Large Area Self-Powered Gamma Ray Detector

RECEIVED
FEB 04 1994
OSTI

Phase II Development of a Source Position
Monitor for Use on Industrial
Radiographic Units

Prepared by
F. E. LeVert

K. E. M. P. Corporation

Prepared for
U.S. Nuclear Regulatory Commission

AVAILABILITY NOTICE

Availability of Reference Materials Cited in NRC Publications

Most documents cited in NRC publications will be available from one of the following sources:

1. The NRC Public Document Room, 2120 L Street, NW., Lower Level, Washington, DC 20555-0001
2. The Superintendent of Documents, U. S. Government Printing Office, Mail Stop SSOP, Washington, DC 20402-9328
3. The National Technical Information Service, Springfield, VA 22161

Although the listing that follows represents the majority of documents cited in NRC publications, it is not intended to be exhaustive.

Referenced documents available for inspection and copying for a fee from the NRC Public Document Room include NRC correspondence and internal NRC memoranda; NRC bulletins, circulars, information notices, inspection and investigation notices; licensee event reports; vendor reports and correspondence; Commission papers; and applicant and licensee documents and correspondence.

The following documents in the NUREG series are available for purchase from the GPO Sales Program: formal NRC staff and contractor reports; NRC-sponsored conference proceedings; international agreement reports; grant publications; and NRC booklets and brochures. Also available are regulatory guides, NRC regulations in the *Code of Federal Regulations*, and *Nuclear Regulatory Commission Issuances*.

Documents available from the National Technical Information Service include NUREG-series reports and technical reports prepared by other Federal agencies and reports prepared by the Atomic Energy Commission, forerunner agency to the Nuclear Regulatory Commission.

Documents available from public and special technical libraries include all open literature items, such as books, journal articles, and transactions; *Federal Register* notices; Federal and State legislation; and congressional reports can usually be obtained from these libraries.

Documents such as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings are available for purchase from the organization sponsoring the publication cited.

Single copies of NRC draft reports are available free, to the extent of supply, upon written request to the Office of Administration, Distribution and Mail Services Section, U. S. Nuclear Regulatory Commission, Washington, DC 20555-0001.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at the NRC Library, 7920 Norfolk Avenue, Bethesda, Maryland, for use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from the American National Standards Institute, 1430 Broadway, New York, NY 10018.

DISCLAIMER NOTICE

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, or any of their employees, makes any warranty, expressed or implied, or assumes any legal liability of responsibility for any third party's use, or the results of such use, of any information, apparatus, product or process disclosed in this report, or represents that its use by such third party would not infringe privately owned rights.

Large Area Self-Powered Gamma Ray Detector

Phase II Development of a Source Position
Monitor for Use on Industrial
Radiographic Units

Manuscript Completed: December 1993
Date Published: January 1994

Prepared by
F. E. LeVert

D. O. Nellis, NRC Technical Monitor

K. E. M. P. Corporation
1725 East Magnolia Avenue
Knoxville, TN 37917

Prepared for
Division of Regulatory Applications
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
NRC FIN L1267

MASTER

zp

ABSTRACT

The purpose of this research was to develop a large area self-powered gamma detector (LASPGD) capable of detecting the movement of sealed radiation sources into and out of industrial radiographic units and to construct a prototype source position monitor (SPM) for these units utilizing the LASPGD. Prototype isotropic and directional LASPGDs, with solid and inert gas dielectrics, were developed and extensively tested using calibrated gamma sources (i.e., Cs-137, and Co-60). The sensitivities of the isotropic detectors, with inert gas dielectrics, were found to be approximately a factor of ten greater than those measured for the solid dielectric LASPGDs. Directionally sensitive self-powered detectors were found to exhibit a forward-to-back hemispherical sensitivity ratio of approximately 2 to 1. Industrial radiographic units containing Ir-192 sources with different activities were used to test the performance of the SPM. The SPM, which utilized a gas dielectric LASPGD, performed as designed. That is, the current generated in the LASPGD was converted to a voltage, amplified and used to control the on/off state of an incandescent lamp. The incandescent lamp, which functions as the source/out warning indicator, flashes at a rate of one flash per second when the source is in use (i.e. out of its shield).

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT.....	iii
LIST OF FIGURES.....	vii
LIST OF TABLES.....	viii
EXECUTIVE SUMMARY.....	ix
NOMENCLATURE.....	xi
FOREWORD	xiii
1.0 INTRODUCTION.....	1
1.1 Background.....	1
1.2 Project Objectives.....	2
2.0 THEORY OF OPERATION OF ISOTROPIC AND DIRECTIONALLY SENSITIVE LASPGDs.....	2
2.1 Analysis of Solid and Gaseous Dielectric LASPGDs.....	3
2.1.1 Solid Dielectric LASPGD.....	3
2.1.2 Gaseous Dielectric LASPGD.....	8
3.0 SOURCE POSITION MONITOR.....	8
3.1 Source Position Monitor Housing Design.....	8
3.2 Current-to-Voltage Converter/Amplifier/Analog Logic Circuit...	11
4.0 EXPERIMENTAL RESULTS.....	13
4.1 Initial Testing of the Solid and Gas Dielectric LASPGD.....	13
4.2 Test of Source Position Monitor on an Industrial Radiographic Unit.....	17
5.0 ENVIRONMENTAL TESTING OF THE PROTOTYPE SPM.....	22
6.0 OPERATION OF THE SPM.....	22
7.0 CONCLUSION.....	25
8.0 RECOMMENDATIONS.....	26
9.0 REFERENCES.....	27
APPENDIX A.....	28

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
1. Schematic representation of the thick collector LASPGD used in interface model analysis.....	4
2. Interface model for two materials.....	5
3. Electron production per photon incident on the surface of helium gas-filled thick collector LASPGD.....	9
4. Cross section view of SPM assembly.....	10
5. Process block diagram of the signal conditioning electronics.....	12
6. Response of gas dielectric LASPGD to Co-60 and Cs-137 gamma rays.....	14
7. Output of electrode structure with 1.27 cm thick tantalum prism surrounded by a 1.27cm thick polyethylene dielectric on all sides.....	15
8. Output of electrode structure with 0.625cm thick polyethylene dielectric covering all surfaces of a Pb-C electrode.....	16
9. Output voltage of second stage amplifier in SPM when a 37 curie Ir-192 source is moved in 21 cm intervals away from the SPM mounted on the shield of the radiographic unit.....	19
10. Output voltage of second stage amplifier in SPM when the 37 curie source moved in 21 cm intervals away from the SPM mounted on source shield.....	21
11A. Battery compartment.....	23
11B. View of SPM controls.....	23
12. Radiographic unit mounting fixture.....	24
13. Top view showing unpotted PCB with potentiometer for adjusting trigger level shown at top edge of PCB.....	24
A.1 Detector housing and assembly.....	29
A.2 Gas dielectric LASPGD.....	31
A.3 SPM mounting fixture.....	32
A.4 Signal conditioning circuit schematic (Sheet 1 of 3).....	33
Current-to-voltage/two stage amplifier analog logic circuit PCB layout board (sheet 2 of 3).....	34
Parts list (sheet 3 of 3).....	35

LIST OF TABLES

	<u>Page</u>
I. LASPGD Electrodes Tested in this Phase II Effort.....	7
II. Response of the SPM to a 2.5 Curie Ir-192.....	20

Executive Summary

This report describes the design and testing of a source position monitor (SPM) for use in industrial radiography. The work was performed under Phase II of a Small Business Innovative Research Contract (SBIR). Phase I of the contract demonstrated the feasibility of developing a large area self-powered detector (LASPGD) for use as a source position monitor for industrial radiography devices. Testing of the gaseous dielectric detector designed for this purpose indicated a sensitivity of 3.3×10^{-8} picoamperes/photon/second for the (average 0.380MeV) gamma rays from Ir-192. This corresponds to a reading of 62 picoamps/Ci at a source to detector distance of 10 cm, which is adequate to detect typical radiography sources which have strengths of from 15 to 200 Ci.

The design of the LASPGD, signal conditioning electronics, and the SPM will be discussed in subsequent sections.

NOMENCLATURE

Ci.....	curie
cm.....	centimeter
Co.....	Cobalt
Cs.....	Cesium
DR.....	dose rate
hr.....	hour
IC.....	integrated circuit
Ir.....	Iridium
KeV.....	kiloelectron volt
kV.....	kilovolt
LASPGD.....	large area self-powered gamma detector
LED.....	light emitting diode
MeV.....	million electron volt
min.....	minute
mm.....	millimeter
mv.....	millivolt
PCB.....	print circuit board
R.....	roentgen
R(E).....	range of an electron in a material
s.....	second
SPM.....	source position monitor
SPGD.....	self-powered gamma detector
Z.....	atomic number

FOREWORD

This report discusses the development of a large area self-powered gamma detector (LASPGD), for use as a source position indicator on radiographic devices used in industrial radioisotope radiography. Self-powered gamma detectors are devices in which the incoming gamma rays interact with the emitter of the detector through the photoelectric, Compton, and pair production processes, to produce an electric current that can be detected in an external electronic circuit. Since no power supply is required to produce this current, the devices are referred to as self powered.

The work described herein was performed under Phase II of the Small Business Innovation Research Program. The testing and analysis conducted earlier under Phase I of this program, demonstrated the feasibility of developing a LASPGD sensitive enough to monitor the position of sources used in industrial radiography. This report describes the testing of solid and gaseous dielectric detectors with sources of Co-60, Cs-137, and Ir-192. The testing showed that a gaseous dielectric detector was able to detect a 2.5 curie Ir-192 source travelling past the detector (mounted about 4 cm above the guide tube of an industrial radiographic unit) at an average speed of over 100 cm/s. This demonstrates that the detector could easily detect typical Ir-192 radiography sources which run in the neighborhood of 15 to 200 curies.

NUREG/CR-4833 is not a substitute for NRC regulations and compliance is not required. The approaches and/or methods described in this NUREG are provided for information only. Publication of this report does not necessarily constitute NRC approval or agreement with the information and recommendations contained herein.

Donald A. Cool, Chief
Radiation Protection and Health
Effects Branch
Division of Regulatory Applications
Office of Nuclear Regulatory Research

Section 1.0 INTRODUCTION

1.1 Background

Self-powered gamma detectors have been employed as monitors of intense gamma ray fields for many years. Very small self-powered gamma detectors with coaxial geometry are used in the Civilian Nuclear Power Program¹. Large surface area devices, which are called Compton diodes^{2,3}, are used at the Los Alamos National Laboratory and the Sandia Laboratories to measure intense gamma dose levels.

Compared to the self-powered gamma detectors used in the Civilian Nuclear Power program, Compton diodes are large active volume devices. The conductive components in Compton diodes are separated by either a vacuum or a dielectric. These direct-energy conversion devices utilize, primarily, the Compton effect to convert a fraction of incident photon energy into an electrical current. Fewell⁴ described the design and construction of dielectric type Compton diodes. A detailed discussion of the theory of operation of Compton diodes was described by Kelly⁵. LeVert et.al.^{6,7} described the theory of operation and the construction of dielectric and vacuum type directionally sensitive large area self-powered gamma detectors.

Typically, the gamma sensitivity of these devices varies with: a) the material and thickness of the central electrode (commonly called the collector); b) the thickness and atomic number of the dielectric material; c) the thickness and material of the outer electrode, which normally encapsulates the dielectric and collector; and, d) the energy of the incident gamma radiation.

In the energy range of interest for radiographic radiation sources, 0.380 to 1.25 MeV, several investigators^{7,8} have shown that the sensitivities of vacuum type diodes vary between 2.5×10^{-3} and 8.2×10^{-3} electrons/photon, respectively. Over the same energy range, the sensitivities of solid dielectric Compton diodes have been shown to vary between 0.78×10^{-3} electron/photon (at 1.25 MeV)² and 0.195×10^{-3} electron/photon* (at 0.400 MeV). These results suggest that the electron current production efficiency of photons decreases with decreasing incident photon energies. The most commonly used radioisotope in industrial radiographic units is Ir-192. This isotope emits gamma rays with an average energy of ~0.380 MeV. The strengths of these sources vary between ~15 and 200 curies. This project required that an LASPGD that utilizes a vacuum or solid dielectric be designed, fabricated and tested for use in a SPM. The SPM must be able to detect a sealed source propelled through a conduit in close proximity to the detector at a high speed.

* Here the dielectric thickness was reduced to compensate for the reduced energy of the incident photons.

This report describes the design of the detector assembly, signal conditioning electronics and alarm logic of the LASPGD based source position monitor. The LASPGD used in the SPM was designed for this specific application. However, the LASPGD designs studied in this Phase II effort can be applied to the following radiation monitoring tasks:

- * Measurement of dose rates from intense gamma ray sources in nuclear power plants.
- * Position sensing of radioactive materials in high background radiation areas.
- * Long-term monitoring of stored radioactive materials.

In addition, the fact that the detector requires no external power makes it attractive for use in certain situations.

1.2 Project Objectives

The specific research and development effort objectives were as follows:

1. Evaluate a wide range of electrode structures to develop a sensitive large area self-powered gamma detector.
2. Develop a prototype current-to-voltage preamplifier, amplifier and an alarm logic circuitry with an annunciator.
3. Fabricate and assemble one isotropic and one directionally sensitive LASPGD.
4. Test both the isotropic and directionally sensitive LASPGD electrode structures to determine the optimum LASPGD design for use in a deliverable prototype SPM.
5. Develop a design for a low-cost, rugged, special purpose radiation detector for commercial use.

Section 2.0

THEORY OF OPERATION OF ISOTROPIC AND DIRECTIONALLY SENSITIVE LASPGDs

The theory of operation of Compton diodes has been discussed extensively by several investigators^{4,5,7}. Below we will briefly discuss the physics of operation of these diodes and the results of the analyses used to aid in the design of the LASPGD employed in the Phase II SPM monitor. The SPM is designed to operate over an energy range of 0.380 to 1.32 MeV. Evans⁹ showed that for some high atomic number (Z) material (e.g., lead and tantalum), the photoelectric interactions are dominant at 0.380 MeV (Ir-192) and

equally as probable as Compton interactions at 0.660 MeV (Cs-137). Between 0.6 and 1.4 MeV, the Compton effect is completely dominant for high Z materials such as tantalum and lead. Thus, the current in the LASPGD is primarily due to Compton interactions when the device is exposed to Co-60. Photoelectric interactions are dominant in detectors exposed to Ir-192. For Cs-137, which emits 0.660 MeV photons, Compton and photoelectric interactions are equally probable interaction mechanisms for gamma rays incident on the LASPGDs.

Compton interaction results in the liberation of electrons that are predominately scattered in the forward direction; therefore, in a solid dielectric LASPGD, (see Figure 1) a unidirectional gamma beam is accompanied by an electron current moving in the same direction. The collector (central electrode) intercepts some of these electrons and some are trapped in the dielectric. Electrons trapped in the dielectric and those reaching the central electrode act together to produce a usable signal in the LASPGD.

When low energy (i.e. ≤ 0.6 MeV) photons are incident on the LASPGD, the production of the usable signal is somewhat more complex. Electrons liberated by incident photons are emitted almost equally in all directions, thereby tending not to produce a dominant electron current that moves in the direction of the incident photons. That is, for photoelectric interactions in a solid dielectric, it is equally likely that the electrons move in a direction away from the collector where they add to the space charge in the dielectric. The heuristic analysis technique used to aid in the design of the LASPGDs used in SPM is discussed below.

2.1 Analysis of Solid and Gaseous Dielectric LASPGDs

2.1.1 Solid Dielectric LASPGD

The output current of the solid dielectric electrode is made of two components: a) the electrostatically induced current caused by the distribution of electrons within the dielectric; and, b) the algebraic difference between the electrons driven into the collector and those knocked off the collector by impinging gamma rays. Experiments conducted in Phase I of this work suggested that the dominant contribution to the electrode current in a solid dielectric detector is the Compton-driven electrons incident upon the collector. The Dellin and MacCallum Interface Model¹⁰ was used to compute the electron distribution in geometrical and material variations of LASPGDs similar to the design shown schematically in Figure 1. The Interface Model, shown schematically in Figure 2, was used to provide the forward and backward components of photon driven currents - in each medium at equilibrium - as calculated in the "P1" approximation¹⁰. Here, equilibrium means that the electron current density changes rapidly to reach a maximum at the electron range, $R(E)$, and then changes very little as a function of depth in the medium. In the model, the electron currents in the dielectric and at the collector-dielectric interface are given by:

$$JF(E, x) (\text{electron/photon}) = (JF_{i+1} - JF_i) (1 - \exp(-x/R_{i,i+1})) + JF_i, \quad (1)$$

for $i = 1, 3$

Figure 1. Schematic representation of typical thick collector LASPGD design used in Interface Model analysis:
 1 - Microdot connector; 2 - Dielectric material;
 3 - Tantalum prism; 4 - Aluminum outer surface; 5 - Torr seal epoxy

Figure 2. Interface model for two materials

$$JB(E,x) \text{ (electron/photon)} = (JB_{i+1} - JB_i) (\exp(-(1-x)/R_{i+1,1}) + JB_i), \quad (2)$$

for $i = 2, 4, \dots$

and

$$JN(E,x) \text{ (coulombs/photon)} = -q(JF(E,x) - JB(E,x))$$

where:

$JF(E,x)$ = the forward photon-driven electron current.

$JB(E,x)$ = the backward photon driven current.

L = the thickness of the dielectric between the cover plate and the collector.

$R(E)$ = the range of electrons of energy "E" created medium "i" in the adjacent medium "i+1" for both forwardly and backwardly scattered electrons.

$JN(E,x)$ = the net charge deposited per Compton scattered photon.

q = charge per electron (1.6×10^{-19} Coulombs).

The model is based on three assumptions: 1) the dielectric material is thicker than the maximum range of the liberated electrons; 2) the central electrode (collector) absorbed most of the gamma rays incident upon it; and 3) the incident gamma flux has parallel geometry. These assumptions allow one to treat the composite structure of the detector as two three-plate systems. The electron current at the collector in this system is the algebraic sum of the net charge at the front and the back faces of the collector. The distribution of electrons within the dielectric was determined using the interface model. The distribution of electrons in the dielectric was used to estimate the contribution of the electrostatically induced current to the net currents of the collector.

The forward and backward equilibrium values for $JF(E,x)$ and $JB(E,x)$ were taken from the Handbook of Photo Compton Data¹⁰. The values of the forward and backward currents include electrons created by photoelectric, Compton and other processes. The net electron current in Equation 3 was weighted by the scattered gamma-ray flux, $-(1-\exp-ux)$, at each position x , starting at $x=0$ through $x=L$, where x was incremented in steps of $L/100$. Backscattering of electrons at the interfaces of the LASPGD materials was also included in the Interface Model. The materials and thicknesses of the various components of the LASPGD suggested by these analyses are given in Table I. The analysis suggested that the LASPGD be designed with: a) an outer enclosure with a thickness greater than the large $R(E)$ of electrons liberated therein; b) a dielectric thickness greater than the range, $R(E)$, of electrons liberated in gamma ray interactions in it;

Table I. IASPGD Electrodes Tested In The Phase II Effort

Detector Type	Collector		Dielectric		Outer Enclosure		Source	Output Current (picoamperes)	Dose Rate (R/min)
	Material	Thickness (cm)	Material	Thickness (cm)	Material	Thickness (cm)			
1. Isotropic	Lead	1.27	Polyethylene	0.62	Aluminum	0.0125	Co-60	-38.6	62.1
							Co-60	- 5.4	15.2
							Cs-137	-13.8	37.16
2. Isotropic	Tantalum	1.27	Polyethylene	1.27/ 1.27	Aluminum	0.0125	Co-60	-43.6	62.1
							Co-60	-6.8	15.2
							Cs-137	-16	37.16
3. Directional	Tantalum/ Carbon	1.27/ 1.87	Polyethylene	0.62	Aluminum	0.075	Co-60	-37.7 ^a	62.1
							Cs-137	-10	37.18
							Co-60	-28.8 ^b	62.1
							Cs-137	-6	
4. Directional	Lead/ Carbon	0.62/ 0.62	Polyethylene	0.62	Aluminum	0.075	Co-60	-16.1 ^c	62.1
							Cs-60	-14.1 ^d	62.1
5. Isotropic	Lead	0.89	Helium	0.62	Aluminum	0.075	Co-60	1892	62.1
							Co-60	441	15

a). Tantalum facing source

b). Carbon facing source

c). Lead facing Source

d). Carbon facing source

and, c) a collector thick enough to absorb 90% or more of the photons impinging upon it. Experimental results discussed in Section 4.1 suggest that the requirement listed in item C can be relaxed with a small penalty in the LASPGD performance.

2.1.2 Gaseous Dielectric LASPGD

The technique used to estimate the current generated in the solid dielectric LASPGD was applied to the gaseous dielectric detectors. The detector current includes two separate contributions: a) the net electron current flowing into or away from the collector; and, b) the space charge induced current caused by a build up of free electrons in the gaseous dielectric. Gamma rays incident on the detector produce electrons in the outer enclosure, the gas, and the collector via photoelectric and Compton interactions. During this analysis, electrons produced in the gas dielectric due to ionization events and photon interactions were neglected. The impact of these assumptions resulted in an underestimation of the output current of the gas-filled LASPGD. Since, the average energy of the electrons created in the outer enclosure by Ir-192 photons is sufficient to make their average range much greater than the dielectric thickness, the space charge contribution to the total output current was neglected during this analysis. The results of the analysis suggested that a 0.625 cm thick collector surrounded by helium gas, with a cross-sectional area of 25 cm², would produce an adequate signal for Ir-192 and Cs-137 sources with activities as low as 2 curies when positioned within 15 cm of the source conduit. The calculated electron production for a 0.625 cm thick tantalum collector is shown in Figure 3.

When adjusted for the difference in electrode material, the results in Figure 3 agree very well with the more exact analyses of Hsu and Lee⁸ and LeVert et. al.⁷.

Section 3.0 SOURCE POSITION MONITOR

3.1 Source Position Monitor Housing Design

All the LASPGD electronics are completely contained within the detector housing as shown in the cross-sectional view in Figure 4. The housing is 17 cm long, 7.5 cm wide and 6.5 cm at its tallest point. The prototype housing was fabricated from 0.075 cm thick aluminum. The design is such that the detector housing (see Figure A.1 in Appendix A) can be made in mass production. A battery compartment, separated from the rest of the electronics, contains two 6 volt lithium batteries, and is an integral part of the housing. This allows easy battery installation and replacement without taking the SPM housing apart. The LASPGD (see Figure A.2 in Appendix A) is mounted in the lower compartment of the housing with the signal conditioning electronics containing the current-to-voltage converter, amplifiers, and analog logic circuits. The signal conditioning

Figure 3. Estimated electron yield per photon incident on a gas dielectric LASPGD with a 0.625 cm thick tantalum collector.

Figure 4. Cross section view of SPM assembly.

electronics are mounted on a single layered printed circuit board (PCB). A microdot connector and a microdot coaxial cable connect the LASPGD and signal conditioning electronics. The LASPGD and signal conditioning electronics are potted with DOW Corning Sylgard^(R). The Sylgard, which provides environmental proofing and mechanical vibration isolation of the electronics and the detector, is transparent and allows access to points on the PCB for trouble shooting. A power control switch, low battery indicator LED and reset switch are mounted on the battery compartment's slanted front face. The source/out warning lamp is mounted on the top of the battery compartment to increase its visibility. The power control switch, low battery LED and source/out warning lamp are connected to the PCB via a 12-pin multi-wire shielded cable that is handwired to the board. Assembly of the SPM housing is documented in Figure A.1 in Appendix A.

The SPM, which weighs 1.5 pounds, is designed to be mounted on the biological shield of the radiographic unit (i.e., projector) in close proximity to the source conduit. A mounting fixture allows the SPM to be clip-mounted onto a projector (see Figure A.3 in Appendix A). The mounting fixture is adjustable from 12.7 up to 35.56 centimeters in diameter. It is designed to fit rectangular and cylindrical geometries.

3.2. Current-To-Voltage Converter/Amplifier/Analog Logic Circuit

Figure 5 shows a process block diagram of the signal conditioning circuit. It includes a current-to-voltage converter, voltage amplifiers and an analog logic circuit for controlling the source/out alarm lamp.

The voltage output of the current-to-voltage converter is -0.10 mV/picoampere. It is fed to a two-stage amplifier with a gain of 100x. The amplitude of the output voltage of the two-stage amplifier is fed to one input of a comparator with a reset trigger level of approximately 1.5 volts.

When the input voltage to the comparator exceeds the preset trigger voltage level, the output state of the comparator changes from a high (~ 6 volts) to a low (~ 2 volts) voltage level. The comparator remains at this low voltage as long as the source is in front or near the LASPGD. The change in the state of the comparator, whose output is coupled to the input of an integrated circuit timer, causes the timer to generate a positive output pulse that lasts 10 seconds. This pulse is used to drive the output of a J-K flip-flop from zero volts to a high positive value, where it remains until the output of the current-to-voltage converter is driven high by gamma interactions in the LASPGD caused by the source as it passes in front of the LASPGD during its retraction. The J-K flip-flop provides an output voltage (6 volts), which controls the conductive state of a MOSFET transistor. The MOSFET transistor acts as a switch that connects an IC flasher to the positive 6 volt dc supply, causing its output to oscillate between 0.0 and 2.5 volts at a one Hertz rate. This oscillatory voltage drives an incandescent lamp that flashes at the rate of one Hertz (i.e., one flash per second). A coaxial cable connection with a LEMO connector is used to provide a means of monitoring the analog output voltage from the

Figure 5. Process block diagram of the signal conditioning electronics

second stage amplifier of the circuit. This output voltage is proportional to the gamma dose rate at the LASPGD.

The current-to-voltage converter, two stage amplifier and analog logic circuit are contained on a 5.08 cm x 7.62 cm two-layer PCB (see Figure A.4). Sheets 1-3 of Figure A.4 document the circuit schematic, PCB layout, and PCB parts list.

Section 4.0 EXPERIMENTAL RESULTS

4.1 Initial Testing of the Solid and Gas Dielectric LASPGD

Based on the analysis conducted in Phase I and subsequent analyses in Phase II, three designs of isotropic detectors and one of a directional LASPGD detector were fabricated and tested before selecting the design to be used in the final SPM prototype. Table I shows the materials and geometrical dimensions of the components used in the LASPGDs.

The detectors were assembled in an inert helium environment at slightly less than atmospheric pressure. Electrical contact between the dielectrics, central electrode and outer enclosures was maintained by using conductive silver epoxy between the adjacent surfaces. By cleaning and drying all of the components at 90°F before assembling each LASPGD, the resistances between the collectors and the outer enclosures were maintained at $>10^{12}\Omega$.

The resistance was measured using a Keithley picoammeter in series with a 2 kV dc power supply. The Keithley picoammeter was also used to measure the leakage currents of each detector. In general, the leakage currents were less than 0.1×10^{-12} amperes. In the analyses of the solid dielectric LASPGDs, a 1 R/s dose rate from a Co-60 source had been estimated to produce a current of $\sim 2.3 \times 10^{-12}$ amperes per square centimeter of detector area.

Initial testing to verify the operability of the LASPGDs was conducted with a 0.5 Ci Cs-137 source at K.E.M.P.'s facilities. Intense high gamma flux field measurements were conducted at the K&S Associate Radiation Detector Calibration Laboratory in Nashville, TN, using a 1200 Ci Cs-137 and a 2000 Ci Co-60 source. The dose rate at the position of the prototype detectors was measured with National Institute of Standards and Technology (NIST) traceable Ion Chambers at both facilities. The responses of prototype LASPGDs 5, 2 and 4 of Table I are shown in Figures 6, 7, and 8, respectively. The sensitivities calculated using the responses of the solid dielectric detectors given in Table I agree very well with values estimated by other investigators^{2,4}.

Figure 6 shows the output current of an isotropic detector consisting of a 6.2 cm x 18.5 cm x 0.9 cm Pb collector with teflon standoffs surrounded by helium gas in a 6.5 cm x 19 cm x 1.5 cm aluminum enclosure. The response of an electrode consisting of a 1.27 cm thick tantalum central electrode surrounded on all sides by 1.27 cm thick polyethylene with an effective frontal area of $\sim 25 \text{ cm}^2$ is shown in Figure 7. Both Figures 6 and 7 show results for isotropic LASPGDs that vary almost linearly with dose rate.

Figure 6. Response of gas dielectric LASPGD to Co-60 and Cs-137 gamma rays. The 0.89 cm thick lead collector frontal area was 114 cm².

Figure 7. Output of electrode structure with 1.27 cm thick Tantalum prism surrounded by a 1.27 cm thick polyethylene dielectric on all sides. The frontal area of the electrode was approximately 28cm².

Figure 8. Output of electrode structure with 0.625 cm thick polyethylene dielectric covering all surfaces of a lead-carbon dielectrode. The lead and carbon were approximately 28cm² in frontal area.

These figures also show that the output currents of the collectors are a function of the thicknesses of each collector and the dielectric surrounding the central electrode.

The gas-filled detector of Figure 6 produces ~1800 picoamperes of current when exposed to a Co-60 dose rate of 62 R/min. The sensitivity of this detector was estimated to be -3.5×10^{-9} picoamperes/photon/s. This value corresponds to ~ 0.04 electrons per incident photon and suggests that some ionization of the gaseous dielectric may have been occurring in the detector. A dose rate of 62 R/min is equivalent to a 1.1 Ci Co-60 source positioned ~2cm away from the surface of the detector. Thus, an output current of ~420 picoamperes can be expected for an LASPGD, similar to that used in Figure 6, positioned at 2cm** away from the source conduit for the situations where the ratio of the detector's length to the speed of the source is ~ 0.12 seconds. This ratio is based on an estimated maximum source speed of 61 cm/s. A detector similar to number 3 of Table I can be expected to generate ~187 picoamperes when exposed to a 10 Ci Co-60 source for ~0.12 seconds.

The results in Figure 8 are for a directionally sensitive electrode. The electrode consisted of a 5.08 cm x 5.08 cm x .625 cm lead plate attached to a carbon plate of identical thickness and cross-sectional area. This structure was surrounded on all sides and edges with 0.3 cm thick polyethylene plates. The ratio of front to back response was found to be ~2.0. Similar results were obtained for tantalum/carbon laminated electrodes.

The results of the measurements conducted with the Co-60 and Cs-137 gamma sources demonstrate that either one of the detector designs given in Table I would be adequate as the detector in a SPM. They also suggest that an LASPGD with helium as a dielectric would be the best LASPGD for use in the source position monitor. The selection of the gas dielectric LASPGD for use in the SPM was also driven by the fact that the SPM will be used on individual radiographic units that may contain a source with an emission energy as low as 50 KeV or as high as 1.25 MeV.

4.2 Test of Source Position Monitor on An Industrial Radiographic Unit

In keeping with the above discussion, a gas dielectric LASPGD was used to build the deliverable prototype SPM. The detector, unlike traditional large area self-powered gamma detectors, was not optimized for situations where Compton liberated electrons in the dielectric material are the primary source of the detector's output current. Hence, a detector consisting of a 0.625 cm thick tantalum electrode with a cross-sectional area of 28.37 cm² electrically isolated from the outer enclosure with 0.5cm diameter teflon

** Based on a review of the design of radiographic cameras, the closest source-to-detector distance achievable as the source is driven in and out of the projector is 1.0 cm.

standoffs was selected for use in the final SPM prototype (see Appendix A). The teflon standoffs were also used to maintain mechanical separation between the outer enclosure and the collector. The volume between the collector and outer enclosure was filled with helium gas at a pressure slightly less than atmospheric in a helium filled glove box. After assembly of the unit, the collector-to-outer housing resistance was $> 10^{13} \Omega$ and leakage current $< 1 \times 10^{-13}$ amperes.

In the initial testing of the gas dielectric LASPGD, the detector was placed in a calibrator with a 0.5 Ci Cs-137 source and the output current measured with a picoammeter. The sensitivity of the detector was measured to be $\sim 1 \times 10^{-8}$ amperes/photon/second. As in the case of Co-60, this result suggests that there is a contribution to the detector's current due to ionization of the gas dielectric. But, the detector showed no detectable transient in its output that could be associated with the buildup of space charge or other ionization effects.

The performance testing of the SPM was conducted at Scientific Inspection Technology, Inc. (SITI), Chattanooga, Tennessee. In addition to verifying the performance of the alarm circuit, the output voltage of the second stage amplifier was monitored during the tests.

Ir-192 sources, housed in separate Century S and SA cameras with activities of 37.5 and 2.5 curies, were used in the performance testing of the SPM. The SPM was mounted on the source conduit of the cameras during the tests. The trigger level voltage of the comparator that controls the state of the source/out indicator was set at 0.05 volts. During the tests, the sources were driven past the detector at very high speeds (average speeds of 106.7 cm/s). The average resident time of the sources in front of the electrode was ~ 52 milliseconds. The source/out warning lamp worked as designed. However, there were some false alarms caused by vibrations of the source conduit.

Since the sources in these devices are manually driven, the rate at which they may be propelled from the camera past the detector will vary. The speeds used in the tests were varied by the SITI personnel. When the detector was attached to the conduit, rapid movement of the source introduced large vibrations in the source conduit, causing the alarm logic to activate. The set point for triggering the comparator in the device was adjusted from 0.050 volts to 1.0 volts, the source/out alarm worked properly with both sources (i.e., the 2.5 and 37 curie Ir-192 sources) with the SPM mounted ~ 4 cm above the source conduit. Subsequent to these tests, the LASPGD and electronics were potted in Dow Corning Sylgard^(R) to prevent false triggering due to mechanical vibrations. The test at the SITI facilities also showed that the system gain could be lowered or the comparator threshold voltage increased to aid in preventing false triggering of the source/out lamp. Instead of reducing the gain of the device, the final prototype has the alarm trigger set point set at 1.0 volt.

In addition to tests in which the source was moved rapidly by the detector's location, measurements were conducted during which the source was moved in 21 cm intervals and the output voltage of the device at each interval measured. The results of these measurements for the 37 curie source are shown in Figure 9. This figure shows that when the 37 curie source was used, the output voltage of

Figure 9. Output voltage of second stage amplifier in SPM when a 37 curie Ir-192 source is moved in 21 cm intervals away from the SPM mounted on the shield of the radiographic unit.

the second stage amplifier was at its maximum (rail) voltage for source-to-detector distances of up to ~42.00 cm. The output voltage of the two-stage amplifier was converted to picoamperes. The voltage-to-current conversion factor for the signal conditioning electronics is 10 mV per ampere generated in the LASPGD. The dose rates at the various source positions given in Figure 9 were calculated using the following expressions:

$$DR(R/hr) = 5.3 * (\text{Source Activity, Millicuries}) / d^2, \quad (3)$$

where d is the distance from the source.

Figure 10 gives the output voltage of the SPM when the 37.7 curie source was moved in 21 cm intervals away from the monitor's position with the detector positioned at a distance of ~6.35 cm away from the source inlet/outlet point on the camera. These measurements were designed to determine whether the current produced when the detector was located ~6.35 cm from the passing source was enough to activate the source/out alarm. The output of the second stage amplifier was greater than 1 volt (The voltage required to activate the Warning Indicator) up to a distance of ~50 cm. This fact suggests that the detector need not be mounted on the source conduit to provide the proper response when the source was pushed out or returned to the shield. The present prototype design calls for the SPM to be mounted, as discussed in Section 3.1 (i.e., approximately 4 cm directly above the source conduit).

Results obtained with a 2.5 curie Ir-192 source positioned ~7.3 cm from the source conduit are given in Table 2. Since it was difficult to know the actual dose rate at the position of the SPM, no attempt was made to estimate the sensitivity of the detector for Ir-192 gamma rays.

Table 2. Response of the SPM to a 2.5 curie Ir-192 Source

Source Position Relative to SPM (cm)	Output Current from Detector (picoamperes)
7.3	291
21	149
44	20
60	4
65	-3.4

Figure 10. Output voltage of second stage amplifier in SPM when the 37 curie Ir-192 source is moved in 21 cm intervals away from the SPM mounted on the source shield.

Section 5.0 ENVIRONMENTAL TESTING OF THE PROTOTYPE SPM

The SPM operating temperature is limited by the operating temperature of the electronics, which cover the full military temperature range of -55°C to 125°C . The operating temperature of the LASPGD is limited by the temperature limits to the Torr Seal epoxy and Teflon standoffs. The device was placed in a temperature controlled kiln and held at 36°C for 48 hours. At the end of the test period, the unit was placed in the 0.5 Ci Cs-137 calibrator. The output of the two-stage amplifier was approximately 10.2 mV and 8.5 mV before and after the high temperature tests, respectively. The internal components of the SPM are completely sealed from moisture by the Sylgard potting compound. The penetrations containing the power switch, alarm indicators and reset button are sealed from moisture penetration with rubber boots.

Section 6.0 OPERATION OF THE SPM

The electronics of the SPM operate on two 6 volt Lithium batteries for 200 hours. The LASPGD operates on the conversion of electromagnetic energy to electron current. That is, it requires no external power source. The battery compartment (see Figure 11A) can be accessed by removing four 0.635 cm 4-40 stainless steel screws. Duracell type batteries are recommended for maximum operating life. If the battery voltage is too low to maintain the required bias on the alarm unit, the "low battery" indicator will begin to flash after the power switch is placed in its "on" position (see Figure 11B for SPM controls).

WARNING
REMOVE BATTERIES FROM THE SPM
BEFORE SHIPMENT OR INACTIVE STORAGE
OF 30 DAYS OR MORE

The following steps must be followed for every measurement made with the SPM.

1. Attach the mounting clamp (see Figure 12) to the shield of its radiographic source.
2. Slide spring clip mounted on the back of the SPM onto the mounting clamp.
3. Place the power switch in the "on" position. The source/out alarm lamp should flash at a frequency rate of one Hertz. If the low battery LED is illuminated, the batteries are low and should be replaced.

Figure 11A. Battery compartment

Figure 11B. View of SPM controls

Figure 12. Radiographic Unit Mounting Fixture

Figure 13. Top view showing unpotted PCB with potentiometer for adjusting trigger level shown at top edge of PCB

4. Depress the reset button to extinguish the source/out lamp. The SPM is in its ready mode. Movement of the source out of its shield will be detected and the source/out alarm indicator activated.

The SPM is designed to detect the passage of Ir-192, Co-60 and Cs-137 at velocities as high as 60.96 cm/sec. Either one of these sources, with activities greater than or equal to 10 curies, will activate the source/out alarm lamp when the source passes within -15 cm of the SPM.

The SPM is supplied with the comparator threshold voltage set to activate the source/out alarm lamp when a 15 Ci Ir-192 source is moved past the detector at a rate of < 91.44 cm/sec. An adjustable potentiometer is provided (see of Figure 13) so the voltage required to trigger the SPM's alarm indicator can be adjusted. Clockwise movement of the potentiometer reduces the threshold triggering level. The SPM will self-trigger once the maximum allowable pot setting is exceeded. The potentiometer can then be moved clockwise through a $1/2$ turn to set the trigger level at 0.5 volts. When the pot is set at its maximum counterclockwise position, the trigger level is set at one volt. At this trigger level an output of approximately 125 picoamperes from the detector is required before the source/out alarm is activated.

Section 7.0 CONCLUSIONS

A prototype SPM has been designed and built to monitor the position of radioisotopic sources used in industrial radiographic units. The primary component of the SPM is the LASPGD used to sense the movement of the source by a fixed location. Several prototype LASPGDs were constructed and tested. The designs included isotropic and directional self-powered detectors. The isotropic LASPGDs were constructed with: a) polyethylene and helium gas as the dielectric materials; b) tantalum and lead collectors; and c) aluminum enclosures. Based on the results of tests conducted using all of the various LASPGD configurations, an isotropic detector design with a helium gas dielectric, a tantalum collector and an aluminum enclosure was chosen for use in the SPM prototype. The detector reveals a sensitivity of ~ 41 picoamperes/R/min when exposed to an Ir-192 gamma source. The test conducted with Co-60 and Cs-137 revealed similar sensitivities for this type of LASPGD.

The test with the prototype demonstrated the SPM was capable of sensing the position of Ir-192 sources with activities well below 10 curies.

Section 8.0 RECOMMENDATIONS

This research and development effort showed that a source position monitor can be developed that will operate over a range of gamma ray energies and dose rates. If either of these LASPGDs are to be used in other applications, further work is needed to optimize the detectors.

Section 9.0
REFERENCES

1. G.Ramirez and L. David, "A Study of Self-Powered Detectors for Mixed Neutron Gamma Radiation Fields", Nucl. Inst. & Met. 88, 1970.
2. W.C. Anderson and L.P. Hocker, "Approximate Energy Sensitivity of LASL Dielectric Radiation Detectors", EG&G, 1183-2125, S-35, 1967.
3. F.E. LeVert, "A Threshold Self-Powered Gamma Detector for Use as a Nuclear Power Monitor", IEEE Trans. on Nucl. Sci., Feb, 1977.
4. T.R. Fewell, "Compton Diodes: Theory and Development for Radiation Detectors", SC-DR-72-0118, 1972
5. J.C. Kelly, "Compton Diodes: Theory and Conjectures", SC-RR-67-855, 1968.
6. S.A. Cox, R.A. Beyerlein and F.E. LeVert, "Development of a Directional Gamma Ray Detector for In-Core Fuel Motion Monitoring", IEEE Trans. Nucl. Sci., Vol. N8.25, #1, Feb. 1978.
7. F.E. LeVert et. al. "Analysis of Self-Powered Gamma Ray Detector With Directional Discrimination", Nucl. Instr. & Meth. (160), 1979.
8. H.H. Hsu and Huan Lee, "Monte Carlo Calculations of the Vacuum Compton Detector Sensitivities", IEEE Trans. on Nucl. Sci., Vol. 36, (6), 1989.
9. R.D. Evans, The Atomic Nucleus, McGraw Hill Book Co., Inc., 1955.
10. T.A. Dellen and C.J. MacCallum, A Handbook of Photo-Compton Current Data, SCL-RR-720086, 1972.

Appendix A

Frontal View

Cross-sectional view

Top view

Notes: 1. See next page for details

Figure A.1

Detector Housing and Assembly

Sheet 1 of 2

1. Upper Battery housing 0.75mm thick aluminum
2. Plastic lens, red
3. Lower housing 0.75mm thick aluminum
4. Black rubber boot, power switch environmental seal
5. 4-40 x .25 RD Phil. HD, 6 PLCS.
6. LED low battery indicator T1 3/4, green
7. Black rubber boot, reset switch environmental seal
8. Battery holder, (2)
9. PCB, signal conditioning electronics
10. 4-40 x .25 RD HD Slotted screw, 4 Plcs
11. Minature LEMO female connector
12. LASPGD (See K.E.M.P. Drawing 34002D104)
13. 6 Volts Duracel battery, (2)
14. Radio Shack Incandesant lamp, 2.5 Volts @ 20mA
15. Battery compartment cover lid, 0.75mm thick aluminum
16. Microdot connector and Microdot coax cable

Figure A.1

Detector Housing and Assembly

Sheet 2 of 2

1. Male Microdot connector
2. Teflon standoff, 0.5 cm dia.
3. Threaded stainless steel mount
4. Helium Gas Dielectric
5. Tantalum collector: 5.58 cm x 5.088 cm x 0.0625 cm
6. O-ring, 2.5 mm dia.
7. O-ring, 1 mm dia
8. Teflon plate
9. Aluminum 0.75 mm thick
10. 4-40 Phil HD screws
11. Aluminum top.

Figure A.2

Gas Dielectric LASPGD

1. SPM
2. Chain hook
3. Linked chain
4. Adjustment mechanism for mounting fixture
5. Source conduit
6. Source Shield of Radiographic Unit
7. Stainless Steel Clamp Blade

Figure A.3

SPM Mounting Fixture

Figure A.4

**Signal Conditioning Circuit
Schematic**

Sheet 1 of 3

Notes:
1. For Parts List, See next page.

Figure A.4

**Current-To-Voltage/Two Stage
Amplifier Analog Logic Circuit
PCB Layout Board**

Sheet 2 of 3

Self-Powered Gamma Detector

Parts List

Resistors

R1	100MOhms, 1/8W
R2,15,16	1KOhms, 1/8W
R3,13,14	100KOhms, 1/8W
R4,6,7,8,9,11	10KOhms, 1/8W
R5	10KOhms, trimpot

Miscellaneous

B1,2	Battery
S1	SPDT momentary switch
S2	DPDT power switch

Capacitors (see Note)

C2	1000pF
C9	0.01uF
C10	10uF, 35V, polarized
C13	220uF, 10V, polarized

Diodes

D1	LED, 5000mcd, 2V/20mA
----	-----------------------

Transistor

T1	MOSFET transistor
----	-------------------

Integrated Circuits

U1	LPC660 quad op amp
U2	OP97 op amp
U3	LP339 quad comparator
U4	7555 timer
U5	CD4013B dual D flip flop
U6	LM3909 LED flasher
U7	MC3404P-5 undervoltage sensing circuit

Lamp

L1	2.5 volt, 20 ma incandesant lamp
----	----------------------------------

Note: All supply voltages
have 0.1 uF filter capacitors
connected to ground

Figure A.4

Parts List

Sheet 3 of 3

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER
(Assigned by NRC. Add Vol., Supp., Rev.,
and Addendum Numbers, if any.)

NUREG/CR-4833

2. TITLE AND SUBTITLE

Large Area Self-Powered Gamma Ray Detector

Phase II Development of a Source Position
Monitor for Use on Industrial Radiographic Units

3. DATE REPORT PUBLISHED

MONTH YEAR

January 1994

4. FIN OR GRANT NUMBER

L1267

5. AUTHOR(S)

F. E. LeVert

6. TYPE OF REPORT

Technical

7. PERIOD COVERED (Inclusive Dates)

9/29/89 - 6/30/91

8. PERFORMING ORGANIZATION - NAME AND ADDRESS (If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)

K.E.M.P. Corporation
1725 East Magnolia Avenue
Knoxville, TN 37917

9. SPONSORING ORGANIZATION - NAME AND ADDRESS (If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)

Division of Regulatory Applications
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

The purpose of this research was to develop a large area self-powered gamma detector (LASPGD) capable of detecting the movement of sealed radiation sources into and out of industrial radiographic units and to construct a prototype source position monitor (SPM) for these units utilizing the LASPGD. Prototype isotropic and directional LASPGDs, with solid and inert gas dielectrics, were developed and extensively tested using calibrated gamma sources (i.e., Cs-137 and Co-60). The sensitivities of the isotropic detectors, with inert gas dielectrics, were found to be approximately a factor of ten greater than those measured for the solid dielectric LASPGDs. Directionally sensitive self-powered detectors were found to exhibit a forward-to-back hemispherical sensitivity ratio of approximately 2 to 1. Industrial radiographic units containing Ir-192 sources with different activities were used to test the performance on the SPM. The SPM, which utilized a gas dielectric LASPGD, performed as designed. That is, the current generated in the LASPGD was converted to a voltage, amplified and used to control the on/off state of an incandescent lamp. The incandescent lamp, which functions as the source/out warning indicator, flashes at a rate of one flash per second when the source is in use (i.e. out of its shield).

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

Large Area, Self-Powered Detector, Gamma Rays, Radiographic,
Source Position Monitor

13. AVAILABILITY STATEMENT

Unlimited

14. SECURITY CLASSIFICATION

(This Page)

Unclassified

(This Report)

Unclassified

15. NUMBER OF PAGES

16. PRICE

END

DATE

FILMED

4/4/94