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Phillips, Lance John, M.S.

San Jose State University, 1994

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***DEVELOPMENT AND CHARACTERIZATION OF A
DUAL PHOSPHOR ALPHA AND BETA RADIATION DETECTOR***

A Thesis

Presented to

Nuclear Science Program

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Lance John Phillips

May, 1994

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ABSTRACT

DEVELOPMENT AND CHARACTERIZATION OF A DUAL PHOSPHOR ALPHA AND BETA RADIATION DETECTOR

by Lance John Phillips

A new dual phosphor detector has been developed as an alternative to the gas ionization type. It allows detection and discrimination of both alpha and beta radiations, small and large configurations, portability, does not need a gas supply, and provides for similar radiation efficiencies as found for the gas proportional type detector. This detector is comparatively durable, has comparatively low manufacturing cost, and has low sensitivity to gamma radiation, which helps ensure a low background response.

Various detector configurations with differing detector surface areas, ZnS (Ag) inorganic scintillant thicknesses, plastic scintillator thicknesses, and photomultiplier tube mounting locations were tested. The best incorporated an edge mount photomultiplier tube, thin plastic scintillator (0.5 mm), a window of two layers of 0.25 mg/cm² aluminized mylar, and a very thin layer of ZnS (Ag) inorganic scintillant.

The average efficiencies and minimum detectable activities (as defined in American Nuclear Standards Institute, 1989 for a ten second count) across the face of the detector for the best detector configuration were approximately: 1% and 38 nCi for ¹⁴C (β, 0.156 MeV); 2.4% and 12 nCi for ¹⁴⁷Pm (β, 0.225 MeV); 9% and 2.3 nCi for ⁶⁰Co (β, 0.319 MeV); 18.5% and 1.0 nCi for ¹³⁷Cs (β, 0.512 MeV); 19.1% and 0.9 nCi for ²⁰⁴Tl (β, 0.763 MeV); 19.3% and 0.9 nCi for ⁹⁰Sr/⁹⁰Y (β, 0.546 MeV & 2.281 MeV); 31.3% and 0.13 nCi for ²³⁹Pu (α, 5.150 MeV); 31.6% and 0.13 nCi for ²⁴¹Am (α, 5.500 MeV).

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I. INTRODUCTION

A. Gas Filled Detectors

1. Detector Usage

Contamination is defined in the nuclear industry as the presence of radioactive material where it is not wanted. The regulatory and administrative limits on the release of personnel, equipment, and waste from locations that contain radioactive material in a form that may allow contamination to occur, fostered the development of various measurement instruments to satisfy these measurement needs. Different forms of radiation detection are utilized to locate and measure contaminating radioactive material throughout the nuclear, medical and research industries. Monitoring for alpha and beta radiations is normally accomplished using thin window detectors containing gas, operating in either the proportional or Geiger-Müller (GM) regions.

A detector operating in the proportional region can be made in various surface area configurations, from hand held size (20 to 100 cm²) for portable survey instruments, to large area surface monitors (greater than 600 cm²) for large area contamination monitoring of personnel, equipment, laundry, and waste. Most proportional detectors require a constant flow of gas to maintain gas purity within the detector (Knoll 1989). The gas supply systems require bulky and cumbersome gas cylinders, which must be replenished occasionally. This usually forces proportional counter systems to be stationary, non-portable systems.

2. Alpha and Beta/Gamma Radiation Discrimination - Proportional Counter

Proportional counter systems do provide good separation of the alpha and beta signals. Alpha radiations have a much higher value for linear energy transfer (LET) and, therefore, shorter range in the detection medium as compared to beta and gamma radiations of the same kinetic energy. For beta and gamma radiations of typical energies, the range in the detection medium exceeds the detector dimensions. This leads to much of the particle energy not being deposited within the detector volume. The number of ion pairs formed in the gas is proportional to only the amount of energy dissipated within the detector volume. Normally the range of alpha particles is smaller than the dimensions of the detector. This allows all of the alpha particle energy to be deposited within the detector volume, leading to higher pulse heights for alpha radiations as compared to beta and gamma radiations. The difference in pulse heights permits separate alpha and beta/gamma voltage plateaus. (Knoll 1989) Employing relatively simple electronic circuits allows the separation of the alpha and beta/gamma signals and, therefore, the determination of the levels of the individual types of contamination present. Since background in these types of detectors is mostly due to gamma radiation, the background rates encountered in the alpha signal are near zero. This allows vastly increased sensitivity to alpha-producing contamination as compared to beta/gamma-producing contamination.

Commercially available alpha/beta sensitive gas flow proportional counters have efficiencies to alpha radiation that range from 15 to 25 percent. Beta radiation efficiencies for ^{137}Cs and $^{90}\text{Sr}/^{90}\text{Y}$ are approximately 30 and 35 percent.

3. Alpha and Beta/Gamma Radiation Discrimination - Geiger-Müller Counter

The detectors operated in the GM region do not require a gas supply and, therefore, are usually portable, but do not allow the separation of the alpha and beta/gamma pulses. Also, this type of detector usually has detector window and wall thicknesses sufficient to prevent any alpha particles from entering the chamber. Any kind of ionizing radiation that enters the detector may lead to the formation of at least one ion pair. The formation of a single ion pair in the fill gas will trigger a full geiger discharge. Any information about the kinetic energy or the LET of the radiation is lost during the full discharge. Being able to identify the LET of the radiation allows the separation of the alpha and beta/gamma signals. In many cases, regulatory limits for radioactive contamination by alpha or beta/gamma emitters are significantly different. The Nuclear Regulatory Commission's guide on radiation surveys at medical institutions (U.S. Nuclear Regulatory Commission 1981) states a limit of 100 dpm/100 cm² for most alpha emitters and 5000 dpm/cm² for most beta/gamma emitters. The Health Physics Society standard (Health Physics Society 1988) states a limit of 300 dpm/100 cm² for most alpha emitters and 5000 dpm/cm² for most beta/gamma emitters. To perform the surveys adequately, the signals need to be separated to allow the establishment of separate alarm points. If the signals are not separated, the background levels are normally too high to allow adequate sensitivity to achieve the normally lower limits established for alpha producing radioactive material contamination.

A second serious drawback in the use of GM detector systems for monitoring contamination on waste, laundry, equipment or personnel is the small surface area configurations, normally from 20 to 100 cm².

4. Detector Window Thickness

Both detectors require very thin windows to allow the radiations to penetrate. The alpha particle range can be determined by examining Figure 1 (Data from Attix 1986). This figure shows the continuous slowing down approximation (CSDA) range of a proton. Due to the z^2 (z is the charge of the alpha particle) dependence of the charged particle stopping power, the range of the alpha particle at an energy E_α is equal to the range of a proton at an energy of $E_\alpha/4$.

Equation 1, derived from discussion in Attix (1986), shows how to relate the CSDA range of a proton to the CSDA range of an alpha particle when the kinetic energy of the alpha particle is a factor of four times greater than that of the proton:

$$\text{at } \frac{1}{4}E_{\alpha} = E_p \quad \text{Range}_{CSDA}^{\alpha} \left(\frac{mg}{cm^2} \right) \cong \text{Range}_{CSDA}^p \left(\frac{mg}{cm^2} \right) \quad (1)$$

For example, to determine the range of an alpha particle of 4 MeV penetrating a window of carbon, the range of a 1 MeV proton penetrating the same window of carbon must first be determined from Figure 1. In this example, the alpha particle has a range of approximately 4 mg/cm². This is comparable to skin, which is considered to have an average thickness of the dead layer of 7 mg/cm² (International Council on Radiation Protection 1977). A survey of some of the commercially available detectors for alpha radiations listed window thicknesses of 0.5 to 0.85 mg/cm².

The beta particle range can be determined by using equation 2 (Shleien 1992). For example, a beta particle with a maximum energy of 0.16 MeV (¹⁴C) has a range of approximately 30 mg/cm². A survey of some of the commercially available detectors for beta radiations listed window thicknesses of 20 to 30 mg/cm².

$$\text{Range}_{\beta} \left(\frac{mg}{cm^2} \right) = 412 \times E^{(1.265 - 0.0954 \times \ln E)} \quad (2)$$

where: E=Maximum energy of the beta in MeV

The objective of this investigation is to develop a detector that has the worthwhile properties of the gas filled detectors, without some of their shortcomings. The goal of the

design is to allow small and large configurations, portability, no gas supply and alpha and beta discrimination. This detector must be durable, should have relatively low manufacturing cost and have very little sensitivity to gamma radiation, especially in the alpha channel, to ensure low background response.

B. Scintillation Detectors

1. Silver Activated Zinc Sulfide

Silver activated zinc sulfide (ZnS (Ag)) is one of the oldest forms of inorganic scintillation material ever used. It has a very high scintillation efficiency comparable to that of NaI(Tl), but is available only as a polycrystalline powder (Knoll 1989). ZnS (Ag) is opaque to its own light pulses and must be applied in a very thin layer to allow the scintillations to be received by the photomultiplier tube (PMT). Thicknesses of greater than about 25 mg/cm² become unusable due to this self attenuation (Knoll 1989). As a result, it is usually limited to thin layers used primarily for alpha particle or other heavy ion detection. Normally, it is applied to a light proof layer of aluminized mylar and light coupled in some manner to a PMT to convert the resultant light pulses to electrical pulses. Its ability to detect alpha radiations is well documented and the material is still in wide use today (Fisenne and Keller 1981). ZnS (Ag) is a commercially available substance and is relatively inexpensive due to the small amounts required to achieve the discussed thin layers.¹

¹ Inorganic Phosphors and Related Chemicals - A Reference. GTE Products Corporation; Chemical and Metallurgical Division; Towanda, PA; 1988.

2. Plastic Scintillation Material

Plastic scintillators are comprised of organic scintillation material which is dissolved in a solvent and then subsequently polymerized. Plastic scintillators are commercially available in a variety of shapes and sizes including rods, cylinders, flat films and relatively thick sheets. This material is also inexpensive when compared to inorganic scintillators. Nuclear Enterprises Technology Limited of Edinburgh, Scotland, manufactures one of the most commonly used plastic scintillators, referred to as NE102A.² It is a multipurpose scintillator used for alpha, beta, gamma, and fast neutron detection (Knoll 1989). National Nuclear Corporation of Sunnyvale, CA uses plastic scintillation material with NE102A type material being used predominantly in the company's numerous types of radioactive contamination monitoring equipment.³

NE102A plastic scintillator can detect alpha, beta and gamma radiations. The scintillation efficiency for heavy charged particles such as alpha particles or protons is always *lower* than that for beta or gamma radiations (Attix 1986). As in gas ionization type detectors, this relationship is also due to the different LET values for alpha particles as compared to those for the beta/gamma radiations. However, in plastic scintillator the higher values of LET, and, thus, higher ionization densities for the alpha particles leads to quenching from damaged molecules and a consequent lowering of the scintillation

² Published Product Literature. Nuclear Enterprises Technology Limited of Edinburgh, Scotland. 1992

³ Published Product Literature. National Nuclear Corporation, Sunnyvale, CA. 1993

efficiency as compared to that for the beta/gamma radiations (Attix 1986). Figure 2 illustrates this difference for electrons and protons (Data from Attix 1986). At low energies of a few hundred keV, the response to protons is smaller by a factor of ten compared with the light yield of equivalent energy electrons. At higher energies the discrepancy is less, but the proton response is always less than the electron response. This relationship holds true for alpha particles as well. However, most alpha particles of interest have energies in the range of four to six MeV. At these energies the discrepancy is even smaller. This makes it very difficult to differentiate the pulses created by the alpha radiations from the pulses created from the beta/gamma radiations using pulse height analysis. Therefore, plastic scintillator alone is usually not used when alpha/beta discrimination is required.

Combining the desirable properties of NE102A plastic scintillator with that of ZnS (Ag) inorganic scintillator in one detector may provide an alternative alpha/beta radiation measurement method to plastic scintillator alone or gas ionization type detection systems.

3. Measurement Concept and Design

The proposed solution is to optically couple a thin layer of ZnS (Ag) to the surface of the NE102A plastic scintillator to create a dual phosphor detector sandwich that possesses the ideal properties of both types of scintillation material. The ZnS (Ag) would primarily respond to the alpha radiation and be applied ideally in a very thin layer to allow transparency to the beta radiations. The plastic scintillator would mainly respond to the beta/gamma radiations, due to most of the alpha radiations being removed by the ZnS (Ag) from the impinging radiation flux prior to reaching the plastic scintillator. The plastic scintillator would act as a light pipe for both its own fluorescence and that from the ZnS (Ag). A PMT would be optically coupled to the plastic scintillator to convert the fluorescence from both materials to an electrical signal. The wavelength of maximum emission is 423 nanometers for the NE102A and 450 nanometers for ZnS (Ag) (Knoll 1989). Since the two wavelengths are relatively close to each other, this should allow the use of only one type of PMT for both wavelengths. The PMT used was a "Bialkali" type manufactured by Hamamutso Corporation and the wavelengths of the emissions were well within the parameters for the tube listed by the manufacture.⁴ The relative pulse height

⁴ Hamamutso PMT Catalog. Hamamutso Photonics. Shizuoka, Japan. 1988.

resultant from an alpha interaction in the ZnS (Ag) is approximately a factor of five times greater than the resultant pulse height from a beta/gamma radiation in NE102A plastic (Knoll 1989). The principal decay constant for the ZnS (Ag) pulse is a factor of 100 times longer than that found for the NE102A plastic (Knoll 1989). Since the ZnS (Ag) alpha scintillations produce a much larger pulse height and longer pulse duration relative to the plastic scintillator, separation of the alpha and beta/gamma signals in such a dual phosphor detector could be done with a relatively simple electronic circuit. The main drawback to the longer pulse duration of the ZnS (Ag) is the advent of detector system dead time considerations. Relatively simple algorithms routinely correct for dead time in a variety of detection systems and could be employed here, if necessary. However, the monitoring of low levels of alpha contamination with a ZnS (Ag) system should not result in count rates great enough to encounter significant levels of dead time.

A literature search for information applicable to the use of ZnS (Ag) and plastic scintillator was performed at the Stanford Physics library, UCSF library, and by contacting Nuclear Enterprises technical department. The two local university libraries provided articles on various uses of ZnS (Ag) scintillator, while Nuclear Enterprises provided literally a list of hundreds of different references on the various uses of plastic scintillator. However, none of the articles or text discussed the incorporation of the two scintillators into one detector.

Various means of optically coupling the ZnS (Ag) to the plastic scintillator were tried. The developed application technique and the related details of the technology are

considered proprietary information of National Nuclear Corporation of Sunnyvale, CA and are discussed briefly here with their permission. A mixture of toluene and ZnS (Ag) powder sprayed onto the surface of the plastic scintillator worked best. The toluene dissolves the outer layer of the plastic scintillator and evaporates rapidly. As the plastic hardens the ZnS (Ag) adheres to it and no glues or any other chemicals are left behind to interfere with the optical coupling or radiation penetration of the two scintillators. This spray technique allows the application of an extremely thin layer of ZnS (Ag) to the plastic scintillator surface. This ensures that the majority of the beta radiations will penetrate the ZnS (Ag) layer and deposit their energy in the plastic scintillator.

The focus of this investigation will be to understand some of the basic characteristics of this new type of detector, to test and compare various detector configurations, and to decide if it is a suitable replacement or alternative for the gas ionization type detectors that have been in common use for many years. The basic characteristics that will be explored here for each detector configuration are Minimum Detectable Activities (MDA) (American Nuclear Standards Institute 1989), efficiencies to various alpha, beta, and beta/gamma sources, beta energy dependence, and surface response uniformity due to efficiency variations with source location on the detector surface.

II. DETECTOR CONFIGURATIONS AND TEST PROCEDURES

A. 4" x 4" Surface Area Detector

The first detector tested had a surface area of 4" x 4" and was 1.5" thick. The PMT was vertically mounted. The ZnS (Ag) was mounted on a sheet of NE102A plastic scintillator, 1.5" thick. See Figure 3 below.

The aluminized mylar used on all of the detectors tested here was 0.25 mg/cm². Two layers of this material yielded a delicate, but light tight, thin window for the detector. The remainder of the detector was wrapped with aluminized mylar and aluminized tape covered with a layer of black plastic tape to ensure a complete light seal and provide a strong, durable outer surface.

B. 8" x 12" Surface Area Detectors

After obtaining the results for the 4" x 4" detector, some changes in the PMT location and ZnS (Ag) layer thickness were made in the design to allow improvement.

The reasons for the changes will be discussed further in Section III of this report. Two new detectors were made, one with a vertical mounted PMT (See Figure 4), as in the previous design, and the other with an edge mount PMT (See Figure 5). Both detectors were increased to an 8" x 12" surface area to examine potential light collection degradation due to increased detector size.

The same two layers of 0.25 mg/cm² aluminized mylar were used, with the same wrapping techniques. The spray technique was improved to allow a thinner, more uniform layer of ZnS (Ag) to be applied. And finally, a thin, 0.5 mm thick sheet of NE102A

plastic scintillator mounted to a 1.5" thick acrylic light pipe was used in place of the solid 1.5" thick scintillator.

C. System Configuration and Setup

All of the detectors were tested using a standard National Nuclear Corporation electronics setup, including high voltage power supply, pulse shaping amplifier with a controllable pulse height discriminator, analog-to-digital converter, and microprocessor driven counter. The system was connected to a printer and all results were printed. Each PMT had an emitter follower type preamplifier and voltage divider connected to it. The emitter follower type preamplifier used does not perform amplification, since it only has a gain of one. Its primary function is to match the impedance of the PMT to that of the amplifier.

Each detector's beta channel was optimized for best "figure of merit" performance using a ^{60}Co source. The "figure of merit" is defined as the net count rate squared divided by the background rate (Knoll 1989). Both the appropriate high voltage and discriminator settings were determined to allow for the best combination of low background count rate and efficiency by maximizing the formula for the "figure of merit."

The alpha channel settings were determined by placing a $^{90}\text{Sr}/^{90}\text{Y}$ source on the detector and raising the discriminator level to eliminate the beta pulses. The channel was then checked with a ^{239}Pu source to show that alpha pulses were still being measured.

D. Testing Procedures

The detectors were tested with six beta or beta/gamma emitting sources (^{14}C , ^{147}Pm , ^{60}Co , ^{137}Cs , ^{204}Tl and $^{90}\text{Sr}/^{90}\text{Y}$) and with two alpha emitting sources (^{239}Pu and ^{241}Am). The associated activities, half-lives, beta and alpha energies and abundances are listed in Table 1.

The testing included sixty second background counts and twenty second source counts. Count rate errors were calculated for each measurement using the following equation:

$$\text{Net Count Rate Error} = \frac{\sqrt{\left(\frac{\text{Source Rate}}{\text{Count Time}} + \frac{\text{Background Rate}}{\text{Background Time}}\right)}}{\text{Net Count Rate}} \quad (3)$$

The MDA was determined for each measurement using the following equation (American Nuclear Standards Institute 1989):

$$\text{MDA (nCi)} = \frac{4.65 \times \sqrt{\frac{\text{BR}}{\text{CT}}}}{\text{EFF.}} \quad (4)$$

where: BR=Background Rate in cps
CT=Count Time in seconds, 10 seconds used
EFF.=Efficiency in counts per nCi

A count was done in the alpha channel to confirm a zero net count rate with a $^{90}\text{Sr}/^{90}\text{Y}$ source present and no beta radiation signal cross talk into the alpha channel. A count was done with the alpha sources using the beta channel to determine the cross talk of the alphas into the beta region.

The 4" x 4" detector was tested with the sources at five locations across the face of the detector, while both 8" x 12" detectors were tested at nine separate locations across

the face of the detector (See Figure 6). The measurements were made with the sources in contact with the detector window to eliminate any error introduced by placing the source at some measured distance. No screening material was used due to the attenuation caused by the material and the possibility that holes in the screen would not consistently align with the radioactive point sources used. It is understood that in a practical situation the radioactive material will be some distance away from the detector and a screening material will be necessary to protect the delicate detector window. Both of these factors will reduce the detectors efficiency to alpha and beta radiations, with a larger effect on the alpha radiation response.

To allow the determination of beta radiation attenuation by the ZnS (Ag) layer, the 8" x 12" detectors were tested both before and after the application of the inorganic scintillant.

III. RESULTS and DISCUSSION

The following results are for the five different detector configurations tested.

Lessons learned from the initial design are incorporated into the revised designs.

Unanswered questions generated by the initial design are explored further with the revised designs. The final design tested yielded the best overall performance.

A. 4" x 4" Vertical Mount Detector with Thick Plastic Scintillator & ZnS(Ag)

1. Detector Setup and Measurement Errors

The first detector tested measured four inches square, by one and one-half inches thick (See Figure 3). The detector measurement results are presented in Tables 2 through 9 for the various nuclides tested. The detector optimization (See section II C) to ^{60}Co and ^{239}Pu resulted in the following settings: high voltage equal to 700 volts; beta channel lower level discriminator of 0.98 volts; alpha channel lower level discriminator of 8.0 volts. The backgrounds at these settings were 25 cps in the beta channel and 1 cps in the alpha channel respectively. The beta cross over into the alpha channel was checked with the $^{90}\text{Sr}/^{90}\text{Y}$ source and found to yield a zero net count rate. The source measurement count rate errors were below five percent in all cases except when measuring the ^{14}C and ^{147}Pm sources. The errors were greater for the ^{14}C and ^{147}Pm measurements due to the low count rates generated by the detector. The results for the beta and beta/gamma source measurements will be discussed first.

2. Beta Particle Detection Performance

Only one measurement at the center of the detector is listed for the ^{14}C source. The measurements at the other locations on the detector surface area showed zero efficiency to the weak beta particles. The measurement at the center of the detector show a very low efficiency of only 0.02%. With the detector window being only 0.5 mg/cm^2 , the 156 keV beta particles from the ^{14}C should penetrate the window. Once the ^{14}C betas penetrate the window, they must then penetrate the ZnS(Ag) before interacting with the plastic scintillator. Because it can be assumed that the weak betas are penetrating the window, the ^{14}C beta particles must be attenuated by a different mechanism. The most probable causes could be: first, the inability of the plastic scintillator and the detector system with its associated electronics to measure such a low beta particle energy; or second, the ZnS(Ag) layer not allowing the beta particles to penetrate to the plastic scintillator layer. To answer this question a new detector was manufactured and measurements were accomplished before and after the ZnS(Ag) layer was applied (See section III parts B, C, D, E).

The results for the ^{147}Pm , ^{137}Cs and the ^{204}Tl sources also show lower than expected efficiencies. Measurements were made at the five locations over the face of the detector as discussed in section II D. They show a very large discrepancy between the measurement made on top of the PMT location as opposed to the measurements at the outside edges of the detector. The ^{147}Pm efficiency at the detector center was 2.5%, but the efficiencies at the corners were all below 0.16%. The ^{137}Cs efficiency at the detector

center jumped to almost 20%, but the corners fell off to less than 7.7%. The ^{204}Tl efficiency at the detector center was approximately 16%, while the detector corners dropped to below 4.2%. The efficiency variations appear to be strongly dependent on the PMT location. To confirm this observation two identical detectors were made, one with a vertical mount PMT and one with an edge mount design as shown in section II of this report.

Both the ^{60}Co and the $^{90}\text{Sr}/^{90}\text{Y}$ source measurements showed relatively high efficiencies and demonstrated reasonable surface response uniformities as compared to the other beta/gamma source measurements. The efficiencies determined for the ^{60}Co source were approximately 14.5% at the detector corners and 21% at the detector center. This lead to an average MDA for ^{60}Co of 1.29 nanocuries. With the $^{90}\text{Sr}/^{90}\text{Y}$, the efficiencies found were approximately 21% at the detector corners and 26% at the detector center, which lead to an average MDA of 0.91 nanocuries.

With the $^{90}\text{Sr}/^{90}\text{Y}$ source, the ^{90}Y beta is of a significantly higher average and maximum energy than that released by the other isotopes measured here (See Table 1). This energy must be significant enough to overcome the detection barriers found for the other beta energies and allow good detectability.

The ^{60}Co beta energy is significantly lower than that of either the ^{137}Cs or ^{204}Tl sources. However, ^{60}Co does have two high energy gammas; 1.17 MeV and 1.33 MeV, which are both emitted with a branching ratio of 1 with each decay (Bromne and Firestone 1986). The 4" x 4" detector incorporated plastic scintillator was 1.5 inches thick. This

thickness allows good efficiency to gamma radiations (Brownell 1961). The assumption is also supported by other measurement results. The ^{137}Cs results are slightly better than the ^{204}Tl results, even though ^{137}Cs has a lower average and maximum beta energy. A 662 keV gamma is emitted with a branching ratio of approximately 0.85 shortly after a ^{137}Cs decay (Brownell and Firestone 1986). Attenuation of this gamma ray may explain the unexpected increase in efficiency. To address the problem, the next detectors were made with thin, 0.5 mm, plastic scintillator, to minimize the gamma response (See section III parts B, C, D, E).

3. Alpha Particle Detection Performance

The alpha response, for both of the alpha sources measured, yielded very different results compared to the beta response measurements. Both the ^{239}Pu and the ^{241}Am source measurements showed relatively high efficiencies and maintained good surface response uniformities as compared to the beta and beta/gamma source measurements (See Tables 8 and 9). The efficiencies determined for the ^{239}Pu source were approximately 30% at the detector corners and 35% at the detector center. This leads to an average MDA for ^{239}Pu of 0.13 nanocuries. With the ^{241}Am , the efficiencies found were approximately 28% at the detector corners and 31% at the detector center, which also leads to an average MDA of 0.13 nanocuries.

B. 8" x12" Vertical Mount Detector - Thin Beta Plastic Scintillator Only

1. Detector Setup and Measurement Errors

The next detector tested incorporated an eight by twelve inch surface area and was 1.5" thick. However, the plastic scintillator was only 0.5 mm thick with the remainder of the original thicknesses of 1.5" being occupied by an acrylic light pipe (See Figure 4). See Tables 10 through 15 for the results of the testing for the various nuclides. The detector optimization to ^{60}Co resulted in the following settings: high voltage equal to 1000 volts and a beta channel lower level discriminator setting of 1.96 volts. The background at these settings was 8 cps in the beta channel. The source measurement count rate errors were below four percent in all cases, except when measuring the ^{14}C and ^{147}Pm sources. The errors were greater for the ^{14}C and ^{147}Pm measurements due to the low count rates generated by the detector.

2. Beta Particle Detection Performance

Measurements were made at the nine locations over the face of the detector, shown in Figure 6, using each beta and beta/gamma source as discussed in section II. The ^{14}C measurement results were better than for the 4" x 4" detector, but there was still a large discrepancy between the efficiency at the center of the detector and the other locations measured. The efficiency at the center increased to almost ten percent, as compared to only 0.02% found for the 4" x 4" detector. The corners and sides of the detector had an average efficiency of approximately 0.15%, while the top and bottom

centers of the detector, positions 2 and 8 (See Figure 6), were approximately 0.4%.

Figure 7 shows a computer generated contour map of the normalized efficiencies for the ^{14}C measurement results. The normalized efficiencies are determined by finding the ratio between the efficiencies at the various locations and the efficiency found at the center of the detector. The normalized efficiencies for the ^{14}C measurement are listed in Table 10. The contour maps were generated by a software program entitled MathCAD. MathCAD uses the matrix of the nine measurement results and generates a continuous contour plot across the face of the detector. The figure demonstrates a "hot spot" at the center of the detector at the PMT location. The normalized efficiency at this location is defined as 1. At the outside corners of the detector the normalized efficiency drops to less than 0.02 (See Table 10).

The results for the ^{147}Pm , ^{60}Co , ^{137}Cs , ^{204}Tl and the $^{90}\text{Sr}/^{90}\text{Y}$ sources also show a similar discrepancy between the centerline efficiency of the detector and the other locations measured (See Tables 11 through 15). Figures 8 and 9 provide computer generated contour maps of the normalized efficiencies for ^{137}Cs and the $^{90}\text{Sr}/^{90}\text{Y}$ results. The figures demonstrate the "hot spots" at the center of the detector for each source measured. They also demonstrate that as the average and maximum energy of the beta particles increase the discrepancy between the efficiency at the center of the detector and at the corners of the detector decreases. The difference starts at approximately a factor of fifty for ^{14}C beta particles and improves with increasing beta particle energy to a factor of 4 for the $^{90}\text{Sr}/^{90}\text{Y}$ source (See Tables 10 and 15).

A further examination of Tables 3, 5, 6, 11, 13, and 14 demonstrates that the ^{147}Pm , ^{137}Cs and ^{204}Tl results for both the efficiencies at the center and at the perimeter of the 8" x 12" detector were improved as compared to the 4" x 4" detector. It can therefore be concluded that the ZnS (Ag) layer present on the 4" x 4" detector was the cause of the beta particle attenuation.

Both the ^{60}Co and the $^{90}\text{Sr}/^{90}\text{Y}$ source measurement efficiencies and surface response uniformities declined as compared to the 4" x 4" detector measurements. The efficiencies determined for the ^{60}Co source dropped to approximately 3% at the perimeter of the detector, while remaining approximately unchanged at the detector center. With the $^{90}\text{Sr}/^{90}\text{Y}$, the efficiencies found dropped to approximately 7.5% at the detector corners and increased a small amount to 30% at the detector center.

Without the thick plastic scintillator, the ^{60}Co decay gammas were detected at a much lower efficiency than with the 4" x 4" detector. The ^{60}Co results now were dependent on beta energy only. The measurement results now fall in line with what might be expected, better than the ^{147}Pm results, while not as good as the ^{137}Cs results.

The $^{90}\text{Sr}/^{90}\text{Y}$ source measurement results yielded efficiencies that declined and surface response uniformities that degraded as compared to the 4" x 4" detector measurements. The results are very similar to that found for the ^{204}Tl source. The ^{90}Y beta is of a significantly higher average and maximum energy than that of ^{204}Tl (See Table 1). The 1.5" thickness of the plastic scintillator used in the 4" x 4" detector was of sufficient thickness to absorb all of the energy of the ^{90}Y beta. However, the 0.5 mm

thickness of the plastic scintillator used in the 8" x 12" detectors may not absorb all of the energy of the ^{90}Y beta and lead to the decreased efficiency and surface response uniformity for these detectors.

C. 8" x 12" Vertical Mount Detector - Thin Beta Plastic Scintillator & ZnS (Ag)

1. Detector Setup and Measurement Errors

One of the purposes of testing the detector before applying the ZnS (Ag) layer was to determine what if any degradation of the beta response would result. The layer of the inorganic scintillator used on this detector was much thinner than was applied to the 4" x 4" detector. Approximately half as much ZnS (Ag) was used on the 8" x 12" detector, which has a surface area six times as great as that of the 4" x 4" detector. This should have resulted in an inorganic scintillator layer twelve times thinner. The other purpose was to determine if such a thinning of the ZnS (Ag) layer would degrade the alpha response characteristics.

The detector discussed here is the same detector as discussed in section III B, but with a thin layer of ZnS (Ag) applied. The measurement results are presented in Tables 16 through 23. The detector optimization to ^{60}Co and ^{239}Pu resulted in the following settings: high voltage equal to 1000 volts; beta channel lower level discriminator of 0.98 volts; alpha channel lower level discriminator of 9 volts. The backgrounds at these settings were 22 cps in the beta channel and 1 cps in the alpha channel. The beta cross over into the alpha channel was checked with the $^{90}\text{Sr}/^{90}\text{Y}$ source and found to yield a zero net count

rate. The source measurement count rate errors were below 3.5 percent in all cases except when measuring the ^{14}C and ^{147}Pm sources. The errors were greater for the ^{14}C and ^{147}Pm measurements due to the low count rates generated by the detector. Nine measurements were made at the locations over the face of the detector using each beta, beta/gamma, and alpha source as discussed previously (See Figure 6). The results for the beta and beta/gamma source measurements will be discussed first.

2. Beta Particle Detection Performance

The optimization of the beta response led to a lower discriminator setting than was used for the testing of this detector before the ZnS (Ag) was applied. Lower discriminator settings usually lead to higher background rates and higher efficiencies. In this case the lower setting increased the background rate from eight counts per second to twenty-two counts per second. Efficiencies also increased for every source measured. The average efficiency went from 1.25 to 2.5 percent for ^{14}C , from 2.1 to 3.4 percent for ^{147}Pm , from 5.1 to 8 percent for ^{60}Co , from 11.3 to 14.5 percent for ^{137}Cs , from 11.9 to 15.2 percent for ^{204}Tl and from 11.2 to 15.1 percent for $^{90}\text{Sr}/^{90}\text{Y}$. The application of the ZnS (Ag) should have led to lower beta efficiencies. Therefore, the increase in beta efficiency here is most likely due to the different low energy discriminator settings. For the edge mount PMT detectors, the discriminator settings were identical for both tests, with and without the ZnS (Ag), to help investigate the problem. The increase in efficiencies indicates that

the new thinner layer of ZnS (Ag) does not affect the beta response as much as did the thicker layer applied to the 4" x 4" detector.

Even though the average efficiencies increased for all of the beta and beta/gamma sources tested, the higher background rates of the detector with the ZnS (Ag) lead to higher values for the MDA's for all but the ^{14}C and ^{147}Pm sources.

There was still a large discrepancy between the efficiencies at the center of the detector and the other locations measured. Figures 10 through 12 show computer generated contour maps, normalized to the efficiency of the center of the detector, for the ^{14}C , ^{137}Cs , and $^{90}\text{Sr}/^{90}\text{Y}$ sources tested (See section III part B 2 for a discussion on the generation of the contour maps). The figures continue to demonstrate the "hot spot" at the center of the detector and that, as the average and maximum beta energy increases, the discrepancy between the efficiency at the center detector and the detector corners decreases. The difference starts at approximately a factor of thirty-three for ^{14}C beta particles and steadily improves with increasing beta particle energy to a factor of 3 for the $^{90}\text{Sr}/^{90}\text{Y}$ source (See Tables 16 and 21).

3. Alpha Particle Detection Performance

The alpha response measurements of the ^{239}Pu and ^{241}Am sources can be found in Tables 22 and 23, respectively. The measurements compared very favorably to the alpha response found for the 4" x 4" detector (See Tables 8 and 9). The larger detector had efficiencies of approximately 31.4% to the ^{239}Pu and 29.9% to the ^{241}Am , which lead to a

MDA of 0.13 nanocuries for the ^{239}Pu and 0.14 nanocuries for the ^{241}Am . The 4" x 4" detector exhibited efficiencies of approximately 30.7% to the ^{239}Pu and 28.9% to the ^{241}Am , which lead to a MDA of 0.13 nanocuries for the ^{239}Pu and 0.14 nanocuries for the ^{241}Am . This shows that the thinning of the ZnS (Ag) layer did not degrade the alpha detection performance.

Alpha source measurements were taken at nine separate locations across the detector as with the beta and beta/gamma source measurements (See Figure 6). The efficiencies at the center of the detector and the other locations measured did not demonstrate the differences as seen during the beta and beta/gamma measurements (See Tables 22 and 23).

D. 8" x12" Edge Mount Detector - Thin Beta Plastic Scintillator Only

1. Detector Setup and Measurement Errors

The next detector tested also had an eight by twelve inch surface area and was one and one-half inches thick, with 0.5 mm thick plastic scintillator and the remainder of the thickness comprised of an acrylic light pipe. However, it integrated an edge mount PMT (See Figure 5). The measurement results are presented in Tables 24 through 29. The detector optimization to ^{60}Co resulted in the following settings: high voltage equal to 1000 volts and a beta channel lower level discriminator of 1.57 volts. The background at these settings was 19 cps in the beta channel. The source measurement count rate errors were below two percent in all cases, except when measuring the ^{14}C and ^{147}Pm sources

where they remained below 4.5 percent. The errors were greater for the ^{14}C and ^{147}Pm measurements due to the low count rates generated by the detector.

Measurements were made at the nine locations over the face of the detector using each beta/gamma source as discussed previously (See Figure 6). The efficiencies, MDA's, and the discrepancy between the efficiency at the center of the detector and the other locations measured were all considerably improved over either the 4" x 4" detector or the vertical mount 8" x 12" detector. The 4" x 4" detector's efficiency and MDA for ^{60}Co was the only exception to this statement. For the smaller detector, the average efficiency was 15.8 percent and the MDA was 1.29 nanocuries for ^{60}Co . For the detector discussed here, the average efficiency was 11.5 percent and the MDA was 1.55 nanocuries for ^{60}Co . This difference was due to the increased gamma sensitivity of the thick plastic scintillator.

2. Beta Particle Detection Performance

The average efficiencies for this edge mount detector were 2.1 percent for ^{14}C , 4.6 percent for ^{147}Pm , 11.5 percent for ^{60}Co , 23.3 percent for ^{137}Cs , 24.5 percent for ^{204}Tl and 21.4 percent for $^{90}\text{Sr}/^{90}\text{Y}$. These efficiencies and the inherent background rates of the detector led to average MDA's which dropped to 9.4 nanocuries for ^{14}C , 4.1 nanocuries for ^{147}Pm , 1.6 nanocuries for ^{60}Co and 0.8 nanocuries for each ^{137}Cs , ^{204}Tl and $^{90}\text{Sr}/^{90}\text{Y}$. The results demonstrate that as the average and maximum energy of the betas increase the overall detector sensitivity decreases.

Figures 13 through 15 show computer generated contour maps, normalized to the efficiency of the center of the detector, for the ^{14}C , ^{137}Cs , and $^{90}\text{Sr}/^{90}\text{Y}$ sources tested (See section III part B 2 for a discussion on the generation of the contour maps). The figures continue to demonstrate the presence of a "hot spot," but the location is now at the center of the detector near the PMT. The figures also demonstrate that, as the average and maximum beta energy increases, the discrepancy between the efficiency at the center of the detector near the PMT and the detector corners decreases. However, this concentration of efficiency has lessened greatly as compared to the vertical mount detector results. The difference starts at approximately a factor of three for ^{14}C beta particles and steadily improves with increasing beta particle energy to a factor of 1.6 for the $^{90}\text{Sr}/^{90}\text{Y}$ source (See Tables 24 and 29). For the vertical mount, 8" x 12" detector, the difference started at approximately a factor of fifty for ^{14}C beta particles and steadily improved with increasing beta particle energy to a factor of 4 for the $^{90}\text{Sr}/^{90}\text{Y}$ source (See Tables 10 and 15).

In summary the edge mount PMT design yielded improved beta radiation efficiencies, MDA's, and surface response uniformity when compared to both that for the 4" x 4" detector and the vertical mount 8" x 12" detector.

E. 8" x12" Edge Mount Detector - Thin Beta Plastic Scintillator & ZnS (Ag)

1. Detector Setup and Measurement Errors

The purpose of the final detector design is to determine if the alpha and beta detection response can be maintained with the application of the ZnS (Ag) layer to the edge mount 8" x 12" detector. The detector discussed here is the same detector as discussed in the section III D, but now has a thin layer of ZnS (Ag) applied. The thickness of the layer of inorganic scintillator used on this detector is approximately the same as that used on the vertical mount 8" x 12" detector. The measurement results are presented in Tables 30 through 37. The detector optimization to ^{60}Co and ^{239}Pu resulted in the following settings: high voltage equal to 1000 volts; beta channel lower level discriminator of 1.57 volts (the same setting as before the application of the ZnS (Ag)); alpha channel lower level discriminator of 8 volts. The backgrounds at these settings were 17 cps in the beta channel and 1 cps in the alpha channel. The beta cross over into the alpha channel was checked with the $^{90}\text{Sr}/^{90}\text{Y}$ source and found to yield a zero net count rate. The source measurement count rate errors were below 3.2 percent in all cases except when measuring the ^{14}C and ^{147}Pm sources. The errors were greater for the ^{14}C and ^{147}Pm measurements due to the low count rates generated by the detector. Measurements were made at the nine locations over the face of the detector using each beta and beta/gamma and alpha source (See Figure 6). The results for the beta and beta/gamma source measurements will be discussed first.

2. Beta Particle Detection Performance

Comparing the edge mount 8" x 12" detector measurement results before and after the application of the inorganic scintillator shows that the average efficiencies for each of the beta and beta/gamma sources dropped after the ZnS (Ag)'s application. A comparison of the average efficiencies and MDA's for the five different detector configurations is presented in Tables 38 and 39. The average efficiencies lowered from 2.1 to 0.96 percent for ^{14}C , from 4.6 to 2.4 percent for ^{147}Pm , from 11.5 to 8.8 percent for ^{60}Co , from 23.3 to 18.5 percent for ^{137}Cs , from 24.5 to 19.1 percent for ^{204}Tl and from 21.4 to 19.3 percent for $^{90}\text{Sr}/^{90}\text{Y}$. The MDA's also worsened with the application of the ZnS (Ag) (See Tables 30 and 35).

The surface uniformity response of this detector as compared to that before the application of the inorganic scintillator has degraded. However, this concentration of efficiency has lessened greatly as compared to the vertical mount detector results. Figures 16 through 18 show computer generated contour maps, normalized to the efficiency of the center of the detector, for the ^{14}C , ^{137}Cs , and $^{90}\text{Sr}/^{90}\text{Y}$ sources tested (See section III part B 2 for a discussion on the generation of the contour maps). The figures continue to demonstrate the presence of a "hot spot," with the location at the center of the detector near PMT. The figures also demonstrate that, as the average and maximum beta energy increases, the discrepancy between the efficiency at the center of the detector near the PMT and the detector corners decreases. The difference starts at approximately a factor of nine for ^{14}C beta particles and steadily improves with increasing beta particle energy to

a factor of 1.7 for the $^{90}\text{Sr}/^{90}\text{Y}$ source (See Tables 30 and 35). For the vertical mount, 8" x 12" detector with ZnS (Ag), the difference started at approximately a factor of thirty-three for ^{14}C beta particles and steadily improved with increasing beta particle energy to a factor of 3 for the $^{90}\text{Sr}/^{90}\text{Y}$ source (See Tables 16 and 21).

Since the discriminator settings were maintained the same and no other changes in the system configuration existed, the reduction in beta efficiency, sensitivity and surface uniformity response of the final detector must be attributed to the presence of the ZnS (Ag) layer.

3. Alpha Particle Detection Performance

The alpha response measurements for the ^{239}Pu and ^{241}Am sources can be found in Tables 36 and 37. A comparison of the average efficiencies and MDA's for the five different detector configurations is presented in Tables 38 and 39. The measurements obtained were almost identical to the alpha response found for the 4" x 4" detector (See Tables 9 and 10) and the vertical mount 8" x 12" detector (See Tables 22 and 23). The edge mount detector had efficiencies of approximately 31.3% for the ^{239}Pu and 31.6% for the ^{241}Am , which lead to MDA's of 0.13 nanocuries for both ^{239}Pu and ^{241}Am . This again shows that the thinning of the ZnS (Ag) layer did not degrade the alpha detection performance.

Alpha source measurements were taken at the nine separate locations across the detector as with the beta and beta/gamma source measurements (See Figure 6). The

efficiencies at the center of the detector and the other locations measured showed a relatively flat response as compared to the beta and beta/gamma source measurements (See Tables 36 and 37).

IV. CONCLUSIONS

The objective of this investigation was to develop a detector which has the worthwhile properties of the gas filled detectors, without some of their shortcomings. The dual phosphor detector investigated here, after integrating the improvements found during this investigation into the final design, should fill this need.

The original 4" x 4" detector design proved to have two major shortcomings that were exposed by refinements in the configuration. The layer of ZnS (Ag) applied was of enough thickness to attenuate a large portion of the beta particles, except at the highest beta energies tested. It was shown that thinning the layer did not degrade the alpha response and greatly improved the beta response. The second shortcoming was the use of 1.5 inch thick plastic scintillator. The thick plastic scintillator did not improve the beta response of the detector, but it did increase the gamma sensitivity. The ability to efficiently detect gamma radiations decreases the system sensitivity to pure beta-emitters because it increases the system background. If the detector were to be designed to detect gamma emitting isotopes, such as ^{60}Co , which emits two energetic gammas one-hundred percent of the time, then thick plastic has been shown to provide a marginal improvement over the thin plastic, but at a serious loss of sensitivity to pure beta-emitters.

The 4" x 4" detector also showed a serious beta radiation uniformity response variance across the face of the detector, with the highest detection efficiency at the PMT location. New detector designs would attempt to improve this problem.

However, the original detector did show very good alpha radiation efficiency, alpha sensitivity and alpha surface response uniformity.

The detector size was increased to 8" x 12" to better understand the beta radiation surface response uniformity degradation seen in the smaller detector results. The first 8" x 12" detector manufactured had the same vertical mounted PMT design and continued to show surface uniformity response concentrated at the PMT location. The vertical mount 8" x 12" detector with a thin ZnS (Ag) layer did show improved beta response with no reduction in alpha response.

The final design employed an edge mount PMT on a 8" x 12" detector with thin plastic scintillator. The beta radiation surface response uniformity problems seen in the previous detector designs were lessened greatly with this new design. However, they still showed increased detection efficiency at the PMT location. The MDA's for the beta and beta/gamma emitting isotopes were the lowest of any of the detector designs, but did show degradation with the application of the ZnS (Ag). The alpha radiation response was very good and was practically identical for all of the various designs.

Commercially available alpha/beta sensitive gas flow proportional counters show efficiencies similar to those of the dual phosphor design. Alpha radiation efficiencies range from 15 to 25 percent for the proportional counters as compared to approximately 30 percent for the final dual phosphor detector. Beta radiation efficiencies for ^{137}Cs and $^{90}\text{Sr}/^{90}\text{Y}$ were approximately 30 and 35 percent, respectively, for the proportional

counters, as compared to approximately 19 percent for either isotope with the final dual phosphor detector.

The dual phosphor detector meets the objective of this investigation. The final design configuration of the detector provides similar performance as compared to radiation detectors utilizing gas ionization techniques. It also eliminates some of the deficiencies of the latter design. It will allow small and large configurations, portability, operation without a gas supply, and alpha/beta discrimination. This detector is relatively durable (except for the window), has relatively low manufacturing cost for both materials and labor, has low gamma sensitivity, if made with a thin plastic scintillator, which ensures a low background response in photon fields, and compares favorably with efficiencies listed for some commercially available gas flow proportional counters.

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TABLES 1 - 39

TABLE 1. TEST SOURCE INFORMATION (Browne and Firestone 1986)

Beta Sources	Isotope	Half-Life (years)	Primary Beta			Secondary Beta			Calibration	
			Maximum Energy (keV)	Average Energy (keV)	Intensity (percent)	Maximum Energy (keV)	Average Energy (keV)	Intensity (percent)	Activity (nCi)	Calibration Date
	C-14	5730	156.473	49.5	100				112	02/01/87
	Pm-147	2.6234	224.6	62	100				234	02/01/87
	Co-60	5.271	319.24	96	100				115.1	04/01/90
	Cs-137	30	511.55	156.8	94.6	1173.2	415	5.4	24.1	06/15/88
	Tl-204	3.78	763.41	238	97.45				183	08/01/84
	Sr/Y-90*	28.5	546.2	196	100	2281.5	934	100	60	03/17/75

*This source not calibrated.

Alpha Sources	Isotope	Half-Life (years)	Primary Alpha			Calibration	
			Energy (keV)	Intensity (percent)	Activity (nCi)	Calibration Date	Test Activity (nCi)
	Pu-239	24131	~5150	100	5.32	10/29/92	5.32
	Am-241*	432.2	~5500	100	176.58	05/11/85	174.21

*This source not calibrated.

TABLE 2. 4"x4" Vertical Mount PMT, Thick Plastic & ZnS C-14

<i>C-14</i> Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
3	1	0.02	131.02	N/A	824.56

Cross talk check in alpha channel with Sr/Y-90 source on contact = 0 net cps.
Am-241 cross talk in beta channel = 2194 cps
Pu-239 cross talk in beta channel = 78.5 cps

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 25 cps beta, 1 cps alpha
High voltage = 700 volts
Discriminator = 0.98 volts beta, 8 volts alpha

*Normalized Efficiency is determined by calculating the ratio between the efficiencies at the various locations and the efficiency found at the center of the detector (Position 3).

**The MDA formula is defined as the detectable activity in nCi which is 4.65 standard deviations above background for a ten second count time and using the listed efficiencies and background rates.
(American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the source during the measurements.

TABLE 3. 4"x4" Vertical Mount PMT, Thick Plastic & ZnS Pm-147

<i>Pm-147</i> Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	2.35	0.16	56.84	0.06	124.89
2	1.4	0.09	94.13	0.04	209.64
3	37	2.51	5.07	1.00	7.93
4	1.05	0.07	124.87	0.03	279.52
5	0.4	0.03	324.68	0.01	733.74
Average		0.57			271.15

Cross talk check in alpha channel with Sr/Y-90
source on contact = 0 net cps.
Am-241 cross talk in beta channel = 2194 cps
Pu-239 cross talk in beta channel = 78.5 cps

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 25 cps beta, 1 cps alpha
High voltage = 700 volts
Discriminator = 0.98 volts beta, 8 volts alpha

*Normalized Efficiency is determined by
calculating the ratio between the
efficiencies at the various locations and
the efficiency found at the center of the
detector (Position 3).

**The MDA formula is defined as the detectable
activity in nCi which is 4.65 standard deviations above
background for a ten second count time and using
the listed efficiencies and background rates.
(American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the
source during the measurements.

TABLE 4. 4"x4" Vertical Mount PMT, Thick Plastic & ZnS Co-60

<i>Co-60</i> Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	389.85	14.58	1.18	0.70	1.37
2	375.15	14.03	1.20	0.67	1.42
3	560.35	20.95	0.97	1.00	0.95
4	392.65	14.68	1.18	0.70	1.36
5	392.3	14.67	1.18	0.70	1.36
Average		15.78			1.29

Cross talk check in alpha channel with Sr/Y-90
source on contact = 0 net cps.
Am-241 cross talk in beta channel = 2194 cps
Pu-239 cross talk in beta channel = 78.5 cps

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 25 cps beta, 1 cps alpha
High voltage = 700 volts
Discriminator = 0.98 volts beta, 8 volts alpha

*Normalized Efficiency is determined by
calculating the ratio between the
efficiencies at the various locations and
the efficiency found at the center of the
detector (Position 3).

**The MDA formula is defined as the detectable
activity in nCi which is 4.65 standard deviations above
background for a ten second count time and using
the listed efficiencies and background rates.
(American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the
source during the measurements.

TABLE 5. 4"x4" Vertical Mount PMT, Thick Plastic & ZnS Cs-137

Cs-137 Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	60.1	7.62	3.60	0.38	2.61
2	53.9	6.84	3.87	0.34	2.91
3	156.5	19.85	1.97	1.00	1.00
4	52.45	6.65	3.95	0.34	2.99
5	56.8	7.20	3.74	0.36	2.76
Average		9.63			2.46

Cross talk check in alpha channel with Sr/Y-90
source on contact = 0 net cps.
Am-241 cross talk in beta channel = 2194 cps
Pu-239 cross talk in beta channel = 78.5 cps

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 25 cps beta, 1 cps alpha
High voltage = 700 volts
Discriminator = 0.98 volts beta, 8 volts alpha

*Normalized Efficiency is determined by
calculating the ratio between the
efficiencies at the various locations and
the efficiency found at the center of the
detector (Position 3).

**The MDA formula is defined as the detectable
activity in nCi which is 4.65 standard deviations above
background for a ten second count time and using
the listed efficiencies and background rates.
(American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the
source during the measurements.

TABLE 6. 4"x4" Vertical Mount PMT, Thick Plastic & ZnS Tl-204

<i>Tl-204</i>	Net	Efficiency	Count Rate	Normalized*	MDA**
Location***	(cps)	(%)	Error (%)	Efficiency	(nCi)
1	50.75	4.05	4.04	0.25	2.46
2	51.45	4.11	4.00	0.26	2.42
3	201.1	16.06	1.70	1.00	0.62
4	47.15	3.77	4.25	0.23	2.64
5	44.5	3.55	4.43	0.22	2.80
Average		6.31			2.19

Cross talk check in alpha channel with Sr/Y-90
source on contact = 0 net cps.
Am-241 cross talk in beta channel = 2194 cps
Pu-239 cross talk in beta channel = 78.5 cps

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 25 cps beta, 1 cps alpha
High voltage = 700 volts
Discriminator = 0.98 volts beta, 8 volts alpha

*Normalized Efficiency is determined by
calculating the ratio between the
efficiencies at the various locations and
the efficiency found at the center of the
detector (Position 3).

**The MDA formula is defined as the detectable
activity in nCi which is 4.65 standard deviations above
background for a ten second count time and using
the listed efficiencies and background rates.
(American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the
source during the measurements.

TABLE 7. 4"x4" Vertical Mount PMT, Thick Plastic & ZnS Sr/Y-90

<i>Sr/Y-90</i> Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	299.7	21.22	1.36	0.81	0.94
2	303.55	21.49	1.35	0.82	0.93
3	368.7	26.10	1.22	1.00	0.76
4	295.55	20.92	1.37	0.80	0.95
5	295.9	20.95	1.37	0.80	0.95
Average		22.14			0.91

Cross talk check in alpha channel with Sr/Y-90
source on contact = 0 net cps.
Am-241 cross talk in beta channel = 2194 cps
Pu-239 cross talk in beta channel = 78.5 cps

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 25 cps beta, 1 cps alpha
High voltage = 700 volts
Discriminator = 0.98 volts beta, 8 volts alpha

*Normalized Efficiency is determined by
calculating the ratio between the
efficiencies at the various locations and
the efficiency found at the center of the
detector (Position 3).

**The MDA formula is defined as the detectable
activity in nCi which is 4.65 standard deviations above
background for a ten second count time and using
the listed efficiencies and background rates.
(American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the
source during the measurements.

TABLE 8. 4"x4" Vertical Mount PMT, Thick Plastic & ZnS Pu-239

<i>Pu-239</i>	Net	Efficiency	Count Rate	Normalized*	MDA**
Location***	(cps)	(%)	Error (%)	Efficiency	(nCi)
1	60.4	30.71	2.91	0.87	0.13
2	62.35	31.70	2.86	0.90	0.13
3	69.35	35.26	2.71	1.00	0.11
4	55.3	28.12	3.04	0.80	0.14
5	54.75	27.84	3.06	0.79	0.14
Average		30.73			0.13

Cross talk check in alpha channel with Sr/Y-90 source on contact = 0 net cps.
Am-241 cross talk in beta channel = 2194 cps
Pu-239 cross talk in beta channel = 78.5 cps

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 25 cps beta, 1 cps alpha
High voltage = 700 volts
Discriminator = 0.98 volts beta, 8 volts alpha

*Normalized Efficiency is determined by calculating the ratio between the efficiencies at the various locations and the efficiency found at the center of the detector (Position 3).

**The MDA formula is defined as the detectable activity in nCi which is 4.65 standard deviations above background for a ten second count time and using the listed efficiencies and background rates. (American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the source during the measurements.

TABLE 9. 4"x4" Vertical Mount PMT, Thick Plastic & ZnS Am-241

<u>Am-241</u> Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	1844.55	28.62	0.52	0.93	0.14
2	1785.55	27.70	0.53	0.90	0.14
3	1975	30.64	0.50	1.00	0.13
4	1767.55	27.42	0.53	0.89	0.15
5	1928.1	29.91	0.51	0.98	0.13
Average		28.86			0.14

Cross talk check in alpha channel with Sr/Y-90
source on contact = 0 net cps.
Am-241 cross talk in beta channel = 2194 cps
Pu-239 cross talk in beta channel = 78.5 cps

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 25 cps beta, 1 cps alpha
High voltage = 700 volts
Discriminator = 0.98 volts beta, 8 volts alpha

*Normalized Efficiency is determined by
calculating the ratio between the
efficiencies at the various locations and
the efficiency found at the center of the
detector (Position 3).

**The MDA formula is defined as the detectable
activity in nCi which is 4.65 standard deviations above
background for a ten second count time and using
the listed efficiencies and background rates.
(American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the
source during the measurements.

TABLE 10. 8"x12" Vertical Mount PMT, Thin Beta Plastic Only, C-14

C-14 Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	5.9	0.14	15.43	0.01	79.06
2	17.3	0.42	6.84	0.04	26.96
3	7.15	0.17	13.20	0.02	65.24
4	5.35	0.13	16.73	0.01	87.19
5	393.45	9.50	1.14	1.00	1.19
6	8.2	0.20	11.84	0.02	56.88
7	3.35	0.08	24.99	0.01	139.24
8	18.35	0.44	6.56	0.05	25.42
9	7.35	0.18	12.91	0.02	63.46
Average		1.25			60.51

Count time = 20 seconds
 Background time = 60 seconds
 Background Rate = 8 cps
 High voltage = 1000 volts
 Discriminator = 1.96 volts

*Normalized Efficiency is determined by calculating the ratio between the efficiencies at the various locations and the efficiency found at the center of the detector (Position 5).

**The MDA formula is defined as the detectable activity in nCi which is 4.65 standard deviations above background for a ten second count time and using the listed efficiencies and background rates. (American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the source during the measurements.

TABLE 11. 8"x12" Vertical Mount PMT, Thin Beta Plastic Only, Pm-147

<i>Pm-147</i> Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	5.45	0.37	16.47	0.03	30.46
2	17.5	1.19	6.78	0.09	9.49
3	6.95	0.47	13.50	0.03	23.89
4	5.95	0.40	15.32	0.03	27.90
5	200.65	13.61	1.62	1.00	0.83
6	8	0.54	12.08	0.04	20.75
7	6.05	0.41	15.11	0.03	27.44
8	19.4	1.32	6.32	0.10	8.56
9	6.3	0.43	14.62	0.03	26.35
Average		2.08			19.52

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 8 cps
High voltage = 1000 volts
Discriminator = 1.96 volts

*Normalized Efficiency is determined by calculating the ratio between the efficiencies at the various locations and the efficiency found at the center of the detector (Position 5).

**The MDA formula is defined as the detectable activity in nCi which is 4.65 standard deviations above background for a ten second count time and using the listed efficiencies and background rates. (American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the source during the measurements.

TABLE 12. 8"x12" Vertical Mount PMT, Thin Beta Plastic Only, Co-60

<i>Co-60</i> Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	53.6	2.00	3.34	0.09	5.62
2	120.3	4.50	2.13	0.20	2.50
3	69	2.58	2.89	0.11	4.37
4	58.8	2.20	3.17	0.10	5.12
5	616.35	23.04	0.91	1.00	0.49
6	74.8	2.80	2.76	0.12	4.03
7	56.15	2.10	3.26	0.09	5.37
8	115.9	4.33	2.17	0.19	2.60
9	60.35	2.26	3.12	0.10	4.99
Average		5.09			3.90

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 8 cps
High voltage = 1000 volts
Discriminator = 1.96 volts

*Normalized Efficiency is determined by calculating the ratio between the efficiencies at the various locations and the efficiency found at the center of the detector (Position 5).

**The MDA formula is defined as the detectable activity in nCi which is 4.65 standard deviations above background for a ten second count time and using the listed efficiencies and background rates. (American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the source during the measurements.

TABLE 13. 8"x12" Vertical Mount PMT, Thin Beta Plastic Only, Cs-137

Cs-137 Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	47.25	5.99	3.60	0.17	1.88
2	99.7	12.65	2.36	0.36	0.89
3	59.45	7.54	3.15	0.21	1.49
4	49.55	6.29	3.50	0.18	1.79
5	278.25	35.30	1.37	1.00	0.32
6	62.7	7.95	3.05	0.23	1.42
7	48.75	6.18	3.54	0.18	1.82
8	99.35	12.60	2.36	0.36	0.89
9	56.4	7.15	3.25	0.20	1.57
Average		11.29			1.34

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 8 cps
High voltage = 1000 volts
Discriminator = 1.96 volts

*Normalized Efficiency is determined by calculating the ratio between the efficiencies at the various locations and the efficiency found at the center of the detector (Position 5).

**The MDA formula is defined as the detectable activity in nCi which is 4.65 standard deviations above background for a ten second count time and using the listed efficiencies and background rates. (American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the source during the measurements.

TABLE 14. 8"x12" Vertical Mount PMT, Thin Beta Plastic Only, TI-204

<i>TI-204</i> Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	85.75	6.85	2.56	0.20	1.64
2	167.6	13.39	1.78	0.39	0.84
3	97.6	7.80	2.38	0.23	1.44
4	88.5	7.07	2.52	0.21	1.59
5	427.5	34.15	1.09	1.00	0.33
6	110.7	8.84	2.23	0.26	1.27
7	86.5	6.91	2.55	0.20	1.63
8	179.35	14.33	1.72	0.42	0.79
9	96.9	7.74	2.39	0.23	1.46
Average		11.90			1.22

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 8 cps
High voltage = 1000 volts
Discriminator = 1.96 volts

*Normalized Efficiency is determined by calculating the ratio between the efficiencies at the various locations and the efficiency found at the center of the detector (Position 5).

**The MDA formula is defined as the detectable activity in nCi which is 4.65 standard deviations above background for a ten second count time and using the listed efficiencies and background rates. (American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the source during the measurements.

TABLE 15. 8"x12" Vertical Mount PMT, Thin Beta Plastic Only, Sr/Y-90

<i>Sr/Y-90</i> Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	95.2	6.74	2.42	0.22	1.67
2	172.35	12.20	1.76	0.40	0.92
3	109.9	7.78	2.23	0.26	1.45
4	103.95	7.36	2.30	0.24	1.53
5	425.95	30.15	1.10	1.00	0.37
6	117.35	8.31	2.16	0.28	1.36
7	109.15	7.73	2.24	0.26	1.46
8	182.65	12.93	1.70	0.43	0.87
9	108.5	7.68	2.25	0.25	1.47
Average		11.21			1.23

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 8 cps
High voltage = 1000 volts
Discriminator = 1.96 volts

*Normalized Efficiency is determined by calculating the ratio between the efficiencies at the various locations and the efficiency found at the center of the detector (Position 5).

**The MDA formula is defined as the detectable activity in nCi which is 4.65 standard deviations above background for a ten second count time and using the listed efficiencies and background rates. (American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the source during the measurements.

TABLE 16. 8"x12" Vertical Mount PMT, Thin Beta Plastic & ZnS, C-14

C-14 Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	16.6	0.40	6.59	0.02	46.60
2	42.6	1.03	3.71	0.06	18.16
3	19.2	0.46	6.00	0.03	40.29
4	24.55	0.59	5.14	0.03	31.51
5	714.1	17.25	0.84	1.00	1.08
6	17.2	0.42	6.44	0.02	44.97
7	17.5	0.42	6.37	0.02	44.20
8	54.3	1.31	3.23	0.08	14.25
9	17.95	0.43	6.26	0.03	43.09
Average		2.48			31.57

Cross talk check in alpha channel with Sr/Y-90
source on contact = 0 net cps.
Am-241 cross talk in beta channel = 2304 cps
Pu-239 cross talk in beta channel = 192 cps

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 22 cps beta, 1 cps alpha
High voltage = 1000 volts
Discriminator = 0.98 volts beta, 9 volts alpha

*Normalized Efficiency is determined by
calculating the ratio between the
efficiencies at the various locations and
the efficiency found at the center of the
detector (Position 5).

**The MDA formula is defined as the detectable
activity in nCi which is 4.65 standard deviations above
background for a ten second count time and using the
listed efficiencies and background rates. (American
Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the
source during the measurements.

TABLE 17. 8"x12" Vertical Mount PMT, Thin Beta Plastic & ZnS, Pm-147

<i>Pm-147</i> Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	13.75	0.93	8.04	0.04	20.02
2	25.05	1.70	5.33	0.08	10.99
3	10	0.68	10.17	0.03	27.53
4	17.7	1.20	6.73	0.06	15.56
5	313.35	21.26	1.28	1.00	0.88
6	14.25	0.97	7.83	0.05	19.32
7	14.85	1.01	7.61	0.05	18.54
8	25.75	1.75	5.24	0.08	10.69
9	9.85	0.67	10.28	0.03	27.95
Average		3.35			16.83

Cross talk check in alpha channel with Sr/Y-90
source on contact = 0 net cps.
Am-241 cross talk in beta channel = 2304 cps
Pu-239 cross talk in beta channel = 192 cps

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 22 cps beta, 1 cps alpha
High voltage = 1000 volts
Discriminator = 0.98 volts beta, 9 volts alpha

*Normalized Efficiency is determined by
calculating the ratio between the
efficiencies at the various locations and
the efficiency found at the center of the
detector (Position 5).

**The MDA formula is defined as the detectable
activity in nCi which is 4.65 standard deviations above
background for a ten second count time and using the
listed efficiencies and background rates. (American
Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the
source during the measurements.

TABLE 18. 8"x12" Vertical Mount PMT, Thin Beta Plastic & ZnS, Co-60

<i>Co-60</i> Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	95.55	3.57	2.41	0.11	5.23
2	185.95	6.95	1.69	0.21	2.69
3	82.95	3.10	2.61	0.09	6.02
4	145.55	5.44	1.92	0.16	3.43
5	901.9	33.72	0.75	1.00	0.55
6	101.85	3.81	2.33	0.11	4.91
7	99.65	3.73	2.36	0.11	5.01
8	217.05	8.11	1.55	0.24	2.30
9	82.5	3.08	2.62	0.09	6.06
Average		7.95			4.02

Cross talk check in alpha channel with Sr/Y-90
source on contact = 0 net cps.
Am-241 cross talk in beta channel = 2304 cps
Pu-239 cross talk in beta channel = 192 cps

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 22 cps beta, 1 cps alpha
High voltage = 1000 volts
Discriminator = 0.98 volts beta, 9 volts alpha

*Normalized Efficiency is determined by
calculating the ratio between the
efficiencies at the various locations and
the efficiency found at the center of the
detector (Position 5).

**The MDA formula is defined as the detectable
activity in nCi which is 4.65 standard deviations above
background for a ten second count time and using the
listed efficiencies and background rates. (American
Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the
source during the measurements.

TABLE 19. 8"x12" Vertical Mount PMT, Thin Beta Plastic & ZnS, Cs-137

<u>Cs-137</u> Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	67.25	8.53	2.93	0.21	2.19
2	121.65	15.43	2.11	0.38	1.21
3	62.75	7.96	3.05	0.20	2.35
4	97.5	12.37	2.39	0.31	1.51
5	318.4	40.39	1.27	1.00	0.46
6	80	10.15	2.66	0.25	1.84
7	76.4	9.69	2.73	0.24	1.93
8	132.85	16.85	2.02	0.42	1.11
9	73.6	9.34	2.79	0.23	2.00
Average		14.52			1.62

Cross talk check in alpha channel with Sr/Y-90
source on contact = 0 net cps.
Am-241 cross talk in beta channel = 2304 cps
Pu-239 cross talk in beta channel = 192 cps

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 22 cps beta, 1 cps alpha
High voltage = 1000 volts
Discriminator = 0.98 volts beta, 9 volts alpha

*Normalized Efficiency is determined by
calculating the ratio between the
efficiencies at the various locations and
the efficiency found at the center of the
detector (Position 5).

**The MDA formula is defined as the detectable
activity in nCi which is 4.65 standard deviations above
background for a ten second count time and using the
listed efficiencies and background rates. (American
Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the
source during the measurements.

TABLE 20. 8"x12" Vertical Mount PMT, Thin Beta Plastic & ZnS, TI-204

TI-204 Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	114.8	9.17	2.18	0.24	2.04
2	196.5	15.70	1.64	0.41	1.19
3	118.85	9.49	2.14	0.25	1.97
4	180.2	14.39	1.71	0.37	1.30
5	485.05	38.75	1.03	1.00	0.48
6	141.5	11.30	1.95	0.29	1.65
7	133.45	10.66	2.01	0.28	1.75
8	218.35	17.44	1.55	0.45	1.07
9	126.45	10.10	2.07	0.26	1.85
Average		15.22			1.48

Cross talk check in alpha channel with Sr/Y-90 source on contact = 0 net cps.
Am-241 cross talk in beta channel = 2304 cps
Pu-239 cross talk in beta channel = 192 cps

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 22 cps beta, 1 cps alpha
High voltage = 1000 volts
Discriminator = 0.98 volts beta, 9 volts alpha

*Normalized Efficiency is determined by calculating the ratio between the efficiencies at the various locations and the efficiency found at the center of the detector (Position 5).

**The MDA formula is defined as the detectable activity in nCi which is 4.65 standard deviations above background for a ten second count time and using the listed efficiencies and background rates. (American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the source during the measurements.

TABLE 21. 8"x12" Vertical Mount PMT, Thin Beta Plastic & ZnS, Sr/Y-90

<i>Sr/Y-90</i> Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	142.6	10.10	1.94	0.32	1.85
2	261.05	18.48	1.41	0.59	1.01
3	146.1	10.34	1.92	0.33	1.81
4	189.25	13.40	1.67	0.43	1.39
5	439.8	31.13	1.08	1.00	0.60
6	168.3	11.91	1.78	0.38	1.57
7	163.7	11.59	1.80	0.37	1.61
8	255.75	18.11	1.43	0.58	1.03
9	153.5	10.87	1.87	0.35	1.72
Average		15.10			1.40

Cross talk check in alpha channel with Sr/Y-90
source on contact = 0 net cps.
Am-241 cross talk in beta channel = 2304 cps
Pu-239 cross talk in beta channel = 192 cps

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 22 cps beta, 1 cps alpha
High voltage = 1000 volts
Discriminator = 0.98 volts beta, 9 volts alpha

*Normalized Efficiency is determined by
calculating the ratio between the
efficiencies at the various locations and
the efficiency found at the center of the
detector (Position 5).

**The MDA formula is defined as the detectable
activity in nCi which is 4.65 standard deviations above
background for a ten second count time and using the
listed efficiencies and background rates. (American
Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the
source during the measurements.

TABLE 22. 8"x12" Vertical Mount PMT, Thin Beta Plastic & ZnS, Pu-239

<i>Pu-239</i> Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	63.55	32.31	3.03	1.02	0.12
2	70.05	35.62	2.87	1.13	0.11
3	62.55	31.81	3.06	1.01	0.13
4	52.15	26.52	3.40	0.84	0.15
5	62.05	31.55	3.07	1.00	0.13
6	62.95	32.01	3.05	1.01	0.12
7	59.55	30.28	3.15	0.96	0.13
8	66.9	34.02	2.94	1.08	0.12
9	56.65	28.81	3.24	0.91	0.14
Average		31.44			0.13

Cross talk check in alpha channel with Sr/Y-90 source on contact = 0 net cps.
Am-241 cross talk in beta channel = 2304 cps
Pu-239 cross talk in beta channel = 192 cps

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 22 cps beta, 1 cps alpha
High voltage = 1000 volts
Discriminator = 0.98 volts beta, 9 volts alpha

*Normalized Efficiency is determined by calculating the ratio between the efficiencies at the various locations and the efficiency found at the center of the detector (Position 5).

**The MDA formula is defined as the detectable activity in nCi which is 4.65 standard deviations above background for a ten second count time and using the listed efficiencies and background rates. (American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the source during the measurements.

TABLE 23. 8"x12" Vertical Mount PMT, Thin Beta Plastic & ZnS, Am-241

<u>Am-241</u> Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	1934.7	30.02	0.51	0.90	0.13
2	2096.5	32.53	0.49	0.98	0.12
3	2104.65	32.65	0.49	0.98	0.12
4	1329.3	20.62	0.62	0.62	0.19
5	2138.45	33.18	0.48	1.00	0.12
6	1945	30.18	0.51	0.91	0.13
7	1749.35	27.14	0.54	0.82	0.15
8	2067.3	32.07	0.49	0.97	0.12
9	1953.9	30.31	0.51	0.91	0.13
Average		29.86			0.14

Cross talk check in alpha channel with Sr/Y-90 source on contact = 0 net cps.
Am-241 cross talk in beta channel = 2304 cps
Pu-239 cross talk in beta channel = 192 cps

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 22 cps beta, 1 cps alpha
High voltage = 1000 volts
Discriminator = 0.98 volts beta, 9 volts alpha

*Normalized Efficiency is determined by calculating the ratio between the efficiencies at the various locations and the efficiency found at the center of the detector (Position 5).

**The MDA formula is defined as the detectable activity in nCi which is 4.65 standard deviations above background for a ten second count time and using the listed efficiencies and background rates. (American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the source during the measurements.

TABLE 24. 8"x12" Edge Mount PMT, Thin Beta Plastic Only, C-14

C-14 Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	67.75	1.64	2.92	0.52	10.61
2	77.4	1.87	2.71	0.60	9.29
3	75	1.81	2.76	0.58	9.58
4	75.25	1.82	2.75	0.58	9.55
5	129.4	3.13	2.05	1.00	5.56
6	98.05	2.37	2.38	0.76	7.33
7	48.25	1.17	3.56	0.37	14.90
8	145.85	3.52	1.92	1.13	4.93
9	54.9	1.33	3.30	0.42	13.09
Average		2.07			9.43

Count time = 20 seconds
 Background time = 60 seconds
 Background Rate = 19 cps
 High voltage = 1000 volts
 Discriminator = 1.57 volts

*Normalized Efficiency is determined by calculating the ratio between the efficiencies at the various locations and the efficiency found at the center of the detector (Position 5).

**The MDA formula is defined as the detectable activity in nCi which is 4.65 standard deviations above background for a ten second count time and using the listed efficiencies and background rates. (American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the source during the measurements.

TABLE 25. 8"x12" Edge Mount PMT, Thin Beta Plastic Only, Pm-147

<i>Pm-147</i> Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	53.8	3.65	3.34	0.57	4.76
2	62.75	4.26	3.05	0.67	4.08
3	58.55	3.97	3.18	0.62	4.37
4	61.75	4.19	3.08	0.66	4.14
5	94.1	6.38	2.43	1.00	2.72
6	75.55	5.13	2.75	0.80	3.39
7	41.05	2.79	3.92	0.44	6.23
8	103.45	7.02	2.31	1.10	2.47
9	54.6	3.70	3.31	0.58	4.69
Average		4.57			4.09

Count time = 20 seconds
 Background time = 60 seconds
 Background Rate = 19 cps
 High voltage = 1000 volts
 Discriminator = 1.57 volts

*Normalized Efficiency is determined by calculating the ratio between the efficiencies at the various locations and the efficiency found at the center of the detector (Position 5).

**The MDA formula is defined as the detectable activity in nCi which is 4.65 standard deviations above background for a ten second count time and using the listed efficiencies and background rates. (American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the source during the measurements.

TABLE 26. 8"x12" Edge Mount PMT, Thin Beta Plastic Only, Co-60

<i>Co-60</i> Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	276.15	10.32	1.37	0.71	1.68
2	308.15	11.52	1.30	0.79	1.51
3	295.75	11.06	1.32	0.76	1.57
4	285.55	10.68	1.35	0.73	1.63
5	388.8	14.54	1.15	1.00	1.19
6	337.45	12.62	1.24	0.87	1.38
7	230.05	8.60	1.51	0.59	2.02
8	382.55	14.30	1.16	0.98	1.21
9	261.4	9.77	1.41	0.67	1.78
Average		11.49			1.55

Count time = 20 seconds
 Background time = 60 seconds
 Background Rate = 19 cps
 High voltage = 1000 volts
 Discriminator = 1.57 volts

*Normalized Efficiency is determined by calculating the ratio between the efficiencies at the various locations and the efficiency found at the center of the detector (Position 5).

**The MDA formula is defined as the detectable activity in nCi which is 4.65 standard deviations above background for a ten second count time and using the listed efficiencies and background rates. (American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the source during the measurements.

TABLE 27. 8"x12" Edge Mount PMT, Thin Beta Plastic Only, Cs-137

<u>Cs-137</u> Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	161.75	20.52	1.82	0.78	0.85
2	188.75	23.94	1.67	0.91	0.73
3	187.1	23.73	1.68	0.90	0.73
4	175.5	22.26	1.74	0.85	0.78
5	207.05	26.26	1.59	1.00	0.66
6	200.55	25.44	1.62	0.97	0.68
7	153.05	19.41	1.87	0.74	0.89
8	217.75	27.62	1.55	1.05	0.63
9	160.2	20.32	1.82	0.77	0.85
Average		23.28			0.76

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 19 cps
High voltage = 1000 volts
Discriminator = 1.57 volts

*Normalized Efficiency is determined by calculating the ratio between the efficiencies at the various locations and the efficiency found at the center of the detector (Position 5).

**The MDA formula is defined as the detectable activity in nCi which is 4.65 standard deviations above background for a ten second count time and using the listed efficiencies and background rates. (American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the source during the measurements.

TABLE 28. 8"x12" Edge Mount PMT, Thin Beta Plastic Only, TI-204

TI-204 Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	280.75	22.43	1.36	0.77	0.77
2	316.25	25.26	1.28	0.87	0.69
3	300.7	24.02	1.31	0.83	0.72
4	288.75	23.07	1.34	0.80	0.75
5	362.3	28.94	1.19	1.00	0.60
6	332.45	26.56	1.25	0.92	0.65
7	245.4	19.60	1.46	0.68	0.89
8	359.9	28.75	1.20	0.99	0.60
9	271.8	21.71	1.38	0.75	0.80
Average		24.48			0.72

Count time = 20 seconds
 Background time = 60 seconds
 Background Rate = 19 cps
 High voltage = 1000 volts
 Discriminator = 1.57 volts

*Normalized Efficiency is determined by calculating the ratio between the efficiencies at the various locations and the efficiency found at the center of the detector (Position 5).

**The MDA formula is defined as the detectable activity in nCi which is 4.65 standard deviations above background for a ten second count time and using the listed efficiencies and background rates. (American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the source during the measurements.

TABLE 29. 8"x12" Edge Mount PMT, Thin Beta Plastic Only, Sr/Y-90

<i>Sr/Y-90</i> Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	250.25	17.72	1.44	0.69	0.98
2	311.3	22.04	1.29	0.86	0.79
3	297.6	21.07	1.32	0.82	0.82
4	271.25	19.20	1.38	0.75	0.90
5	361.2	25.57	1.19	1.00	0.68
6	323.85	22.93	1.26	0.90	0.76
7	237	16.78	1.48	0.66	1.03
8	385.3	27.28	1.15	1.07	0.64
9	280.3	19.84	1.36	0.78	0.87
Average		21.38			0.83

Count time = 20 seconds
 Background time = 60 seconds
 Background Rate = 19 cps
 High voltage = 1000 volts
 Discriminator = 1.57 volts

*Normalized Efficiency is determined by calculating the ratio between the efficiencies at the various locations and the efficiency found at the center of the detector (Position 5).

**The MDA formula is defined as the detectable activity in nCi which is 4.65 standard deviations above background for a ten second count time and using the listed efficiencies and background rates. (American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the source during the measurements.

TABLE 30. 8"x12" Edge Mount PMT, Thin Beta Plastic & ZnS, C-14

C-14 Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	5.15	0.12	15.34	0.07	132.03
2	26.75	0.65	4.88	0.35	25.42
3	23.5	0.57	5.28	0.31	28.93
4	18.65	0.45	6.11	0.24	36.46
5	76.4	1.85	2.68	1.00	8.90
6	30.65	0.74	4.50	0.40	22.18
7	21.1	0.51	5.65	0.28	32.23
8	141.7	3.42	1.93	1.85	4.80
9	14.65	0.35	7.16	0.19	46.41
Average		0.96			37.48

Cross talk check in alpha channel with Sr/Y-90 source on contact = 0 net cps.
Am-241 cross talk in beta channel = 1947 cps
Pu-239 cross talk in beta channel = 127 cps

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 17 cps beta, 1 cps alpha
High voltage = 1000 volts
Discriminator = 1.57 volts beta, 8 volts alpha

*Normalized Efficiency is determined by calculating the ratio between the efficiencies at the various locations and the efficiency found at the center of the detector (Position 5).

**The MDA formula is defined as the detectable activity in nCi which is 4.65 standard deviations above background for a ten second count time and using the listed efficiencies and background rates. (American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the source during the measurements.

TABLE 31. 8"x12" Edge Mount PMT, Thin Beta Plastic & ZnS, Pm-147

<i>Pm-147</i> Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	6.85	0.46	13.66	0.11	35.33
2	28.4	1.93	4.92	0.44	8.52
3	24.1	1.64	5.47	0.37	10.04
4	20.95	1.42	6.00	0.33	11.55
5	64.4	4.37	3.01	1.00	3.76
6	35.5	2.41	4.28	0.55	6.82
7	23.55	1.60	5.55	0.37	10.28
8	99.15	6.73	2.36	1.54	2.44
9	12.8	0.87	8.46	0.20	18.91
Average		2.38			11.96

Cross talk check in alpha channel with Sr/Y-90
source on contact = 0 net cps.
Am-241 cross talk in beta channel = 1947 cps
Pu-239 cross talk in beta channel = 127 cps

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 17 cps beta, 1 cps alpha
High voltage = 1000 volts
Discriminator = 1.57 volts beta, 8 volts alpha

*Normalized Efficiency is determined by
calculating the ratio between the
efficiencies at the various locations and
the efficiency found at the center of the
detector (Position 5).

**The MDA formula is defined as the detectable
activity in nCi which is 4.65 standard deviations above
background for a ten second count time and using
the listed efficiencies and background rates.
(American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the
source during the measurements.

TABLE 32. 8"x12" Edge Mount PMT, Thin Beta Plastic & ZnS, Co-60

Co-60 Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	92.95	3.48	2.45	0.25	4.73
2	222.5	8.32	1.53	0.60	1.97
3	184.4	6.89	1.69	0.50	2.38
4	176.4	6.60	1.73	0.47	2.49
5	372.3	13.92	1.18	1.00	1.18
6	228.6	8.55	1.51	0.61	1.92
7	204	7.63	1.61	0.55	2.15
8	468.85	17.53	1.04	1.26	0.94
9	161.45	6.04	1.82	0.43	2.72
Average		8.77			2.28

Cross talk check in alpha channel with Sr/Y-90
source on contact = 0 net cps.
Am-241 cross talk in beta channel = 1947 cps
Pu-239 cross talk in beta channel = 127 cps

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 17 cps beta, 1 cps alpha
High voltage = 1000 volts
Discriminator = 1.57 volts beta, 8 volts alpha

*Normalized Efficiency is determined by
calculating the ratio between the
efficiencies at the various locations and
the efficiency found at the center of the
detector (Position 5).

**The MDA formula is defined as the detectable
activity in nCi which is 4.65 standard deviations above
background for a ten second count time and using
the listed efficiencies and background rates.
(American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the
source during the measurements.

TABLE 33. 8"x12" Edge Mount PMT, Thin Beta Plastic & ZnS, Cs-137

<i>Cs-137</i> Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	88.35	11.21	2.52	0.43	1.47
2	149.95	19.02	1.89	0.74	0.86
3	124.9	15.84	2.08	0.61	1.04
4	124.45	15.79	2.09	0.61	1.04
5	203.4	25.80	1.61	1.00	0.64
6	157.8	20.02	1.84	0.78	0.82
7	128.35	16.28	2.05	0.63	1.01
8	204.7	25.97	1.60	1.01	0.63
9	128.4	16.29	2.05	0.63	1.01
Average		18.47			0.95

Cross talk check in alpha channel with Sr/Y-90
source on contact = 0 net cps.
Am-241 cross talk in beta channel = 1947 cps
Pu-239 cross talk in beta channel = 127 cps

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 17 cps beta, 1 cps alpha
High voltage = 1000 volts
Discriminator = 1.57 volts beta, 8 volts alpha

*Normalized Efficiency is determined by
calculating the ratio between the
efficiencies at the various locations and
the efficiency found at the center of the
detector (Position 5).

**The MDA formula is defined as the detectable
activity in nCi which is 4.65 standard deviations above
background for a ten second count time and using
the listed efficiencies and background rates.
(American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the
source during the measurements.

TABLE 34. 8"x12" Edge Mount PMT, Thin Beta Plastic & ZnS, Tl-204

<i>Tl-204</i> Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	149.65	11.95	1.89	0.46	1.37
2	250.7	20.03	1.44	0.78	0.82
3	207.3	16.56	1.59	0.64	0.99
4	208.25	16.64	1.59	0.65	0.99
5	322.45	25.76	1.27	1.00	0.64
6	243.05	19.42	1.47	0.75	0.85
7	223.7	17.87	1.53	0.69	0.92
8	333.65	26.65	1.24	1.03	0.62
9	213.5	17.05	1.57	0.66	0.96
Average		19.10			0.91

Cross talk check in alpha channel with Sr/Y-90
source on contact = 0 net cps.
Am-241 cross talk in beta channel = 1947 cps
Pu-239 cross talk in beta channel = 127 cps

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 17 cps beta, 1 cps alpha
High voltage = 1000 volts
Discriminator = 1.57 volts beta, 8 volts alpha

*Normalized Efficiency is determined by
calculating the ratio between the
efficiencies at the various locations and
the efficiency found at the center of the
detector (Position 5).

**The MDA formula is defined as the detectable
activity in nCi which is 4.65 standard deviations above
background for a ten second count time and using
the listed efficiencies and background rates.
(American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the
source during the measurements.

TABLE 35. 8"x12" Edge Mount PMT, Thin Beta Plastic & ZnS, Sr/Y-90

Sr/Y-90 Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	174.8	12.37	1.74	0.48	1.33
2	270.8	19.17	1.39	0.75	0.86
3	230.45	16.31	1.51	0.64	1.01
4	232.85	16.48	1.50	0.65	1.00
5	360.8	25.54	1.19	1.00	0.64
6	271.75	19.24	1.38	0.75	0.85
7	236.45	16.74	1.49	0.66	0.98
8	401	28.39	1.13	1.11	0.58
9	272.1	19.26	1.38	0.75	0.85
Average		19.28			0.90

Cross talk check in alpha channel with Sr/Y-90
source on contact = 0 net cps.
Am-241 cross talk in beta channel = 1947 cps
Pu-239 cross talk in beta channel = 127 cps

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 17 cps beta, 1 cps alpha
High voltage = 1000 volts
Discriminator = 1.57 volts beta, 8 volts alpha

*Normalized Efficiency is determined by
calculating the ratio between the
efficiencies at the various locations and
the efficiency found at the center of the
detector (Position 5).

**The MDA formula is defined as the detectable
activity in nCi which is 4.65 standard deviations above
background for a ten second count time and using
the listed efficiencies and background rates.
(American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the
source during the measurements.

TABLE 36. 8"x12" Edge Mount PMT, Thin Beta Plastic & ZnS, Pu-239

<u><i>Pu-239</i></u> Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	66.25	33.69	2.96	0.99	0.12
2	57.4	29.19	3.21	0.86	0.14
3	56.4	28.68	3.25	0.84	0.14
4	69.75	35.47	2.87	1.04	0.11
5	66.95	34.04	2.94	1.00	0.12
6	51.85	26.37	3.41	0.77	0.15
7	68	34.58	2.92	1.02	0.12
8	60.2	30.61	3.13	0.90	0.13
9	57.45	29.21	3.21	0.86	0.14
Average		31.31			0.13

Cross talk check in alpha channel with Sr/Y-90
source on contact = 0 net cps.
Am-241 cross talk in beta channel = 1947 cps
Pu-239 cross talk in beta channel = 127 cps

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 17 cps beta, 1 cps alpha
High voltage = 1000 volts
Discriminator = 1.57 volts beta, 8 volts alpha

*Normalized Efficiency is determined by
calculating the ratio between the
efficiencies at the various locations and
the efficiency found at the center of the
detector (Position 5).

**The MDA formula is defined as the detectable
activity in nCi which is 4.65 standard deviations above
background for a ten second count time and using
the listed efficiencies and background rates.
(American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the
source during the measurements.

TABLE 37. 8"x12" Edge Mount PMT, Thin Beta Plastic & ZnS, Am-241

<i>Am-241</i> Location***	Net (cps)	Efficiency (%)	Count Rate Error (%)	Normalized* Efficiency	MDA** (nCi)
1	2388.75	37.06	0.46	1.23	0.11
2	1914.25	29.70	0.51	0.98	0.13
3	1472.9	22.85	0.58	0.76	0.17
4	2324.8	36.07	0.46	1.19	0.11
5	1945.85	30.19	0.51	1.00	0.13
6	1893.3	29.37	0.52	0.97	0.14
7	1928.8	29.92	0.51	0.99	0.13
8	2148.9	33.34	0.48	1.10	0.12
9	2309.5	35.83	0.47	1.19	0.11
Average		31.59			0.13

Cross talk check in alpha channel with Sr/Y-90
source on contact = 0 net cps.
Am-241 cross talk in beta channel = 1947 cps
Pu-239 cross talk in beta channel = 127 cps

Count time = 20 seconds
Background time = 60 seconds
Background Rate = 17 cps beta, 1 cps alpha
High voltage = 1000 volts
Discriminator = 1.57 volts beta, 8 volts alpha

*Normalized Efficiency is determined by
calculating the ratio between the
efficiencies at the various locations and
the efficiency found at the center of the
detector (Position 5).

**The MDA formula is defined as the detectable
activity in nCi which is 4.65 standard deviations above
background for a ten second count time and using
the listed efficiencies and background rates.
(American Nuclear Standards Institute 1989)

***See Figure 6 for the locations of the
source during the measurements.

TABLE 38. Summary of Average Efficiencies for Each Detector Configuration

Isotope	4"x4"	8"x12"	8"x12"	8"x12"	8"x12"
	Vertical PMT with ZnS	Vertical PMT no ZnS	Vertical PMT with ZnS	Edge PMT no ZnS	Edge PMT with ZnS
	Avg. Eff. (%)	Avg. Eff. (%)	Avg. Eff. (%)	Avg. Eff. (%)	Avg. Eff. (%)
C-14	0.02	1.25	2.48	2.07	0.96
Pm-147	0.57	2.08	3.35	4.57	2.38
Co-60	15.78	5.09	7.95	11.49	8.77
Cs-137	9.63	11.29	14.52	23.28	18.47
Tl-204	6.31	11.9	15.22	24.48	19.1
Sr/Y-90	22.14	11.21	15.1	21.38	19.28
Pu-239	30.73		31.44		31.31
Am-241	28.86		29.86		31.59

Efficiencies taken from Tables 2 through 37 of this report.

TABLE 39. Summary of Average MDA's for Each Detector Configuration

Isotope	4"x4"	8"x12"	8"x12"	8"x12"	8"x12"
	Vertical PMT with ZnS MDA (nCi)	Vertical PMT no ZnS MDA (nCi)	Vertical PMT with ZnS MDA (nCi)	Edge PMT no ZnS MDA (nCi)	Edge PMT with ZnS MDA (nCi)
C-14	825.00	60.51	31.57	9.43	37.48
Pm-147	271.00	19.52	16.83	4.09	11.96
Co-60	1.29	3.90	4.02	1.55	2.28
Cs-137	2.46	1.34	1.62	0.76	0.95
Tl-204	2.19	1.22	1.48	0.72	0.91
Sr/Y-90	0.91	1.23	1.40	0.83	0.90
Pu-239	0.13		0.13		0.13
Am-241	0.14		0.14		0.13

MDA's taken from Tables 2 through 37 of this report.

FIGURES 7 - 18

Figure 7. Vertical Mount PMT, Thin Beta Plastic Only, ^{14}C

Figure 8. Vertical Mount PMT, Thin Beta Plastic Only, ^{137}Cs

Figure 9. Vertical Mount PMT, Thin Beta Plastic Only, $^{90}\text{Sr}/^{90}\text{Y}$

Figure 10. Vertical Mount PMT, Thin Beta Plastic & ZnS, ^{14}C

Figure 11. Vertical Mount PMT, Thin Beta Plastic & ZnS, ^{137}Cs

Figure 13. Edge Mount PMT, Thin Beta Plastic Only, ^{14}C

Figure 14. Edge Mount PMT, Thin Beta Plastic Only, ^{137}Cs

Figure 15. Edge Mount PMT, Thin Beta Plastic Only, $^{90}\text{Sr}/^{90}\text{Y}$

Figure 16. Edge Mount PMT, Thin Beta Plastic & ZnS, ^{14}C

Figure 17. Edge Mount PMT, Thin Beta Plastic & ZnS, ^{137}Cs