AN ABSTRACT OF THE THESIS OF

Alysse K. Bak for the degree of Masters of Science in Radiation Health Physics presented on April 22, 2005.

Title: Assessing and Evaluating the Energy and Angular Dependence of the Self-indicating Instant Radiation Alert Dosimeter (SIRAD).

Abstract approved: Redacted for Privacy

Kathryn A. Higley

The Self-indicating Instant Radiation Alert Dosimeter, SIRAD™, manufactured by JP Labs*, is a dosimeter that can be used by emergency response personnel. It is a user-friendly, inexpensive, and disposable radiation dosimeter. It monitors high doses, 5-200 rads, of ionizing radiation. The card resembles the size of a credit card and is always active and ready to use. It can be worn around the neck like an ID badge, or even placed in one's wallet. When the dosimeter is exposed to radiation there is a permanent color change on the chemical sensing strip. This color change is cumulative and proportional to dose. The individual will be able to immediately self-assess any dose to which they might be subjected. SIRAD is designed to provide the wearer and medical professionals instant, easy, and accurate

* JP Labs., 120 Wood Avenue, Middlesex, NJ 08846, E-mail: sirad@jplabs.com, Internet: www.jplabs.com

on the radiation exposure of the victim. This will help assess the health risks and guide in the treatment of the victim.

An evaluation of the cards to their response to gamma exposures between 2.5 and 125 rads was conducted. Cs-137, Ra-226, and Co-60 gamma sources were used to measure this response. Angular dependence of the badges was also measured using the Cs-137 and Ra-226 sources. The badges were read and evaluated using a commercially available flatbed scanner and Adobe Photoshop 7.0® software. The device can also be read by personnel by using the color reference charts already built into the device. Six doses; 2.5 rads, 5 rads, 7.5 rads, 10 rads, 40 rads, and 125 rads, were tested. The results yielded a possibility of energy dependence but no angular dependence for the Cs-137 cards at a 15° angle and for the Ra-226 cards at a 45°.

Assessing and Evaluating the Energy and Angular Dependence of the Self-indicating Instant Radiation Alert Dosimeter (SIRAD)

by
Alysse K. Bak

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Alysse K. Bak, Author

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ASSESSING AND EVALUATING THE ENERGY AND ANGULAR DEPENDENCE OF THE SELF-INDICATING INSTANT RADIATION ALERT DOSIMETER (SIRAD)

1. INTRODUCTION

Following the tragic events of September 11th, there has been a fear instilled in many people of the possibility of a nuclear terrorist attack which may include the use of a "dirty bomb" or radiological dispersal device (RDD). In order to protect our first responders from radiation exposure, there is a need for a durable device which can quickly provide an indication of high radiation exposure. The Self-indicating Instant Radiation Alert Dosimeter, SIRAD^{TM}, manufactured by JP Labs, is a dosimeter that is targeted for use by emergency response personnel. It is used for the determination of personnel exposure from radiation sources that a first responder may encounter during a possible nuclear conflict or radiological accident. It is a user-friendly, inexpensive, and disposable radiation dosimeter. It monitors high doses, 5-200 rads, of ionizing radiation. When the badge is exposed to radiation, its chemical sensing strip will change a shade of blue which will correspond to a dose on the adjacent color reference chart. The card resembles the size of a credit card and is always active and ready to use. It can be worn around the neck like an ID badge, or even placed in one's wallet.

The SIRAD dosimeter was put under an evaluation at Oregon State University to determine its response to different gamma exposures as well as its angular dependence. Angular dependence is important to test for because the wearer of the SIRAD may be exposed from any angle. Self-shielding or other factors may contribute to erroneous readings. In-house irradiators were used to subject the badges to pre-determined doses for evaluation. The cards were evaluated with a commercially available flatbed scanner and Adobe Photoshop 7.0® software. The objective of this evaluation is to determine if the card meets the manufacturer claims and to see if this is a reliable dosimeter for emergency response personnel to utilize. The results will indicate if SIRAD works according to the SIRAD manual that can be accessed through JP Labs.

2. LITERATURE REVIEW

2.1 SIRAD

The Self-indicating Instant Radiation Alert Dosimeter, SIRAD™, manufactured by JP Labs, is a dosimeter that can be used by emergency response personnel. It is a user-friendly, inexpensive, and disposable radiation dosimeter. It monitors high doses, 5-200 rads, of ionizing radiation. The card resembles the size of a credit card and is always active and ready to use. It can be worn around the neck like an ID badge, or even placed in one's wallet. The dosimeter does not need a power source. The sensing strip is protected by a black UV film. By lifting the film, the sensing strip and the color reference chart can be easily viewed. The card is coated with an anti-glare and scratch resistant film which protects the sensing strip and plastic card. Figure 2.1 shows the SIRAD badge prior to exposure to radiation and the black UV protective film which covers the badge.

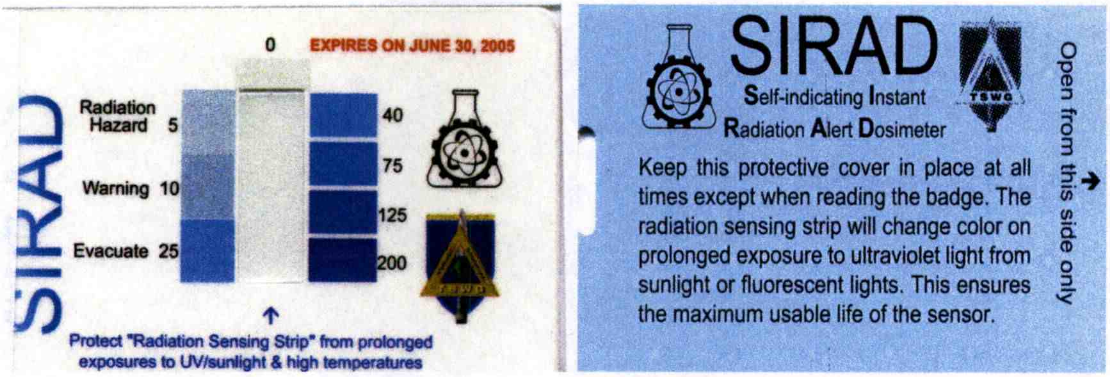

Figure 2.1 A SIRAD badge prior to radiation exposure (left) and the black UV protective film for the SIRAD badge (right).

When SIRAD is subjected to radiation, the chemical sensing strip in the middle of the card will change color. The strip will turn a shade of blue which can be compared to one of the pre-printed color bars with a dose-number printed on either side of the sensing strip. As the dose increases the intensity of the color blue will deepen. The person wearing the dosimeter should be able to match the sensing strip to one of the color bars to determine their dose.

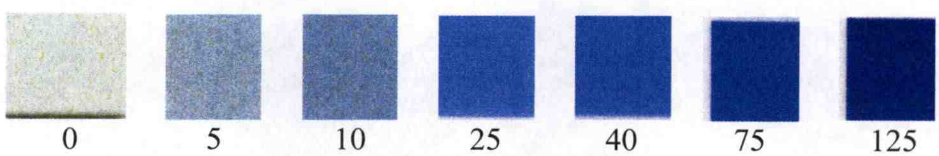

Figure 2.2 Color bars taken from a SIRAD badge.

The sensing strip is composed of diacetylenes (R-C≡C-C≡C-R, where R is a substituent group). Diacetylenes are of a unique group of compounds and are colorless solid monomers. When irradiated with high energy radiations such as X-ray, gamma rays, electrons, and neutrons, they usually form red or blue-colored polymers/plastics. (JP Labs, 2005a) The color of the strip will intensify proportionally to dose when it is irradiated. Low Cost (Casualty) Shelf Indicating Dosimeter (LOCCSID) is another name often given to SIRAD technology.

According to manufacturer claims, the ability of the sensing strip to detect radiation while it is shielded and exposed is discussed as follows. When the sensing strip is unprotected, it is sensitive to all types of radiation that have energies higher than approximately 10 eV. SIRAD has the potential to monitor X-rays (60 keV and higher), high energy electrons and high energy beta particles. When the sensing strip is covered with its black UV protective film it will absorb high LET (linear energy transfer[2]) particles of moderate (MeV) energies. Electrons greater than 1 MeV and photons greater than 10 keV may be able to penetrate through the .01cm thick black UV protective film and may be monitored by the sensing strip[3]. (JP Labs, 2005a)

SIRAD is a one-time use dosimeter with an expiration date (shelf-life). The expiration date expresses the manufactures limited liability of the product. They claim to have made reasonable efforts to make this product in its early stages free from defects for a period of one year if it is used and stored properly. This expiration date is dependent upon the dosimeter being stored at room temperature, < 25° C, and protected from overexposure to ultraviolet and sunlight. If SIRAD is stored at higher temperatures and/or unshielded from any ultraviolet and sunlight for extended

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[2] Linear energy transfer (LET) is the energy transferred per unit length of the track and is usually express in keV/μm. It should be noted that for a given type of charge particle, the higher the energy, the lower the LET and therefore the lower its biologic effectiveness. High-LET particle include alphas, betas (lower energy), protons, and neutrons. (Hall, 2000)

[3] The manufacturers website states that "protons" can be monitored; as these are high LET particles they would require energies >> MeV to penetrate the cover. Most likely this is a typographical error.

amounts of time, the strip may undergo polymerization resulting in a false positive reading which can therefore reduce the shelf life of the dosimeter. An example of overexposure to light is more than four hours of direct sunlight. If the strip is subjected to prolonged exposures of higher temperatures and/or ultraviolet/sunlight, a false positive reading could result. The card is designed to be read under fluorescent light. However, reading the strip numerous times under sunlight or normal ambient light should have insignificant effects on the sensing strip. If the sensing strip is left unprotected under direct exposures for a few weeks to ambient light, or one day to diffused sunlight, a faint blue color will appear on the strip. JP Labs recommends keeping the black film cover on all the time except for when reading the dosimeter and to avoid exposures to high temperatures and UV/sunlight. They also recommend adhering to the expiration date on the back of the card. (JP Labs, 2005b)

Other ambient conditions SIRAD may be exposed to are humidity, microwave radiation, and accidental laundry cycles. JP Labs claims that the dosimeter will hold up when subjected to such conditions. SIRAD is essentially unchanged by ambient or high humidity. If the badge gets wet, it should be wiped dry. Since microwave radiation is non-ionizing it will have no effect on the sensing strip; however a slight heating effect may occur due to its plastic make-up. (JP Labs, 2005b) Even though the badge will not be affected by being placed in a few normal laundry cycles of washing and drying, it should be thrown out or returned. SIRAD should not be subjected to extended periods of exposure to temperatures higher than 90° C because this may damage the sensing strip. In the event SIRAD is exposed to a fire, it will burn and melt due to its plastic composition. (JP Labs, 2005b)

For emergency situations there is a need for a dosimeter that is instant, easy to read, practically non-destructible, and monitors all types of radiation. SIRAD's description claims that it is designed with all of these properties and will be very beneficially especially in a time when there is a high threat of radiological terrorism. SIRAD may be used for determining personnel exposure from a radiation source that one may encounter during a possible nuclear conflict or radiological accident. SIRAD can be very valuable for first-responders to have because it gives an immediate reading which might help prevent any additional exposure. This can also aid in the assessment of the health risks and guide in treatment of a victim. (JP Labs, 2005d)

SIRAD has the potential to provide additional benefits to the wearer. It can help assist the wearer of what actions he should or should not take. The sensing strip will provide an early warning to leave the affected area and give an indication as to what the wearer's level of radiation exposure is if it is less than 200 rads. The strain on the healthcare system will be reduced because there will be no need to estimate doses by other methods which may take several days. SIRAD will also help people take preventive care and make affected people attentive of their increased risk of cancer. (JP Labs, 2005e)

It is important to realize that SIRAD does not measure dose-rate. Because it is an integrating, high-range device, it cannot detect dirty bombs, radiation sources, radioactive material, and pre-irradiated material or people. The dosimeter will not monitor low doses (<1 rad) of radiation. The manufacturers state that the wearer should be able to visually detect about 1-2% of the highest dose listed. For the 0-200 rads SIRAD, one may only see a shade of blue comparable to 2-4 rads. If using spectroscopy or optical densitometry to read the chemical strip, color detection is approximately 0.5-1% of the highest dose listed. For this card the lowest dose detectable is about 1-2 rads. It should only be used to measure the exposure to radiation to which a person may be subjected to. (JPLabs, 2005f)

2.2 DOSIMETERS USED BY EMERGENCY RESPONSE PERSONNEL

Ionizing radiation is "any radiation displacing electrons from atoms or molecules, thereby producing ions. Examples of ionizing radiation are alpha (α), beta (β), and gamma (γ) radiation and short-wave ultra-violet light. Ionizing radiation may produce severe skin or tissue damage" (Hall, 2000, pg. 536). Since ionizing radiation is known to cause cancer, it is important to monitor this type of radiation.

When it comes to monitoring radiation dose, SIRAD is a new device that is good for first responders and those without a dosimetry program. Other more commonly used dosimeters by emergency response personnel are TLDs, electronic dosimeters, and ionization chambers.

2.2.1 Thermo Luminescent Dosimeter (TLD)

Thermoluminescence occurs when a crystal emits light when it is heated after being exposed to radiation. A TLD is based on of this effect. The absorption of energy from ionizing radiation will excite atoms in a crystal which results in the production of free electrons and holes in the thermoluminescent crystal. These in turn are trapped by the activators or by imperfections within the crystalline lattice which traps the excitation energy in the crystal. The heating of the crystal releases the excitation energy as light. A glow curve is created by the heating of the irradiated crystal at a uniform rate and measures the emitted light as the temperature increases. The light output is directly proportional to the amount of thermoluminescent material and to the dose received. There are several formulations of compounds that are used as TLDs. Common ones include LiF, CaF_2:Dy, $CaSO_4$, and many others. Each has unique sensitivities and fading characteristics. (Cember, 1996, pg. 369)

TLDs are used as personal and environmental integrating dosimeters. After being worn for a designated period of time, the TLD is analyzed, typically by being sent to an analytical laboratory. The badge can only be read once during processing and are essentially "reset" by the effort. TLDs are beneficial to wear because they can monitor low doses of radiation (0.001 rad) and are independent of dose rate. The badge has the capabilities of being recycled for multiple uses and is inexpensive. It is small and light weight so it will not interfere with a person's task in an emergency situation. TLDs often lack uniformity in response and batch calibration is needed.

The TLD can also undergo fading and can be light sensitive. No permanent record is retained within the TLD. TLDs have supplanted film badges as the preferred method for monitoring personnel exposure. This is primarily due to cost.

2.2.2 Electronic Dosimeters

Electronic dosimeters are a combination of the constant progression of solid-state electronics and electronic data processing. They come in many shapes, sizes, weights, and capabilities. Accurate electronic dosimeters have been referred to as being more useful for personal dosimetry and dose tracking than a TLD. They have the capability to display instantaneous dose rate and can integrate over time to display cumulative dose. Several electronic dosimeters are equipped with built in alarms.

Many electronic type dosimeters are being used by emergency response personnel because they are easy to use and no experience or knowledge about how they work is needed. Many electronic dosimeters have the capability to transfer data to a computer. Electronic dosimeters also require the use of a power source. They can be specifically designed to suit specific needs, i.e., firefighters in extreme heat. However, they can be expensive, bulky, and fragile at times depending on its application. Examples of electronic dosimeters are: electronic personal dosimeters which resemble a pager and have the ability to detect beta and gamma radiation over a wide range of dose rates and doses; Canberra's Mini-Radiac Personal Radiation Monitor which is designed for the needs of first responders and is gamma energy dependent at +/- 20% 80 keV to 3 MeV; and the Canberra DINEUTRON which is a portable unit for neutron dosimetry and works within an energy range of 0.025 eV to 15 MeV.

2.2.3 Ionization Chambers

Ionization chambers are used for its capabilities of measuring gamma-ray exposure and beta dose rates with corrections. They have responses that are proportional to absorbed energy and are used to make dose measurements. Most ionization chambers have an air-equivalent wall and measure exposure as opposed to dose. Ionization chambers are typically not very sensitive, and consequently are not for detecting contamination. They are more often used for assessing exposure or dose. These instruments are also known for their fragility and for being expensive.

The portable ion chamber comes in many different designs. They are commonly used as survey meters for radiation monitoring. An ion chamber consists of "a closed air volume of several hundred cm^3 from which the saturated ion current is measured using a battery-powered electrometer circuit" (Knoll, 2000, pg. 145). The walls of the chamber are just about air equivalent. The ion chambers yield fairly accurate measurements of the exposure for gamma-ray energies. The measurements of the reading are just high enough and just low enough to avoid considerable attenuation in the walls or entrance window and to create electronic equilibrium in the walls, respectively. There are other types of portable ion chambers that are used for dose measurements. These are based on the charge integration principle. The chamber is usually charged and placed in a radiation field for a period of time. The drop in the voltage is then used as a measure of the total integrated ionization charge. (Knoll, 2000)

2.3 BIOLOGICAL RESPONSE (SYMPTOMS) TO RADIATION

Acute whole-body irradiation can occur if one is exposed to a situation including ionizing radiation. Early radiation lethality is usually death occurring within a few weeks of an exposure to a specific high-intensity exposure to radiation. Soon after exposure, symptoms will appear for a limited period of time known as the prodromal radiation syndrome. The symptoms in this syndrome will vary. They usually depend on the time of onset, maximum severity, and duration depending on the size of the dose. Two main groups of this syndrome are gastrointestinal (nausea, vomiting, diarrhea etc.) and neuromuscular (fatigue, apathy, sweating, fever, headache). All symptoms will not be evident unless the dose is > 10 Gy (1000 rad), which is considered supralethal. Receiving a supralethal dose will likely cause neuromuscular symptoms and likely death. Those receiving a dose of ~4 Gy (400 rad) will experience gastrointestinal symptoms with possible recovery. (Hall, 2000)

When exposed to a whole-body dose of ~2 Gy (200 rad) the hematopoietic syndrome appears. At this dose, blood forming organs (bone marrow) are the most sensitive. This causes cell populations to be significantly reduced and the repopulation of mature functioning blood cells is hindered. The loss of mature blood cells can lead to anemia and an increased risk of infection. Symptoms of this syndrome include malaise, fatigue, and epilation. Death can occur within a few months due to the damage done to the bone marrow or infection. (Hall, 2000)

The gastrointestinal syndrome will develop at exposures of .10 Gy (1000 rad). The intestinal epithelium is destroyed and there is almost complete destruction of bone marrow. All effects of the hematopoietic syndrome occur. Other symptoms present in this kind of exposure include severe nausea, vomiting and explosive diarrhea. Death will likely occur within several weeks. (Hall, 2000)

The last syndrome to occur is the cerebrovascular syndrome which is present at exposures $>$ 20 Gy (2000 rad). Severe damage is done to the central nervous system (CNS) and other organ systems. Symptoms include all hematopoietic and gastrointestinal syndrome symptoms as well as unconsciousness within minutes. Death is certain within hours or days depending on the magnitude of the dose. (Hall, 2000)

3. MATERIALS

3.1 SIRAD BADGES

The SIRAD with a 0-200 rad color reference chart was evaluated. The card's features and abilities have already been discussed in section 2.1.

3.2 IRRADIATORS (RADIATION SOURCES)

Oregon State University's Radiation Center sources were used to irradiate the cards: a Cs-137 irradiator, the Gammacell 220 Co-60 irradiation unit, and a Ra-226 needle. The Cs-137 irradiator has an 8 Ci source and was assayed on June 8, 2004[4]. Cesium 137 has a half life of 30.07 years and undergoes radioactive decay, emitting a beta particle and a 0.662 MeV gamma. (EPA, 2005a) The Gammacell 220 Co-60 irradiation unit delivers an exposure rate[5] of 8.38E+4 R h^{-1}. The Co-60 source was 1022.611 Ci on March 5, 2005. Co-60 undergoes radioactive decay and emits beta particles as well as two gamma rays at 1.173 MeV and 1.332 MeV (EPA, 2005b) The half life of Co-60 is 5.271 years. The Ra-226 needle is a pedigreed, traceable, 10 mCi source with an exposure rate of 94.1 mR h^{-1} at one foot as of February 1, 2005. (Union Miniere, 1974) Radium 226 is found in the U-238 decay series. It emits two

[4] Radiation Center Health Physics Procedure 18, Revision #8, Oct. 2004
[5] Radiation Center Health Physics Procedure 21, Revision #5, Feb. 2000

alphas with energies of 4.784 MeV and 4.602 MeV as well as a .186 MeV gamma. It has a half life of 1599 years. (EPA, 2005c)

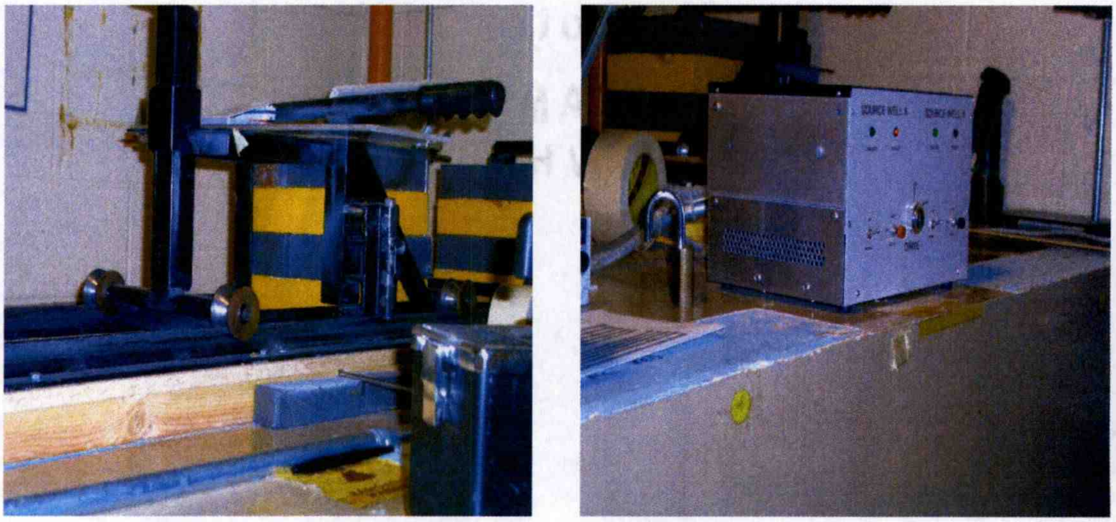

Figure 3.1 Cs-137 irradiator. Well A (Large Source) at 10.5 in. over plexiglass shield is shown on the left. The Cs- 137 irradiator odometer and control box are shown on the right.

Figure 3.2 Gammacell 220 Co-60 irradiation unit.

Figure 3.3 Ra-226 needle.

3.3 VICTOREEN CONDENSER R-METER

Two Victoreen Condenser R-Meters* were used to help determine the traveling dose within the chamber of the Co-60 irradiator. The traveling dose is the amount of dose the cards will receive in the time it takes for them to move from their starting point at the top of the sample chamber down the column to the source assembly and back up. The Victoreen Condenser R-Meter is an instrument that yields quick and accurate measurements of total-X-ray exposure in roentgens. It is a.c. operated and may be used with a suitable timing device to determine average X-ray intensity. It has a dust-tight electrometer with a viewing microscope system, a lighting system for the microscope, an on/off light, and necessary operating controls. The Condenser R-Meter is used with interchangeable ionization chambers. The ionization chamber is sensitive to X-ray radiation in the normal X-ray therapy ranges. Thick wall chambers can be used to receive accurate measurements of high energy radiation, i.e. Co-60 and Radium sources. (Victoreen[6])

The ionization chamber is charged by the charger-electrometer unit of the Condenser R-Meter to a predetermined voltage. When the active volume (ionization chamber) is placed in an X-ray field, the air within the ionization chamber is ionized in proportion to the X-ray intensity. The ions will attract to oppositely charged electrodes within the chamber. This ion migration reduces the charge of the capacitor.

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* The Victoreen Condenser R Meters are not certified.

[6] The Victoreen Instrument Company, 10101 Woodland Avenue, Cleveland, Ohio 44104. "Instruction Manual – Condenser R-Meter

As a result, the potential difference across its electrodes is reduced. The scale reading for this potential is equivalent to the X-ray exposure of the chamber. The exposure is read in roentgens. (Victoreen)

3.4 EPSON PERFECTION 2480 PHOTO™ SCANNER

An Epson Perfection 2480 PHOTO™ scanner was used to capture images. It is a flatbed color image scanner with a Color Epson MatrixCD™ line sensor. It reaches an optical resolution of 2400 dpi. The scanner has a color hardware bit depth of 48-bits per pixel internal, 48-bits per pixel external and a grayscale hardware bit depth of 16-bits per pixel internal and 16-bits per pixel external. Depending on the image editing software, external bit depth is selectable to 16 bits. The scanners optical density is 3.2 Dmax. (Epson, 2005)

The Epson Perfection 2480 PHOTO™ scanner has a start, copy, scan to E-mail, Scan and Save buttons. It is 10.83in wide, 16.5in deep, 3.4in high, and weighs 6lbs. Its maximum read area is 8.5" x 11.7" (21.6cm x 29.7cm). A white cold cathode fluorescent lamp is its light source. A Hi-Speed USB 2.0 is the necessary interface for the printer. The scanner operates on a 2400 dpi high-speed mode. It is reliable up to a MCBF – 10,000 cycles. The scanner is compatible with most Windows programs containing Pentium®II or higher and iMac® or any G3 or later with built-in USB. (Epson, 2005)

Figure 3.4 Epson Perfection 2480 PHOTO™ scanner.

3.5 ADOBE PHOTOSHOP 7.0®

Adobe Photoshop 7.0® software was used in conjunction with the Epson scanner to read and evaluate the badges. The software contains a File Browser which allows you to search for images visually instead of by file name. The software has a histogram feature which displays the luminosity, red, green, and blue distributions and values for a picture. It also calculates the standard deviation for each graph. Information on how the program calculates the standard deviation has not been found. It is not in the literature and calls to Adobe technical support and headquarters have not been successful. Two ways in which the standard deviation may be calculated are by Full Width at Half Maximum or by summing the square difference of the points on a graph.

Photoshop requires Intel Pentium II or better, 128 MB of RAM, 280 MB of available hard disk space, a color monitor with a 16-bit color or greater video card, 800 x 600 or greater monitor resolution, and a CD-ROM drive. It is also compatible with most Windows programs. (EBay, 2005)

4. METHODS

Two hundred SIRAD badges were provided to Oregon State University by Todd Brethauer, Technical Support Working Group (TSWG) Science Advisor at the US Department of Defense located in Washington, D.C. The following doses where chosen for evaluation: 2.5 rads, 5 rads, 7.5 rads, 10 rads, 40 rads, and 125 rads. Ten cards were irradiated at each dose with each group having its own control card. One card was kept as an overall control for comparison. A control card and a set control is a card that was not subjected to any radiation, kept at room temperature, and protected from ultraviolet/sunlight. There is no physical difference between the two types of control cards. All six doses were tested using the Cs-137 irradiator. The Ra-226 needle only irradiated the 2.5 rad, 5 rad, 7.5 rad, and 10 rad card sets and only 40 rads and 125 rads were tested with the Co-60 irradiator.

Time for irradiation using the Cs-137 irradiator, Co-60 irradiation unit and the Ra-226 needle were calculated by using the exposure rates for each source and the known doses. A conversion factor was not needed because "an exposure of 1 roentgen is frequently considered approximately equivalent to an absorbed dose of 1 rad" (Cember, 1996, pg. 178).

$$Time = \frac{Dose}{ExposureRate}$$

Equation 4.1

The times were then converted into the proper time units needed for each irradiator.

Table 4.1 Cs-137 irradiation times for SIRAD badges.

Cs-137 Irradiation Times			
mRad	Rate (mR/h)	Time (h)	Time (min)
2500	5780	0.43	25.95
5000	5780	0.87	51.90
7500	5780	1.30	77.85
10000	5780	1.73	103.81
40000	5780	6.92	415.22
125000	5780	21.63	1297.58

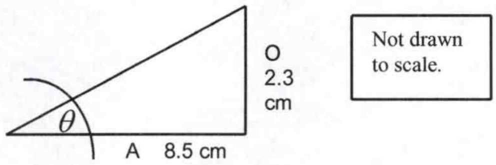
Table 4.2 Ra-226 irradiation times for SIRAD badges.

Ra-226 Irradiation Times		
mRad	Rate (mR/h)	Time (sec)
2500	94.1	95642.93
5000	94.1	191285.9
7500	94.1	286928.8
10000	94.1	382571.7

Table 4.3 Co-60 irradiation times for SIRAD badges.

Co-60 Irradiation Times		
Dose (Rad)	Exposure Rate (R/h)	Time (sec)
40	8.38E+04	1.72E+00
125	8.38E+04	5.37E+00

The Cs-137 series was used to represent a mid-range gamma energy exposure. The badges were exposed to all six doses. Each irradiation was configured by having a card set of 10 cards taped together in a small stack. Using a spacer and tape, card number ten was raised to a 15° angle. The angle was calculated the following way:



$$\theta = \arctan \frac{O}{A}$$

$$\theta = \arctan \frac{2.3cm}{8.5cm}$$

$$\theta = 15^{0}$$

Equation 4.2 Angle determination for the Cs-137 series.

The adjacent side, A, is the length of the SIRAD card and the opposite side, O, is the height of the spacer.

Figure 4.1. Set of ten SIRAD cards with a 15° angle created by a spacer.

In order to receive the proper doses, the settings for the Cs-137 irradiator were taken from Radiation Center Health Physics Procedure (RCHPP) 18 table 3: The Decay Corrected Exposure Rates and Odometer Settings for Wells A and B at 10.5 in.

and 2.5 in. above the Wells. Following Well A, large source information for the first half of 2005, the head Health Physicist (HP) of Oregon State University's Department of Nuclear Engineering and Radiation Health Physics set the odometer at 192.2 and the plexiglass shield at 10.5 in. With guidance from the head HP, the set of cards were placed on the plexiglass shield with card number ten on the top. Each card set was irradiated for the appropriate amount of time.

Figure 4.2 Card set placed on the plexiglass over Well A of the Cs-137 irradiator.

Each card was labeled with isotope, date irradiated, card number, and dose received. As mentioned earlier, each set of cards has its own control card. Each card was scanned individually and all cards were placed in the same area of the scanner. The scanner was set at a dpi of 1200. This resolution was chosen because of its quality and speed. Figure 4.3 shows a jig that was set up on the scanner to ensure that all of the cards were placed in the same spot to help deter any variance in the card readings.

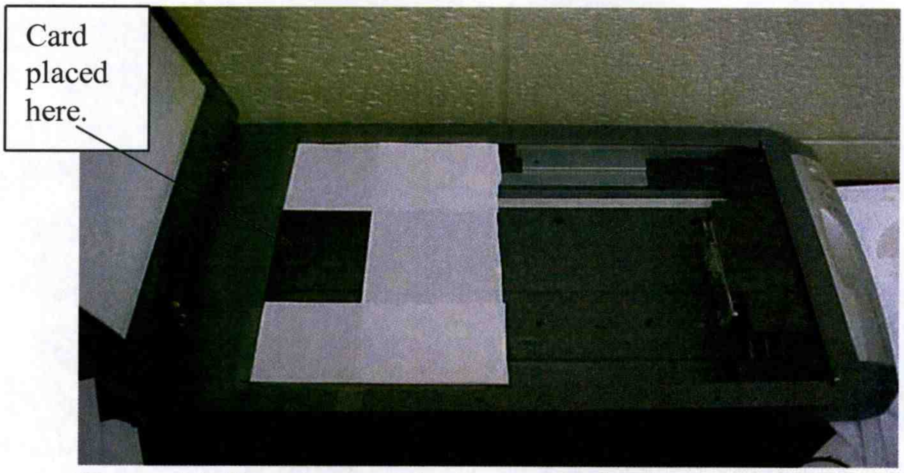


Figure 4.3 Jig set-up on the Epson Perfection 2480 PHOTO™ scanner bed.

Once the card was scanned it was saved and opened in the Adobe Photoshop 7.0® application. Using this software, the portion of the card being evaluated was highlighted and a histogram was created. The histogram provided intensity readings for luminosity, red, green, and blue. It also provided the standard deviation for each reading.* Figure 4.4 is an example of what the luminosity, red, green, and blue histograms look like.

* The standard deviation for 2.5 rads and 7.5 rads card sets was calculated by taking the average of the 0 and 5 rads color chart readings and the 5 and 10 rads color chart readings, respectively. This is based on the assumption of linearity between these points on a graph. The numbers for luminosity, red, green, and blue were calculated from equations resulting from set control graphs.

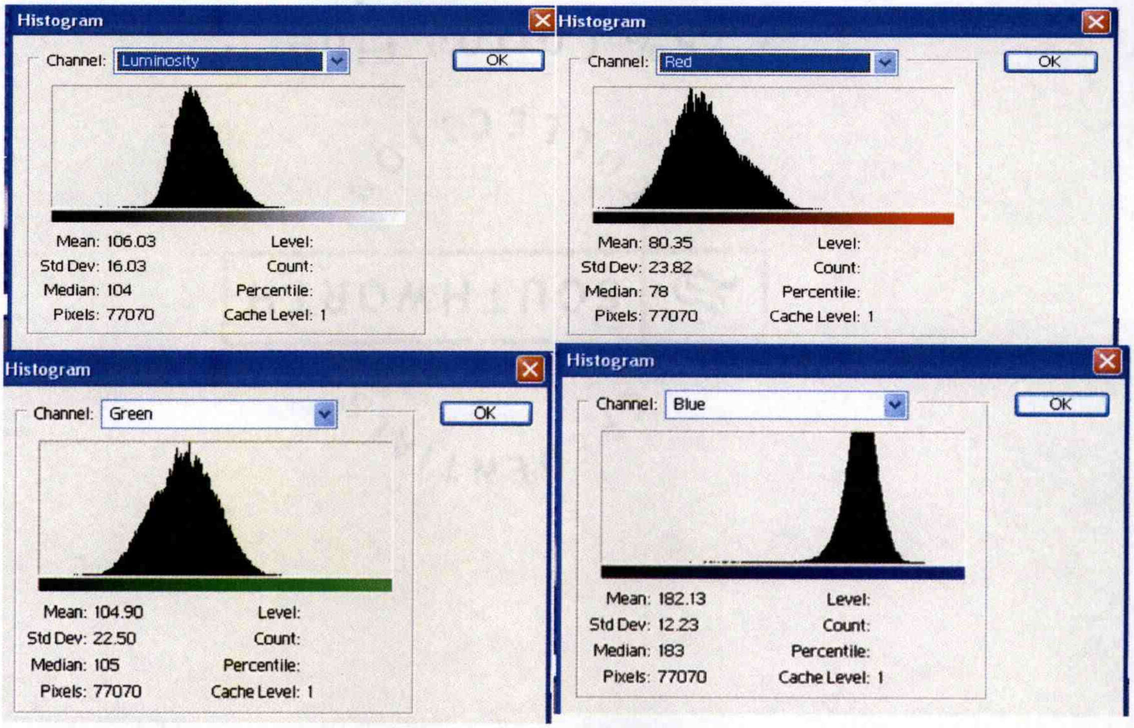


Figure 4.4 Histograms. The luminosity, red, green, and blue histograms for 75 rads on the SIRAD overall control color chart created by Adobe Photoshop 7.0®.

The numbers were recorded, entered into Microsoft Excel®, and graphed. The graphs display the intensity values for each card and the set control with error bar values taken from the histograms. These graphs can be seen in Appendix A-D. For the control card and each set control card, the entire color reference chart and the sensing strip were read. All irradiated cards had only their sensing strip read. Each set's control card was compared to the overall control. Each color on the color chart and the strip was individually read and compared.

The Ra-226 needle was used to irradiate badges at 2.5 rads, 5 rads, 7.5 rads, and 10 rads. Angular dependence was also tested. Since the Ra-226 needle is an isotropic source, it is placed in the center of a rotating wheel. Each card was individually attached to a holder and placed within a slot exactly one foot from the source. Card number ten was used to test for angular dependence at 45°. Since the cards were not stacked like those in the Cs-137 sets, the angle was measured a different way. An inch was measure and marked in two directions and then the card was place against a peg creating a 45° angle. The cards were read and evaluated in the same manner as those in the Cs-137 series.

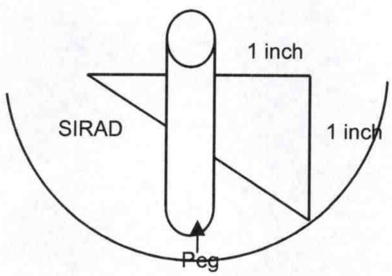


Figure 4.5 SIRAD badge set at a 45° angle on the Ra-226 wheel. Not drawn to scale.

Figure 4.6 Ra-226 needle. SIRAD badges are attached to holders and inserted into slots on the wheel one foot from the source.

The Gammacell 220 Co-60 irradiation unit was used to irradiate doses of 40 rads and 125 rads. The cards were taped ten together with no angular dependence being tested for card number ten. They were placed in a beaker. The beaker was then placed inside the chamber of the irradiator. The irradiation times for each dose were double checked by the head HP with a computer program designed especially for the Co-60 irradiator. A Victoreen Condenser R-Meter was placed inside the chamber to check for traveling dose. The cards were not present in the chamber during traveling dose runs. The traveling dose was tested a total of six times, three for each R-Meter. These cards were also read in the same manner as the Cs-137 and Ra-226 series.

Figure 4.7 Gammacell 220 Co-60 irradiation unit.

5. RESULTS

5.1 CONTROL CARDS

The overall control card was used as reference for the set control cards. The overall control card and the set control cards are blank cards not subjected to any radiation. Each dose from the color reference chart on all the controls was read, charted, and graphed. A histogram was created to compare each set control in each series with the overall control. There was slight or no variation among the cards and they were statistically similar to the overall control. Examples of these graphs can be found in Appendix A. There were a total of 12 set control cards and one overall control card. The intensity values for each card were averaged and plotted on a semi-log graph to form a calibration curve with error bars at two standard deviations. These graphs can be seen in figures 5.2 -5.5.

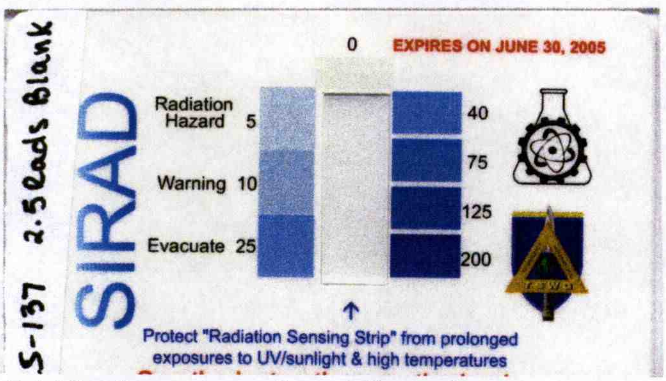


Figure 5.1 Blank set control card from the Cs-137 2.5 rads set.

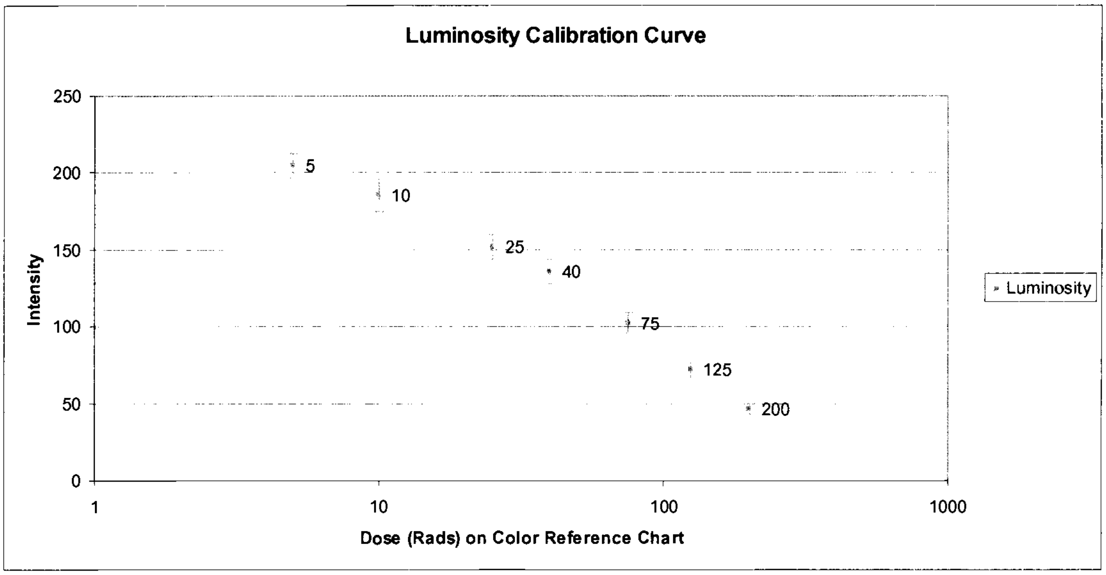


Figure 5.2 Luminosity Calibration Curve. Each point represents the average values of each dose on the color reference charts for all of the control cards in the evaluation. Error bars were calculated to two standard deviations.

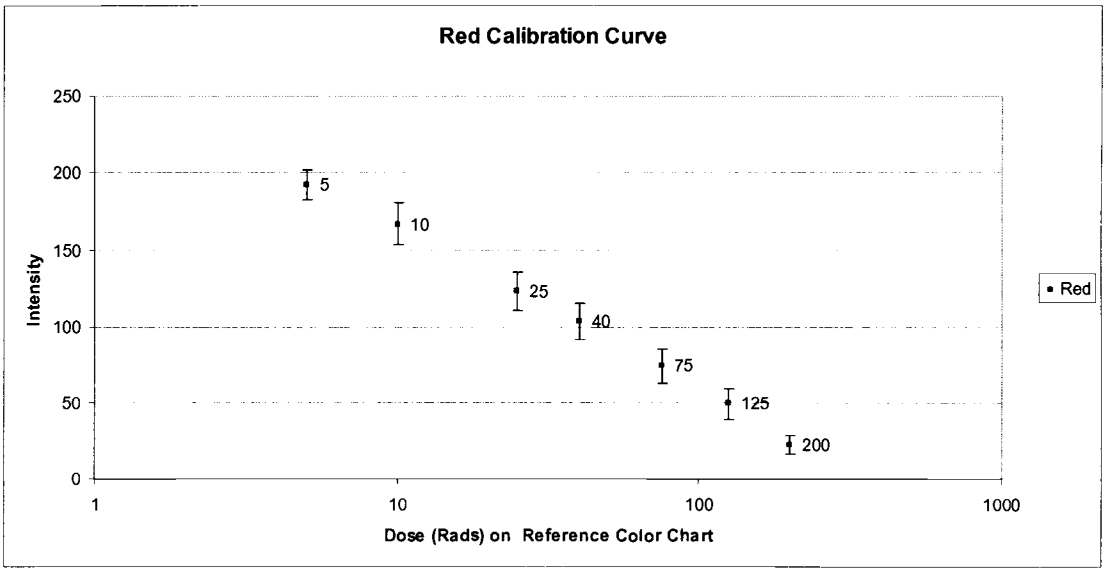


Figure 5.3 Red Calibration Curve. Each point represents the average values of each dose on the color reference charts for all of the control cards in the evaluation. Error bars were calculated to two standard deviations.

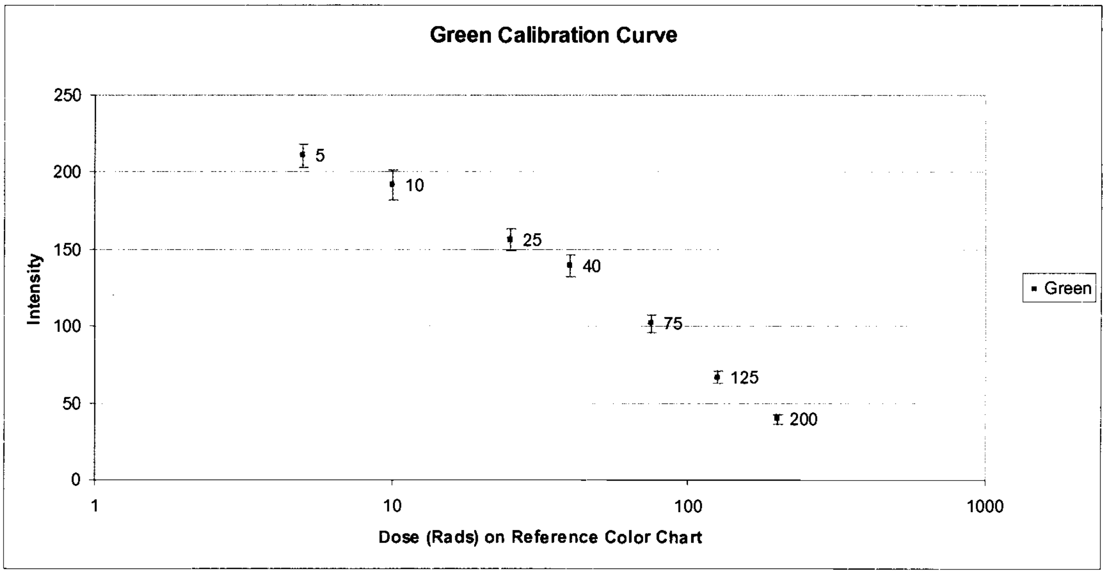


Figure 5.4 Green Calibration Curve. Each point represents the average values of each dose on the color reference charts for all of the control cards in the evaluation. Error bars were calculated to two standard deviations.

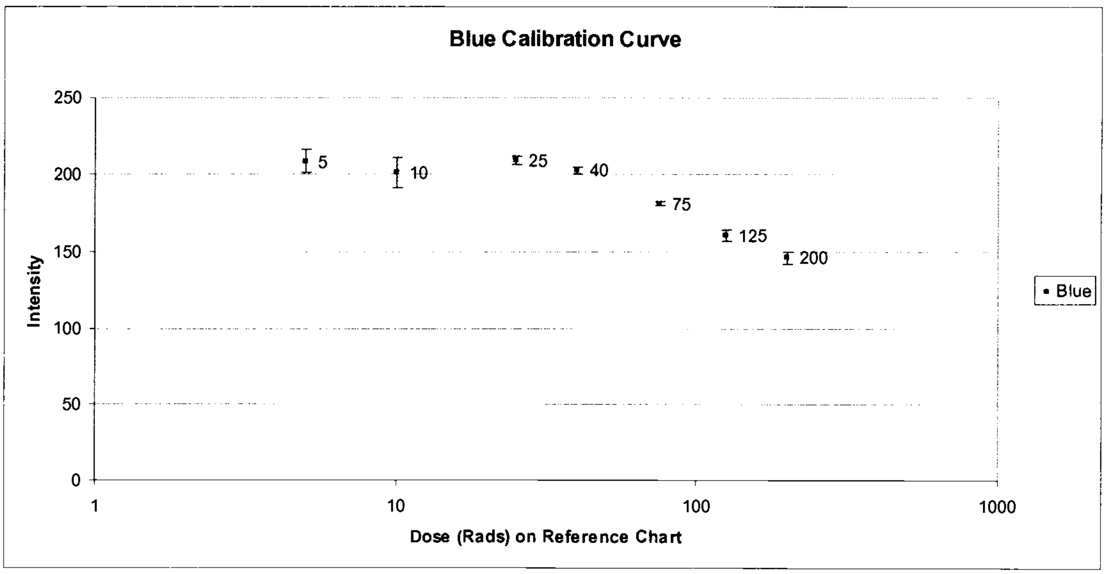


Figure 5.5 Blue Calibration Curve. Each point represents the average values of each dose on the color reference charts for all of the control cards in the evaluation. Error bars were calculated to two standard deviations.

Table 5.1 Average of Control Card Intensity Values

Average of Control Card Intensity Values, n = 12								
Parameter Measured	**Color Key Listed Dose (rads)**							
	0	5	10	25	40	75	125	200
Luminosity	227.67	204.86	185.30	151.83	135.60	102.08	71.76	45.98
Red	227.71	192.13	167.09	123.15	103.31	74.07	49.26	22.11
Green	231.63	210.62	191.59	155.71	139.49	101.60	66.55	39.49
Blue	206.67	208.66	201.24	209.25	202.81	181.08	160.75	145.95
Standard Deviation of Average Control Card Intensity Values								
Parameter Measured	0	5	10	25	40	75	125	200
Luminosity	5.35	8.17	10.80	8.014	7.71	6.68	5.39	3.32
Red	7.21	9.83	13.47	12.24	11.91	11.28	10.04	5.85
Green	4.86	7.56	9.79	7.21	7.00	5.54	3.94	2.74
Blue	4.23	7.59	9.36	2.91	2.34	1.12	3.57	4.02

5.2 Cs-137 EXPOSURES

All six doses were evaluated in the Cs-137 series. The values for each card were charted and graphed. All ten cards in the set were compared to each other as well as the set control in a bar graph. Error bar values were taken from the Adobe Photoshop 7.0® histograms. These graphs can be seen in Appendix B. Card number ten was used to test for angular dependence (AD) at 15°. Intensity values for cards one through ten in each set were averaged for each dose and plotted on the calibration curve for comparison. The error bars were calculated to two standard deviations. Card number one and number ten for 10 rads is displayed to show the similarity in their dose and color.

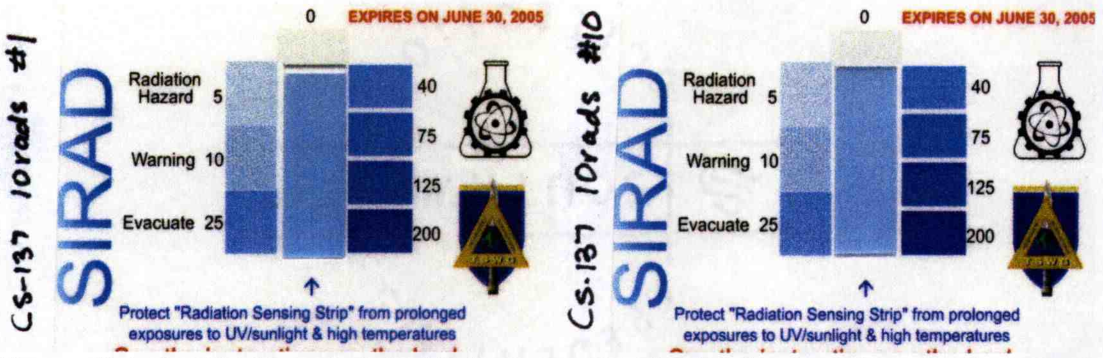


Figure 5.6 Cs-137 10 rads SIRAD badges. SIRAD badge number one irradiated to 10 rads by the Cs-137 irradiator (left) and SIRAD badge number 10 irradiated to 10 rads by the Cs-137 irradiator (right) are shown side by side to show the uniformity of the color on the sensing strips. Card number 10 was placed at a 15° angle to test for angular dependence.

Table 5.2 Average Color Readings for Cs-137 Irradiated Cards

Averaged Color Readings for Cs-137 Irradiated Cards, n = 10 per dose						
Parameter Measured	**Dose delivered to cards (rad)**					
	2.5	5	7.5	10	40	125
Luminosity	211.19	195.799	186.442	178.25	119.168	66.259
Red	200.58	177.31	164.562	154.29	94.425	58.69
Green	216.741	202.443	192.734	184.585	118.708	53.691
Blue	210.295	210.519	212.352	209.625	189.168	154.312
Standard Deviations of the Averaged Color Readings for Cs-137 Irradiated Cards						
Parameter Measured	2.5	5	7.5	10	40	125
Luminosity	2.252269	3.259631	2.531803	4.010719	3.870123	7.297107
Red	3.073844	4.132946	3.103429	4.650047	3.882797	3.935457
Green	1.887396	3.186137	2.118473	4.256313	4.919926	9.331073
Blue	3.015416	2.028825	10.52353	2.432726	2.845391	6.151486

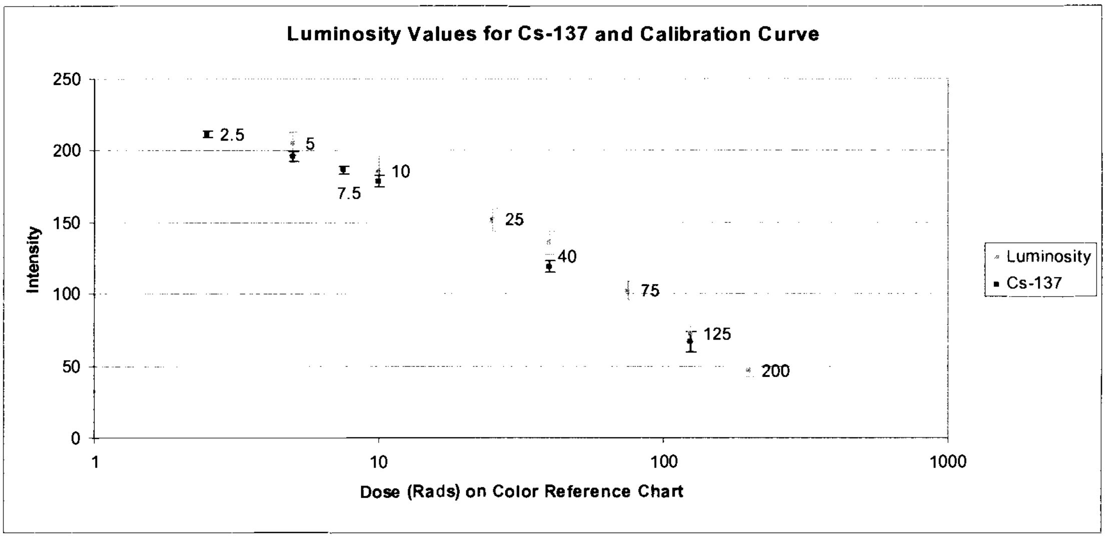


Figure 5.7 Luminosity Values for Cs-137 and Calibration Curve. Each gray point represents the average values of each dose on the color reference charts for all of the control cards in the evaluation. Each black point represents the average value for all ten cards at each dose irradiated in the Cs-137 irradiator. Error bars were calculated to two standard deviations.

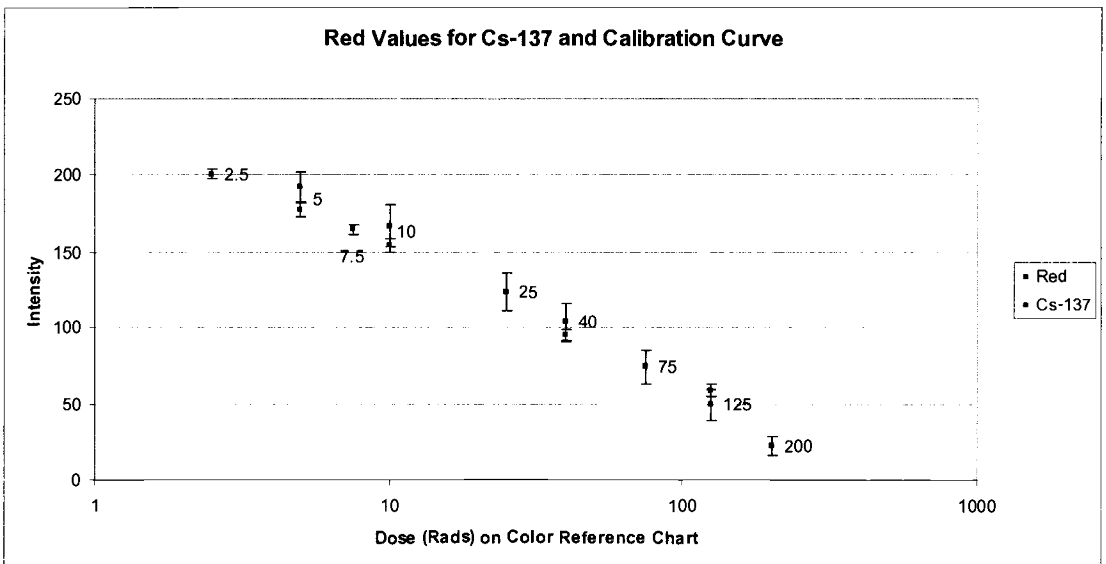


Figure 5.8 Red Values for Cs-137 and Calibration Curve. Each red point represents the average values of each dose on the color reference charts for all of the control cards in the evaluation. Each black point represents the average value for all ten cards at each dose irradiated in the Cs-137 irradiator. Error bars were calculated to two standard deviations.

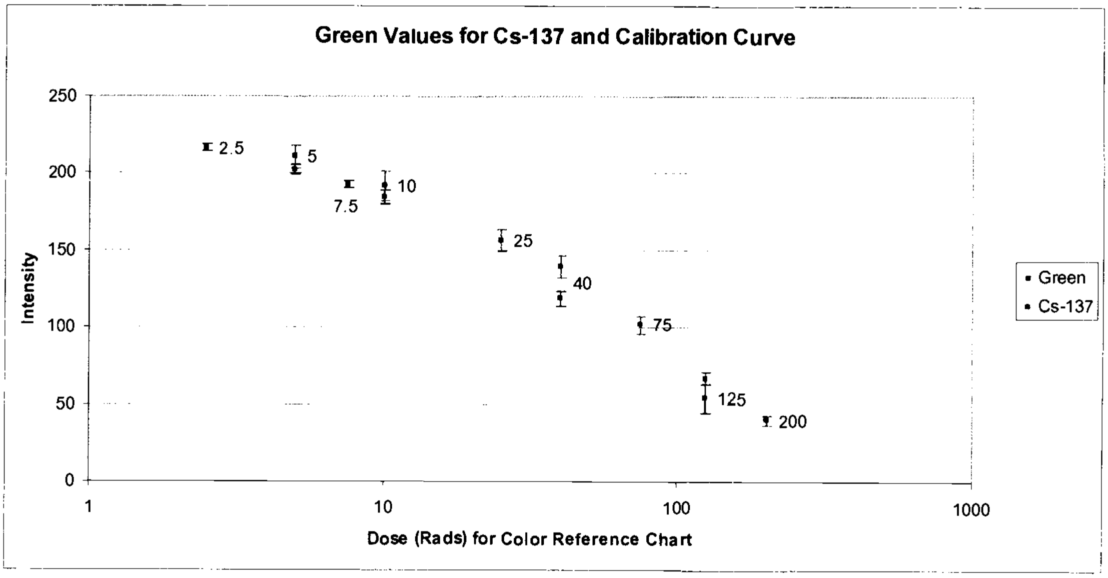


Figure 5.9 Green Values for Cs-137 and Calibration Curve. Each green point represents the average values of each dose on the color reference charts for all of the control cards in the evaluation. Each black point represents the average value for all ten cards at each dose irradiated in the Cs-137 irradiator. Error bars were calculated to two standard deviations.

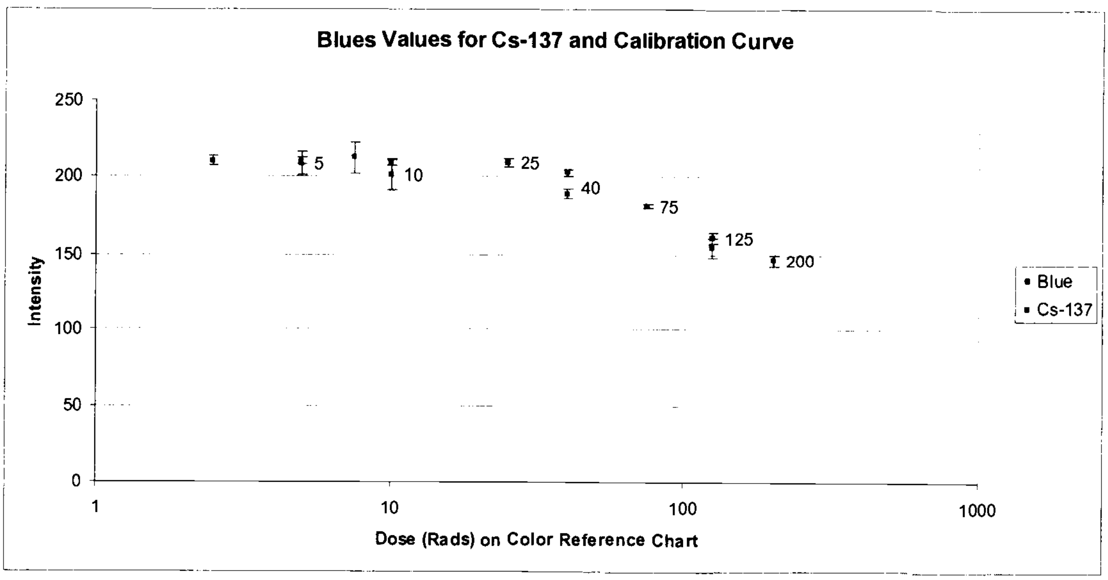


Figure 5.10 Blue Values for Cs-137 and Calibration Curve. Each blue point represents the average values of each dose on the color reference charts for all of the control cards in the evaluation. Each black point represents the average value for all ten cards at each dose irradiated in the Cs-137 irradiator. Error bars were calculated to two standard deviations.

5.3 Ra-226 EXPOSURES

The SIRAD cards in the Ra-226 series were subjected to 2.5 rads, 5 rads, 7.5 rads, and 10 rads. The values for each card were charted and graphed. All ten cards in the set were compared to each other as well as the set control in a bar graph. Error bar values were taken from the Adobe Photoshop 7.0® histograms. These graphs can be seen in Appendix C. Card number ten was used to test for angular dependence (AD) at 45°. Intensity values for cards one through ten in each set were averaged for each dose and plotted on the calibration curve for comparison. The error bars were calculated to two standard deviations. Card number one and number ten for 2.5 rads is displayed to show the similarity in their dose and color.

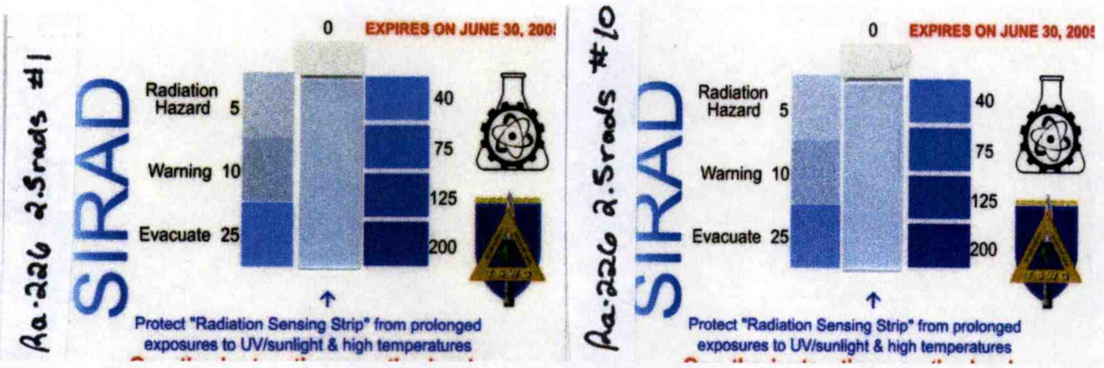


Figure 5.11 Ra-226 2.5 rads SIRAD badges. SIRAD badge number one irradiated to 2.5 rads by the Ra-226 needle (left) and SIRAD badge number 10 irradiated to 2.5 rads by the Ra-226 needle (right) are shown side by side to show the uniformity of the color on the sensing strips. Card number 10 was placed at a 45° angle to test for angular dependence.

Table 5.3 Averaged Color Readings for Ra-226 Irradiated Cards

Averaged Color Readings for Ra-226 Irradiated Cards, n = 10 per dose				
Parameter Measured	**Dose delivered to cards (rad)**			
	2.5	5	7.5	10
Luminosity	203.202	184.78	173.731	162.174
Red	187.275	162.843	149.178	136.128
Green	209.566	191.239	179.455	167.079
Blue	212.47	209.945	209.985	206.93
Standard Deviations of the Averaged Color Readings for Ra-226 Irradiated Cards				
Parameter Measured	2.5	5	7.5	10
Luminosity	2.435402	3.05697	2.040925	3.185037
Red	2.742023	3.667152	2.446509	3.404739
Green	2.59689	3.247624	2.248105	3.364646
Blue	2.14886	2.97637	1.815128	2.463277

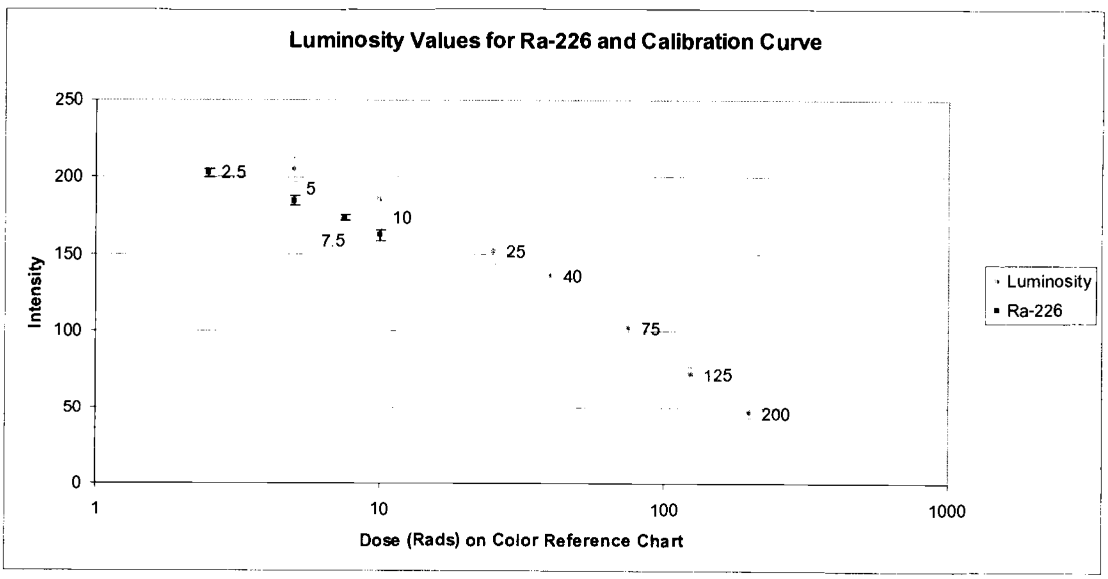


Figure 5.12 Luminosity Values for Ra-226 and Calibration Curve. Each gray point represents the average values of each dose on the color reference charts for all of the control cards in the evaluation. Each black point represents the average value for all ten cards at each dose irradiated in the Ra-226 irradiator. Error bars were calculated to two standard deviations.

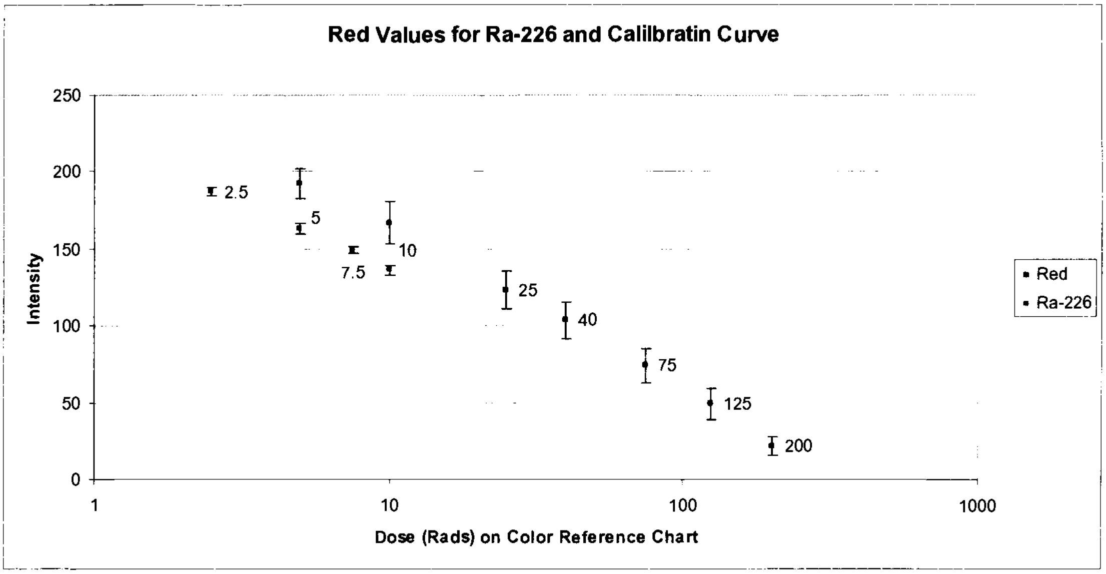


Figure 5.13 Red Values for Ra-226 and Calibration Curve. Each red point represents the average values of each dose on the color reference charts for all of the control cards in the evaluation. Each black point represents the average value for all ten cards at each dose irradiated in the Ra-226 irradiator. Error bars were calculated to two standard deviations.

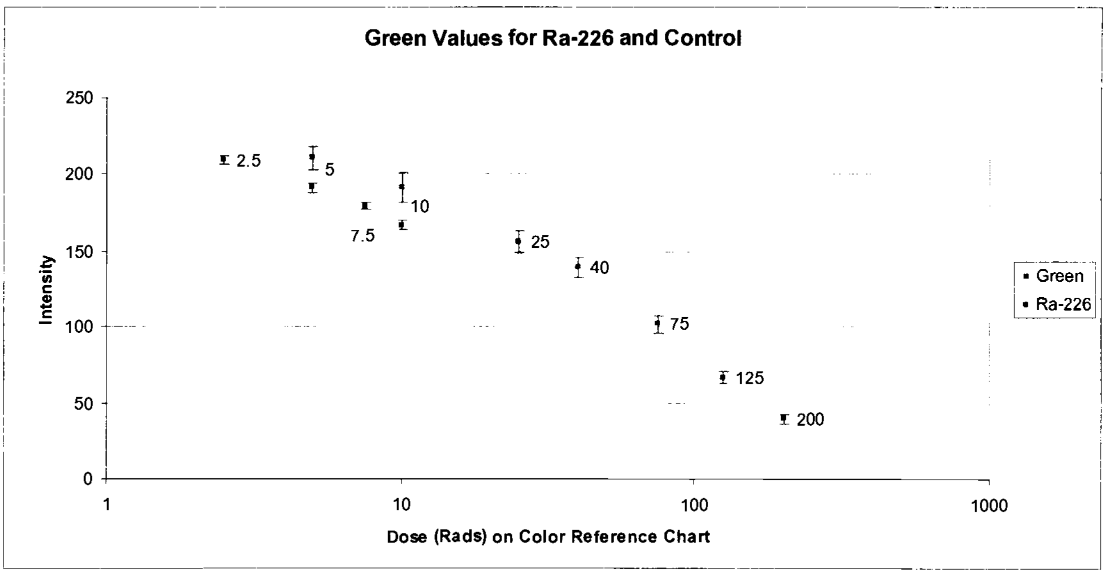


Figure 5.14 Green Values for Ra-226 and Calibration Curve. Each green point represents the average values of each dose on the color reference charts for all of the control cards in the evaluation. Each black point represents the average value for all ten cards at each dose irradiated in the Ra-226 irradiator. Error bars were calculated to two standard deviations.

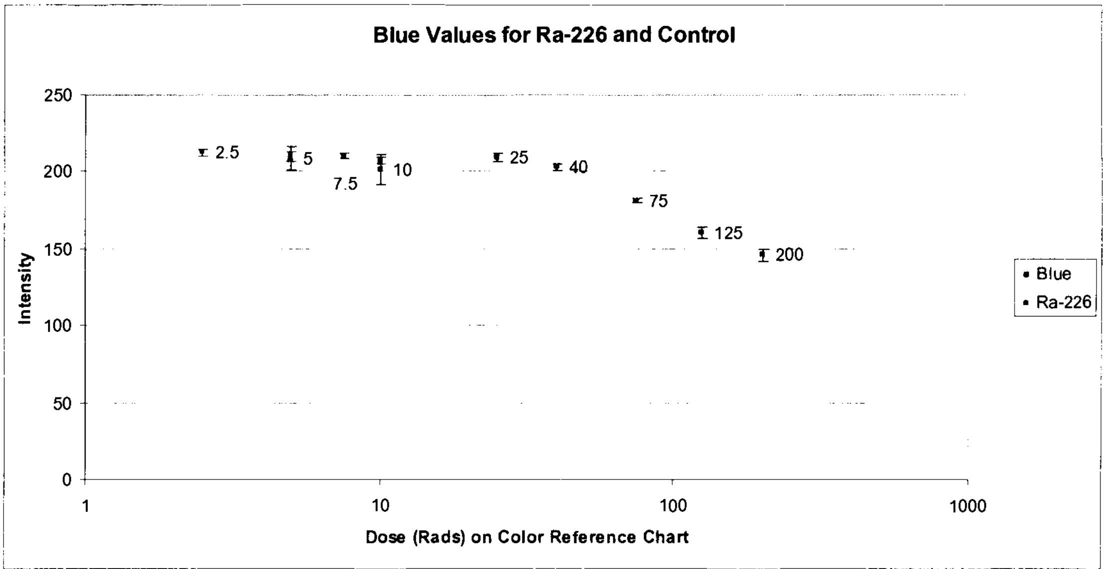


Figure 5.15 Blue Values for Ra-226 and Calibration Curve. Each blue point represents the average values of each dose on the color reference charts for all of the control cards in the evaluation. Each black point represents the average value for all ten cards at each dose irradiated in the Ra-226 irradiator. Error bars were calculated to two standard deviations.

5.4 Co-60 EXPOSURES

The Co-60 series did not test for angular dependence so only card one is displayed. Only 40 rads and 125 rads were tested with the Gammacell Co-60 irradiation unit. All ten cards in the set were compared to each other as well as the set control in a bar graph. Error bar values were taken from the Adobe Photoshop 7.0® histograms. These graphs can be seen in Appendix D. Intensity values for cards one through ten was averaged for 40 rads and plotted on the calibration curve for comparison with the 125 rads color reference chart values. The error bars were calculated to two standard deviations.

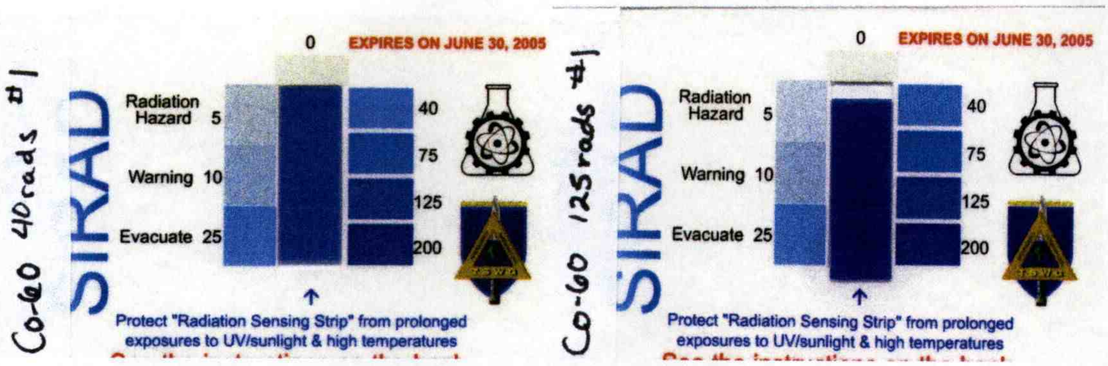


Figure 5.16 Co-60 40 and 125 rads SIRAD badges. SIRAD badge number one irradiated to 40 rads (left) and 125 rads (right) by the Gammacell 220 Co-60 irradiation unit.

Table 5.4 Averaged Color Readings for Co-60 Irradiated Cards

Averaged Color Readings for Co-60 Irradiated Cards, n = 10 per dose	
Parameter Measured	**Dose delivered to cards (rad)**
	125
Luminosity	66.72
Red	61.496
Green	53.461
Blue	152.118
Standard Deviations of the Averaged Color Readings for Co-60 Irradiated Cards	
Parameter Measured	125
Luminosity	5.243001685
Red	1.644903239
Green	7.053607115
Blue	5.619567401

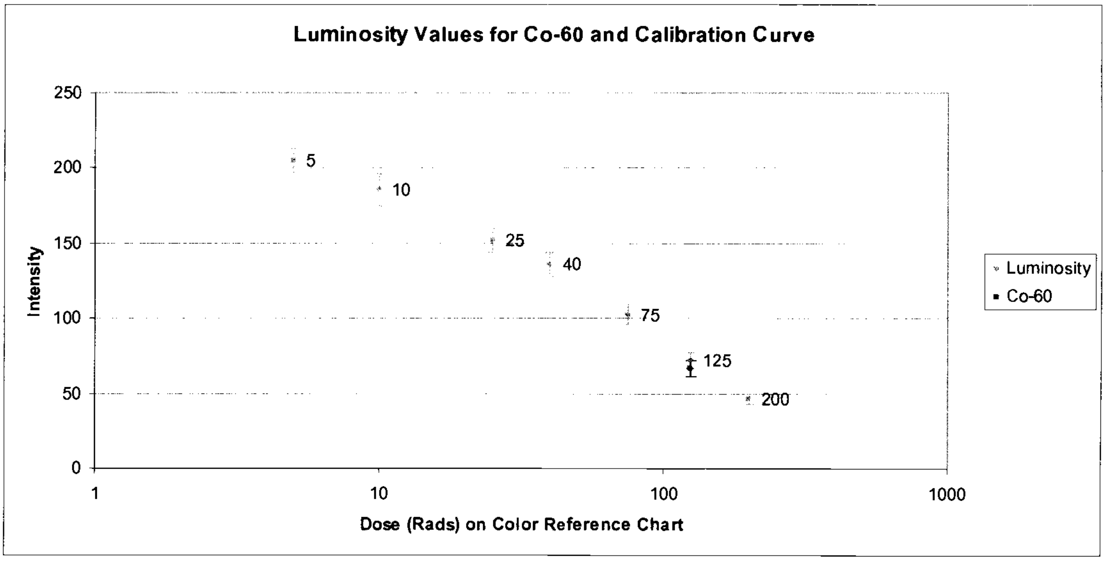


Figure 5.17 Luminosity Values for Co-60 and Calibration Curve. Each gray point represents the average values of each dose on the color reference charts for all of the control cards in the evaluation. Each black point represents the average value for all ten cards at 40 rads irradiated by the Gammacell Co-60 irradiation unit compared to 125 rad values. Error bars were calculated to two standard deviations.

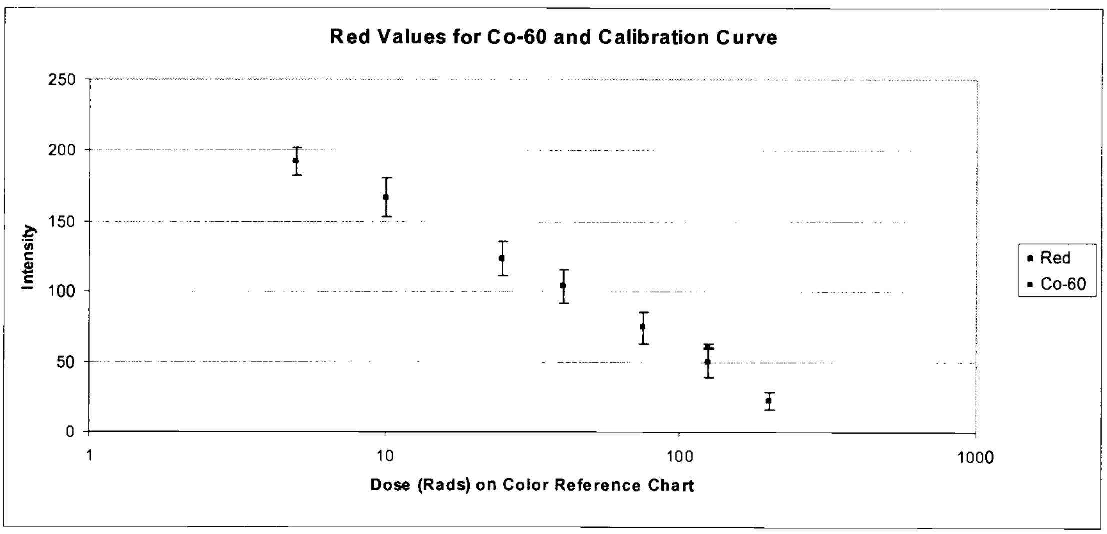


Figure 5.18 Red Values for Co-60 and Calibration Curve. Each red point represents the average values of each dose on the color reference charts for all of the control cards in the evaluation. Each black point represents the average value for all ten cards at 40 rads irradiated by the Gammacell Co-60 irradiation unit compared to 125 rad values. Error bars were calculated to two standard deviations.

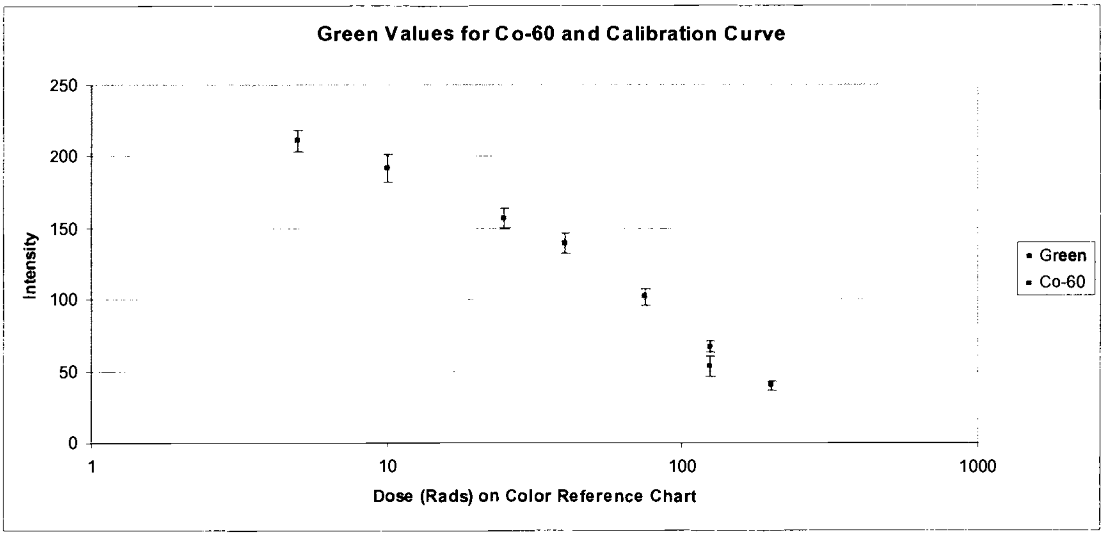


Figure 5.19 Green Values for Co-60 and Calibration Curve. Each green point represents the average values of each dose on the color reference charts for all of the control cards in the evaluation. Each black point represents the average value for all ten cards at 40 rads irradiated by the Gammacell Co-60 irradiation unit compared to 125 rad values. Error bars were calculated to two standard deviations.

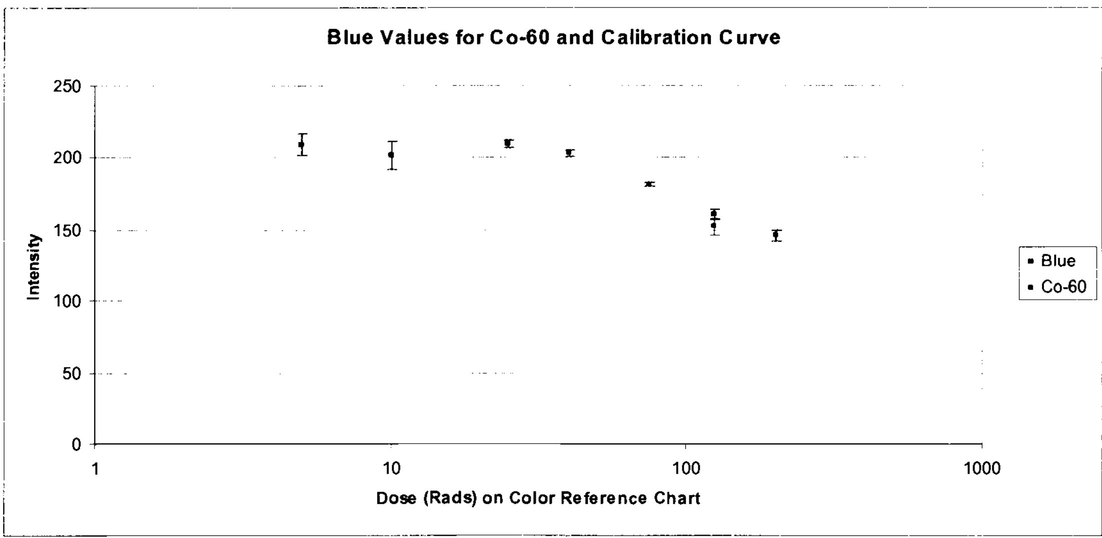


Figure 5.20 Blue Values for Co-60 and Calibration Curve. Each blue point represents the average values of each dose on the color reference charts for all of the control cards in the evaluation. Each black point represents the average value for all ten cards at 40 rads irradiated by the Gammacell Co-60 irradiation unit compared to 125 rad values. Error bars were calculated to two standard deviations.

6. DISCUSSION

6.1 CONTROL CARDS

According to the histograms created to compare all of the set controls with the overall control, all of the set controls from each series, Cs-137, Ra-226, and Co-60, showed slight or no variance among each other. This is due to the luminosity, red, green, and blue statistics taken from the histograms created by Adobe Photoshop 7.0® for each color and each card being similar. The calibration curves created by averaging all of the control cards together show the red intensity values being the most consistent and the best indicator. This comparison shows consistency in the make up and capabilities of the SIRAD cards.

6.2 Cs-137 EXPOSURES

The Cs-137 exposures showed all of the cards fell within the standard deviations of the color reference charts calculated by Adobe Photoshop 7.0®. Since all the cards in the set fell within the control cards standard deviation and closely resembled each other, it is assumed that there was no appreciable attenuation or shielding taking place. When compared to the set control, card number ten, which was raised to a 15 ° angle to test for angular dependence, kept the same pattern as the rest of the cards in the set. This shows that there was no angular dependence expressed in this evaluation between 0° and 15°.

When the intensity values for each dose were averaged and compared to the calibration curve there was a slight inconsistency with the 40 rad readings for luminosity, green and blue. Red intensity readings were all within two standard deviations.

6.3 Ra-226 EXPOSURES

Results from the Ra-226 series were not as clear as those in the Cs-137 and Co-60 series. According to standard deviation values computed by Adobe Photoshop 7.0®, the 2.5 rad and 7.5 rad card sets were found to be within the error bounds of the set control. These values were calculated from equations on the set control card graph (see Appendix C). Based on an assumption of linearity between two points on the graph, the standard deviations for 2.5 rads and 7.5 rads were calculated by taking the average of the standard deviations from 0 rads and 5 rads and 5 rads 10 rads, respectively.

The 5 rads card set did not display statistically similar intensity readings for red and for cards number one and eight for luminosity. The 10 rads card set showed inconsistent values on all of the red intensity readings except for cards number six, seven, and ten. Luminosity readings showed cards number three and five outside of the set control values. It also showed green intensity readings for card number three not meeting the set controls values.

As a result of card sets 5 rads and 10 rads showing deviations from the set control, gamma attenuation calculations were done. Using the mass attenuation coefficient, $\frac{\mu}{\rho}$, for Tissue-Equivalent Plastic[7], which was used to represent the UV film, attenuation was calculated. A value of .9998 was calculated for the .01 cm film concluding that there was no attenuation occurring. Attenuation was also calculated for the total thickness, .11cm, of the card and the UV film combined, and resulted in a value of .9982. Attenuation for the UV film was calculated using Ra-226 gamma emitting progeny. Calculations were done for the gamma energies most probable per decay. Table 6.1 displays the results to these calculations.

[7] Value was taken from the Handbook of Health Physics and Radiological Health, 3rd ed, edited by Bernard Shleien, Lester A. Slaback, Jr. and Brian Kent Birky. Baltimore, Williams & Wilkins , 1998, 5-24

Table 6.1 Gamma Ray Attenuation for selected Ra-226 progeny. The gamma energies which were the most probable per decay were chosen to check for attenuation of the UV film. The equation used was: I/I0 = e-µt, where I/I0 is the fraction of gamma-ray intensity transmitted through an absorber of thickness, t, per gamma-ray intensity at zero absorber thickness. (Cember, pg. 134) The energy absorption coefficient and density for Tissue Equivalent plastic were used to represent the black UV film. Gamma energies, energy absorption coefficient, and density were found in Table 8.14, Table 5.1, and Table 5.4, respectfully, in the Handbook of Health Physics and Radiological Health, 3rd ed.

Gamma Ray Attenuation for the Ra-226 Series						
Isotope	Gamma E(MeV)	μ/ρ (cm^2/g)	ρ (g/cm^3)	μ (cm^{-1})	Thickness of film (cm)	I/I_0
Ra-226	0.1862	0.014504	1.127	0.016346	0.01	0.999837
Rn-222	0.512	0.094924	1.127	0.106979	0.01	0.998931
Pb-214	0.0108	3.7386	1.127	4.213402	0.01	0.958741
	0.29521	0.118162	1.127	0.133169	0.01	0.998669
	0.35192	0.110862	1.127	0.124941	0.01	0.998751
Bi-214	0.60931	0.088067	1.127	0.099252	0.01	0.999008
	1.1203	0.065475	1.127	0.07379	0.01	0.999262
	1.7645	0.05262	1.127	0.059303	0.01	0.999407

Since there was no attenuation found, the Ra-226 needle is certified, and all of the cards were consistent with each other within their sets, the irradiation times were recalculated and all graphs, numbers, and charts were double checked. There were no discrepancies found. However, when the intensity values were averaged for each dose and then compared with the calibration curve, none of the intensity values fell within two standard deviations of the control values. This indicates the possibility that the SIRAD cards may be energy dependent.

Card number ten, which was tested for angular dependence at an angle of 45°, showed consistency with the rest of the cards in its respective set. There was no angular dependence observed on the card between a 0° and 45° angle.

6.4 Co-60 EXPOSURES

The Co-60 irradiator was used for the 40 rad and the 125 rad sets. The timer on the irradiator only allowed for time in the unit of seconds. To get a dose of 40 rads and 125 rads, calculations yielded a time of 1.72 seconds and 5.37 seconds, respectively. Since these numbers were unable to be used, 2 seconds for the 40 rads set and 6 seconds for the 125 rads set was used. Knowing that higher doses would come out on the cards, adjustments in the calculations were made to account for the added time in the irradiator. These adjustments showed the cards were supposed to receive doses of 46.56 rads and 139.67 rads. However, when the cards went through the evaluation process and also looking at them visually, it was evident that the new adjusted doses were incorrect.

Since the irradiation times were so short, it was determined that the cards were receiving a traveling dose. Victoreen Condenser R-Meters were used to determine this dose. Out of six trials between two R-Meters, an average traveling dose of 77 rads was calculated. This number was added onto the adjusted doses. The 40 rads card had received a dose of 123.56 rads and the 125 rads card received a dose of 216.67 rads. Using the corrected doses the 125 rads card exceeded the cards capability of determining its dose and the 40 rads card set was renamed as the 125 rads set. The new 125 rads set according to Adobe Photoshop 7.0® standard deviation showed no variances between the cards and the set control at values for 125 rads. This was also true when the 125 rads set was compared to the calibration curve.

7. CONCLUSION

The Self-indicating Instant Radiation Alert Dosimeter was found to have no or slight energy dependence among the isotopes of Cs-137, and Co-60. However, it is possible that the card does have an energy dependence based on the results from the Ra-226 series. The evaluation displayed no angular dependence between 0° and 45°. Based on the findings of this evaluation, it is recommended that JP Labs examine the cards energy dependence to sources of similar strengths and characteristics of Ra-226. It is also recommended to test more angles and other isotopes. A human evaluation for visually reading the dosimeters should be conducted as well.

The dosimeter is an easy, cheap, and beneficial device for first responders to utilize in their line of work. It will give them an indication of whether or not they were exposed to any type of radiation which includes the aforementioned isotopes. However, it may be affected by intense heat such as a fire and false-positive readings can result if the card is not cared for properly. It will also not be suitable for low dose monitoring. Therefore, it is strongly recommended to wear another form of dosimetry, such as a TLD, when using SIRAD. Using this device first responders have the potential to better monitor themselves and take any appropriate actions to reduce any further exposure.

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APPENDICES

Appendix A

Control Card Picture and Graphs

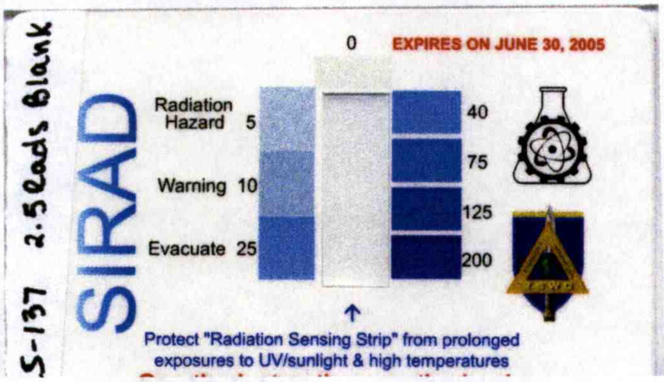

Figure A-1 Blank set control card from the Cs-137 2.5 rads set.

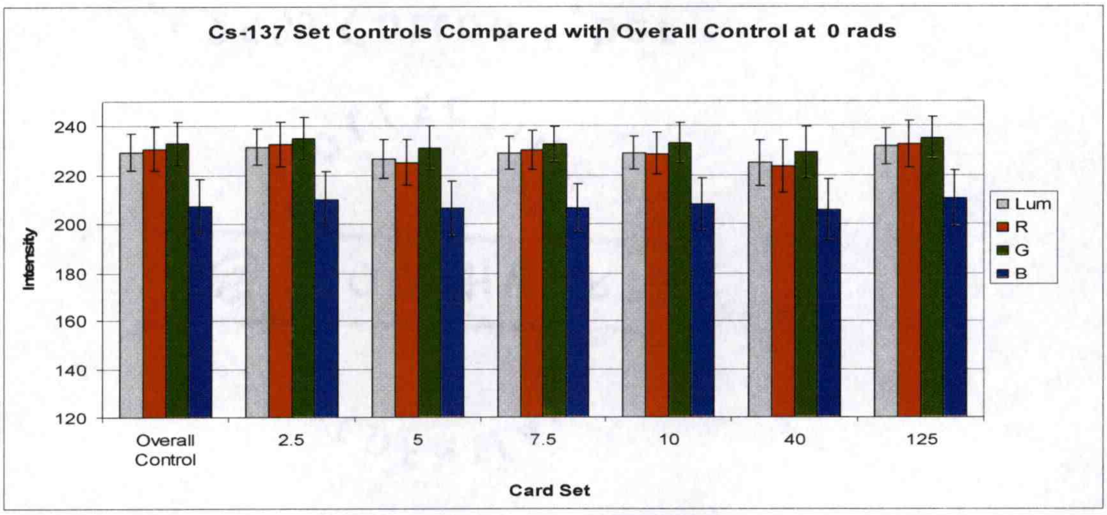

Figure A-2 The Cs-137 set controls (blank cards) compared to the overall control card at 0 rads, where the intensity for luminosity (grey bars), red, green, and blue are shown for each set control in the Cs-137 Series and the overall control card.

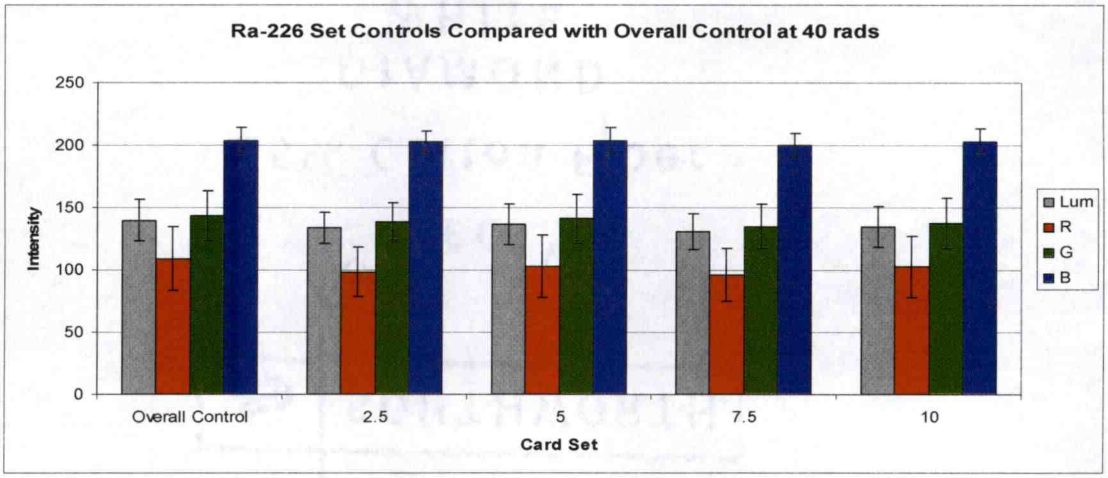

Figure A-3 The Ra-226 set controls (blank cards) compared to the overall control card at 40 rads, where the intensity for luminosity (grey bars), red, green, and blue are shown for each set control in the Ra-226 Series and the overall control card.

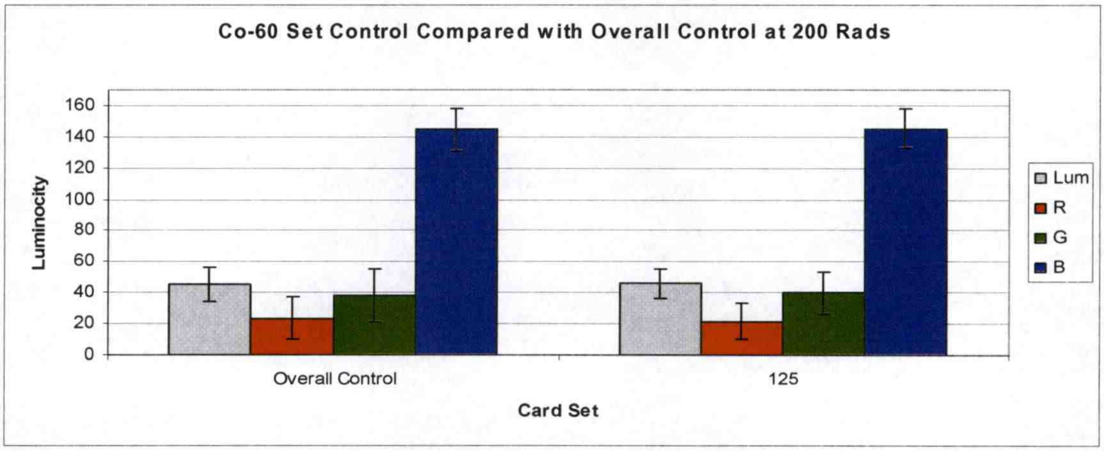

Figure A-4 The Co-60 set controls (blank cards) compared to the overall control card at 200 rads, where the intensity for luminosity (grey bars), red, green, and blue are shown for each set control in the Co-60 Series and the overall control card.

Appendix B

Cs-137 Pictures and Graphs

All six doses were evaluated in the Cs-137 series. Card number ten was used to test for angular dependence (AD) at 15°. Card number one and number ten are displayed to show the similarity in their dose and color.

<u>Cs-137 – 2.5 Rads Card Set</u>

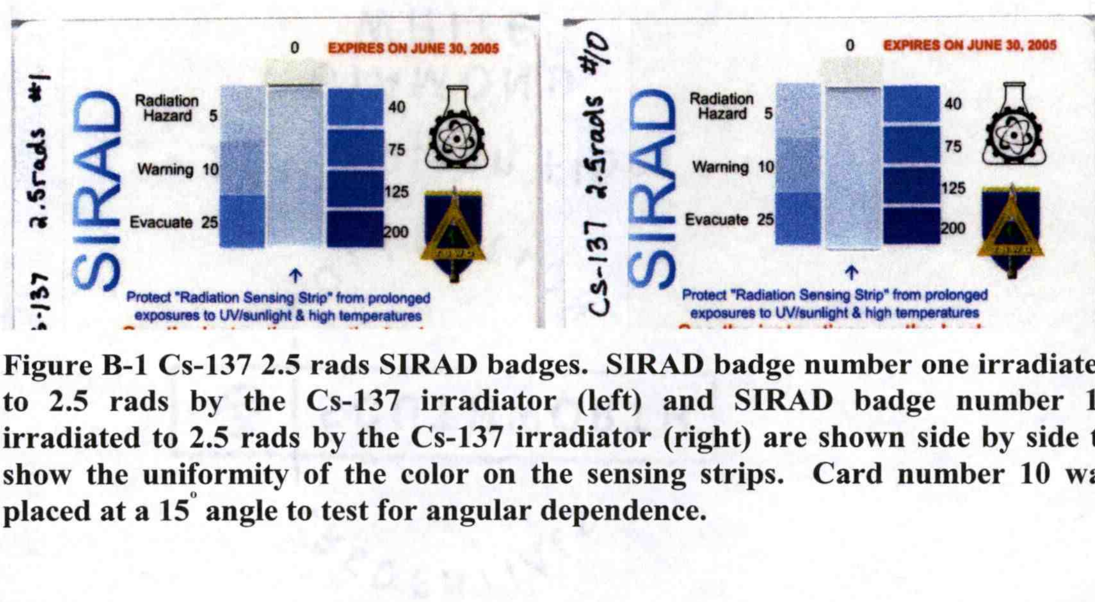

Figure B-1 Cs-137 2.5 rads SIRAD badges. SIRAD badge number one irradiated to 2.5 rads by the Cs-137 irradiator (left) and SIRAD badge number 10 irradiated to 2.5 rads by the Cs-137 irradiator (right) are shown side by side to show the uniformity of the color on the sensing strips. Card number 10 was placed at a 15° angle to test for angular dependence.

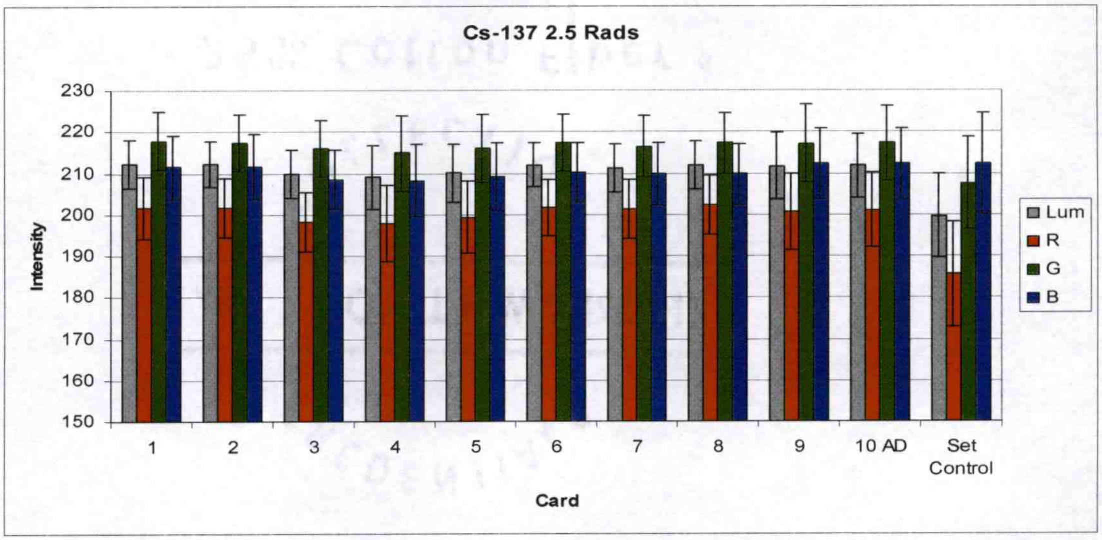

Figure B-2 Cs-137 2.5 rads card set compared to the set control. Each individual card is listed 1-10AD on the x-axis. The tenth card in this set was used to test for angular dependence, AD. The set control card values are for 2.5 rads. Since there is not a color chart for 2.5 rads, the values were calculated from equations taken from figure B-3. The y-axis represents the intensity readings for luminosity (grey bars), red, green, and blue obtained from the 2.5 rads histograms created by Adobe Photoshop 7.0®.

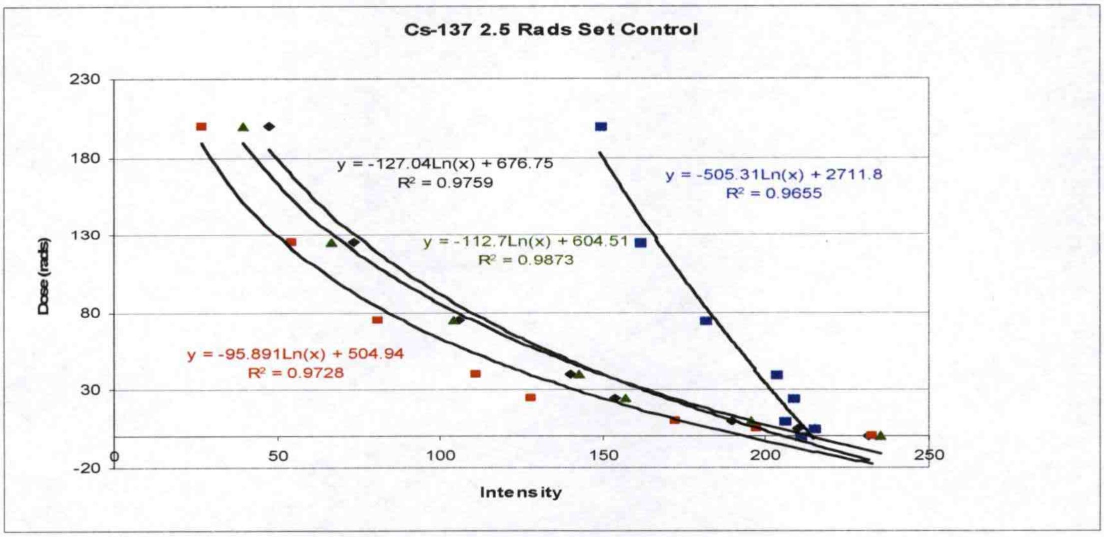

Figure B-3 Cs-137 2.5 rads set control graph. Histogram readings for luminosity (black diamonds), red (red squares), green (green triangles), and blue (blue squares) were plotted for each color on the set control card. These readings were graphed with their corresponding dose. Intensity values for 2.5 rads were calculated using the equation of the line.

Cs-137 – 5 Rads Card Set

Figure B-4 Cs-137 5 rads SIRAD badges. SIRAD badge number one irradiated to 5 rads by the Cs-137 irradiator (left) and SIRAD badge number 10 irradiated to 5 rads by the Cs-137 irradiator (right) are shown side by side to show the uniformity of the color on the sensing strips. Card number 10 was placed at a 15° angle to test for angular dependence.

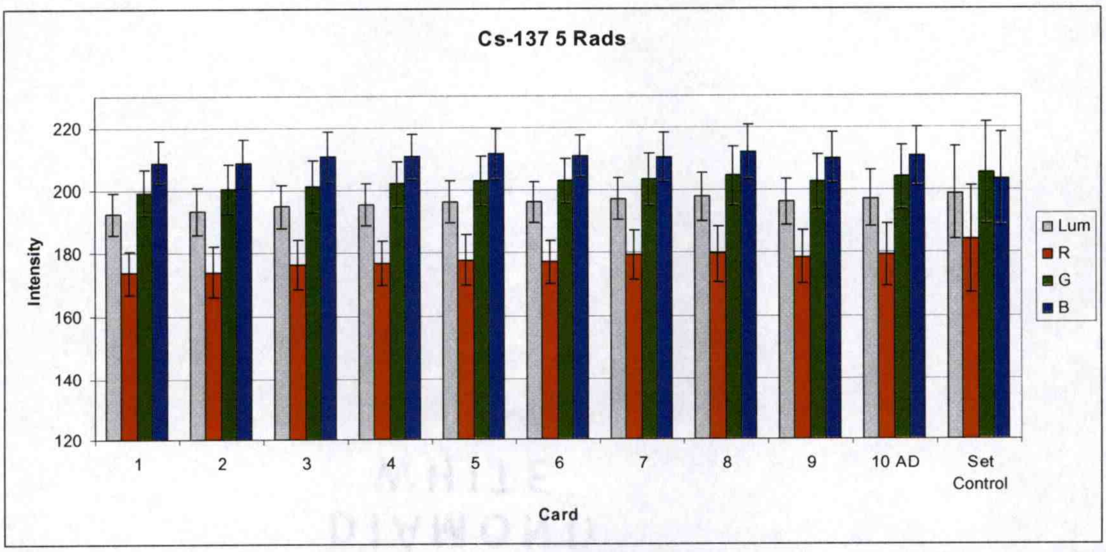

Figure B-5 Cs-137 5 rads card set compared to the set control. Each individual card is listed 1-10AD on the x-axis. The tenth card in this set was used to test for angular dependence, AD. The set control card values are for 5 rads. The y-axis represents the intensity readings for luminosity (grey bars), red, green, and blue, obtained from the 5 rads histograms created by Adobe Photoshop 7.0®.

Cs -137 – 7.5 Rads Card Set

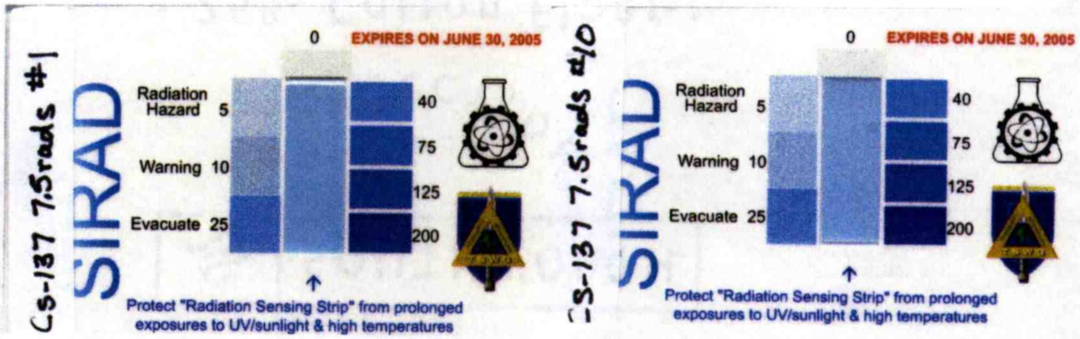

Figure B-6 Cs-137 7.5 rads SIRAD badges. SIRAD badge number one irradiated to 7.5 rads by the Cs-137 irradiator (left) and SIRAD badge number 10 irradiated to 7.5 rads by the Cs-137 irradiator (right) are shown side by side to show the uniformity of the color on the sensing strips. Card number 10 was placed at a 15° angle to test for angular dependence.

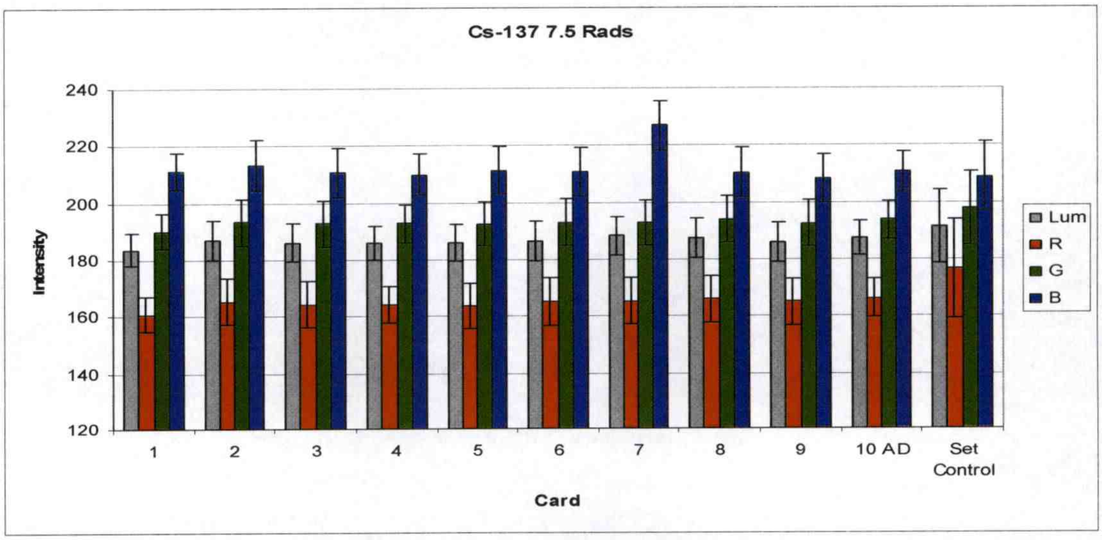

Figure B-7 Cs-137 7.5 rads card set compared to the set control. Each individual card is listed 1-10AD on the x-axis. The tenth card in this set was used to test for angular dependence, AD. The set control card values are for 7.5 rads. Since there is not a color chart for 7.5 rads, the values were calculated from equations taken from figure B-8. The y-axis represents the intensity readings for luminosity (grey bars), red, green, and blue, obtained from the 7.5 rads histograms created by Adobe Photoshop 7.0®.

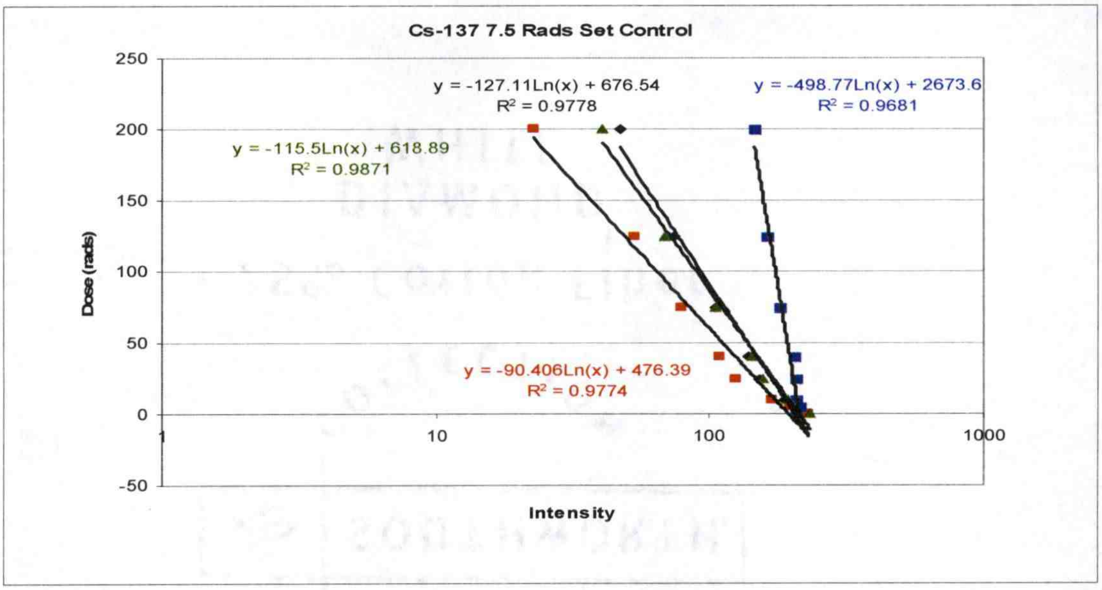

Figure B-8 Cs-137 7.5 rads set control graph. Histogram readings for luminosity (black diamonds), red (red squares), green (green triangles), and blue (blue squares) were plotted for each color on the set control card. These readings were graphed with their corresponding dose. Intensity values for 7.5 rads were calculated using the equation of the line.

<u>Cs-137 – 10 Rads Card Set</u>

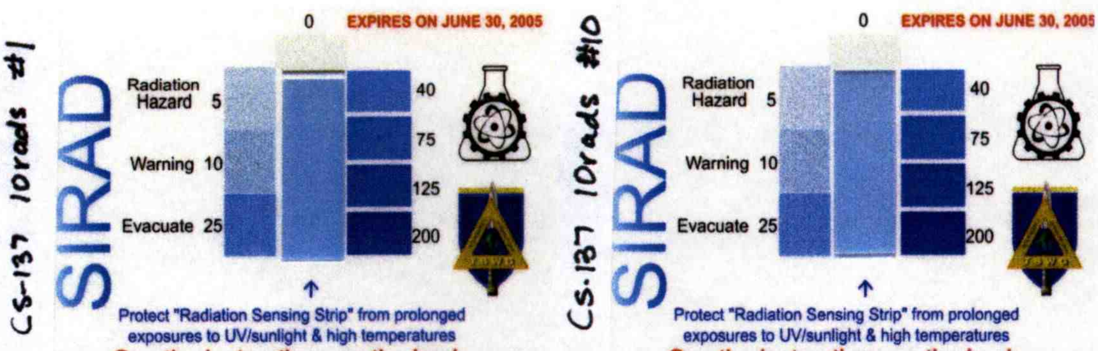

Figure B-9 Cs-137 10 rads SIRAD badges. SIRAD badge number one irradiated to 10 rads by the Cs-137 irradiator (left) and SIRAD badge number 10 irradiated to 10 rads by the Cs-137 irradiator (right) are shown side by side to show the uniformity of the color on the sensing strips. Card number 10 was placed at a 15° angle to test for angular dependence.

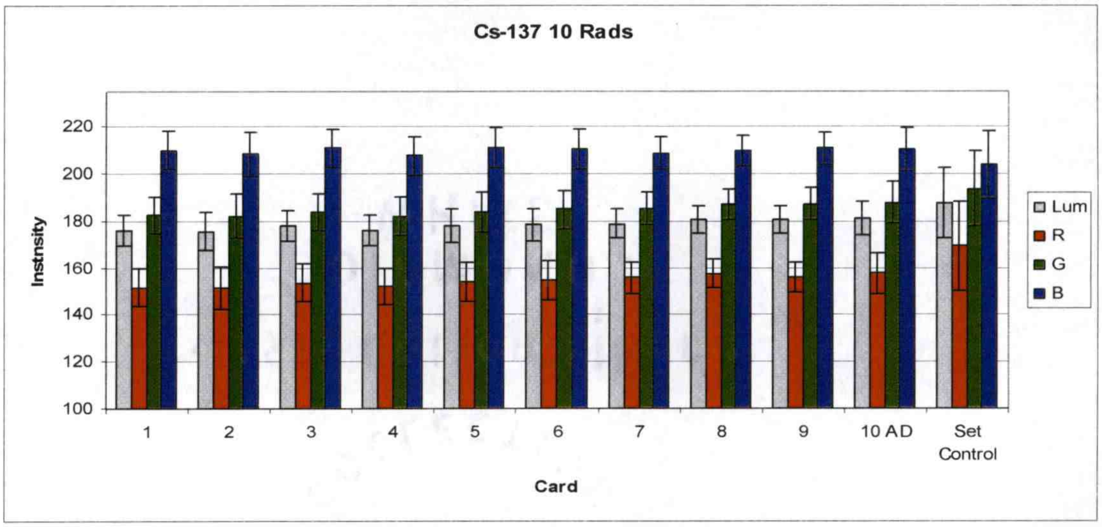

Figure B-10 Cs-137 10 rads card set compared to the set control. Each individual card is listed 1-10AD on the x-axis. The tenth card in this set was used to test for angular dependence, AD. The set control card values are for 10 rads. The y-axis represents the intensity readings for luminosity (grey bars), red, green, and blue, obtained from the 10 rads histograms created by Adobe Photoshop 7.0®.

Cs-137 – 40 Rads Card Set

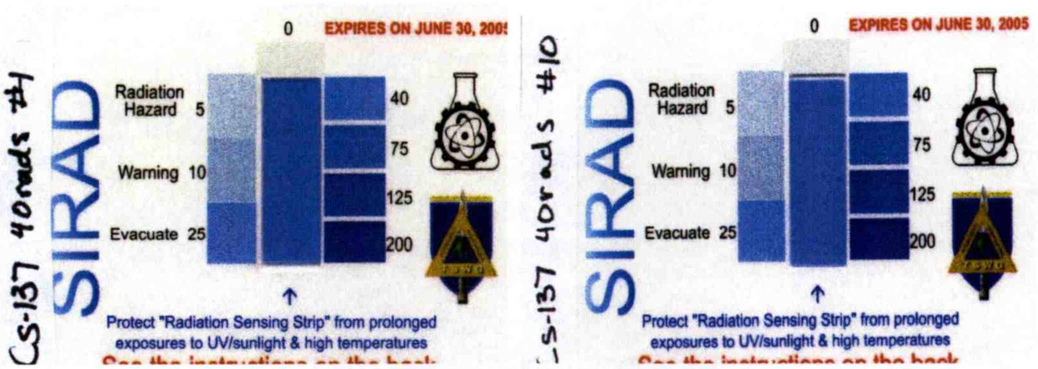

Figure B-11 Cs-137 40 rads SIRAD badges. SIRAD badge number one irradiated to 40 rads by the Cs-137 irradiator (left) and SIRAD badge number 10 irradiated to 40 rads by the Cs-137 irradiator (right) are shown side by side to show the uniformity of the color on the sensing strips. Card number 10 was placed at a 15° angle to test for angular dependence.

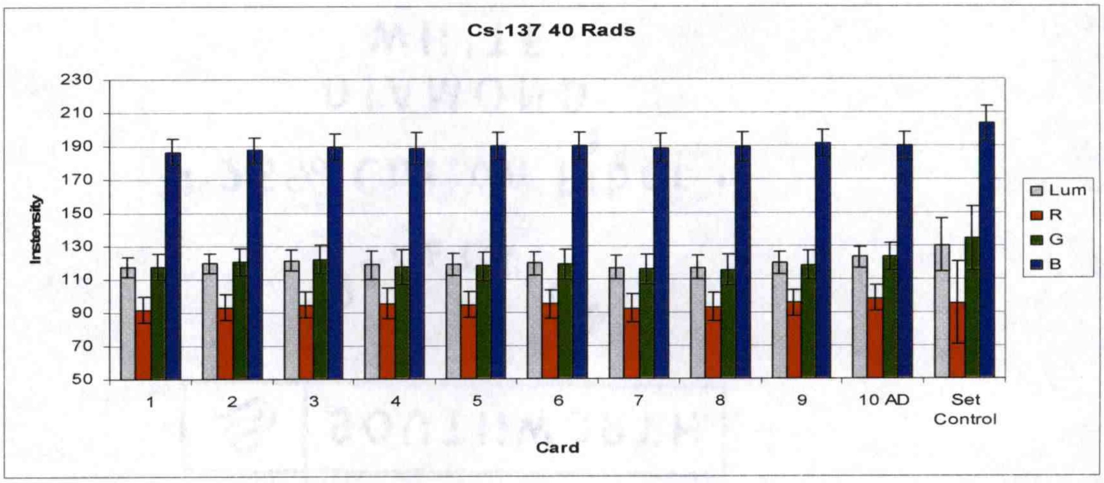

Figure B-12 Cs-137 40 rads card set compared to the set control. Each individual card is listed 1-10AD on the x-axis. The tenth card in this set was used to test for angular dependence, AD. The set control card values are for 40 rads. The y-axis represents the intensity readings for luminosity (grey bars), red, green, and blue, obtained from the 40 rads histograms created by Adobe Photoshop 7.0®.

Cs-137 – 125 Rads Card Set

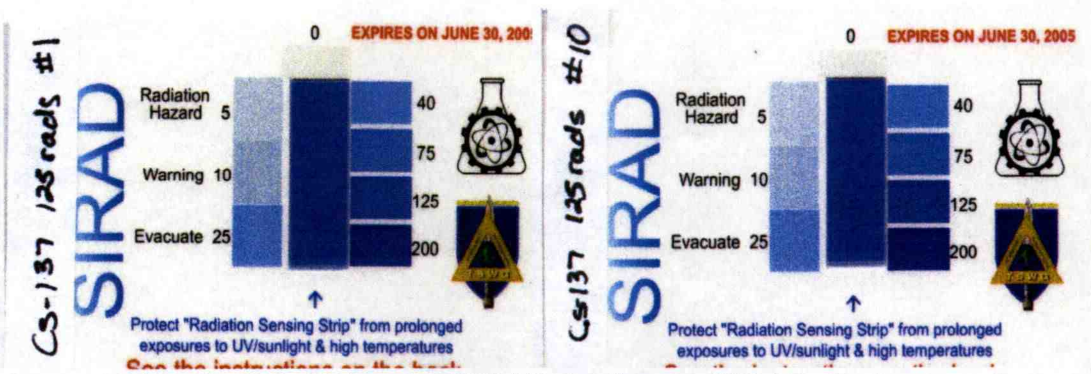

Figure B-13 Cs-137 125 rads SIRAD badges. SIRAD badge number one irradiated to 125 rads by the Cs-137 irradiator (left) and SIRAD badge number 10 irradiated to 125 rads by the Cs-137 irradiator (right) are shown side by side to show the uniformity of the color on the sensing strips. Card number 10 was placed at a 15° angle to test for angular dependence.

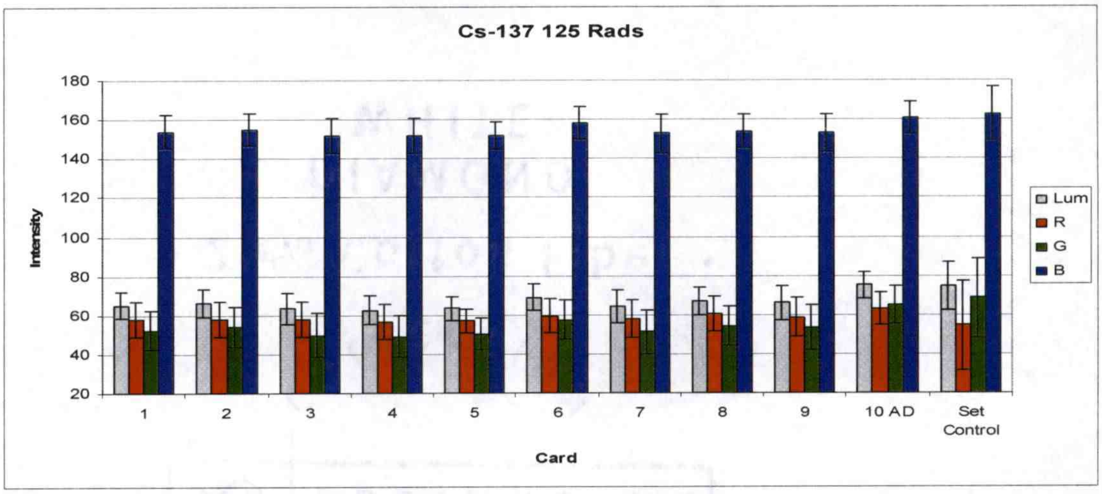

Figure B-14 Cs-137 125 rads card set compared to the set control. Each individual card is listed 1-10AD on the x-axis. The tenth card in this set was used to test for angular dependence, AD. The set control card values are for 125 rads. The y-axis represents the intensity readings for luminosity (grey bars), red, green, and blue, obtained from the 125 rads histograms created by Adobe Photoshop 7.0®.

Appendix C

Ra-226 Pictures and Graphs

The SIRAD cards in the Ra-226 series were subjected to 2.5 rads, 5 rads, 7.5 rads, and 10 rads. Card number ten was used to test for angular dependence (AD) at 45°. Card number one and number ten are displayed to show the similarity in their dose and color.

<u>**Ra-226 – 2.5 Rads Card Set**</u>

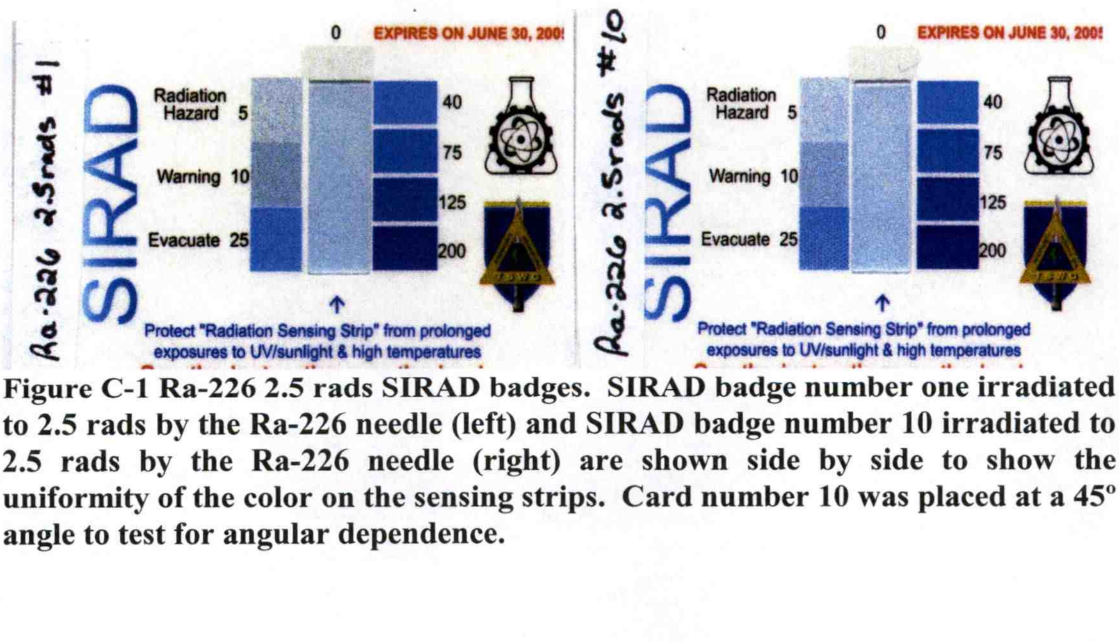

Figure C-1 Ra-226 2.5 rads SIRAD badges. SIRAD badge number one irradiated to 2.5 rads by the Ra-226 needle (left) and SIRAD badge number 10 irradiated to 2.5 rads by the Ra-226 needle (right) are shown side by side to show the uniformity of the color on the sensing strips. Card number 10 was placed at a 45° angle to test for angular dependence.

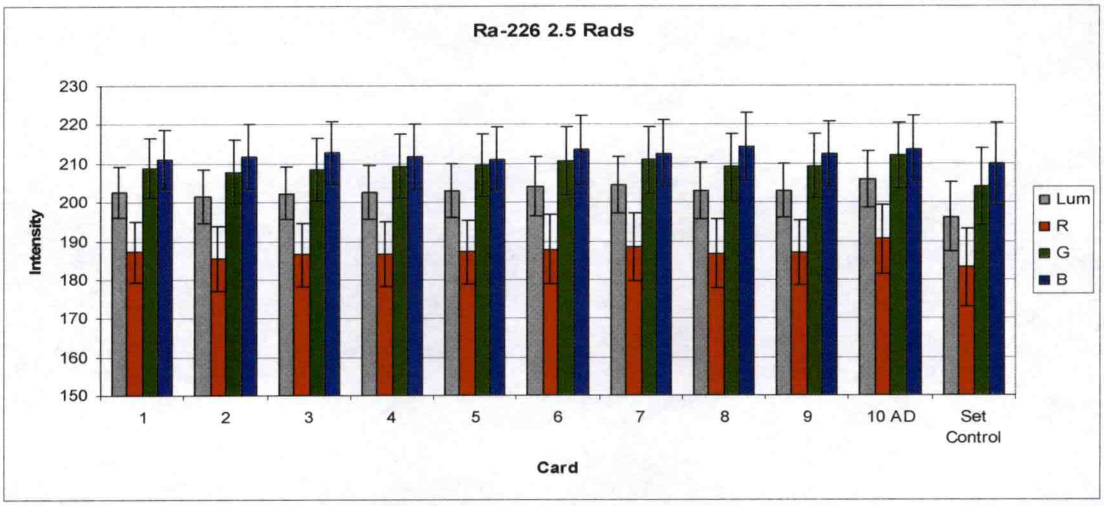

Figure C-2 Ra-226 2.5 rads card set compared to the set control. Each individual card is listed 1-10AD on the x-axis. The tenth card in this set was used to test for angular dependence, AD. The set control card values are for 2.5 rads. Since there is not a color chart for 2.5 rads, the values were calculated from equations taken from figure C-3. The y-axis represents the intensity readings for luminosity (grey bars), red, green, and blue, obtained from the 2.5 rads histograms created by Adobe Photoshop 7.0®.

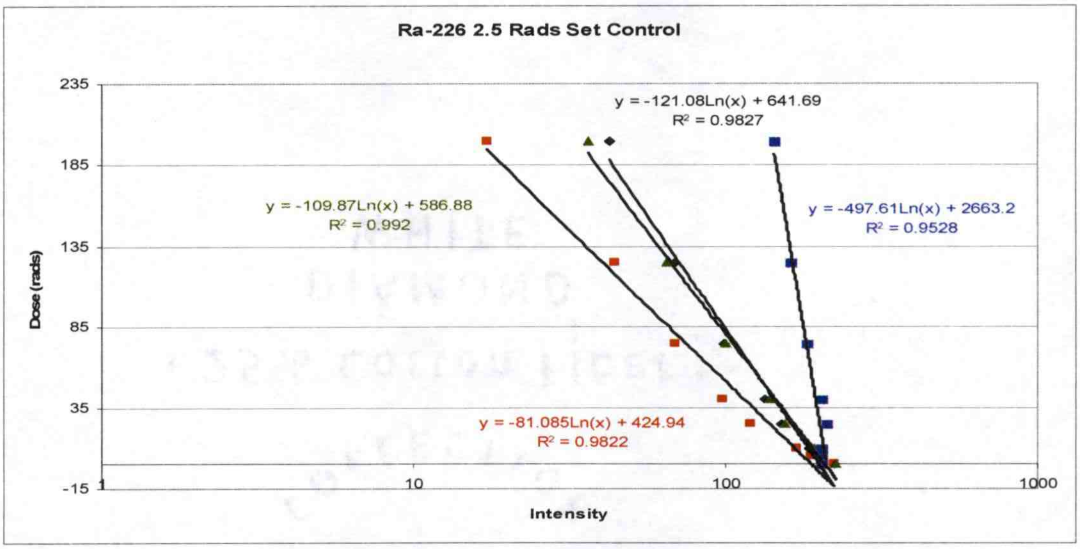

Figure C-3 Ra-226 2.5 rads set control graph. Histogram readings for luminosity (black diamonds), red (red squares), green (green triangles), and blue (blue squares) were plotted for each color on the set control card. These readings were graphed with their corresponding dose. Intensity values for 2.5 rads were calculated using the equation of the line.

Ra-226 – 5 Rads Card Set

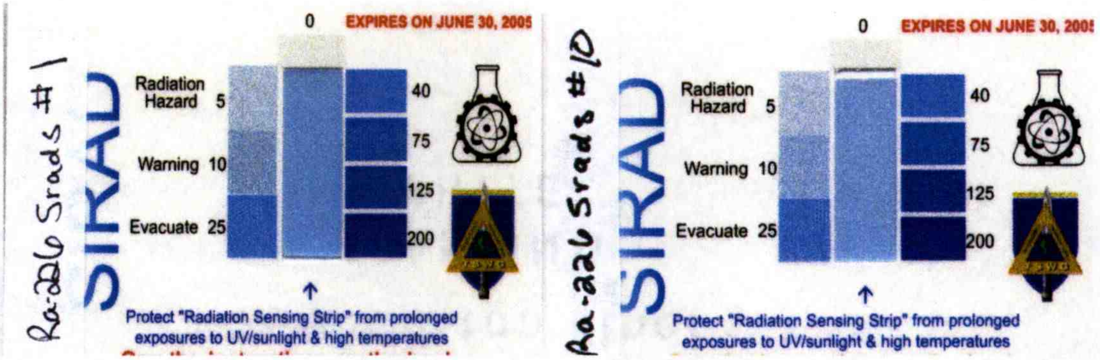

Figure C-4 Ra-226 5 rads SIRAD badges. SIRAD badge number one irradiated to 5 rads by the Ra-226 needle (left) and SIRAD badge number 10 irradiated to 5 rads by the Ra-226 needle (right) are shown side by side to show the uniformity of the color on the sensing strips. Card number 10 was placed at a 45° angle to test for angular dependence.

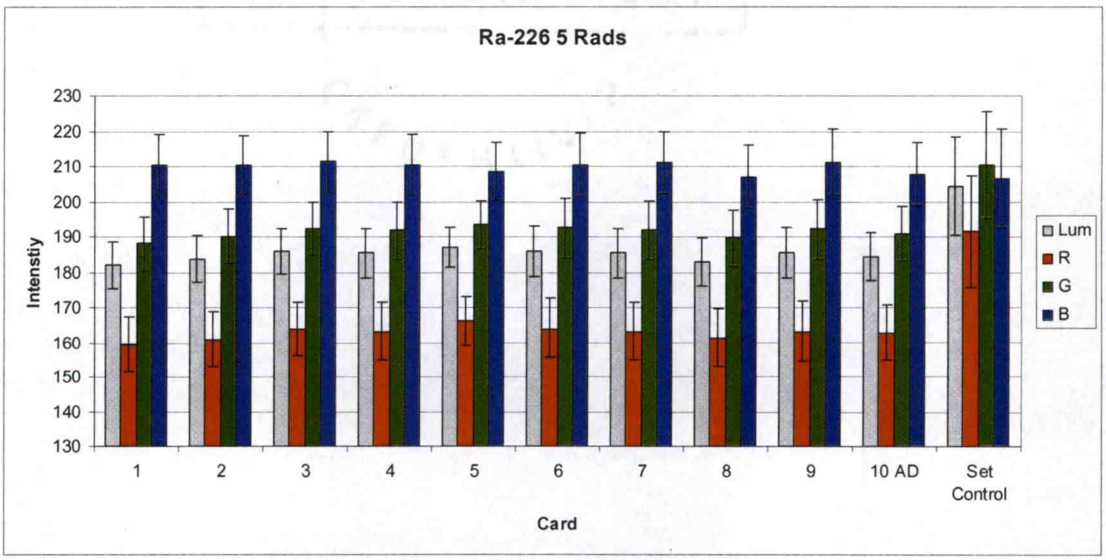

Figure C-5 Ra-226 5 rads card set compared to the set control. Each individual card is listed 1-10AD on the x-axis. The tenth card in this set was used to test for angular dependence, AD. The set control card values are for 5 rads. The y-axis represents the intensity readings for luminosity (grey bars), red, green, and blue, obtained from the 5 rads histograms created by Adobe Photoshop 7.0®.

Ra-226 – 7.5 Rads Card Set

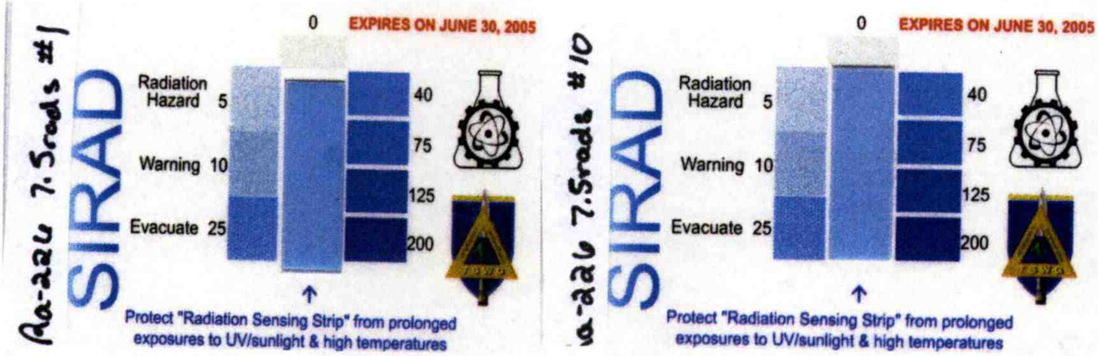

Figure C-6 Ra-226 7.5 rads SIRAD badges. SIRAD badge number one irradiated to 7.5 rads by the Ra-226 needle (left) and SIRAD badge number 10 irradiated to 7.5 rads by the Ra-226 needle (right) are shown side by side to show the uniformity of the color on the sensing strips. Card number 10 was placed at a 45° angle to test for angular dependence.

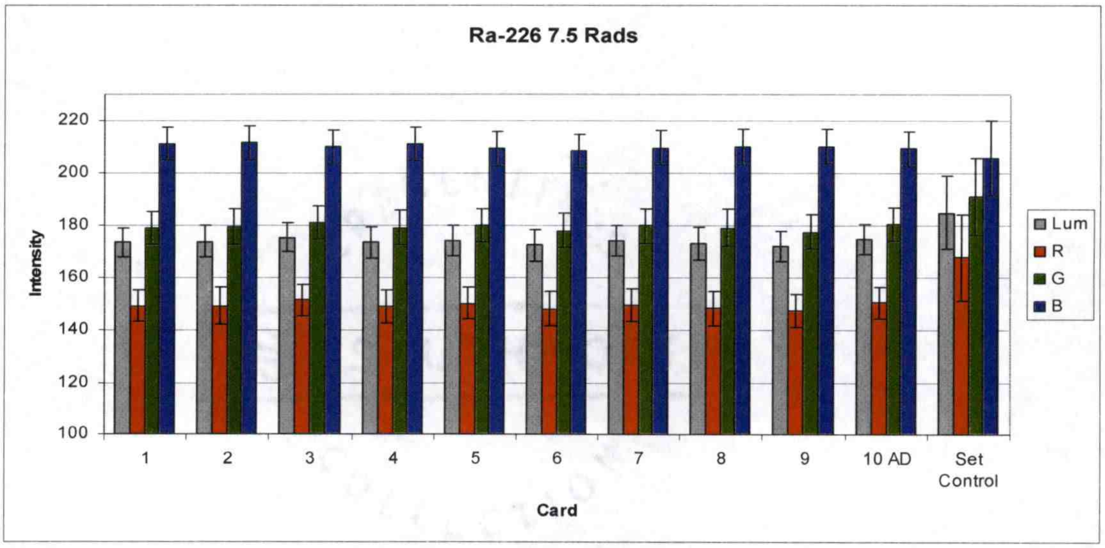

Figure C-7 Ra-226 7.5 rads card set compared to the set control. Each individual card is listed 1-10AD on the x-axis. The tenth card in this set was used to test for angular dependence, AD. The set control card values are for 7.5 rads. Since there is not a color chart for 7.5 rads, the values were calculated from equations taken from figure C-8. The y-axis represents the intensity readings for luminosity (grey bars), red, green, and blue, obtained from the 7.5 rads histograms created by Adobe Photoshop 7.0®.

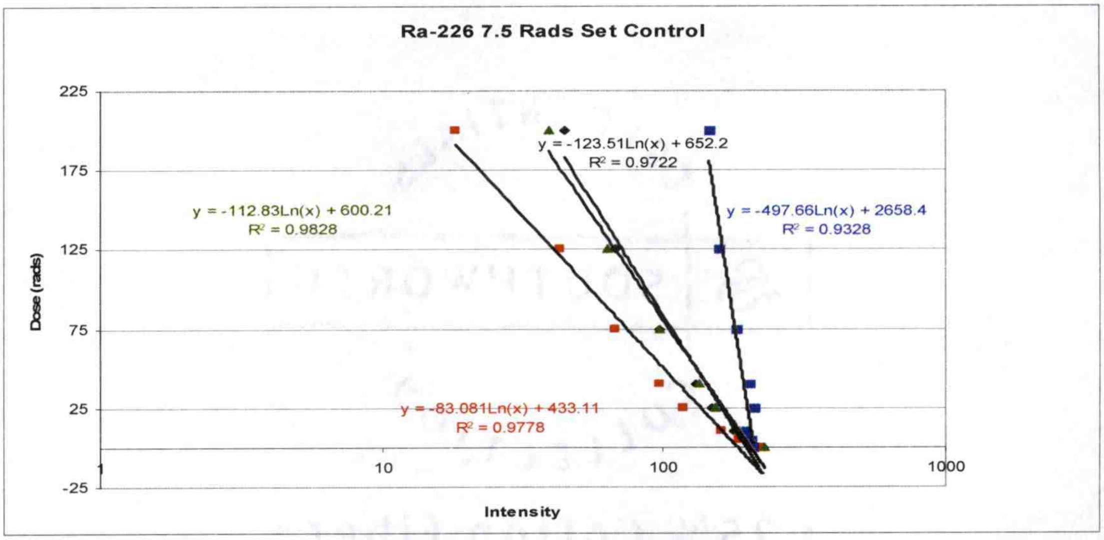

Figure C-8 Ra-226 7.5 rads set control graph. Histogram readings for luminosity (black diamonds), red (red squares), green (green triangles), and blue (blue squares) were plotted for each color on the set control card. These readings were graphed with their corresponding dose. Intensity values for 7.5 rads were calculated using the equation of the line.

<u>Ra-226 – 10 Rads Card Set</u>

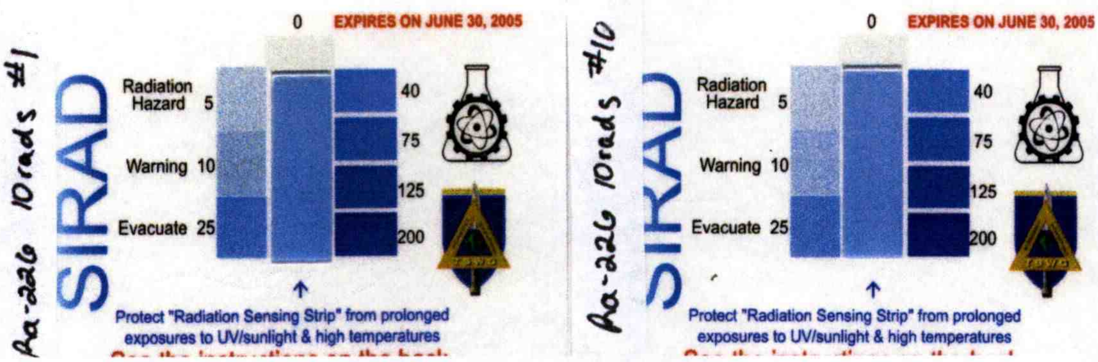

Figure C-9 Ra-226 10 rads SIRAD badges. SIRAD badge number one irradiated to 10 rads by the Ra-226 needle (left) and SIRAD badge number 10 irradiated to 10 rads by the Ra-226 needle (right) are shown side by side to show the uniformity of the color on the sensing strips. Card number 10 was placed at a 45° angle to test for angular dependence.

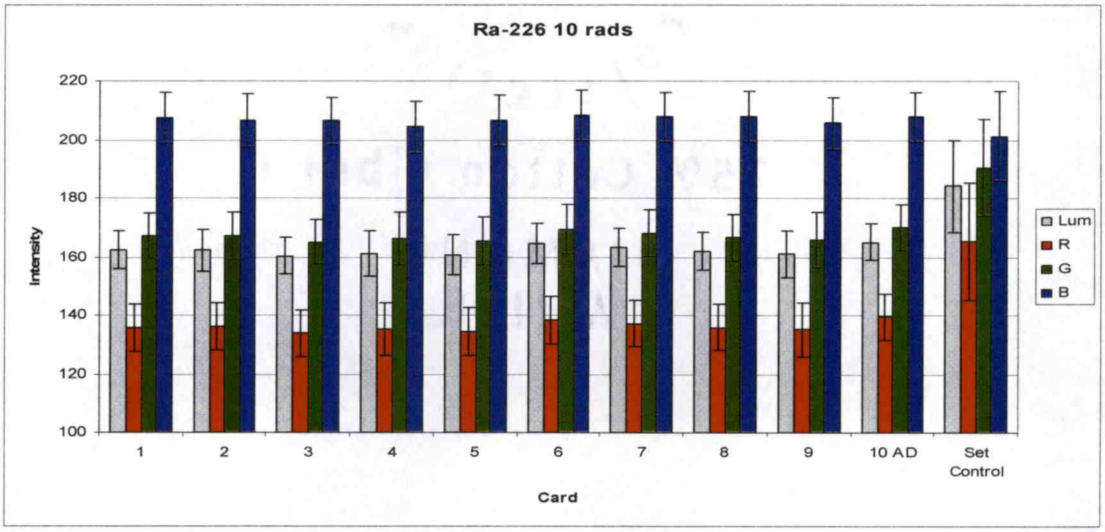

Figure C-10 Ra-226 10 rads card set compared to the set control. Each individual card is listed 1-10AD on the x-axis. The tenth card in this set was used to test for angular dependence, AD. The set control card values are for 5 rads. The y-axis represents the intensity readings for luminosity (grey bars), red, green, and blue, obtained from the 10 rads histograms created by Adobe Photoshop 7.0®.

Appendix D

Ra-226 Pictures and Graphs

The Co-60 series did not test for angular dependence so only card one is displayed. Only 40 rads and 125 rads were tested with the Gammacell Co-60 irradiation unit.

<u>**Co-60 – 40 Rads Card Set**</u>

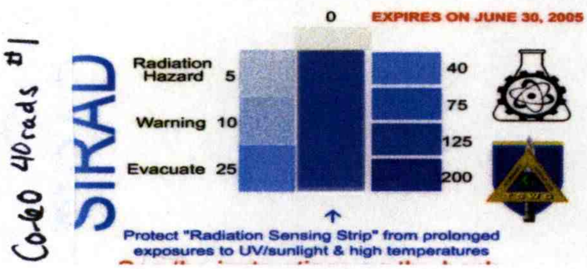

Figure D-1 Co-60 40 rads SIRAD badge. SIRAD badge number one irradiated to 40 rads by the Gammacell 220 Co-60 irradiation unit.

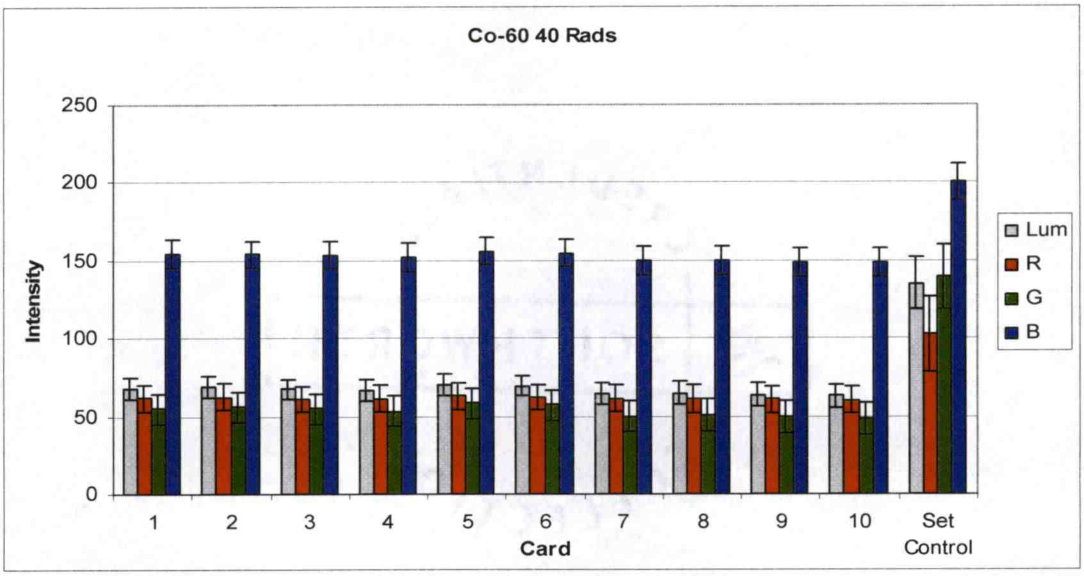

Figure D-2 Co-60 40 rads card set compared to the set control. Each individual card is listed 1-10 on the x-axis. The set control card values are for 40 rads. The y-axis represents the intensity readings for luminosity (grey bars), red, green, and blue, obtained from the 40 rads histograms created by Adobe Photoshop 7.0®.

<u>**Co-60 – 125 Rads Card Set (Initial)**</u>

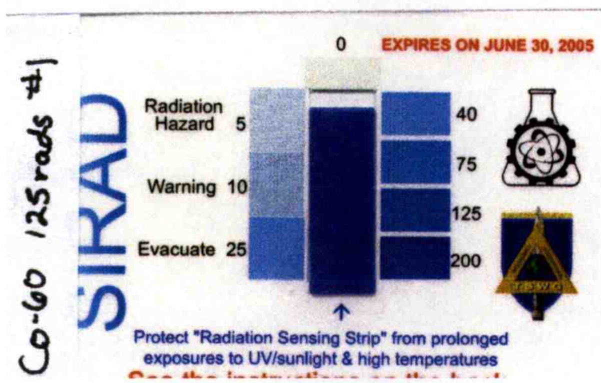

Figure D-3 Co-60 125 rads SIRAD badge, I. SIRAD badge number one irradiated to 125 rads by the Gammacell 220 Co-60 irradiation unit.

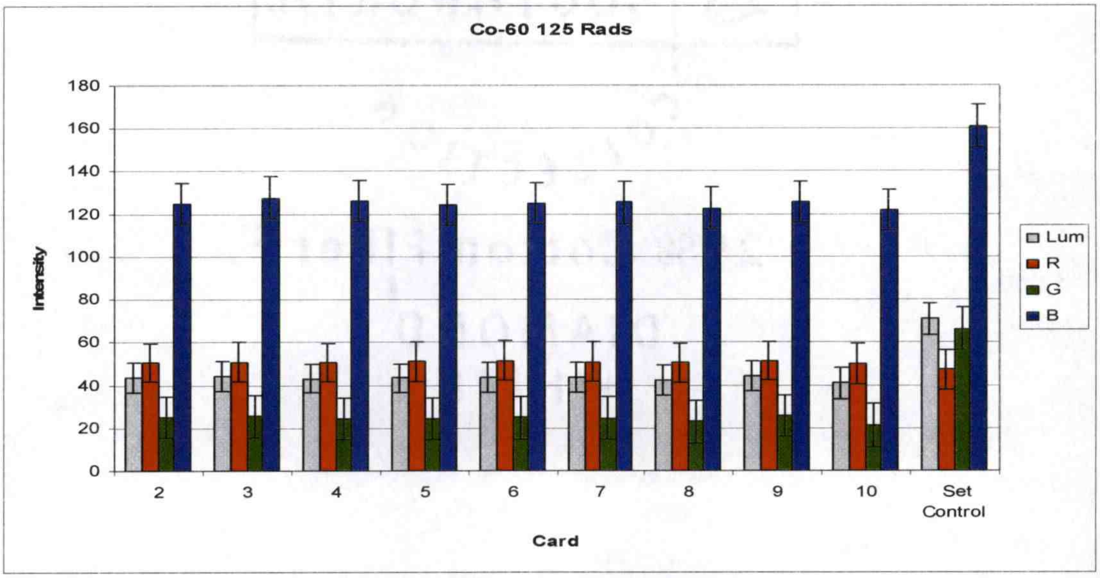

Figure D-4 Co-60 125 rads card set compared to the set control, I. Each individual card is listed 1-10 on the x-axis. The set control card values are for 125 rads. The y-axis represents the intensity readings for luminosity (grey bars), red, green, and blue, obtained from the 125 rads histograms created by Adobe Photoshop 7.0®.

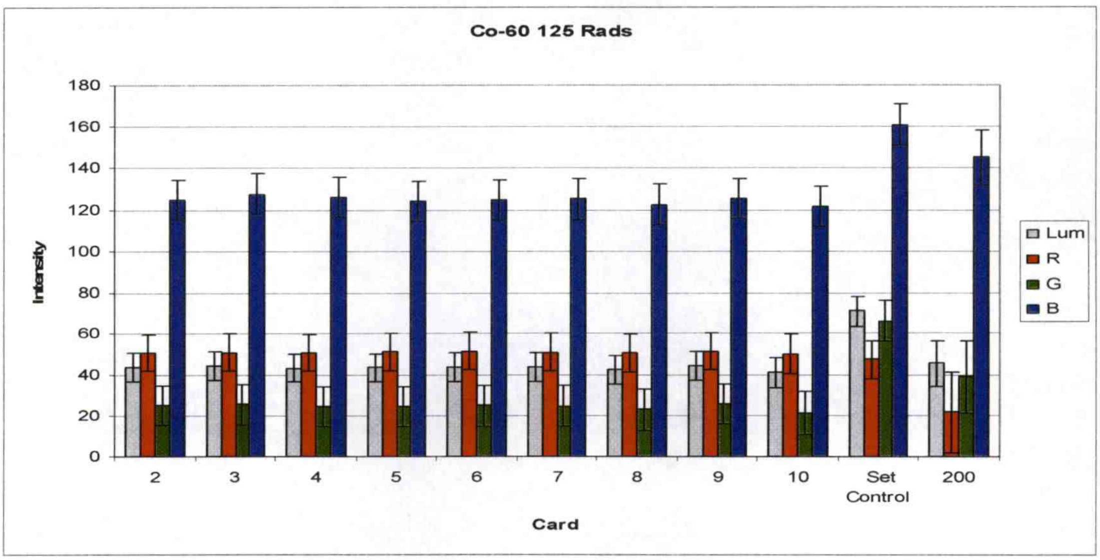

Figure D-5 Co-60 125 rads card set compared to the set control for 125 rads and 200 rads. Each individual card is listed 1-10 on the x-axis. The set control card values are for 125 rads. The set control values for 200 rads are also listed for comparison. The y-axis represents the intensity readings for luminosity (grey bars), red, green, and blue, obtained from the 125 rads histograms created by Adobe Photoshop 7.0®.

<u>**Co-60 – 125 Rads Card Set (Formerly the 40 Rads Card Set)**</u>

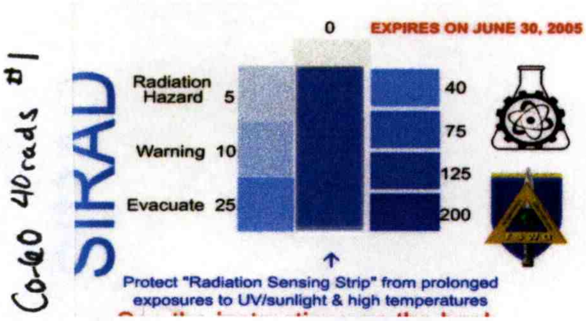

Figure D-6 Co-60 125 rads SIRAD badge, II. SIRAD badge number one irradiated to 125 rads by the Gammacell 220 Co-60 irradiation unit. The dose subjected to this card was formally thought to be 40 rads. It was renamed 125 rads.

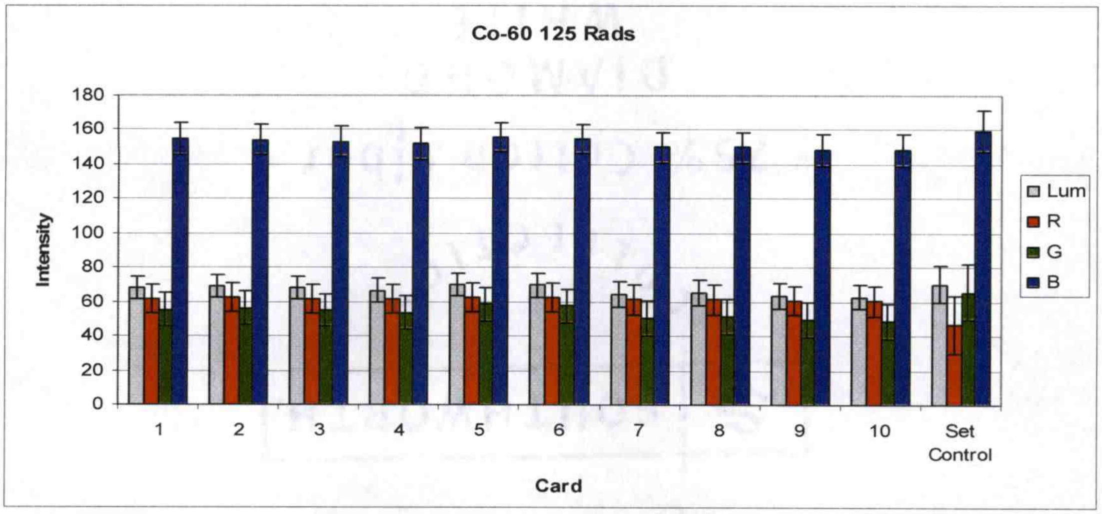

Figure D-7 Co-60 125 rads card set compared to the set control, II. Each individual card is listed 1-10 on the x-axis. The values for each card are the same as those for the 40 rads card set and are compared to the 125 rads values for the set control card. The y-axis represents the intensity readings for luminosity (grey bars), red, green, and blue, obtained from the 40 rads histograms created by Adobe Photoshop 7.0®.