Robotic Measurement of Holdup Deposit Volume in Gaseous Diffusion Piping to Quantify U-235 Content – 18375

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ABSTRACT
During D&D of old gaseous diffusion uranium enrichment facilities, radiometric assay of U-235 holdup in pipes is a costly, time consuming, and labor-intensive process. Subject to human interpretation using approximate modeling, radiometric assay introduces significant challenges. Taking advantage of routine demolition activities in which D&D cuts pipes open, robotic in-pipe assay is explored. The novel method introduced here generates models of the internal pipe and deposit surface geometries that are used to derive volumetric quantities. The pipe surface is sensed using a non-contact inductive proximity sensor and the deposit surface is sensed using an optical laser triangulation sensor. These sensors are mounted on a spinning disk and driven down the pipe to construct a helical point cloud of discrete measurements. Surfaces are fit to each of the two point clouds to create a watertight volume that represents the holdup. This provides the location and volume per foot of pipe that is used to compare against criticality incredible (CI) thresholds during evaluation. The robotic system collects data autonomously, deploying and returning to the same pipe opening from which it is launched. This provides redundant measurements of the pipe and deposit surfaces as well as odometry used in localization.

INTRODUCTION
Deactivated gaseous diffusion plants have miles of piping once used for processing uranium hexafluoride. Though these pipes were nominally sealed, any small leak through which wet air entered would cause the formation of uranium-bearing holdup deposits. Before these plants can be torn down, pipes must be inspected to ensure that the volume of U-235 remaining in the pipes is below a criticality incredible (CI) threshold. In any case where the CI threshold is exceeded, pipes must be removed and cleaned at great expense. Even sub-millimeter thick deposits can be a concern for some pipe diameters. The work presented in this paper develops a robot and methodology for precise volumetric measurement of deposits inside pipes.

Fig 1. Side view of robot for volumetric deposit measurement suspended in launch rig (left). Robot deployed in process piping with visible yellow holdup deposit (right).

In the past, radiation measurements were taken manually from outside pipes. This method is costly and
time consuming, requiring personnel to position and dwell with a radiation detector externally over miles of pipe. It also requires personnel exposure to radiation. Internal robotic radiometric assay can be deployed, but it can underestimate U-235 content due to self-attenuation of gamma rays in the deposit. If the deposit thickness is known, the magnitude of self-attenuation within the deposit can be calculated. Alternately, with assumptions of enrichment and density, a volumetric measurement could be used as an independent method to compute U-235 content.

Robotic pipe inspection methods have been implemented for water, sewer, natural gas, and other applications [1,2,3]. The goal of these systems is to characterize the structural integrity of the pipe instead of deposit material inside the pipe. Standard robotic methods such as time-of-flight LiDAR (Light Detection And Ranging) are not precise enough to accurately and reliably detect sub-millimeter thick deposits. Optical triangulation sensors have the precision to profile the interior surfaces of deposits, but they are not enough. Assuming a nominal pipe diameter does not take into account sagging, ovalling, imprecise fabrication, or geometric variation created in the pipe-manufacturing process. Because of this variation from a nominal, round pipe, the pipe wall must also be precisely mapped.

The methodology introduced here combines a map of the pipe geometry, generated from non-contact inductive proximity sensors, and a map of the free surface of the uranium deposit, from optical triangulation sensors. The robot is driven through the pipe while spinning a disk containing the inductive and triangulation sensors. The resulting mapped pipe and deposits are described by a point cloud of discrete measurements which must be converted into a volumetric quantity. By reconstructing pipe and deposit measurements into two distinct surfaces, and then forming into a watertight mesh, deposit volume and Cl-criteria violation can be determined for any location along the pipe.

Inductive proximity and optical triangulation sensors with the required precision have a limited sensing range, and therefore the sensors must be positioned close to the pipe wall. While sensors mounted with compliant mechanisms might achieve the needed range while also allowing passage over thicker deposit accumulations, such mechanisms would induce error in the sensor positions relative to the robot. This then necessitates precision centering. The selected approach uses passive 3-wheel umbrella mechanisms on both the front and rear of the robot to maintain centering within millimeters.

Concerns in the design phase about the possibility of dragging deposit material in the pipe (though later dismissed) pushed the design team to go tetherless. Continuous connection via wireless means is not guaranteed with potential interference from a metal pipe. With no tether and no wireless communication, the robot must operate independently from launch into a pipe to recovery. This necessitates onboard data logging, software for sensible error response, and safeguard sensors. A spinning laser rangefinder on the robot’s front surface checks for overly thick deposits or other debris that might impact the spinning sensor disk. Forward-looking time-of-flight proximity sensors detect closed valves ahead of the robot and cause it to back out. Backward-looking time-of-flight proximity sensors check for the open pipe end as the robot backs out after inspecting a length of pipe. Front mounted cameras provide visual imaging of the pipe illuminated with LED lighting.

This paper presents the motivation for robotic inspection of gaseous diffusion piping, a volumetric approach developed, the robotic system designed to implement it, and on-site proof-of-application testing. The work supports ongoing D&D activities at the former Portsmouth Gaseous Diffusion Enrichment Facility, including thorough inspection of a large amount of process piping, and has application elsewhere.
in the DOE Complex for similar quantification and screening of uranium holdup deposits in piping as a safer, faster, and more cost-effective alternative to traditional external NDA measurements.

VOLUMETRIC SENSING METHOD

Overview
The volumetric deposit sensor shown in figure 1 is a metasensor comprised of two main sub-sensors, (1) an inductive proximity sensor and (2) an optical triangulation displacement sensor. Mounted radially along a disk, they collect point measurements of the pipe and deposit surfaces. The inductive sensor measures the distance to the pipe surface, regardless of the presence of deposit, and the optical triangulation sensor measures the contours of the deposit surface. Rotational and longitudinal motion of the volumetric sensor disk, combined with robot localization, generates helical point clouds of the pipe and deposit surfaces. Surface fitting methods were employed to facilitate calculation of a volume of material present per unit length of pipe. The two classes of sensors were chosen for their reported accuracy and precision, at the cost of narrow sensing ranges. The inductive sensor has a sensing range of 0-20mm and the optical triangulation sensor has a sensing range of 20-50mm. This drove tight clearances between the pipe surface and the sensors, which demanded proper safeguarding against impacting large deposits or debris in the pipes.

Figure 1. The volumetric sensor disk designed to measure holdup deposits inside pipes. The volumetric sensor is comprised of two sub-sensors, an inductive proximity sensor (SICK IMA18-20NE1ZC0K) and an optical triangulation displacement sensor (SICK OD1-B035H15A15).

Volumetric Sensor Calibration
Characterization and calibration of the volumetric sensor disk under varying environmental factors, such as temperature and offset, were performed to ensure the accuracy necessary to measure sub-millimeter surface deposits. The orientation and position of each of the sensors relative to the center of the monolithic disk was measured using a coordinate-measuring machine (CMM), accurate to ±0.005 mm [4]. Accurate offset measurements and sensor locations provide the information necessary to transform
individual range measurements into point clouds in a common coordinate frame for the geometry of both pipe and deposit. This makes computation of deposit volume possible.

Natively, the inductive sensors output an analog voltage signal that conveys the distance to a sensed metallic object. To ensure an accurate offset, the underlying transformation from voltage to offset distance was characterized. The basic operating principle of the inductive proximity sensor involves the production of eddy currents in a metallic object by an inductive field emanating from the sensor. The transfer of energy through the inductive field to the object produces a net energy loss in the oscillating circuit within the inductive sensor [5]. The voltage output reflects this power loss and depends not only on the offset of the object, but also its shape and material properties. Differences in material properties can have an adverse effect on the performance of the sensor, most notably in the reduction available sensing range [6]. To identify the relationship of voltage to offset, the voltage response of the inductive sensor was recorded at a set of discretized ranges. A piecewise continuous linear function was fit to the discrete measurements and used as the mapping from any arbitrary voltage measurement to its physical offset. The process was automated using a Computer Numerical Control (CNC) Mill, leveraging its precision and accuracy to actuate the inductive sensor to known and repeatable offsets from the target surface. The sensing range of the inductive sensor was split into thirty-two discrete offsets separated by 0.635 mm. At each offset, one thousand sensor readings were taken as a sample set of the voltage response at that height. The mean voltage was used as the calibration value for the given offset. Figure 2 shows the experimental setup as well as a characteristic voltage-offset calibration curve. Sensor and ambient temperatures were also recorded to incorporate the thermal characterization. Bare and 2 mil nickel plated 9.525 mm (⅜ in) precision ground steel plates measuring 305 mm x 152 mm (12 in x 6 in) were used as target objects during characterization and calibration.

Since neither the inductive nor the optical triangulation sensors are thermally compensated by their manufacturers, temperature changes to their internal circuits and components produce a net effect on measurements. For the inductive sensor, the repeatability of measurements as specified by the manufacturer when the ambient temperature is not held constant amounts to 0.3mm over a range of ±5°C from 25°C [6]. When ambient temperature is held constant, the repeatability becomes ±0.05 mm, a significant increase in repeat accuracy. To achieve this constant temperature repeatability while under non-isothermal assumptions, thermal characterization was performed to quantify temperature drift. The
testing was conducted inside a thermal chamber capable of forced and free convective heating and cooling. The inductive sensor was fixed 12 mm from a metal surface and the voltage response, sensor temperature, and ambient temperature were recorded as the sensor cooled from near 50°C to ambient via free convection. The results showed an average temperature dependence of 0.017 V/°C, or 0.030 mm/°C, significant relative to the sub-millimeter allowable deposit thickness. Thus, over the 10°C range in which the non-constant temperature repeatability was specified, the experimental non-constant temperature repeatability is experimentally verified to be on average 0.3 mm. To incorporate this characterization with the offset calibration curve, the temperatures recorded at each offset during CNC testing are used as the baseline to which every measurement is compared. Using the difference between the inductive sensor’s current temperature and temperature at calibration with the slope recovered from thermal characterization, the voltage measured can be corrected for temperature drift. After applying temperature compensation, voltage is mapped to the calibration curve as seen in figure 2.

A similar testing procedure to that of the inductive sensor was used to characterize the temperature dependence of the optical triangulation sensors. The optical triangulation sensor outputs an offset in millimeters, which simplifies the incorporation of the thermal calibration. The temperature used as a fixed reference to generate the drift correction was taken from a manual calibration. This manual calibration sets the zero of the sensor to precisely 35 mm from the face of the sensor using a custom-made tool. The temperature of the sensor recorded during this manual calibration is used as the reference temperature. The optical triangulation sensor manufacturer specifies a temperature drift of ±0.024 mm/°C [7]. Experimentally, the optical triangulation sensor showed a temperature drift on average of ±0.012 mm/°C. The resulting thermal characterizations of each sensor are shown in figure 3.

![Figure 3. Typical results of thermal characterization of an inductive proximity sensor (left). Typical results of thermal characterization of an optical triangulation sensor (right).](image)

**ROBOTIC SYSTEM**

The robot constructed to deploy this volumetric deposit characterization was dubbed PipeDream. The method relies upon four key mechatronic components. The first robot’s electronics enclosure, which protects and enables fully-contained onboard power, safeguarding, and datalogging. The second is the physical sensor disk and the mechanism that actuates its rotation, which must be closely controlled. The third is the robot’s suspension system, which keeps its wheels in contact with the pipe or deposit surface. The final key component is the robot’s front sensing assembly, which houses the robot’s visual imaging and geometric mapping sensors. Additional structure, electronics, and software enable robotic mobility,
data logging, and safeguarding. Figure 4 presents an annotated photograph of the PipeDream system.

**Body Structure and Mechanism**

PipeDream is an eight-foot-long tetherless autonomous robot designed to traverse 30-inch pipes. The robot’s main body, however, comprises a 10-inch diameter by 42-inch long cylindrical shell as shown in figure 5. This houses the robot’s electronics and enables fully-contained onboard power, safeguarding, and data logging. The shell’s narrow cylindrical design enables use of this same PipeDream body in multiple pipe sizes down to at least 16-inch nominal diameters. The compartment can be accessed via a sealed lid running along the robot’s length, but all sensing, user interaction, battery charging, and data transfer occurs via the fore- and aft-mounted sensors and user interface panel discussed later.

![Figure 4. Annotated photograph of PipeDream.](image)

![Figure 5. PipeDream’s mechanical shell with annotations indicating the interface of the sealing cover and the rotary mechanism and suspension.](image)

The robot’s key sensor, its volumetric measurement disk, is mounted at the rear of the main body on a 1.5-inch diameter aluminum tube (seen in figure 5) that forms the spine of the robot’s rotation module and rear suspension. The disk is driven by the robot’s rotation module, (exploded view in figure 6), which uses an 8-inch thin-section X-type bearing and a 180:1 gearbox and pinion reduction to support and actuate the sensor disk. A 12-contact hollow body slip ring enables power and signal transfer to and from the disk’s inductive, triangulation, and temperature sensors. The disk’s rotational position is tracked using a motor encoder and an indexing pulse from an embedded magnet that is registered by a separate magnetic switch.
Figure 6. Exploded view of PipeDream’s rotary mechanism with annotations indicating how it mounts to the robot’s main body and the volumetric sensor disk.

**Centering Suspension and Mobility**

To maintain the precise and consistent offsets required by PipeDream’s volumetric sensor, the robot uses two three-wheeled suspension modules. These modules bracket the body and sensor disk to position it in the instantaneous center of the pipe and deposit surface. Each suspension module consists of an umbrella-like series of links and collars as shown in figure 7. Within each module, each of the three legs consists of two links pinned together and attached to separate collars. The large link (shown in magenta) is pinned to a fixed collar (green), whereas the small link (shown in blue) is pinned to a collar (red) that slides on the center tube (yellow). This sliding collar is compressed by a spring to add a constant restoring force to the system. When in the pipe, this spring forces the legs outward, providing an equal normal force between every wheel and the inner surface of the pipe.

With each suspension module’s three legs pinned symmetrically to these two collars, the suspension becomes a freely coupled system that forces all the jointed legs to move in unison as they comply with a given pipe-and-deposit surface diameter. The central (yellow) tube, and thus the robot body and sensor disk, remains at the in the instantaneous center of the pipe even when the robot moves over a deposit.

Figure 7. A PipeDream suspension module (left) and an exaggerated conceptmodel of its centering movement in closed (center) and open (right) configurations.

PipeDream moves in gaseous diffusion pipes via three powered wheel assemblies on its front suspension module. The wheels of the rear suspension module are idlers. To provide sufficient clearance with the pipe wall, the motors for the powered wheels are housed within their hubs as shown in figure 8. Figure 9
shows an annotated exploded view of one wheel assembly.

Figure 8. (Left) PipeDream suspension in a pipe. Note the tight clearance between the wheel modules and pipe wall. (Right) Closeup of a PipeDream wheel module.

Figure 9. Annotated exploded view of one PipeDream wheel module illustrating how the motor assembly is housed within the hollow tire. This provides the clearance necessary for PipeDream to drive in 30-inch diameter pipes.

**Auxiliary Sensing and Safeguarding**

Gaseous diffusion piping cascades undergoing D&D may contain cut pipe ends, closed sections, and in-pipe obstructions. For this reason, PipeDream must actively monitor and safeguard its autonomous movement using multiple auxiliary sensors. The inherent narrow clearance between the volumetric sensor disk and the pipe-and-deposit surface further complicates safeguarding operations.

The robot’s primary safeguarding sensor is a spinning laser rangefinder mounted to the front of PipeDream’s fore-mounted sensing assembly shown in figure 10 (left). Each range returned by the sensor is thresholded against a minimum safe radial distance as to safeguard the disk from obstacles.

PipeDream’s secondary safeguarding sensor is a triad of forward-looking time-of-flight laser distance sensors mounted to the robot’s front sensing assembly. These sensors, one of which is also labeled in figure 10 left, look down the pipe in front of the robot to prevent collision with closed pipe ends and other large blockages. This front sensor assembly also houses PipeDream’s LED (light-emitting diodes)
illumination and cameras, which are cross-eyed to provide a full view of the pipe around the center-mounted laser rangefinder.

Figure 10. (Left) View of front sensor assembly and (right) rear operator interface box. One end-of-pipe sensor is also visible.

The final robot safeguard is an additional triad of time-of-flight laser distance sensors that detect the open end of a pipe as PipeDream reverses. One such sensor is mounted to each leg of the robot’s rear suspension module as labeled in figure 10 right. When the rear wheels are approximately 15 cm from the open end of the pipe, the sensors exit the open end of the pipe and trigger a logic signal to indicate the robot should stop. With both triads of distance sensors, a voting system is used to increase resilience to sensor failure and anomalous readings. Two of the three sensors must report a state change in order for the robot to take action.

**Power, Electronics, and Computing**

Aggressive project schedule determined much of the selection of electronic components for PipeDream. This balanced against freedom from severe constraints of mass and size that allowed commercial off-the-shelf (COTS) components to be selected for the majority of electronic systems.

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

Power to the various internal direct current (DC) buses of PipeDream (48, 24, 12, and 5 volts) are generated via COTS DC/DC converters. Motor drives are powered directly from the main battery bus as is a shunt regulator which prevents excessive bus voltage during motor backdriving. Batteries and inputs to the converters, drives and shunt are protected with ordinary automotive thermal fuses.

PipeDream’s volumetric deposit characterization disk relies heavily on the signal quality relayed from the metasensor’s inductive, triangulation, and temperature sensors. To avoid degradation of the analog signals from the inductive and temperature sensors, data for these are converted as close to the sensors as possible.
using a multi-channel data acquisition board (Labjack T7), which communicates to the main computer using Ethernet. Power and signal paths to the rotating sensor head flow through the slip ring and into PipeDream’s body shell and electronics. Schedule and the required hollow body configuration necessitated use of a slip ring (MOOG 12 contact type AC4598-12F) not explicitly designed for low noise or high bandwidth signals. Careful attention to wire pairing, wire pair twisting, shielding, and communication protocol allows successful communication between the acquisition board and computer with tolerable data loss.

The three locomotion motors and the single sensor disk rotation motor are brushless DC (Maxon EC-max 30 series) with integrated gearheads driven by Copley digital drives (Accelnet Micro Panel type ACJ) networked via Controller Area Network (CAN) bus. Robot localization in pipes is accomplished via reading a encoder on one of its three rear idler wheels acquired through counter inputs of a second data acquisition board (Labjack T7). In addition, this board handles input and output needs for the robot’s user interface and end-of-pipe detection.

PipeDream’s main computer is a fanless embedded Intel quad core i7 system (Adlink MXE-5501). This computer is designed for high-reliability systems. The computer has 4 ethernet ports allowing both cameras and both Labjack boards to be on separate ports to minimize bandwidth issues. This computer has 6 serial ports that were used to minimize the reliance on USB, which can have software addressing and reliability issues. This computing architecture is outlined in figure 11.

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

The core component in the software is the system executive. The system executive has a state machine that controls PipeDream’s motion and monitors it for faults. When the operator presses the switch to launch the robot, the executive begins by indexing itself off the open edge of the pipe. It then drives forward until the robot’s forward-looking sensors detect a closed valve in front of it. Once this closed end
of the pipe is detected the system executive backs the robot out until its rear end-of-pipe sensor detect the original pipe opening. During each state, the executive checks the status of the robot for factors including in-pipe obstructions (modeled by its spinning laser rangefinder), battery voltage, and operation of critical components. The system executive also manages other functions such as turning on and off various sensors and starting and stopping data logging, based on the current state of the robot. The state machine for the system executive is illustrated in figure 12.

Figure 12. Diagram of the PipeDream state machine that governs the robot’s data logging and mobility during in-pipe NDA. SB – start button, CS – check status, USB – USB state, REOP – rear end-of-pipe sensor state, RP – spinning laser rangefinder state (indicating detection of a in-pipe obstacle), PV – pipe valve, P – prior state, S – current state, E – entering state, dir – current direction of travel.

VOLUMETRIC POST-PROCESSING
The heart of PipeDream’s functionality is the ability to generate volumetric measurements of deposits from dense point cloud data. The method involves collecting a pair of inner and outer point clouds and calculating a volume from a surface mesh based on these measurements. Points on the pipe wall measured by the inductive sensor form the outer surface while measurements of deposit by laser triangulation form the inner surface. As data are captured in a helical chain caused by translation down the pipe paired with rotating sensors they first need to be converted from relative depth measurements into a global coordinate frame. This transformation is done during data collection, with relative sensor positions calibrated ahead of time. The coordinate frame origin is set at the start of each run. Figure 13 shows a point cloud generated by inductive sensors (blue) and triangulation sensors (red).
Figure 13. Full point cloud data of a mapped pipe. Inductive sensors (blue) measure the pipe wall while laser triangulation sensors (red) detect deposits within the pipe.

After a pipe scan, data are transferred to a secondary offboard computer to handle post-processing, data analysis, and determination of deposit volume. This work created a custom algorithm for extracting very accurate volume estimates from data point clouds. Volume estimates are generated iteratively over 0.3-m (12-inch) segments of pipe length, with a 0.15-m (6-inch) step size, though these parameters are arbitrary given sufficient sample density. These segments are then unwrapped to 2.5 dimensions of radians, radius from measurement center, and translation distance along the pipe. This unwrapping accomplishes several things: allows for faster surfaces meshing, more intuitive visualization, and the ability to linearly interpolate with respect to a radius measurement. Interpolating over the radius maintains the prior understanding of a smoothly varying pipe and deposit surface while significantly simplifying the surface reconstruction problem. The ability to linearly interpolate radii makes surface meshing much easier since a first order method can be used in the unwrapped space that is as accurate as much more computationally expensive second order methods in X, Y, Z space.

The unwrapped point clouds are projected onto a 2D plane to perform triangulation. Delaunay triangulation is a very popular approach and is used here. Delaunay triangulation is a tessellation of the Voronoi diagram, and this approach ensures all points are meshed without intersecting meshes. Delaunay triangulation inherently encourages regularly shaped meshes and avoids sliver triangles which in this case may not accurately represent the true surface. Moving from 3D to 2D reduces the time complexity from O(N^2) to O(N log N) [8], which is substantial when dealing with dense point data sets.

Once the individual point clouds are meshed, edge points for each surface are meshed with corresponding points on the alternate mesh. This forms a complete watertight volume, as shown in figure 14, whose volume can be computed. Surface normals for the entire mesh are checked and uniformly oriented before generating signed volume tetrahedrons over each triangulation as demonstrated by [9]. The summation of these signed tetrahedrons is the final volume for the current section of pipe.

Figure 14. Inductive sensor measurements (blue) and triangulation sensor measurements (red) are unwrapped to a 2.5D representation (left). These points are meshed into two surfaces and then combined to form a watertight mesh whose volume can be directly calculated (right).

EXPERIMENTAL RESULTS

Testing and verification of the volumetric system as integrated with the robotic platform before deployment involved (1) evaluation of effectiveness of inductive sensor calibrations, (2) analysis of
reported volume of clean, deposit free pipe, and (3) analysis of reported volume of a known deposit geometry. The inductive sensor calibrations were evaluated by rotating the volumetric sensor while the robot sat stationary inside the pipe. Since the pipe is devoid of any deposit the inductive sensors and optical triangulation sensors should produce surface geometries that overlap.

Figure 15. Unwrapped response of volumetric sensor spinning stationary in bare steel pipe. This shows agreement in the general shape of surface of the pipe from the two sensors.

From figure 15, while the macro appearance of the surface topography reported by the two sensors is similar, relative to a sub-millimeter deposit thickness, there exists a significant constant offset between the two generated surfaces. On average, the offset between the inductive and optical triangulation sensors amounts to 0.5 mm. Multiple factors could have influenced this bias, such as improper interpretation, incorporation, or reporting of CMM disk measurements, material property mismatch between the inductive sensor calibration piece and the metal of the pipe, limitations on the accuracy of temperature drift correction due to wide error bounds on thermal sensing, and unaccounted-for influences on inductive calibration curves, such as target metal temperature. In light of this constant offset, the testing cadence was adapted to include a step to remove the sensor bias by leveraging deposit free data to establish a baseline bias that is removed from data recorded with a deposit present in the pipe. This, while impractical in the field, produced promising results once the data were detrended. Figure 16 shows the results of such analysis on a circumferential deposit measuring 2.4 mm thick. The data are conveyed as grams U-235 per linear foot of pipe, computed from the volume calculation with the assumption of 6.37 g/cc deposit density and 3% enrichment. The number used for CI threshold in this work was 75 g/ft (246 g/m) for 30” pipes, though this is not verified by nuclear criticality safety experts. The deposit was placed approximately 1.7 m into the pipe and extended along the pipe for another 0.6 m. In both cases, with and without the deposit, the regions in which no deposit was present are consistent between the two data sets. Removing the bias from the with deposit dataset via the without deposit dataset, the reported deposit thickness was calculated as 2.45 mm, within the reported repeat accuracy of the inductive and optical triangulation sensors. The width of the apparent deposit from the data is wider than 0.6 m because of the way in which the data is post-processed. The 0.15-m (6-inch) step size of the analysis adds approximately 0.3 m of added length to any given deposit as the per foot mass is the maximum of all overlapping 0.15-m (6-inch) sections. This produces a trapezoid-like shape, adding artificial length to the deposit.
Figure 16. Results from a controlled test in a cold pipe. The mass per foot with and without deposit is the same along the first 1.5 meters of pipe, however when the sensor disk reaches the artificial deposit there is a jump in measured volume equivalent to the true volume of deposit in the pipe.

With the understanding that the bias present in the system would be unaccounted for during the first deployment of the system in facility piping, data collection in a clean nickel-plated process pipe was necessary for proper calculation of deposit volume in an arbitrary pipe. A section of visibly clean process piping was cut to be used as a baseline of volumetric sensor bias for process piping. Data from spinning in place in the clean nickel-plated pipe is shown in figure 17. The prominent features in this data are the loss of inductive sensor readings and the large, 5-8 mm, constant offset between the inductive and optical triangulation measurements. This was thought to be caused by two factors, (1) the material properties of the process piping differed more than anticipated from the nickel plates used in calibration and (2) this difference truncated the maximum sensing range, causing the sensor to report higher voltages at lower offsets.

Knowing that the pipe was visibly devoid of deposit, except for a small collection of debris at the bottom of the pipe from cutting, a self-calibration procedure was developed to attempt to recover the proper calibration curve. With the assumption that the optical triangulation data represented the true offset of the inductive sensor at a given radial position, voltage measurements were remapped to new offsets. Figure 18 conveys the severity in difference between the CNC calibration curve and the self-calibration curve. Because the inductive sensor did not travel beyond 10-14 mm from the surface of the pipe, only a partial calibration could be recovered within this range.
Figure 17. Response of the volumetric sensor while spinning in place in a visibly clean piece of 30” (0.76 m) process piping.

Re-fitting the self-calibration data with a piecewise linear function, a new calibration was generated, using the mean sensor temperature during operation as the new reference temperature. Figure 18 shows the comparison between the application of the original and self-calibration inductive calibration curves to the data collected in a pipe on the process floor with visible evidence of deposit. This shows that the self-calibration was a step in the right direction, reducing the average, however it overcompensated and produced negative thickness measurements. This implies that the optical triangulation sensor was viewing a surface beyond the surface of the pipe, which is physically impossible.

Figure 18. Self-calibration procedure attempts to recover the proper transform from voltage to offset of the inductive sensor when exposed to nickel plated process piping (left). Application of the self-calibration results in a reduction of offset bias, but overcompensates and results in negative thickness (right).

CONCLUSIONS

In this paper, an approach for making direct volumetric measurements of holdup deposits in situ was developed and deployed as a proof-of-application. The novelty of this work required the design and extensive characterization of a new kind of sensor capable of making volumetric estimation of sub-millimeter deposits. The volumetric sensor was capable of detecting and quantifying deposit volumes,
thickness, and locations along a pipe. In the process of characterization and calibration, the volumetric sensor showed a wide range of responses due to external factors, such as temperature and pipe material properties. Proper calibration of the volumetric sensor’s sub-sensors achieved as specified accuracies for a given target material. With further investigation of the impact of the process piping’s effect on the inductive sensor and continued erosion of volumetric sensor bias, results from process pipe mapping will echo the results from bare steel pipe.

Beyond the evolution and maturity of the volumetric sensor, key topics to be addressed in further development include formulation of probabilistic sensor models for determining volumetric certainty, iteration of mechanical subsystems to achieve better mobility and centering, and general rework on the system as a whole.

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