DESIGN AND PERFORMANCE TESTING OF THE FIU/DOE INTERNAL/EXTERNAL PIPE CONTAMINATION ASSESSMENT SYSTEM

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ABSTRACT

The D&D of nuclear facilities will generate a large volume of pipes, structural beams, and columns that are potentially contaminated. While some are indeed heavily contaminated and are best treated as radioactive waste in the traditional manner, many of these are likely to be clean. The problem is to economically prove that they are clean. Due to the nature of these items, traditional survey techniques involving manually checking all surfaces areas with a hand probe are impossible and/or quite expensive. Since these objects have been installed, used, and removed from operation, they have irregular shapes, are covered with paint or other debris, have protrusions, and have inaccessible inner surfaces. These characteristics all make alpha/beta assay very difficult.

Canberra Industries has designed, manufactured, and tested the Mobile Internal/External Pipe Assessment System under a contract with FIU-HCET under the FETC/DOE program. The system has several unique features. Gamma detectors are used, since gamma rays are not easily absorbed. For most situations, we can now assay the inner surface of pipes, or the hidden surfaces inside welds, behind rivets or bolts, or under paint. Quantitative spectroscopy is used to identify nuclides and compare their activity to the appropriate limit. Germanium detectors are used to make accurate identification of the nuclides. Multiple Ge detectors[4] and large detectors (8 cm diameter) are used for maximum sensitivity and good performance for all contamination locations. Mathematical calculations via Canberra's ISOCS software are used to develop specific energy-efficiency calibrations for each type and size of pipe or structural element.

The pipe/object is transported on a belt conveyor thorough a shielded counting chamber containing the collimated detectors. The system can count pipes, I-beams, U-channels, L-beams, Box beams, up to 24 x 24 in. in cross section and up to 10 ft in length, and up to 7000 lb in weight. Quantitative gamma spectral assay is performed for the length of pipe corresponding to one square meter of surface. The results are adjusted using appropriate scaling factors to account for non-gamma emitters, and then compared against the USNRC RG1.86 release criteria (e.g. 1000 dpm/100 cm^2).

Some measured performance capabilities obtained during the acceptance testing are presented in the following table for 6 in. Schedule 40 pipe, moving at 3 ft/min. or 1.7 tons/hr.

Nuclide	**Contamination Location**	**Volumetric LLD (pCi/g)**	**Surficial LLD (dpm/100 cm^2)**
Cs-137	External	0.16	100
Co-60	External	0.14	46
U-238 (Th-234)	External	2.4	808
Th-232 (Ac-228)	External	0.34	125
Cs-137	Ext+Internal	0.20	61
Co-60	Ext+Internal	0.08	26
U-238 (Th-234)	Ext+Internal	2.32	724
Th-224 (Ac-228)	Ext+Internal	0.45	74

It can be seen that the performance is quite adequate for nuclides expected to be dominant from reactors several years after shutdown, for either internal or external contamination. Higher throughputs can also be used and still have acceptable performance. For Uranium/Thorium fuel facilities, external contamination is easy, while internal contamination is more difficult, but still probably economical. For Plutonium facilities (results not shown here) free-release is not practical, but the counter can be used to show that these objects are not TRU, and thus disposed as conventional radioactive waste.

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INTRODUCTION

Within the past few years there has been a great increase in actual decontamination and decommissioning (D&D) of nuclear facilities within the US DOE and at similar facilities in other countries, and at research and at commercial Nuclear Power Plants (NPP). Most all of these facilities are physically large, and have little residual value as a building after decontamination. Consequently, they are most likely to be totally demolished. Because of their large construction, there are many structural elements like I-beams, U or C channels, angles, or box beams. Because of the nature of the facility operation, there are also many pipes. These pipes and structural elements are a major part of the volume of waste, and if they must be considered radioactive, are a major D&D cost element. But, most of these items are probably not contaminated at all, or perhaps only slightly contaminated such that simple cleaning techniques will remove it. However, they generally are presumed to be contaminated simply because they are from within the nuclear facility. The common practice of hand surveying with gross alpha/beta instruments to prove that they are clean is very expensive, is not very reliable as it depends upon human perfection, is difficult to develop reliable instrument calibration factors, can be fooled by hidden or covered contamination, and generates little documentation proving to others that the results are reliable. Considering this material as contaminated is also very expensive.

The instrument described here addresses these problems with a combination of laboratory-quality nuclear assay techniques and practical automated handling techniques for the objects to be assayed. Our approach uses Germanium gamma spectroscopy to uniquely identify those radionuclides that are present, and also show those that are not. Each nuclide is quantified individually. The activity is then compared with the release limit for that nuclide. If the activity from all nuclides is acceptable, individually and as a group, then the item is considered clean. The system is completely automated. All that must be done is to feed pipes in one side, and remove them from the other.

The system described here was designed and constructed by Canberra Industries, Meriden, CT, under Contract ITB97-48 from Florida International University, Hemispheric Center for Environmental Technology. It is funded by the US DOE under the FETC program. The contract was awarded in 1998, and the system delivered September, 1999. To house the unit and protect it from the elements, it is constructed within a 20 ft ISO Sea-Land container. This also makes it easily moved between various job sites. The assay system was designed to work as a stand-alone system, for pipes/objects presumed to be clean, and also to work in conjunction with two other systems being built for HCET/FIU by others. One is a mobile cleaning unit that grit-blasts the insides and outsides of the pipes. The output of the cleaning station will feed directly into the assay system for tandem operation. The other contract is for an automated unloading unit following the assay unit to take the pipes/objects and sort them into the proper clean/contaminated pile.

DESIGN PROBLEMS AND SOLUTIONS

The most difficult part of this project lies in the requirement to demonstrate that items assayed are in compliance with the criteria Table 1. This table is now incorporated in Reg. Guide 1.86 and DOE Order 5400.5. Unfortunately, the values in this table were developed many years ago based upon the capabilities of instrumentation at that time, rather than based upon dose or risk. However, today's instrumentation is considerably different and vastly more capable. And, these regulations do not address volumetric contamination. Other organizations have addressed the release of scrap including volumetric contamination quite recently. These include IAEA[1], European Commission[2], and the US NRC[3]. All have generated volumetric contamination criteria that are reasonably consistent. Nevertheless, the parameters in Table 1 are those most common in US current use, and the ones required to be met under this contract. But, in anticipation of changes in these requirements, the instrument is also capable of meeting these future volumetric limits.

The fundamental **problem** with Table 1 is that it is a surface activity limit, not a volumetric limit. This essentially requires that the user prove that **all** surfaces meet the criteria. This includes the insides of pipes, cracks between surfaces where they join together, surfaces covered with paint or corrosion or pigeon droppings, etc. Conventional technology uses alpha and beta sensitive detectors. However, detectors are very difficult to get inside pipes, and impossible to detect activity down small fissures in cracks or welds, or between joined surfaces; complete disassembly is required. Alpha and beta radiation do not penetrate much paint or corrosion or other surface layers either, so complete removal of these surface coatings is required. Both the cleaning and disassembly steps are expensive. The **solution** is to use the gamma radiation from these nuclides. Gammas penetrate much further through mass and therefore can be much more accurately and reliably measured anywhere on, or inside, the objects, for most items. Hidden or covered contamination are unlikely to be missed. Activity inside the pipes and beams can be measured from the outside. In most situations, difficult-to-measure nuclides are correlated with easy-to-measure ones. Sometimes this is by natural decay (e.g. Pa-234m for U-238); sometimes this is by other nuclides that are known to be present (e.g. U-235 for U-238 if the enrichment is known, Am-241 for Pu-239 if the production method and age is known, Ni-63 by Co-60 in NPPs based upon 10CFR61 analysis history). These correlation factors can be introduced into the software and used for the release certification process.

Another **problem** is that Table 1 has different release criteria for different nuclides. Alpha emitters can have limits of 100, 1000, and 5000 dpm/100 cm^2. Beta emitters are present all four release categories, and have these same three limits. Which one is the correct one to use? It depends upon the nuclide. However, conventional alpha and beta detectors used for this purpose do not give any information about the identity of the nuclide generating the signal. They just record

Table 1.
Reg. Guide 1.86 Limits (relevant portions)

Radionuclide	**Average Contamination dpm/100 cm^2 averaged over an area of <1 m^2**
Transuranics, Ra-226, Ra-228, Th-228, Pa-231, Ac-227, I-125, I-129	100
Th-Natural, Th-232, Sr-90, Ra-223, Ra-224, U-232, I-131, I-133	1,000
U-Natural; U-235, U-238, and associated decay products, alpha emitters	5,000
Beta-gamma emitters (radionuclides with decay modes other than the alpha emission or spontaneous fission) except Sr-90 and others noted above.	5,000

gross counts. Those techniques that only do alpha or beta measurements have a problem deciding which release criteria are the correct ones. The **solution** is to do gamma spectroscopy on each pipe or structural shape. When done properly, the specific radionuclide will be identified. In addition, when calibrated correctly, the activity of each specific nuclide will be known for comparison to the proper limits.

One way to perform gamma spectroscopy is with NaI detectors, however they have **problem**s. They require some form of stabilization to keep from drifting with time, temperature, and count-rate. While the resolution is adequate to resolve Cs-137 from Co-60 in NPP pipes, it is not adequate to resolve Fe-59 that will also be present, and cannot address the special problems from Uranium contamination (low energy, low yield) at the low activities required to be measured here. The **solution** is to use Ge detectors. Normally these have too low efficiency to meet the requirements here, however, Canberra has recently introduce the Broad Energy Ge detector (BEGe). The BEGe is unique in the industry, as it combines in one detector a wide diameter for high efficiency, a thin entrance layer for good low energy efficiency, is not very thick for lower cost and lower background, and has good resolution at both low and high energies. Four such detectors are included.

Location of the radioactivity is a **problem**, or rather the fact that it is rarely known in advance where the radioactivity is. This causes the problem with alpha/beta hand survey techniques, in that the contamination can be easily hidden. Using gammas is part of the **solution**, as is a geometrical design which minimize the change in counting efficiency, regardless of where the contamination is located. The four detectors are located in a vertical rectangular array surrounding the object, to minimize the effects of radial non-uniformity. The mechanical adjustment allows different detector placements for the various size/shaped objects. The object is then moved horizontally through the detector array during the count cycle, minimizing the effects of linear non-uniformity.

Background is a **problem**. The instrument will be used at the D&D site, and to minimize extra labor, should be as close where the objects originate. Since it is a contaminated site, there certainly will be elevated amounts of radioactivity present at the site, thus elevating the background. To make matters worse, the radioactivity is being moved around as work is being done. It is difficult to protect against this problem. Moving the pipe monitor at a far distance increases the transportation labor. Adding external shielding is expensive. Fortunately, spectroscopy devices such as the **solution** implemented here are much more easily shielded than gross counting devices. The process of scattering gamma radiation changes its energy, and since gamma spectroscopy only examines the exact energy from the nuclide of interest, these scattered photons are not counted as part of any nuclide. Scattering a gamma takes much less shielding than completely absorbing it, which would be required by gross counting devices. Moreover, it allows the use of "shadow shields". These are partial shields that prevent straight line access to the detector from the outside world, but allow scattered access. Gross counters must have a fully enclosed shield, which complicates the process of loading/unloading of long items, as required here.

Another **problem** is that the limits in Table 1 are those for the average activity in a 1 m^2 area. Implemented within the **solution** here is a counting technique to independently assay each 1 m^2 segment of the pipe/object. Based upon the shape of the object, and the transit speed under the detectors, the computer will know when to stop one count and to immediately begin the next. The activity found (or LLD if not found) can then be compared to the appropriate limit. There is also a separate limit for removable contamination, which is lower. For most pipes/objects, it will be easy to prove that the removable contamination does not exist. Any simple cleaning process, like washing with water, will remove this material, and if this is done, it is an easy manner to prove statistically the adequacy of the process. If this cannot be done, or is not economical to do, then compliance with the removable limits averaged over 1 m^2 can be done for the Reactor nuclides, and at reduced throughput for the Uranium nuclides with external contamination.

Adequate documentation is a **problem**. Sending potentially contaminated items to the general environment is a very politically sensitive problem. The wise user will be very certain that he has met all of the requirements, and will want to maintain excellent documentation to

prove that to the regulators and other interested stakeholders. Ge gamma spectroscopy is an excellent **solution**. Each 1 m^2 segment of the pipe or structural shape will have a separate gamma spectrum stored. This record will have *every* parameter that was used for acquisition and analysis. This is a standard feature of the Canberra CAM file. Included in the file are things such as amplifier gain setting, HV settings, counts for each channel, specific analysis algorithms used, parameters for each part of the algorithm, intermediate results, and final results for each nuclide. A Ge gamma spectrum also can prove internally that it was acquired correctly. If the peaks are in the proper location, the gain is OK. If the peaks are the proper width, then the resolution is OK. If the multiple detectors agree, and if multiple lines from a nuclide agree, then the efficiency is likely to be OK. This record can (and should) be examined at the end of each day to assure that things were OK. In addition, it should be archived for examination in the future, if necessary.

Calibration of these devices to determine detector efficiency is a **problem**. Normally, this involves expensive traceable radioactive sources distributed in the exact measurement geometry. However, the **solution** included here does this all in the computer. Canberra has previously developed the *In Situ* Object Counting System (ISOCS) which includes mathematical calibration software for complex objects, like drums, pipes, boxes, discs, plates, spheres, etc. This software allows each of these geometries to be calibrated without any radioactive sources. Additional features have been added to handle the sample shapes and source distributions expected to be encountered. This means that the user can quickly create new detector/pipe/shielding configurations in the field, without the traditional time and expense of purchasing sources, distributing them in representative manner on surrogates of the object, and disposing of them as radioactive waste. The calibration accuracy is of the order of 5% for high energies and 8-10% for low energies, at 1 s.d., which is probably more accurate than can be done with conventional radioactive source techniques for these geometries. For each new geometry, creating the new calibration takes just a few minutes.

Table 1 requirements are currently a **problem**. However, the NRC recently passed a dose based residual contamination limit of 25 mRem/yr, and the DOE has indicated concurrence with that value. The codification of the DOE Orders, and the impending NRC assumption of regulatory oversight, all look promising for future incorporation of these risk/dose based release limits. These would be generally volumetric limits, i.e. expressed in pCi/g, instead of dpm/100 cm^2. The IAEA[1], the European Commission[2] and the NRC[3] have all published documents suggesting such limits. The **solution** for the future implementation of this long awaited change is built in. The assay results can be computed in pCi/g for each object or group of objects. The volumetric limits that meet the 25 mRem/yr limit are much easier to measure, and even those proposed by the NRC and others at 1 mRem/yr can generally be met. Therefore, this product should have a long technological lifetime.

It is a very difficult **problem** to have one instrument that address all the major D&D situations, and we don't have a complete **solution**, however, these situations can be classified into several groups. Reactors, like at Hanford and Savannah River, and commercial NPPs have contaminants that are generally dominated by Co-60, Cs-137, Mn-54, Co-58, Fe-59, etc., or where these nuclides are suitable surrogates for other contaminants. They are relatively easy to measure even on the inside surfaces of these pipes. Uranium processors, like Fernald, Piketon, Paducah, K-25, FUSRAP and UMTRAP sites, have various enrichments of Uranium. Uranium can be measured on the external surfaces, but at somewhat reduced throughputs on the internal surfaces. Fuel reprocessors, like at Hanford, Savannah River are very difficult to measure at free-release levels, even if the contamination is on the outside surfaces. Nevertheless, the counter is still useful as it can easily prove that this piping is not TRU, which is 10-100 times more expensive for disposal than normal radioactive waste.

THE IMPLEMENTED DESIGN

Detector: This is the key component of the system. Four Germanium (Ge) detectors are included to minimize the effects of spatial non-uniformity of the

radioactivity, although the basic design could also accommodate two for lower costs. To meet the measurement needs for reactor contamination conventional and small Ge detectors can be used. However, to provide a system that can be used for both Reactor and Uranium sites, and to measure the more difficult reactor nuclides, the new Canberra model BE5025 Ge detectors have been supplied. These detectors are 8 cm in diameter for maximum efficiency, but only 2.5 cm thick to minimize the background. Resolution is good throughout the range of use; 750 eV at 122 keV and 2200 keV at 1332 keV. The low energy carbon fiber entrance window and thin Ge dead layer on the front of the detector maximize the efficiency at low energies. Each detector is mounted in a 90° horizontal swivel arm configuration. This means that each detector can be oriented either up, sideways, or down, with the LN cryostat being outside the shield and pointing up. This makes all four detectors interchangeable.

Shielding. The detectors are surrounded by 4 in. of low radioactive content steel, or 2 in. of low background lead is some locations. Normal steel has Co-60, which could be a problem in NPP measurements, but this special steel does not. The shielding is designed so that it can accommodate either two or four detectors. The shielding fully surrounds the detectors on all sides, except for the openings to allow the conveyor to enter and exit. The total shield weight is 11,000 lb.

Counting Geometry. Detectors are placed both above and below the conveyor. The vertical adjustment allows the top detectors to be lowered to just above the pipes/objects. The lateral adjustment of the detectors allows the grouping of four to more closely "surround" the object to make the response as uniform as possible over the surface area of the object.

Sample Handling Mechanism. A heavy duty V-belt roller conveyor has been chosen. The belt width and shield opening are of sufficient size to allow objects up to 24 x 24 in. cross-section to be counted. The conveyor length is 38 ft which allows loading of one 10 ft object while counting a second one while unloading a third one. The belt material is heavy enough to support the 7000 lb design criteria weight, but thin enough to not significantly affect the efficiency of the lower two detectors. It is of common commercial design so that replacement parts can be easily obtained. Belt speed is continuously variable up to 10 fpm. Very slow speeds are done incrementally in small segments. Sensors detect the leading edge of the object and start the count. When the prescribed 1 m^2 area of the pipe has passed by the detectors, a new count is started. This continues until all of the pipe/object has been counted. After the count is complete, and after the fate of the object is decided, the computer generates a visible signal to the operator (colored lights) and a computer signal to the (future) sorter device which then diverts the object toward the good or the bad pile. Figure 1 shows a schematic view of the system without the enclosure.

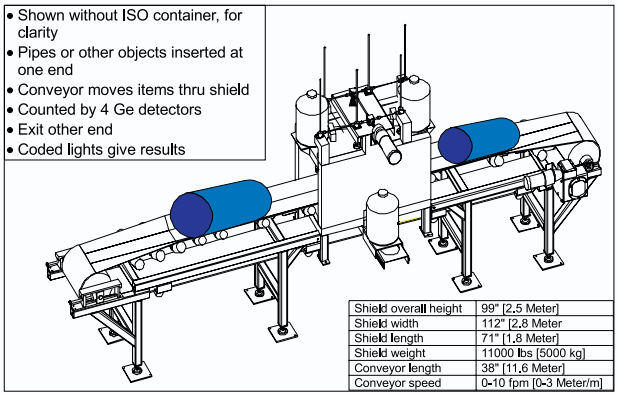

Figure 1.
Overall View of Pipe and Object Counting System

Electronics: Canberra's ICB NIM family is used. These electronics are completely computer controlled with no manual knobs to set or accidentally misadjust. Each instrument setting is stored with each analysis record for complete documentation. A high speed DEC AXP computing platform is also provided.

Spectroscopy Software: The core of the software is the Canberra Genie gamma spectroscopy software. This is in very common use throughout the nuclear industry. Special batch programs have been written to fully control the machine, analyze the data, decide the disposition of the object, and store the data.

Calibration Software: The ISOCS software[4] is included as part of the system. The ISOCS efficiency calibration methodology utilizes a factory "characterization" to define the energy-spatial efficiency

response function for the specific detector used. Here, all four detectors have been made to the same physical size, so they all have the same efficiency. The energy-space response function was determined by Canberra at the factory, using a combination of Monte Carlo (MCNP) calculation techniques and NIST traceable multi-energy radioactive calibration sources. These parameters are entered into a file delivered with the system, and used by the ISOCS software. The physical principles and parameters that apply to the interaction of photons with matter have been programmed into the ISOCS software. To create efficiency calibrations, the user first selects a basic template that approximates the configuration that has been counted. The source dimensions and construction, any shielding or collimation, and the detector location are entered into the template form. The ISOCS software then combines all of the above data to calculate an efficiency for the user-specified energies. These energy/efficiency/error triplets are then used by the Genie software to create the efficiency calibration curve used for spectral analysis. Extensive testing and validation of the ISOCS software methodology has been performed, which concludes that the calibrations generated should be accurate to within 5-10%[5].

For this project five new ISOCS geometry templates have been created to simulate the range of surface contamination expected. These include pipes, box shaped tubes, L-shaped angles, H or I shaped beams, and C or U shaped beams. Surface contamination can be placed on any or all surfaces, at any location.

Enclosure: The entire system has been placed in a modular enclosure for field operation and transport. The enclosure is a 20 ft Sea-Land ISO-Container. The enclosure houses the shield, the conveyor control electronics, the AXP computer, the detectors, and the ICB NIM electronics. There is a small work area for the operator. The conveyor enters the shield through one side of the enclosure, and exits the opposite. Figure 2 shows the plan layout of the units. Figure 3 is a photograph of the exterior showing several 12 in. diameter short pipes exiting. Figure 4 shows the interior of the container, showing the shield, and three of the four LN containers for the detectors. The electronics console is on the right out of the field of view.

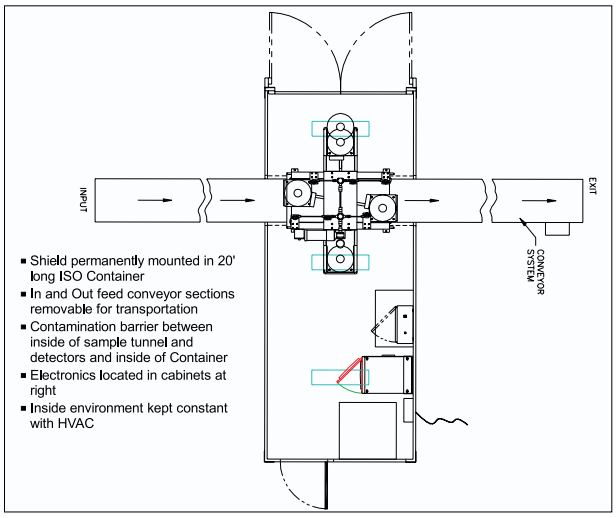

Figure 2.
Plan Layout of Unit Inside 20 ft ISO Sea-Land Container

Figure 3.
Interior of Unit

Figure 4.
Exterior of Unit with 12 in. Diameter Pipes

OPERATION OF THE UNIT

The pipes or other objects will be grouped according to type for counting campaigns. A typical campaign groupings will be 6 in. Schedule 40 pipes for internal or external reactor contamination; 6 in. Schedule 40 pipes for Uranium external contamination; 8 in. wide flange I-beams for Uranium contamination, … etc.

Each campaign will require a different computer configuration, and may require a different detector/shielding configuration. The computer configuration will be predefined by the technical staff, so that all the operator must do is define the campaign type. The detector/shielding configuration may require manual mechanical adjustments, but these can be accomplished in half hour or less by one operator.

Once the unit has started the operation is automatic. All the operator must do is feed it pipes or structural shapes. When the leading edge of the first pipe reaches the detector, the acquisition is started. When 1 m^2 of pipe has passed the detector, that acquisition is stopped and another immediately started. The analysis of the first 1 m^2 then starts and the nuclide activities are compared to the decision limits. Each next segment is counted and analyzed in turn, until the full pipe is done. This point is sensed automatically. The process starts up again when the next pipe reaches the detector. If any section of the pipe is contaminated, the pipe is considered contaminated and will be so classified. As the pipes come out the opposite end of the shield, they are associated with the good/bad logic level. This level then actuates coded lights telling an unloading operator what to do with the pipe. Alternately, the level actuates a (future) mechanical device that diverts the pipes into the appropriate pile. The pipes can be continually fed, as long as there is approximately a 2-3 ft gap between pipes.

For maximum throughput, the operation staff should consist of an operator to feed the unit. At the full throughput, this is a full time job. There also needs to be somebody to bring new feed material to the operator and remove classified material from the unit. This is probably a half time position, and he can do other things the rest of the time. Finally, there needs to be technical resource assigned. This person would perform daily QC checks, review all operations and QA data to make sure it is OK, perform calibrations and setup new campaign protocols as needed. This is estimated to be a quarter time position.

TECHNICAL PERFORMANCE

A series of computer optimizations was performed for the preliminary design of this counter. These computer simulations were used to optimize the design and then to predict the performance. These predictions are presented in the following tables. At the completion of the project, validation tests were performed, which confirmed the accuracy of the predicted performance.

Material supply companies were consulted to determine common pipe and structural element sizes that were in normal construction use 20-50 years ago. This included pipes, channels, angles, square tubes, and

Table 2.
Standard Pipe Sizes Considered for this Project

Nominal size (in.)	**6**	**8**	**8**	**8**	**8**	**10**	**16**	**24**
Schedule	**40**	**10**	**40**	**80**	**100**	**40**	**40**	**40**
Actual OD (in.)	6.625	8.625	8.625	8.625	8.625	10.75	16	24
ID (in.)	6.065	8.329	7.981	7.625	7.437	10.02	15.25	22.624
Thickness (in.)	0.28	0.148	0.322	0.5	0.594	0.365	0.375	0.688
Lb/ft length	18.97	13.4	28.55	43.39	50.93	40.48	62.58	175
Ft/m^2 surface (inside + outside)	3.26	2.47	2.47	2.47	2.47	1.98	1.29	0.86

I-beams. For each of these, the dimensions were tabulated. Then a subset was chosen for these calculations. It was determined that pipes are representative of the performance of the rest of the geometries, as they have similar outside sizes surface areas, and wall thickness' which are the important parameters here. Consequently, the design was optimized using the pipe model. Table 2 shows the parameters of pipes that were used in the design calculations.

For each of these pipes, various efficiency computations were made with differing detector sizes, different detector placement strategies, and different collimator sizes to determine the optimum configuration. The following Figures 5-7 show the predicted efficiency for the various pipe sizes and schedules.

Figure 5 shows the effect of various sizes of Schedule 40 pipe. Here the contamination is assumed to be on the inside of the pipe. Larger diameters have lower efficiency, but not by very much, and is easily accounted for by the efficiency calibration.

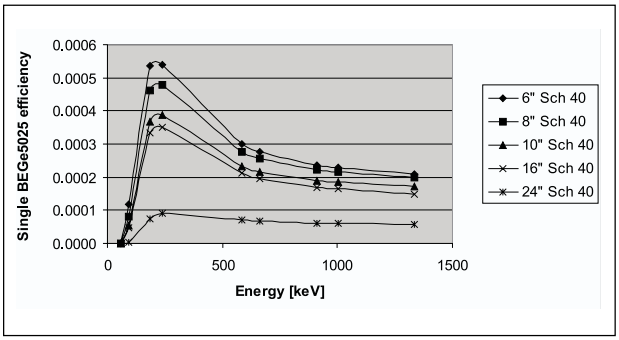

Figure 5.
Internal Contamination in Various Sizes
of Schedule 40 Pipes

Figure 6 shows the effect of various thickness' (Schedules) of the same diameter pipe. As expected, thicker pipes have lower efficiency, but since the pipe thickness is known in advance by the campaigns, proper calibrations can account for this variation.

Figure 7 shows again the same five pipes as in the first graph, but this time the contamination is on the external surface of the pipe. The improvement (compared to internal contamination) is factors of five or so at low energies, but efficiencies are nearly the same at high energies.

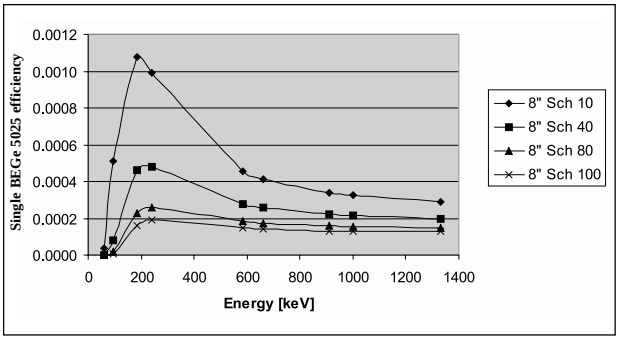

Figure 6.
Internal Contamination in 8 in. Pipes
of Various Thickness'

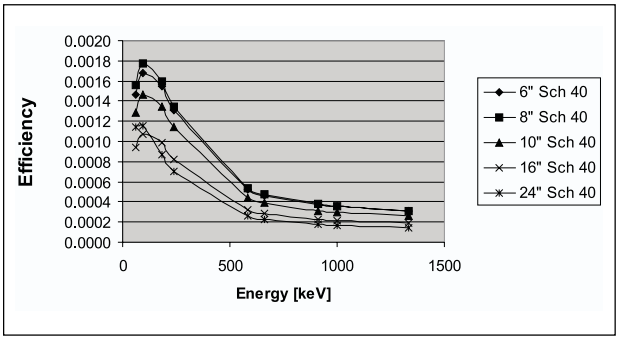

Figure 7.
External Contamination on Various Sizes
of Schedule 40 Pipes

Based upon this data, computations were performed to determine the Lower Limit of Detection (LLD) for various scenarios. The LLD was determined as the *a priori* activity giving a 5% probability of a false positive decision and a 5% probability of a false negative decision.

Table 3 shows the various gamma energies that were used, the detector FWHM at that energy, the effective photon yields, and the Table 1 value for non-removable activity for that nuclide in a 1 m^2 surface area. Effective photon yields (e.g. on Am-241, U-235, Tl-208) have an additional factor to make the activity of the surrogate nuclide equal that of the desired nuclide.

Table 4 shows the performance of the counter when used at Reactor facilities. The system can process 4-8 tons/hr (limited here by maximum belt speed). Note that in all cases the LLD values are a small fraction of the Table 1, Reg. Guide 1.86 limit. Note also, that the volumetric values are well under 1 pCi/g, which is also a very small fraction of the various proposed volumetric limits.

Table 3.
Nuclides and Energies Used, FWHM and Table 1 Limits

Nuclide Name (nuclide used)	Energy (keV)	FWHM (keV)	Effective Yield (fraction)	Table 1 Limit (dpm/100 cm²)
Pu-239 (Am-241)	60	0.8	0.036	100
U-238 (Th-234)	94	0.8	0.04	5000
U-238nat (U-235)	186	0.85	0.011	5000
Th-228 (Pb-212)	239	0.9	0.44	100
Th-228 (Tl-208)	583	1.4	0.31	100
Cs-137	662	1.5	0.86	5000
Th-232 (Ac-228)	911	1.9	0.28	1000
U-238 (Pa-234m)	1001	2	0.008	5000
Co-60	1332	2.3	1	5000

Table 4.
Reactor Configuration Performance

Pipe Size	**6 in.**	**8 in.**	**10 in.**	**16 in.**	**24 in.**	**8 in.**	**8 in.**	**8 in.**	**8 in.**	**6 in.**	**8 in.**	**10 in.**	**16 in.**	**24 in.**
Schedule	**40**	**40**	**40**	**40**	**40**	**10**	**40**	**80**	**100**	**40**	**40**	**40**	**40**	**40**
				– *Internal contamination* –							– *External contamination* –			
Count time min	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Thruput f/m*	6.52	4.94	3.96	2.58	1.72	4.94	4.94	4.94	4.94	6.52	4.94	3.96	2.58	1.72
Thruput t/hr*	3.71	4.23	4.81	4.84	9.03	1.99	4.23	6.43	7.55	3.71	4.23	4.81	4.84	9.03
LLD pCi/g														
Cs-137	0.26	0.25	0.26	0.29	0.45	0.33	0.25	0.24	0.25	0.16	0.13	0.14	0.20	0.13
Co-60	0.29	0.27	0.28	0.31	0.43	0.40	0.27	0.24	0.24	0.20	0.17	0.18	0.24	0.18
LLD dpm/100 cm² averaged over 1 m²														
Cs-137	164	178	210	234	686	110	178	263	321	97	96	116	162	199
Co-60	182	193	223	254	648	133	193	259	300	123	121	144	198	270
Fraction of 1.86 limit														
Cs-137	0.03	0.04	0.04	0.05	0.14	0.02	0.04	0.05	0.06	0.02	0.02	0.02	0.03	0.04
Co-60	0.04	0.04	0.04	0.05	0.13	0.03	0.04	0.05	0.06	0.02	0.02	0.03	0.04	0.05

** For Tables 4-6, the thruput is conservatively stated assuming that both inside and outside surfaces are potentially contaminated. If only one of the surfaces is potentially contaminated, then the thruput is approximately twice that shown.*

Table 5.
Uranium/Thorium Configuration Performance

Pipe Size	**6 in.**	**8 in.**	**10 in.**	**16 in.**	**24 in.**	**8 in.**	**8 in.**	**8 in.**	**8 in.**	**6 in.**	**8 in.**	**10 in.**	**16 in.**	**24 in.**
Schedule	**40**	**40**	**40**	**40**	**40**	**10**	**40**	**80**	**100**	**40**	**40**	**40**	**40**	**40**
				– *Internal contamination* –							– *External contamination* –			
Count time min	5.00	6.00	7.50	9.00	60.0	2.50	6.00	10.0	15.0	1.00	1.00	1.30	2.00	2.50
Thruput f/m*	0.65	0.41	0.26	0.14	0.01	0.99	0.41	0.25	0.16	3.26	2.47	1.52	0.65	0.34
Thruput t/hr*	0.37	0.35	0.32	0.27	0.08	0.40	0.35	0.32	0.25	1.86	2.12	1.85	1.21	1.81
LLD pCi/g														
U-238 (Th-234)	11.1	12.7	15.4	15.3	59.6	6.88	12.7	31.3	48.4	1.83	1.53	1.40	1.52	0.67
U-238nat (U-235)	5.75	5.30	5.23	5.17	4.72	7.74	5.30	5.41	5.32	4.80	4.08	3.67	3.94	2.11
Th-228 (Ac-228)	0.10	0.09	0.09	0.09	0.07	0.15	0.09	0.08	0.08	0.10	0.09	0.08	0.08	0.05
Th-228 (Pb-212)	0.16	0.14	0.12	0.12	0.07	0.29	0.14	0.10	0.08	0.24	0.21	0.19	0.20	0.11
Th-232 (Ac-228)	0.22	0.18	0.17	0.17	0.09	0.43	0.18	0.13	0.10	0.37	0.32	0.28	0.30	0.18
U-238 (Pa-234m)	8.04	6.77	6.14	6.17	3.21	15.94	6.77	4.67	3.77	13.8	11.9	10.6	11.2	6.76
LLD dpm/100 cm² averaged over 1 m²														
U-238 (Th-234)	6922	9049	12441	12472	90450	2295	9049	33761	61367	1143	1085	1133	1236	1022
U-238nat (U-235)	3583	3765	4222	4203	7159	2581	3765	5844	6741	2990	2896	2962	3204	3204
Th-228 (Ac-228)	63	64	71	70	102	50	64	90	98	64	63	63	68	71
Th-228 (Pb-212)	98	96	101	101	110	97	96	110	108	149	147	150	160	172
Th-232 (Ac-228)	135	130	134	136	134	142	130	138	131	229	226	229	243	271
U-238 (Pa-234m)	5013	4812	4957	5022	4863	5317	4812	5044	4781	8574	8455	8569	9124	10255
Fraction of 1.86 limit														
U-238 (Th-234)	1.38	1.81	2.49	2.49	18.09	0.46	1.81	6.75	12.27	0.23	0.22	0.23	0.25	0.20
U-238nat (U-235)	0.72	0.75	0.84	0.84	1.43	0.52	0.75	1.17	1.35	0.60	0.58	0.59	0.64	0.64
Th-228 (Ac-228)	0.63	0.64	0.71	0.70	1.02	0.50	0.64	0.90	0.98	0.64	0.63	0.63	0.68	0.71
Th-228 (Pb-212)	0.98	0.96	1.01	1.01	1.10	0.97	0.96	1.10	1.08	1.49	1.47	1.50	1.60	1.72
Th-232 (Ac-228)	0.14	0.13	0.13	0.14	0.13	0.14	0.13	0.14	0.13	0.23	0.23	0.23	0.24	0.27
U-238 (Pa-234m)	1.00	0.96	0.99	1.00	0.97	1.06	0.96	1.01	0.96	1.71	1.69	1.71	1.82	2.05

Table 5 shows the performance for the machine setup at a Uranium facility. Here the count times have been set to where the LLD is nominally at the Table 1 limits or a bit below it. Now, the throughput is much lower, especially if the contamination is on the inside. For the base comparison 6 in. Schedule 40 pipe, the system can process 0.65 fpm, or 0.37 tons/hr. The throughput goes up to 1 fpm for thinner Schedule 10 pipes, and down to 0.1 for big and/or thick pipes. However, when the contamination is on the outside surface, the situation is much better. Now, the throughput is 3.2 fpm for 6 in. pipe, dropping somewhat for larger pipes. This should address most of the suspected contaminated pipes. Most of them were not used to transport radioactive materials, but were just running through areas where external contamination was present. Although calculations have not been done, the external pipe contamination performance is believed to be the same for external contamination on structural shapes.

Table 6.
Plutonium TRU Configuration Performance

Pipe Size	**6 in.**	**8 in.**	**10 in.**	**16 in.**	**24 in.**	**8 in.**	**8 in.**	**8 in.**	**8 in.**	**6 in.**	**8 in.**	**10 in.**	**16 in.**	**24 in.**
Schedule	**40**	**40**	**40**	**40**	**40**	**10**	**40**	**80**	**100**	**40**	**40**	**40**	**40**	**40**
				– *Internal contamination* –							– *External contamination* –			
Count time min	0.50	0.50	0.50	0.50	5.00	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Thruput f/m*	6.52	4.94	3.96	2.58	0.17	4.94	4.94	4.94	4.94	6.52	4.94	3.96	2.58	1.72
Thruput t/hr*	3.71	4.23	4.81	4.84	0.90	1.99	4.23	6.43	7.55	3.71	4.23	4.81	4.84	9.03
LLD pCi/g NOTE: in the U.S., non-TRU = <100,000 pCi/g														
Pu-239 (Am-241)	8401	2 E4	5 E4	7 E4	2 E7	411	2 E4	9 E5	7 E6	6	5	5	7	3
Pu-239 (129 keV)	2 E4	2 E4	2 E4	2 E4	7 E4	7 E3	2 E4	5 E4	1 E5	1552	1303	1371	1870	1018

The last scenario presented here in Table 6 for Plutonium processing facilities. Because the Table 1 free-release limits are so low, and because the gamma yields are also very low and very weak energies, they are impossible to detect at the Table 1 limits. Nevertheless, there is a very good alternative use for this equipment. Much of this material could potentially be classified as TRU Waste. This is very expensive, because of the high costs for shipping, certification, and disposal at WIPP. The system described here could be used to prove that the material is not TRU. The cost savings from reclassifying material from TRU to non-TRU category, is much greater than the cost savings from moving material from the radioactive to the non-radioactive category. The following table shows the capability of the machine when setup at a Pu processing facility. For the internal contamination case, Pu-239 can be measured directly. For the external contamination, Am-241 is easier, although both are acceptable. It was assumed here that the material was from weapons grade Pu that had a 20-30 year Am ingrowth.

The throughputs are much like the reactor contamination situation; basically as fast as the machine will mechanically operate, for all but the thickest pipe.

COMPARISON OF PREDICTED LLDS TO MEASURED LLDS

During the Factory Acceptance Testing, several tests were done to validate the computer modeling and predictions. The first of these was to compare the ISOCS mathematical efficiency calibration against that of a radioactive source. Here, the baseline 10 ft long 6 in. diameter Schedule 40 pipe was used. A series of 1 x 1 ft thin Am-241 + Eu-152 calibration sources were wrapped around the inside of the pipe to simulate internal contamination. Then they were wrapped around the outside of the pipe to simulate external contamination. The pipe was counted as an “unknown” sample. The counting configuration was with the four BEGe detectors in a rectangular grid array, 4 in. from the top and bottom of the pipe, 6 in. horizontal separation between the top and bottom detectors. Table 7 shows the results. The comparisons were within 25% of the calibrated value, which is good agreement, considering the propagated errors from counting, calibrations, standard activity, and source configuration.

Next, tests were performed to see if the predicted LLD values were met. Here, the blank baseline 10 ft long 6 in. diameter Schedule 40 pipe was used. Conveyor speed was set at 3 fpm, one of the contract specifications. The counting time for a 1 m^2 segment for internal (only) contamination was 129 seconds, at this speed.

Table 7.
Project Validation of ISOCS Calibration Method

Location	Nuclide	Activity (μCi)		Ratio
		Measured	Known	Measured/Known
External	Am-241	98	106	0.92
External	Eu-152	17	17	1.0
Internal	Am-241	128	106	1.20
Internal	Eu-152	21	17	1.17

The predicted values were generally at some other count time, but were converted to the measured count time. In general, the LLDs predicted during the proposal phase were within a factor of 1.5 of the actual measured values when the project was completed, as shown in Table 8.

ECONOMICS CALCULATIONS

To estimate the operations costs of the device proposed herein, the following conditions were used. These are believed to be realistic estimates, but are based upon good operating conditions and adequate supply material.

Capital investment A cost was computed to purchase a second unit like the one proposed here. The development and testing costs of this first unit were not included. The cost was depreciated over 10 years, with zero residual value.

Cost of Capital A simple model assuming annual 5% interest on half of the principal was used.

Maintenance Costs The price of a service contract was used to account for all routine and non-routine costs.

Consumables They are only electricity and Liquid Nitrogen, office supplies and are negligible.

People to operate and support the unit

operator full time, Salary + Overhead = $75K/yr, used full time on this project.

material handler to bring/remove pipes, Sal + OH = $50K/yr, used half time on this project.

technical resource, Sal + OH = $100K/yr, used quarter time on this project.

Table 8.
Measured LLDs and Comparisons to Predictions

Nuclide	Contamination Location	Measured LLD dpm/100 cm^2	Predicted (converted to same count time)	Ratio (P/M)
U-238 (Th-234)	External only	808	780	1.0
U-238 (Pa-234m)	External only	4498	5847	1.3
Th-228 (Pb-212)	External only	157	102	0.7
Th-232 (Ac-228)	External only	125	156	1.3
Co-60	External only	46	59	1.3
Cs-137	External only	100	46	0.5
U-238 (Th-234)	Internal+External	724	n/a	n/a
U-238 (Pa-234m)	Internal+External	2642	n/a	n/a
Th-228 (Pb-212)	Internal+External	108	n/a	n/a
Th-232 (Ac-228)	Internal+External	74	n/a	n/a
Co-60	Internal+External	26	n/a	n/a
Cs-137	Internal+External	61	n/a	n/a

Training Required A technical resource must be available periodically that knows gamma spectroscopy, QA/QC procedures, how to setup the system, how to interpret reports, and how to do normal adjustments. This is typically a 3-4 week training period assuming basic physics and chemistry knowledge. Operator training is approximately 1-2 weeks.

Site setup Approximately 4 d with two people to offload from transport vehicle, connect to site power, setup the conveyors, install electronics from shipping to use configuration, and test things out. Preparation for shipping is half that.

Design Life 10 years.

Production Rate Assume the operator has an adequate supply of pipes or objects. Assume that the operator can feed material at a 3 ft gap between objects. Assume 10 ft objects are the nominal object to be counted. This reduces the machine throughput to 0.77 of the value shown in the LLD computation tables. Ten productive working hours per day are assumed for the operator, and a proportional amount for the rest of the crew. 150 productive days per year are assumed. This totals 1500 productive hours per year, which also allows adequate time for non pipe-counting tasks and down time. Table 9 shows the production rates expected.

Table 10 shows the annual amortized operating costs and the processing costs for Reactor contamination monitoring, for external contamination monitoring at Uranium facilities, and for external or bulk contamination monitoring to prove that items are not TRU. Note that the processing costs here are very favorable when compared to the nominal $500/ton radioactive waste disposal costs.

For a fair economic comparison to other systems not using gamma spectroscopy, the costs for removing surface coatings and the cost to remove all projections should be considered.

Table 9.
Expected Production Rates for 6 in. Schedule 40 Pipe

Type of Facility	Counting Speed (fpm)	Processing Rate (ton/hr)	Annual Production (lineal ft)	Annual Production (tons)
Uranium Ext contamination	3.3	0.77	228,000	4,100
Reactor Ext or internal	6.5	0.77	450,000	4,300
Pu Facility Ext contamination	6.5	0.77	450,000	4,300

Table 10.
Expected Operating Costs

	Range of Costs
Annual Operating Costs	132-164 $K/yr
Linear Processing Costs	0.32-0.72 $/ft
Massemetric Processing Costs	30-38 $/ton

CONCLUSION

The system has been completed, tested, and delivered. The completion was on schedule. The testing indicated that the mathematical calibration software included with the system performs correctly, and that the LLDs on the as-built system were essentially as predicted. The unit can successfully count pipes and other objects like structural beams, and demonstrate compliance with Regulatory Guide 1.86 criteria for Reactor contamination and for external Uranium/Thorium contamination. The LLDs for volumetric contamination are also quite compatible with those suggested by EC, IAEA and NRC (draft) for free release for most common D&D nuclides. The amortized operating cost is approximately $40 per ton (of nominal 6 in. pipe). As of this writing, the unit was awaiting the first demonstration deployment at a Nuclear Power Plant undergoing decommissioning.

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