Volume 2: Task 2.2

Radiological Instrumentation Assessment
for King County
Wastewater Treatment Division

August 2005

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Pacific Northwest National Laboratory
Richland, Washington 99352

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Executive Summary

Staff of the King County Wastewater Treatment Division (WTD) have concern about the aftermath of a radiological dispersion event (RDE) leading to the introduction of significant quantities of radioactive material into the combined sanitary and storm sewer system in King County, Washington. Radioactive material could come from the use of a radiological dispersion device (RDD). RDDs include "dirty bombs" that are not nuclear detonations but are conventional explosives designed to spread radioactive material (National Council on Radiation Protection and Measurements (NCRP) 2001). Radioactive material also could come from deliberate introduction or dispersion of radioactive material into the environment, including waterways and water supply systems.

This document, Volume 2 of PNNL-15163, is an assessment of the radiological instrumentation needs for detection of radiological or nuclear terrorism in support of decisions to treat contaminated wastewater or to bypass the West Point Treatment Plant (WPTP) and in support of radiation protection of the workforce, the public, and the infrastructure of this publicly-owned treatment works (POTW).

Two broad categories of scenarios were considered in Volume 1. The first category includes events that may be suspected from the outset, such as an explosion of a dirty bomb in downtown Seattle. The explosion would most likely be heard, but the type of explosion (e.g., natural gas, industrial explosion, or terrorist RDD) may not be immediately known. Emergency first responders must be able to quickly detect the radioisotopes previously listed, assess the situation, and deploy a response to contain and mitigate (if possible) detrimental effects resulting from the incident. In such scenarios, advance notice of 3 to 4 hours might be available before any contaminated wastewater reaches a treatment plant.

The second category includes events that could go initially undetected by emergency personnel. Examples of such a scenario include the inadvertent or surreptitious introduction of radioactive material into the sewer system. Intact rogue radioactive sources from industrial radiography devices, well-logging apparatus, or moisture density gages may get into wastewater and be carried to a treatment plant. Other scenarios include a terrorist deliberately putting a dispersible radioactive material into wastewater. Alternatively, a botched terrorism preparation of an RDD may result in radioactive material entering wastewater without anyone's knowledge. Drinking water supplies, bottled or packaged beverages, and foodstuffs may also be contaminated, with the result that some or most of the radioactivity ends up in wastewater. In some of these scenarios, the first evidence that an incident has occurred may be detection of radioactive material in wastewater.

Fixed radiation detection instrumentation should be deployed in a defense-in-depth system that provides 1) early warning of significant radioactive material on the way to the WPTP, including identification of the radionuclide(s) and estimates of the soluble concentrations, with a floating detector located in the wet well at the Interbay Pump Station and telemetered via secure wideband communications to all authorized locations, 2) monitoring at strategic locations within the plant, including

    a) the pipe beyond the hydraulic ram in the bar screen room
    b) above the collection funnels in the fine grit facility
    c) in the sampling tank in the raw sewage pump room
    d) downstream of the concentration facilities that produce 6% blended and concentrated biosolids.

Engineering challenges exist for these applications. Explosion-proof, corrosion resistant housings and temperature compensation must be designed for detectors. Cable-length challenges may exist for delivering power to detectors and retrieving required signals out of potentially explosive and corrosive environments. It will be necessary to engineer floating detectors that cannot become dams or become excessively fouled with grease between reasonable service intervals, and that can rise and fall with varying wastewater levels and flow rates. It is also necessary to deploy both ultra-sensitive detectors to provide early warning and identification and detectors capable of functioning in high-dose rate environments that are likely under some scenarios, capable of functioning from 10 microrems per hour (background) up to 1000 rems per hour, a full eight orders of magnitude (a factor of 100,000,000). While such instrumentation exists for other applications, all of this engineering will require deploying prototypes and perhaps dealing with unforeseen complications.

Software supporting fixed spectroscopic detectors would be developed to provide prompt, reliable, and simple interpretations of spectroscopic outputs that are of use to operators and decision-makers. Software to provide scientists and homeland security personnel with sufficient technical detail for identification, quantification, waste management decisions, and for the inevitable forensic and attribution needs must be developed. Such software is not an off-the-shelf product as of March 2005 but it is expected that, with sufficient resources and collaboration between government agencies, scientists, and vendors, it can be specified and developed within two years or less.

Computational modeling using the Monte Carlo N-Particle (MCNP) software has demonstrated that useful detection capabilities can be deployed. In particular, any of the isotopes examined can be detected at levels between 0.01 and 0.1 microcurie (μCi) per gallon. Thus, a 1 Ci source dissolved in 10 million gallons of water could be detected within minutes.

In addition to fixed instruments, general purpose instruments that can be used to determine the nature and extent of radioactive contamination and measure radiation levels for purposes of protecting personnel and members of the public should be available to WTD personnel. One or more portable radioisotope identifiers (RIIDs) should be available to WTD personnel. Small, portable battery-powered personal radiation monitors should be widely available to WTD personnel. The personal monitors can be used for personal and group radiation protection decisions, and to alert management to the need to get expert backup.

All uses of radiological instrumentation will require training and periodic retraining of personnel, as well as periodic calibration and maintenance of instruments. Routine "innocent" alarms will occur due to medical radionuclides that are legally discharged into sanitary sewers on a daily basis. Innocent alarms may also be triggered by WTD workers who have recently been treated with medical radioisotopes. Instrumentation must provide signals that distinguish between routine medical discharges and off-normal occurrences that are due to malicious acts or undetected accidents. Operators and others who deal with instrument signals must be prepared to deal with innocent but real alarms, while being vigilant for alarms indicating malicious or other serious discharges.

It is recommended that the King County Wastewater Treatment Division seek Homeland Security resources to become the model POTW in the U.S. to design, deploy, and test such radiological instrumentation.

Contents

Figures

Tables

Abbreviations

ANSI	American National Standards Institute
Bq	becquerel (1 nuclear transition per second)
CdZnTe	cadmium zinc telluride [detector]
Ci	curie (3.7×10^{10} nuclear transitions per second)
cps	counts per second
FWHM	full width at half maximum
gal	gallon
GEB	Gaussian energy broadening
GM	Geiger-Müller [detector]
GPS	global positioning system
HPGe	high-purity germanium
IND	improvised nuclear device
MCNP	Monte Carlo N-Particle [computer code]
mg	milligram
mrem	millirem
NaI(Tl)	thallium-doped sodium iodide [detector]
NCRP	National Council on Radiation Protection and Measurements
PNNL	Pacific Northwest National Laboratory
POTW	publicly-owned treatment works
PVC	polyvinyl chloride
RDD	radiological dispersion device
RDE	radiological dispersion event
RIID	radioisotope identifier
RPM	radiation portal monitor
SCADA	Supervisory Control and Data Acquisition
TBq	terabecquerel (10^{12} Bq; 1 Ci = 0.037 TBq)
UPS	uninterruptible power supply
VAC	volts (alternating current)
WPTP	West Point Treatment Plant
WTD	Wastewater Treatment Division

1.0   Introduction

> *In the United States there are no identified cases in which radioactive materials in sewage systems are a threat to the health and safety of publicly-owned treatment works (POTW) workers or the general public. However, there have been a small number of facilities where elevated levels of man-made radioactive materials were detected. Based upon this past experience, there is a concern that radioactive material could concentrate in sewage sludge and ash and could pose a threat to the health and safety of workers or the public.*
> (Interagency Steering Committee on Radiation Standards 2003).

Staff of the King County Wastewater Treatment Division (WTD) have concern about the aftermath of a radiological dispersion event (RDE) leading to the introduction of significant quantities of radioactive material into the combined sanitary and storm sewer system in King County, Washington. Radioactive material could come from the use of a radiological dispersion device (RDD). RDDs include "dirty bombs" that are not nuclear detonations but are conventional explosives designed to spread radioactive material (National Council on Radiation Protection and Measurements (NCRP) 2001). Radioactive material also could come from deliberate introduction or dispersion of radioactive material into the environment, including waterways and water supply systems.

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Volume 1 of PNNL-15163 (Strom 2005) reviewed the basics of radiation, radioactive material, and radiation protection. Two broad categories of scenarios were considered in Volume 1. The first category includes events that may be suspected from the outset, such as an explosion of a dirty bomb in downtown Seattle. The explosion would most likely be heard, but the type of explosion (e.g., natural gas, industrial explosion, or terrorist RDD) may not be immediately known. Emergency first responders must be able to quickly detect the radioisotopes listed in Volume 1 (^{60}Co, ^{90}Sr, ^{137}Cs, ^{192}Ir, ^{226}Ra, plutonium, and ^{241}Am), assess the situation, and deploy a response to contain and mitigate (if possible) detrimental effects resulting from the incident. In such scenarios, advance notice of 3 to 4 hours might be available before any contaminated wastewater reaches a treatment plant.

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Pacific Northwest National Laboratory (PNNL) staff made two visits to WTD facilities serving downtown Seattle and points north to determine strategic locations for fixed detector placement, and to refine the radiological risk assessment (Volume 1 of PNNL-15163, Strom 2005, referred to as "Vol. 1 in

this report). Engineering constraints on detector design and locations were determined. Vendors were contacted to discuss the availability of the types of equipment required. Monte Carlo calculations were performed to predict detector capabilities. Needs and uses of portable radiation detection equipment available on the state of Washington approved equipment list were assessed.

While Volume 1 covered only briefly the event of the detonation of an improvised nuclear device (IND), accidents at nuclear reactors or sabotage of spent nuclear fuel shipment, the instrumentation described in Volume 2 has significant capabilities for responding to such events.

2.0   Types and Features of Radiation Measuring Instruments

This section provides background information on instruments that are of interest in the context of detecting and responding to radiological terrorism. It is important to recognize that RDEs can be silent, that is, radioactive material is silently and secretly dispersed via deliberate contamination of food, beverage, water, air, crops, or elsewhere in the environment. This possibility requires special detection and identification capabilities.

Instruments are grouped into four categories: instruments that detect radiation, instruments that measure radiation levels and amounts (dose-rate and dose), instruments that identify radioisotopes, and instruments that can measure how much of a radioisotope is present (activity or activity concentration).

2.1 Instrument Capabilities

Various kinds of detector and associated electronics have particular strengths and weaknesses. In the sections that follow, instruments are categorized as having

- high sensitivity for rapid detection
- good accuracy for measurement of radiation levels
- capability to function in and measure intense radiation levels
- capability to identify radioactive materials, or
- capability to measure the activity of known radioactive materials.

2.1.1 High Sensitivity for Rapid Detection

Some instruments, such as those employing Geiger-Müller (GM) detectors, are very sensitive to alpha, beta, and gamma radiation. With modest training, users of such instruments can distinguish among the three types of radiation. However, GM detectors are much less suitable for accurate measurement of radiation levels.

Other instruments, like the radiation "pagers" used by law enforcement agencies, are quite sensitive to gamma radiation, are small, portable, rugged, and have long battery life. Some have built-in alarming capability to warn the user when a certain radiation level is exceeded. They, too, are not accurate for measurement of radiation levels, and should not be relied on for that purpose.

Detectors employing large volume plastic scintillators, such as the radiation portal monitors (RPMs) that are deployed at U.S. land border crossings, are extremely sensitive to gamma radiation, but have very limited capabilities for identifying which radioactive material is emitting the radiation. Such detectors also have significant neutron detection capabilities for the detection of special nuclear materials that have the potential to be used to make an improvised nuclear device (homemade atomic bomb).

As of March, 2005, development of highly sensitive RPMs with spectroscopic capability is underway in the U.S. and elsewhere.

2.1.2 Accurate Measurement of Radiation Levels (Radiation Dose Rates)

Portable instruments are available for the accurate measurement of radiation levels (radiation dose rates) from a variety of gamma and x radiation sources, in units such as millirems per hour (mrem/hour) or

rems/hour. Such instruments are generally of the air ionization type, or use a plastic scintillator coupled to a photomultiplier tube.

2.1.3 Measurement of Intense Radiation Levels

Under one of the scenarios in Vol. 1, it is possible that radioactive material in the form of pellets of ^{60}Co may reconcentrate at one or more locations in the system. Also, an intact radioactive source of high strength (high activity), such as an industrial radiography source or brachytherapy source, may find its way into the system. In particular, reconcentration may occur in the grit facility or the rock box in the bar screen room. Such an event could lead to dangerously high radiation levels requiring prompt local evacuation to at least 100 feet away.

2.1.4 Identification of Radioactive Material

Characteristics of radionuclides of concern are listed in **Table 1** (reproduced from Vol. 1). These are of particular interest because they are plentiful in relatively large amounts. Half-lives and principal radiation types are shown. The "D-values" are internationally-recognized "dangerous" amounts of these radionuclides (International Atomic Energy Agency (IAEA) 2003) in units of curies or terabecquerels (TBq), where 1 Ci = 0.037 TBq. For the most common chemical forms of these radionuclides, note the incredibly small mass associated with a dangerous amount of radioactivity. As shown in the last three columns, these radioactive materials may have industrial, medical, or defense uses.

Table 1. List of radionuclides of concern. Some emit more than one kind of radiation. D-values are threshold values for dangerous amounts in curies, terabecquerels, and milligrams (mg) if the radionuclide is not diluted with non-radioactive material. Use or origin indicates where the radionuclides may be in use.

Radionuclide	Symbol	Half-life	Radiation			D-value			Use or Origin		
			alpha	beta	gamma	Ci	TBq	mg	Industrial	Medical	Defense
cobalt-60	^{60}Co	5 years		β	γ	0.8	0.03	0.7	x	x	
strontium-90	^{90}Sr	28 years		β		30	1	450	x	x	
molybdenum-99	^{99}Mo	66 hours		β	γ	8	0.3	0.017		x	
iodine-131	^{131}I	8 days		β	γ	5	0.2	0.04		x	
cesium-137	^{137}Cs	30 years		β	γ	3	0.1	44	x	x	
iridium-192	^{192}Ir	75 days		β	γ	2	0.08	0.2	x	x	
radium-226	^{226}Ra	1600 years	α	β	γ	1	0.04	1,000	x		
uranium	U	4.5 billion years	α	β	weak			-	x		x
americium-241	^{241}Am	432 years	α		γ	2	0.06	580	x		x
plutonium	Pu	24,000 years	α	β	weak	2	0.06	-	x		x

Identification of various radionuclides, such as ^{60}Co, ^{90}Sr + ^{90}Y, ^{137}Cs, ^{192}Ir, ^{226}Ra, ^{239}Pu, and ^{241}Am requires gamma spectroscopy equipment, usually based on sodium iodide (NaI) detectors, high purity germanium (HPGe) detectors, cadmium zinc telluride (CdZnTe) detectors, or other solid-state or scintillation detectors. The outputs of such detectors are fed into multichannel analyzers that provide "color vision" for gamma and x radiation. Each radionuclide listed above has a particular gamma signature that is identifiable by gamma spectroscopy. The gamma signatures are distinct from those of common medical radionuclides like ^{67}Ga, ^{99m}Tc, ^{99}Mo, ^{131}I, and ^{201}Tl. The ^{90}Sr+^{90}Y pair, while not emitting gamma radiation, does produce some x radiation that can be detected using gamma spectroscopy equipment.

Some radionuclides, such as ^{238}Pu, emit virtually no gamma radiation and very little x radiation, and can only be detected by their emissions of α-particles. Such radionuclides are only hazardous if inhaled or ingested, and are not likely to affect health of WTD workers.

2.1.5 Measurement of Amount (Activity) or Concentration (Activity per Unit Volume) of Radioactive Material

One must know what radioactive material is present in order to measure the activity (in curies, Ci; or becquerels, Bq; see Volume 1) or volume concentration (in curies per gallon, Ci/gal; or becquerels per cubic meter, Bq/m^3) of a radioactive material. Additionally, one must know where the material is with respect to the detector. If the sample to be measured is in a small vial, one can put it on or near a detector and have a good idea what the geometric efficiency is. On the other hand, if the sample is dissolved or suspended in a large volume of water, sensitivity is significantly diminished for a detector near the surface. For a dispersed sample, surrounding a detector with it provides the best compromise for maximizing sensitivity for measuring the activity or volume concentration of a radioisotope

2.2 Standards

Radiation detection instruments should meet applicable standards, such as the recent ANSI N42 series (American National Standards Institute (ANSI) 2004a; 2004b; 2004c; 2004d).

2.3 Portability

Radiation detection instruments can be made to be portable, "luggable," or require fixed installation. Radiation pagers can be clipped to a belt or hand-held. Other survey instruments are hand-held, such as a "pancake" GM detector connected to a hand-held ratemeter or scaler. Still others, such as hand-held radioisotope identifiers (RIIDs), are more appropriately termed luggable, since their weight and size make them a burden for use over an 8-hour day.

Portability is not of interest for fixed-installation instruments that function as remote detectors.

2.4 Power and Battery Life

Some instruments require standard 117 VAC electric power, while others may operate on rechargeable or disposable batteries.

Instruments requiring computers, such as gamma spectroscopic systems, should have uninterruptible power supplies (UPSs) that can power the system during brief power outages.

2.5 Protection from Radioactive Contamination and Capability to Be Decontaminated

Radioactive contamination is just like any other kind of dirt, with the additional property of being radioactive. If radiological instruments become contaminated with radioactive material, that is, dirty, they will continuously sense the presence of the radioactive material on the instrument, raising the background indication of the instrument.

In a wastewater environment, there may also be biohazardous materials present that can contaminate an instrument.

Thus it is vitally important to keep instruments, and any detectors attached to them, free of radioactive contamination. This may be done by using plastic sheaths or other removable or strippable coatings.

2.6 Operating Environment Limitations

Instruments for permanent placement in WTD facilities, such as a wet well, bar screen room, raw sewage pump room, fine grit facility, or biosolids facility, may need to be housed in waterproof, explosion-proof, corrosion resistant housings. Temperature stability of detectors can be addressed by insulation and installation of low-power thermostatically-controlled heaters to keep temperature constant and above operating facility temperature.

Instrument housings in contact with wastewater must be durable and easily cleaned of layers of grease or other material that may build up.

2.7 Cable Length

The length of cabling for power, control, and data is a critical problem for instrumentation located in explosive, corrosive, or wet areas. Currently, options are being explored to manage this problem.

2.8 Telemetry

Some of the output information for fixed instrumentation may be amenable to transmission via a Supervisory Control and Data Acquisition (SCADA) system, but secure wideband communications capability to interface through a hardware firewall with the Internet would be highly desirable, permitting authorized personnel at remote locations to access, read out, diagnose, and control the systems.

GPS capability for portable systems would be highly desirable for coordinating and managing data in the aftermath of an RDE.

2.9 Readouts, Displays, Alarms

The various categories of instruments described in Section 2.1 have a variety of readout, display and alarm capabilities. Ideally, readouts would be very simple and would lead to pre-determined actions. There are opportunities for development of software and systems that minimize the need for advanced training in radiological matters.

2.10 Calibration

All radiation detection instruments must be periodically calibrated. Most portable instruments should be calibrated every 6 months, and tested on various ranges. Spectroscopic instruments should have energy calibrations and tests with a calibration source at least every 6 months. Calibration is needed whether instruments are in use or not.

2.11 Operational Checks

All portable instruments should be put through daily operational checks with a small radioactive check source each day they are used. Permanently-installed radiation detectors should be checked on a periodic basis. The period for such checks depends on the ease of getting to the instrument to perform the checks and the expected reliability of the instrument in its environment.

2.12 Maintenance

Routine maintenance includes recharging of rechargeable batteries, and replacement of disposable batteries.

For fixed instruments, inspection of cables and detector condition will be required at intervals to be determined from experience.

2.13 Operator Training

Operator training must cover routine checks and routine maintenance (e.g., changing batteries and cleaning), operation, and interpretation of readouts and information, as well as decisions that must be made based on instrument results. Operators need to be trained in contamination control and in decontaminating instruments and detectors that become contaminated.

3.0   How Radiological Instruments Can Support King County WTD's Mission

Radiological instruments can serve the following functions:

- provide early warning of significant radioactive material in wastewater on its way to the WPTP
- provide nearly real-time warnings within the plant of material that was not detected prior to reaching the plant
- identify the radionuclides at various locations in interceptors and in the WPTP
- determine the volume concentration (Ci/gal or Bq/m^3) in wastewater
- determine the activity in rocks, grit, rags, and biosolids
- measure the radiation levels that workers or members of the public may be exposed to
- warn workers of significantly elevated radiation levels
- measure doses to workers, equipment, and microbes.

3.1 Provide Early Warning

Given notification an hour before contaminated wastewater arrives at the WPTP, operators can decide whether to bypass the plant or treat the contaminated water. Treating may be the best option in some cases, and these will be outlined in the Radiological Emergency Response Plan. If the decision is made to treat, then there are options that may arise depending on what radionuclides are involved.

3.2 Provide Nearly Real-time Warnings within the WPTP

Instrumentation within the plant may be very much more sensitive than instrumentation deployed in a wet well upstream of the plant. Nearly real-time warnings may arise from various locations within the plant, including the rock box, rags waste stream, grit facility, raw sewage pump area, and the thickened, blended sludge piping. Each path or wastestream can lead to different radiological conditions that may expose workers, and different risk management decisions concerning how to manage a particular waste stream.

3.3 Identify Radionuclides

Identification of radionuclides can lead to decisions to bypass or treat, and to invoke other options for waste management and worker protection. It also alerts other public agencies to the specific nature of a potential radiological problem.

3.4 Determine Volume Concentrations and Activities

Waste management decisions will depend on the activity and concentration of radioactive materials in various waste streams, and enable managers to predict dose rates and radiation hazards to workers and the public.

3.5 Measure Radiation Levels (Dose Rates)

Direct radiation measurements will facilitate worker protection and enable managers to cordon off areas to all but essential personnel, and limit stay times in areas with high radiation levels. Additionally, dose rate measurements are needed to plan recovery operations.

3.6 Warn Workers of High Radiation Levels (Dose Rates)

In conjunction with fixed location instruments, alarming personal dosimeters can help keep workers' doses as low as reasonably achievable while permitting them to work confidently in areas of low radiation hazard.

3.7 Help with Forensics and Attribution

If an RDE is the result of criminal or malicious actions, law enforcement and radiation regulatory agencies will immediately get involved. All of the radiation measurement results from fixed and portable instruments will be needed to assess the problem and guide investigations.

3.8 Recording of Doses to Workers, Public, and the Environment

Having radiation measurement results available, recording them, and communicating them can help manage fear and enhance peace of mind. Doses received on the job may later become a subject of litigation, and having measurement records will inevitably help with this problem

4.0   Detection Capabilities of Fixed Radiological Instruments

Computational research was performed to simulate the photon response of two configurations of fixed thallium-doped sodium iodide NaI(Tl) scintillation detectors to radionuclides suspended in wastewater for the purpose of determining concentrations that could be detected above background for a variety of medical and industrial radionuclides.

4.1 Detectors Modeled

Two thick crystal types, the 2 inch by 2 inch (2×2) and 3 inch by 3 inch (3×3) with a right circular cylinder geometry, are chosen due to availability, ruggedness, and overall energy response. Two different detector locations are also considered. The first has the detector sealed in a polyvinyl chloride (PVC) pipe and submerged in the contaminated water. The second has the detector sealed in PVC then surrounded by a rubber buoy and floated atop the contaminated stream.

The response of the detectors to various radionuclides was simulated using the Monte Carlo N-Particle (MCNP) computer code versions MCNP-5 (X-5 Monte Carlo Team 2004) and MCNP-X (Hendricks et al. 2005). These computer codes allow the accurate simulation of the radiation interactions with the NaI(Tl) and the surrounding environment. Not included in the simulation is the response of the associated detector electronics (e.g., photomultiplier tube and multichannel analyzer).

1.1   4.2 Sampling Geometry Descriptions

Each of the NaI(Tl) detectors, 2×2 and 3×3 are represented in MCNP as simple right circular cylinders. The NaI(Tl) material is then surrounded by thin (0.5 mm) aluminum on the front and sides with 1-inch at the back to represent the effect of the photomultiplier tube on the incident radiation. This description is based on the specification of Canberra model 802 (www.canberra.com) detectors.

Surrounding the aluminum clad detectors is a 0.25-inch thick 4-inch diameter PVC to seal the detectors from intrusion of water. This configuration with be referred to as the detector unit.

The detector unit is then placed in two separate scenarios. The first has the detector unit submerged in water contained in a small PVC box, modeled after the sampling station in the raw sewage pump room at WPTP, shown in Figure 1. The box that was modeled was made of 1/2 in. thick PVC, 30 in. high, 22 in. wide, 11 in. thick, with a water depth of 24.5 in. The sampling box and detector is graphically represented in Figure 2 and in several views in Appendix A.

The second scenario places the detector unit within a 60-cm (2-foot) diameter 1-inch thick spherical rubber buoy that could be floated in the wet well at the Interbay Pump Station, shown in Figure . This buoy allows the detector unit to float on top of the contaminated stream. This is graphically represented in Figure 4

Figure **4.** Cross section of model of floating detector. Dark blue is NaI(Tl), yellow is water, light blue is rubber, green is PVC, magenta is aluminum. . It is recognized that in a fielded device, part of the buoy would reside under the water. For this initial study assuming that the entire buoy is above water is a conservative assumption. The water below the floating buoy detector was taken as a cylinder with a 60 cm radius and 60 cm deep.
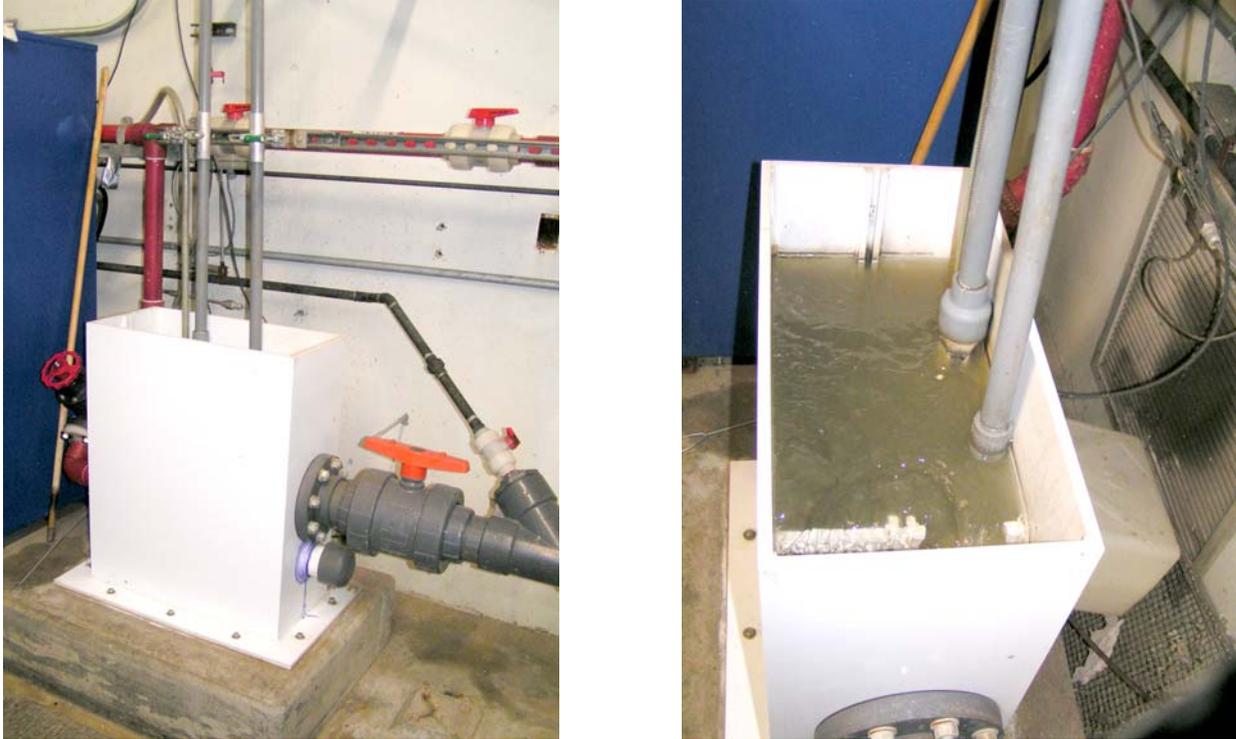
 Figure 1. Sampling box in WPTP raw sewage pump room. Left: Side view, right: Looking downward into the wastewater with the overflow near the bottom of the picture.

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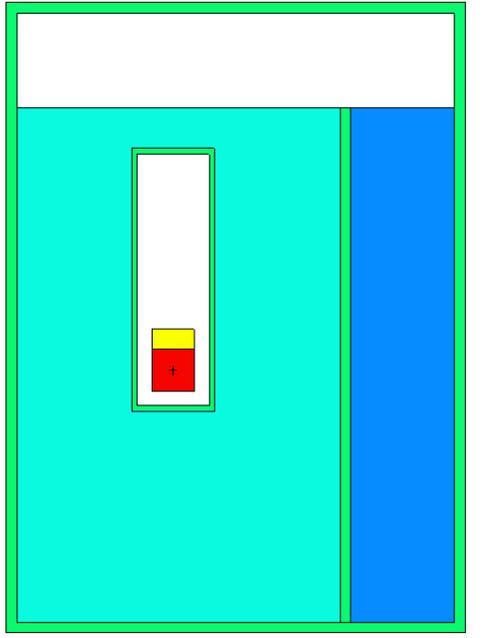
Figure 2. Sampling box detector setup for MCNP modeling. Red is NaI(Tl), green is PVC, light blue is water, and dark blue is foamy water at 50% density spilling over the overflow, white is dry air, yellow is aluminum.
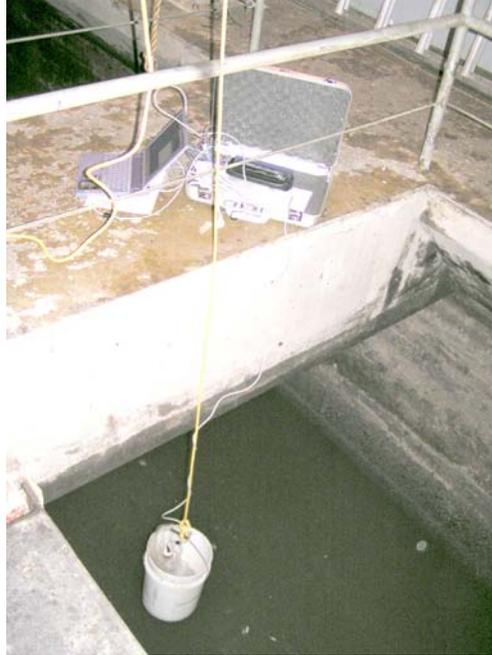
Figure 3. The wet well at the Interbay Pump Station. The floating detector would have to rise and fall with changing wastewater levels.
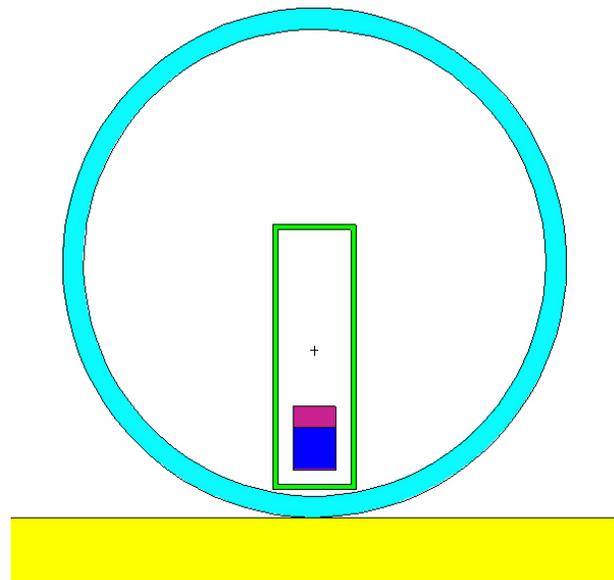
Figure 4. Cross section of model of floating detector. Dark blue is NaI(Tl), yellow is water, light blue is rubber, green is PVC, magenta is aluminum.

Example listings of the MCNP input files are included in Appendix A.

4.3 Material Description

Several basic materials are used in the models. **Table 2** gives the chemical composition and density of these materials.

<center>**Table 2**. Material Composition.</center>

Material	Density (g/cc)	Composition (MCNP description)	Reference
Dry Air	1.205E-3	Carbon (6000 1.24E-4 weight fraction)	ICRU-37, pg. 27
		Nitrogen (7014 0.7555267 weight fraction)	
		Oxygen (8016 0.231781 weight fraction)	
		Argon (18000 0.0012827 weight fraction)	
Aluminum	2.702	Elemental (13027 1 atom fraction)	CRC Handbook of Chemistry and Physics, 74th ed.
Sodium Iodide	3.667	Sodium (11000 1 atom fraction)	CRC Handbook of Chemistry and Physics, 74th ed.
		Iodine (53000 1 atom fraction)	
Water	1	Hydrogen (1000 2 atom fraction)	CRC Handbook of Chemistry and Physics, 74th ed.
		Oxygen (8000 1 atom fraction)	
Polyvinyl Chloride	1.406	Hydrogen (1000 6 atom fraction)	The Merck Index, 11th ed.
		Carbon (6000 4 atom fraction)	
		Chlorine (17000 2 atom fraction)	
Rubber	0.95	Hydrogen (1000 12	MatWeb for density of

Material	Density (g/cc)	Composition (MCNP description) atom fraction)	Reference
			vulcanized natural rubber; The Merck Index, 11th ed. For chemical composition
		Carbon (6000 4 atom fraction)	

4.4 Radionuclide Source Descriptions

There are eleven different radionuclide sources used in this study. Of these radionuclides, ten are direct photon emitters while only ^{90}Sr + ^{90}Y produces x radiation photons through bremsstrahlung.

Of the ten photon emitters the photon emissions with an intensity greater than 0.5% were included in the MCNP source term. The photon spectra of these radionuclides used are given in **Table 3**. These spectra are from the NUDAT database maintained by National Nuclear Data Center, www.nndc.bnl.gov/nudat2 .

Table 3. Photon emission spectra.

Radionuclide	Photon Energy (MeV)	Intensity (fraction)
Co-60	1.173228	0.9985
	1.332492	0.999826
Mo-99	0.0405845	0.0105
	0.018251	0.0107
	0.366421	0.01191
	0.018367	0.0202
	0.777921	0.0426
	0.140511	0.0452
	0.181068	0.0599
	0.7395	0.1213
Tc-99m	0.020619	0.00639

Radionuclide	Photon Energy (MeV)	Intensity (fraction)
	0.018251	0.0214
	0.018367	0.0407
	0.140511	0.8906
I-131	0.00411	0.0055
	0.029461	0.0138
	0.722911	0.0177
	0.029782	0.0254
	0.080185	0.0262
	0.284305	0.0614
	0.636989	0.0717
	0.364489	0.817
Cs-137	0.036378	0.00661
	0.00447	0.009
	0.031817	0.0196
	0.032194	0.0358
	0.661657	0.851
Ir-192	0.075368	0.00533
	0.4164688	0.00669
	0.3744852	0.00726
	0.075749	0.01025
	0.061486	0.012
	0.00891	0.0153
	0.063	0.0205
	0.065122	0.0263
	0.4845751	0.03187
	0.2057943	0.0334
	0.00944	0.0396

Radionuclide	Photon Energy (MeV)	Intensity (fraction)
	0.066831	0.0446
	0.588581	0.04517
	0.6124621	0.0534
	0.60441105	0.082
	0.2959565	0.2872
	0.30845507	0.2968
	0.4680688	0.4781
	0.31650618	0.8271
Ra-226	0.0117	0.008
	0.186211	0.0359
Pb-214	0.25887	0.00524
	0.83904	0.00587
	0.089784	0.00897
	0.78596	0.0107
	0.0532275	0.012
	0.08683	0.0128
	0.087349	0.0244
	0.074815	0.0633
	0.241997	0.0743
	0.077107	0.1055
	0.0108	0.133
	0.295224	0.193
	0.351932	0.376
Bi-214	0.0111	0.00598
	0.07929	0.00661
	1.58322	0.0069
	1.38531	0.00757

Radionuclide	Photon Energy (MeV)	Intensity (fraction)
	2.11855	0.0114
	1.66128	0.0115
	0.806174	0.0122
	1.4015	0.0127
	1.28096	0.0143
	0.665453	0.0146
	2.44786	0.0157
	1.15519	0.0163
	1.509228	0.0211
	1.84742	0.0211
	1.40798	0.0215
	1.729595	0.0292
	0.934061	0.0303
	1.377669	0.04
	0.768356	0.0494
	2.20421	0.0508
	1.23811	0.0579
	1.120287	0.151
	1.764494	0.154
	0.609312	0.461
Am-241	0.0263448	0.024
	0.0595412	0.359
	0.0139	0.369

The ^{90}Sr + ^{90}Y beta spectrum was taken from the compilation at www.doseinfo-radar.com . This site has compiled various beta emission spectra for direct use in MCNP. The beta spectrum used is given in Table 4.

Table 4. ^{90}Sr + ^{90}Y beta spectrum

Energy (MeV)	Intensity (fraction)
5.71E-02	1.18E-01
1.71E-01	1.23E-01
2.86E-01	1.19E-01
4.00E-01	1.01E-01
5.14E-01	7.67E-02
6.28E-01	7.08E-02
7.42E-01	7.17E-02
8.57E-01	7.15E-02
9.71E-01	7.04E-02
1.08E+00	6.85E-02
1.20E+00	6.57E-02
1.31E+00	6.19E-02
1.43E+00	5.69E-02
1.54E+00	5.07E-02
1.66E+00	4.30E-02
1.77E+00	3.42E-02
1.88E+00	2.46E-02
2.00E+00	1.50E-02
2.11E+00	6.43E-03
2.23E+00	1.13E-03

For the floating detector case only a portion of the water immediately below the detector was used. This source volume was a right circular cylinder 60-cm in diameter and 60-cm thick. This volume was chosen based on the transmission fraction of ^{60}Co photons (Vol. 1). By using a smaller source volume a balance is struck between the simulation runtime and the accurate of the result.

4.5 Tally Description

Simulation of the detector response is accomplished using the F8 type tally for photons. This tally represents the simulated detector pulses due to incident radiation, in other words the probability of an incident photon interacting with the NaI(Tl). This tally was modified using the Gaussian Energy Broadening (GEB) special tally treatment.

Using this treatment results in the photopeaks simulated in the detector broadening to properly represent that of NaI(Tl). The parameters used to define the GEB specify the full width at half maximum (*FWHM*) of the observed energy broadening in the physical detector. This treatment follows

$$FWHM = a + b\sqrt{E + cE^2}$$

where

a is 0 for this simulation

b is 0.05086 for this simulation

c is 0.30486 for this simulation

E is the photon energy in MeV

The values of *a*, *b*, and *c* in the FWHM equation were formulated to yield a *FWHM* value of 7% at the 661 keV photon energy line of ^{137}Cs (Siciliano et al. 2004). The 7% *FWHM* is typical for NaI(Tl).

Fluence information was also collected at several surfaces of the model, the outer PVC, outer aluminum, and the outer NaI(Tl) surfaces. While this data has been collected it currently is not used in the analysis.

4.6 Variance Reduction

As stated earlier, two versions of MCNP have been used for this analysis, MCNP-5 and MCNP-X. The reason for this is that MCNP-X allows the use of a variance reduction method known as importance splitting. This option is not allowed in MCNP-5 for F8 tallies at the present, and is not needed for the photon sources. The use of importance splitting, however, was instrumental in getting acceptable results with the ^{90}Sr + ^{90}Y bremsstrahlung source.

The importance splitting method essentially splits each source particle into *i* parts at the cell boundaries. As a particle moves from a cell into an adjacent cell if the adjacent cell has a higher importance value the particle is split into the number of particles equal to the ratio of the importance values. This allows for the creation of particle showers to speed up convergence of the tally. A detailed discussion of this variance reduction method can be found in the MCNP manual (Hendricks et al. 2005).

4.7 Results

The MCNP results for the pulse height tally are expressed as a probability of an event depositing a particular amount of energy (divided into 1-keV energy bins) in the detector per nuclear transition at randomly chosen locations throughout the source volume.

Such probabilities can be summed over all energy bins (gross counting yield), or summed over energy bins that comprise one or more photopeaks in a spectrum (photopeak counting yield). Figure shows the MCNP results summed over photopeaks for various radionuclides. Two different geometries were used for ^{60}Co (60 cm radius by 60 cm deep cylinder of water underneath floating detector, and 120 cm radius by 120 cm deep cylinder of water underneath floating detector). The 8-fold larger volume increased the gross counting yield in the 3×3 floating system for ^{60}Co by some 27%, but only very slightly increased the counting yield in the photopeaks by 20%. This indicates that using even larger volumes in the calculations would result in very little change in the results.
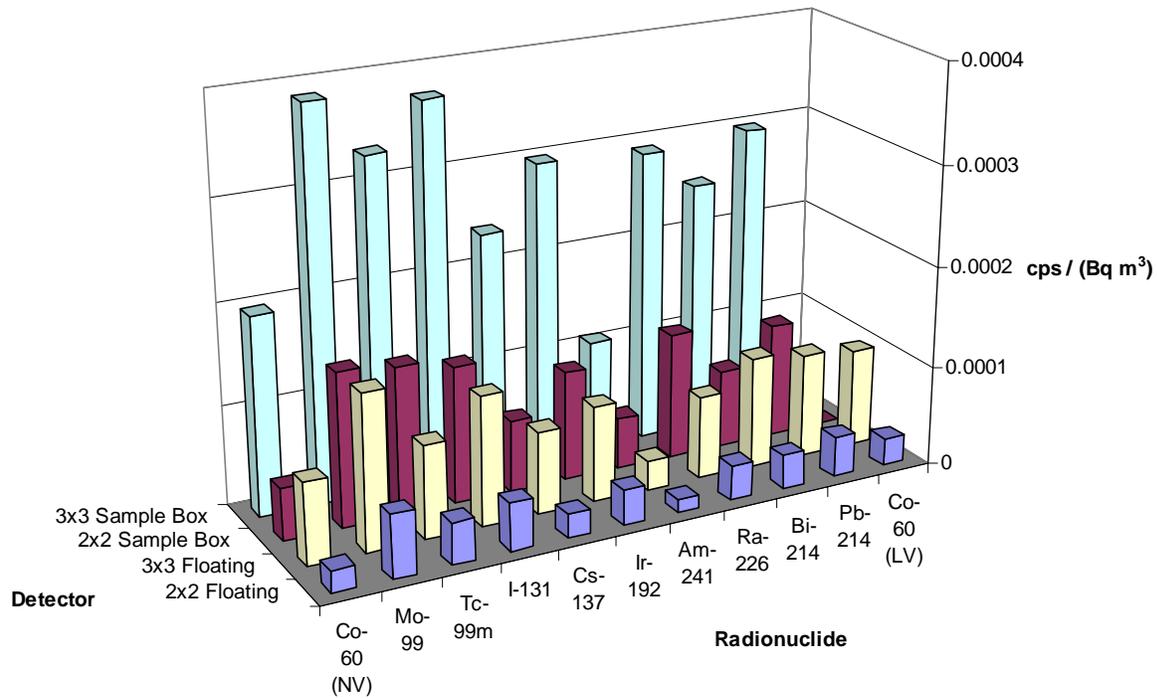
Figure 5. Volume counting yield for full energy events (photopeaks) for the radionuclides in each of the four detector configurations.

The simulated spectra are displayed in Appendix A. As can be seen from these figures the radionuclides of interest have readily identifiable spectra, with exception of $^{90}Sr + ^{90}Y$, which exhibits no photopeak but rather a broad, and relatively weak, x-ray spectrum. The 3×3 detector is always superior to the 2×2 detector, and generally placing either detector in the sample box yields better sensitivity than when it is floating (the only exception is $^{90}Sr + ^{90}Y$). The final two figures in this set give show the ^{226}Ra spectra with progeny (^{214}Bi and ^{214}Pb) included. These figures differ in that Figure assumes that none of the radon stays in solution in the water, while Figure assumes that 90% of the radon escapes from the water.

4.8 Relationship Between MCNP Results and Detection Capabilities

The relationship between activity, volume, and concentration is

$$C = \frac{A}{V},$$

where

  C = radionuclide concentration (Ci/gal or Bq/m^3)

  A = the activity (Ci or Bq)

  V = the volume that A is dissolved or suspended in.

We introduce the concept of volume counting yield, Y_V, defined as the observed count rate (counts per second) per unit concentration (Bq/m^3), or (counts/second)/(Bq/m^3). This unit can be rearranged to give (counts)/(nuclear transition/m^3) or (counts × m^3)/(nuclear transition).

21

One can derive Y_V from the MCNP tally results by multiplying the raw tally results summed over photopeaks or gross spectra by the source volume. The two floating detector volumes used were 0.68 m^3 (179 gal.) and 5.43 m^3 (1434 gal.). The net volume of water in the sampling box was 0.0815 m^3 (21.5 gal.). The Y_V values are plotted in Figure 5. The amount of activity concentration needed to produce one additional count per second above background in either gross counts or in photopeaks for various isotopes and four detector configurations is shown in Table 5.

Table 5. Activity concentration in Bq/m^3 to produce 1 additional count per second above background in either gross counts or in photopeaks for various isotopes and four detector configurations.

Radionuclide	Peak (MeV)	(Bq/m^3) to produce 1 additional c/s			
		2x2 Floating	2x2 Sample Box	3x3 Floating	3x3 Sample Box
Co-60 (normal volume)	Peak Total	45,318	19,016	12,278	5,082
Co-60 (normal volume)	Total	2,178	1,478	929	617
Co-60 (large volume)	Peak Total	36,306		10,268	
Co-60 (large volume)	Total	1,708		731	
Sr/Y-90	Total Brems	53,371	76,018	25,699	35,766
Mo-99	Peak Total	16,144	6,530	6,473	2,587
Mo-99	Total	2,700	1,363	1,211	612
Tc-99m	1.41E-01	24,212	6,803	10,807	3,030
Tc-99m	Total	3,266	1,236	1,542	590
I-131	Peak Total	20,964	7,341	7,803	2,672
I-131	Total	2,382	1,150	1,085	520
Cs-137	6.62E-01	40,824	14,032	12,239	4,224
Cs-137	Total	2,327	1,324	1,025	575
Ir-192	Peak Total	28,113	9,187	10,452	3,365
Ir-192	Total	2,417	1,144	1,099	519
Am-241	5.95E-02	73,855	19,738	34,247	9,259
Am-241	Total	16,443	5,203	7,898	2,519
Ra-226	1.86E-01	28,108	7,965	12,179	3,449
Ra-226	Total	3,245	1,308	1,520	619
Bi-214	Peak Total	29,669	12,952	9,071	4,011
Bi-214	Total	2,195	1,392	951	593
Pb-214	Peak Total	24,593	8,785	9,673	3,363
Pb-214	Total	3,101	1,371	1,429	631

Assuming that about one net count per second could be distinguished during a 2 minute count (giving about 120 counts greater than background), one can begin to gauge the concentrations of radionuclides that these detectors can register. The largest of these numbers (^{241}Am and floating 2×2 detector) is about 2 microcuries per cubic meter (µCi/m^3), or about 0.007 µCi/gal. For the floating 3×3 detector, the numbers are about half these values, about 1 µCi/m^3 or about 0.004 µCi/gal. In each case, one can see about 6 times lower concentrations of ^{60}Co than of ^{241}Am. The use of gross count rate may be more sensitive, but this depends on background levels.

Since it was shown in Vol. 1 that a millicurie per gallon produces no more than one rem per hour, these detection thresholds show that dose rates well below 0.00001 rem per hour, or 0.01 mrem per hour, could be detected with a 2-minute counting time. One can easily detect one curie of any of the listed radionuclides dissolved in 10 million gallons of water, a concentration of 0.1 µCi/gal.

Only for ^{90}Sr + ^{90}Y are the sample box configurations less efficient than the floating detectors.

4.9 Conclusions from MCNP Calculations

The use of a submerged or floating NaI(Tl) based detector (2×2 or 3×3) allows effective collection of photon spectra from contaminated water. The simulated spectra are readily identifiable with exception of ^{90}Sr + ^{90}Y. It is not surprising that ^{90}Sr + ^{90}Y is not identifiable given that the mechanism of photon production, bremsstrahlung, that has a dependence on the atomic number of the media. In these cases the media is water, for which the atomic number of oxygen, 8, is used. While no photopeak characteristic of ^{90}Sr + ^{90}Y exists, it is possible to determine the presence of a radionuclide contaminant purely based on the total detector count rate, dependent on background levels.

These calculations have demonstrated that deploying such detectors would be useful in providing early detection and identification of radionuclides in wastewater.

5.0 Recommendations to King County WTD for Radiological Instruments

Several recommendations are clear from the work to date.

5.1 Fixed Gamma Spectroscopy Instruments for Early Warning and Quantitative Threat Characterization

Fixed radiation detection instrumentation should be deployed as part of a defense-in-depth system that provides early warning of significant radioactive material on the way to the WPTP and monitoring at strategic locations within the plant. Such systems should be able to identify the radionuclide(s) and provide estimates of the soluble concentrations.

There is an additional need for detectors capable of functioning in high-dose rate environments that are likely under some scenarios. Such detectors must be capable of functioning from 10 microrems per hour (background) up to 1000 rems per hour, a full eight orders of magnitude (a factor of 100,000,000). In most locations, fixed dose-rate monitors such as area monitors used in nuclear facilities would provide high radiation level capabilities in the case of a large, concentrated source in wastewater, either dissolved or entrained.

5.1.1 Early Warning from the Interbay Pump Station

Early warning is quite feasible. Deployment of a 3" $\times$ 3" NaI(Tl) scintillation detector in a floating buoy in the wet well of the Interbay Pump Station (Figure), with a computer workstation in the control room would provide the needed capability. Cabling challenges and temperature stabilization can be overcome. Results would be telemetered via the Secure wideband communications to all authorized locations, including the control room, the South Jackson Street building, and technical support staff off site.

5.1.2 WPTP Bar Screen Room

A 3" $\times$ 3" NaI(Tl) scintillation detector system should be installed on the pipe beyond the hydraulic ram in the rags waste stream in the bar screen room, shown in Figure . This detector should be shielded, and shielding should be wrapped around the pipe itself. A high dose rate monitoring system should be installed in this location as well. Such a combination of detectors provides sensitive, low-level identification and quantification of radioactive materials, and can provide useful information if the low-level system becomes overwhelmed.

The high level detector can also serve to detect intact sealed sources that may wind up in the rock box.

Figure 6. Proposed detector location (arrow) to monitor the rags waste stream in the discharge pipe from the hydraulic ram in the bar screen room at WPTP.

5.1.3 Fine Grit Facility

A dose-rate monitoring system above the collection funnels in the fine grit facility (Figure) would provide warning and radiation level measurements in the event of an RDE that resulted in insoluble chunks of radioactive material, as discussed in Vol. 1.

Figure 7. Dose rate monitoring equipment should be located near the grit collection funnels (bottom of photo) in the grit facility

5.1.4 Sampling Tank in the Raw Sewage Pump Room

A 3" × 3" NaI(Tl) scintillation detector system should be installed in the sampling tank in the raw sewage pump room (Figure), along the lines of the design described in Section 4.

Figure 8. Workers inspect the sampling tank in the raw sewage pump room

5.1.5 6% Thickened, Blended Sludge Pipes

A 3" × 3" NaI(Tl) scintillation detector system should be installed downstream of the concentration facilities that produce 6% thickened blended sludge on the way to the anerobic digesters. One potential location is at a point where the thickened, blended sludge passes through a single pipe (Figure 9).
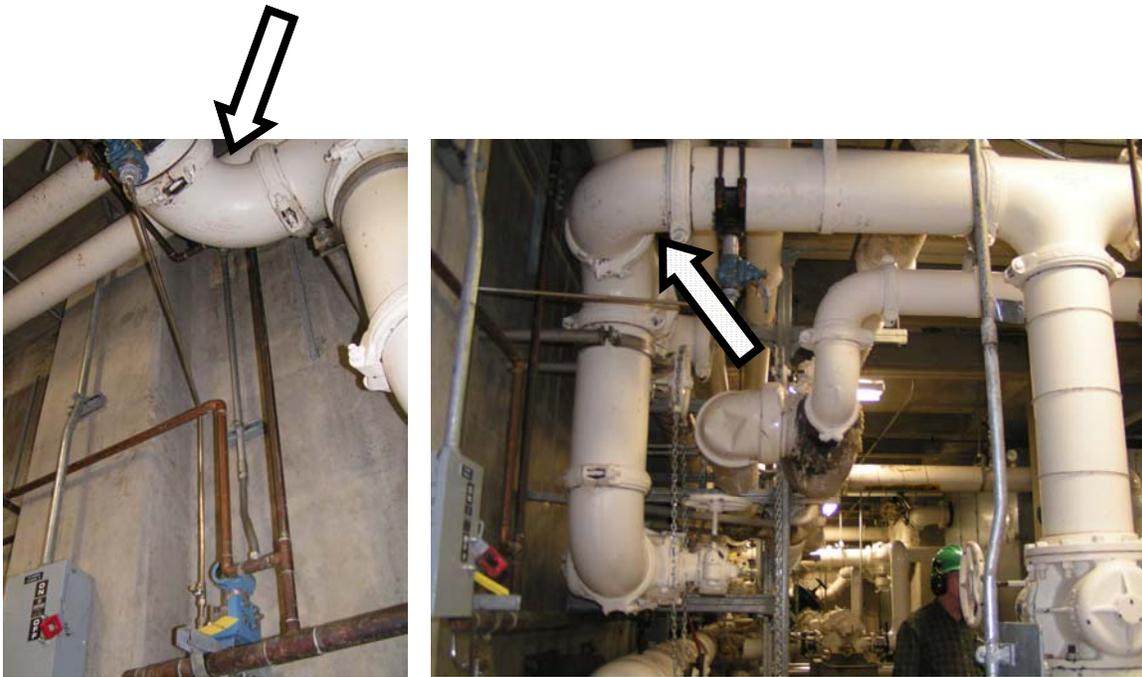
Figure 9. Arrows indicate potential location inside a 90° elbow for monitoring thickened, blended sludge.

5.1.6 Engineering Challenges

Engineering challenges exist for these applications. Explosion-proof, corrosion resistant housings and temperature compensation must be designed for detectors. Cable-length challenges may exist for delivering power to detectors and retrieving required signals out of potentially explosive and corrosive environments. It will be necessary to engineer floating detectors that cannot become dams or become excessively fouled with grease between reasonable service intervals, and that can rise and fall with varying wastewater levels and flow rates.

It is also necessary to deploy both ultra-sensitive detectors to provide early warning and identification and detectors capable of functioning in high-dose rate environments that are likely under some scenarios, capable of functioning from 10 microrems per hour (background) up to 1000 rems per hour, a full eight orders of magnitude (a factor of 100,000,000). While such instrumentation exists for other applications, all of this engineering will require deploying prototypes and perhaps dealing with unforeseen complications.

Software supporting fixed spectroscopic detectors would be developed to provide prompt, reliable, and simple interpretations of spectroscopic outputs that are of use to operators and decision-makers. Software to provide scientists and homeland security personnel with sufficient technical detail for identification, quantification, waste management decisions, and for the inevitable forensic and attribution needs must be developed. Such software is not an off-the-shelf product as of March 2005 but it is expected that, with

sufficient resources and collaboration between government agencies, scientists, and vendors, it can be specified and developed within two years or less.

5.2 Portable Instruments

In addition to fixed instruments, general purpose instruments that can be used to determine the nature and extent of radioactive contamination and measure radiation levels for purposes of protecting personnel and members of the public should be available to WTD personnel.

5.2.1. Portable Radioisotope Identifiers (RIIDs)

One or more portable radioisotope identifiers (RIIDs) should be available to WTD personnel for surveying and identifying contaminants in screening waste (rags), grit, and biosolids, as well as anywhere else that radioactivity may concentrate. These are not on the list of approved instruments maintained by the state of Washington.

5.2.2 Personal Radiation Monitors

Small, portable battery-powered personal radiation monitors should be widely available to WTD personnel. The personal monitors can be used for personal and group radiation protection decisions, and to alert management to the need to get expert backup.

From the list of state-approved instruments, we recommend that WTD purchase one Item No. 15 (EPD Mk2 Dosimeter Reader), one Item No. 16 (Utility Software Site License for EPD Mk2), and as many EPD Mk2 Siemens EPD MK2 Dosimeters as needed. If the MK2 is no longer available, then we recommend getting the next generation instrument from Siemens.

5.2.3 Portable, General Purpose Radiological Instruments

From the state-approved list, we recommend that you purchase one of the Areva/Cogema/ Canberra/Aptec/NRC suitcases "Item No. 12" ERKADV (Emergency Response Kit, Advanced) at $7,750 each. This kit contains a radiation detection instrument (ADM-300) that can handle alpha, beta, and gamma detection. WTD probably does not need everything in the kit, so we would focus on the built-in detectors and the external GM pancake probe. The XP110 Large Area X-Ray Probe is not needed.

We also recommend the purchase of 10 to 20 RadAlert "Inspectors," a multi-purpose GM-based instrument that can be operated in the count mode, count rate mode, and in the dose rate mode.

5.3 Laboratory Instruments

A liquid scintillation counter that can detect any radioactive materials (alpha-, beta-, and gamma-emitters) in water samples should be available for laboratory analysis of samples. Typical liquid scintillation counters analyze a 1 mL water sample in 10 mL of "liquid scintillation cocktail," a mixture of a solvent, surfactants, and wavelength-shifting fluors that give off light when ionizing radiation is absorbed by them. Such instruments can give very accurate results and can identify and measure radionuclides that do not emit gamma or x radiation.

A liquid scintillation counter is a lower priority than other instruments described above.

5.3 Training

All uses of radiological instrumentation will require training and periodic retraining of personnel, as well as periodic calibration and maintenance of instruments. Routine innocent alarms will occur due to medical radionuclides that are legally discharged into sanitary sewers on a daily basis. Innocent alarms may also be triggered by WTD workers who have recently been treated with medical radioisotopes. Instrumentation must provide signals that distinguish between routine medical discharges and off-normal occurrences that are due to malicious acts or undetected accidents. Operators and others who deal with instrument signals must be prepared to deal with innocent but real alarms, while being vigilant for alarms indicating malicious or other serious discharges.

5.4 Funding

The King County Wastewater Treatment Division should seek Homeland Security or EPA resources to become the model POTW in the U.S. to design, deploy, and test such radiological instrumentation, and integrate the use of such instrumentation into its radiological emergency response plan.

6.0   Conclusions and Next Steps

This report is the second of three volumes. The first volume, a radiological risk assessment, contains basic information on radiation and radioactive materials, and develops scenarios that could lead to the introduction of radioactive material into a combined storm and sanitary sewer system. Vol. 1 analyzes the consequences resulting from various scenarios.

6.1 Conclusions

Based on the analysis in Volume 1 and a second visit to the King County WTD, this document, Volume 2 of PNNL-15163, provides an assessment of the radiological instrumentation needs for detection of radiological or nuclear terrorism, in support of decisions to treat contaminated wastewater or to bypass the West Point Treatment Plant (WPTP), and in support of radiation protection of the workforce, the public, and the infrastructure of this POTW.

Two broad categories of scenarios were considered in Volume 1. The first category includes events that may be suspected from the outset, such as an explosion of a "dirty bomb" in downtown Seattle. The explosion would most likely be heard, but the type of explosion (e.g., sewer methane gas or RDD) may not be immediately known. Emergency first responders must be able to quickly detect the radioisotopes listed in Vol. 1, assess the situation, and deploy a response to contain and mitigate (if possible) detrimental effects resulting from the incident. In such scenarios, advance notice of about an hour or two might be available before any contaminated wastewater reaches a treatment plant.

The second category includes RDEs that could go initially undetected by emergency personnel. Examples of such a scenario would be the inadvertent or surreptitious introduction of radioactive material into the sewer system. Intact rogue radioactive sources from industrial radiography devices, well-logging apparatus, or moisture density gauges may get into wastewater and be carried to the treatment plant. Other scenarios include a terrorist deliberately putting a dispersible radioactive material into wastewater. Alternatively, a botched terrorism preparation of an RDD may result in radioactive material entering wastewater without anyone's knowledge. Drinking water supplies may also be contaminated, with the result that some or most of the radioactivity ends up in wastewater. In these cases, the wastewater management and treatment infrastructure may be the first opportunity that government has to detect such events.

Fixed radiation detection instrumentation should be deployed in a defense-in-depth system that provides 1) early warning of significant radioactive material on the way to the WPTP, including identification of the radionuclide(s) and estimates of the soluble concentrations, with a floating detector located in the wet well at the Interbay Pump Station and telemetered via the secure wideband communications to all authorized locations, 2) monitoring at strategic locations within the plant, including

  a) the pipe beyond the hydraulic ram in the bar screen room
  b) above the collection funnels in the fine grit facility
  c) in the sampling tank in the raw sewage pump room
  d) downstream of the concentration facilities that produce 6% blended and concentrated biosolids.

Engineering challenges exist for these applications. Explosion-proof, corrosion resistant housings and temperature compensation must be designed for detectors. Cable-length challenges may exist for delivering power to detectors and retrieving required signals out of potentially explosive and corrosive

environments. It will be necessary to engineer floating detectors that cannot become dams or become excessively fouled with grease between reasonable service intervals, and that can rise and fall with varying wastewater levels and flow rates. It is also necessary to deploy both ultra-sensitive detectors to provide early warning and identification and detectors capable of functioning in high-dose rate environments that are likely under some scenarios, capable of functioning from 10 microrems per hour (background) up to 1000 rems per hour, a full eight orders of magnitude (a factor of 100,000,000). While such instrumentation exists for other applications, all of this engineering will require deploying prototypes and perhaps dealing with unforeseen complications.

Software supporting fixed spectroscopic detectors would be developed to provide prompt, reliable, and simple interpretations of spectroscopic outputs that are of use to operators and decision-makers. Software to provide scientists and homeland security personnel with sufficient technical detail for identification, quantification, waste management decisions, and for the inevitable forensic and attribution needs must be developed. Such software is not an off-the-shelf product as of March, 2005, but it is expected that, with sufficient resources and collaboration between government agencies, scientists, and vendors, it can be specified and developed within two years or less.

Computational modeling using the Monte Carlo N-Particle (MCNP) software has demonstrated that useful detection capabilities can be deployed. In particular, any of the isotopes examined can be detected at levels between 0.01 and 0.1 µCi per gallon. Thus, a 1 Ci source dissolved in 10 million gallons of water could be detected within minutes.

In addition to fixed instruments, general purpose instruments that can be used to determine the nature and extent of radioactive contamination and measure radiation levels for purposes of protecting personnel and members of the public should be available to WTD personnel. One or more portable RIIDs should be available to WTD personnel. Small, portable battery-powered personal radiation monitors should be widely available to WTD personnel. The personal monitors can be used for personal and group radiation protection decisions, and to alert management to the need to get expert backup.

All uses of radiological instrumentation will require training and periodic retraining of personnel, as well as periodic calibration and maintenance of instruments. Routine "innocent" alarms will occur due to medical radionuclides that are legally discharged into sanitary sewers on a daily basis. Innocent alarms may also be triggered by WTD workers who have recently been treated with medical radioisotopes. Instrumentation must provide signals that distinguish between routine medical discharges and off-normal occurrences that are due to malicious acts or undetected accidents. Operators and others who deal with instrument signals must be prepared to deal with innocent but real alarms, while being vigilant for alarms indicating malicious or other serious discharges.

6.2 Next Steps

The King County Wastewater Treatment Division should seek Homeland Security resources to become the model POTW in the U.S. to design, deploy, and test such radiological instrumentation.

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Appendix A. MCNP Results

Appendix A contains graphs of spectra for ten radionuclides, ^{60}Co, ^{90}Sr + ^{90}Y, ^{99}Mo, ^{99m}Tc, ^{131}I, ^{137}Cs, ^{192}Ir, ^{214}Bi, ^{214}Pb, ^{226}Ra, and ^{241}Am that would be observed in each of the four detector configurations described in Section 4. Additional drawings of the detector layouts are also shown.

Table 6 shows the numerical results in cps/(Bq/m^3) from the MCNP calculations.

Table 6. Numerical results in cps/(Bq/m^3) from the MCNP calculations for each photopeak, for all photopeaks, and for gross counts for various radionuclides.

Radio-nuclide	Peak (MeV)	2×2 Floating	2×2 Sample Box	3×3 Floating	3×3 Sample Box
Co-60	1.17E+00	1.31E-05	3.00E-05	4.61E-05	1.09E-04
	1.33E+00	8.92E-06	2.26E-05	3.54E-05	8.76E-05
	Peak Total	2.21E-05	5.26E-05	8.14E-05	1.97E-04
	Total	4.59E-04	6.77E-04	1.08E-03	1.62E-03
Mo-99	3.66E-01	2.43E-05	5.58E-05	5.19E-05	1.22E-04
	1.41E-01	1.85E-05	5.01E-05	4.34E-05	1.13E-04
	1.81E-01	7.64E-06	1.52E-05	1.92E-05	4.04E-05
	7.40E-01	1.15E-05	3.20E-05	4.00E-05	1.11E-04
	Peak Total	6.19E-05	1.53E-04	1.54E-04	3.87E-04
	Total	3.70E-04	7.33E-04	8.26E-04	1.64E-03
Tc-99m	1.41E-01	4.13E-05	1.47E-04	9.25E-05	3.30E-04
	Total	3.06E-04	8.09E-04	6.49E-04	1.69E-03
I-131	7.23E-01	1.40E-05	3.16E-05	3.70E-05	8.20E-05
	2.84E-01	3.12E-05	9.78E-05	8.31E-05	2.69E-04
	6.37E-01	2.02E-06	5.64E-06	6.43E-06	1.88E-05
	3.64E-01	5.09E-07	1.22E-06	1.67E-06	4.35E-06
	Peak Total	4.77E-05	1.36E-04	1.28E-04	3.74E-04
	Total	4.20E-04	8.70E-04	9.21E-04	1.92E-03
Cs-137	6.62E-01	2.45E-05	7.13E-05	8.17E-05	2.37E-04
	Total	4.30E-04	7.55E-04	9.76E-04	1.74E-03
Ir-192	6.04E-01	2.52E-05	7.96E-05	6.50E-05	2.08E-04
	4.68E-01	8.45E-06	2.31E-05	2.39E-05	6.93E-05
	3.17E-01	1.89E-06	6.15E-06	6.75E-06	1.99E-05
	Peak Total	3.56E-05	1.09E-04	9.57E-05	2.97E-04

Radio-nuclide	Peak (MeV)	2×2 Floating	2×2 Sample Box	3×3 Floating	3×3 Sample Box
	Total	4.14E-04	8.74E-04	9.10E-04	1.93E-03
Am-241	5.95E-02	1.35E-05	5.07E-05	2.92E-05	1.08E-04
	Total	6.08E-05	1.92E-04	1.27E-04	3.97E-04
Ra-226	1.86E-01	3.56E-05	1.26E-04	8.21E-05	2.90E-04
	Total	3.08E-04	7.64E-04	6.58E-04	1.62E-03
Bi-214	1.38E+00	1.49E-05	3.87E-05	4.81E-05	1.23E-04
	7.68E-01	5.35E-06	1.06E-05	1.67E-05	3.11E-05
	1.12E+00	6.41E-06	1.25E-05	1.99E-05	4.13E-05
	1.76E+00	3.51E-06	7.77E-06	1.28E-05	2.52E-05
	6.09E-01	3.51E-06	7.60E-06	1.28E-05	2.89E-05
	Peak Total	3.37E-05	7.72E-05	1.10E-04	2.49E-04
	Total	4.56E-04	7.19E-04	1.05E-03	1.69E-03
Pb-214	2.42E-01	1.27E-05	3.02E-05	2.97E-05	7.41E-05
	2.95E-01	1.37E-05	3.73E-05	3.50E-05	9.69E-05
	3.52E-01	1.43E-05	4.63E-05	3.87E-05	1.26E-04
	Peak Total	4.07E-05	1.14E-04	1.03E-04	2.97E-04
	Total	3.23E-04	7.30E-04	7.00E-04	1.58E-03
Co-60 (large volume)	1.17E+00	1.58E-05		5.45E-05	
	1.33E+00	1.18E-05		4.29E-05	
	Peak Total	2.75E-05		9.74E-05	
	Total	5.85E-04		1.37E-03	
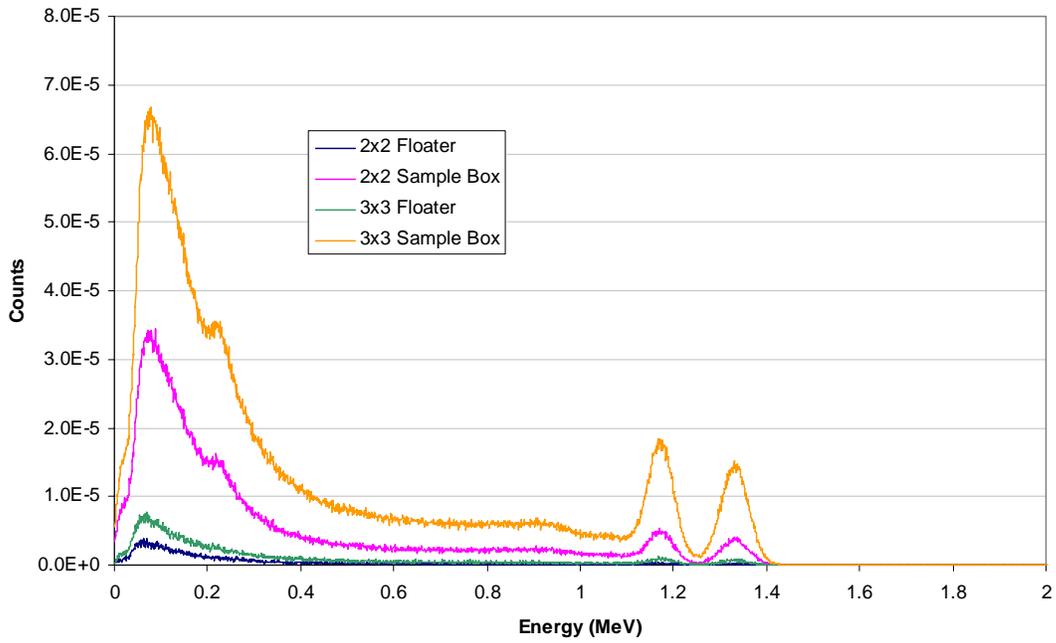
Figure 10. ^{60}Co Detector Comparison. (Linear Scale)
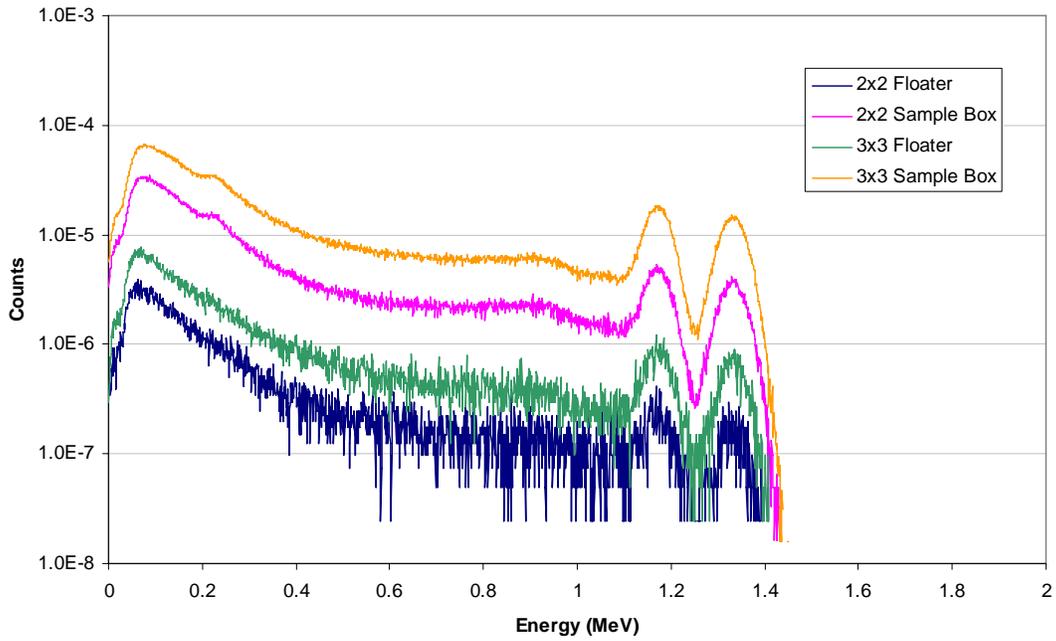
Figure 11. ^{60}Co Detector Comparison. (Log Scale)
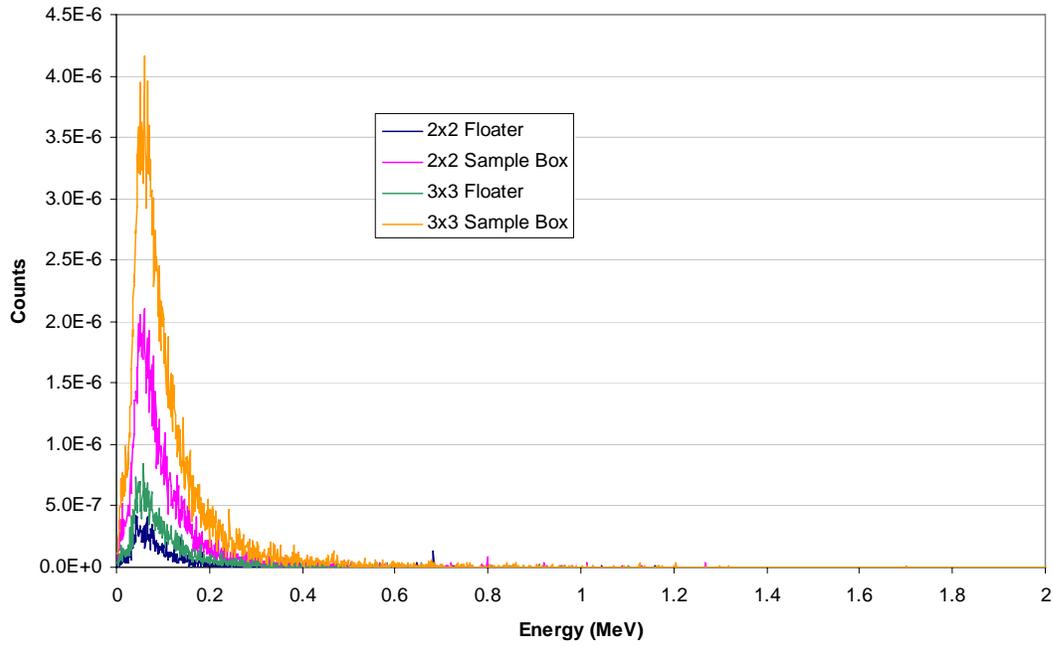
Figure 12. ^{90}Sr/Y Detector Comparison. (Linear Scale)
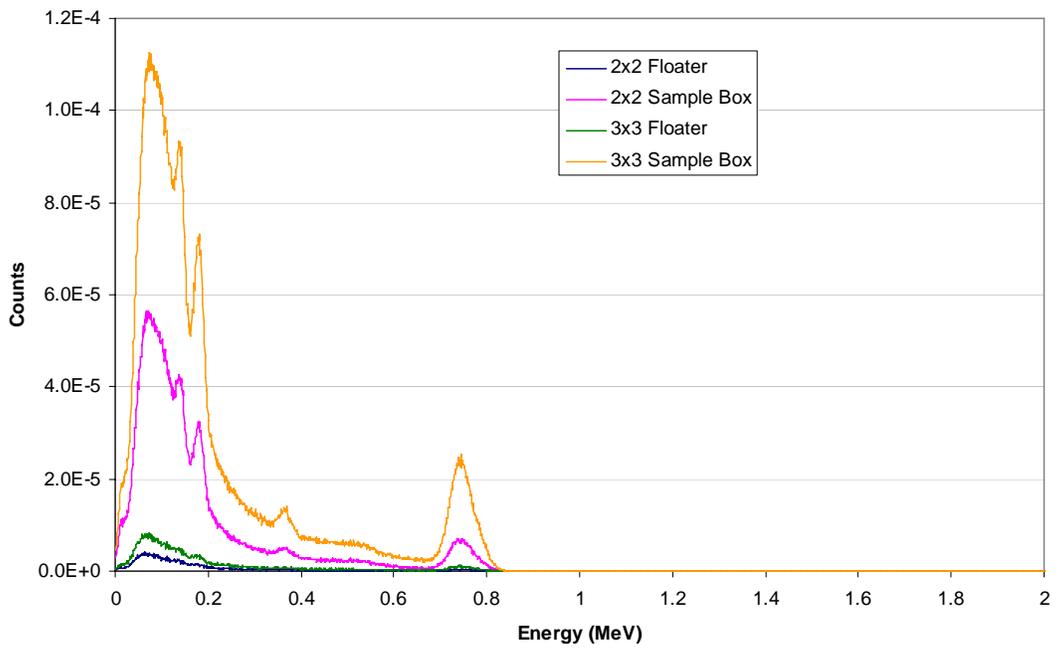
Figure 13. ^{99}Mo Detector Comparison. (Linear Scale)
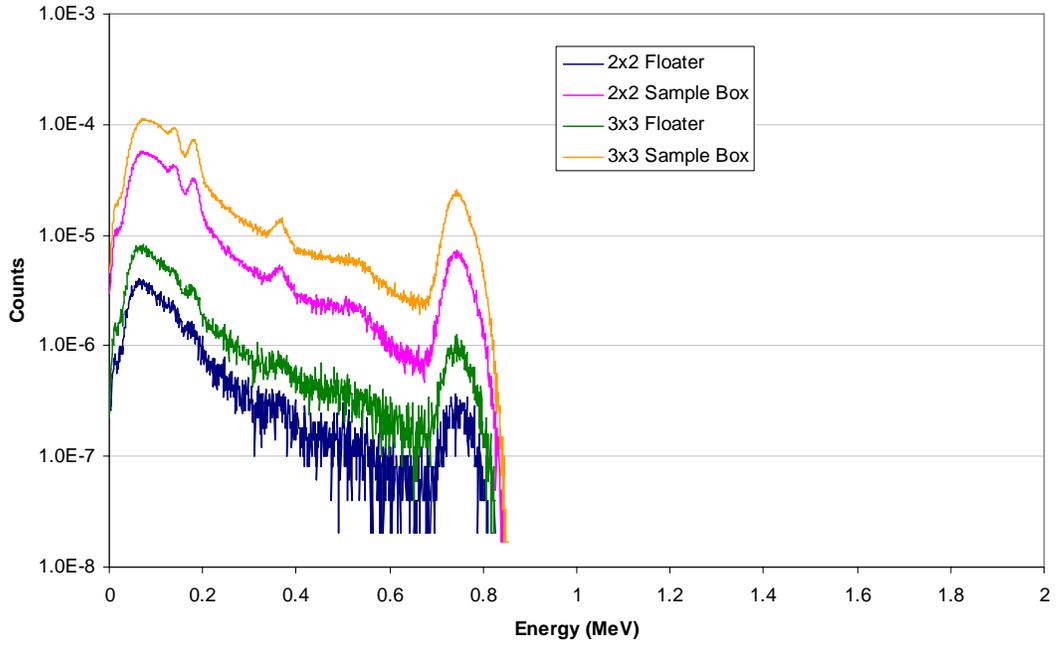
Figure 14. ^{99}Mo Detector Comparison. (Log Scale)
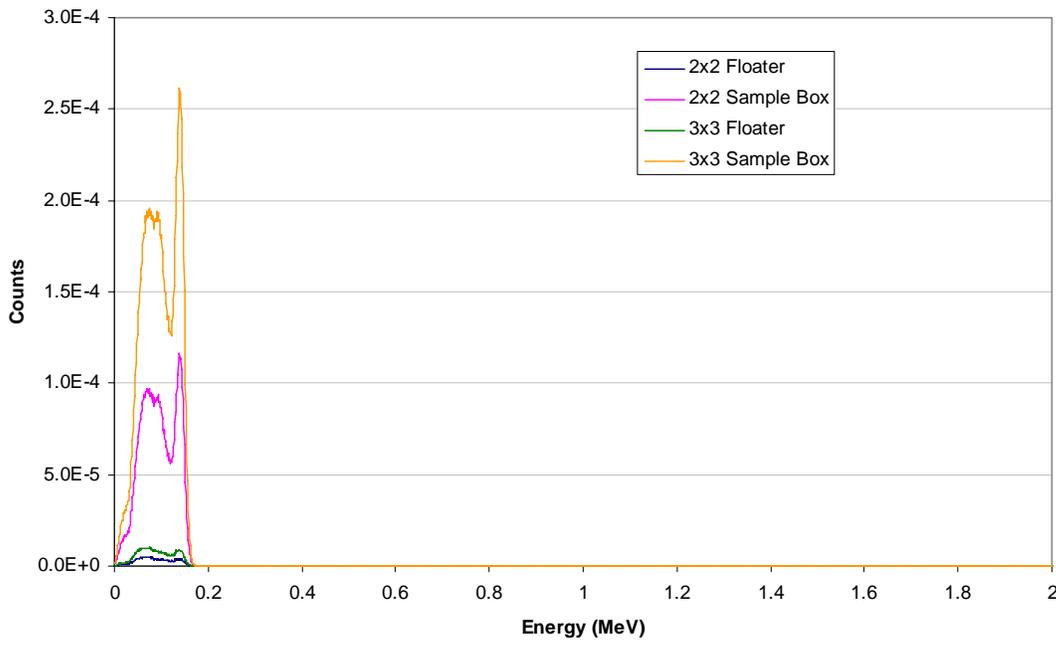
**Figure 15.** ^{99m}Tc Detector Comparison. (Linear Scale)
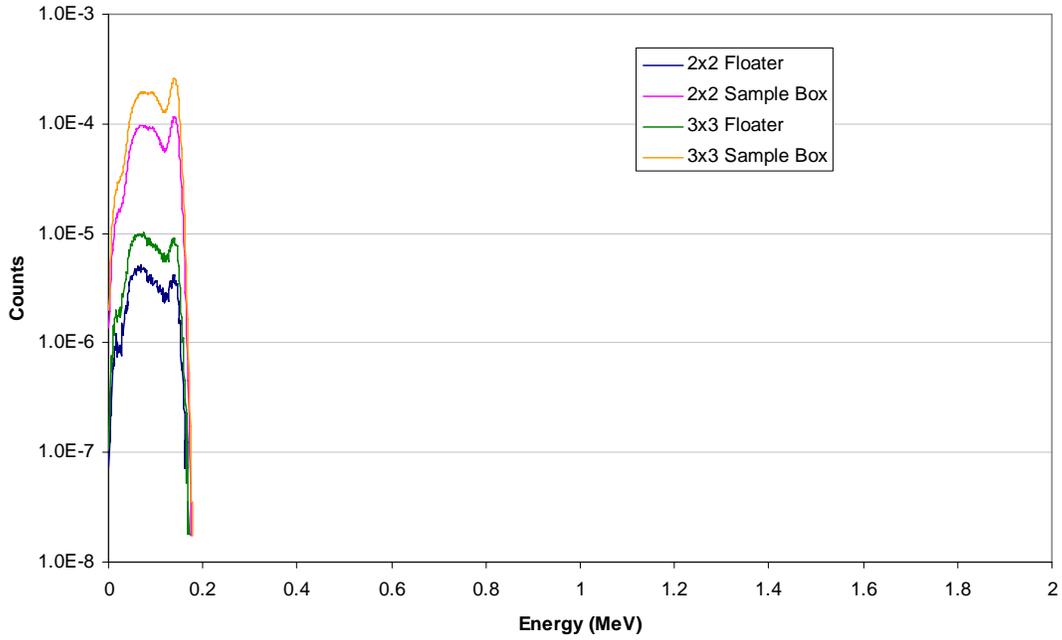
**Figure 16.** ^{99m}Tc Detector Comparison. (Log Scale)
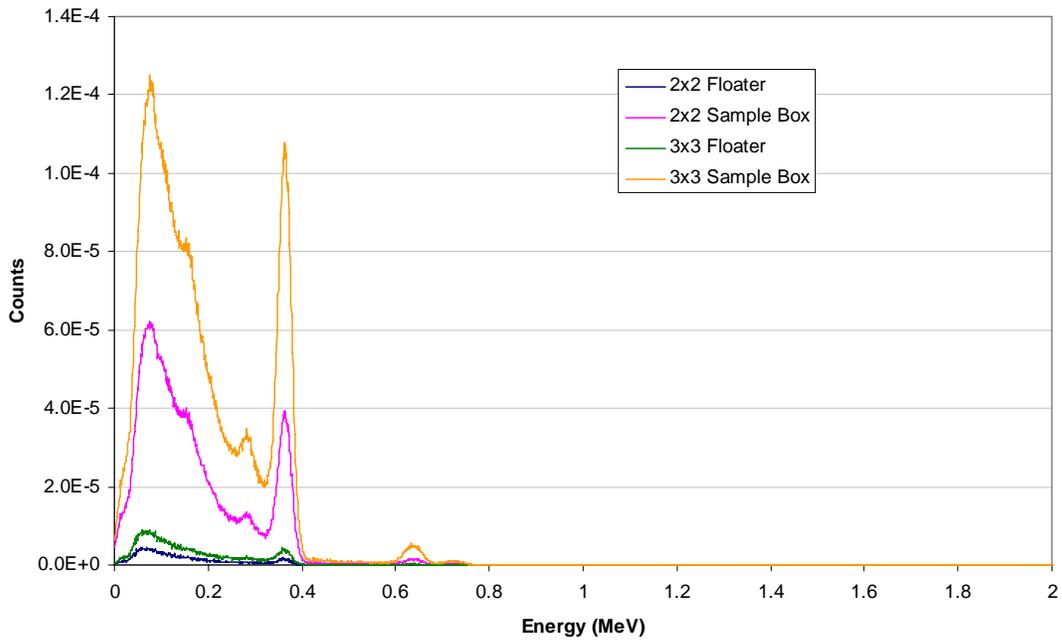
**Figure 3.** ^{131}I Detector Comparison. (Linear Scale)
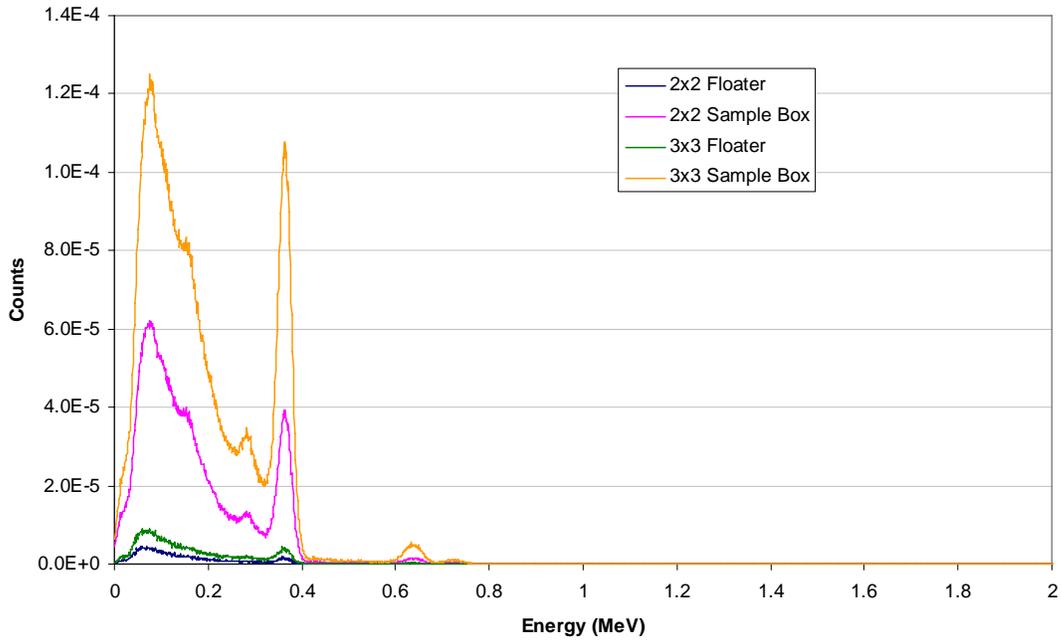
Figure 4. ^{131}I Detector Comparison. (Log Scale)
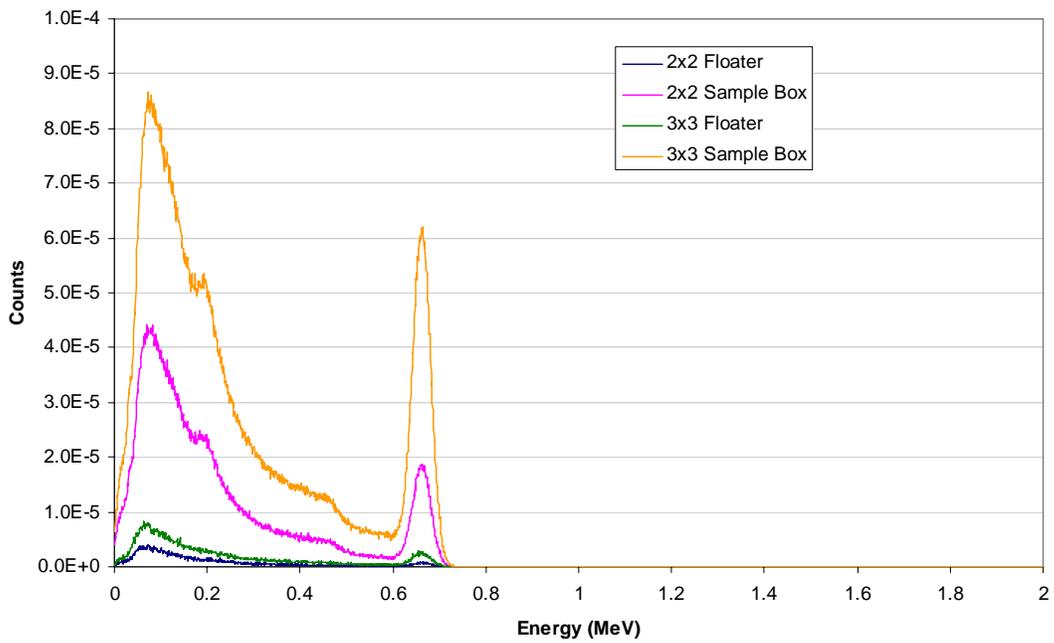
Figure 19. ^{137}Cs Detector Comparison. (Linear Scale)
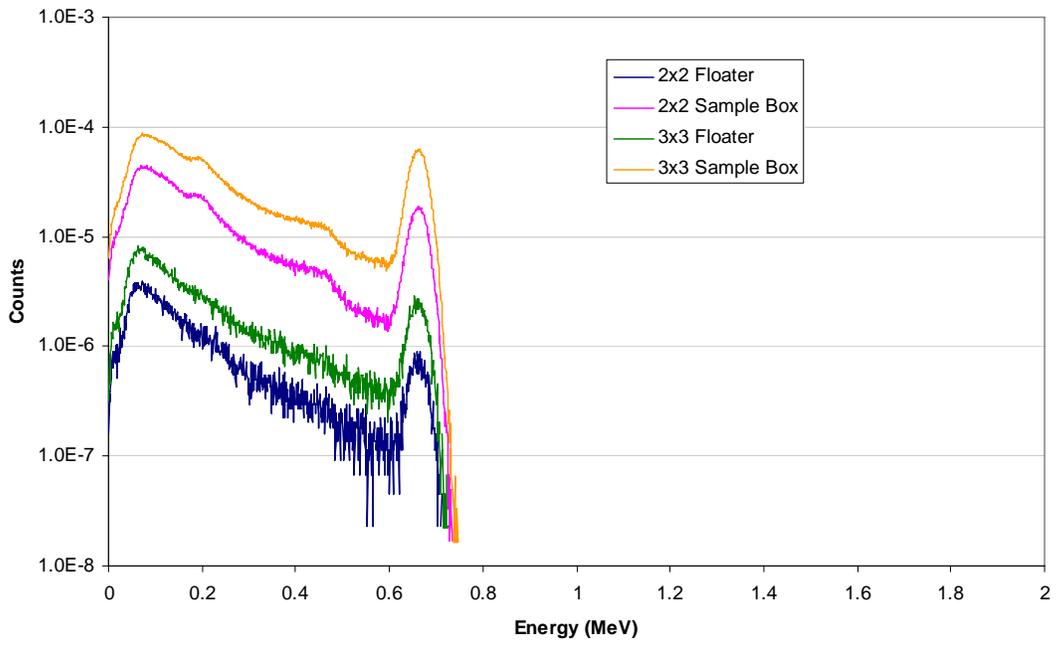
**Figure 20.** ^{137}Cs Detector Comparison. (Log Scale)
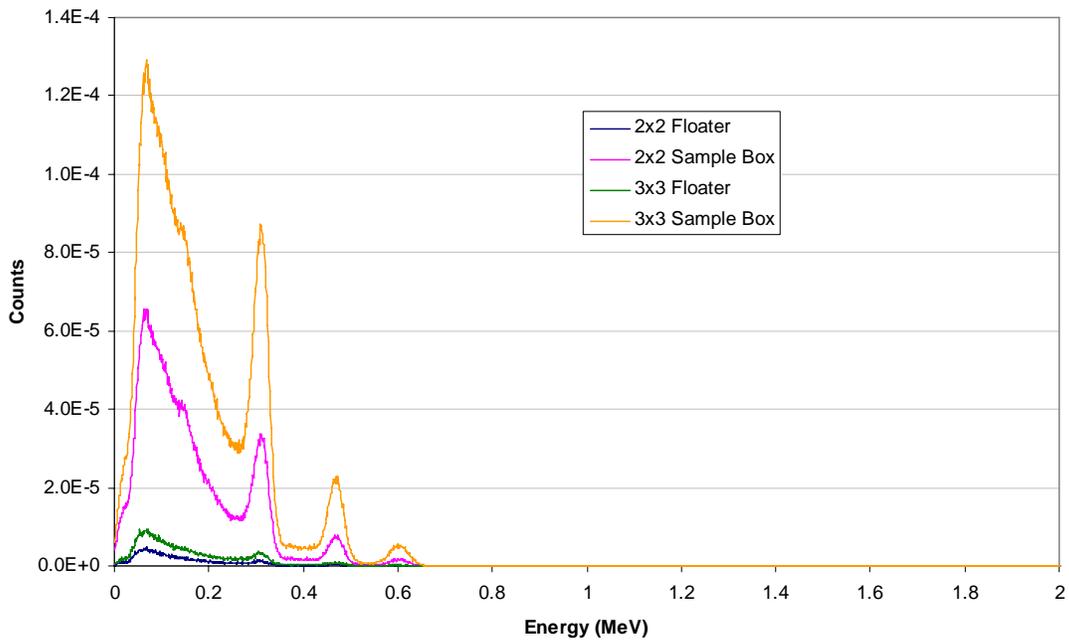
Figure 21. ^{192}Ir Detector Comparison. (Linear Scale)
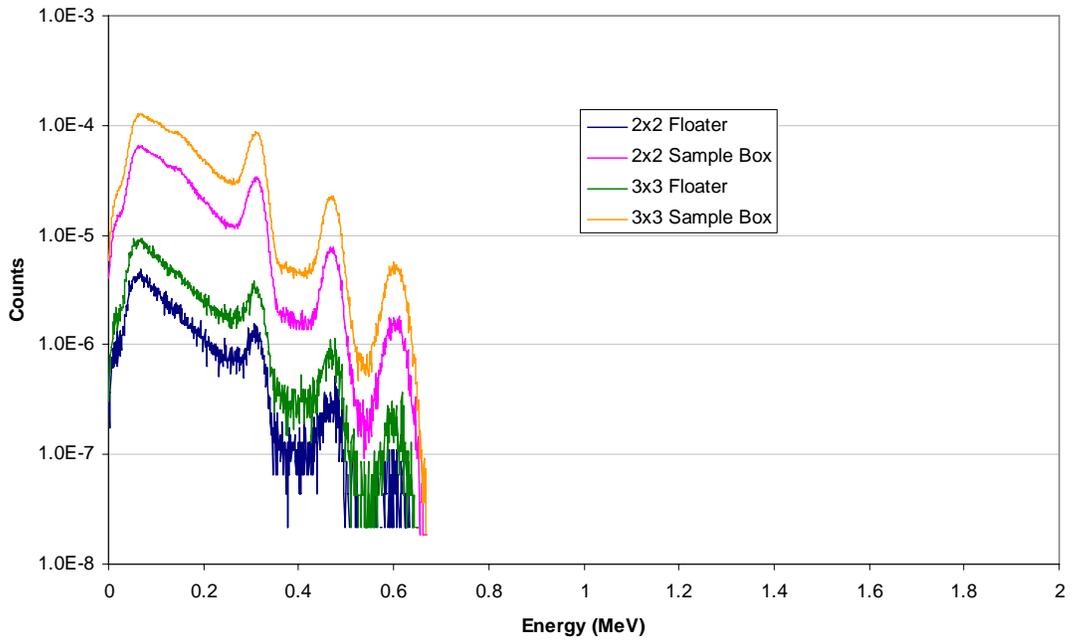
Figure 22. ^{192}Ir Detector Comparison. (Log Scale)
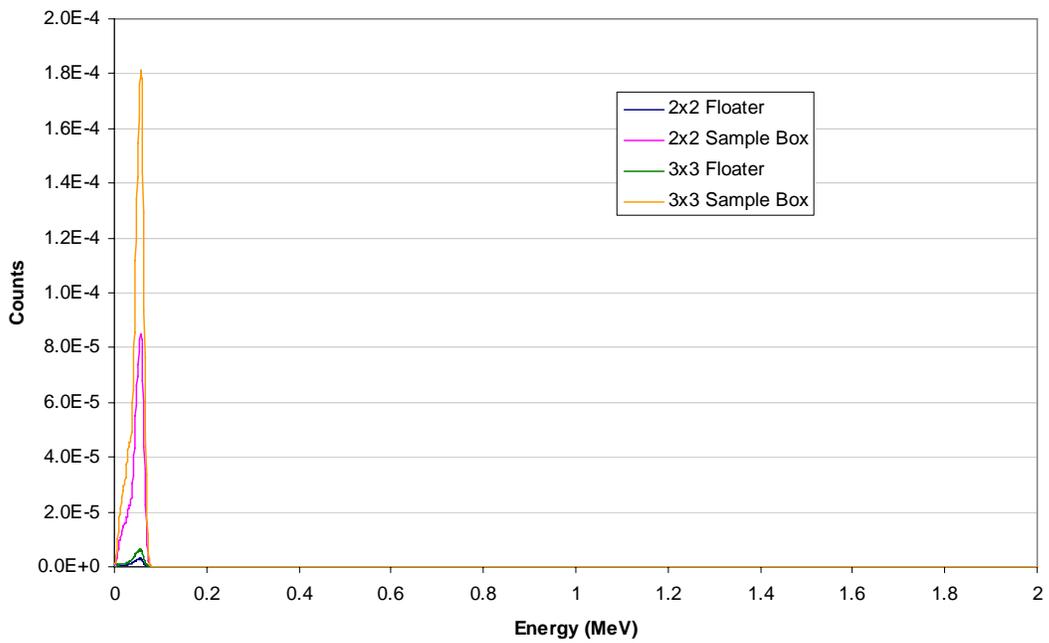
Figure 23. ^{241}Am Detector Comparison. (Linear Scale)
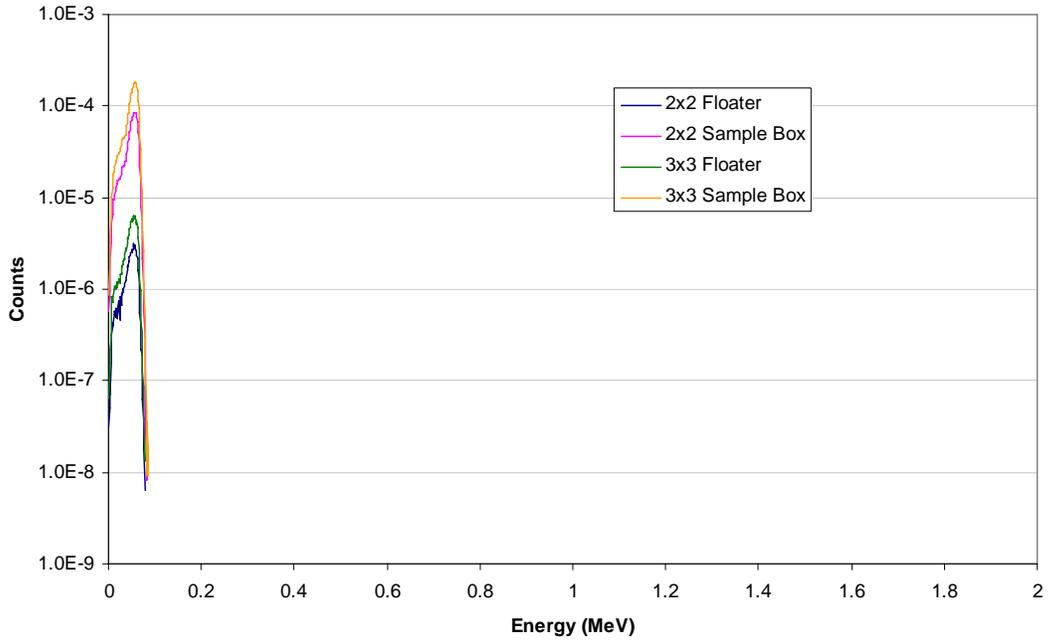
Figure 24. ^{241}Am Detector Comparison. (Log Scale)
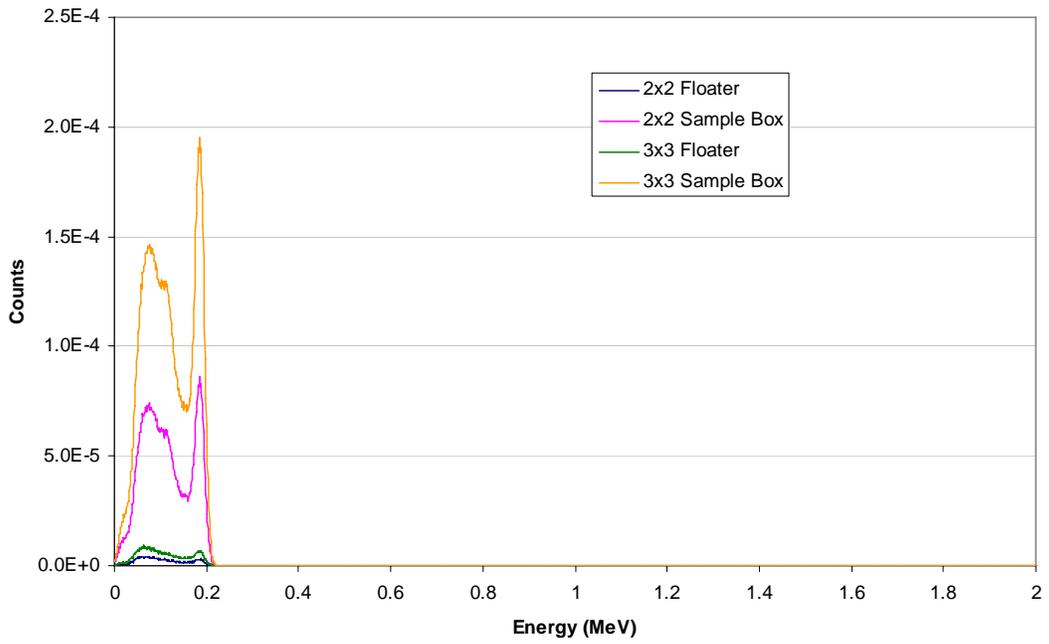
Figure 25. ^{226}Ra Detector Comparison. (Linear Scale)

46
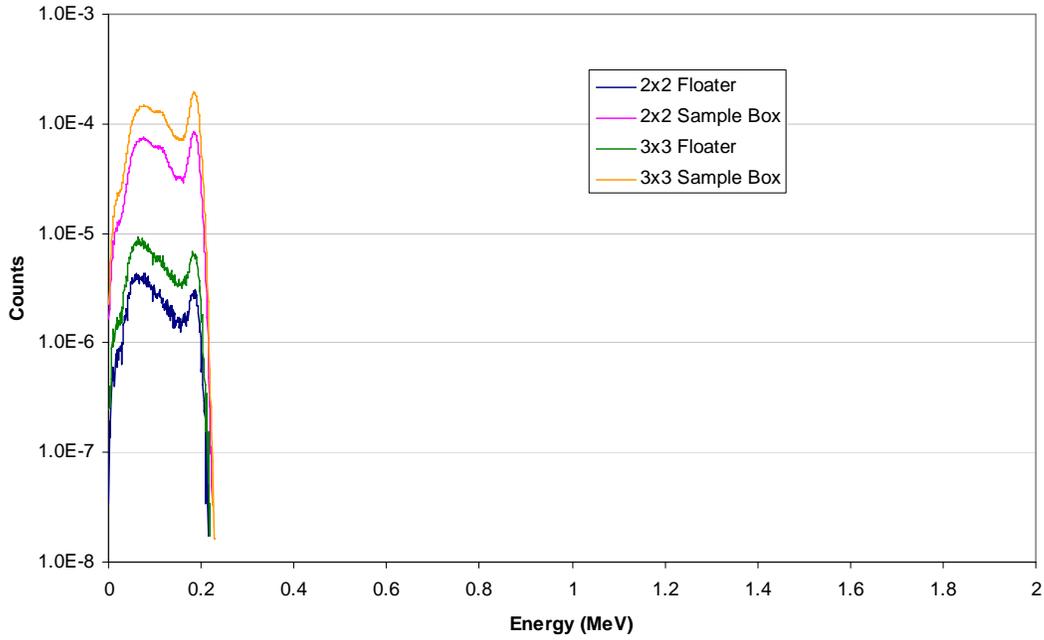
Figure 26. ^{226}Ra Detector Comparison. (Log Scale)
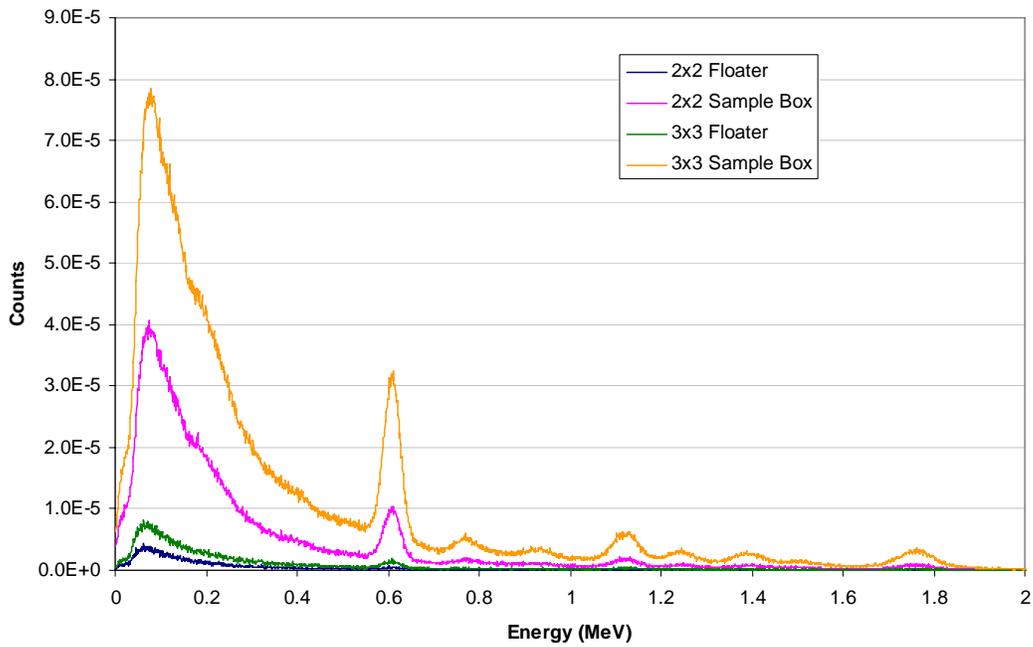
Figure 27. ^{214}Bi Detector Comparison. (Linear Scale)
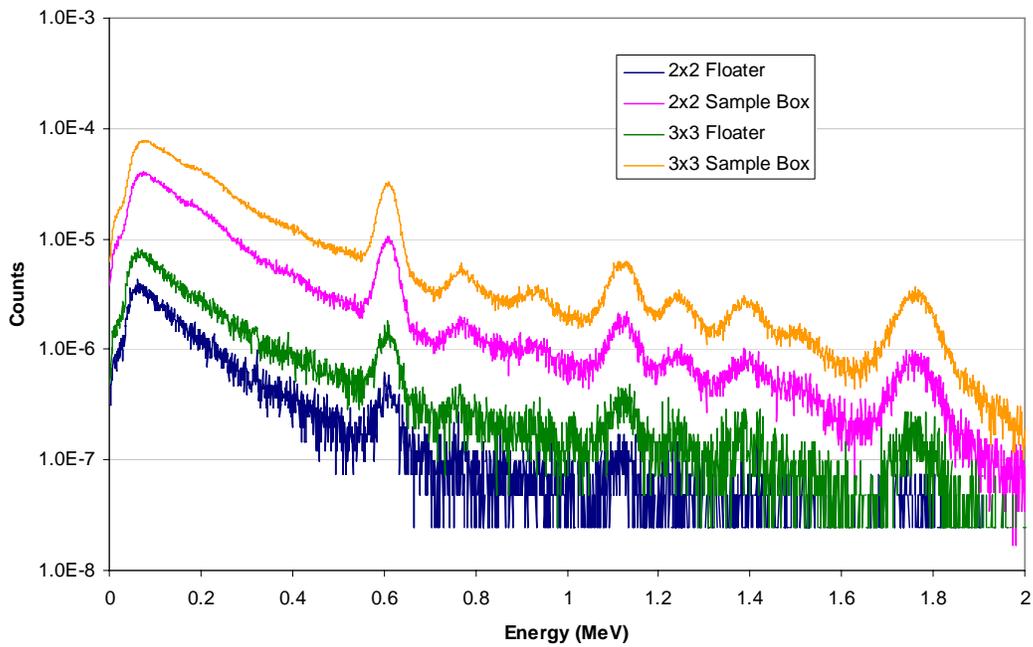
Figure 5. ^{214}Bi Detector Comparison. (Log Scale)
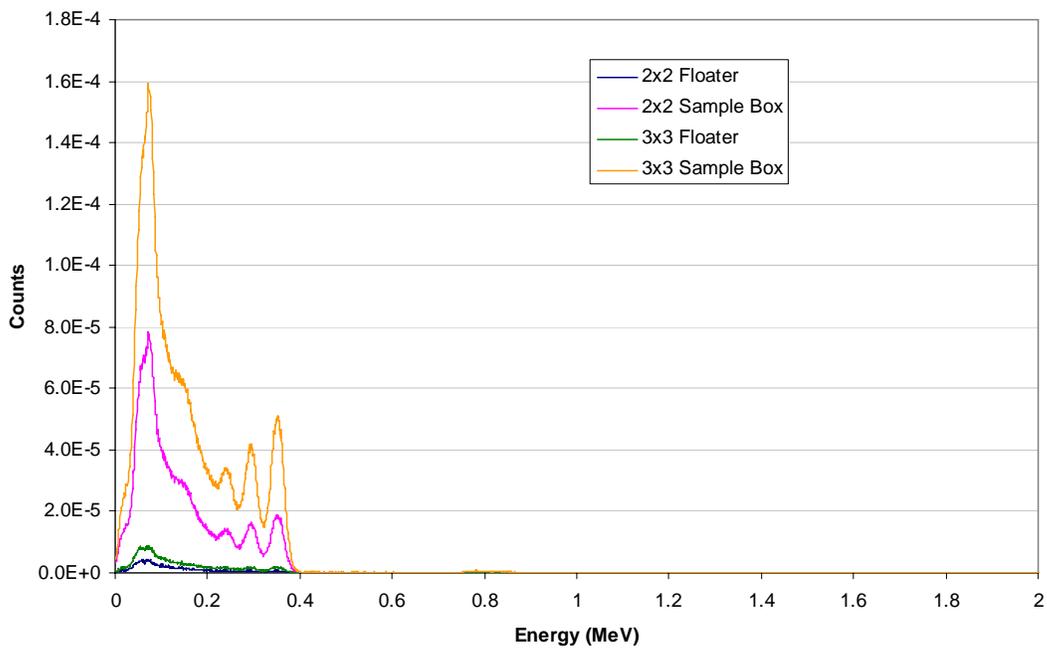
Figure 6. ^{214}Pb Detector Comparison. (Linear Scale)
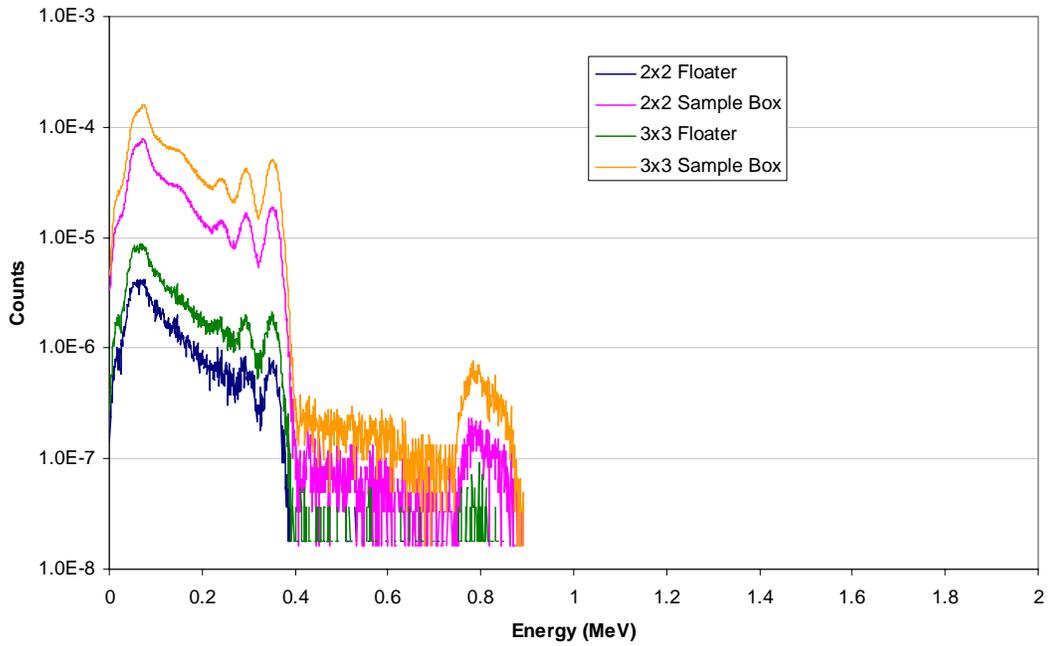
Figure 30. ^{214}Pb Detector Comparison. (Log Scale)
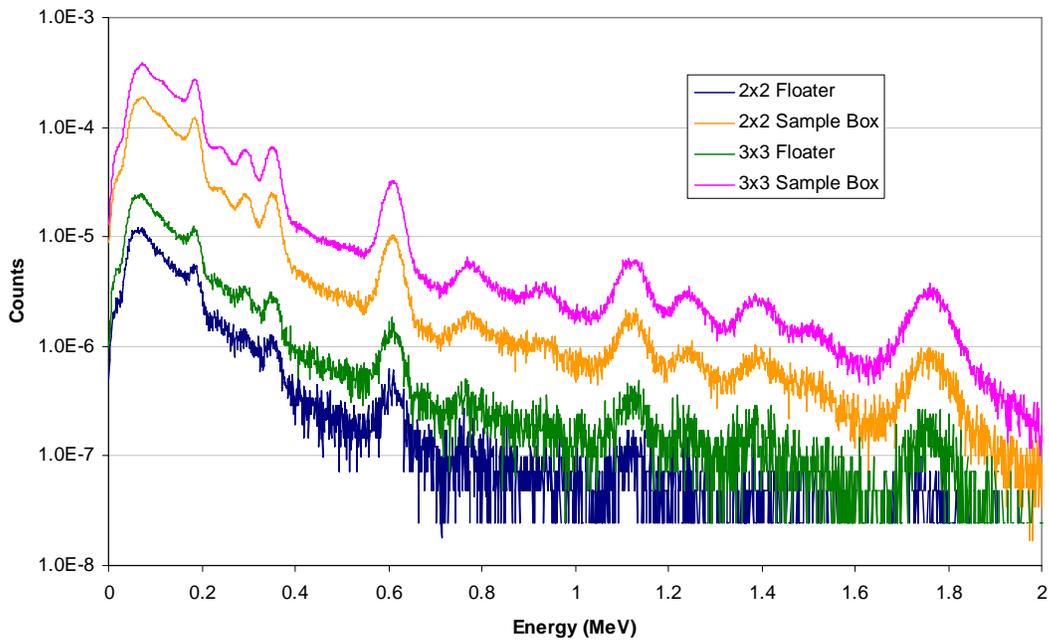
**Figure 31.** ^{226}Ra plus Progeny Detector Comparison, Radon Escape Fraction=0. (Log Scale)
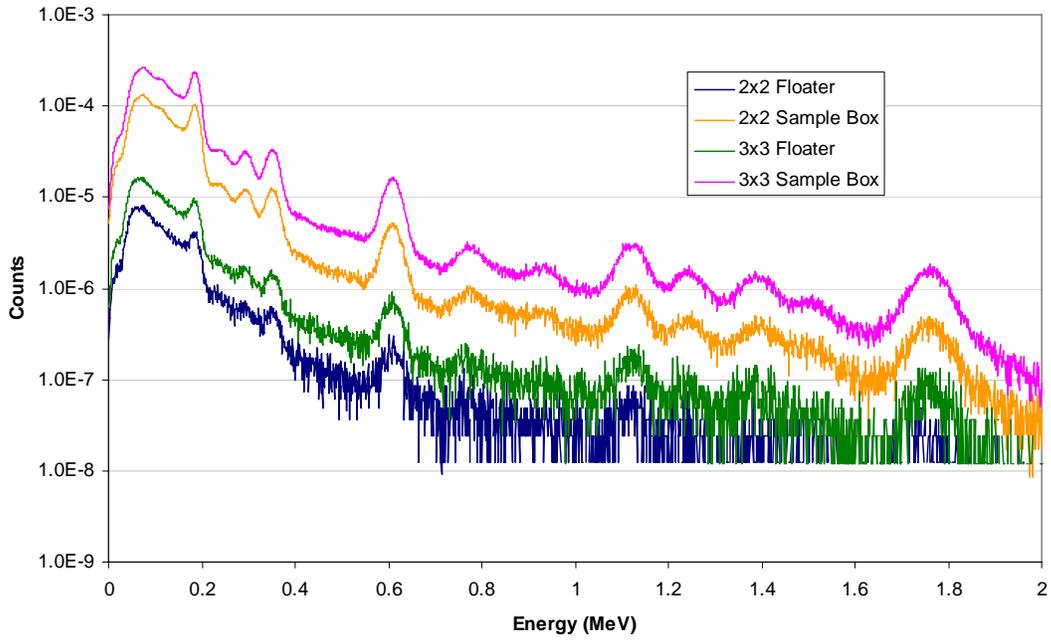
**Figure 32.** [226]Ra plus Progeny Detector Comparison, Radon Escape Fraction=0.5. (Log Scale)
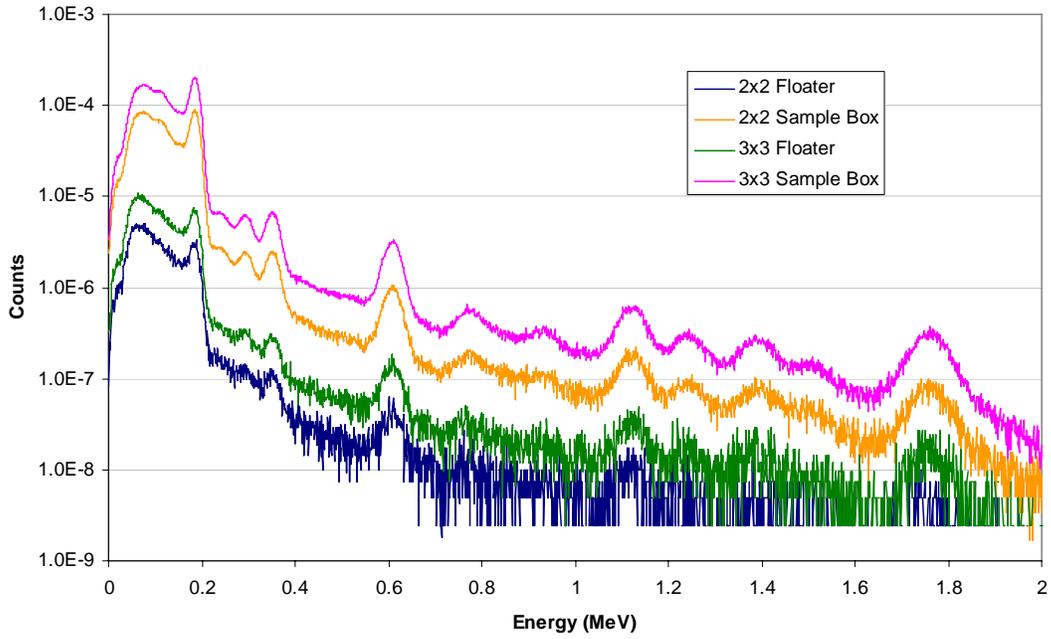
Figure 33. [226]Ra plus Progeny Detector Comparison, Radon Escape Fraction=0.9. (Log Scale)
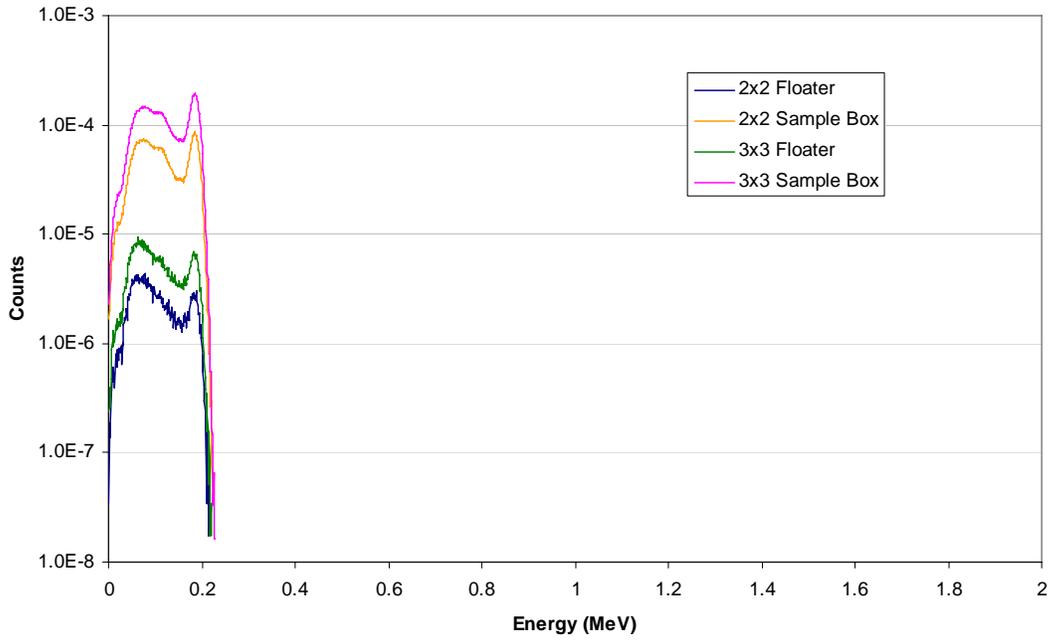
Figure 34. ^{226}Ra plus Progeny Detector Comparison, Radon Escape Fraction=1. (Log Scale)
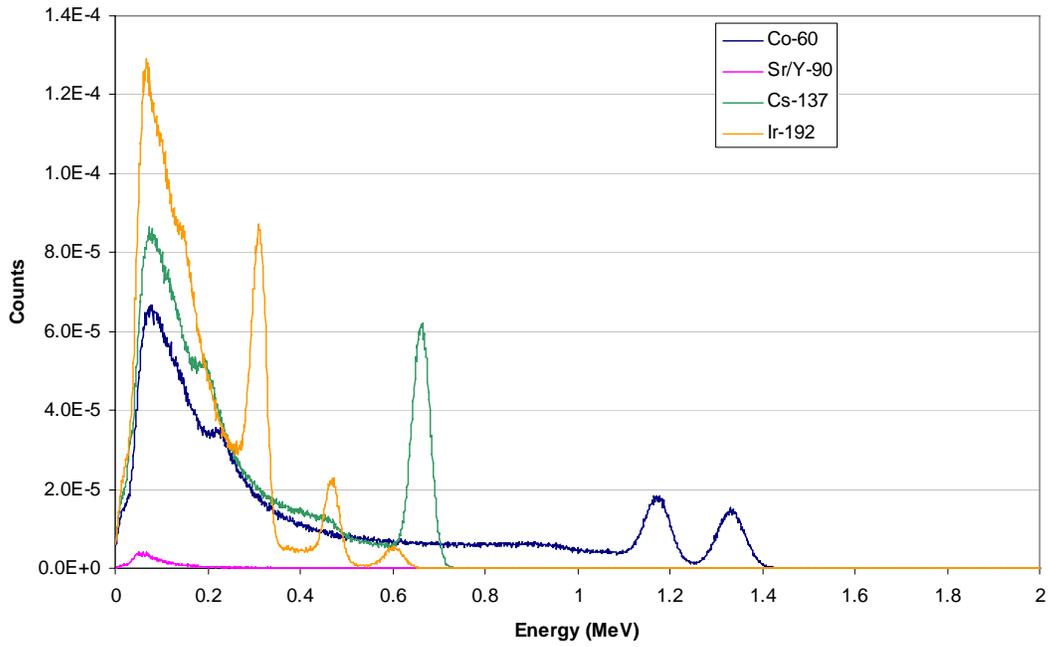
**Figure 35.** Multi Nuclide Detector Comparison. 3×3 Sample Box Detector
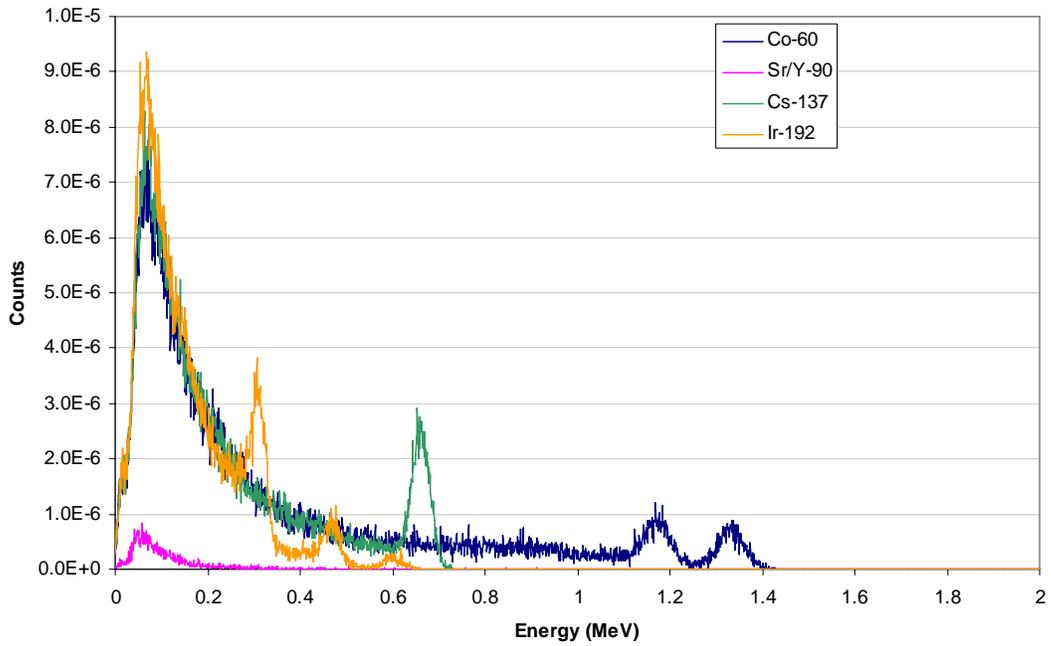
Figure 36. Multi Nuclide Detector Comparison. 3×3 Floating Detector
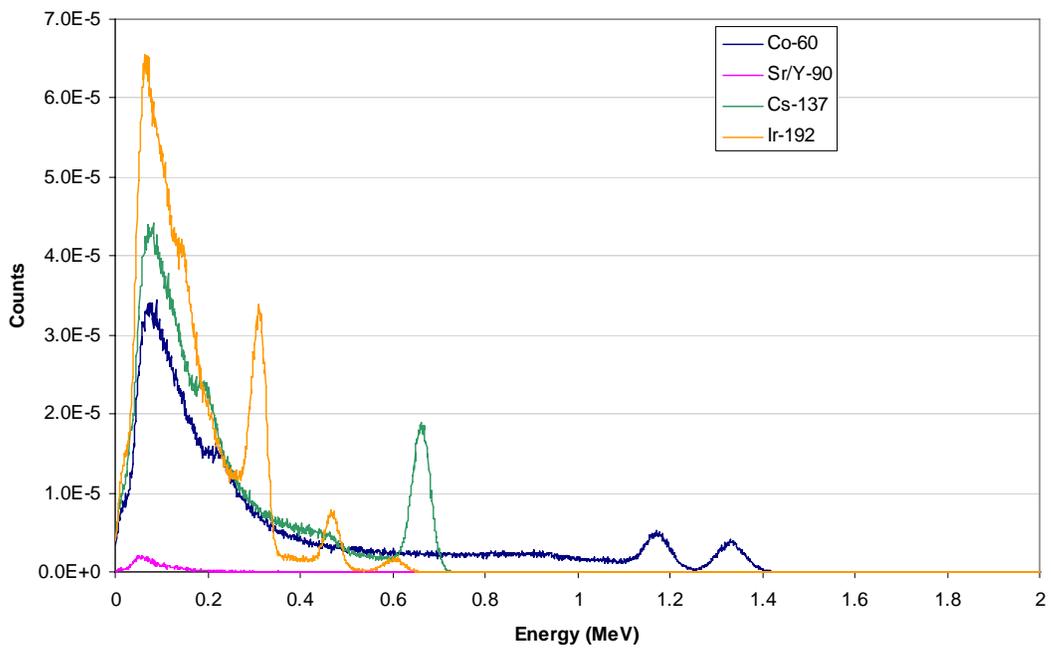

Figure 37. Multi Nuclide Detector Comparison. 2×2 Sample Box Detector
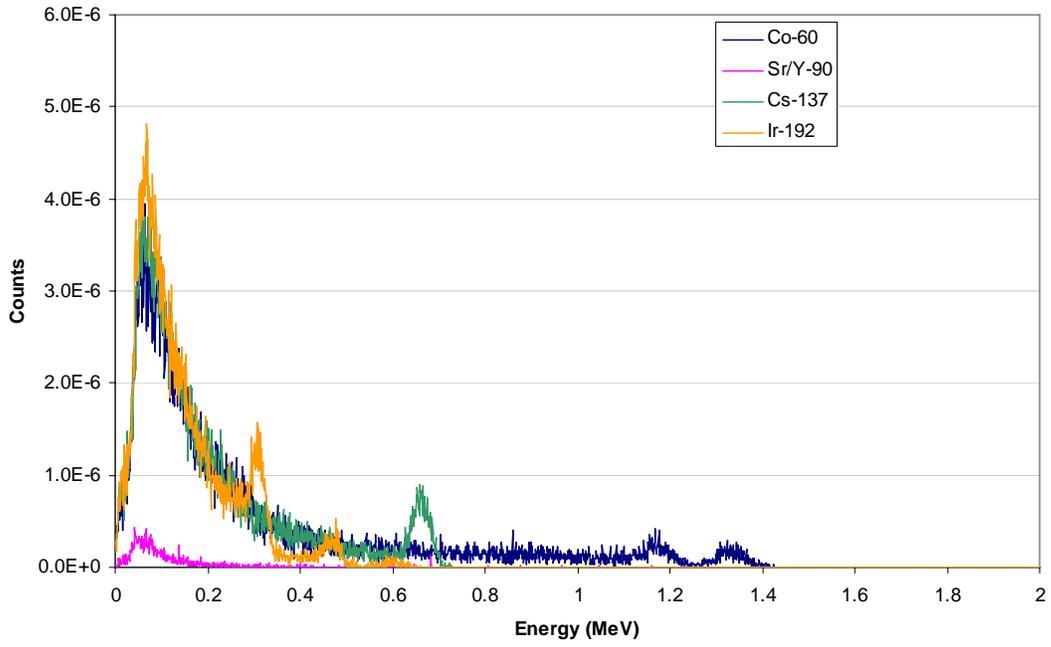
**Figure 38.** Multi Nuclide Detector Comparison. 2×2 Floating Detector
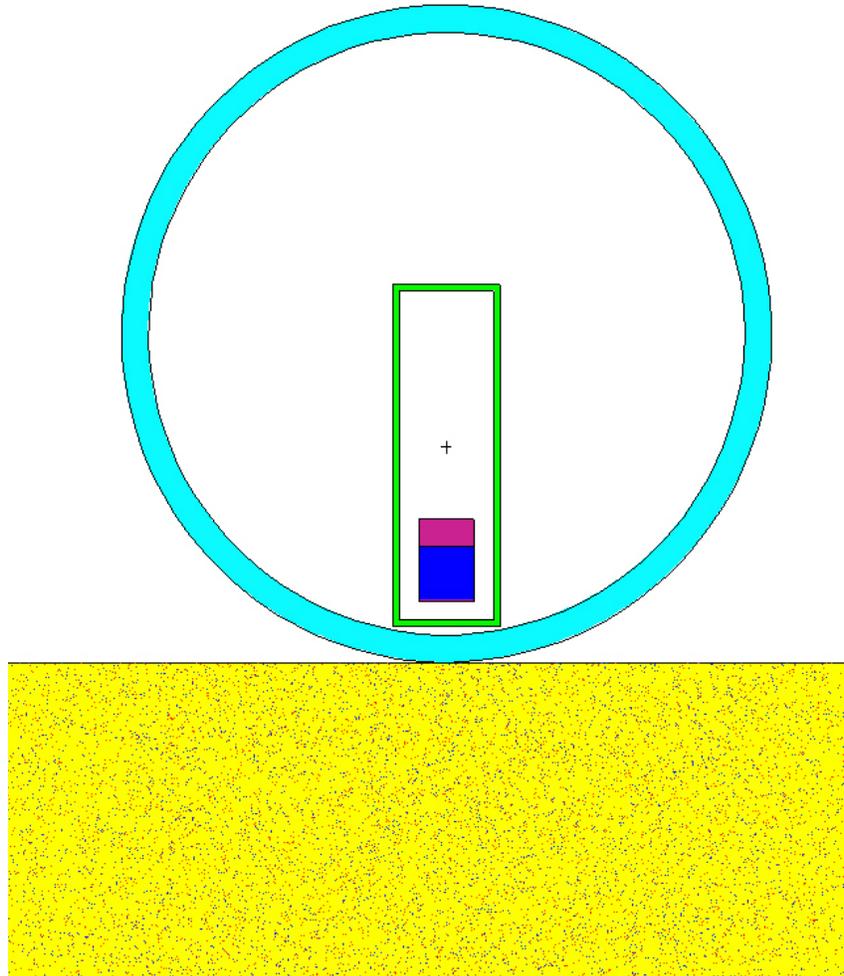
Figure 7. Floating detector cross section. Dark blue is NaI(Tl), yellow is water, light blue is rubber, green is PVC, magenta is aluminum. Dots in water represent locations of individual nuclear transitions.
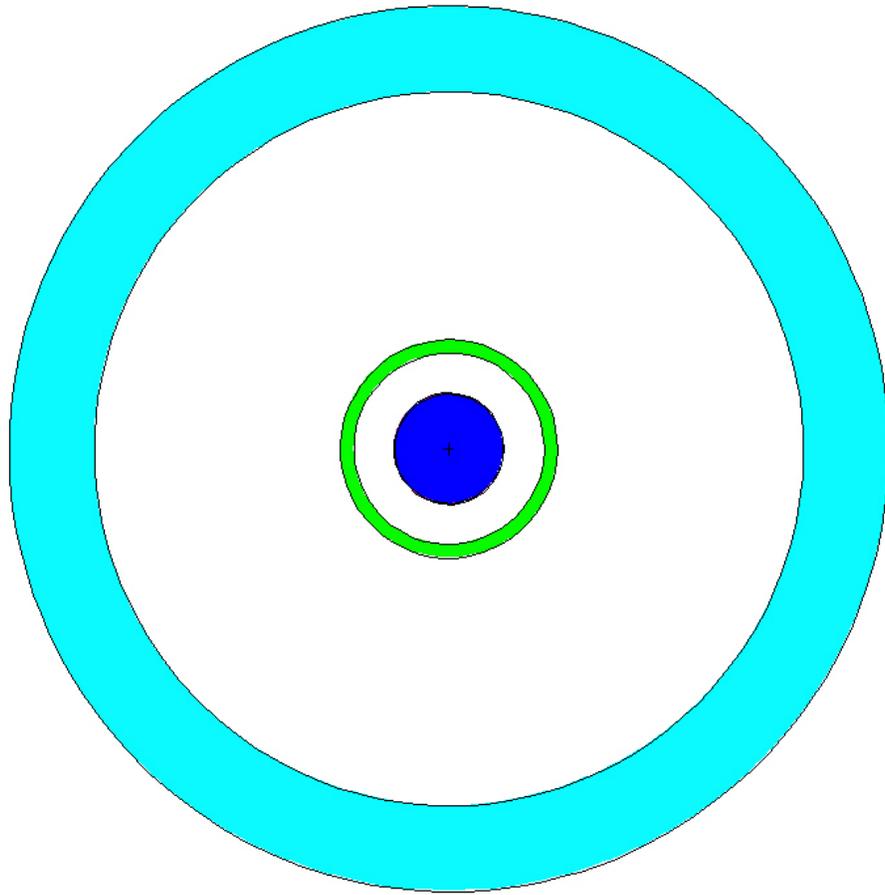
Figure 40. Floating detector horizontal cross section through sodium iodide crystal. Dark blue is NaI(Tl), light blue is rubber, green is PVC.
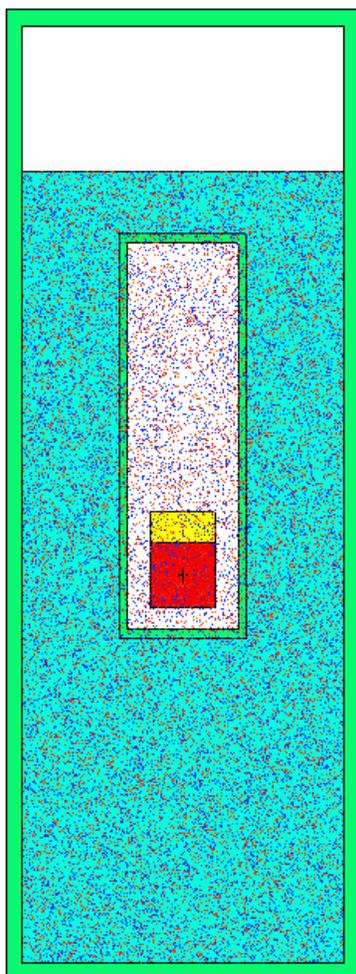
Figure 8. Sample box detector cross section seen from end. Red is NaI(Tl), green is PVC, light blue is water, white is dry air, yellow is aluminum. Dots in water represent locations of individual nuclear transitions in all planes, i.e., in front of and behind the detector suspended in the water.
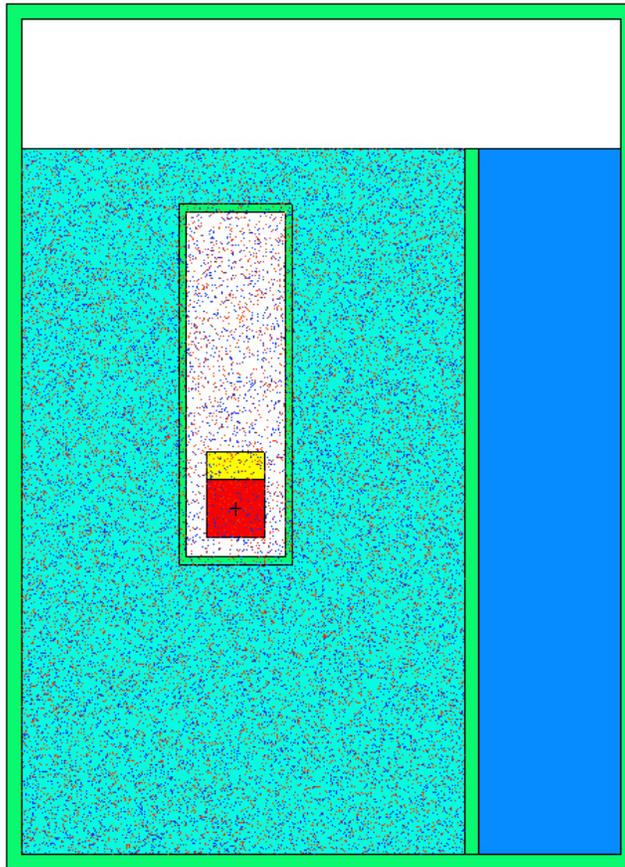
Figure 9. Sample box detector cross section seen from side. Red is NaI(Tl), green is PVC, light blue is water, dark blue is water at 50% density (that is, frothy, foamy water spilling over the top of the overflow), white is dry air, yellow is aluminum. Dots in water represent locations of individual nuclear transitions in all planes, i.e., in front of and behind the detector suspended in the water.
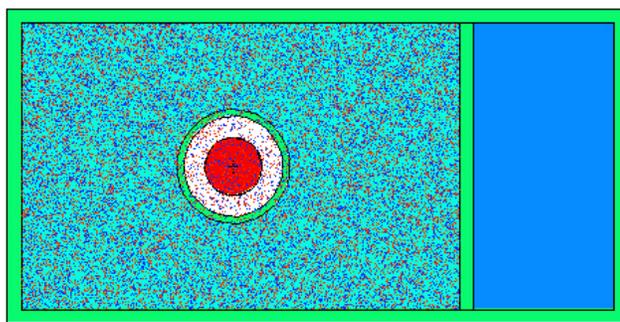
Figure 10. Sample box detector cross section (through detector) seen from top. Red is NaI(Tl), green is PVC, light blue is water, dark blue is water at 50% density (that is, frothy, foamy water spilling over the top of the overflow), white is dry air, yellow is aluminum. Dots in water represent locations of individual nuclear transitions in all planes, i.e., in front of and behind the detector suspended in the water.