected again after the last run in order to detect any potential radiation contamination on the robot itself. The following is a nominal timeline of these four main runs and important pre-run steps.

19. 15min Detector Warmup
20. Systems Checkout
21. Pre-run trials in pipe
22. 3min Background Collection
23. 3min Energy Calibration
24. Reprogramming and testing
25. Robot inserted in pipe
26. 6min Autonomous Run 1
27. 6min Autonomous Run 2
28. 6min Autonomous Run 3
29. 12min Slow (1 ft/min) Run
30. 3min Background Collection
31. Remove memory stick

Each autonomous run in the hot pipe involved operators in PPE (Figure 22) successfully rolling, raising, and aligning RadPiper’s launch cart at the pipe opening, jogging the robot into the
piping, and initiating data collection. RadPiper then autonomously traversed to its return point (based on time), reversed direction, and stopped upon reaching the open end of the pipe. The four main runs and calibrations run took approximately 1.25 hours to complete.

Preliminary results were reported in a post-operations meeting. These included $^{235}\text{U}$ measurements of approximately 1 g/ft. This is higher than the first hot pipe, but still with many readings so low as to be affected by signal-to-noise. Visual imagery showed visible deposit along the pipe wall, including “texture” in the deposit. Internal pipe joints and vacuum fitting were also imaged and geometrically mapped as discussed below. UV fluorescence imagery again detected essentially nothing.

Radiation Results

The initial grams/foot $^{235}\text{U}$ results for the 10 ft/sec runs are shown in Figure 23. With approximately 1 g/ft and RadPiper traveling at 10 ft/min, the counts received by the detector are so low as to be subject to signal-to-noise limitations. Results for the slower run (at 1 ft/min) are overlaid in Figure 31. Note the significantly lower noise in the data. In Figure 32, data from RadPiper (averaged over 5’ intervals) are compared to preliminary results from traditional NDA at Portsmouth, which also use 5’ intervals. The RadPiper data serve as an upper bound for the traditional NDA data.

During its three main runs at 10 ft/min, RadPiper collected a median of 1796 counts in the peak region of interest (59.87 counts/second) using 30-second or 5’ averaging. Comparable data for Portsmouth’s external NDA measurements are not yet provided.
Figure 31: $^{235}$U g/ft results for RadPiper’s slow run (1 ft/min) in the second hot pipe compared to its three main runs at 10 ft/min.

Figure 32: Preliminary comparison of RadPiper’s and Portsmouth’s 2σ bounds for the second hot pipe. RadPiper’s upper bounds (solid lines) and lower bounds (dotted lines) for its three main 10 ft/min runs are shown using a running average of g/ft over 5’, reported for each foot of pipe. Portsmouth’s preliminary external NDA data are given for 5’ sections. The reported g/ft is in blue and the two-sigma upper bound is in green (the lower bound would go below zero). Note that RadPiper’s results are an upper bound over the preliminary Portsmouth NDA result.

Geometric Results

RadPiper’s second hot pipe measures 39’ 6” long from the open end to a reducer that RadPiper cannot fully traverse. Centered at 24’ in is a 12” vacuum spool attached to the right-side pipe wall and parallel to the ground plane. For its 10 ft/min runs, the robot was programmed to stop and reverse after traversing the first 30’ of pipe. RadPiper’s main spinning laser rangefinder,
mounted on the rear of the robot (Figure 26), mapped this section of the pipe. The results are shown in Figure 33 using a color scale based on distance to the pipe’s center axis.

Figure 33: Geometric results for the second hot pipe colored by range from the center of the pipe. Top view (top) and end view (bottom left). Note the vacuum spool on the opposite side as for the first hot pipe, and the visibility of peeling deposit hanging down from the top of the pipe (blue).

Imagery Results

RadPiper took 2944 camera images in the second hot pipe, including 1472 visual images illuminated by white LEDs and 1472 illuminated by ultraviolet in an attempt to view ultraviolet fluorescence of deposit material. No ultraviolet fluorescence was visible; however, there was a thin coating of light yellow deposit material along the pipe wall from the open end and more deposit texture inside the pipe (Figure 36 and Figure 37). Figure 34 and Figure 35 show the flange weld, reducer, and vacuum fitting with additional deposit detail.

Figure 34: (Left) RadPiper’s view of the flange joint inside the second hot pipe with the vacuum spool piece visible in the distance. (Right) RadPiper’s closest view of the reducer.
Figure 35: (Left) RadPiper image of the vacuum fitting and (right) detail of the deposit directly beyond the fitting. Note the pattern on the right side of the pipe wall.

Figure 36: RadPiper images of deposit texture in the second hot pipe.
Commentary

RadPiper’s cold, warm, and hot testing at DOE Portsmouth demonstrated traversal of multiple pipes along with collection and analysis of $^{235}$U g/ft over more than an order of magnitude. Deployment was handled by Portsmouth operators in appropriate PPE at speeds and certainties unattainable with external manual NDA methods. Post-processing displayed readily interpretable radiation, visual, and geometric information localized along the pipe. These results are consistent: they matched at the standup presentation after ops and they match now.

Despite these successes, testing also revealed a number of improvement avenues for the prototype RadPiper system:

1. Successful post-processing required the expertise of the developer.
2. Pipe run distances and return conditions needed to be manually coded and deployed.
3. Safeguarding features needed to be manually changed for particular pipes, e.g. to preclude encountering a reducer that the robot could have traversed but collimators would have collided against.
4. Robot weight exceeded guideline for handling by 2 workers but provides weight and lifting handles appropriate for 4 workers. Notably, in the days of setup, cold test, warm test, hot test, and to this day the robot has not needed to be lifted by workers. The launch rig easily rolls, lifts, and aligns the robot to a pipe without any lifting by Portsmouth operators.
5. The first-of-kind prototype was developed on a tight timeline and had inherent weaknesses in sealing, terminal block wiring, user interface layout and marking, and procedure documentation.
6. The first-of-kind robot, detection, and data logging software functioned as intended but were under-engineered and lacked features desirable for future evolution.
7. The first-of-kind visualization displays $^{235}$U g/ft and imagery localized along the pipe but many improvements are apparent and desirable for future evolution.
Perspectives and Findings

The September-October 2017 cold, warm, and hot testing of RadPiper at DOE Portsmouth achieved all goals of pipe traversal, $^{235}$U measurement, training and operations by operators in PPE, and displaying of analyzed radiation, visual, and geometric information. The success was a Kitty Hawk moment. RadPiper’s testing demonstrated robotic in-pipe measurement of holdup deposit to a resolution, accuracy, and speed unachievable by alternate methods. Key highlights include:

1. Pipe traversal at the unprecedented speed (for accurate holdup assay) of 10 ft/min.
3. Accurate measurements with tight error bounds of source strengths that varied from <1 g/ft to 17.65 g/ft.
4. Output of industry-standard g/ft $^{235}$U measurements at 2-inch intervals, or 3-6 times more frequently than the external manual NDA practice of every 6-12 inches or more.
5. Deployment by Portsmouth operators wearing appropriate PPE into process pipes at multiple heights and locations.
6. Display of visual deposit appearance and internal pipe features in fully lit, full coverage high definition and correlated to pipe location.
7. Reporting of precise geometry for pipe interiors as mapped by the robot’s spinning laser rangefinder.
8. Mapping of the shape, dimension, and location of the hot pipe openings and contaminated vacuum fittings that the robot passed.
9. Sensing of deposit fluorescence in high definition and full coverage with intense ultraviolet light. This sensing mode returned no observable fluorescence.

PipeDream: Volumetric Deposit Characterization

Executive Summary

PipeDream is a pipe-crawling robotic NDA platform for D&D of gaseous diffusion process piping that uses a method for volumetric deposit characterization. The initial proof-of-application prototype was successfully hot tested by operators at the DOE Portsmouth facility on 18-21 September 2017. The testing achieved the goals of traversing pipe, deployment by facility personnel, and collecting data from nickel-plated pipes with and without holdup deposit. The data collected was a key and necessary step in the development and calibration of the PipeDream volumetric sensor. Key highlights include:

1. Pipe traversal at three-feet-per-minute, half the operational speed, to ensure rich first-look data sets.
2. Volumetric sensor data compared between clean piping and pipe with some visible holdup.
3. Determination that nickel-plated piping has 6-7 times greater impact on inductive proximity sensors than experimentally derived.
4. Sensor calibration corrected for nickel-plated piping using warm pipe data.
5. Generation of self-calibrations for inductive sensors based on warm pipe data sets.
6. Stereo display of visual deposit appearance and internal pipe features in fully lit, full coverage high definition and correlated to pipe location.

These goals did not address the broader system capabilities for auto-analysis, auto-reporting, auto-archiving, and integration with full-scale site operations for screening pipe. These are all addressable in the future and secondary in scope and difficulty to the fundamentals of calibration, robotics, and method as demonstrated in this testing.

Figure 38: Portsmouth operators in PPE deploying PipeDream in the hot pipe (cell X-33-4-1).
Warm Pipe Testing

The warm testing, conducted in a short process pipe section cleaned of deposit material, provided the much needed first data set for the inductive proximity sensors response in nickel-plated process piping. The presence of nickel plating and the pipe’s steel composition differed from the piping used for calibrations during development.

Two different tests were run in the warm pipe, (1) stationary testing, spinning the volumetric sensor in place and recording data at a single location for 10 minutes and (2) dynamic testing, jogging the robot manually forward and back while spinning the volumetric sensor and recording data. The first test provided the means to gauge and improve the performance of sensor calibrations. The second test provided data for estimating a bias volume present in the system due to persistent geometric calibration errors in sensor locations. PipeDream did not traverse autonomously in the warm pipe due to the short length and curved end section.

Stationary Testing

Stationary data collected allowed PipeDream to acquire a large sample set of what should be the same 2D profile of pipe. This data set demonstrated the presence of voltage clipping in the inductive proximity sensor responses due to the nickel plating/steel composition. Figure 40 shows the response of the inductive and triangulations sensors spinning in place inside the warm pipe.
The voltage clipping is a result of the maximum voltage reportable by PipeDream’s analog to digital converter (10.1V). During development, the 10.1V maximum represented a 20-22 mm offset. With nickel-plated process piping, that maximum voltage represents approximately a 14 mm offset, a reduction of 4-8 mm of sensing range. This reduction matches the error observed between the inductive and triangulation sensors in Figure 40.

Assuming the warm pipe had zero deposit thickness enables after-the-fact calibration. The self-calibration curve that produced the minimum error (maximum overlap) between the inductive and triangulation responses was back-solved. This analysis disregarding areas with debris from pipe cutting and with voltage clipping and only used the inductive sensors positioned next to the triangulation sensors, as to minimize the influence of disc asymmetry. Using this subset of the warm pipe stationary data, Figure 41 shows the resulting self-calibration for inductive sensors IMA0 and IMA2 next to the two triangulation sensors.
Figure 41: (Left) IMA0 inductive sensor self-calibration. (Right) IMA1 inductive sensor self-calibration. The raw self-calibration represent the remapping of all points collected, which contains noise. A third-order polynomial is fit to this data and represents the self-calibration curve. Note the increase in slope and loss of range in the presence of the nickel-plated pipe.

This data set is limited due to lack of data on all possible offsets (inductive sensors only passed 10-14 mm away from the surface of the pipe). Figure 42 shows the calculated deposit thickness before and after this calibration, which decreased from 6-8 mm to a range of -0.2-0.25 mm. Given the approximate minimum sensed thickness of 0.1 mm, this self-calibration performs well.

Figure 42: (Left) Error between inductive and triangulation sensor pairs before self-calibration. (Right) Error between inductive and triangulation sensor pairs after self-calibration. The error was reduced from 6-8 mm to -0.2-0.25 mm, twice the minimum sensed thickness capabilities of a properly calibrated system.

**Dynamic Testing**

Figure 43 shows a 3D point cloud from the data collected while jogging back and forth in the warm pipe. The spirals overlap because the data were recorded in both the forward and reverse directions of travel. Debris from cutting can be seen in the triangulation sensor data covering the bottom of the pipe.
Hot Pipe Testing

Hot pipe testing, conducted in-situ in cell X-33-4-1, including the stationary data collection as in the warm pipe as well as autonomous traversal and data collection for up to 22’ 7”. Travel was limited to the section of pipe before a circumferential weld seam due to larger than normal sag in the mechanical centering suspension (approximately 5 mm). This caused the inductive sensors, which have a nominal 12 mm offset from the pipe, to be nominally 7 mm from the bottom of the pipe as the disc rotated. To ensure safe operation and egress, PipeDream was monitored remotely through the WiFi connection and stopped manually based on visual confirmation of the weld seam. Figure 44 shows the left and right camera images from PipeDream near the circumferential weld seam.
Figure 44: (Left) Right cross-eye camera image, (Right) Left cross-eye camera image of the circumferential weld seam seen during operation of PipeDream.

Stationary Testing

Similarly to the warm pipe stationary testing, the disc was spun in place and data were continuously logged for 10 minutes at the entrance of the hot pipe. Figure 45 shows the response of the inductive and triangulation sensors using the original calibrations. Since there is visible evidence of deposit, self-calibration cannot be performed using this data set. Applying the self-calibration obtained from the warm pipe data sets, Figure 46 shows the performance of the self-calibration on the hot pipe inductive data. Unfortunately, the resulting thickness remaining between the inductive and triangulation responses is reported as negative. This implies the triangulation sensor is reading a surface past the surface the inductive sensor is, which is physically impossible. The measured thickness is on average around -0.4 to -0.6 mm with a range of -3.5 to 1 mm.
Figure 45: The response of the inductive and triangulation sensors while spinning in place in the warm pipe. The voltage clipping was less of an issue in this data set. There exists a 3-7.5 mm difference between the inductive and triangulation responses, comparable to the 4-8 mm seen in the warm pipe data set.

Figure 46: (Left) Hot pipe stationary response error before applying self-calibration, (Right) after applying self-calibration. The resulting thickness is reported as negative, meaning the self-calibration is unsuccessful in correcting the inductive sensor response in the hot pipe.

**Dynamic Testing**

Data collection during pipe traversal was split into forward and reverse runs. Since PipeDream was stopped manually, data collection on the forward and reverse runs were handled differently. Forward runs launched all subsystems and recorded all pertinent data, while reverse runs only consisted of the essential data for volumetric modeling, namely odometry, inductive sensor, triangulation sensor, and inertial data.
Perspectives and Findings

Considering factors beyond the limited data for self-calibration, the inaccuracies of the measured deposit thickness could be attributed to differences in plating thickness, steel composition, and interference from deposit material not seen in the warm pipe. Experiments conducted by Portsmouth personnel produced data indicating the deposit material, UO$_2$F$_2$, had no effect on the inductive sensor readings. However, this conclusion is based on differential comparison of measurements which showed an offset prediction error between 0.1-0.2 mm. Next steps include further analysis of the deposit material and process piping influence on the inductive sensor. Additional development beyond sensing technology includes:

1. Improving estimates of robot position and attitude to increase fidelity of volumetric model.
2. Revisiting selection of slip ring for improved signal performance through rotating mechanism.
3. Iterating on current suspension design to improve disc centering capability.
4. Continuing software development to increase autonomy.
5. Performing mechanical and electrical scalability studies for different pipe diameters.