

AN ABSTRACT OF THE DISSERTATION OF

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Kathryn A. Higley

The Field Instrument for Detecting Low Energy Radiation (FIDLER) is an established radiation detector used for locating plutonium and its progeny. Recent advances have allowed this instrument to be integrated with Global Positioning and data logging instruments. Using this technology, a FIDLER is walked over an area and pertinent radiological and position information is stored in the logger. Scanning efficiency was examined theoretically, with the use of the Monte Carlo photon/electron transport program Electron Gamma Shower 4 (EGS4). Experimentally, scanning was completed with the use of a tracked cart system that moved an ^{241}Am source beneath a FIDLER. As is done in the field a collection time of 2 s was used in both cases. How signal processing affects FIDLER response was also examined. Results clearly show that scanning efficiency decreases with increasing speed. For a FIDLER not subject to signal processing, experimental scanning efficiencies remained above 1% up to 100 cm s^{-1} . Sources at depth recorded lower efficiencies, mainly due to attenuation of the low energy photon, dropping below 1% near 30 cm s^{-1} and reaching nearly 0.1% at 100 cm s^{-1} . In order to take full advantage of this technology the lowest response time of the meter attached to the FIDLER must be used, but results in large variability in the recorded

scanning efficiencies for each speed. Therefore, contamination can potentially be missed or over/under estimated. To resolve this problem higher response times can be used but efficiency is sacrificed, dropping below EGS4 worst predictions. With these results in mind using the FIDLER with positioning and data logging technology produces questionable results at best. Therefore, results gathered by the FIDLER in this manner should not be relied upon to make any conclusions regarding site contamination.

An Examination of the Scanning Detection Efficiency of the FIDLER in Relation to
Data Logging and Global Positioning Technology.

by

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Craig M. Marianno, Author

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CONTRIBUTING AUTHORS

David Hunter provided technical information and equipment for the first manuscript. Dr. Todd Palmer helped develop the computer simulations used throughout this work. Craig Moss helped in data collection and data analysis for the final manuscript.

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*For my parents, George and Kay Locatelli. I would have never have made it
this far without them!*

An Examination of the Scanning Detection Efficiency of the FIDLER in Relation to Data Logging and Global Positioning Technology

Chapter 1. INTRODUCTION

Detecting plutonium in the field is a difficult process. In the early years of the nuclear industry, when plutonium contamination became a concern in field surveys, alpha sensitive detectors were employed. Besides their probes being easily punctured in the field, alpha detection provides its own set of problems. Alphas have a range in air of only centimeters and if any kind of absorbing material is placed over the contamination this range is reduced to microns. Therefore, to detect alpha contamination, near contact monitoring is required. Furthermore, if any type of overburden is present, even rain or snow, alpha monitoring is not possible (Taschner, 1989). A new method had to be developed which would not be subject to the difficulties that alpha detection presented.

1.1 THE FIDLER

Plutonium not only emits alpha radiation, but isotopic mixtures of the element emit uranium and neptunium L x-rays (13.6, 17.2 and 20.2 keV) that are produced by internal conversion in the progeny of plutonium and ^{241}Am (Tinney, 1968). Furthermore, ^{241}Am formed from the beta decay of ^{241}Pu emits 60 keV gamma rays. With this knowledge, Livermore National Laboratory developed a special type of scintillation detector that could detect plutonium photon emissions. First described by Schmidt and Koch (1966), this detector used a thin sodium-iodide (NaI) scintillation

crystal attached to a battery-operated photomultiplier tube (PMT) and single channel analyzer (SCA). Early versions of this instrument were used to locate plutonium contamination based on the detection of the 17 keV plutonium x-rays (Schmidt and Koch, 1966). Since the 17 keV x-ray can be easily attenuated by overburden, later versions of the instrument were not only used to detect the 17 keV x-ray, but also the 60 keV gamma from ^{241}Am (Lindeken and Koch, 1968). For aged weapons grade plutonium (WGPu), especially in cases where overburden due to erosion into soil has occurred, it is best to monitor for the 60 keV gamma (Taschner, 1989). This instrument, being employed in the field to detect low energy photon radiation, was given the name of the Field Instrument for Detecting Low Energy Radiation, or FIDLER (Schmidt and Koch, 1966).

The advantages of using photons to detect plutonium in field surveys have been previously discussed (e.g., Tinney et al. 1969, Bruns 1982). Unlike an alpha probe, the FIDLER does not have to be placed in contact with the contaminated surface. This minimizes the potential for detector damage and for point-by-point measurement. With photons, detector performance is not as hindered by overburden such as vegetation, water, snow or soil. The health hazard is also minimized because the survey can be conducted after the radioactivity has been "tied down."

The FIDLER is a unique piece of equipment. In preliminary studies Lindeken and Koch (1967) showed that the most efficient thickness of NaI scintillator for detecting both the 17 keV and 60 keV photons, taking into account signal-to-noise ratio, was approximately 1/16" or 0.16 cm. Today, FIDLERs typically have a NaI crystal thickness of 0.16 cm and diameter of 12.7 cm. This configuration provides a large

surface area for detection while its thickness allows higher energy photons to preferentially pass through without interaction. The detector entrance window can either be made of beryllium or aluminum (Taschner, 1989). Aluminum foil is typically used in the field due to it being more rugged. The crystal is optically coupled through a quartz light pipe to a PMT. The entire system is joined to a battery-operated SCA equipped with a count rate meter and regulated high voltage power supply. Laboratory versions of this detector are employed to characterize soil samples. Field versions weigh approximately 6 lbs and can be carried by an individual or mounted on a vehicle (Figure 1.1 and Figure 1.2).

As a system, the FIDLER has been employed in the field for many years. The first reported use of the instrument was in 1967 (Greenhouse et al., 1967). Here it was employed to monitor a 75 m² area non-uniformly contaminated with ²³⁹Pu. Using the detector, "hot spots" of contamination were located and the total activity of the site was estimated to be between 250 to 650 μ Ci. Because of its proven use in the field, the FIDLER has been employed by the U.S. Army, Navy and Air Force. It is also used at the national laboratories including: the Nevada Test Site (NTS), Hanford, Los Alamos, Rocky Flats Environmental Technology Site and Oak Ridge.

1.2 RESEARCH WITH THE FIDLER

Technical studies on the FIDLER are limited. Initial work was primarily an introduction to the instrument (Schmidt and Koch, 1966). A brief comparison was made pitting the FIDLER against a xenon filled proportional counter. The sensitivity and the signal to noise ratio were shown to be better in the FIDLER. In addition,

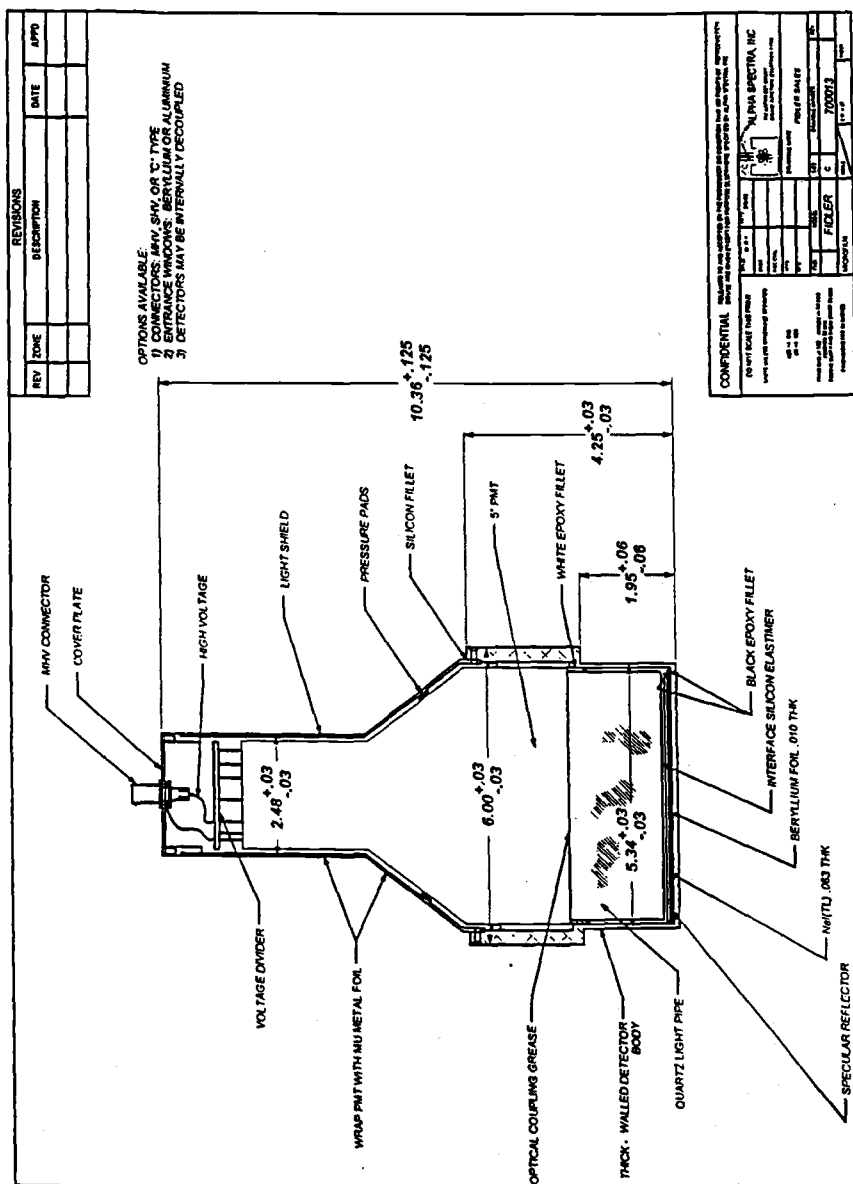


Figure 1.1. Schematic of a FIDLER Probe. Reproduced courtesy of Alpha Spectra, Inc.¹

¹ Alpha Spectra, Inc. Scintillation Detectors, 715 Arrowst Ct, Grand Junction, CO 81505

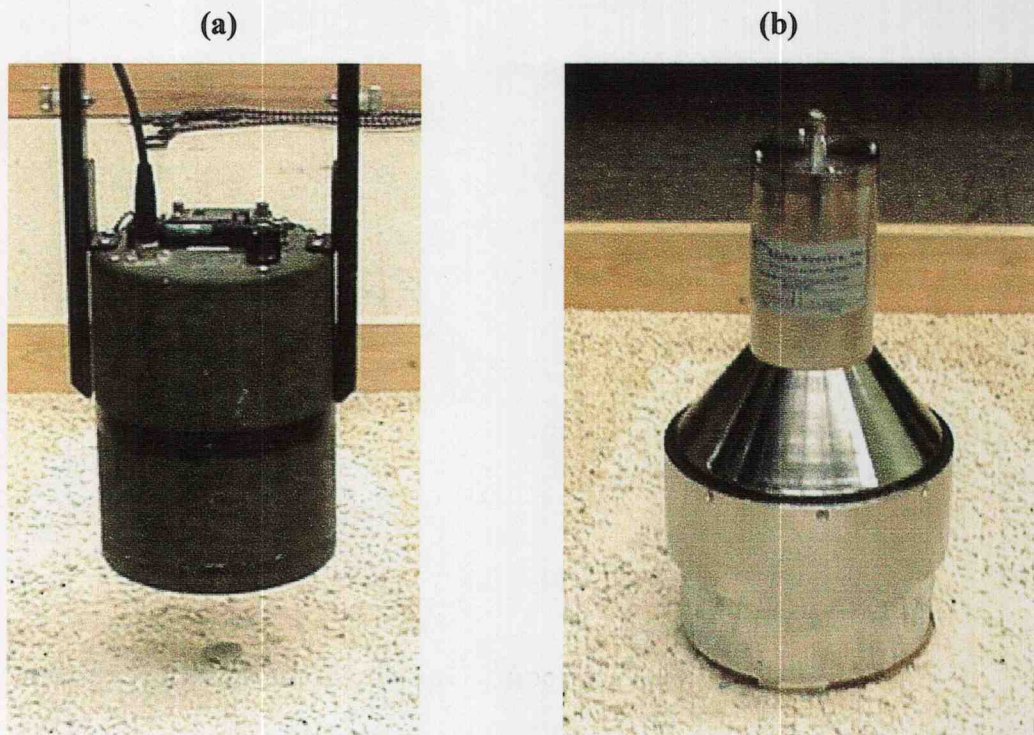


Figure 1.2. Examples of two types of FIDLERs employed in the field. The FIDLER in (a) is produced by APTEC-Nuclear Research Corporation (NRC)². It is the primary FIDLER used by the United States Armed Forces such as the U.S. Army. The FIDLER in (b) is made by Alpha Spectra, Inc. and can be used in the field as well as the laboratory.

² APTEC-NRC, Inc. 125 Titus Avenue, Warrington, PA 18976 U.S.A

approximate minimum detectable concentration (MDC) of plutonium for a stationary FIDLER were stated. With a known background and using a distributed plutonium source, it was determined the ratio of the standard deviation of a single reading, $\sigma(a)$, to the background count rate, B , is related to the count rate meter time constant (RC) by:

$$\frac{\sigma(a)}{B} = \frac{1}{\sqrt{2B * RC}} \quad \text{Eq. 1.1}$$

Schmidt and Koch (1966) used a 3σ criterion for detectability and determined the MDC is:

$$MDC \left[\frac{\mu\text{g of Pu metal}}{m^2} \right] = \frac{3\sigma(a)}{S} = \frac{3}{S} \sqrt{\frac{B}{2RC}} \quad \text{Eq. 1.2}$$

where S is the sensitivity of the detector in counts (c) / μg of Pu metal /min/ m^2 . Using $S = 23 \text{ c min}^{-1}$ per μg of Pu m^{-2} , $RC = 0.1 \text{ min}$ and with a varied background between 300 and 1000 min^{-1} , it was determined any contamination higher than $40 \mu\text{g m}^{-2}$ could definitely be detected and levels between 9 and $40 \mu\text{g m}^{-2}$ could possibly be detected.

Measurements conducted with the FIDLER can be influenced by photon attenuation. Even small attenuation will decrease detection sensitivity and as a result will underestimate the true contamination level of an area. A technique was investigated for estimating and correcting for overburden attenuation. To minimize the effect, Tinney and Hoeger (1969) investigated intensity ratio measurements between the 17 keV x-ray and the 60 keV gamma ray. This method can be described by the equation:

$$\frac{I_X}{I_\gamma} = \frac{I_{0X}}{I_{0\gamma}} e^{(\mu_\gamma - \mu_X)X} \quad \text{Eq. 1.3}$$

where I_x is the attenuated intensity of the 17 keV photon, I_γ is the attenuated intensity of the 60 keV photon, I_0 is the unattenuated intensity of the respective photons, μ is the linear attenuation coefficient, and X is the overburden thickness. If $I_{0x}/I_{0\gamma}$ is known, a simple calibration procedure can be used to establish the relationship between I_x/I_γ and overburden attenuation. It was indicated that overburden attenuation could be estimated for a plutonium point source or area source containing small amounts of ^{241}Am . For samples containing more than 500 ppm ^{241}Am , the 60 keV Compton continuum contributed too many counts in the 17 keV peak and therefore could not be neglected. It was also concluded that under field conditions problems associated with non-uniformity in contaminant distribution and overburden composition would severely limit the usefulness of this technique.

The effect of temperature on FIDLER response was also examined (Hoeger and Tinney, 1969). Pulse amplitude and resolution of the detector are temperature dependent. In this work, as temperature increased up to 80° F, pulse amplitude increased with a corresponding decrease in resolution. It was concluded that components in the voltage divider network were responsible. Using two different high voltage (HV) supplies, results showed a maximum HV variation of less than $\pm 2.9\%$ over the temperature range of -20° F to +132° F. The HV variations are small, but the resulting change in phototube gain can not be neglected. For example, a 10-stage phototube with a 1% change in HV will cause a 10% change in gain (Hoeger and Tinney, 1969).

Much of the work completed on the FIDLER has regarded calibration of the instrument (Tinney and Koch, 1967; Tinney, 1968; Tinney et al., 1969). In all cases a

point source of either ^{241}Am or plutonium was employed and moved laterally away from the detector, which was 30.5 cm above the surface. Using symmetry, a point source at any given lateral displacement will produce the same detector count rate as a narrow ring source having the same radius and total activity. After recording the count rate at each distance away from the detector, the "trapezoid method of approximate integration" (Tinney and Koch, 1967) was employed to determine the sensitivity of the FIDLER as a function of contaminant area and detector height. A personal computer (PC) program available today, HotSpot (Homann, 1994), can perform this calibration automatically after a researcher inputs source information and count rate data.

Tinney and Koch (1967) concentrated their efforts on the 17 keV x-ray of ^{239}Pu . It was determined that for contamination areas greater than 1 m^2 with a detector height of 1 ft, the sensitivity of the FIDLER was approximately constant at 28 c min^{-1} per μg of Pu m^{-2} . Using typical variations in background and Eq. 1.2, the estimated MDC level was between 2 and $3.5\text{ }\mu\text{g m}^{-2}\text{ }^{239}\text{Pu}$.

Adding to earlier work, Tinney (1968) demonstrated a method to calibrate the FIDLER with an ^{241}Am source. By calibrating with this source, estimates of plutonium activity within a given area could be proposed. This method was developed because of the difficulty of obtaining isotopically pure sources of plutonium. Using the calibration technique of Tinney and Koch (1967) for the 17 keV x-ray with a $\text{RC} = 0.2\text{ min}$ and an assumed background of 200 c min^{-1} , the minimum detectable ^{241}Am point source activity and area source activity were calculated. These values were $9.41 \times 10^{-3}\text{ }\mu\text{Ci}$ for a point source and $1.92 \times 10^{-2}\text{ }\mu\text{Ci m}^{-2}$ for an area source. By multiplying these results by the measured L x-ray yields for specific plutonium isotopes it was possible to

establish point source and area source detection sensitivities for plutonium. This was accomplished by determining the quantity (μg) of each plutonium isotope needed to provide the same 17 keV x-ray activity as 1 μCi (alpha) of ^{241}Am . The minimum detectable activity (MDA) and MDC of each plutonium isotope could be calculated by multiplying the appropriate correction factor by the MDA and MDC of ^{241}Am .

Tinney (1968) and Tinney et al. (1969) took into account that in most cases plutonium contamination in the field will consist of mixtures of its isotopes (238-242) in addition to ^{241}Am resulting from the beta decay of ^{241}Pu . Knowing that the exact isotopic composition will depend on the irradiation history, chemical separation and age of the material, a method for calculating the specific activity (17 keV) of a mixture of plutonium isotopes was laid out by the researchers (Tinney 1968):

$$SA \left[\frac{\text{x-rays}}{\text{min}} \right] / \left[\frac{\mu\text{g mixture}}{\mu\text{g}} \right] = W_{238} A_{238} R_{238} + W_{239} A_{239} R_{239} + W_{240} A_{240} R_{240} + 387 W_{241} t + W_{242} A_{242} R_{242}$$

Eq. 1.4

where W is the weight fraction of the isotope at the time of chemical separation, A is the alpha specific activity of the isotope (disintegrations/min/ μg), R is the x-ray to alpha ratio of the isotope, and t is the time from chemical separation in days. Values of A and R are tabulated (Tinney, 1968). The term $387 W_{241} t$ takes into account the increase in ^{237}Np L x-rays intensity resulting from the initial weight fraction of ^{241}Pu (W_{241}), which decays via β emission. The above method could be used for material that is less than 5000 d old as a "back of the envelope" calculation in the field. In addition, this formula can only be used if W and t are known. In most cases because these values are unknown, laboratory analysis is required to accurately obtain specific activity. Using

the x-ray specific activity calculated from Eq. 1.4, the mass (μg) of plutonium mixture that would yield the equivalent 17 keV x-ray activity as 1 μCi of ^{241}Am can be determined. The ^{241}Am MDA and MDC determined through earlier calibration are then used to calculate the plutonium mixture MDA and MDC.

The detection sensitivity of the 60 keV photon emitted by ^{241}Am was also examined (Tinney, 1968; Tinney et al., 1969). Using the established calibration technique (Tinney and Koch, 1966) it was determined that the MDA for the ^{241}Am 60 keV photon was $1.90 \times 10^{-2} \mu\text{Ci}$ (alpha) and the MDC was $3.6 \times 10^{-2} \mu\text{Ci m}^{-2}$. These values can be employed to determine the ^{241}Pu contamination level. Using an equation similar to Eq 1.4, the specific activity of the 60 keV photon from a plutonium/ameridium sample will be (Tinney, 1968):

$$SA = 387W_{241}t \quad \text{Eq. 1.5}$$

As with Eq. 1.4 the use of this equation requires knowledge of the initial ^{241}Pu weight fraction, W_{241} . In most cases laboratory analysis will be required.

Part of the calibration research involved determining the most efficient setting for the discriminator in the SCA of the FIDLER (Tinney, 1968). Using a multichannel analyzer (MCA) and a 10.7 μCi ^{241}Am source, Tinney found the optimum discrimination levels for both the 17 keV and 60 keV photons. For the lower energy photon the detector resolution was found to be 57% full-width-at-half-maximum (FWHM); for the higher energy gamma ray, 19.2% FWHM.

1.3 MORE CAN BE DONE

Thirty years after the advent of the FIDLER fundamental questions have not been answered about the instrument. In a time where technological advances and mass remediation efforts are taking place it is essential these questions be asked and answered. Due to past research on the instrument, the accepted method of calibration is for uniformly distributed surface contamination. Contamination faced by individuals in the remediation community is rarely uniform or on the surface and is most likely under some amount of vegetation or soil. In the first field-tests (Greenhouse et al., 1967, Tinney and Koch, 1967), the distribution of the contamination "was not uniform." Heterogeneously distributed contamination or hot particles are becoming of increasing interest to groups (i.e., private industry, Department of Energy, the United States Air Force, Navy and Army) that must survey and remediate sites where this type of contamination is prevalent. Since individual point sources with individual activities are of a concern, it is now important to concentrate on determining accurate minimum detectable activity levels. A first step in this process should be the examination of the FIDLER's efficiency at detecting these hot particles.

Scanning efficiency has never been adequately addressed. In all discussions of the FIDLER the instrument is "carried" over the contaminated site and yet the calibration of the instrument is done statically (e.g., Greenhouse et al., 1967, Tinney, 1968). Only at one point in the early research is scanning efficiency mentioned (Tinney and Koch, 1967) and only to state "a 5σ criterion for detectability" is warranted. There was no mention of sensitivity as a function of survey speed. Marianno and Higley (1999a) showed that the scanning efficiency for a 60 keV photon point source, directly

below the FIDLER, is nearly an order of magnitude lower than the corresponding static efficiency. Marianno and Higley (2000) also produced preliminary scanning efficiency data for only three different speeds. Further investigation in this area needs to be completed for the remediation community.

In this age of "bigger, better and cheaper," individuals in the remediation profession are attempting to remediate areas as rapidly as possible while maintaining a high level of detection efficiency. Due to this mind-set, detectors, in some cases, are being attached to data collectors and positioning systems to locate contamination. The earliest work in this field deals with the use of ultrasonic ranging devices (Berven et al., 1990, Fragoso et al., 1998), but now some individuals are beginning to use Global Positioning Systems (GPS) (Wright et al., 2000; Egidi et al., 2000). The FIDLER is a detector that is being attached to a GPS. A data collector attached to both the GPS and detector allows radiological data with corresponding ground location to be stored and later retrieved for mapping. Unfortunately, with this new use of technology existing FIDLER calibration methods may lack the ability to locate isolated point contamination known as hot particles.

Research should be completed on the FIDLER in light of this new technology and the deficiencies of past studies. The work presented here examines FIDLER scanning efficiency in relation to hot particle contamination using data collection/positioning technology.

Detector scanning sensitivity has been studied. Sommers (1975) moved calibrated sources under detectors to determine detection frequencies for velocities ranging from 2.4 to 15 cm s⁻¹. It was concluded that source detection frequencies were

strongly dependent on source strength, survey velocity, background activity, detector sensitivity and the time constant of the survey meter. In Sommers' study, for the instruments to reach a detection frequency of 90% at scanning speeds of 10 to 15 cm s⁻¹ a source strength of 10,000 to 15,000 β min⁻¹ was required.

Olsher et al. (1986) determined the scanning sensitivity of alpha detection instrumentation by measuring hot spot detection frequency under "realistic survey conditions." Using ZnS scintillation detectors, 40 surveyors were asked to survey five stations containing alpha activity levels between 64 and 672 decays min⁻¹. Detection frequency and false positive frequency were determined. For alpha source activity between 392 and 913 decays min⁻¹, a 50% detection frequency was reported.

With regard to the FIDLER, these earlier works are of limited use. Speed is quantified only in Sommers (1975), but in relation to scanning a land area, 10 to 15 cm s⁻¹ is extremely slow. Additionally, Sommers' study only considered Geiger-Muller and ion chamber beta-gamma survey instruments. In Olsher (1986), FIDLERs were not used either. In both studies, the capability of the surveyor to recognize an elevated count rate was studied, and detection sensitivity took into account the efficiency of the surveyors. Surveyor efficiency is not an issue with the data collection technology. Within an observation interval, if a count rate corresponding to a level higher than the known MDA is noted, then contamination is concluded to be present. The decision ability of the observer can be neglected.

The most complete study available on detector scanning sensitivity is located in NUREG-1507 (Abelquist et al., 1997). This report provides analysis of both static and scan MDCs. However, only specific types of detectors are examined, not the FIDLER.

It was noted in the analysis that scan sensitivity is very dependent on scanning speed, but an in-depth analysis of scanning sensitivity as a function of speed was never examined. Like the earlier studies, NUREG-1507 also considers the efficiency of the surveyors in distinguishing contamination from background.

Though limited and not related to FIDLERs, these earlier works can be used as a framework for further study. As part of the study presented in the following chapters, a new lab apparatus allows a FIDLER to hang above a shielded area while a platform containing soil is moved beneath. This is similar to Sommers (1975), but with a wider velocity range, from approximately 10 to 100+ cm s^{-1} .

Monte Carlo techniques are employed in conjunction with laboratory studies to examine scanning efficiency of one FIDLER system. Results are described in subsequent chapters.

Chapter 2

An Innovative Technique in Scanning Land Areas with a Multi-FIDLER System.

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2.1 ABSTRACT

Remediation can be a long and tedious effort. One possible step in this process is the scanning of land to locate elevated areas of radiological contamination. By adapting existing global positioning technology with radiation detection systems, this process can be significantly accelerated. The Field Instrument for Detecting Low Energy Radiation (FIDLER) was used in conjunction with a Global Positioning System (GPS) and Trimble® data logger. With this system two different land areas were scanned using two different scanning methods. In the first method, three FIDLERs were attached to a baby jogger and were used to scan a 20 acre site devoid of vegetation. The second technique involved individuals carrying the instruments over a 15 acre site that contained vegetation. Here the FIDLERs were waved in front of the workers in 50 cm arcs. In all cases, radiological and position data were collected by the data loggers. Using these results, accurate maps were generated for each site clearly illustrating areas and spots of elevated activity. By employing this technique over 250,000 data points pertaining to position and count rate were used to map nearly 40 acres of land in under three weeks.

2.2 INTRODUCTION

It is to the advantage of anyone involved with the remediation process to do a job as quickly and efficiently as possible. Unfortunately, remediation is not an area where corners should be cut or the job rushed to the point where mistakes are made and contamination is missed. Luckily, some technological advances have come about which will save time in the remediation process and therefore money.

A key step in the remediation effort is the evaluation of a site to locate and characterize areas of contamination. Different techniques are employed either together or separately to achieve these goals: *in-situ* gamma spectroscopy, soil sampling, and scanning with a detector system. *In-situ* gamma spectroscopy is an effective step. Using a detector, such as a high purity germanium (HPGe), can allow several different types of nuclides to be identified and their concentration in an area calculated. Depending on the topography, background and type of nuclide present this process can be cumbersome. There are few ways to save time in this process. The detector is suspended from a tripod or mounting device and a spectrum is allowed to accumulate over a prescribed period of time. The spectrum is then used to calculate pertinent radiological information of the surrounding area.

Sampling is an essential step. Analysis of contaminated soil samples provides great amounts of information. Not only can nuclides be identified either chemically or with laboratory detectors, but also radionuclide concentration in the soil can be explicitly determined. This step can take a great deal of time. Depending on the level of expected contamination, hundreds to thousands of samples may be taken and individually analyzed (U.S. NRC, 1997). The collection and analysis of samples can take several man-hours to accomplish.

Scanning too is an important step. Here detectors are slowly moved over areas and "hot spots" are located. In the past, to scan areas individuals have relied on headphones attached to their instruments to locate contamination. Once contamination was located, scanning would stop while the location was marked. As with *in-situ* gamma spectroscopy, this process could be slow and tedious depending on background

and site topography. A new use of existing technology has come about that may save time in the scanning process.

This method, which is employed in the field, uses detector systems in conjunction with data collectors and a positioning system to locate contamination. Until recently only ultrasonic ranging devices (Fragoso et al., 1998; Berven et al., 1990) have been employed, but now some individuals are beginning to use Global Positioning Systems (GPS) (Wright et al., 2000; Egidi et al., 2000). Using a differential GPS, surveys can be performed with positional accuracy of less than 1 m. A data logger attached to both the GPS and detector allows radiological data with corresponding ground location to be stored which can later be retrieved to a personal computer for mapping. While the old scanning method was slow and tedious the detector-positioning system combination allows fast, accurate high-density scanning over large land areas.

This paper will briefly discuss the use of a GPS-detector system to locate plutonium/ameridium contamination that resulted from an accident over three decades ago.

2.3 SYSTEM DESCRIPTION

A specialized scintillation detector was used to locate low energy photon emitting nuclides such as ^{241}Pu ($E_\gamma = 17 \text{ keV}$) and ^{241}Am ($E_\gamma = 60 \text{ keV}$). This detector is known as the Field Instrument for Detecting Low Energy Radiation (FIDLER) (Tinney et al., 1969). This low energy photon detector has a 12.7 cm diameter, 0.16 cm thick NaI(Tl) crystal with an entrance window either made of aluminum or beryllium foil. This configuration allows lower energy photons to be absorbed in the crystal while

allowing high-energy photons to pass through without interaction. The FIDLER weighs about 6 lbs. and can easily be carried by an individual in the field.

Two makes of FIDLERs were employed for this survey. The first type was the APTEC-NRC FIDLER (Model #XP-100), the principle x-ray probe employed by the U. S. Armed Forces (Figure 1.2a). This probe is a hardened instrument package designed to sustain potentially rough treatment in the field. The crystal, PMT and associated electronics are contained in an aluminum body approximately 0.4 cm thick. A multifunction rate meter (Model #ADM-300) is attached to the instrument so an operator can read count rate. This meter can also be attached to a data collector via a RS232 cable. The second type of FIDLER was a Bicron³ (Model #G5) attached to a Ludlum⁴ meter (Model #2221). Like the APTEC-NRC probe, the Bicron is encased in an aluminum body (0.5 cm thick). Each FIDLER was set to register the 60 keV photon emitted by ²⁴¹Am.

The FIDLERs were carried by two different methods. In the first case, the FIDLER probes were suspended approximately 7.6 cm from the surface on a "baby jogger" (Figure 2.1). The two APTEC-NRC detectors were placed on opposite sides near the front tire, the Bicron was in the center, 15 cm behind the front two. The Bicron detector was placed in the center primarily because it fit best in the baby jogger. The detector centers were approximately 25 cm from each other. This distance allowed an overlap of about 10 cm in their effective scanning areas. When the terrain did not allow the use of the jogger, three workers physically carried the detectors

³ Bicron Radiation Measurement Products, 6801 Cochran Rd. Solon, OH 44139

⁴ Ludlum Measurements Inc. 501 Oak Street P.O. Box 810 Sweetwater, Texas 79556

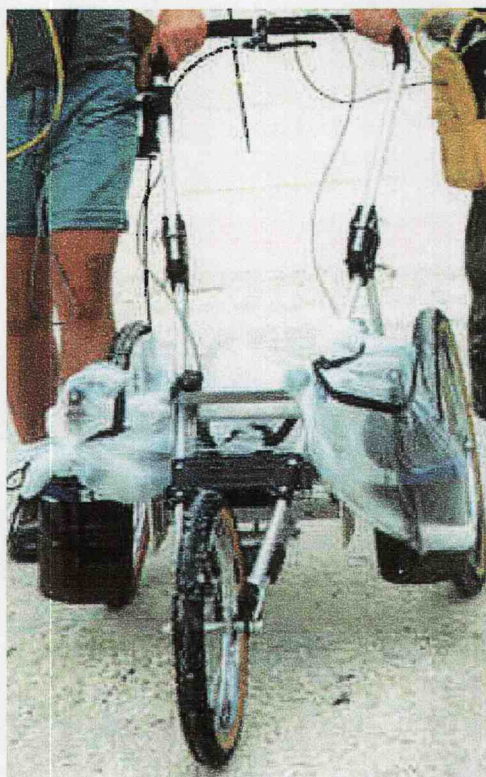


Figure 2.1. FIDLER-baby jogger setup used in the field. The two APTEC-NRC FIDLERs used on the outside of the baby jogger were attached to two separate GPS receivers. If contamination was detected in the center by the Bicron FIDLER, location could be inferred from the position data of the other two detectors. This set-up produced a scanning footprint approximately 1.1 m wide. The picture here only has the two APTEC-NRC FIDLERs on the baby jogger.

approximately 7.6 cm above the surface. At this height the FIDLERs have an effective scanning radius of about 30 cm and an average scanning efficiency of ~1% at speeds near 0.5 m s^{-1} (Marianno and Higley, 1999a).

Data collectors were attached to all three FIDLERs while two separate GPS receivers were attached to the outside detectors. The GPS equipment was carried in a 40 lb backpack and used high accuracy survey grade receivers downloading position information accurate to less than 1 m. The position data was sent to Trimble™ data collectors at 1 s intervals. The count rates determined by the FIDLERs were downloaded to the collector every 2 s.

2.4 SITE DESCRIPTION

Two different topographical locations were examined using the GPS-FIDLER system. Site #1 was a 20 acre site that was relatively flat and devoid of vegetation. Site #2 was 15 acres and was almost completely covered with low-lying vegetation and had several deep animal burrows.

2.5 RADIOLOGICAL SURVEY

The flat terrain of site #1 and lack of vegetation made scanning with the baby jogger convenient. Due to the placement of the detectors on the cart the effective scanning width was approximately 1.1 m. The scan rate was kept at a pace of between 0.5 and 1 m s^{-1} . Passes were made along tracks no greater than 1 m wide so that an overlap of about 10 – 15 cm occurred between passes. The 20 acres of area #1 took about eight days to complete and over 200,000 data points were accumulated.

Site #2 was more of a challenge. Due to its vegetation and burrows the FIDLERs had to be carried by three workers. The outside detectors (hooked to the GPS) were kept about 1 m apart, while the third FIDLER was carried in the center about 1 m behind. While walking over the site, the carried FIDLERs were slowly waved in about 50 cm arcs in front of the workers so that a larger area could be scanned with some overlap. In addition, the separation of the detectors made it easier for the carriers to walk while not sacrificing the scanning capabilities of the FIDLER. Since the center detector was not attached to a GPS, the FIDLER position was strictly controlled so its location reading could be traced in case contamination was registered. Due to the terrain the scanning speed was slower than when the jogger was used; therefore, the 15 acre site took six days to complete with 80,000 data points collected.

2.6 DATA ANALYSIS

Data from each survey were downloaded and analyzed each night. During breaks and at the end of the day the survey data were saved into a database. Every evening AUTOCAD® was employed to plot radiological data with corresponding map points. To aid in the analysis, color codes were used to classify data points according to their count rate. A surveyed quadrant of site #2 is provided to illustrate the utility of the system (Figure 2.2). A majority of the data is colored light green indicating the count rate levels are at or near background levels. As the survey approaches or passes over a hot spot the detectors begin to register the radiation. The data points change to darker colors that indicate elevated radiation fields. Away from a radiation source, the data points return to green due to the lower count rate recorded by the system. The large

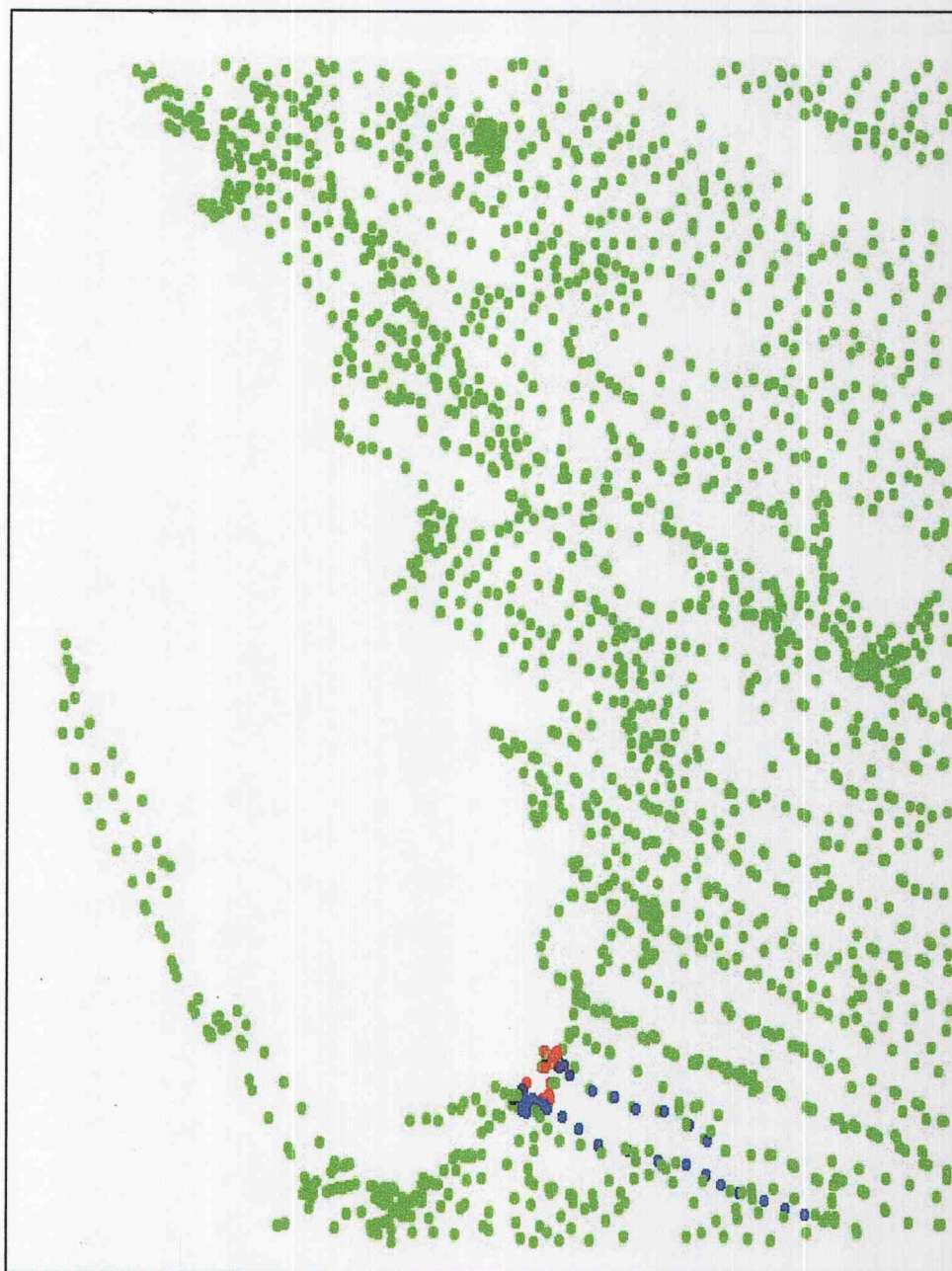


Figure 2.2. Count rate data mapped to specific locations from site #2. The different colors represent the relative count rate registered by each FIDLER. Light green indicates a count rate of less than 700 counts per minute (cpm); Blue, 701 to 1400 cpm; Orange, 1401 to 5000 cpm; Orange, 5001 to 10000 cpm. The red spots indicate the highest recorded count rates that are above 10001 cpm. This quadrant is only 150 ft. by 150 ft. and contains over 2600 data points.

square without any data points is a building located in the grid area. This one quadrant is approximately 150 ft by 150 ft., but it contains over 2600 data points of position and radiological information.

Similar maps were created for both sites with elevated count rate levels distinguished by different colored markers. The resulting maps were employed to determine how further remediation efforts (i.e., in-situ gamma spectroscopy and soil sampling) should be carried out. In addition, where elevated spots existed due to discrete sources the location was revisited with the GPS and FIDLER and the contamination was removed, thus remediating specific sites within an area of concern.

2.7 CONCLUSION

The examination of a land area during remediation can be a slow and tedious process. Due to the sensitivity of certain steps of the process, such as in-situ spectroscopy and soil sampling, few methods can be used to accelerate the work. However, utilizing GPS-detector systems has the potential of hastening the scanning process. The GPS-FIDLER system mentioned here scanned nearly 40 acres of land mapping out two entire sites in under three weeks with the number of data points relaying count rate and ground location exceeding 250,000. The resulting maps were then employed to determine further courses of action in the remediation process.

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Chapter 3

Theoretical Efficiencies for a FIDLER Scanning Hot Particle Contamination

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3.1 ABSTRACT

Many cold war facilities are reaching the end of their life span. As these sites grow older their missions are switching from production roles to clean up and remediation. Radioactive contamination at these sites can vary from fission products to low energy gamma emitters such as $^{239,241}\text{Pu}$ and ^{241}Am . This contamination can be distributed homogeneously or in the form of discrete particles. A simulation using Electron Gamma Shower 4 (EGS4) examines the theoretical detection efficiency for detecting discrete contamination of the Field Instrument for Detecting Low Energy Radiation (FIDLER). Using a 60 keV gamma source both static and scanning efficiencies were examined for a FIDLER 7.62 cm above the surface. Efficiency was examined as a function of depth, distance, and speed. For particles at or near the surface, the static efficiency (60 keV photons detected divided by total number emitted) was above 1% for a detection radius up to 20 cm. Scanning results showed that, for a particle near the surface, detection efficiency was above 1% up to speeds of 1 m s^{-1} . For a source at depth, both scanning and static efficiency were lower due to attenuation by the soil.

3.2 INTRODUCTION

As sites across the nation involved with the nuclear industry and weapons production reach the end of their working life, their role is changing from production to clean up and remediation. These sites contain many different types of radioactive contamination not only fission products but also low energy photon emitters such as $^{239,241}\text{Pu}$ and ^{241}Am . Contaminants can exist as homogeneously distributed sources

and/or heterogeneously deposited point sources known as discrete or hot particles. Interest in hot particles is increasing especially among groups (i.e. private industry, Department of Energy, the United States Air Force, Navy and Army) that must survey and remediate sites where this type of contamination is prevalent.

There are various methods of detecting hot particle, low energy photon emitters. These techniques can include in-situ gamma spectroscopy, soil sampling and scanning with a field instrument for detecting low-energy radiation (FIDLER). Gamma spectroscopy has the advantage of specifically determining isotopic contamination via the spectrum it collects. Depending on the background, distribution of the source, type of soil and topography of the land this method can be time consuming. With proper soil sampling, radionuclide concentration can be accurately determined, but with hot particle contamination this could be comparable to finding a needle in a haystack. Surface scanning is useful because it can cover large areas and locate contamination as evidenced by increased count rate. By using some combination of all three techniques hot particle contamination may be located. However, while in-situ spectroscopy and soil sampling have been examined thoroughly, little research has been completed on the scanning abilities of the FIDLER (Schmidt and Koch, 1966; Tinney and Hoeger, 1969; Tinney et al. 1969; Albequist, 1999; Marianno and Higley, 1999a).

The FIDLER is a useful tool in surveying land areas. This sodium iodide detector can range in diameter from five to eight inches with a thickness of approximately 1/16". Its diameter provides a large surface area for detection while its thickness allows higher energy photons to preferentially pass through without interaction. Laboratory versions of this detector are employed to characterize soil

samples. Field versions weigh approximately six pounds and can be carried by an individual or mounted on a vehicle.

There are a variety of techniques for deploying the FIDLER in the field. Typically this detector is used with a rate meter, sometimes attached to headphones, to locate hot particles. This method is slow and tedious. Recently some individuals have attached data collectors and Global Positioning Systems (GPS) to the FIDLER. This innovation allows fast, accurate, high-density scanning over large land areas.

The purpose of this paper is to examine the theoretical FIDLER detection efficiency when scanning for hot particles. Currently, little work has been completed on determining the scanning efficiency for the FIDLER. Abelquist and Brown (1999) estimated minimum detectable concentrations (MDC) while scanning buildings and land areas. However, this paper does not specifically address FIDLERs. NUREG-1507 also examines scanning MDCs for various instruments, but does not discuss FIDLERs. When FIDLERs were first introduced in the mid-1960's, research was focused on static efficiencies (Schmidt and Koch, 1966; Tinney, 1968; Tinney et al., 1969). Marianno and Higley (1999a) have examined both static and scanning efficiencies for the FIDLER, but the FIDLER in question used a type of signal processing that affected detection efficiency. With the lack of knowledge in this area, a brief examination of theoretical FIDLER scanning efficiency is useful.

3.3 METHODS AND MATERIALS

The geometry of the simulation was relatively simple. The FIDLER was modeled as a sodium iodide crystal of radius 6.35 cm and thickness 0.16 cm. A 4 cm

thick quartz light-pipe of the same radius was placed behind the crystal. Absorbers in front of the crystal included aluminum foil (0.01 cm thick), aluminum casing (0.36 cm thick) which overlaps the edge of the crystal by 0.30 cm and a polyethylene O-ring (0.36 cm thick). Aluminum housing with a thickness of 0.41 cm was placed around this set-up. Dry air at normal temperature and pressure (NTP = 20 °C, 1 atm.) was between the source and detector. The source was placed on the surface, 2 cm, 4 cm and 6 cm below the surface of coral-like soil with a density of 1.55 g cm^{-3} .

Detection efficiency was examined in two different ways. First, a static efficiency was calculated for a source at 5 cm increments from the center of the detector. Second, a scanning efficiency was calculated for a simulated detector moving at speeds ranging from 10 cm s^{-1} to 100 cm s^{-1} . In both cases the detector was set at 7.62 cm above the surface. The simulated source for this test was a ^{241}Am photon source with an energy of 60 keV.

To simulate a scanning FIDLER some simplifications had to be made. It is difficult to simulate a moving detector; therefore the source was allowed to move in relation to the instrument. In this manner the hot particle then becomes a line source whose length is determined by the scanning speed and the time of data collection. In the field most meters will export data to collectors in one or two second bins. For this simulation the bin width was 2 s. Therefore the length of this line source was two times the scanning speed with the FIDLER placed at the center of the line (Figure 3.1). The line source was also centered under the detector. Photons with an energy of 60 keV were released isotropically, and uniformly along the line.

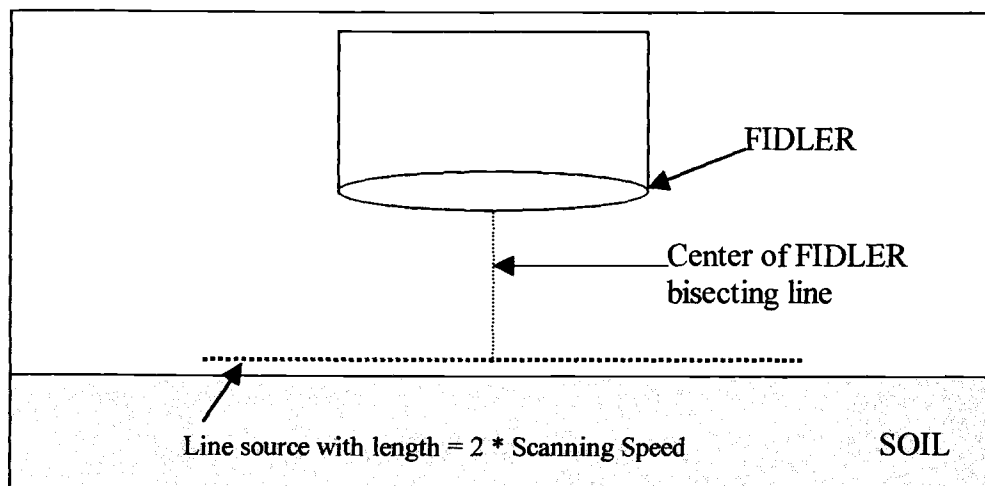


Figure 3.1. Scanning FIDLER-hot particle system. To simulate a moving FIDLER the hot particle was modeled as a line source. The length of the source is equal to the scanning speed multiplied by the sampling time, which in this case is 2 s.

Photon transport simulations were run using Electron Gamma Shower (EGS4) with the bound Compton cross section improvements (Namito et al., 1998). For each speed, one million histories were run. Detection efficiency was calculated as the total number of 60 keV photons absorbed by the crystal divided by the number of photons emitted. Static and scanning efficiency as a function of speed was plotted.

3.4 RESULTS AND DISCUSSION

Static efficiency results are plotted in Figure 3.2. This plot is similar to one produced by Marianno and Higley (1999a) and has been shown to match well with experimental results for surface sources. For the surface case, as the source moves away from the FIDLER the detection efficiency rapidly drops and is below 1% at less than 30.48 cm (1 ft) from the detector's center. Further calculations reveal that at 60 cm the efficiency is only 0.02%. Detection efficiency drops rapidly as source depth increases due to attenuation from the soil. Directly below the detector under 6 cm of soil, the efficiency is less than 0.4%. This information implies that detection capabilities of the FIDLER are limited when surveying for ^{241}Am . Depending on a hot particle's activity, the useful detection radius is less than 30 cm from its center and the depth should be above 6 cm.

Increased scanning speed negatively affects the FIDLER detection efficiency. For a hot particle on the surface when the FIDLER is stationary, the efficiency is approximately 9%. As the detector begins to move there is a gradual decrease in efficiency (Figure 3.3). This is expected; as speed increases the source is under the detector for less time. With less time, fewer counts are registered and a drop in

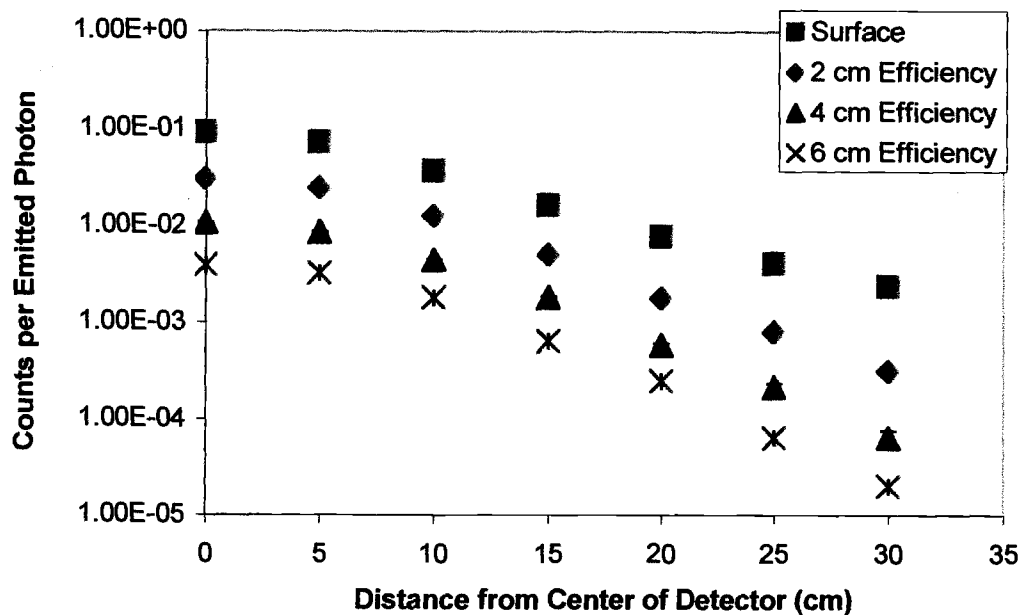


Figure. 3.2. FIDLER theoretical static detection efficiency for 60 keV photons as a function of depth and distance. For a point source, as depth and distance from the detector increases, detection efficiency rapidly decreases. At depths greater than 4 cm the efficiency is very low (below 1%).

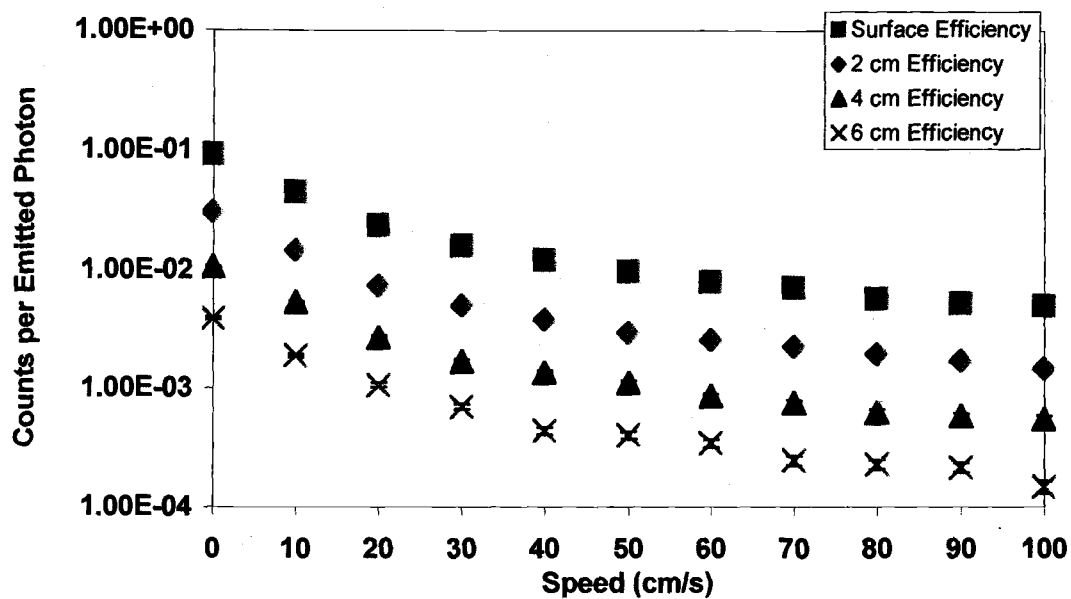


Figure 3.3. Theoretical FIDLER scanning efficiency for a point source as a function of depth and scanning speed. As speed increases, efficiency decreases.

efficiency is noted. Fortunately this decrease is not rapid. At a normal walking speed, approximately 1 m s^{-1} , the detection efficiency is nearly 1%. Similar results are illustrated for a buried hot particle. The efficiency is much lower in this case because of the increased attenuation by the soil. Therefore, if the potential exists for buried hot particles, a slower scanning speed is warranted. At higher speeds the efficiencies are low, but if the hot particles have high activity, surveys will have better accuracy. Conversely, if the contamination is of low activity then a slower speed should be used to better locate the source.

3.5 CONCLUSION

Many sites across the nation are switching from a production role to clean up and remediation. Radioactive contamination can exist as homogeneously deposited contamination or hot particles. Different methods are employed to detect this type of contamination including the FIDLER. Used with a GPS and data collector large land areas can be surveyed rapidly and with a good deal of accuracy. Different organizations including private industry, the United States Air Force, Army and Navy are using this technology but little research has been completed on the FIDLER-data collector system. This research shows that as scanning speed increases detection efficiency decreases. For speeds of 1 m s^{-1} and lower, the detection efficiency ranges between 1% to 8% for sources at or near the surface. For a hot particle buried under 4 cm of soil, detection efficiency is still above 0.1% up to 1 m s^{-1} . At 6 cm, detection efficiency is above 0.1% only up to 20 m s^{-1} . Therefore for a given area depending on the suspected activity and depth contamination scanning speed must be kept relatively

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low. Actual experimentation with existing FIDLER systems should be completed to examine more closely the effect of scanning speed and detection efficiency.

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Chapter 4

Signal Processing and its Effect on Scanning Efficiencies for a Field Instrument for Detecting Low Energy Radiation.

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4.1 ABSTRACT

Signal processing within a radiation detector affects detection efficiency. Currently, organizations such as private industry, the United States Navy, Army, and Air Force are coupling some detector systems with data collection devices to survey large land areas for radioactive contamination. As detector technology has advanced and analog data collection has turned to digital, signal processing is becoming prevalent in some instruments. Using a NIST traceable ^{241}Am source, detection efficiency for a field instrument for detecting low energy radiation (FIDLER) was examined for both a static and scanning mode. Experimental results were compared to Monte Carlo generated efficiencies. Stationary data compared nicely to the theoretical results. Conversely, scanning detection efficiencies were considerably different from their theoretical counterparts. As speed increased, differences in detection efficiency approached two orders of magnitude. To account for these differences, a quasi-time dependent Monte Carlo simulation was created mimicking the signal processing undertaken by the FIDLER detection system. By including signal processing, experimental results fell within the bounds of the Monte Carlo generated efficiencies, thus demonstrating the negative effects of such processing on detection efficiencies.

4.2 INTRODUCTION

The mission of individuals in the remediation profession is to remediate areas as rapidly as possible while maintaining a high level of detection efficiency. In some cases survey equipment is being attached to data collectors and Global Positioning Systems (GPS) to accurately locate contamination (Marianno et al., 1999; Wright et al.,

2000; Egidi et al., 2000). Until recently individuals relied on analog techniques: using headphones or an audible setting to scan land areas to locate contamination. This method is slow and tedious, but relatively accurate. Conversely, the detector-positioning system combination allows fast, high-density scanning over large land areas. Unfortunately with this new use of technology, existing detector systems may lack the ability to locate some types of contamination, such as hot particles (Marianno et al., 2000).

The FIDLER is a useful tool for surveying land areas containing low energy photon emitters such as plutonium and americium (Tinney et al., 1969). This sodium iodide detector typically has a crystal diameter of 12.7 cm with a thickness of 0.16 cm. Its diameter provides a large surface area for detection while its thickness allows higher energy photons to preferentially pass through without interaction. Laboratory versions of this detector are employed to characterize soil samples. Field versions weigh approximately six pounds and can be carried by an individual or mounted on a vehicle. The FIDLER is an instrument that has taken advantage of the new positioning-data collection technology. Unfortunately data coming from the detector to the meter may be subject to different types of signal processing depending upon the manufacturer of the detector

The research presented here focuses on one type of signal processing employed by an existing manufacturer. This company produces a multi-function meter that is used not only with their FIDLER, but also with their Geiger-Muller (GM) tube. To understand how the signal processing affects the FIDLER response, it is necessary to describe how it is used in the GM detector.

At the beginning of a scanning period an operating voltage of +500 V is applied to the GM-tube. Coinciding with this increase in voltage, a megacycle-oscillator (clock) is activated, and time in 1 μ s increments is followed. After a pulse is registered, the clock stops and the accumulated time is recorded. At this same moment the anode voltage of the GM is immediately reduced to a low bias level. This standby voltage is maintained for approximately 2 ms, a period of time longer than the dead time and recovery time of the GM tube. Following this pause the high voltage is again applied to the tube and the megacycle oscillator is activated. This process is repeated continuously during the meter update period (2 s) to obtain a "statistically reliable" average of time between counts (TBC). A statistically reliable count rate occurs when at least 256 counts have been employed to determine the average. If 256 counts have not been registered, the TBC information from the previous update period will be added to the current.⁵ This addition of previous periods can go as far back as 16 update intervals (32 s). To determine count rate, an algorithm within the meter divides the average TBC by a constant that reflects the sensitivity of the detector.⁶ This gives a value of microseconds per count. The count rate, given in counts per minute, is updated at the end of each 2 s period.

This technique, originally designed for use with GM tubes, has the advantage of eliminating dead time losses and saturation. When the multi-function survey meter is used with the FIDLER, the same signal processing method is employed- including the 2 ms delay period. While this may be effective with GM detection systems, this

⁵ Al Zirkus. APTEC-NRC, Inc. 125 Titus Avenue Warrington PA 18976 U.S.A 973-361-5600

⁶ Ibid.

technique used in conjunction with the FIDLER reduces scanning detection efficiency. The purpose of this work is to analyze how signal processing can influence scanning efficiency of the FIDLER.

4.3 METHODS AND MATERIALS

Computer simulation and field experiments were employed to examine the effect of signal processing on detection efficiency. To model the FIDLER response to a 60 keV ^{241}Am source, a computer simulation of a FIDLER was produced using Electron Gamma Shower 4 (EGS4) (Nelson et al., 1985). To benchmark EGS4's results, field experiments were conducted to determine stationary and scanning FIDLER detection efficiencies. EGS4 simulations were executed using the bound Compton cross section improvements (Namito et al., 1998).

To experimentally determine the detection efficiency for the FIDLER, a National Institute of Science and Technology (NIST) traceable 1.008 μCi ^{241}Am source was employed. Stationary detection efficiencies were calculated by placing a FIDLER in a tripod suspending its face 7.6 cm (~ 3 in) above the soil surface. Count rate was recorded after the detector was exposed to the source for 15 s. The source was moved radially outward in 5 cm increments to 30 cm. Detection efficiency was calculated by dividing the recorded count rate by the source's 60 keV photon emission rate.

Scanning efficiency was determined by passing over the ^{241}Am source at three different speeds (Figure 4.1). A 6.5 m (20 ft.) line was painted on top of coral-like soil. The ^{241}Am source was placed approximately 4.9 m (15 ft.) into the line. Three walking paces were employed: one step every 2 s, one step per second and two steps per second.

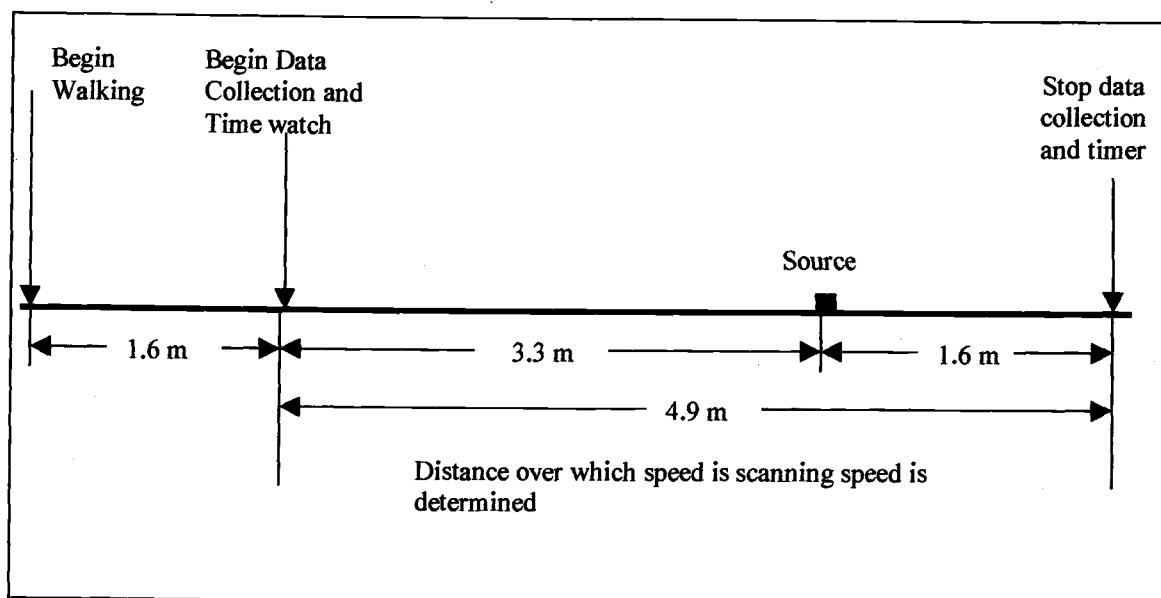


Figure 4.1. Diagram of experimental set-up used in the field to determine scanning efficiency for the FIDLER. The experimenter would begin by setting a steady pace for the first 1.6 m (From the left of the diagram). After the pace has been set, the data logger and a timer are activated. Data collection and the timer are stopped after the experimenter has passed the ^{241}Am source by 1.6 m. The time to traverse the 4.9 m was recorded so a speed could be associated with each calculated efficiency.

Initially, the experimenter would begin to walk at a fixed pace, once the front of the FIDLER passed 1.6 m (5 ft.) from its starting point the data collector was activated and a stop watch started. The experimenter, attempting to keep a constant pace, would walk until the end of the line was reached. At this point, data collection would cease and the time that it took to traverse 4.9 m would be recorded. From this timing data, an average speed was calculated. This process was repeated at least three times for each speed. Data from the meter was sampled in two-second bins. The bin with the largest count rate was used to determine the peak counting efficiency of the set-up. Both stationary and scanning detection efficiencies were compared to the Monte Carlo results.

The EGS4 simulated geometry of the FIDLER was similar to that of Marianno et al. (2000). The FIDLER was modeled as a sodium iodide crystal of radius 6.35 cm and thickness 0.16 cm. A quartz light-pipe of radius 6.35 cm and thickness 4 cm was placed behind the crystal. Aluminum foil (0.01 cm thick) was positioned in front of the crystal and, overlapping the edge of the NaI by 0.30 cm, was part of the aluminum casing (0.35 cm thick). Aluminum housing was placed around this set-up, 0.41 cm thick. Air at normal temperature and pressure (NTP = 20 °C, 1 atm.) was between the source and detector. The source was placed on a soil surface with a density of 1.55 g cm^{-3} .

A simulation of the experimental set-up was created to examine static efficiency. The FIDLER was suspended 7.62 cm (3 in.) above the surface and a 60 keV photon source was moved in 5 cm increments away from the center of the detector out to 30 cm. Detection efficiency was calculated by dividing the total number of 60 keV photons absorbed in the crystal by the number of photons isotropically emitted from the

source. For this particular simulation 1,000,000 photons were released at each 5 cm increment from the detector. EGS4 results were plotted with the corresponding experimental data and compared.

Originally the scanning efficiency simulation was similar to that developed by Marianno et al. (2000). Rather than simulating a moving FIDLER, the source was allowed to move in relation to the detector. In this manner, the hot particle becomes a line source whose length is determined by the scanning speed and the time of data collection. With an observation interval of 2 s, the length of the line source was twice the scanning speed. The line source was also centered under the detector. The 60 keV photons were released isotropically at random places along the line. As with the static case, efficiency was calculated by dividing the total number of 60 keV photons absorbed in the crystal by the number of photons emitted. Both theoretical and experimental results were compared on a graph.

Using the previously described simulation, experimental and theoretical results could not be reconciled. Consequently, a signal processing EGS4 simulation was developed. In a sample undergoing radioactive decay, the most probable time for the next decay can be calculated with the probability density function (Knoll, 2000):

$$p(t) = Ae^{-At} \quad \text{Eq. 4.1}$$

where t is time in microseconds and A is the 60 keV photon emission rate. A cumulative probability density function can be related to a random number so that the most probable time for the next decay can be calculated:

$$t = \frac{-\ln(\xi) * 1 \times 10^6 \left[\frac{\mu s}{s} \right]}{A \left[\frac{60 \text{ keV photons}}{s} \right]} \quad \text{Eq. 4.2}$$

where ξ is a random number between zero and one. Once the time for a photon emission was determined the photon was transported. The EGS4 FIDLER simulation then treated the 60 keV pulses like the multi-function meter described earlier: TBC is recorded and a 2000 μs (2 ms) pause follows each count that is registered. If 256 counts are not registered within the current observation interval, the TBC from the previous interval is included in the count rate calculation. The count rate was determined by dividing the average time between counts by the intrinsic efficiency of the detector (0.977), inverted and multiplied by $1 \times 10^6 \mu s s^{-1}$. This results in a simulated count rate in units of counts per second. To properly compare the field data and the EGS4 results, the simulated source had a 60 keV photon emission rate of 13389 γs^{-1} , simulating a 1.008 μCi ^{241}Am source. The scanning efficiency was calculated by dividing the simulated count rate by the photon emission rate.

In addition to the efficiency calculation there are other differences between the original model and the signal processing simulation. When time between counts is employed to determine count rate, this value then becomes dependent on the instantaneous location of a photon emission. At greater distances from the detector the flux is reduced, therefore so is the probability of interaction with the detector crystal. Unlike the original simulation, photons can no longer be released at random locations along the line source, instead the location of the released photon is a function of the source starting point and the scanning speed of the detector:

$$x = x_0 + vt \quad \text{Eq. 4.3}$$

where x is the point the photon is emitted, x_0 is the initial position at the beginning of the interval, v is the scanning speed and t is the total time elapsed in the interval. The starting position was chosen so that at least 256 counts were collected to determine count rate.

In order for counts to be registered when the source is not near the detector, a background was programmed within the simulation. This “background” released a photon isotropically underneath the center of the detector. In the field experiment the average background count rate was approximately 5 counts per second. From Marianno and Higley (1999) and Marianno et al. (2000) it is known that the efficiency of the FIDLER is nearly 10% for a source directly underneath the crystal. Therefore the background decay rate was chosen to be 54 Bq. The rate at which the background photons were released was determined using Eq. 4.2. Due to statistical variations in count rate which occur in a 2 s observation interval each speed was repeated 10 times so that an average efficiency could be calculated with corresponding standard deviation. The average efficiency was plotted against the experimental data and compared.

Scanning efficiency was analyzed for a FIDLER moving at speeds ranging from 10 cm s^{-1} to 110 cm s^{-1} . Two scanning scenarios were examined (Figure 4.2): the best case where the source is directly under the center of the detector in the middle of the observation interval (2 s) and the worst case where the hot particle is under the center of the detector at the end of the observation interval. This was determined the worst case

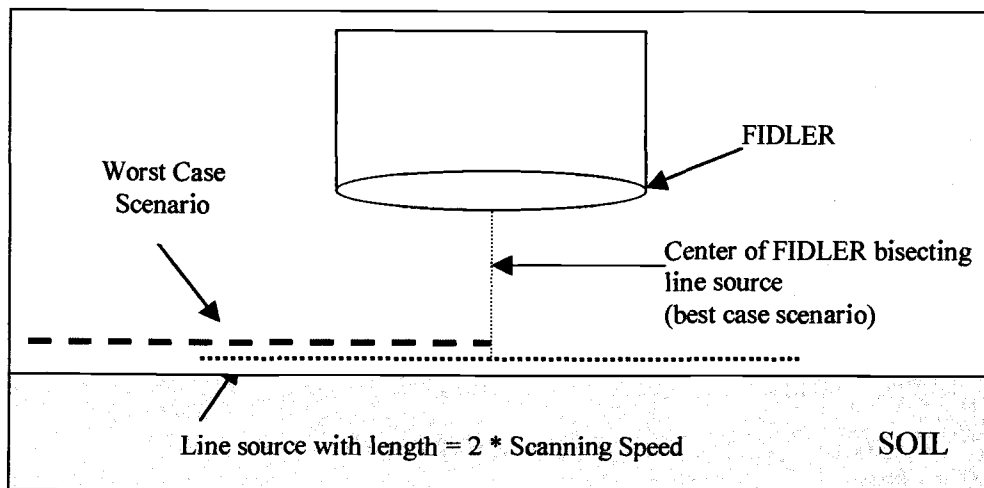


Figure 4.2. Best and worst case scenarios used with the EGS4 scanning simulations. The highest observed count rate or efficiency for a given speed should occur when the detector bisects the line in the middle of the 2 s observation interval (Best Case). Conversely, the lowest count rate happens when the 60 keV photon source is under the detector for the last few moments of the observation interval (Worst Case).

because if an observation interval ended while the source was under the center of the detector the next interval would begin at this point. Then, the count rate from each of these intervals would essentially be the same.

4.4 RESULTS AND DISCUSSION

When considering stationary detection efficiencies, the EGS4 and experimental results matched well with one another (Figure 4.3). As distance increased from the center of the detector, efficiency fell at a steady rate. Except for the data points at 20 and 30 cm, all results lie within 2σ of one another. The larger differences at these two points may be a result of experimental source position errors. In the field the topography of the land was uneven therefore it was sometimes difficult to get the source exactly the same distance as its EGS4 counterpart. Also, because of the uneven surface, sometimes the source would “face” away from the detector possibly causing some self-shielding.

Another possible reason for the difference, at least at 30 cm, may be the signal processing of the instrument. At this distance the detection efficiency is low ($\sim 0.2\%$), therefore within each update period, 256 counts may not be registering within the meter. The lower observed efficiency could result of averaging with previous observation intervals. Otherwise, it is believed that signal processing did not have much effect on data collection because of the 15 s count time. With a longer accumulation time for a stationary source, the relative number of counts per 2 s period should not significantly change. Therefore the count rate reported by the system should compare nicely to a system that reports only analog data.

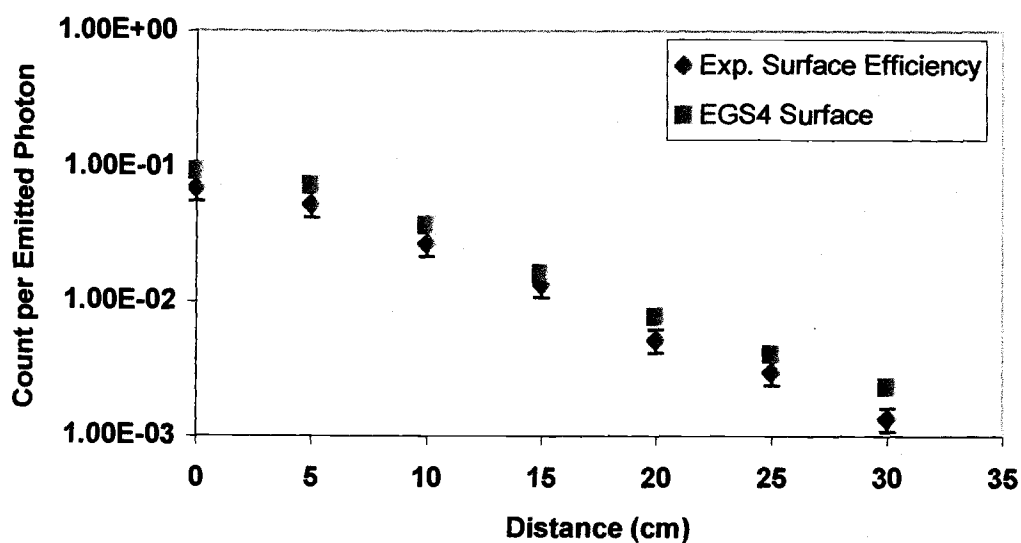


Figure 4.3. FIDLER experimental and theoretical detection efficiency for a 60 keV photon surface source as a function of distance. For a stationary FIDLER 7.6 cm above the surface detection efficiency rapidly falls as the source is moved away from the detector. The theoretical and experimental results match well with one another. The larger differences at 20 and 30 cm may results from poor source positioning in the field experiment.

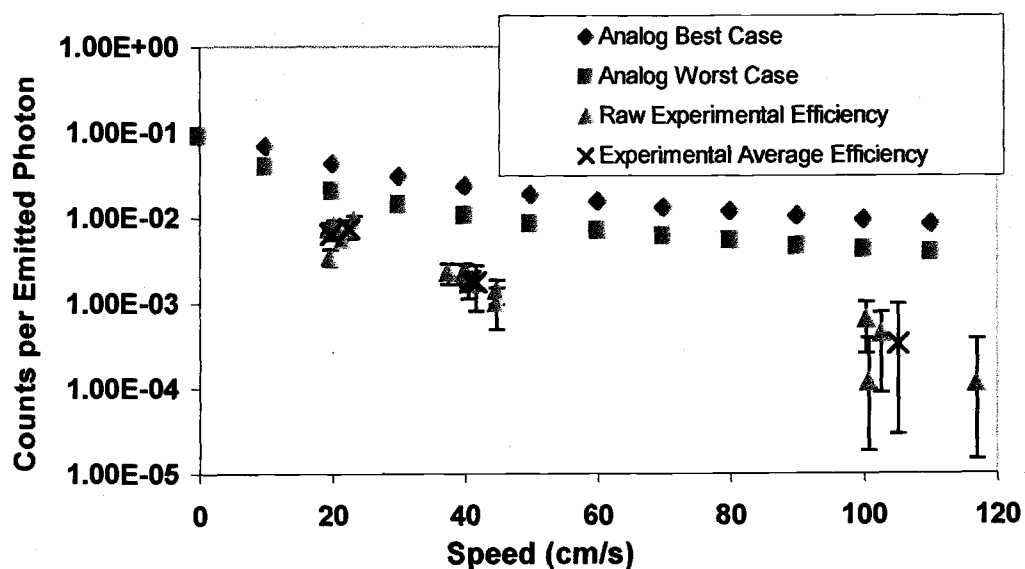


Figure 4.4. FIDLER scanning efficiency for 60 keV photon surface source as a function of speed. As speed increases the scanning efficiency of the FIDLER decreases. Theoretical results, which base their efficiency on analog methods, are higher than the experimental efficiencies resulting from signal processed data.

Conversely, scanning efficiency results from the computer simulation were considerably higher than the experimental data (Figure 4.4). Both sets of data showed similar trends: as speed increased, detection efficiency decreased at a steady rate. However, the magnitudes of the theoretical detection efficiencies were consistently higher than the experimental results. Since the only difference between the stationary detector simulation and the scanning simulation was the treatment of the source (a point versus line source) it was concluded that the reason for the difference is due to the signal processing undertaken by the instrument.

TBC is affected by distance from the source and scanning speed. As a hot particle moves under the FIDLER, the relative count rate can change rapidly between 2 s periods. When the particle is over 50 cm from the detector, only background is being registered. Then, suddenly it passes over a source with an emission rate of $10^4 \gamma \text{ s}^{-1}$. At a higher rate of speed, less than 256 photons will be registered in the 2 s observation interval and the background count rate will be averaged into the source count rate. This results in a lower reported count rate by the meter. Conversely, the EGS4 simulation records the analog results with no averaging: total counts collected in a 2 s period. When the analog method is employed the theoretical efficiencies are higher than the experimental results. In fact, as speeds approached 1 m s^{-1} differences between both the scenarios (analyzed by the simulation) and experimental results were greater than one order of magnitude.

To verify the reasoning for the lower experimental efficiency the signal processing code was developed. For the best case scenario (the source is directly under the detector mid-way through the 2 s observation interval) at speeds below 40 cm s^{-1}

more than 256 counts are being detected by the FIDLER: no averaging takes place. Below this speed, the analog method and signal processing technique give similar results with the second simulation giving a slightly lower efficiency (Figure 4.5). The lower efficiency may be due to the fact that as speed increases fewer counts are being employed to determine the average TBC. Past 40 cm s^{-1} , less than 256 counts are being registered in the observation interval, therefore previous intervals are being averaged with the source count rate. Since previous observation intervals primarily contain the background count rate, this rapidly drives down the detection efficiency. The worst case scenario shows similar results, but since the source is only under the detector for the last portion of the observation interval, averaging with previous intervals begins at lower speeds ($\sim 20 \text{ cm s}^{-1}$).

The EGS4 signal processing results were compared to the experimental data (Figure 4.6). As illustrated by the plot, the experimental efficiencies lie between the best and worst case EGS4 data. This implies that similar processing occurs within the detector and is decreasing detection efficiency. Furthermore, it suggests that the EGS4 signal processing simulation can be used as a tool to estimate this FIDLER's response in the field.

One might argue a better method of comparing results would be to run simulations exactly like the experiment: start the particle 3.3 m from the source and let it move at the average experimental speeds. This was attempted and differences between the experimental and EGS4 results were noted. It is believed these differences are due primarily from experimental error and possible biasing. There are several sources of error within the experiment. First, a constant speed while walking is difficult

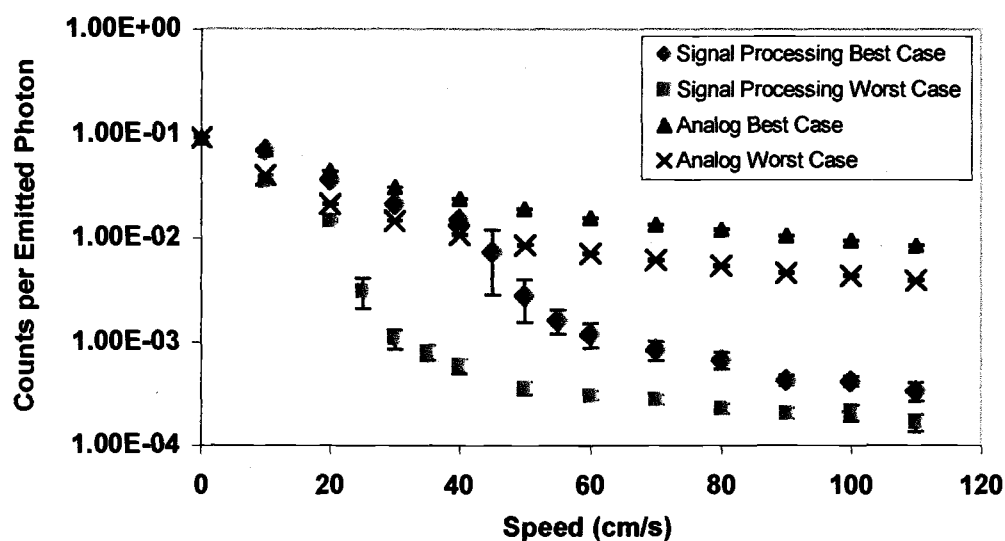


Figure 4.5. EGS4 analog and signal processing scanning efficiencies for a FIDLER in detecting 60 keV photons. When more than 256 counts are registered within an observation interval, the signal processed and analog efficiencies are similar. Once averaging with previous observation intervals begins, there is a drastic drop in scanning efficiency for the signal processing simulation.

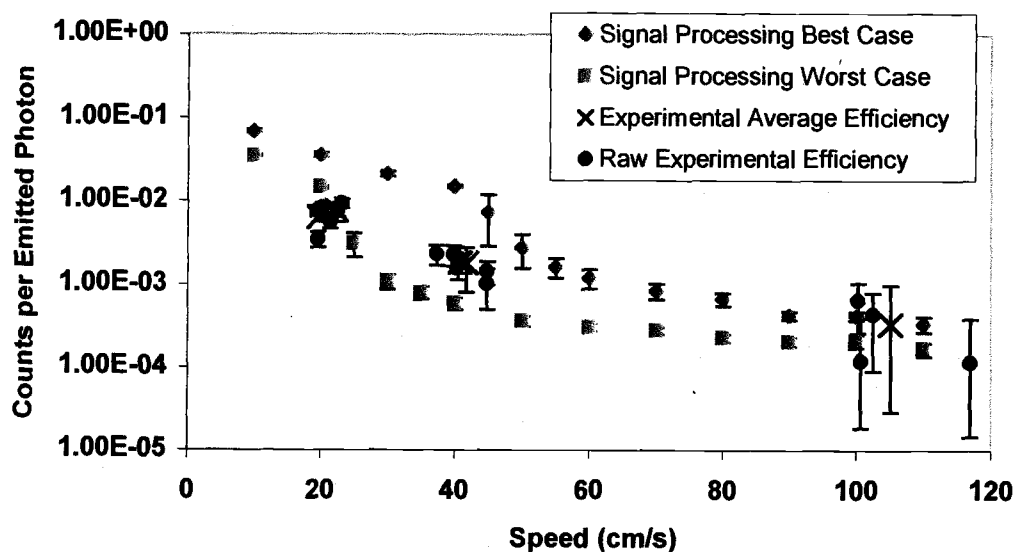


Figure 4.6. Scanning efficiency from the EGS4 signal processing simulation compared to experimental results. The experimental efficiencies are bounded by the best and worst case scanning scenarios of the simulation. Both sets of results are lower than the data collected from the EGS4 analog model.

to maintain and is a large source of error. The starting point was approximately 3 m from the source, but the data collector and stopwatch were manually activated and could have been started up to ± 5 cm from the start point. Also, once the detector was positioned above the source, the experimenter could be unknowingly altering speed and biasing the result. It is clear from both the analog and signal processing EGS4 results that detection efficiency is extremely dependent on source position relative to the detector. All of the above sources of error will affect the source position and, as these errors vary from run to run, so will the detection efficiency. Using the best and worst case scenarios, however, gives a clear upper and lower bound to detection efficiencies and should be employed to compare results when large experimental errors are possible. In the case presented here, the upper and lower bounds surround the experimental results indicating that signal processing is negatively affecting detection efficiency.

4.5 CONCLUSION

Radiation detection systems are taking advantage of the advances in positioning technology. Land areas that previously would require several individuals to slowly scan and locate contamination have the potential of now being completed faster with a relatively higher degree of accuracy. The FIDLER is one such instrument being employed with GPS technology to scan large land areas. The results presented here illustrate that signal processing can severely affect the detection scanning efficiency of discrete or hot particle contamination. Differences between one signal processing technique and an analog method showed detection efficiency differences approaching one order of magnitude as scanning speed increased. Further research, especially using

experimental equipment that can expressly control speed, should be completed using a variety of detectors to analyze the signal processing effect. A greater understanding of signal processing and its affect on radiation detection efficiency will not only benefit the manufacturers radiation survey systems but also the remediation community at large.

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Chapter 5

An Experimental Determination of FIDLER Scanning Efficiency at Specific Speeds

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5.1 ABSTRACT

As part of mass remediation efforts across the country some radiation detection systems are now being used in conjunction with positioning system technology. This technique has been used for almost a decade and has had success in accelerating preliminary remediation work while also reducing potential clean up costs. However, little work has been completed on how the sensitivity of these detection systems are affected when used with this technology. To better understand scanning efficiency for a detector attached to a positioning system, a device was developed which moved soil at a constant speed underneath a Field Instrument for Detecting Low Energy Radiation (FIDLER). Count rate was sampled every 2 s as a ^{241}Am source passed under at speeds ranging from $\sim 10 \text{ cm s}^{-1}$ to 100 cm s^{-1} . A surface source and a buried source were both examined. Experimental detection efficiency was calculated and compared to Monte Carlo generated results. For the surface source, the efficiency dropped to a value of approximately 1% at 100 cm s^{-1} . At the same speed, the buried source had a detection efficiency of 0.1%, primarily due to attenuation of the low energy photon in the soil. It was also noted that the response time of the meter affected the scanning efficiency. With a response time set at 1 s, higher average efficiencies were recorded but with a large standard deviation from the mean. Higher response time setting had the effect of reducing the variability of the reading, but also reducing efficiency.

5.2 INTRODUCTION

The determination of scanning efficiency for radiation detectors has never been more important than today. Across the nation many sites, involved with the nuclear

industry or weapons production, are being subjected to mass remediation efforts. As part of this work, several types of detectors are being attached to positioning systems so that spatial and corresponding radiological data may be collected concurrently during surveys. (Berven et al., 1990; Fragoso et al., 1998; Wright et al., 2000; Egidi et al., 2000). With the use of a positioning system, large land areas can be scanned for radioactivity more rapidly than the past. Previously, individuals would traverse a site, stop and with a detector either accumulate a spectrum (*in-situ* spectroscopy) or while continually walking with a system set in an audio mode, attempt to locate contamination. With this new use of technology the tedious work of marking contaminated spots may be over, but is the scanning efficiency of these systems sensitive enough to locate contamination at levels that are a concern?

Integrating new or existing positioning technology into present radiation detection methods has the potential advantage of increasing productivity. One of the first studies by Berven et al. (1991) used ultrasonics to locate a field surveyor on a site and radio frequency transmission to send and store data to a central station. This study indicated that using the Ultrasonic Ranging and Data System (USRADS) resulted in the collection of a "greater quantity and higher quality of radiological data with less effort in data transcription and analysis" with only slightly more field effort compared to conventional methods (Berven et al., 1991). Employing a similar method, Fragoso et al. (1998) evaluated a site on Mare Island, California. Using a detection array of four 2 X 2 NaI detectors coupled with an ultrasonic and data management system they were able to locate and classify areas of contamination. Employing this technology, on this

site, reduced the cost of remediation and waste disposal by up to 75% (Fragoso et al., 1998).

Global Positioning Systems (GPS) and data loggers are now being coupled with detectors in the field. Wright et al. (2000) employed a Global Positioning Radiometric Scanner (GPRS), which consisted of two plastic scintillation detectors mounted on the front of a HUMMER. By employing this system on a 240 acre site, over 69,000 independent measurements were collected with corresponding location data. The maps that were generated permitted the identification of "highly contaminated zones, contaminated roadways, sharp and gradual contamination boundaries," hot spots and clean areas (Wright et al., 2000). Similarly, Egidi et al. (2000) concluded that by using a GPS-detector system, in addition to a well-designed database, allowed for the rapid evaluation of field conditions following remediation of a Superfund site. Marianno et al. (1999) described the use of the Field Instrument for Detecting Low Energy Radiation (FIDLER) with a GPS system and found similar advantages.

While the adaptation of detector and positioning technology shows great promise, the scanning efficiency of such systems has not been adequately examined. One of the most complete studies on scanning sensitivity is presented in NUREG-1507 (Abelquist et al., 1997). It was noted in this work that scan sensitivity is very dependent on scanning speed, but an in-depth analysis of scanning sensitivity as a function of speed was never examined. Marianno and Higley (1999) showed that scanning efficiency drops drastically as speed increases. NUREG-1507 also states that scanning sensitivity is dependent on an arbitrarily chosen observation interval and the skill of an observer to discern contamination above background levels. However,

surveyor efficiency is not an issue with the data collection technology. If an elevated count rate is recorded during an observation interval (usually 2 s) then contamination is concluded to be present. The decision ability of the observer can be neglected.

The purpose of this study is to examine scanning efficiency at specific speeds when a FIDLER is attached to a data logger. The FIDLER is a device developed in mid 1960's to detect the low energy photon emissions from plutonium and its progeny (Schmidt and Koch, 1966). Typically, this NaI detector has a crystal 0.16 cm thick and 12.7 cm in diameter. The diameter provides a large surface area for photons to interact with the crystal, while the thickness allows the higher energy photons to preferentially pass through without interaction. Versions of this instrument were designed to respond to nuclear accidents and "broken arrow" events. Laboratory versions of this detector are employed to characterize soil samples. Since the FIDLER is one instrument currently employed with GPS technology it is important to examine its efficiency in detecting low energy photons in the scanning mode.

5.3 METHODS AND MATERIALS

In order to analyze the scanning efficiency of a FIDLER, an apparatus was constructed which could move soil underneath the detector at a various speeds (Figure 5.1). This method was chosen because it was easier to shield a stationary detector as opposed to a moving one. This device included a 1 m² wooden tray whose bottom was covered with 2 cm of coral sand (density $\cong 1.55 \text{ g cm}^{-3}$). The cart, attached to a chain, was placed on an 18 ft long track and moved with a 1/6 HP DC motor. The speed of the cart ranged from approximately 10 cm s⁻¹ to over 100 cm s⁻¹. An Alpha Spectra©

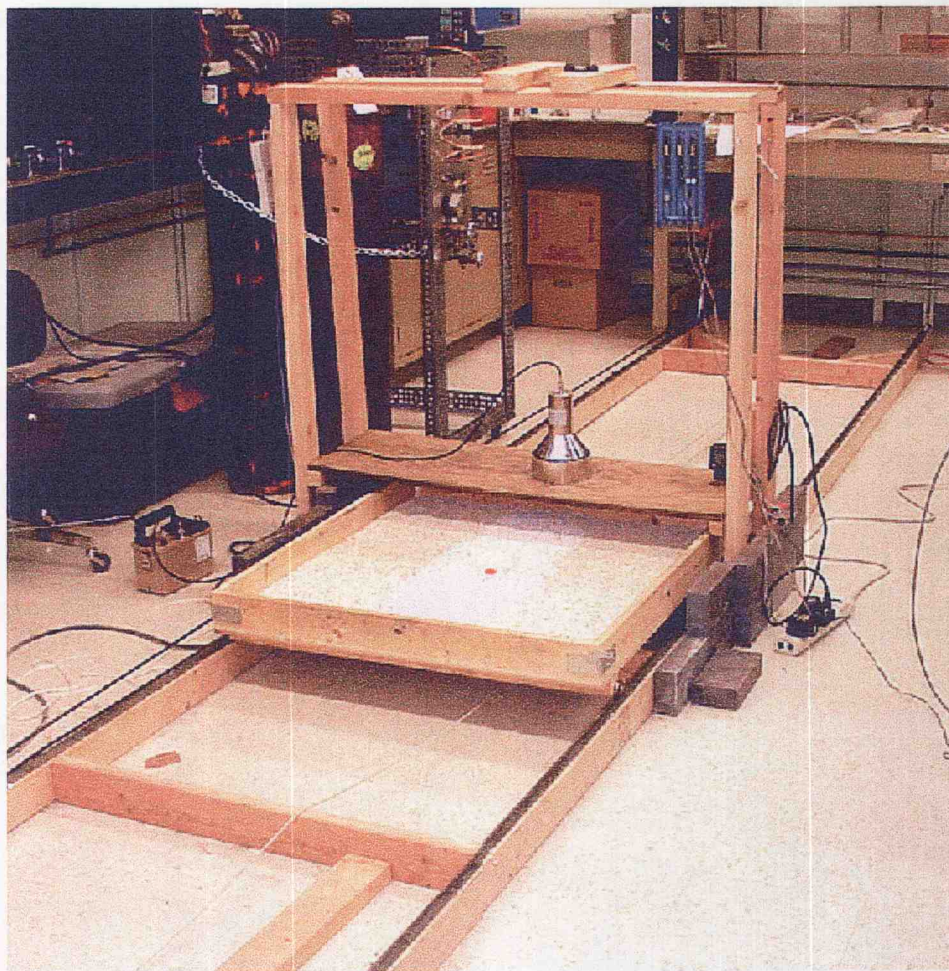


Figure 5.1. Device used to examine scanning efficiencies for the FIDLER/data logger system. The FIDLER, attached to a shelf was suspended over the 18 ft. long track. The detector to surface distance was approximately 7.6 cm. The cart would start at the far end of the track after the data logger had registered its first count. Data collection stopped after the Ludlum meter registered a count rate at background levels.

(Serial #03200A) FIDLER was suspended in the middle of the track, approximately 1.75 m from the starting point of the cart. A light switch attached to a timer was used to determine the time for the tray to pass beneath the FIDLER. When the tray passed beneath the detector a beam of light was broken, activating a timer. With the knowledge that the tray was 94.9 cm long, scanning speed could be determined. In addition, within the scanning area, 1 m² of lead bricks was placed over the flooring to reduce background radiation.

The static efficiency of the FIDLER was initially examined. The height of the FIDLER was adjusted so that its face was approximately 7.6 cm (~3 in.) above the surface of the coral sand. This height was chosen so the detection efficiency losses due to distance would be minimized. In addition, this FIDLER height has been employed in the field (Marianno et al., 1999). A 0.74 μCi ²⁴¹Am source was put in the middle of the cart, on the surface, and the cart was moved so that the source was directly below the FIDLER. After exposing the detector to the source for 1 min, the cart was moved outward in 5 cm increments, to 30 cm. The count rate of the 60 keV photon emitted from the ²⁴¹Am source was recorded at each distance and static detection efficiency was plotted as a function of distance. These results were compared to earlier work by Marianno and Higley (1999)

Tests were subsequently run to determine FIDLER scanning efficiency as a function of speed. With the detector at the same height, the cart was moved into its starting position and the speed set on the motor. At this point the source was 2.2 m from the center of the detector. The FIDLER was attached to a Ludlum 2350-1 (Serial #157660) data logger and count rate was sampled every 2 s. The response time

constant was set to its lowest setting, 1 s. After the meter registered its first observation interval, the motor was activated. Once the source was 1.3 m past the FIDLER, the motor was deactivated. The data acquisition to the logger was stopped after the count rate returned to background levels. The cart was then manually returned to its starting point. Each speed was repeated 10 times so an average speed and scanning efficiency could be calculated with corresponding standard deviation. Scanning efficiency was calculated by dividing the 2 s interval with the largest registered count rate of the source's 60 keV photon. To analyze how response time effects scanning sensitivity, these same runs were repeated twice more: Once with the response time set to 3 s, and the last set of runs at 5 s. Scanning efficiency as a function of speed was plotted and examined.

Background was also recorded for the experiment with the data logger. Without the source, the cart was moved under the detector. The logger was activated and collected at least 130 of the 2 s observation intervals, which were used to determine an average background. Standard deviation from the mean was also calculated for these values.

Once the surface tests were completed, scanning efficiency was investigated for a source at depth. Here, the same source was placed under approximately 1.5 cm of the coral sand. Both static and scanning efficiency were examined for this source configuration. Also, the same response time tests were completed.

To further analyze scanning efficiency, the experimental results were compared to Monte Carlo generated scanning efficiencies. Using Electron-Gamma Shower Version 4 (EGS4) (Nelson et al., 1985) with the bound Compton cross section

improvements (Namito et al., 1998), the FIDLER was modeled as a sodium iodide crystal of radius 6.35 cm and thickness 0.16 cm. Behind the crystal was a quartz light-pipe of radius 6.35 cm and thickness 4 cm. Absorbers in front of the crystal included Be (0.03 cm thick) and, overlapping the edge of the NaI by 0.30 cm, was part of the aluminum casing (0.35 cm thick). An aluminum outer housing, 0.41 cm thick, was placed around the detector. Air at normal temperature and pressure (NTP = 20 °C, 1 atm.) was between the source and detector. The soil used in the simulation was calcium carbonate coral sand with a density of 1.55 g cm^{-3} .

The simulation was similar to that of Marianno et al. (2000a,b) for a moving FIDLER. A best case model is examined where the source is directly below the detector in the middle of the 2 s observation interval and a worst case, where the source is under the detector only at the end of the interval. A simulated background is also used. Unlike the lower background present in the previous work, the simulated background was set at 105 decays per second. This corresponded to the laboratory background count rate of approximately 630 counts per minute. The source was treated as a line whose length is dependent on the scanning speed (Marianno et al., 2000a,b). Detection efficiency was calculated dividing the net 60 keV photons absorbed in the crystal by the number of photons isotropically emitted from the source, $9829 \text{ } \gamma \text{ s}^{-1}$. This corresponded to the emission rate of a $0.74 \text{ } \mu\text{Ci } ^{241}\text{Am}$ source.

5.4 RESULTS AND DISCUSSION

Measured and calculated static efficiency results for both the surface and sub-surface tests are presented in Figures 5.2 and 5.3, respectively. This data compares

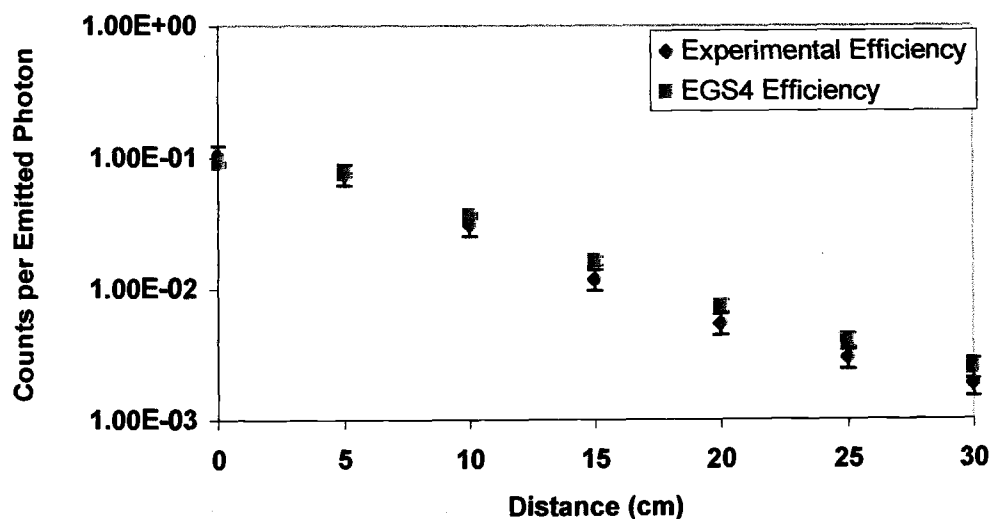


Figure 5.2. Static efficiency for a ^{241}Am surface source as a function of distance from the detector. As distance from the center of the FIDLER increases there is a steady decrease in detection efficiency. Past 20 cm it is below 1% and approaches 0.1% near 30 cm.

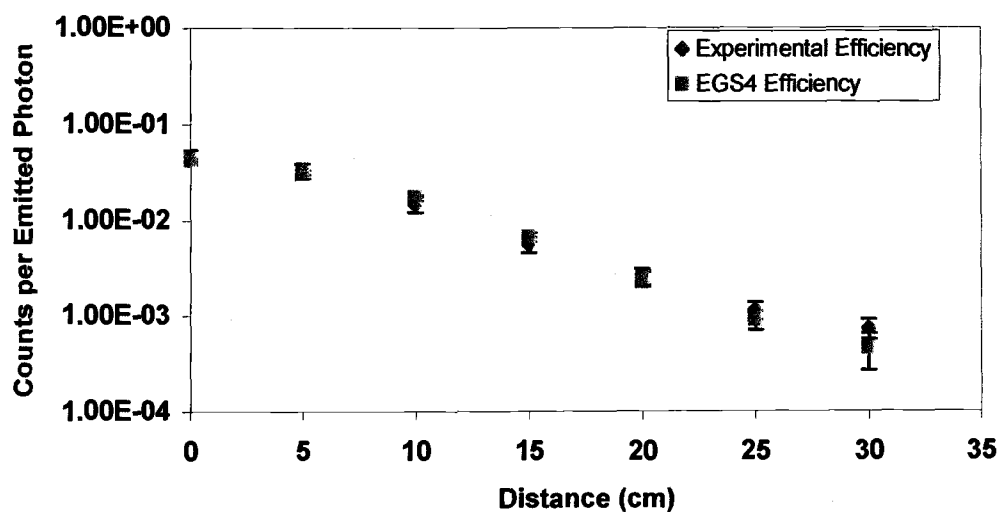


Figure 5.3. Static efficiency for an ^{241}Am source, 1.5 cm below the surface, as a function of distance. Like the surface case, as distance increases, detection efficiency decreases. Efficiency here is somewhat lower due to the attenuation of the 60 keV photon by the soil overburden.

nicely to simulation results of Marianno and Higley (1999a). As the point source is moved laterally away from the detector, efficiency gradually decreases. For the surface source (Figure 5.2), detection efficiency remains above 0.1% up to 30 cm from the center of the detector. This implies that, for a FIDLER 7.6 cm from the surface, the useful scanning area is limited to no more than 30 cm from the instrument for low activity sources. A more rapid decrease in detection sensitivity is witnessed when the source is beneath 1.5 cm of coral sand (Figure 5.3). Primarily due to overburden attenuation of the 60 keV photon, efficiency drops below 1% at less than 15 cm from the detector. Illustrating that for subsurface contamination, even when the FIDLER is close, low energy photons are difficult to detect.

Results for surface scanning efficiency are presented in Figure 5.4. With the response time set at 1 s, the experimental data fits within the best and worst case predictions generated by EGS4. The experimental and theoretical results demonstrate similar trends. A decrease in scanning efficiency occurs rapidly between 10 cm s⁻¹ and approximately 40 cm s⁻¹. After this point, the rate of decrease is less severe, almost approaching a constant. As speed increases the detector is exposed to the source for less time; therefore fewer counts are registered resulting in a smaller scanning efficiency as speed increases. The plot shows that up to approximately 60 cm s⁻¹ that efficiency remains above 1%.

The shape of the efficiency curve is a result of source-detector geometry. In the frame of a moving detector the point source is a line. Count rate is proportional to flux (ϕ) and the flux from a line source at a point is (Shleien et al., 1998):

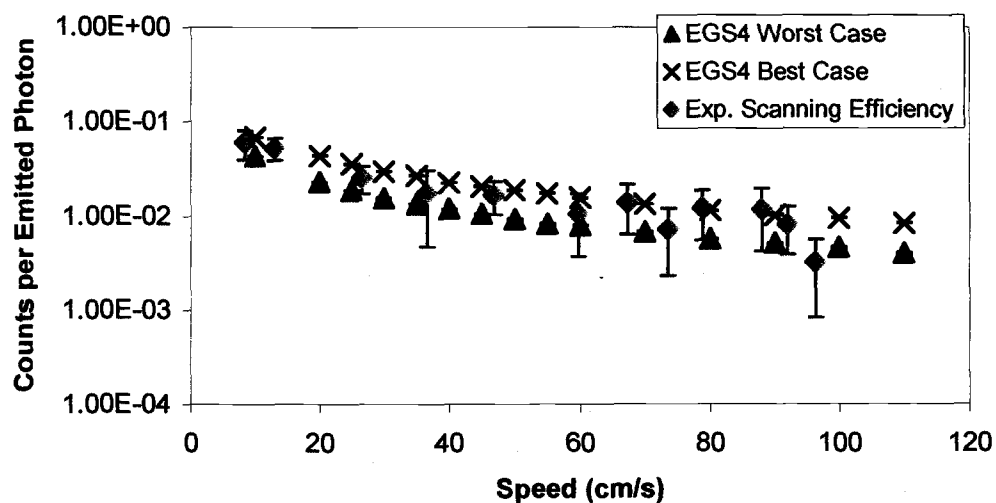


Figure 5.4. Scanning efficiency of an ^{241}Am surface source as a function of speed. With the response time set equal to 1 s the experimental values primarily lie within the best and worst case scanning efficiencies generated with EGS4. However, the 1σ errors with the experimental data points are quite large.

$$\phi = \frac{S_l \theta}{4\pi h} \quad \text{Eq. 5.2}$$

where S_l is the source strength per unit length, h is the perpendicular distance of the point from the line and θ is the angle subtended from the point to both ends of the line. From Eq. 5.2, flux is highly dependent on S_l and somewhat on angle. Primarily because small changes in speed, in the lower range, have a greater affect on S_l , the efficiency rapidly drops. As higher scanning speeds are achieved, angle has less influence because θ approaches a constant ($\cong 180^\circ$). At higher speeds, S_l changes less rapidly with increases in speed. The almost constant slope of the line at the higher speed is a result of this effect.

For a ^{241}Am source buried 1.5 cm in soil, similar results were noted (Figure 5.5). However, due to the increased attenuation of the 60 keV photon by the soil, the efficiencies are lower. Again, EGS4 results map closely to the experimental values, with the experimental efficiencies being closer to the best case prediction. Also there appears to be more variability in the reading. This may result from the 1 s response time used during these runs. Regardless, scanning efficiency drops below 1% earlier than the surface case, between 30 and 40 cm s^{-1} , indicating if sub-surface contamination is present a slower scanning speed is warranted.

It is important to note that the standard deviations associated with the average scanning efficiencies in both Figures 5.4 and 5.5 are large. Experimental standard deviations presented in these figures are 1σ . If 2σ errors were reported they would be approximately the same magnitude as the data points and would overwhelm the graphs. The reason for these large errors is due to the choice of response time.

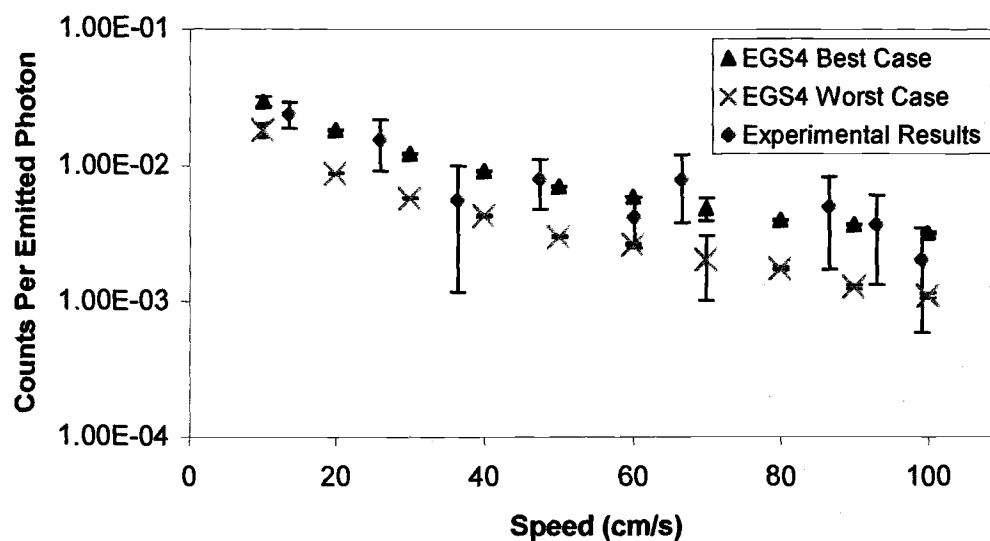


Figure 5.5. FIDLER scanning efficiency for a buried source. These efficiencies are lower than the results for a surface source. This is primarily due to attenuation by the soil of the 60 keV photon emitted from ^{241}Am . Standard deviations in the experimental averages are 1σ .

The response time plays a large role in the errors associated with the average efficiencies. The response algorithm in the 2350-1 is set so that the detector will react to increases and decreases in count rate roughly as a function of the response time setting multiplied by e ($e = 2.718$)⁷. For instance, if a meter with a response time of 5 s has a source placed beneath it, and this source has a peak count rate of 10000 cpm, it will take approximately

$$t = 5 \text{ s} * e = 5 \text{ s} * 2.718 \approx 15 \text{ s}$$

for the registered count rate to reach its peak. Similarly, once the source is removed, it will take approximately 15 s for the meter to register background levels. This has the affect of smoothing data when statistical fluctuations in count rate appear during routine surveys. A longer response time can be desirable during surveys because a meter will be less likely to overreact due to sudden changes in background count rate.

Additionally, with a slower decay time, a large change in count rate will less likely be missed because a sudden "jump" in count rate will slowly return to background.

In the initial experiment, the count rate is not subjected to the smoothing effects of a longer response time. As a consequence the standard deviation in the average efficiencies are large because the count rates, which are derived from a 2 s interval, are influenced more by count rate fluctuations. Table 5.1 contains a list of the average recorded background count rates. Notice that while the averages are all similar (near 600 cpm) the standard deviation in each value is nearly ± 100 cpm. Large fluctuations, without the smoothing affect of the longer response time, will affect the recorded count

⁷ Richard Smola, Ludlum Measurements Inc. 1-800-622-0828

Collection Date	Average Background (CPM)	Standard Deviation	Response Time Setting (s)
20-Apr-00	596	88	5
20-Apr-00	632	87	5
21-Apr-00	621	79	5
21-Apr-00	600	72	5
21-Apr-00	582	61	5
24-Apr-00	558	135	1

Table 5.1. Average background with corresponding standard deviations. These values were calculated by averaging the values of at least 130, 2 s, observation intervals. The large fluctuations in background count rate can significantly affect scanning detection efficiency depending on the time response setting.

rates. Due to the short response times, larger variations around the mean are expected. With large variations resulting from the lower response time it is possible to either completely miss hot particle contamination or over estimate the magnitude of that contamination.

Figure 5.6 illustrates how scanning efficiency is affected by response time. As this value increases there is a corresponding decrease in efficiency. With the longer response setting, the time for a given source strength to reach its highest count rate is longer (i.e. 3 s response time implies ~ 9 s for the count rate to reach its peak). Therefore the largest count rate in a 2 s observation interval will get lower as response time increases. This effect is seen in Figure 5.6. The lower response time efficiency values (1 s) are closest to the theoretical values, but as response time increases from 3 s then to 5 s, the efficiency also decreases. In fact, the higher response times have efficiencies lower than the EGS4 worst case predictions. Similar results were noted for the source at depth case.

A positive consequence of this affect is the standard deviations in the average efficiencies significantly decrease. In Figure 5.6, the standard deviations associated with the 3 s and 5 s settings are 2σ in magnitude rather than the 1σ of the lower setting. This is a result of the smoothing affect that the response time induces.

As an aside, it may be argued that simulations should have been run with the source starting in a position 2.2 m from the detector, as was done in the laboratory experiment. This was determined inadequate. In the first case, the experimenter activated the cart's movement. Due to human nature, the cart would not always be started at the same exact time in relation to data acquisition. This would cause the

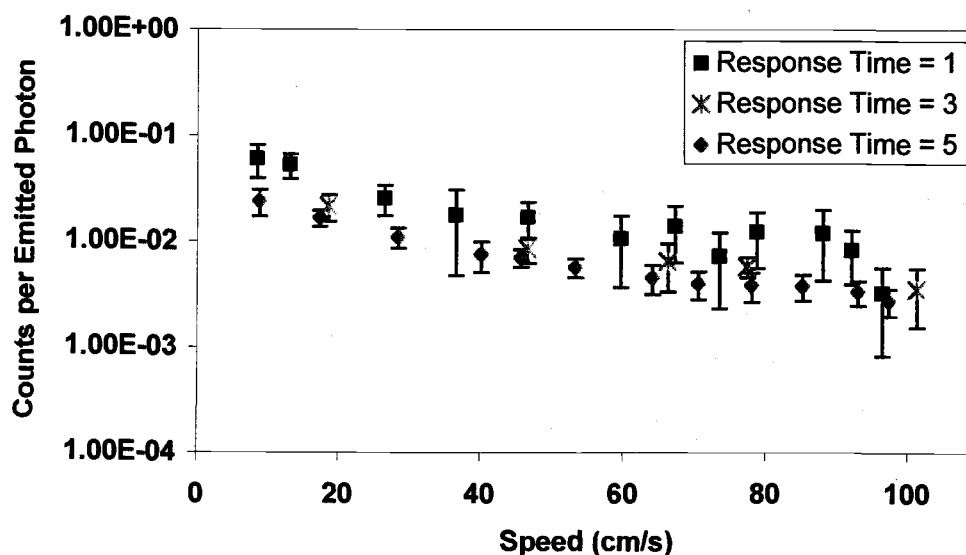


Figure 5.6. The effect of response time on scanning efficiency. As response time increases, there is a corresponding decrease in efficiency. An effect of the increased time setting is that the count rate, which is used to calculate efficiency, is now subjected to the smoothing effect. This reduces the variation in values between runs. The error bars for the higher response times are 2σ , as opposed to the 1σ values for the 1 s setting.

source to have a slightly different starting position within the second observation interval (i.e. reach the detector at different times/positions). This would cause differences between experimental and simulation results. Furthermore, with the laboratory system there is a small acceleration time at higher speeds that EGS4 could not simulate. By having a best and worst case expectation, a rough estimate of the scanning efficiency (regardless of starting time and cart acceleration) can be provided.

5.5 CONCLUSION

Radiation detection equipment attached to positioning systems has the potential of significantly increasing the speed of remediation work while decreasing costs. Over the last 10 years several people have used these systems with great success, but the scanning efficiencies of detectors employed in this mode is not completely understood. With the use Monte Carlo simulation and a cart system, the ability of a FIDLER to detect point sources was examined for a wide range of speeds. For a surface source, as speed increased from 10 cm s^{-1} to 100 cm s^{-1} , the detection efficiency decreased to below 1%. However, over most of the energy range the efficiency was maintained near 1%. For a buried source scanning efficiencies were lower, primarily from attenuation of the low energy photon by the soil. It was also noted that the response time setting of the meter does affect the scanning efficiency. By using the lowest setting, higher average scanning efficiencies were recorded, but these values had greater variability. Conversely, by using higher response times variability in results decreased, but so did scanning efficiency. For individuals using such a system in the field a trade off must be faced: While a higher response time may give better precision the effect is to reduce

your detection efficiency with the possibility of missing contamination. From the results of this study it is clear that more work needs to be done to fully comprehend how using existing radiation detection systems with data logging technology affects scanning efficiencies.

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Chapter 6. CONCLUSION

For over 35 years the FIDLER has been a useful instrument in detecting plutonium contamination. It is a light, portable instrument that is a convenient alternative to employing alpha probes, the previous method of detecting plutonium in the field. As a thin crystal NaI detector it is able to preferentially detect low energy photons emitted by isotopic mixtures of plutonium and its progeny. While the lower energy photon emissions (~17 keV) of these elements can be located by the FIDLER, it is sometimes useful to use the 60 keV photon emitted from ^{241}Am , a result of the β decay of ^{241}Pu . Early studies demonstrated this instrument's usefulness and sensitivity to static operation, but little work has been completed on its ability to locate contamination in a pure scanning mode.

Many sites associated with the weapons program of the cold war are switching from production to clean up and remediation. These areas have widespread plutonium contamination, and as a result the FIDLER is being employed. At these facilities, radioactive contamination can exist not only as homogeneously deposited contamination, but also in the form of discrete or hot particles. Early studies of the FIDLER concentrated on homogeneous contamination; however hot particles are becoming of increasing interest to groups (i.e., private industry, Department of Energy, the United States Air Force, Navy and Army) that must survey and remediate sites where this type of contamination is prevalent. In addition, new technology is being used with the FIDLER to increase its productivity while scanning these areas. In light of the fact that hot particles are becoming a concern and with the advent of new types of technology, which promote the use of the FIDLER in scanning mode, research was

conducted to examine the scanning efficiency of the FIDLER with regards to this new type of technology.

In the course of remediation, different methods are employed to locate contamination. Scanning with a FIDLER is one of these techniques. However, using a FIDLER in the scanning mode can be a slow and tedious process. Prior to the use of GPS and data loggers, individuals would slowly walk over sites, with the instrument in audio mode, and listen for an increased count rate to pinpoint contamination. Once located, these areas would be marked for later cleanup. The FIDLER has recently been attached to GPS and data loggers in the hopes that this process can be accelerated. Here, the FIDLER is slowly moved over a site while the data logger collects radiological and position information. After the work is completed, maps can be generated of entire sites indicating areas and spots of contamination. The GPS-FIDLER system mentioned in this work scanned approximately 40 acres, mapping two entire sites in under three weeks. The number of data points relaying count rate and ground location exceeded 250,000. The resulting maps generated by this process were employed to formulate the remediation strategy of the site.

Even though several organizations (such as the Department of Energy, private industry, the United States Air force, Army and Navy) are employing this technology, little research has been conducted in this field prior to this work. The research on the FIDLER is the first step in examining detector scanning efficiency when used with data collectors on positioning systems. In NUREG-1507 research on other detector systems showed scanning sensitivity is extremely dependent on speed. However an in-depth analysis of how detector sensitivity changes with specific speeds was not presented. An

initial step in the examination of the FIDLER's scanning sensitivity was the development of computer simulations using EGS4. Results clearly indicated that as scanning speed increased detection efficiency decreased. Also shown was that as the source was placed at depth it became more difficult to detect due to the ^{241}Am 60 keV photon being attenuated in soil. In the idealized environment of the EGS4 simulation, speeds from 10 cm s^{-1} to 100 cm s^{-1} had scanning efficiency range from 8% to approximately 1% for sources at or near the surface. For a hot particle buried in up to 4 cm, detection efficiency is still above 0.1% up to 100 cm s^{-1} . At 6 cm lower depths detection efficiency is above 0.1% only up to 20 m s^{-1} . These results indicated that for a given area depending on the suspected activity and depth of contamination, scanning speed must be kept relatively low.

Initial experimental examination of scanning efficiency revealed how digital technology can affect results. Using a FIDLER-data logging system, an ^{241}Am source was scanned at three different speeds. Upon comparing efficiency results with EGS4 generated efficiencies, differences were noted. By adjusting the simulation, making it a more time-dependent representation, it was shown that the type of signal processing executed by the FIDLER's meter severely reduced scanning efficiency. At higher scanning speeds, the meter that employed signal processing reported count rates that were an order of magnitude lower than a non-processed detector signal. It was concluded from this study that not only should more research be conducted regarding signal processing, but also research on instruments not subject to signal processing should be examined. In addition, a more accurate method of controlling speed would be beneficial toward this work.

By developing a device that moved a source beneath a FIDLER at constant speed, a more in-depth analysis of scanning efficiency was undertaken. Attached to a chain drive, a cart containing soil was moved beneath the detector. With the FIDLER set at 7.6 cm above the soil surface, scanning efficiency of a surface source and a source at depth was examined. In the case of scanning for the ^{241}Am source on the surface, as speed increased from 10 cm s^{-1} to 100 cm s^{-1} , the detection efficiency decreased to below 1%. These results followed EGS4 predictions. However there was a large magnitude in variability associated with the average scanning efficiencies. This result indicates that with high variability it would be possible to miss or underestimate contamination. By increasing the response time of the meter, variability was reduced. However, scanning efficiency also dropped below the EGS4 simulation's lowest predictions. For individuals using such a system in the field a trade off must be faced. While a higher response time may give better precision, the effect is to reduce the detection efficiency with the possibility of missing contamination.

The FIDLER is an instrument that has worked successfully for years. With the adaptation of positioning system/data logging technology, the ability for the FIDLER to scan large areas can be greatly accelerated. However, the experimental and theoretical results of this study show that the FIDLER is extremely sensitive to speed and overburden attenuation. Using the FIDLER to collect 2 s "windows" of radiological information of an area and then infer the extent of contamination will likely produce inaccurate results. Even using an instrument that was not subject to signal processing, large variability in results occurred. This indicated that, while at times a high signal might be registered for a given amount of radiation, it might be missed at others.

Therefore results gathered by the FIDLER in this manner should be considered questionable at best. This work also indicates that further research should be completed on other types of instruments that are being used with the positioning system/data logging technology. Having a full understanding of how all detectors respond with this technology will allow individuals such as the general public, who rightfully scrutinize remediation efforts, to have greater faith in survey results.

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The following are programs written in MORTRAN, the programming language of EGS4. The first is the non-signal processing simulation for the FIDLER. It can be used to simulate a point source or a line source

!INDENT M 4;

!INDENT F 2;

"This is a model of a NRC FIDLER detector. It can"
 "look at its detection efficiency for particles. At"
 "different depths and different distances from the"
 "center. IT does not include PRESTA. This model "
 "allows the particles to move in relation to the "
 "detector simulating a moving detector in relation"
 "to a stationary particle. This examines the "
 "Efficiency of the FIDLER in Detecting a point "
 "source when the detector is moving. "

" CRAIG M. MARIANNO "
 "I also made this look at alpha spectra's detector "
 "I added a Be window instead of Al. Changed "
 "thickness from 0.01 to 0.254. "

"---STEP 1 OVER-RIDE OF MACROS-----"

```
REPLACE {$MXMED} WITH {7}
REPLACE {$MXREG} WITH {51}
REPLACE {$EBIN} WITH {60}
;
REPLACE {;COMIN/SCORE/;} WITH
{;COMMON/SCORE/ESCORE($MXREG),EHIST,EBIN($EBIN),NCOMPT,
NPHOT,NPE;}
$ENERGY PRECISION ESCORE,TOTAL,EHIST;
;
REAL DETD,ALFOIL,ALRING,DETTH,NAITHC,ALTHC,INRRAD,
POLYERING;
;
REAL EVAC,EVAC1,EVAC2,EAIR,EAL,EATOL,DET_DIST,DET_DIST,
```

TOTE,EQTZ,EMYL,ENAI,EORING,SPEED,TIME,INC_PART,INIT_PART,
EFF,ERR_EFF;

;

INTEGER DECAYS,INC_DECAYS,ANSWER;

;

;COMIN/BOUNDS,CYLDTA,MEDIA,MISC,PLADTA,EDGE,RANDOM,
SCORE,STACK,THRESH,USER/;

"----STEP 2 PRE-HATCH INITIALIZATION----"

\$TYPE MEDARR(24,7)/\$\$'QRTZ',20*' '\$\$'NAI',21*' '\$\$'POLYE',19*' ',
\$\$'AL',22*' '\$\$'AIR',21*' '\$\$'ATL',21*' '\$\$'BE',22*' ';

"ATL stands for atoll composition. IT is similar to bone."

TIME=2.0; "TIME IS IN SECONDS"

DECAYS=37000 * TIME; "NUMBER OF DECAYS THAT HAPPEN PER
SECOND"

NPLN=45;

NREG=\$MXREG;

NMED=7;

DO J=1,NMED[DO I=1,24[MEDIA(I,J)=MEDARR(I,J);]]

"Setting media. Since there were so many regions it was easier to"

"use do-loops."

"Vacuum"

DO K=1,51,10[MED(K)=0;]

K=0;

DO K=10,50,10[MED(K)=0;]

K=0;

"QUARTZ"

/MED(2), MED(12), MED(22)/=1;

"NAI"

/MED(3), MED(13)/=2;

"ALUMINUM FOIL"

MED(4)=7;

"O-ring"

/MED(16),MED(26)/=3;

"AL"

DO K=32,37[MED(K)=4;]

K=0;

```

/MED(14),MED(15),MED(24),MED(25)/=4;
/MED(17),MED(27)/=4;

```

```

"AIR"

```

```

/MED(5),MED(6),MED(7)/=5;
DO K=8,38,10[MED(K)=5;]
K=0;
DO K=42,48[MED(K)=5;]
K=0;
MED(23)=5;

```

```

"Johnson Atoll"

```

```

DO K=9,49,10[MED(K)=6;]
K=0;

```

```

"SETTING ENERGY CUTOFFS FOR EACH REGION"

```

```

KCOMP=0;
DO I=1,NREG [
ECUT(I)=0.571;
PCUT(I)=0.001;
IRAYLR(I)=1;
IEDGFL(I)=1;"This for for K-Shell X-rays"
"KEK Low Energy Photon Scattering Switches"
INCOHR(I)=1; "INCOHERENT SCATTERING OPTION FOR REGION I"
IPROFR(I)=1; "COMPTON PROFILE OPTION FOR REGION I"
LPOLAR(I)=1; "LINEAR POLARIZATION EFFECT ON PHOTON
SCATTERING"
]

```

```

"----CALL HATCH----"

```

```

;OUTPUT;('STARTING PROGRAM FOR FAT/BONE CYLINDER//
'CALL HATCH TO RETRIEVE CROSS SECTION DATA');
CALL HATCH;
;OUTPUT ECUT(1)-0.511,AE(1)-0.511,PCUT(1),AP(1);
('IN PROGRAM ELECTRONS ARE FOLLOWED DOWN TO',F7.4,' MEV'/
'IN PEGS4 DATA FILE ELECTRONS FOLLOWED DOWN TO',F7.4,' MEV'/
'IN PROGRAM PHOTONS ARE FOLLOWED DOWN TO',F7.4,' MEV'/
'PHOTONS FOLLOWED DOWN TO',F7.4,' MEV'/);

```

```

CALL EDGSET(2,51);
CALL RMARIN; "For random number"

```

```

"----INITIALIZATION OF HOWFAR----"

```

```

"since all plane are centered and parallel to one another the PNORM"
"and PCOORDS could be set in a general way"
DO I=1,NPLN[

```

```
PNORM(1,I)=0.0;PNORM(2,I)=0.0;PNORM(3,I)=1.0;
PCOORD(1,I)=0.0;PCOORD(2,I)=0.0;
```

```
]
```

"TO ALLOW MORE MATERIALS TO BE ADDED TO THE CRYSTAL I PLACED THESE"

"MATERIAL THICKNESS HERE SO THEY CAN JUST BE CHANGED HERE AND NOT"

"IN THE FOLLOWING DO-LOOPS"

```
ALFOIL=0.0254;"ALuminum foil THICKNESS"
```

```
NAITHC=0.16; "NAI THICKNESS"
```

```
ALTHC=0.406; "AL THICKNESS"
```

```
DETTH=4.953;"DETECTOR THICKNESS"
```

```
POLYERING=0.356;
```

```
ALRING=0.3458; "This number is POLYERING - ALFOIL"
```

"I WANT THE CRYSTAL FACE TO START AT A SPECIFIC DISTANCE FROM"

"THE GROUND. THE CRYSTAL FACE WILL BE IN THE NEGATIVE Z AREA"

"WITH THE GROUND BEING THE ORIGIN. IN THE NEGATIVE AREA ALL DISTANCES"

"WILL BE IN RELATION TO THE CRYSTAL FACE"

"SETTING CYLINDER RADIUS"

"RADIUS' FOR THE CYLINDERS AND RINGS"

```
INRRAD=6.05;
```

```
DO K=1,8[CYRAD2(K)=INRRAD**2;] "INNER RADIUS OF DET. WINDOW"
K=0;
```

"NAI RAD PLUS A LITTLE OVERLAP FROM QUARTZ LIGHT PIPE"

```
DO K=10,17[CYRAD2(K)=(INRRAD + 0.30)**2;]
```

```
K=0;
```

```
DO K=19,26[CYRAD2(K)=(7.3516)**2;]
```

```
K=0;
```

```
DO K=28,35[CYRAD2(K)=(7.55)**2;]
```

```
K=0;
```

```
DO K=37,44[CYRAD2(K)=(3000)**2;]
```

```
K=0;
```

"----INITIALIZATION OF AUSGAB----"

```
DO I=1,$EBIN[EBIN(I)=0.00;]
```

```

BWIDTH=0.001;
NCOMPT=0;
"----STEP 6 PARTICLE PARAMETERS----"
IQIN=0;" PHOTON"
EIN=0.060;
WTIN=1.0;
PVAL=0.0;
OUTPUT PVAL; (' INCIDENT POLARIZATION',1PE12.5);
PRATIO=0.5+PVAL*0.5;

```

```

OPEN(18,FILE='jatol4',status='unknown');
OPEN(19,FILE='det1',status='unknown');
"----SHOWER CALL----"

```

"This has been moved inside this do-loop because the height of the"
 "detector will be changed for one problem."

```

DO J=1,35[PCOORD(3,J)=0.0;]
"This is the point where the detector h will be changed"
"It will be adjusted every 6 inches."
"DISTANCE FROM FRONT OF DETECTOR TO SOIL"
DO J=0,0[DETD=-7.62 + float(j)*15.6;
;
%F
      write(18,95) DETD
95  format(F7.2)
%M

```

```

DO N=1,37,9[
PCOORD(3,N)=DETD - DETTH;]
N=0;

```

```

DO N=2,38,9[
PCOORD(3,N)=DETD - ALTHC - POLYERING - ALRING - ALFOIL -
NAITHC;]
N=0;

```

```

DO N=3,39,9[
PCOORD(3,N)=DETD - ALTHC - POLYERING - ALRING - ALFOIL;]
N=0;

```

```

DO N=4,40,9[
PCOORD(3,N)=DETD - ALTHC - POLYERING - ALRING;]
N=0;

```

```
DO N=5,41,9[
PCOORD(3,N)=DETD - ALTHC - POLYERING;]
N=0;
```

```
DO N=6,42,9[
PCOORD(3,N)=DETD - ALTHC;]
N=0;
```

```
DO N=7,43,9[
PCOORD(3,N)=DETD;]
N=0;
```

```
DO N=8,44,9[
PCOORD(3,N)=0.0;]
N=0;
```

```
DO N=9,45,9[
PCOORD(3,N)=50;]
N=0;
```

"THIS WILL BE DONE A GIVEN NUMBER OF TIMES REPRESENTING A
GIVEN NUMBER"
"IN THE SOIL"

```
NCASE=50000;
:RUN;;
PRINT*, 'WHERE DOES PARTICLE START? What Speed?, What Depth?';
READ*, INIT_PART, SPEED, ZIN;
DET_DIST=SPEED * TIME;
;
%F
    WRITE(18,131)
131 FORMAT(2X,'N',5X,'X',9X,'Y',9X,'Z',8X,'R',11X,'COUNTS',
    *12X,'ERROR')
%M
;
```

```
"ZIN=0.0;"
DO K=0,0["ZIN=2. * FLOAT(K);"
    YIN=0.0;
```

"This adjusts the X distance from the origin."
DO N=1,NCASE[\$RANDOMSET XINC;
XIN=-XINC*DET_DIST + INIT_PART;
CHK=XIN**2+YIN**2;

```

"MAKES SURE THE PHOTON STARTS IN THE PROPER REGION"
IF(CHK.LE.CYRAD2(1))[IRIN=9;GOTO :STRT:;]
ELSEIF(CHK.LE.CYRAD2(10))[IRIN=19;GOTO :STRT:;]
ELSEIF(CHK.LE.CYRAD2(19))[IRIN=29;GOTO :STRT:;]
ELSEIF(CHK.LE.CYRAD2(28))[IRIN=39;GOTO :STRT:;]
ELSEIF(CHK.LE.CYRAD2(37))[IRIN=49;]
:STRT:
DO I=1,1[EHIST=0.0;
  CALL ISRC(UIN,VIN,WIN);
  CALL SHOWER(IQIN,EIN,XIN,YIN,ZIN,UIN,VIN,WIN,IRIN,WTIN);
"SETTING THE OUTPUT ENERGY IN BIN. BEGINNING IS EXCLUDED
WHILE"
"END IS INCLUDED. EX: IN 0,0.001 WOULD BE IN THE 0.001 BIN."
  $RANDOMSET VALUE;
  IF(VALUE.LT.PRATIO)[UFI=0.0; VFI=0.0; WFI=0.0;]
  ELSE
  [UFI=0.0; VFI=0.0; WFI=0.0;
  UF(1)=UFI; VF(1)=VFI; WF(1)=WFI;]
  IBIN=MIN0(IFIX(EHIST/BWIDTH + 0.999),$EBIN);
  IF(IBIN.NE.0)[EBIN(IBIN)=EBIN(IBIN)+1;]
  ]"THIS ENDS THE SHOWER LOOP"

;]"THIS ENDS X POSITION LOOP"
"THIS DETERMINES THE AVERAGE COUNT RECIEVED IN 2 SECONDS"
ERR_CNTS=SQRT(EBIN(60));
EFF=EBIN(60)/FLOAT(NCASE);"average efficiency"
ERR_EFF= EFF*SQRT((ERR_CNTS/EBIN(60))**2 + (1/FLOAT(NCASE)));
;
%F
  write(18,35) EBIN(60),ERR_CNTS,SPEED,EFF,ERR_EFF
  write(18,96)
35  format('Total Counts in 2 seconds is ',F15.2,' +/- ',F10.2 /,
  * 'At a speed of ',F6.2,' cm/s the average FIDLER efficiency is ',
  * 1PE15.8,' +/- ',1PE15.8 /)
96  format(' ',/)
  write(6,35) EBIN(60),ERR_CNTS,SPEED,EFF,ERR_EFF
  write(6,96)
%M
;
PRINT*,'DO YOU WANT ANOTHER STARTING POINT?;
READ*,ANSWER;
IF(ANSWER.EQ.1)[EBIN(60)=0.;GOTO :RUN:;]
;]"THIS ENDS Z POSITION LOOP"
]"THIS ENDS THE DO LOOP FOR CHANGING THE DETECTOR HEIGHT"

```


"---OUTPUT OF RESULTS----"

"THIS CHECKS TO MAKE SURE TOTAL ENERGY CHECKS OUT"

TOTAL=0.0;

DO I=1,\$MXREG[TOTAL=TOTAL+ESCORE(I);]

"SUMING UP ENERGY DEPOSITION THROUGHOUT SIMULATION JUST"

"AS A CHECK"

"IN QUARTZ"

EQTZ=ESCORE(2) + ESCORE(12) + ESCORE(22);

"The crystal"

ENAI=ESCORE(3) + ESCORE(13);

"IN MYLAR"

EMYL=ESCORE(4);

"In aluminum"

EAL=ESCORE(17)+ESCORE(27);

EAL=EAL+ESCORE(14)+ESCORE(24)+ESCORE(15)+ESCORE(25);

DO K=32,37[EAL=EAL+ESCORE(K);]

"IN O-RING"

EORING=ESCORE(16) + ESCORE(26);

"IN AIR"

EAIR=ESCORE(23);

DO K=8,38,10[EAIR=EAIR + ESCORE(K);]

DO K=42,48[EAIR=EAIR + ESCORE(K);]

DO K=5,7[EAIR=EAIR + ESCORE(K);]

"IN VACUUM"

DO J=1,51,10[EVAC1=EVAC1+ESCORE(J);]

DO J=10,50,10[EVAC2=EVAC2+ESCORE(J);]

EVAC=EVAC1+EVAC2;

DO J=9,49,10[EATOL=EATOL+ESCORE(J);]

;

%F

write(18,221),ENAI

write(18,251),EQTZ

write(18,222),EMYL

write(18,223),EAL

write(18,224),EAIR

write(18,250),EORING

```

write(18,225),EATOL
write(18,226),EVAC
TOTE=ENAI+EQTZ+EMYL+EAL+EAIR+EATOL+EVAC+EORING
write(18,227),TOTE,TOTAL
221 format('Energy deposited in NaI is: ',F15.3)
251 format('Energy deposited in quartz is: ',F15.3)
222 format('Energy deposited in mylar is: ',F15.3)
223 format('Energy deposited in Al is: ',F15.3)
224 format('Energy deposited in AIR inside detector is: ',F15.3)
250 format('Energy deposited in O-RING is: ',F15.3)
225 format('Energy deposited in Soil is: ',F15.3)
226 format('Energy deposited in Vacuum is: ',F15.3)
227 format('Does added (',F15.3,') = total E= ',F15.3)
do 49 j=1,51
    write(18,228),j, ESCORE(j)
228 format('ESCORE(',I3,')= ',F15.3)
49 continue
PRINT*, 'NUMBER PHOTONS ENTERING CRYSTAL:', NPHOT
PRINT*, 'NUMBER COMPTON SCATTERS:', NCOMPT
PRINT*, 'NUMBER PHOTOELECTRIC:', NPE
%M
;
STOP;END;
"-----"

```

```

SUBROUTINE AUSGAB(IARG);
COMIN/EPCONT,SCORE,STACK/;
$ENERGY PRECISION ESCORE,EHIST;

```

```

IRL=IR(NP);
IAUSFL(18)=1;
IAUSFL(20)=1;

```

```

IF(IARG.LE.4)[
    ESCORE(IRL)=ESCORE(IRL)+EDEP;
    IF(IRL.EQ.3.OR.IRL.EQ.13)[
        EHIST=EHIST+EDEP;]
]

```

```

IF(IQ(NP).EQ.0.AND.E(NP).GT.(0.059998))[

```

```

    IF(IRL.EQ.3.OR.IRL.EQ.13)[
        NPHOT=NPHOT+1;
        IF (IARG.EQ.17)[NCOMPT=NCOMPT+1;]
    ]

```

```

    IF(IARG.EQ.19)[NPE=NPE+1;]

```

]

]

RETURN;

END;

"-----"

SUBROUTINE HOWFAR;

COMIN/CYLDTA,EPCONT,PLADTA,STACK/;

IRL=IR(NP);

IF(IRL.EQ.1.OR.IRL.EQ.11.OR.IRL.EQ.21.OR.IRL.EQ.31)[
IDISC=1;RETURN;]

IF(IRL.EQ.10.OR.IRL.EQ.20.OR.IRL.EQ.30.OR.IRL.EQ.40)[
IDISC=1;RETURN;]

IF(IRL.EQ.50.OR.IRL.EQ.51.OR.IRL.EQ.41)[
IDISC=1;RETURN;]

"INNER CYLINDERS"

ELSE IF(IRL.LE.9)[

\$PLAN2P(IRL,IRL+1,1,IRL-1,IRL-1,-1);

\$CYLNDP(IRL-1,1,IHIT,TCYL);

IF(IHIT.EQ.1)[\$CHGTR(TCYL,IRL+10);]

RETURN;

]

"SECOND OUT"

ELSE IF(IRL.LE.19)[

\$PLAN2P(IRL-1,IRL+1,1,IRL-2,IRL-1,-1);

\$CYL2(IRL-11,IRL-10,IRL-2,IRL+10);

RETURN;

]

"THIRD OUT"

ELSE IF(IRL.LE.29)[

\$PLAN2P(IRL-2,IRL+1,1,IRL-3,IRL-1,-1);

\$CYL2(IRL-12,IRL-10,IRL-3,IRL+10);

RETURN;

]

"4TH OUT"

```

ELSE IF( IRL.LE.39)[
$PLAN2P( IRL-3, IRL+1, 1, IRL-4, IRL-1, -1);
$CYL2( IRL-13, IRL-10, IRL-4, IRL+10);
RETURN;
]

```

```

"5TH OUT"
ELSE IF( IRL.LE.49)[
$PLAN2P( IRL-4, IRL+1, 1, IRL-5, IRL-1, -1);
$CYL2( IRL-14, IRL-10, IRL-5, 51);
RETURN;
]
END;

```

```

"*****"

```

```

SUBROUTINE ISRC( UIN, VIN, WIN);

```

```

COMIN/DEBUG, STACK, THRESH, UPHIOT, USEFUL, RANDOM/;

```

```

$RANDOMSET RNNO43;
PHI=2.*PI*RNNO43;

```

```

$RANDOMSET RNNO44;
WIN=((2.*RNNO44)-1.);

```

```

UIN=SQRT(1.-WIN*WIN)*COS(PHI);
VIN=SQRT(1.-WIN*WIN)*SIN(PHI);

```

```

RETURN;
END;

```

```

*****

```

This next program is the signal processing version of the FIDLER program. It is also written in MORTRAN. This was only used for the APTEC-NRC FIDLER.

```
!INDENT M 4;
!INDENT F 2;
```

```
*****
"This is a model of a NRC FIDLER detector. It can"
"look at its detection efficiency for particles. At"
"different depths and different distances from the"
"center. IT does not include PRESTA. This model "
"allows the particles to move in relation to the "
"detector simulating a moving detector in relation"
"to a stationary particle. This examines the "
"Efficiency of the FIDLER in Detecting a point "
"source when the detector is moving. "
"
"          CRAIG M. MARIANNO          "
"I also made this look at alpha spectras detector "
"I added a Be window instead of Al. Changed "
"thickness from 0.01 to 0.254. "
*****
```

```
"----STEP 1 OVER-RIDE OF MACROS-----"
```

```
REPLACE {$MXMED} WITH {7}
REPLACE {$MXREG} WITH {51}
REPLACE {$EBIN} WITH {60}
;
REPLACE {;COMIN/SCORE/;} WITH
{;COMMON/SCORE/EScore($MXREG),EHIST,EBIN($EBIN),NCOMPT,
NPHOT,NPE;}
$ENERGY PRECISION ESCORE,TOTAL,EHIST;
;
REAL DETD,ALFOIL,ALRING,DETH,NAITHC,ALTHC,INRRAD,
POLYERING;
;
REAL EVAC,EVAC1,EVAC2,EAIR,EAL,EATOL,DET_DIST,DET_DIST,
TOTE,EQTZ,EMYL,ENAL,EORING,SPEED,TIME,INC_PART,INIT_PART,
EFF,ERR_EFF;
;
```

INTEGER DECAYS,INC_DECAYS,ANSWER;

;

;COMIN/BOUNDS,CYLDTA,MEDIA,MISC,PLADTA,EDGE,RANDOM,
SCORE,STACK,THRESH,USER/;

"----STEP 2 PRE-HATCH INITIALIZATION----"

\$TYPE MEDARR(24,7)/\$\$'QRTZ',20*'',\$\$'NAI',21*'',\$\$'POLYE',19*' ',

\$\$'AL',22*' ', \$\$'AIR',21*'',\$\$'ATL',21*'',\$\$'BE',22*' ';

"ATL stands for atoll composition. IT is similar to bone."

TIME=2.0; "TIME IS IN SECONDS"

DECAYS=37000 * TIME; "NUMBER OF DECAYS THAT HAPPEN PER
SECOND"

NPLN=45;

NREG=\$MXREG;

NMED=7;

DO J=1,NMED[DO I=1,24[MEDIA(I,J)=MEDARR(I,J);]]

"Setting media. Since there were so many regions it was easier to"

"use do-loops."

"Vacuum"

DO K=1,51,10[MED(K)=0;]

K=0;

DO K=10,50,10[MED(K)=0;]

K=0;

"QUARTZ"

/MED(2), MED(12), MED(22)/=1;

"NAI"

/MED(3), MED(13)/=2;

"ALUMINUM FOIL"

MED(4)=7;

"O-ring"

/MED(16),MED(26)/=3;

"AL"

DO K=32,37[MED(K)=4;]

K=0;

/MED(14),MED(15),MED(24),MED(25)/=4;

/MED(17),MED(27)/=4;

"AIR"

/MED(5),MED(6),MED(7)/=5;

DO K=8,38,10[MED(K)=5;]

K=0;

DO K=42,48[MED(K)=5;]

K=0;

MED(23)=5;

"Johnson Atoll"

DO K=9,49,10[MED(K)=6;]

K=0;

"SETTING ENERGY CUTOFFS FOR EACH REGION"

KCOMP=0;

DO I=1,NREG [

ECUT(I)=0.571;

PCUT(I)=0.001;

IRAYLR(I)=1;

IEDGFL(I)=1;"This for for K-Shell X-rays"

"KEK Low Energy Photon Scattering Switches"

INCOHR(I)=1; "INCOHERENT SCATTERING OPTION FOR REGION I"

IPROFR(I)=1; "COMPTON PROFILE OPTION FOR REGION I"

LPOLAR(I)=1; "LINEAR POLARIZATION EFFECT ON PHOTON SCATTERING"

]

"----CALL HATCH----"

;OUTPUT;'STARTING PROGRAM FOR FAT/BONE CYLINDER'//

' CALL HATCH TO RETRIEVE CROSS SECTION DATA'/);

CALL HATCH;

;OUTPUT ECUT(1)-0.511,AE(1)-0.511,PCUT(1),AP(1);

('IN PROGRAM ELECTRONS ARE FOLLOWED DOWN TO',F7.4,' MEV/

'IN PEGS4 DATA FILE ELECTRONS FOLLOWED DOWN TO',F7.4,' MEV/

'IN PROGRAM PHOTONS ARE FOLLOWED DOWN TO',F7.4,' MEV/

'PHOTONS FOLLOWED DOWN TO',F7.4,' MEV'/);

CALL EDGSET(2,51);

CALL RMARIN; "For random number"

"----INITIALIZATION OF HOWFAR----"

"since all plane are centered and parallel to one another the PNORM"

"and PCOORDS could be set in a general way"

DO I=1,NPLN[

PNORM(1,I)=0.0;PNORM(2,I)=0.0;PNORM(3,I)=1.0;

PCOORD(1,I)=0.0;PCOORD(2,I)=0.0;

]

"TO ALLOW MORE MATERIALS TO BE ADDED TO THE CRYSTAL I PLACED THESE"

"MATERIAL THICKNESS HERE SO THEY CAN JUST BE CHANGED HERE AND NOT"

"IN THE FOLLOWING DO-LOOPS"

ALFOIL=0.0254;"ALuminum foil THICKNESS"

NAITHC=0.16; "NAI THICKNESS"

ALTHC=0.406; "AL THICKNESS"

DETHH=4.953;"DETECTOR THICKNESS"

POLYERING=0.356;

ALRING=0.3458; "This number is POLYERING - ALFOIL"

"I WANT THE CRYSTAL FACE TO START AT A SPECIFIC DISTANCE FROM"

"THE GROUND. THE CRYSTAL FACE WILL BE IN THE NEGATIVE Z AREA"

"WITH THE GROUND BEING THE ORIGIN. IN THE NEGATIVE AREA ALL DISTANCES"

"WILL BE IN RELATION TO THE CRYSTAL FACE"

"SETTING CYLINDER RADIUS"

"RADIUS' FOR THE CYLINDERS AND RINGS"

INRRAD=6.05;

DO K=1,8[CYRAD2(K)=INRRAD**2;] "INNNER RADIUS OF DET. WINDOW"

K=0;

"NAI RAD PLUS A LITTLE OVERLAP FROM QUARTZ LIGHT PIPE"

DO K=10,17[CYRAD2(K)=(INRRAD + 0.30)**2;]

K=0;

DO K=19,26[CYRAD2(K)=(7.3516)**2;]

K=0;

DO K=28,35[CYRAD2(K)=(7.55)**2;]

K=0;

DO K=37,44[CYRAD2(K)=(3000)**2;]

K=0;

"----INITIALIZATION OF AUSGAB----"

DO I=1,\$EBIN[EBIN(I)=0.00;]

BWIDTH=0.001;

NCOMPT=0;

"----STEP 6 PARTICLE PARAMETERS----"


```

IQIN=0;" PHOTON"
EIN=0.060;
WTIN=1.0;
PVAL=0.0;
OUTPUT PVAL; (' INCIDENT POLARIZATION',1PE12.5);
PRATIO=0.5+PVAL*0.5;

```

```

OPEN(18,FILE='jatol4',status='unknown');
OPEN(19,FILE='det1',status='unknown');
"----SHOWER CALL----"

```

"This has been moved inside this do-loop because the height of the"
 "detector will be changed for one problem."

```

DO J=1,35[PCOORD(3,J)=0.0;]
"This is the point where the detector h will be changed"
"It will be adjusted every 6 inches."
"DISTANCE FROM FRONT OF DETECTOR TO SOIL"
DO J=0,0[DETD=-7.62 + float(j)*15.6;
;
%F
      write(18,95) DETD
95  format(F7.2)
%M

```

```

DO N=1,37,9[
PCOORD(3,N)=DETD - DETTH;]
N=0;

```

```

DO N=2,38,9[
PCOORD(3,N)=DETD - ALTHC - POLYERING - ALRING - ALFOIL -
NAITHC;]
N=0;

```

```

DO N=3,39,9[
PCOORD(3,N)=DETD - ALTHC - POLYERING - ALRING - ALFOIL;]
N=0;

```

```

DO N=4,40,9[
PCOORD(3,N)=DETD - ALTHC - POLYERING - ALRING;]
N=0;

```

```

DO N=5,41,9[
PCOORD(3,N)=DETD - ALTHC - POLYERING;]
N=0;

```

```
DO N=6,42,9[
PCOORD(3,N)=DETD - ALTHC;]
N=0;
```

```
DO N=7,43,9[
PCOORD(3,N)=DETD;]
N=0;
```

```
DO N=8,44,9[
PCOORD(3,N)=0.0;]
N=0;
```

```
DO N=9,45,9[
PCOORD(3,N)=50;]
N=0;
```

"THIS WILL BE DONE A GIVEN NUMBER OF TIMES REPRESENTING A
GIVEN NUMBER"
"IN THE SOIL"

```
NCASE=50000;
:RUN;;
PRINT*, 'WHERE DOES PARTICLE START? What Speed?, What Depth?';
READ*, INIT_PART, SPEED, ZIN;
DET_DIST=SPEED * TIME;
;
%F
WRITE(18,131)
131 FORMAT(2X,'N',5X,'X',9X,'Y',9X,'Z',8X,'R',11X,'COUNTS',
*12X,'ERROR')
%M
;

"ZIN=0.0;"
DO K=0,0["ZIN=2. * FLOAT(K);"
YIN=0.0;
```

"This adjusts the X distance from the origin."
DO N=1,NCASE[\$RANDOMSET XINC;
XIN=-XINC*DET_DIST + INIT_PART;
CHK=XIN**2+YIN**2;

"MAKES SURE THE PHOTON STARTS IN THE PROPER REGION"
IF(CHK.LE.CYRAD2(1))[IRIN=9;GOTO :STR1;:]

```

ELSEIF(CHK.LE.CYRAD2(10))[IRIN=19;GOTO :STRT:;]
ELSEIF(CHK.LE.CYRAD2(19))[IRIN=29;GOTO :STRT:;]
ELSEIF(CHK.LE.CYRAD2(28))[IRIN=39;GOTO :STRT:;]
ELSEIF(CHK.LE.CYRAD2(37))[IRIN=49;]
:STRT:
DO I=1,1[EHIST=0.0;
  CALL ISRC(UIN,VIN,WIN);
  CALL SHOWER(IQIN,EIN,XIN,YIN,ZIN,UIN,VIN,WIN,IRIN,WTIN);
"SETTING THE OUTPUT ENERGY IN BIN. BEGINNING IS EXCLUDED
WHILE"
"END IS INCLUDED. EX: IN 0,0.001 WOULD BE IN THE 0.001 BIN."
  $RANDOMSET VALUE;
  IF(VALUE.LT.PRATIO)[UFI=0.0; VFI=0.0; WFI=0.0;]
  ELSE
    [UFI=0.0; VFI=0.0; WFI=0.0;
    UF(1)=UFI; VF(1)=VFI; WF(1)=WFI;]
    IBIN=MIN0(IFIX(EHIST/BWIDTH + 0.999),$EBIN);
    IF(IBIN.NE.0)[EBIN(IBIN)=EBIN(IBIN)+1;]
  ]"THIS ENDS THE SHOWER LOOP"

;]"THIS ENDS X POSITION LOOP"
"THIS DETERMINES THE AVERAGE COUNT RECIEVED IN 2 SECONDS"
ERR_CNTS=SQRT(EBIN(60));
EFF=EBIN(60)/FLOAT(NCASE);"average efficiency"
ERR_EFF= EFF*SQRT((ERR_CNTS/EBIN(60))**2 + (1/FLOAT(NCASE)));
;
%F
  write(18,35) EBIN(60),ERR_CNTS,SPEED,EFF,ERR_EFF
  write(18,96)
35  format('Total Counts in 2 seconds is ',F15.2,' +/- ',F10.2 /,
  * 'At a speed of ',F6.2,' cm/s the average FIDLER efficiency is ',
  * 1PE15.8,' +/- ',1PE15.8 /)
96  format(' ',/)
  write(6,35) EBIN(60),ERR_CNTS,SPEED,EFF,ERR_EFF
  write(6,96)
%M
;
PRINT*,'DO YOU WANT ANOTHER STARTING POINT?';
READ*,ANSWER;
IF(ANSWER.EQ.1)[EBIN(60)=0.;GOTO :RUN:;]
;]"THIS ENDS Z POSITION LOOP"
]"THIS ENDS THE DO LOOP FOR CHANGING THE DETECTOR HEIGHT"

"---OUTPUT OF RESULTS----"
"THIS CHECKS TO MAKE SURE TOTAL ENERGY CHECKS OUT"

```

```
TOTAL=0.0;
DO I=1,$MXREG[TOTAL=TOTAL+ESCORE(I);]
```

```
"SUMING UP ENERGY DEPOSITION THROUGHOUT SIMULATION JUST"
"AS A CHECK"
```

```
"IN QUARTZ"
EQTZ=ESCORE(2) + ESCORE(12) + ESCORE(22);
```

```
"The crystal"
ENAI=ESCORE(3) + ESCORE(13);
```

```
"IN MYLAR"
EMYL=ESCORE(4);
```

```
"In aluminum"
EAL=ESCORE(17)+ESCORE(27);
EAL=EAL+ESCORE(14)+ESCORE(24)+ESCORE(15)+ESCORE(25);
DO K=32,37[EAL=EAL+ESCORE(K);]
```

```
"IN O-RING"
EORING=ESCORE(16) + ESCORE(26);
```

```
"IN AIR"
EAIR=ESCORE(23);
DO K=8,38,10[EAIR=EAIR + ESCORE(K);]
DO K=42,48[EAIR=EAIR + ESCORE(K);]
DO K=5,7[EAIR=EAIR + ESCORE(K);]
```

```
"IN VACUUM"
DO J=1,51,10[EVAC1=EVAC1+ESCORE(J);]
DO J=10,50,10[EVAC2=EVAC2+ESCORE(J);]
EVAC=EVAC1+EVAC2;
```

```
DO J=9,49,10[EATOL=EATOL+ESCORE(J);]
```

```
;
```

```
%F
  write(18,221),ENAI
  write(18,251),EQTZ
  write(18,222),EMYL
  write(18,223),EAL
  write(18,224),EAIR
  write(18,250),EORING
  write(18,225),EATOL
  write(18,226),EVAC
  TOTE=ENAI+EQTZ+EMYL+EAL+EAIR+EATOL+EVAC+EORING
```

```

      write(18,227),TOTE,TOTAL
221  format('Energy deposited in NaI is: ',F15.3)
251  format('Energy deposited in quartz is: ',F15.3)
222  format('Energy deposited in mylar is: ',F15.3)
223  format('Energy deposited in Al is: ',F15.3)
224  format('Energy deposited in AIR inside detector is: ',F15.3)
250  format('Energy deposited in O-RING is: ',F15.3)
225  format('Energy deposited in Soil is: ',F15.3)
226  format('Energy deposited in Vacuum is: ',F15.3)
227  format('Does added (',F15.3,') = total E= ',F15.3)
      do 49 j=1,51
          write(18,228),j, ESCORE(j)
228  format('ESCORE(',I3,')= ',F15.3)
49  continue
      PRINT*,NUMBER PHOTONS ENTERING CRYSTAL:',NPHOT
      PRINT*,NUMBER COMPTON SCATTERS:',NCOMPT
      PRINT*,NUMBER PHOTOELECTRIC:',NPE
%M
;
STOP;END;
"-----"

```

```

SUBROUTINE AUSGAB(IARG);
COMIN/EPCONT,SCORE,STACK/;
$ENERGY PRECISION ESCORE,EHIST;

```

```

IRL=IR(NP);
IAUSFL(18)=1;
IAUSFL(20)=1;

```

```

IF(IARG.LE.4)[
  ESCORE(IRL)=ESCORE(IRL)+EDEP;
  IF(IRL.EQ.3.OR.IRL.EQ.13)[
    EHIST=EHIST+EDEP;]
]

```

```

IF(IQ(NP).EQ.0.AND.E(NP).GT.(0.059998))[

```

```

  IF(IRL.EQ.3.OR.IRL.EQ.13)[
    NPHOT=NPHOT+1;
    IF (IARG.EQ.17)[NCOMPT=NCOMPT+1;]

```

```

  IF(IARG.EQ.19)[NPE=NPE+1;]
]

```

```

]

```

```
RETURN;
END;
```

```
"-----"
```

```
SUBROUTINE HOWFAR;
COMIN/CYLDTA,EPCONT,PLADTA,STACK/;
```

```
IRL=IR(NP);
```

```
IF(IRL.EQ.1.OR.IRL.EQ.11.OR.IRL.EQ.21.OR.IRL.EQ.31)[
IDISC=1;RETURN;]
```

```
IF(IRL.EQ.10.OR.IRL.EQ.20.OR.IRL.EQ.30.OR.IRL.EQ.40)[
IDISC=1;RETURN;]
```

```
IF(IRL.EQ.50.OR.IRL.EQ.51.OR.IRL.EQ.41)[
IDISC=1;RETURN;]
```

```
"INNER CYLINDERS"
```

```
ELSE IF(IRL.LE.9)[
$PLAN2P(IRL,IRL+1,1,IRL-1,IRL-1,-1);
$CYLNDR(IRL-1,1,IHIT,TCYL);
IF(IHIT.EQ.1)[$CHGTR(TCYL,IRL+10);]
RETURN;
]
```

```
"SECOND OUT"
```

```
ELSE IF(IRL.LE.19)[
$PLAN2P(IRL-1,IRL+1,1,IRL-2,IRL-1,-1);
$CYL2(IRL-11,IRL-10,IRL-2,IRL+10);
RETURN;
]
```

```
"THIRD OUT"
```

```
ELSE IF(IRL.LE.29)[
$PLAN2P(IRL-2,IRL+1,1,IRL-3,IRL-1,-1);
$CYL2(IRL-12,IRL-10,IRL-3,IRL+10);
RETURN;
]
```

```
"4TH OUT"
```

```
ELSE IF(IRL.LE.39)[
$PLAN2P(IRL-3,IRL+1,1,IRL-4,IRL-1,-1);
$CYL2(IRL-13,IRL-10,IRL-4,IRL+10);
```

```
RETURN;
]
```

```
"5TH OUT"
ELSE IF(IRL.LE.49)[
$PLAN2P(IRL-4,IRL+1,1,IRL-5,IRL-1,-1);
$CYL2(IRL-14,IRL-10,IRL-5,51);
RETURN;
]
END;
```

```
"*****"
```

```
SUBROUTINE ISRC(UIN,VIN,WIN);
```

```
COMIN/DEBUG,STACK,THRESH,UPHIOT,USEFUL,RANDOM/;
```

```
$RANDOMSET RNNO43;
PHI=2.*PI*RNNO43;
```

```
$RANDOMSET RNNO44;
WIN=((2.*RNNO44)-1.);
```

```
UIN=SQRT(1.-WIN*WIN)*COS(PHI);
VIN=SQRT(1.-WIN*WIN)*SIN(PHI);
```

```
RETURN;
END;
```