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Laboratory Evaluation of the Pipe Explorer™ Gamma Measurement and Deployment Capability

Topical Report for Task 3

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For

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SECTION 1

INTRODUCTION

The DOE is faced with the responsibility of decommissioning and dismantling many of its nuclear process facilities. Much of this will involve piping systems which may or may not be contaminated with radioactive material. It is important to be able to differentiate contaminated from non-contaminated material, since the disposal costs for radioactive waste are significant (on the order of hundreds of dollars per cubic foot). In the case of pipes, this determination may be particularly difficult if the pipes are not easily accessible. As a solution to this problem, SEA is developing an inverting membrane technology, called Pipe Explorer[™] which uses commercial gamma spectroscopy systems to characterize the radiation levels inside of pipes.

The primary components of the technology are illustrated in Figure 1. The heart of the system is an air-tight membrane which is initially spooled inside of a canister. The end of the membrane protruding out of the canister is folded over and attached to a basepipe. With this configuration, when the canister becomes pressurized the pressure force on the membrane causes the membrane to be pulled from the spool. This continues until the membrane is completely off the spool. A radiation detector is attached to the end of the membrane and towed into the pipe as the membrane continues to evert. The detector cabling is also towed into the pipe. To retrieve the system from a pipe the process is simply reversed, where the cabling, detector, and membrane are wound back onto the spool. The system can thus be used to move a detector freely back and forth through a pipe to provide high resolution analysis of the location of radioactive contamination in pipes. This unique method can deploy the detector and analyze piping systems with multiple elbows and vertical runs. The membrane also serves to protect the expensive detector from contamination.

Prototype systems were developed to demonstrate the basic concept and capabilities of the inverting membrane pipe inspection system. Two deployment canisters were fabricated (design details are provided in Reference 1). The first is capable of operating at pressures up to 50 psi and is motor driven. A control box accompanies this canister which enables semi-automatic operation of the system from a remote location of up to 50 feet away. A second deployment canister was also developed which is hand portable and manually operated. A portable computer system is configured to record radiation measurements of detectors deployed with both canisters. When coupled with the larger canister the system also records deployment parameters such as detector depth, deployment air pressure, and tether tension. Details of the two deployment canisters, the control system, and the computer system are discussed in Section 2.1.

Figure 1. Inverting membrane deployment sequence.

Deployment tests were carried out with the integrated system in a wide variety of piping configurations, which ranged from straight runs in small diameter pipes (1.5-in I.D.) to runs in larger diameter pipes with multiple 90 degree elbows. From these tests the operating capabilities of the system were determined. The tested piping configurations that were used to determine these specifications are described in Section 2.2.

Two different gamma scintillation detectors were acquired in order to demonstrate the capability of the Pipe Explorer™ system to deploy detectors into pipes. The sensitivity of these detectors (to radiation inside of pipes) was analyzed using the neutron/photon transport code MCNP. The results of the analysis under several different configurations and detector geometries is detailed in Section 3.2. A critical factor in using detectors inside of pipes is the minimum detectable activity. This is a figure of merit that relates the detected counts to background radiation levels. This is explained and calculated in Section 3.2.

SECTION 2

LAB SCALE TESTS OF THE DEPLOYMENT SYSTEM

The lab scale tests conducted for the deployment system were designed to determine the operational limits of selected membranes in various pipe geometries as well as the performance capabilities of the Pipe ExplorerTM instrumentation and control system. The tests were limited to a maximum deployable length of 200 feet, which corresponds to the length of tether material on the canister spool. The small manually controlled canister was used for all the membrane tests due to the relative ease of use for the given test setup. The larger semiautomated remote controlled canister was used in the performance tests of the system.

2.1. Membrane Tests

The goal of the membrane material tests were to identify and characterize low cost material available in sizes ranging from 1.5- to 12-inch diameter. A total of 257 manufacturers were surveyed. Samples of material were supplied by several of the manufacturers. Based on SEA's experience with SEAMISTTM membranes, several types of membrane material were selected for testing. Those materials of interest were 100 percent low density polyethylene (LDPE), linear low density polyethylene (LLDPE), and high density polyethylene (HDPE).

Three basic tests were performed on these materials. The first was a series of burst tests which was designed to determine the maximum operating pressure of the material in different pipe configurations. The second test was designed to provide information on the wear resistance and coefficient of friction of the material against various tether materials. The third test was designed to determine the relative ease of inversion through 90 degree elbows.

The burst tests were done for three different configurations in 2-, 3-, and 4-inch pipe. The intent was to determine the burst pressure for three pipe diameters for the three different candidate materials. The first series of tests determined the burst membrane pressure in a straight section of pipe. The test setup consisted of a 36-inch section of pipe fitted to the small canister snout. Material was then cut to 24-inch length and fully deployed in the pipe. The pressure was then increased slowly until burst at the membrane's end occurred. The second series of tests was performed to determine the burst pressure of materials when held in a 90 degree corner. The test setup was identical to the previous test with the addition of a 90 degree elbow placed on the end of the pipe. Material slightly longer than the pipe length was loaded in the canister and deployed until the tip of the membrane extended into the 90 degree elbow. The material was then manually held at this position and the pressure was increased slowly until burst

occurred. The last test configuration introduced a pipe tee in the test section. The test setup was similar to the one above with the addition of a pipe tee at the mid point of 36-inch pipe section. A 24-inch section of material was loaded on the canister and fully deployed. The pressure was then slowly increased until burst occurred. Table 1 below summarizes the results of these tests. The trials listed below indicate average burst pressure results.

Table 1. Summary of membrane burst pressure tests.					
Trial #	Material	Pipe size (sch. 40 PVC)	Burst pressure (psi) Straight section	Burst Pressure (psi) Held in corner	Burst Pressure (psi) Tee section
1	LDPE 4 mil	3	11.0	8.0	6.5
2	LDPE 2 mil	2	16.0	10.0	9.0
3	LDPE 2 mil	4	9.0	6.8	NT
4	LLDPE 4 mil	2	NT	11.0	NT
5	LLDPE 6 mil	2	NT	14.0	NT
6	HDPE 2 mil	2	12.0	NT	6.8
7	HDPE 2 mil	4	7.5	NT	3.2

Note: NT = Not Tested.
 LDPE = Low density polyethylene
 LLDPE = Linear low density polyethylene
 HDPE = High density polyethylene

2.2. Deployment Tests

The first series of deployment tests was designed to determine the limits of the membrane materials independent from the deployment canister capability. A 200-foot 4-inch PVC pipe structure was assembled for the first series of tests (Figure 2). The three materials listed in the previous section were deployed with a 1/4-inch diameter tether from the small canister. The LDPE and the LLDPE materials managed to complete the piping system at a nominal deployment pressure of 3 psi. The HDPE material deployed around the first three corners then stuck in the fourth elbow. HDPE is a stiffer film than the other polyethylenes and frequently displayed this type of behavior.

When a membrane is retrieved, a significant amount of wear can occur at the location of elbows potentially creating a hole in the membrane. The wear resistance of these membranes was compared relative to one another upon retrieval. The HDPE appeared to be the most wear resistant with no noticeable scarring of the material. The LDPE was the second best wear resistance with minimal scarring of the material. The LLDPE showed the most damage with large holes torn in the first two elbows.

Figure 2. 200-foot 4-inch PVC pipe structure.

A mockup of the proposed detector was fabricated to determine the ability of the detector to deploy in various piping systems. The detector mockup assembly consisted of two 1.1-inch diameter by 3.25-inch long aluminum cylinders mounted on a flexible harness (similar in geometry of the CsI(Na) detector used in subsequent experiments). The mockup was first deployed through the piping system described in Figure 2 with 2-mil LLDPE membrane material. Minor damage to the membrane occurred due to tether wear on the membrane at the first elbow during retrieval of the system. The second deployment test with the mockup detector was run in the 2-inch PVC piping system shown in Figure 3. Similar damage to the membrane occurred.

The force required to retrieve a membrane once it has been deployed is a function of the total mass of the tether deployed, the number of elbows encountered, and the coefficient of friction between the tether material on the membrane and the membrane on itself. In order to minimize this force and reduce the amount of force transmitted to the tether, the coefficient of friction between the tether and the membrane must be minimized. It was determined from the above test results on membrane wear that the tether would need to be wrapped with a slick material. Several tests were conducted to determine the

Figure 3. 100-foot 2-inch PVC pipe structure.

material that would provide the lowest coefficient of friction when in contact with LDPE. These tests concluded that a fine weave nylon ribbon would be used.

Two gamma detectors were tested in three different piping systems with Pipe Explorer™. The larger of the two detectors (2.25-inch diameter by 11.25-inch long NaI(Tl) Bicron detector) is capable of deployment in 3-inch straight pipe sections and/or 6-inch pipe sections with elbows. A piping system was assembled to test the deployment capability of the detector as shown in Figure 4. Due to the physical size of this detector, it is not able to fit inside the deployment canister. Therefore, the membrane is deployed to the halfway point and the canister is pulled aside while the detector is attached and placed in the pipe. There were no problems associated with this deployment approach.

The second detector was tested with the use of the large Pipe Explorer™ canister. This provided a system level checkout prior to the Phase I demonstration. Two different piping systems were used. The first is the 3-inch PVC piping system shown in Figure 5. This piping system is designed to emulate the piping system proposed for the Phase I demonstration. This test provided the first indication of the importance of minimizing tether mass. During the first deployment, the pressure limit for the membrane would not allow the detector to be deployed more than 60 feet. This was determined to be caused by the excess mass of the tether, which was originally designed to contain three instrumentation cables (two RG-58 coaxial and one 6 conductor 22 AWG cables). Only one of the RG-58 cables is required to run the Rexion detector, and therefore the second coaxial cable was removed. A second deployment with the new reduced tether mass proceeded the entire length with no problem. The same system was also successfully deployed in the 2-inch PVC piping system shown in Figure 6.

Deployed with Bicron Detector
Total Run 74'
Plan View

Deployed with Bicron Detector
Total Run 74'
Side View

Figure 4. 74-foot 4-inch and 6-inch PVC pipe structure.

Figure 5. 116-foot 3-inch PVC pipe structure.

Figure 6. 200-foot 2-inch PVC pipe structure.

Other deployment tests were conducted to determine the deployment characteristics in small diameter tubing or hose. The canister used for these tests was the small manually operated canister without a detector or detector mockup and the tether and membrane material was 3-inch layflat 2-mil LDPE. The first test was deployed in a 1-inch I.D. hose 25 feet long with a 360 degree bend at the mid-section (Figure 7). The deployment pressure required was 6.5 psi. The second test was run with the same tether and membrane and was run in a 16-foot long 3/4-inch I.D. hose configured in a large circle. The deployment rate was noticeably slower than the 1-inch hose and required a high deployment pressure of 10 psi. Once fully deployed, the membrane reached a maximum pressure of 14 psi before bursting.

Figure 7. 25-foot 1-inch rubber hose.

2.3. Lab Scale Test Summary

The Pipe Explorer™ deployment system was tested to determine the capabilities of various components of the system. Membrane tests were conducted to help select the optimum membrane material with respect to burst pressure, ruggedness, and cost. Deployment tests in piping system mockups evaluated the system's ability to negotiate a range of pipe diameters, physical layouts, and number of elbows. Integrated system tests incorporated actual detectors (or detector mockups) and tethers, assessing the impact of towing this hardware through the inverted membrane.

Membrane evaluations determined that, in general, the low density polyethylene membrane material in a 0.004-inch thickness provides the ideal combination of good burst strength, adequate elongation to resist puncture, is relatively slippery to minimize friction, and is flexible enough that it does not require excessive pressure to invert. This is a very inexpensive material (approximately \$0.05/lineal foot) and readily available in a range of diameters.

The tests in the piping mockups illustrated the system's ability to transport the detector through 200-foot long pipe networks in sizes ranging from 2- to 4-inch diameter, with multiple elbows. In 3-inch and larger diameter pipes, emplacement was straightforward and four or more elbows could be negotiated by the membrane and detector (as the pipe diameter increases, the towing force available for a given air pressure increases by the square of the pipe radius). Emplacements in 2-inch diameter pipe were somewhat more difficult, with a limit of two elbows for a full 200-foot pipe run, using the actual detector and tether assemblies. Tests (without detectors) showed that the system could even emplace in 0.75-inch diameter hose.

The integrated tests evaluated the membrane wear characteristics using actual detectors and tethers. Modifications to the detector harness (a pair of flexible straps which held the detectors) and the tether assembly reduced damage to the membrane in the elbow sections by effectively minimizing the friction. These tests also showed that, if the membrane fails due to tearing or bursting, it is still retrievable in the normal fashion.

SECTION 3

RADIATION DETECTION

3.1 Gamma Radiation Detection System

The primary intent of this development effort was to create an effective and versatile mechanism for transporting instruments into pipes. Gamma radiation detectors were chosen as the first type of instrument to demonstrate with the deployment system. Two such detectors were acquired for this purpose. The first is a standard NaI(Tl) scintillation detector built by Bicron. This detector has a large 2-inch diameter by 2-inch long detector area which makes it quite sensitive. It also exhibits a relatively high energy resolution of 8 percent which makes it capable of limited spectroscopy measurements. However, this detector package is large (2.2-inch diameter by 11-inch long) and therefore limited to deployment in larger pipes. In order to deploy into small diameter pipes with elbows, a second detector was built for SEA by Rexion Components. This one uses a 1.125-inch diameter by 1.118-inch long CsI(Na) scintillation crystal. This detector has a high gamma detection efficiency (29 percent for Cs-137) but is limited to 30 percent energy resolution. While this limits the use of the detector for spectroscopy measurements it still allows energy discrimination for more sensitive gamma detection, where energy windows can be utilized to minimize the influence of background counts. A significant amount of analysis was done to determine the optimum size of this detector. A discussion of this is included in Appendix A.

The gamma scintillation detectors are connected to a Canberra AccuSpec NaI Plus board. This is a 2,048 channel multichannel analyzer (MCA), placed inside a docking station coupled to a portable 486 laptop computer. This enables the data acquisition system to be portable. The MCA card inside the computer is capable of providing the DC power required for preamps, pulse amplification, and the high voltage required for the Bicron detector.

3.2 Discussion of Minimum Detectable Activities

Threshold values for radioactive contamination are established by the DOE to determine if materials can be released for unrestricted use, and range from hundreds to thousands of disintegrations per minute per 100 cm² (dpm/100 cm²). These values are set as activity levels above background and are on the order of a few percent of the total background activity. The ability to detect a surface contamination activity level is thus dependent on the statistical variation of background measurements. The minimum detectable activity (MDA) is a quantitative evaluation of what activity levels are significant above background. The MDA is determined from the formula (Reference 2) :

$$MDA = k (2.71 + 4.65 s_b)$$

Where:

MDA = minimum detectable activity (dpm/100 cm²)

k = proportionality constant relating detection geometry, detection time, and detector efficiency

s_b = standard deviation of the background level

The proportionality constant, k, is determined by two factors. The first is the detector efficiency (E_d) which is the ratio of pulses counted on the multi-channel analyzer (MCA) to gammas incident on the detector. This is determined by measuring counts from a radiation standard. The second factor is the gamma interaction probability (E_g) which is dependent on the geometry of the radioactive source and proximity of the detector to the source. It is the probability that a gamma emitted will come into contact with the detector. This factor is determined through modeling of the detection geometry with the Monte Carlo radiation transport code MCNP (Reference 3).

As an example of a determination of MDA consider the situation of the CsI(Na) detector resting on the bottom of a 2-inch I.D. pipe. If the pipe is uniformly coated around the interior over a length of 80 cm with contaminants then the factor E_g is determined by MCNP calculations to be

$$E_g = 0.1091$$

The detector efficiency is determined by placing a calibrated Cs-137 source (certified at 31,800 Bq) directly on the detector surface and integrating the total counts over a 10 minute period. This was done for both radiation flux on the detector face and on the side wall of the detector and was determined to have an average value of

$$E_d = 0.2606 \text{ (for energy range 50 keV to 1.5 MeV)}$$

The two efficiency factors are then combined with the sample time (t) to determine k through the relation

$$k = 1 / (E_g \cdot E_d \cdot t)$$

Two factors are variable in the determination of MDA. The first is the time period (t) over which the MCA acquires counts. The second factor affecting the MDA is the standard deviation of the background count. This also varies with time since the standard deviation is simply the square root of the total counts detected. However, the background can also be minimized by measuring activity over energy ranges which exclude lower energies, since this is where most of the background activity occurs. To illustrate this, a plot of MDA versus sample time is shown in Figure 8 where the MCA was configured

Figure 8. Minimum detectable activity levels anticipated for Pipe ExplorerTM system field test, according to Reference 2.

to measure the counts over a region of interest (ROI) extending from ± 15 percent of 662 keV (appropriate for Cs-137 detection). The general case is also shown over the energy range 50 keV to 1.5 MeV. A more important effect on the MDA is determined by the shielding of background around the detector. For example, the shielding provided by pipe walls will noticeably decrease the count rate relative to background, where schedule 40 steel pipe generally decreases background by ~ 30 percent. These background measurements were conducted inside a schedule 40 pipe, which is representative of the emplacement configuration.

3.3 Gamma Detection Inside 2-Inch Pipe

When conducting surveys of pipes with the Pipe ExplorerTM system, the primary uncertainty in determining the MDA is the proportionality constant k . This factor is proportional to the ratio of the number of gamma emissions from contamination area to the number of photons that interact with the detector. This is determined combining the detector efficiency (E_d) with the gamma interaction probability (E_g). As discussed in the previous section, the interaction probability is calculated by running the computer code called MCNP, which models the geometry of the pipe, detector, and the source along the pipe interior. Figure 9 illustrates the geometry used in the MCNP models. What makes this factor difficult to determine exactly is that it varies depending on the geometry of the radiation inside the pipe as well as the position of the detector inside of the pipe. To illustrate this fact compare two cases of significantly different contamination situations inside of a pipe. Both correspond to the threshold value limit of

Figure 9. Geometry used in the MCNP calculations.

1,000 dpm/100 cm². The first case is for a distributed source where the radiation is evenly spread around the internal circumference of the pipe. The analysis is done for 2-inch-diameter (5.08 cm) pipe. In order to get a 100 cm² active area, the contamination is modeled as being spread along a length of 2.5 inches (6.27 cm). The MCNP code was run to model the REXON CsI(Na) detector inside steel pipe with this contamination geometry. The model was simplified in that it only included the crystal size, a 1.125-inch diameter, 1.188-inch long cylinder. The calculation did not take into account photo multiplier tube (PMT) geometry or the housing around the detector. The energy of the contamination that was modeled corresponded to Cs-137 with an energy of 662 keV. The result was a probability of any gamma being emitted from the surface interacting with the detector of $E_g = 0.12$. A second case was run to compare this to a point source contamination with an activity of 1,000 dpm. The same detector size was used with the detector centered inside of the pipe. This run resulted in a probability of gamma interaction of 0.17. This is not a significant difference from the previous case.

Another factor which affects the proportionally constant k is the position of the detector inside the pipe, where it is more sensitive to the point source case than it is for the distributed source. The first example models the same distributed contamination region discussed above, where the internal circumference of 2-inch pipe is evenly coated with radioactive material along a length of 2.5 inches. Several simulations were run, where the radial position of the detector inside of the pipe was varied. This corresponded to the detector being moved from one wall of the pipe to the other. The results of these runs are shown in the plot in Figure 10. For this case, the results of the photon interaction probability are not highly sensitive to position of the detector inside of the pipe. The variation for the extremes, where the detector is in the center of the pipe compared to the detector at the edge of the pipe, is only 17 percent. A second set of simulations was conducted for a point source of 1,000 dpm. In this case, the detection results are more sensitive to position of the detector within the pipe, which can be seen in the plot of Figure 11. Comparison of the detector directly over the point source to when the detector is moved away from the source to the far end of the pipe show a variation in interaction probability by a factor of 6.5.

A difficulty in surveying pipes is that an a-priori knowledge of the contamination distribution inside the pipe is not known. Therefore, the question arises, which proportionality constant should be used in determining the activity levels measured and for determining MDAs. The conservative approach is to choose the worst case scenario and use that in all situations. This worst case scenario corresponds to the situation of a 1000 dpm point source with the detector at the wall opposite the point source.

This conservative proportionality constant will vary depending on the size of the pipe being surveyed and with the size of detector being used in the survey. MCNP models were analyzed for the CsI(Na) detector, which has crystal size of 1.125-inch diameter by 1.188-inches long. Simulations were

Figure 10. Gamma interaction probability variation with detector position inside of a 5.08 cm (2-inch) I.D. steel pipe. Contamination is modeled as 100 cm² area evenly distributed on pipe interior.

Figure 11. Gamma interaction probability variation with detector position inside of a 5.08 cm (2-inch) I.D. steel pipe. Contamination is modeled as a point source on the pipe wall.

run for the point source contamination in a variety of pipe sizes. The results of these are shown in Table 2 where the proportionality constant is shown for pipe diameters ranging from 1 1/2 inches in diameter to 4 inches in diameter.

Table 2. Gamma interaction probabilities for the Rexion detector in piping with point source contamination.			
Pipe I.D. (in)	Pipe O.D. (in)	Amount detector off-center (in)	Probability
1.5	1.75	0.18	1.954×10^{-1}
2.0	2.25	0.43	8.202×10^{-2}
2.5	2.75	0.68	4.412×10^{-2}
3.0	3.50	1.93	3.112×10^{-2}
3.5	4.00	1.18	2.133×10^{-2}
4.0	4.50	1.43	1.587×10^{-2}

3.4 Laboratory Tests of Detection Capability

Several tests were conducted to illustrate the detection sensitivity of the Pipe Explorer™ system. In these tests, radiation sources were placed inside of 3-inch diameter, schedule 40 steel pipe. These sources included two uranium-235 sources with nominal circular surface areas of 1-inch diameter and activity levels on the order of 13,000 and 28,000 dpm. In addition, a cobalt-60 distributed source was placed inside the pipes. This source is a 10 by 15 centimeter flexible rectangle with an NIST traceable calibrated activity of 1,500 dpm, thus resulting in an activity of 1,000 dpm/100 cm². The test used the Bicron detector which has a 2- by 2-inch NaI(Tl) crystal. The detector was moved along the length of the pipe in 3-inch increments. The detector was left in each position for four minutes while data was acquired. Total counts were then recorded in two regions of interest (ROI)s. The first region corresponded to the entire spectrum (9 keV to 1.5 MeV). This was most applicable to the U-235 readings. The second ROI was more narrow. It covered the energy range from 500 keV to 1.5 MeV. Results of the tests are shown in Figures 12 and 13. The first figure shows data from ROI1. It is evident where the two U-235 sources are located. The second figure shows data from the second ROI. The Co-60 source can clearly be seen above background levels.

3.5 Summary of the Performance and Improvements to the Detection System

Laboratory tests of the radiation detection system used with the Pipe Explorer™ showed that the system is capable of measuring low activity sources inside of pipes. This includes high energy sources

Figure 12. Results of a survey of a 3-inch I.D. steel pipe with U-235 foils placed inside.

Figure 13. Results of a survey of a 3-inch I.D. pipe with a 1000 dpm/100 cm² Co-60 source inside.

(1 MeV) with 1000 dpm/100 cm² activity. It also includes lower energy sources like U-235 (185 keV), with total activities of 12,000 dpm. With U-235 the resulting gamma activity is reduced since the gamma yield of U-235 is 0.54 gamma emissions per disintegration.

Based on the tests conducted and the analysis carried out with MCNP, it was determined that the detection system is capable of measuring activities of 1000 dpm/100 cm² with high gamma production sources. For radiation sources with gamma yields as low as 0.5 gammas per disintegrations levels of 5000 dpm/100 cm² are measurable. It is estimated that low level activity of radioisotopes with gamma yields <0.1 will be extremely difficult to detect with the system (at threshold values). Furthermore, gamma energies below 25 keV will be difficult to detect due to shielding from scintillation detector housings. A list of the radioisotopes that meet these two criteria are shown in Appendix B.

After laboratory testing of the Pipe ExplorerTM system, it became evident that several improvements could be made to the radiation detection portion of the system. The first improvement will decrease the amount of time required to detect threshold levels of radioactive contamination. As noted in Section 3.2, sampling times required to achieve MDAs of 1000 dpm/100 cm² are on the order of 16 minutes. When surveying extensive lengths of pipe, such sampling times become cumbersome. Sampling time can be significantly reduced with the use of a rate meter as opposed to a counting device used with the current system. Therefore, one improvement to incorporate in the next generation of the Pipe ExplorerTM system is to supplement the multi-channel analyzer with a rate meter which has an analog output. A second improvement to the system would be to develop a methodology to differentiate between point sources of contamination as opposed to distributed sources of contamination. As noted in Section 3.3, the gamma interaction probabilities vary differently depending on what geometry of contamination is present. One method to ascertain whether or not the contamination is distributed or a point source would be to change the position of the detector within the pipe. The most straight forward method of doing this would be to put a centering device on the detector, however, this requires a significant modification to the deployment system and also significantly decreases the detector mobility in smaller diameter pipes, especially those that include elbows. A simpler approach is to rely on the deployment system to change the position of the detector in the pipe. This can be done by varying the tension on the tether. With a large amount of tension on the tether, the detector tends to be pulled up somewhat from the bottom of the pipe. When the tension is released the tether rests completely on the bottom of the pipe. While this will not quantitatively determine where the detector is in relation to the pipe wall, it is possible to note changes in the activity levels noted as the detector is moved up and down. Comparisons of these changes to what is expected based on MCNP modeling as noted in Figures 10 and 11, could be used to determine whether or not the contamination is distributed or more like a point source.

Another method to improve the Pipe ExplorerTM system is to obtain a wider variety of detector sizes. It is clear that the larger the detector, the more sensitive it is. If a suite of detectors was available so that the maximum size detector could be chosen for whatever particular pipe was being inspected, then the sensitivity of the detection would be greatly enhanced.

SECTION 4

SUMMARY

This task evaluated the deployment and measurement capabilities of the Pipe Explorer™ radiological measurement system. Previous tasks surveyed the piping and radiological characteristics of several DOE facilities, and developed the specifications and design of the Pipe Explorer™ system components.

The deployment system includes the emplacement canister, the tether assembly, the monitoring/control system, and the membrane. Two deployment canisters were fabricated: one for long (200 ft.) deployments which is capable of relatively high pressures and semi-automatic operation, and the other for shorter (100 ft. maximum) pipe lengths under manual control. Both systems include adequate conductors in the tether assembly to provide total count as well as gamma spectroscopy measurements with the multichannel analyzer in the monitoring system. The monitoring and control system records and displays operational parameters during the deployment (such as canister air pressure, tether tension, and detector location in the pipe), conducts the gamma measurements, and controls the motorized deployment to allow essentially unattended operation. The membrane material chosen for lab tests and field deployments is an inexpensive, readily available low density polyethylene film manufactured in tubular form. This material is inexpensive, puncture resistant with good elongation properties, and can sustain the pressure required for most deployment conditions.

The laboratory evaluations of the integrated deployment system demonstrated the following capabilities:

- Typical membrane burst pressure ranged from about 6 to 12 psi for the low density polyethylene materials, depending on the test configuration and pipe diameter.
- Emplacement pressures required for deployments in 2- to 4-inch diameter pipes ranged from 3 to 5 psi (these tests included detectors and ran in pipe networks up to 200- feet long with multiple elbows). In a benchtop test evaluating the minimum diameter limit given the current membrane materials, a membrane was successfully deployed (without detectors) in a 0.75-inch diameter 16-foot long, hose requiring a maximum of 10 psi.
- The control system used with the large canister allows unattended operation and monitoring of the characterization operation.
- The large canister presently can accommodate multiconductor tether and membrane material for emplacements up to 200 feet in total length. By reducing the tether volume, this can be increased to 300 feet with no modifications to the canister.

The radiological measurement system uses standard scintillation crystals coupled to photomultiplier tubes for gamma measurements. Detector output is analyzed by a multichannel analyzer (MCA)

which provides the total integrated count over a specified time interval (over multiple energy regions of interest, if required) as well as energy spectral analysis for speciation of the isotopes. Two detectors were developed for this effort. One is relatively large, capable of emplacement in 3-inch straight or 6-inch diameter pipes with elbows. Using a 2-inch diameter by 2-inch long NaI(Tl) crystal, this is a commonly available detector readily integrated with MCA software and hardware. The other detector, incorporating a CsI(Na) crystal approximately 1-inch diameter by 1-inch long, was custom fabricated for this application and deployed in pipes as small as 2-inch diameter (with elbows) and 1.5-inch diameter (in straight runs). The response of the detectors, under various geometric configurations and with a range of radioactive source energies and geometries, was modeled with Monte Carlo techniques to evaluate measurement sensitivity to conditions anticipated in the field. This information was coupled with measured detector efficiencies to determine Minimum Detectable Activity levels relevant to evaluation of the threshold measurement capabilities. The basic capabilities demonstrated in this effort are:

- Threshold surface activity levels as low as 1000 dpm/100 cm², with high gamma production efficiency isotopes, are measurable with the Pipe Explorer™ system in its current configuration given enough counting time. If the gamma production efficiency is below 0.5 gammas per disintegration, however, the measurement threshold is raised to 5000 dpm/100 cm². For isotopes with gamma production efficiencies below 0.1, the threshold measurement values are well above 10,000 dpm/100 cm².
- In general we will not know *a priori* the geometric configuration of the contamination on the pipe's surface. Some knowledge of the configuration is required to relate the detector measured counts to the surface activity. If, for example, the contamination is distributed over the pipe's surface, the radial location of the detector inside the pipe is not crucial (hence detector centering is not required). If the contamination is a point source, however, interpretation of the detector measurement incurs an uncertainty of as much as a factor of 6.5 under the modeled conditions. In general, we do not expect the nature of contaminants in the pipes to result in concentrated deposits.
- Larger detectors result in better sensitivity (and consequently better MDAs). However, larger detectors cannot negotiate elbows in the smaller pipe sizes, so the largest detector possible must be selected for a given pipe emplacement to optimize sensitivity and deployment range.

SECTION 5
REFERENCES

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2. Berger, J. D., "Manual for Conducting Radiological Surveys in Support of License Termination," NUREG/CR-5849, Oak Ridge Associated Universities, December 1993, SECTION V.
3. "MNCP4 Monte Carlo Neutron and Photon Transport Code System," CCC-200A/B, Oak Ridge National Laboratory, operated by Martin Marietta Energy Systems, Inc., for the U.S. Department of Energy.

APPENDIX A

DETECTOR DESIGN STUDIES

The dominant factor that affects the design and sensitivity limitations of a detector is the geometry of the detector inside of the pipe. Since radiation is emitted isotropically, then only a fraction of the total emitted energy is intercepted by the detector. Therefore, not only the size of the detector but also the orientation of it will affect the number of photons detected. In order to analyze this factor, a Monte Carlo radiation transport code called MCNP was used. The code is capable of modeling neutron and photon interactions through different geometries and materials. The code is maintained and continues to be developed by the Applied Theoretical Division of Los Alamos National Laboratory. Distribution of the code is controlled by the Radiation Shielding Information Center (RISC) at Oak Ridge, Tennessee. For our analysis a PC version of the code was obtained and run on a 486 desktop computer.

MCNP is suited for modeling cylindrical detectors located inside of contaminated pipes. The parameters involved for the modeling of the cylindrical detector inside of a contaminated pipe are shown in Figure A-1, where the primary parameters varied were the detector diameter and length, source size and location, and the pipe diameter. The results of these MCNP calculations are discussed individually below.

To model radioactive contamination inside of pipes, the distribution of the contamination was assumed to fall into one of three geometries around the pipe interior: 1) even distribution, 2) in a line, and 3) as a point.

A.1. Even Distribution Source Model

The most likely geometry to be encountered in actual pipe inspections is the first case which consisted of a thin film of contamination evenly distributed around a pipe's interior circumference. The length of the contamination was chosen to be much longer than the detector so that the gamma interaction with the detector was the same as if the contaminated area was infinitely long. The activity level was set at 1000 dpm/100 cm² in all contaminated lengths of pipe. This is illustrated in Figure A-2 where a plot of the count rate from a 5.08 cm (2-inch) diameter by 5.08 cm (2-inch long detector) in a 10.16 cm (4-inch) I.D. pipe is plotted as a function of the length of the contaminated area. With the modeled contaminated area 80 cm long (detector is located at the center) the count rate from the detector is 122 counts per minute (cpm) (note that the data in Figure A-2 reflects a detection efficiency of 25 percent). This is approximately 95 percent of the count rate that would be detected for a continuously

Variable Parameters:	
A	- Pipe diameter
a	- Detector diameter
L	- Detector length
L_R	- Length of contaminated area on pipe wall
Z	- Axial distance between detector and source area (center-center)

Figure A-1. Geometry and parameters used by MCNP in analysis to determine detector sensitivity.

Figure A-2. Detailed counts as a function of contamination area length in 4-inch I.D. steel pipe. The detector is 2-inch diameter by 2-inch long with an assumed efficiency of 25 percent.

contaminated pipe based on an extrapolation of the curve shown in Figure A-2. A contaminated area 80 cm long was the maximum length used for all of the modeling done with a distributed case. The data shown in Figure A-2 is reproduced in Figure A-3 where the count rate has been normalized to the rate found for the 80 cm long source region. This was done so that any subsequent data obtained from models using a distributed source region can be scaled for cases where the contamination region should be shorter.

The effect of detector size on obtainable count rate was determined by modeling varied diameter detectors inside of steel pipe. The count rate as a function of detector length was determined for 5.08 cm (2-inch) I.D. pipe and 10.16 cm (4-inch) I.D. pipe. The results of these simulations are shown in Figures A-4 and A-5 respectively.

Figure A-3. Normalized detailed counts as a function of contamination area length in 4-inch I.D. steel pipe. The detector is 2-inch diameter by 2-inch long with an assumed efficiency of 25 percent.

Detector response for 0.5, 0.75, 1.0, 1.25, & 1.5 inch diameters as a function of detector length. Assume 25% detector efficiency.

Figure A-4. Count rate versus detector length for detectors ranging in diameter from 1.27 cm to 3.81 cm. Model assumes 25 percent detector efficiency. Pipe diameter is 5.08 cm (2-inch).

Figure A-5. Count rate versus detector length for detectors ranging in diameter from 1.27 cm to 8.89 cm. Model assumes 25 percent detector efficiency. Pipe diameter is 10.16 cm (4-inch).

A.2. Line-Distribution Source Model

In some instances liquids or sludges may have caused the contamination to pool at the bottom of a horizontal pipe. In this case the radiation source was modeled as a line at the pipe wall. The line was ± 40 cm from the detector center with an overall activity level of 12,560 dpm for a 10-cm I.D. pipe and 6283 dpm for a 5-cm I.D. pipe. This level was chosen since a circumferential swipe around the pipe interior would result in 1000 dpm per 100 cm². Again, a detector efficiency of 25 percent is assumed. The results for these analysis are listed in Table A-1. For the cases of 5.08-cm and 10.16-cm I.D. pipe the detected count rates are shown for both a centered detector and a detector at the pipe wall. The effect due to the detector being off-center is much more dramatic for this asymmetrical case than for the distributed source.

Table A-1. Detected count rates for a line source inside of pipes.				
Pipe I.D. (cm)	Detector diameter (cm)	Detector length (cm)	Distance off-center (cm)	Counts (cpm)
5.08	2.54	2.54	0.0	29
5.08	2.54	2.54	1.25	82
10.16	5.08	5.08	0.0	53
10.16	5.08	5.08	2.52	164

A.3. Point-Source Model

The geometry was also modeled for the case of a 1000 dpm point radiation source at the pipe wall. This was done for a 2.54-cm diameter, 2.54-cm long detector in 5.08-cm I.D. pipe. The count rate assuming a 25 percent efficiency is plotted in Figure A-6 as a function of separation distance between the point source and the detector center.

A.4. Size Limitations

The larger the volume of a scintillation detector the more sensitive it will be. Therefore, it is desirable to make the detectors for pipe inspections as large as possible. However, the size is limited by the requirement that these detector be capable of negotiating elbows in the piping. The maximum length of a detector that can pass around a bend is dependent on the pipe and detector diameter. In addition, the maximum length of the detector package is dependent on the pipe bend radius. To illustrate how the limitation on detector length is dependent on these parameters, the maximum detector length in 5.08-cm I.D. pipe is shown in Figure A-7 as a function of detector diameter for a variety of bend radii.

Figure A-6. Count rate as a function of separation distance from a point source in 2-inch pipe.

Figure 7. Maximum detector length as a function of detector diameter as limited by deployment through an elbow in 5.08 cm I.D. (2-inch) pipe. Relationship is shown for elbow bend radius of 0, 2, 3, and 6 cm.

APPENDIX B

DETECTABLE ISOTOPES

Table B-1 presents a list of beta-gamma emitters potentially detectable by the pipe inspection system. The radionuclide, its half-life, the gamma energy in keV and the percentage yield are presented in the table. The radionuclides in Table A-1 were selected on the following criteria:

- 25 KeV gamma because lower energy gammas are absorbed by the housing of most detectors.
- 300 day half-life because the pipe inspection system is intended for the identification of residual radionuclides in piping and ducts in older nuclear facilities where shorter lived radionuclides will have decayed before decommissioning.
- 0.1 gamma per decay which selects those radionuclides that produce sufficient gammas per disintegration for detection.

Six decay series of radionuclides are included in Table A-1: Rh-106--Ph-106, Th-232, Pu-241--Am-241, Np-237, U-238, U-235

If activity equilibrium exists in any of the decay series, such as would be the case for the U-238 series in uranium ore, the gamma activity of any daughter product can be used to determine the activity of other members of the series. For example U-238 is an alpha emitter which would not be detected by the pipe inspection system based on its alpha emissions alone. However when U-238 is in activity equilibrium with its decay products, an activity measurement of the gammas from Bi-214 will equal the activity of its parent U-238, e.g. 150 pCi of Bi-214 indicates the presence of 150 pCi of U-238 and each of its decay products. Thus each radionuclide in the decay series listed may be detected using the characteristic gamma listed in Table A-1 providing the series is in activity equilibrium.

Table B-1. Beta-gamma emitters potentially detectable with the Pipe Explorer™ system.			
Radionuclide	Half-Life (Days)	Gamma-Line Energy (KeV)	Gamma Yield (%)
NA-22	0.9529E+03 D	511.00	179.79
NA-22	0.9529E+03 D	1274.53	99.94
AL-26	0.2630E+09 D	1808.70	99.76
AL-26	0.2630E+09 D	511.00	163.62
K-40	0.4665E+12 D	1460.80	10.67
Ti-44	0.1728E+05 D	67.85	91.00
Ti-44	0.1728E+05 D	78.38	96.60
Ti-44	0.1790E+05 D	67.88	94.40
Ti-44	0.1790E+05 D	78.34	96.20
MN-54	0.3121E+03 D	834.85	99.98
CO-60	0.1925E+04 D	1173.24	99.90
CO-60	0.1925E+04 D	1332.50	99.98
KR-85	0.1867E+00 D	151.17	75.40
KR-85	0.1867E+00 D	304.87	14.00
TC-98	0.1534E+10 D	652.41	99.75
TC-98	0.1534E+10 D	745.35	99.82
RH-101	0.4340E+01 D	306.86	94.00
RH-101	0.1205E+04 D	127.21	73.00
RH-101	0.1205E+04 D	198.00	71.00
RH-101	0.1205E+04 D	325.20	13.40
RH-102	0.2070E+03 D	475.06	39.00
RH-102	0.2070E+03 D	511.00	29.44
RH-102	0.1059E+04 D	475.06	95.00
RH-102	0.1059E+04 D	631.29	56.00
RH-102	0.1059E+04 D	697.49	44.00
RH-102	0.1059E+04 D	766.84	34.00
RH-102	0.1059E+04 D	1046.59	34.00
RH-102	0.1059E+04 D	1112.84	19.00
RH-106	0.3670E+03	—	—
PH-106 (Series)	0.3472E-03	512.00	21.00

Table B-1. Beta-gamma emitters potentially detectable with the Pipe ExplorerTM system
(Continued).

Radionuclide	Half-Life (Days)	Gamma-Line Energy (KeV)	Gamma Yield (%)
SN-126	0.3653E+08 D	26.35	15.61
SN-126	0.3653E+08 D	87.57	37.00
SB-125	0.9972E+03 D	27.20	13.20
SB-125	0.9972E+03 D	27.47	24.60
SB-125	0.9972E+03 D	427.89	29.40
SB-125	0.9972E+03 D	463.38	10.45
SB-125	0.9972E+03 D	600.56	17.78
SB-125	0.9972E+03 D	635.90	11.32
I-129	0.5735E+10 D	29.45	19.96
I-129	0.5735E+10 D	29.77	37.02
I-129	0.5735E+10 D	33.60	13.16
CS-134	0.1213E+00 D	30.97	16.70
CS-134	0.1213E+00 D	127.50	12.70
CS-134	0.7532E+03 D	569.32	15.43
CS-134	0.7532E+03 D	604.70	97.60
CS-134	0.7532E+03 D	795.84	85.40
CS-137	0.1096E+05 D	661.66	85.21
BA-133	0.1621E+01 D	31.82	15.20
BA-133	0.1621E+01 D	32.19	28.00
BA-133	0.1621E+01 D	36.40	10.20
BA-133	0.1621E+01 D	275.92	17.50
BA-133	0.3843E+04 D	30.63	35.10
BA-133	0.3843E+04 D	30.97	64.90
BA-133	0.3843E+04 D	35.00	23.30
BA-133	0.3843E+04 D	81.00	34.10
BA-133	0.3843E+04 D	302.85	18.33
BA-133	0.3843E+04 D	356.02	62.05
PM-144	0.3630E+03 D	36.85	22.10
PM-144	0.3630E+03 D	37.36	40.40
PM-144	0.3630E+03 D	42.30	15.40

Table B-1. Beta-gamma emitters potentially detectable with the Pipe Explorer™ system
(Continued).

Radionuclide	Half-Life (Days)	Gamma-Line Energy (KeV)	Gamma Yield (%)
PM-144	0.3630E+03 D	476.78	42.00
PM-144	0.3630E+03 D	618.01	98.60
PM-144	0.3630E+03 D	696.49	99.49
PM-145	0.6465E+04 D	36.85	21.50
PM-145	0.6465E+04 D	37.36	39.00
PM-145	0.6465E+04 D	42.30	14.90
PM-146	0.2020E+04 D	36.85	14.70
PM-146	0.2020E+04 D	37.36	27.00
PM-146	0.2020E+04 D	42.30	10.20
PM-146	0.2020E+04 D	453.88	65.00
PM-146	0.2020E+04 D	735.93	22.50
PM-146	0.2020E+04 D	747.24	34.00
SM-145	0.3400E+03 D	38.17	39.40
SM-145	0.3400E+03 D	38.72	71.60
SM-145	0.3400E+03 D	43.80	27.50
SM-145	0.3400E+03 D	61.22	12.15
EU-150	0.1308E+05 D	39.52	23.10
EU-150	0.1308E+05 D	40.12	41.80
EU-150	0.1308E+05 D	45.40	16.20
EU-150	0.1308E+05 D	333.97	96.00
EU-150	0.1308E+05 D	439.40	80.00
EU-150	0.1308E+05 D	584.27	52.60
EU-152	0.6667E-01 D	41.54	12.50
EU-152	0.6667E-01 D	89.85	69.93
EU-152	0.4947E+04 D	39.52	21.00
EU-152	0.4947E+04 D	40.12	38.00
EU-152	0.4947E+04 D	45.40	14.80
EU-152	0.4947E+04 D	121.78	28.40
EU-152	0.4947E+04 D	344.28	26.60
EU-152	0.4947E+04 D	778.90	12.96

Table B-1. Beta-gamma emitters potentially detectable with the Pipe ExplorerTM system
(Continued).

Radionuclide	Half-Life (Days)	Gamma-Line Energy (KeV)	Gamma Yield (%)
EU-152	0.4947E+04 D	964.13	14.34
EU-152	0.4947E+04 D	1112.12	13.55
EU-152	0.4947E+04 D	1408.01	20.87
EU-154	0.3194E-01 D	35.82	13.00
EU-154	0.3194E-01 D	41.54	14.70
EU-154	0.3194E-01 D	68.17	37.00
EU-154	0.3194E-01 D	100.88	25.00
EU-154	0.3138E+04 D	123.07	40.40
EU-154	0.3138E+04 D	722.30	20.00
EU-154	0.3138E+04 D	873.20	12.09
EU-154	0.3138E+04 D	996.30	10.34
EU-154	0.3138E+04 D	1004.76	17.90
EU-154	0.3138E+04 D	1274.51	34.40
EU-155	0.1710E+04 D	43.00	12.50
EU-155	0.1710E+04 D	86.54	32.80
EU-155	0.1710E+04 D	105.31	21.80
TB-157	0.3616E+05 D	42.31	71.00
TB-157	0.3616E+05 D	43.00	129.00
TB-157	0.3616E+05 D	48.70	51.00
LU-173	0.5004E+03 D	51.35	42.00
LU-173	0.5004E+03 D	52.39	75.00
LU-173	0.5004E+03 D	59.40	30.80
LU-173	0.5004E+03 D	78.65	11.10
LU-173	0.5004E+03 D	272.09	18.50
LU-174	0.1420E+03 D	44.68	12.40
LU-174	0.1420E+03 D	52.97	19.60
LU-174	0.1420E+03 D	54.07	34.50
LU-174	0.1420E+03 D	61.30	14.40
LU-174	0.1209E+04 D	51.35	23.80
LU-174	0.1209E+04 D	52.39	42.00

Table B-1. Beta-gamma emitters potentially detectable with the Pipe Explorer™ system
(Continued).

Radionuclide	Half-Life (Days)	Gamma-Line Energy (KeV)	Gamma Yield (%)
LU-174	0.1209E+04 D	59.40	17.40
HF-172	0.6831E+03 D	52.97	36.00
HF-172	0.6831E+03 D	54.07	63.00
HF-172	0.6831E+03 D	61.30	26.00
HF-172	0.6831E+03 D	125.82	11.00
HF-178	0.1132E+05 D	54.61	23.00
HF-178	0.1132E+05 D	55.79	40.00
HF-178	0.1132E+05 D	63.20	16.70
HF-178	0.1132E+05 D	88.87	63.10
HF-178	0.1132E+05 D	93.18	17.20
HF-178	0.1132E+05 D	213.43	81.70
HF-178	0.1132E+05 D	216.67	64.70
HF-178	0.1132E+05 D	257.64	16.70
HF-178	0.1132E+05 D	325.56	94.10
HF-178	0.1132E+05 D	426.36	96.90
HF-178	0.1132E+05 D	454.05	16.60
HF-178	0.1132E+05 D	495.02	71.40
HF-178	0.1132E+05 D	574.21	89.10
TA-179	0.6538E+03 D	54.61	13.00
TA-179	0.6538E+03 D	55.79	23.00
BI-207	0.1176E+05 D	72.80	19.70
BI-207	0.1176E+05 D	74.97	33.30
BI-207	0.1176E+05 D	84.90	14.80
BI-207	0.1176E+05 D	569.70	97.80
BI-207	0.1176E+05 D	1063.66	74.08
BI-208	0.1344E+09 D	72.80	12.32
BI-208	0.1344E+09 D	74.96	20.80
BI-208	0.1344E+09 D	2614.70	99.80
TH-229	0.2681E+07 D	85.43	16.47
TH-229	0.2681E+07 D	88.47	27.14

Table B-1. Beta-gamma emitters potentially detectable with the Pipe ExplorerTM system
(Continued).

Radionuclide	Half-Life (Days)	Gamma-Line Energy (KeV)	Gamma Yield (%)
TH-229	0.2681E+07 D	100.00	12.43
U-235	0.2571E+12 D	143.76	10.50
U-235	0.2571E+12 D	183.72	54.00
NP-237	0.7817E+09 D	29.37	13.99
NP-237	0.7817E+09 D	86.50	12.60
AM-241	0.1579E+06 D	59.53	35.90
AM-243	0.2696E+07 D	74.67	66.00
CM-243	0.1041E+05 D	99.55	14.30
CM-243	0.1041E+05 D	103.76	23.00
CM-243	0.1041E+05 D	117.00	10.80
CM-243	0.1041E+05 D	228.18	10.60
CM-243	0.1041E+05 D	277.60	14.00
CM-243	0.1063E+05 D	99.55	14.30
CM-243	0.1063E+05 D	103.76	23.00
CM-243	0.1063E+05 D	117.00	10.80
CM-243	0.1063E+05 D	228.18	10.60
CM-243	0.1063E+05 D	277.60	14.00
CM-245	0.3105E+07 D	99.55	13.61
CM-245	0.3105E+07 D	103.76	21.88
CM-245	0.3105E+07 D	117.00	10.29
CM-247	0.5698E+10 D	402.60	72.00
CF-249	0.1281E+06 D	333.44	15.51
CF-249	0.1281E+06 D	387.95	66.00
CF-251	0.3287E+06 D	104.61	15.48
CF-251	0.3287E+06 D	109.29	24.69
CF-251	0.3287E+06 D	123.00	11.73
CF-251	0.3287E+06 D	176.60	17.70
TH-232 (Series)	0.5147E+13 D	2614.00	100.00
PU-241 (Series)	0.1672E+06 D	60.00	36.00
AM-241 (Series)	0.1672E+06 D	60.00	36.00
NP-237 (Series)	0.7811E+09 D	1560.00	100.00

Table B-1. Beta-gamma emitters potentially detectable with the Pipe Explorer™ system
(Continued).

Radionuclide	Half-Life (Days)	Gamma-Line Energy (KeV)	Gamma Yield (%)
U-238 (Series)	0.1646E+13 D	609.00	47.00
U-238 (Series)	0.1646E+13 D	1120.00	17.00
U-238 (Series)	0.1646E+13 D	1764.00	17.00
U-235 (Series)	0.2591E+12 D	143.00	11.00
U-235 (Series)	0.2591E+12 D	185.00	54.00

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