AN ABSTRACT OF THE THESIS OF

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Title: Assessing and Evaluating the Self-indicating Instant Radiation Alert Dosimeter (SIRAD) for Gamma and Neutron Response.

Abstract approved:

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Kathryn A. Higley

The Self-indicating Instant Radiation Dosimeter (SIRAD) is credit card size, self reading, single use dosimeter produced by JP Laboratories. The SIRAD has a chemical strip that changes color based upon incident radiation. The color change is instantaneous and cumulative. The card was designed for first responders as a way for them to have integrating dosimeters without the need for processing facilities. The SIRAD has a range of 0 to 200 rads.

Multiple SIRAD cards were exposed to known radiation fields of a gamma source (Cs-137) and two different neutron sources: a PuBe source and the thermal column of the Oregon State University's TRIGA reactor. The chemical strips of each card were compared to the reference dose color key provided with the SIRAD cards. The cards gamma response to Cs-137 was consistent with the manufacturer's claim. The cards did not show a response to either the fast neutrons of the PuBe source or the thermal neutrons from the reactor.

Quantitative measurements of SIRAD response was done using a commercially available document scanner. The scanner was tested to determine the variation in readout across the scannable surface and whether multiple scans would affect the chemical strip. Multiple scanners were examined to determine their consistency in results. The first test showed that the area of scanner utilized would not affect the results. The second test showed that the chemical strip does not change significantly with multiple scans. The third test showed that for accurate comparisons a single scanner must be used.

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Assessing and Evaluating the Self-indicating Instant Radiation Alert Dosimeter (SIRAD) for Gamma and Neutron Response

by

H. Michael Stewart, Jr.

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H. Michael Stewart, Jr, Author

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Chapter 1 – Introduction

The Self-indicating Instant Radiation Alert Dosimeter (SIRAD) was produced by JP Laboratories[1]. The SIRAD is a credit card size, self reading, single use dosimeter designed for first responders as a way to monitor possible radiation exposure. The use of the SIRAD card will allow the user to have a limited radiation dosimetry program without the need to process dosimeters. The SIRAD card has a chemical strip that changes color based upon the dose received[1]. The color change in the chemical strip is instantaneous and cumulative. The strip color is read by comparing reference color blocks on the card. The user can then approximate their exposure. Because the color change is based on a chemical reaction, the card cannot be reset. The card has a listed exposure range of 0 rads to 200 rads.

Multiple SIRAD cards were exposed to known gamma and neutron radiation fields and their responses measured. The gamma source was a secondary NIST traceable Cs-137 source used for calibrations[2]. The neutron sources were a PuBe source (Appendix B) and the Oregon State University TRIGA Mark II reactor system (Anderson 1986). For the gamma source, the cards were exposed to radiation fields from 2.5 to 125 rads. For the neutron sources, the cards were exposed to radiation fields from 5 to 35 rads.

Under normal use the determination of dose is somewhat subjective. It is based on the individual's ability to discern and compare the developed color to the reference

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[1] JP Laboratories. Website www.jplabs.com/html/what_is_sirad.html on March 9, 2005.

[2] Oregon State University, Radiation Center Health Physics Procedures # 18. Maintenance and Calibration procedures for Radiation Protection Instrumentation (Including Operator Training Manual and Operating Procedures for the Radiation Center Gamma Instrument Calibration Facility). Revision #8, October 2004.

blocks. For this research an optical scanner was used with a software package to measure the change after radiation exposure. The software provided a numerical reading of luminosity, red, green and blue. Average values of these four parameters were taken from the chemical strips. They were subsequently compared to the color key provided on each card. The use of a scanner and software removed the human element of uncertainty in determining the color.

Optical scanners are inexpensive, common workplace tools. They can provide a logical means to capture and record the SIRAD cards. However, consistency in performance is essential if they are to be used for this task. As a side issue, three tests were done to evaluate their use. The first test was looking at different areas of a single scanner to determine if the readings would vary. The second test was looking at multiple readings of a single card to determine if the chemical strip would change due to repeated exposure from the high intensity light of the scanner. The third test was comparing readings of four additional scanners to determine if the readings varied among different scanners. These three tests showed what scanner parameters need to be held constant.

Endnotes

Anderson, T V. Oregon State TRIGA Reactor Training Manual, Volume 1, 3rd Edition; 1990.

Chapter 2 – Literature Review

2.1 Self-indicating Instant Radiation Alert Dosimeter

The Self-indicating Instant Radiation Alert Dosimeter (SIRAD) was produced by JP Laboratories[3]. The SIRAD is a credit card size, self reading, single use dosimeter. It is designed to allow first responders to monitor high radiation exposure without the need to process dosimeters. The SIRAD card has a chemical strip that changes color based upon the dose received (see Fig 2.1). The change in the chemical strip is instantaneous and cumulative. The strip color is visually compared to reference color squares on the card to approximate exposure. The card can be used in temperatures from -20°C to 60°C. The manufacturer includes an expiration date on each card that is just over a year from manufacture date. The card contains no hazardous chemicals and can be disposed of as normal waste[4].

The SIRAD Card has a listed exposure range of 0 rads to 200 rads. The active strip is made from proprietary diacetylene, polymeric binders and shelf life extenders[4]. The polymer structure is coated on a polyester film and dried. The coating is laminated and the laminated film cut into dimensions of 0.8 cm by 2.5 cm, and placed in the card. Since this is an organic material, the response is largely tissue equivalent. According to the manufacturer, the change in color is independent of the energy and dose rate. The manufacturer states that the change in color is independent of the type of radiation. The

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[3] JP Laboratories. Website www.jplabs.com/html/what_is_sirad.html on March 9, 2005.

[4] JP Laboratories. Website www.jplabs.com/html/manual.html on March 9, 2005.

manufacturer claims that the cards can monitor all kinds of x-rays (>10 eV), electrons, photons, alpha particles and neutrons (including thermal and epi-thermal)[5].

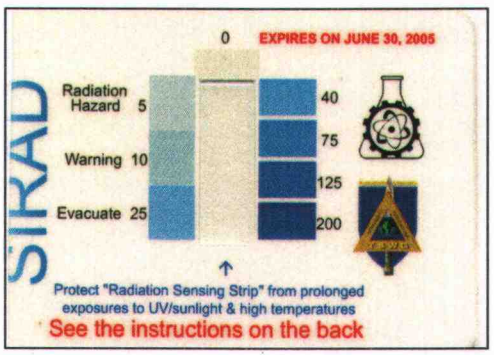


Figure2.1: SIRAD Card Unexposed

The diacetylenes used in the SIRAD are colorless solid monomers. They polymerize to a colored polymer upon thermal annealing or exposure to radiation. The color change is due to the breaking and reforming of chemical bonds by a process called cross linking. The polymerized product appears blue to the eye. The more energy deposited, the more polymerization and the darker the shade of blue. The specific diacetylenes utilized by the manufacturer are purported to have a high radiation reactivity and low thermal reactivity[5].

The manufacturer states that the cards have a shelf life of three months at 60°C and at least one year at room temperature. The color strip can also change due to extended exposure to ultraviolet light. The cards come with a protective cover to keep unwanted light from striking the strip (see Fig 2.2). According to the manufacturer, the cards should be read under a fluorescent light to determine the color change[5].

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[5] JP Laboratories. Website www.jplabs.com/html/manual.html on March 9, 2005.

The SIRAD card is currently the only dosimeter utilizing a chemical strip for personnel on the market. All other types of dosimeters currently being marketed require the use of a battery and/or calibration. The SIRAD card requires neither a battery nor any calibration.

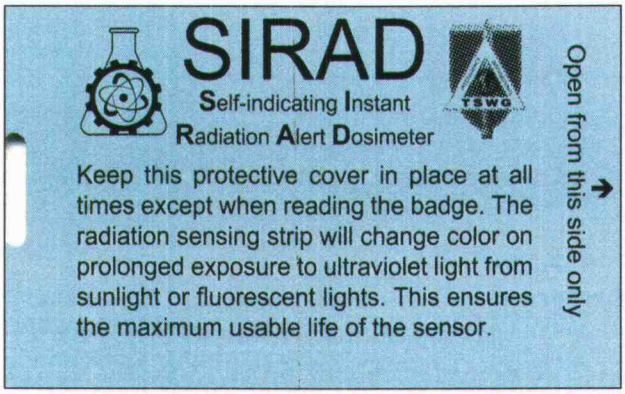


Figure 2.2: SIRAD Card Cover. This is used to protect the reactive strip from UV light.

Chapter 3 – Materials and Methods

3.1 Radiation Dose using Cs-137

For a baseline, a single SIRAD card was chosen to be an overall control card. This control card was not exposed to any radiation and kept with all the experimental cards to ensure that any unknown factors would be the same for all cards. This card was scanned into a file (see Fig 3.1) and the reference dose color strip and the chemical strip were analyzed using Photoshop. The card color key values were then tabulated (see Table 4.1). The data recorded included a histogram of each reference dose color and the chemical strip (see Appendix A). The software package analyzed the luminosity, and the colors red, green and blue for each selected region of interest. The software also provided an estimate of the standard deviation of the luminosity and color based upon the histogram created. A search for information about how the standard deviation was calculated by the manufacturer has not yielded any information. The manual does not discuss the method and phone calls to the developer have not yielded an answer[6]. The two most probable ways of calculating the standard deviation is from the Full Width at Half Maximum or by summing the squared differences of the graph points and calculating the variance.

[6] Adobe\Photoshop7.0\Help\help.html

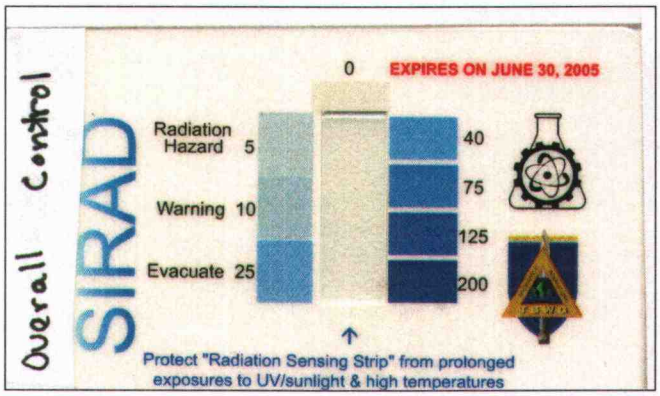


Figure3.1: SIRAD Overall Control

SIRAD card sets were exposed to a Cs-137 source. Cs-137 has a gamma ray energy of 662 keV and a half life of 30.17 years. The dose rate of the Cs-137 source utilized from the Oregon State University Radiation Center is 5780 mR/hr at the position 192.2 of the well counter[7] utilized in this experiment (see Fig 3.2). Doses of 2.5, 5, 7.5, 10, 40 and 125 rads were delivered. A set of cards consisted of 11 for each level of radiation exposure of interest. One of these cards was used as a control and was not exposed but is kept with the other ten to determine if any other changes occur with the set. The exposure times for each dose are tabulated in Table 3.1.

[7] Oregon State University, Radiation Center Health Physics Procedures # 18. Maintenance and Calibration procedures for Radiation Protection Instrumentation (Including Operator Training Manual and Operating Procedures for the Radiation Center Gamma Instrument Calibration Facility). Revision #8, October 2004.



Figure 3.2: Well Counter Control for the Oregon State University's Cs-137 source



Figure 3.3: SIRAD Card Geometry with Well Counter

Table 3.1 Radiation times utilized for Cs-137 source

Dose (rad)	Rate (mrad/hr)	Dose Time (hr)	Dose Time Actual
2.5	5780	0.432	25 min 57 sec
5	5780	0.865	51 min 54 sec
7.5	5780	1.298	1 hr 17 min 24 sec
10	5780	1.730	1 hr 43 min 48 sec
40	5780	6.920	6 hr 55 min 13 sec
125	5780	21.626	21 hr 18 min 47 sec

3.2 Radiation Dose Application using a Neutron source

3.2.1 Radiation Dose Application using a PuBe source

To determine if the interaction of the chemical shows any dependence upon the type of incident radiation, a neutron source was used to expose sets of cards. The neutron source used was a 3 Ci PuBe source which has a half life of 86.4 years (see Fig 3.4) (Appendix B). This source is a combination neutron gamma source. The Pu decays by alpha particle and the Be absorbs the alpha and emits a neutron and gamma. The average energy of the neutron emitted is 4.5 MeV (Shleien et. al 1998). This is considered to be a fast neutron source (Shleien et. al 1998). Based upon information provided about the PuBe source (Appendix B), it has a neutron dose rate of 200 mrad/hr at 16.2 cm. An ion chamber was used to determine the gamma dose rate at 16.2 cm (the point of exposure). It was found to be 18 mrad/hr. The combined neutron and gamma dose rate is 218 mrad/hr.

The first test completed was using unmoderated neutrons for 5 rad. The second test consisted of placing a polyethylene block behind the card set to thermalize the neutrons with an exposure of 10 rad. A third test was done with one SIRAD card being cut down to just the strip and placed within a 10 inch Bonner Sphere (see Fig 3.5). This test was done for 5 rad with just the neutron exposure rate for a period of 25 hours.

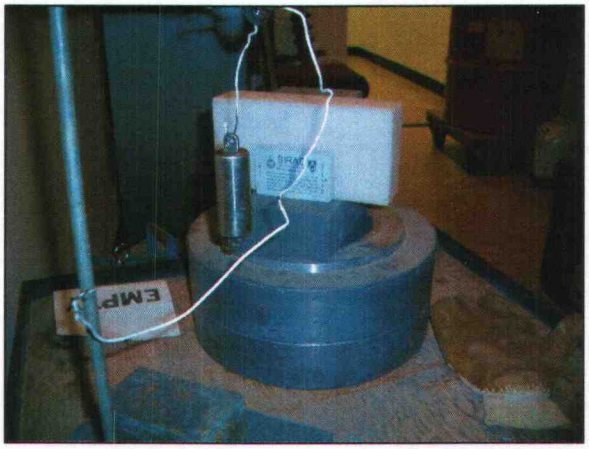


Figure 3.4: PuBe Source Setup

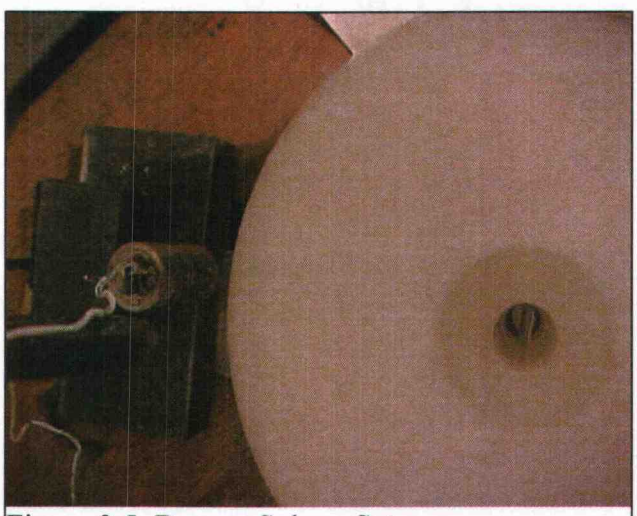


Figure 3.5: Bonner Sphere Setup

3.2.2 Radiation Dose Application using the TRIGA Thermal Column

To determine if the interaction of the chemical strip is sensitive to thermal neutrons, the thermal column of the Oregon State University TRIGA Mark II reactor was utilized. The thermal column is an area outside of the reactor core and moderator (but inside the shielding) that is filled with graphite. The horizontal centerline of the thermal column is inline with the centerline of the reactor core. A sample can be placed in the

thermal column for irradiation to look primarily at thermal neutron reactions (Anderson 1986). One SIRAD card was placed into a part of the reactor with an ionization chamber (Victoreen CDV-715R Serial Number 140679). The ionization chamber was used because in addition to neutrons there are also gamma rays in the reactor thermal column. The readings from the ionization chamber (which is insensitive to neutrons) is plotted in figure 3.6. The experiment was designed to provide an exposure of approximately 25 R gamma dose. Summing the area under the graph shows a gamma dose of 26.1 R. Any dose appearing on the SIRAD card above 26.1 R would be due to the thermal neutrons.

The neutron dose for the thermal column was then calculated. The neutron flux in the thermal column is 8 x 10^{10} n cm^{-2} s^{-1} at 1 MW [8]. The flux is scalable with power and with the reactor at 100 W the flux is 8 x 10^{6} n cm^{-2} s^{-1}. The dose rate for thermal neutrons based upon the flux is 980 x 10^{6} n cm^{-2} rem^{-1} (10 CFR 20). The quality factor for thermal neutrons is 2 (10 CFR 20). The time that the reactor was at 100 W was 21 minutes. The absorbed dose calculation for the neutron component is then:

$$X = \left(\frac{8x10^{6}\, n\, cm^{-2}\, s^{-1}}{980x10^{6}\, n\, cm^{-2}\, rem^{-1}}\right)\left(21\min\frac{60s}{\min}\right)\left(\frac{1rad}{2rem}\right) = 5.1rad \quad \text{Equation 3.1}$$

With the neutron and gamma component, the SIRAD card should have an exposure of 31 rads. The conversion factors shown above are for converting thermal neutrons to rem (10 CRF 20). Since the SIRAD reads in rads, the quality factor for thermal neutrons was divided out, dropping the dose estimate by 50%. With a quality factor of 2 (for thermal neutrons) the dose equivalent delivered would have been 10.2 rem.

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[8] Oregon State University TRIGA Specification Thermal Column
http://n3.oregonstate.edu/facilities/radiation_center/spec4.html on March 3, 2005

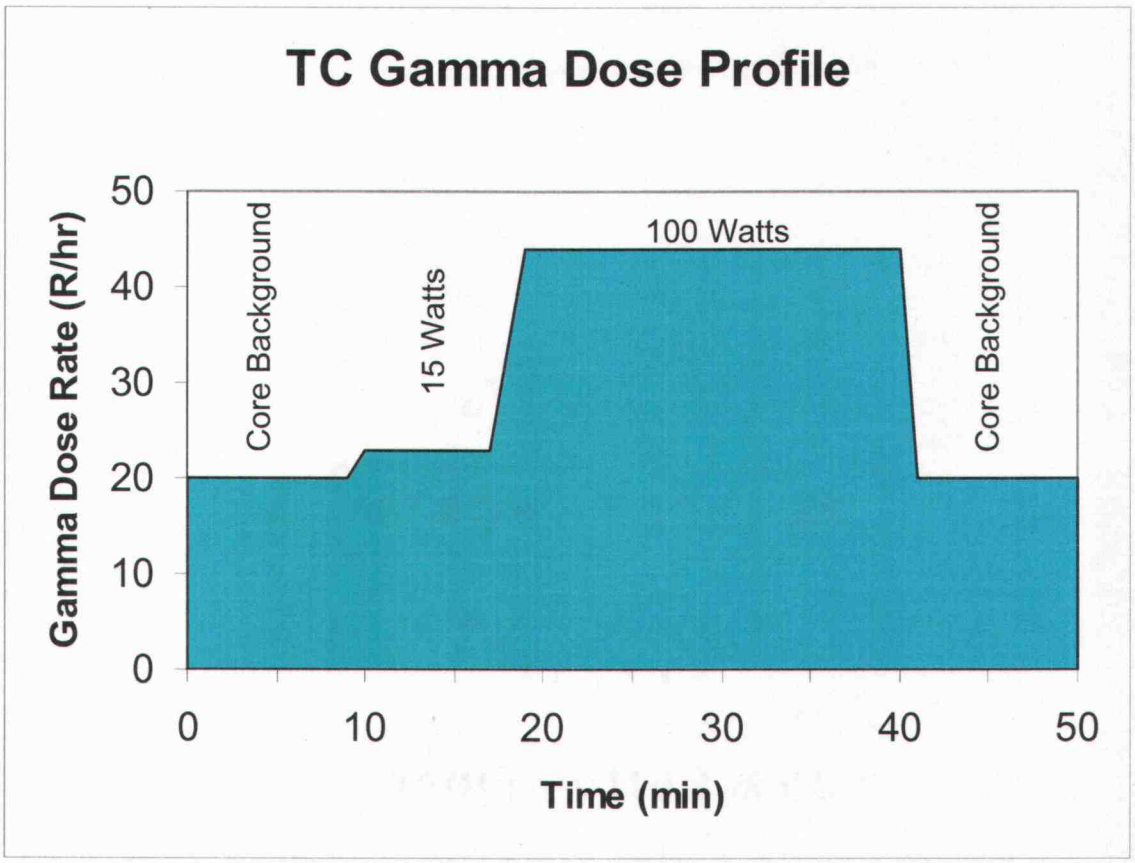


Figure 3.6: Ionization Chamber reading over time gamma exposure rate. The summation of the area is the total gamma exposure. The Core Background is the reading in the thermal column when the reactor is not in operation. This time was needed for opening and closing the thermal column shield. The reactor is initially started at 15 Watts and held there for eight minutes by protocol. The reactor was then brought up to 100 Watts for the time period indicated.

3.3 Use of scanner

The scanner used for reading of all radiation exposed cards was an Epson® model 2480[9]. This scanner has a scan area of 8.5" by 11.7". The photoelectric device is a Color Epson MatrixCCD™ line sensor which is a white cold cathode fluorescent lamp. The

[9] Epson Model 2480. Website www.epson.com/cgi-bin/Store/consumer on February 28, 2005.

maximum optical resolution is 2400 dpi and has an optical density of 3.2 Dmax (Epson). The optical resolution used for this research was 300 dpi with this scanner.

3.3.1 Scanner Test One – Scanner Areas

One of the questions that this project is looking at is the use of a scanner for analyzing the cards. The main scanner used in this project is an Epson® 2480. An area of the scanner was fixed for the reading of the cards using a paper jig (see Fig 3.7). Tests were done to determine if there is any type of effect from the scanner. The first test was to see if the cards read differently on different areas of the scanner surface. The cards were read at seven different points (see Fig 3.8).

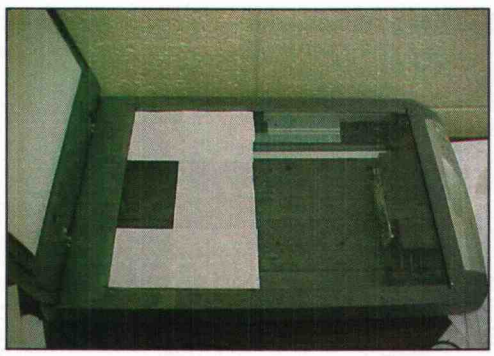


Figure 3.7: Scanner Jig for reading SIRAD cards on the EPSON scanner

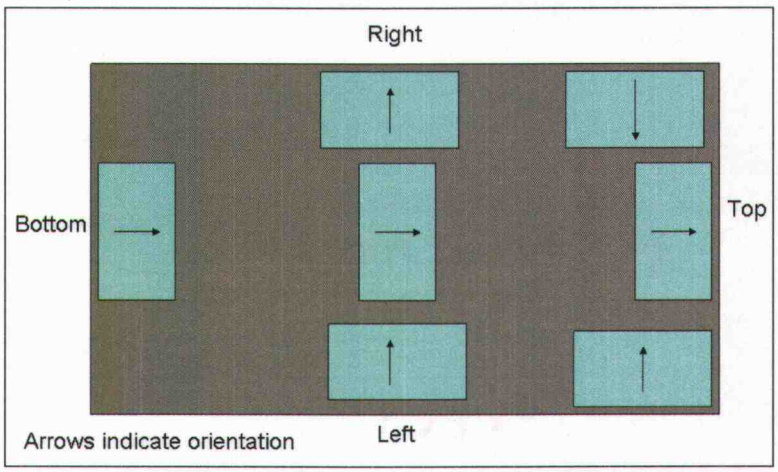


Figure 3.8: Areas of Scanner tested with SIRAD card

3.3.2 Scanner Test Two – Multiple Scans of a singular Card

Another test of the scanner was doing multiple readings of an unexposed card to determine if the chemical strip reading would change with multiple scans. The scanner does utilize a fluorescent light which is what the manufacturer says the cards should be read under. The card was scanned 100 times and a reading of the chemical strip was done every 20 times.

3.3.3 Scanner Test Three – Different Scanners

The third test was to determine how different scanners treat the same image. An unexposed card was used on four different scanners. The scanners utilized were a Canon FB620U at 75 dpi, HPScanJet 8250 at 200 dpi, HPScanJet 5200C at 150 dpi and HPScanJet C7116 at 400 dpi. Using the scanned image from the Epson® 2480 as the control, the scanned information from the other four scanners were compared.

3.4 Adobe® Photoshop 7.0

The software program used to analyze the SIRAD cards was Adobe® Photoshop 7.0[10]. This software program allows the input of an image from multiple resources including a scanner. The image can then be analyzed by the user. For this research, the area of interest was selected and then the program provided a histogram of the response intensities for luminosity, the color red, the color green and the color blue. The software provided an average intensity response and a standard deviation for each of the three colors and the brightness. These are the values used to compare the color strip to the card colors for determining dose response.

The software used for all readings of cards was Photoshop 7.0. After the card of interest was scanned into the computer, the image was sent to Photoshop 7.0. A region of interest was selected using the pointer. The selected region of interest was then looked at by the software histogram. The histogram provided an intensity of the luminosity, red, green and blue (see Fig 3.9). The software provided a mean intensity number and standard deviation across the selected area. For all sets of cards, the control card was read for all color bars of respective dose and the unexposed chemical strip. For all exposed cards, only the chemical strip was read to compare with the respective color bar dose. The data from Photoshop 7.0 was used to ensure reproducibility. The data from the software was then inputted to a spreadsheet program.

---

[10] Adobe Photoshop 7.0. Website www.adobe.com on March 9, 2005.

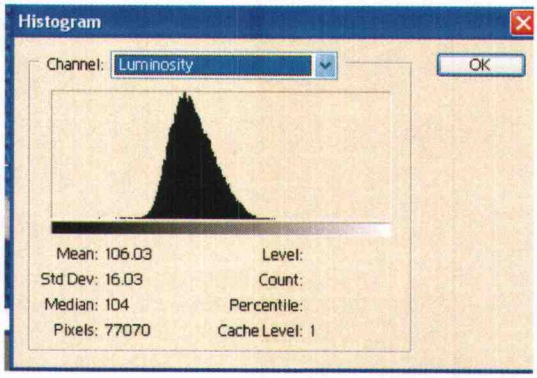


Figure 3.9a: Luminosity Graph Sample

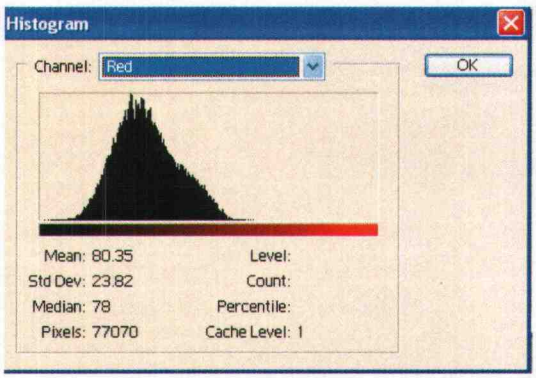


Figure 3.9b: Red Graph Sample

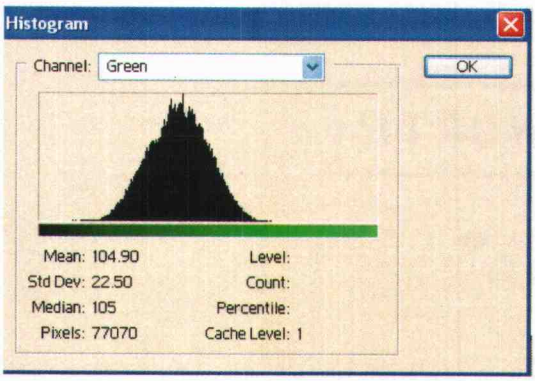


Figure 3.9c: Green Graph Sample

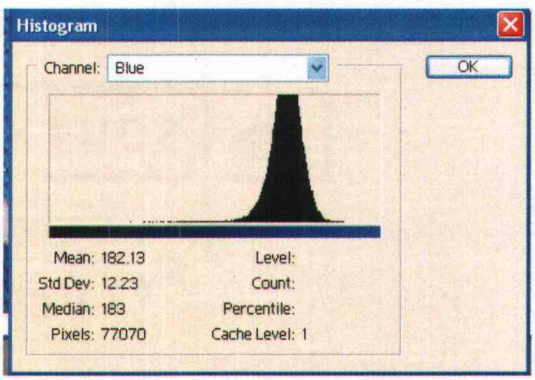


Figure 3.9d: Blue Graph Sample

Figure 3.9 Histograms from Photoshop 7.0. Using the overall SIRAD control card and the color code of 75 Rads, these histograms were created from Photoshop 7.0 for the luminosity, the color red, the color green and the color blue.

Endnotes

Shleien, B., Slaback, L.A. & Birky, B.K. 1998. Handbook of Health Physics and Radiological Health. Baltimore: Williams & Wilkins.

Anderson, T.V. 1986. Oregon State TRIGA Reactor Training Manual, Volume #1, 3rd Edition.

10 Code of Federal Regulation part 20. January, 2002. Office of the Federal Register National Archives and Records Administration

Chapter 4 – Results

4.1 Overall Control Card

The overall control card was read using the scanner and software for the card reference dose colors (see Table 4.1). The control cards for all seven cesium doses were analyzed (see Tables 4.2 through 4.5). The intensities were averaged for each reference dose color and the standard deviation was found. The average intensities of the luminosity, the color red, the color green and the color blue were then graphed (see Figs 4.1 through 4.4) on a semi-log plot.

Table 4.1 Results from the eight color keys on the SIRAD Overall Control Card. Data from Photoshop 7.0 of intensities and standard deviations for luminosity, and the colors red, green and blue.

Overall Control - Read 2/8/05 - Resolution 1200 dpi									
Scanner Parameter	Color Key Reference Dose								Unexposed Sensing Strip
	0	5	10	25	40	75	125	200	
Lum*	229.44	208.29	193.94	158.59	139.75	106.08	73.84	45.46	224.91
Red	230.67	197.07	179.47	133	109.01	80.54	54.51	23.47	224.9
Green	232.95	213.56	198.96	161.76	143.42	104.96	67.4	38.15	227.84
Blue	207.2	210.66	206.48	211.42	203.91	181.8	161.14	144.69	209.22
Standard Deviation									
Dose	0	5	10	25	40	75	125	200	Strip
Lum	7.56	12.91	13.29	16.5	16.51	16.03	12.58	11.05	6.09
Red	8.9	15.36	20.85	25.26	25.68	23.73	21.67	13.72	7.87
Green	8.83	14.24	15.09	19.71	20.36	22.55	19.63	17.05	7.11
Blue	11.08	12.99	10.44	10.2	10.71	12.41	12.44	13.59	7.83

* - Luminosity

Table 4.2. SIRAD Control Cards (Luminosity). The color keys from each of the control cards from the seven sets of cards were analyzed. The intensities are tabulated along with the calculated average and standard deviation.

SIRAD Control Cards for Luminosity								
	Color Key Reference Dose (rad)							
Control Card Set	0	5	10	25	40	75	125	200
1	229.4	208.3	193.9	158.6	139.8	106.1	73.8	45.5
2	231.6	209.6	189.6	153.9	139.9	105.8	73.5	47.8
3	226.6	199.0	176.4	146.0	130.0	97.3	68.2	45.3
4	229.0	210.2	188.2	152.4	139.6	105.6	74.4	47.0
5	229.0	207.3	187.5	154.5	138.4	104.2	75.5	47.6
6	224.9	201.3	176.9	144.9	130.3	97.6	69.7	44.5
7	231.7	208.5	187.9	155.7	139.2	104.3	74.7	46.9
Average	228.9	206.3	185.8	152.3	136.7	103.0	72.8	46.4
Standard Deviation	2.5	4.4	6.6	5.1	4.5	3.8	2.8	1.3

Table 4.3. SIRAD Control Cards (Red). The color keys from each of the control cards from the seven sets of cards were analyzed. The intensities are tabulated along with the calculated average and standard deviation.

SIRAD Control Cards for the color Red								
	Color Key Reference Dose (rad)							
Control Card Set	0	5	10	25	40	75	125	200
1	230.7	197.1	179.5	133.0	109.0	80.5	54.5	23.5
2	232.7	197.2	172.1	127.9	111.0	80.9	54.5	26.8
3	225.2	184.4	156.3	114.5	95.2	66.2	42.7	20.3
4	230.2	198.2	170.1	124.9	109.4	78.8	53.0	22.7
5	228.7	194.5	169.2	127.5	107.9	78.6	55.4	25.7
6	223.5	186.9	156.9	112.8	95.3	66.2	44.4	19.2
7	232.7	196.9	170.7	129.4	109.5	78.7	54.4	23.8
Average	229.1	193.6	167.8	124.3	105.3	75.7	51.3	23.1
Standard Deviation	3.6	5.6	8.4	7.7	6.9	6.6	5.3	2.7

Table 4.4. SIRAD Control Cards (Green). The color keys from each of the control cards from the seven sets of cards were analyzed. The intensities are tabulated along with the calculated average and standard deviation.

SIRAD Control Card for the color Green								
	Color Key Reference Dose (rad)							
Control Card Set	0	5	10	25	40	75	125	200
1	233.0	213.6	199.0	161.8	143.4	105.0	67.4	38.2
2	235.0	215.0	195.5	157.0	142.9	104.3	66.8	39.7
3	231.1	205.5	183.5	150.3	134.2	97.6	64.1	39.6
4	232.6	215.7	194.4	156.2	143.3	105.2	69.2	40.9
5	233.1	213.1	193.7	157.9	141.7	102.7	69.4	40.0
6	229.2	207.7	184.0	149.3	134.4	98.0	65.5	38.8
7	235.1	213.8	193.8	158.8	142.2	102.9	68.6	39.6
Average	232.7	212.0	192.0	155.9	140.3	102.2	67.3	39.5
Standard Deviation	2.1	3.9	5.9	4.5	4.2	3.2	2.0	0.9

Table 4.5. SIRAD Control Cards (Blue). The color keys from each of the control cards from the seven sets of cards were analyzed. The intensities are tabulated along with the calculated average and standard deviation.

SIRAD Control Cards for the color Blue								
	Color Key Reference Dose (rad)							
Control Card Set	0	5	10	25	40	75	125	200
1	207.2	210.7	206.5	211.4	203.9	181.8	161.1	144.7
2	210.1	214.5	205.8	208.1	203.0	181.4	161.3	149.1
3	206.2	203.6	193.0	208.7	202.8	180.5	159.9	144.8
4	206.3	213.8	204.7	206.6	202.4	181.0	160.9	146.2
5	208.0	211.1	203.9	210.2	203.7	181.5	162.3	148.4
6	205.7	206.9	193.8	209.0	203.3	180.9	161.0	143.9
7	210.4	211.6	203.1	210.7	203.9	181.4	162.9	149.1
Average	207.7	210.3	201.5	209.2	203.3	181.2	161.4	146.6
Standard Deviation	1.9	3.8	5.7	1.6	0.6	0.4	1.0	2.2

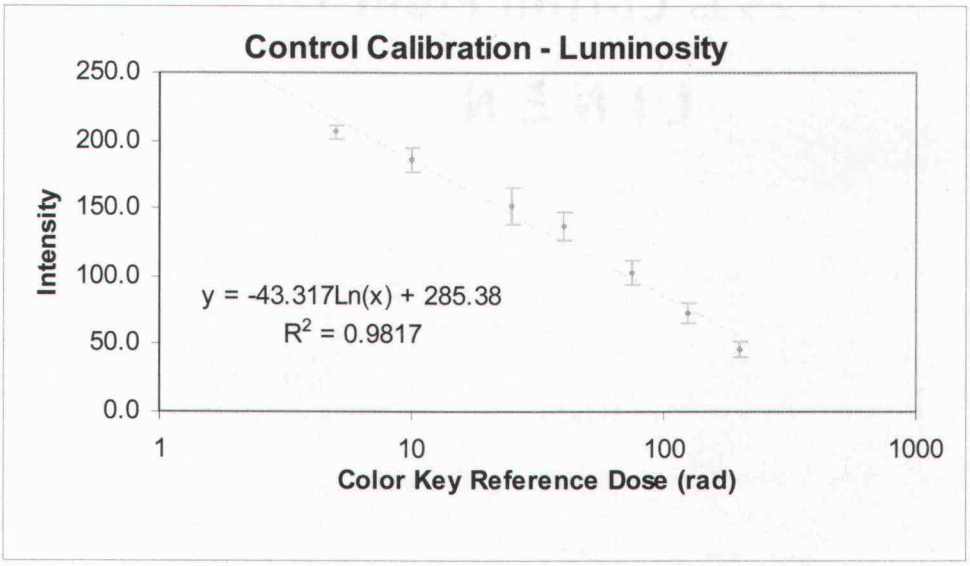


Figure 4.1. SIRAD Control Cards (Luminosity). Color Key Reference Dose versus Intensity. The error bars are two standard deviations.

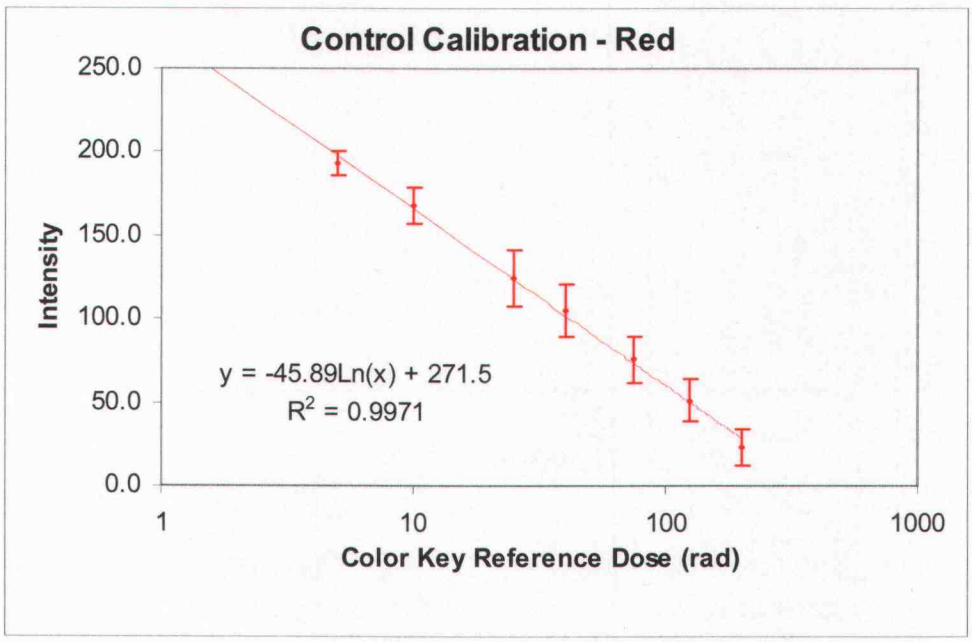


Figure 4.2. SIRAD Control Cards (Red). Color Key Reference Dose versus Intensity. The error bars are two standard deviations.

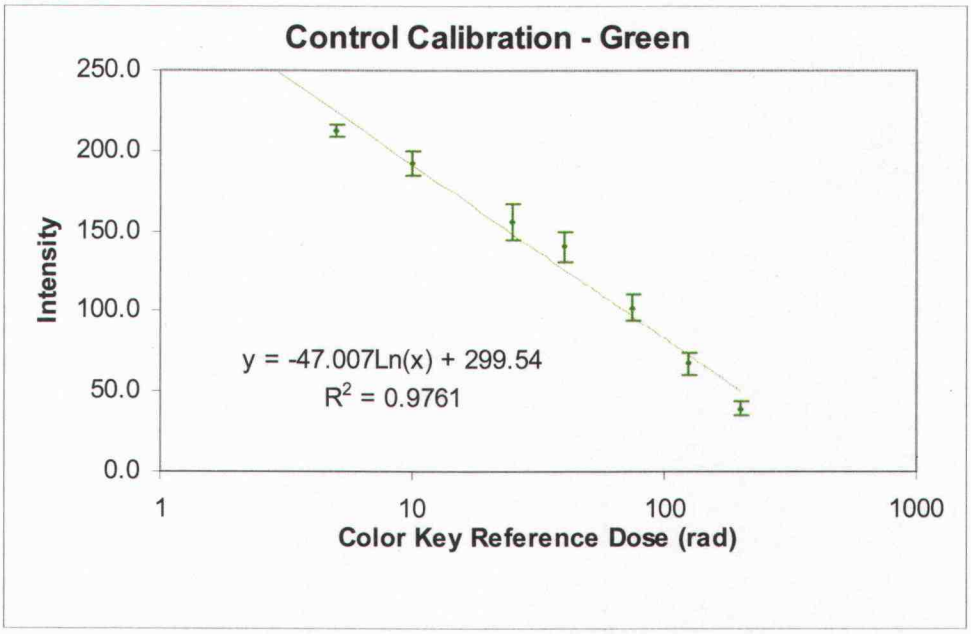


Figure 4.3. SIRAD Control Cards (Green). Color Key Reference Dose versus Intensity. The error bars are two standard deviations.

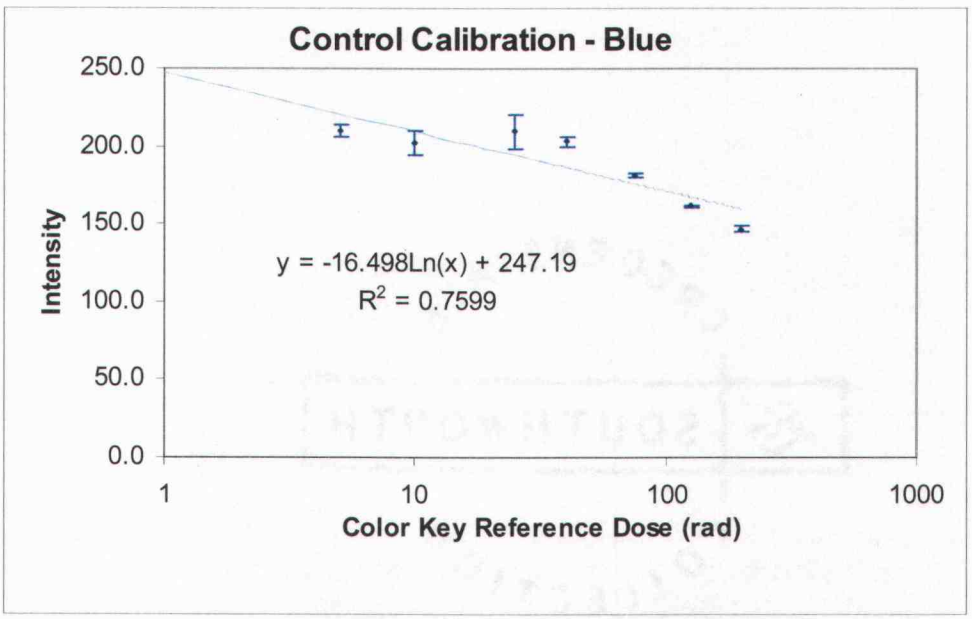


Figure 4.4. SIRAD Control Cards (Blue). Color Key Reference Dose versus Intensity. The error bars are two standard deviations.

4.2 Cs-137 Cards

Sets of 10 SIRAD cards were each exposed to 2.5, 5, 7.5, 10, 40 and 125 rads. Each exposed card was measured using the Epson scanner with Adobe Photoshop. The values for luminosity, red, green and blue were recorded. Average values and their ± 2 standard deviations were plotted as a function of dose (see Figs 4.5 through 4.8). For comparison the color key values (see Figs 4.1 through 4.4) are also included. A representative card from each exposure level is shown for visual comparison (see Figs 4.9 through 4.14).

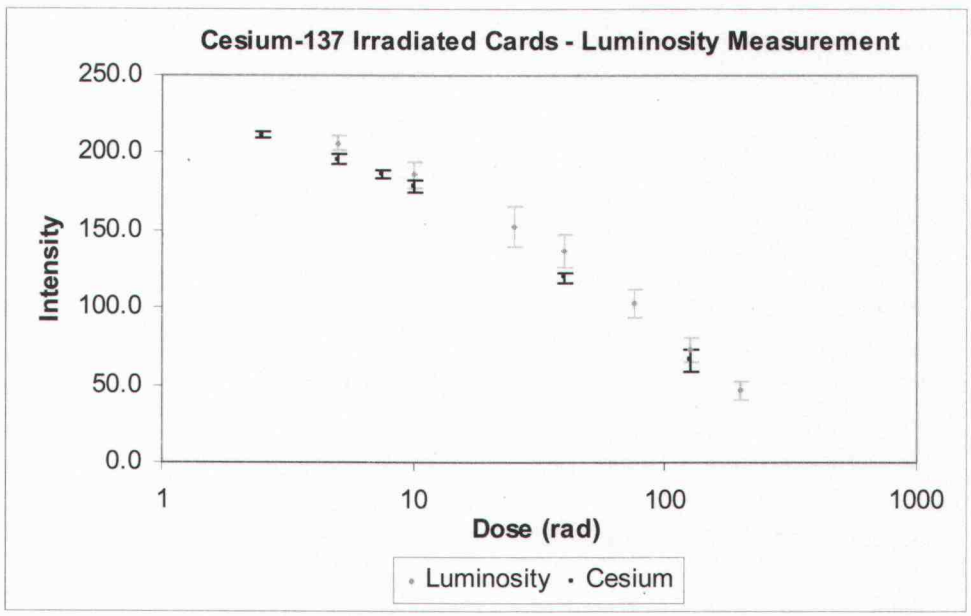


Figure 4.5. Cesium 137 Irradiated Cards versus Luminosity. The measured luminosity of the irradiated cards are plotted versus their total dose. The error bars are two standard deviations.

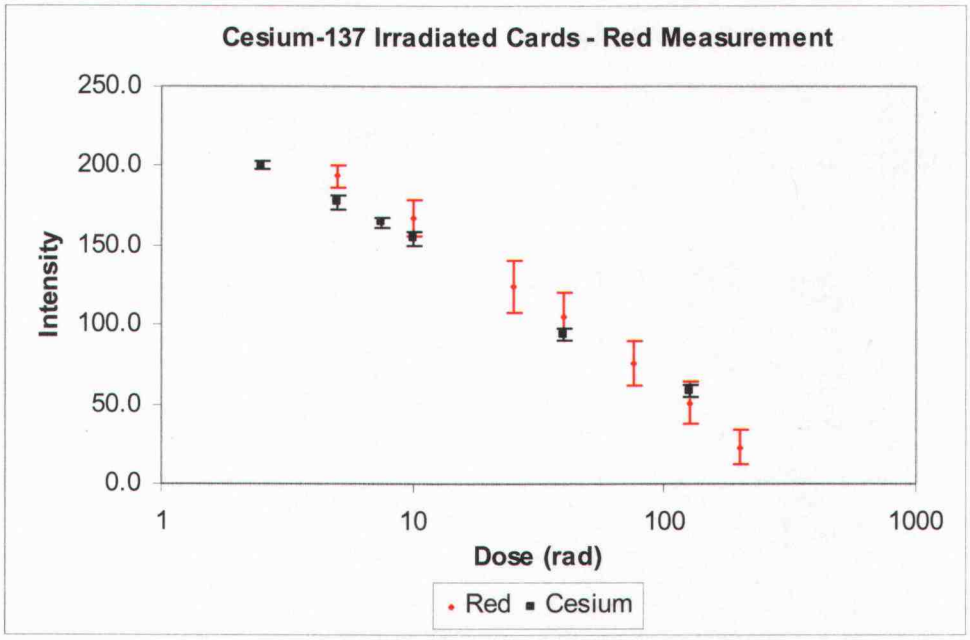


Figure 4.6. Cesium 137 Irradiated Cards versus the color Red. The measured red of the irradiated cards are plotted versus their total dose. The error bars are two standard deviations.

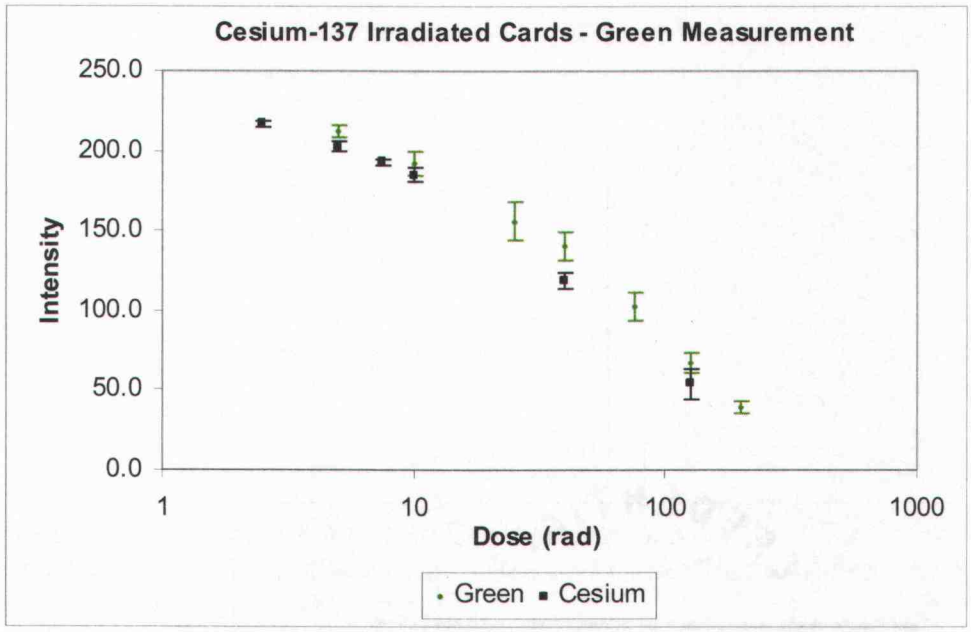


Figure 4.7. Cesium 137 Irradiated Cards versus Green. The measured green of the irradiated cards are plotted versus their total dose. The error bars are two standard deviations.

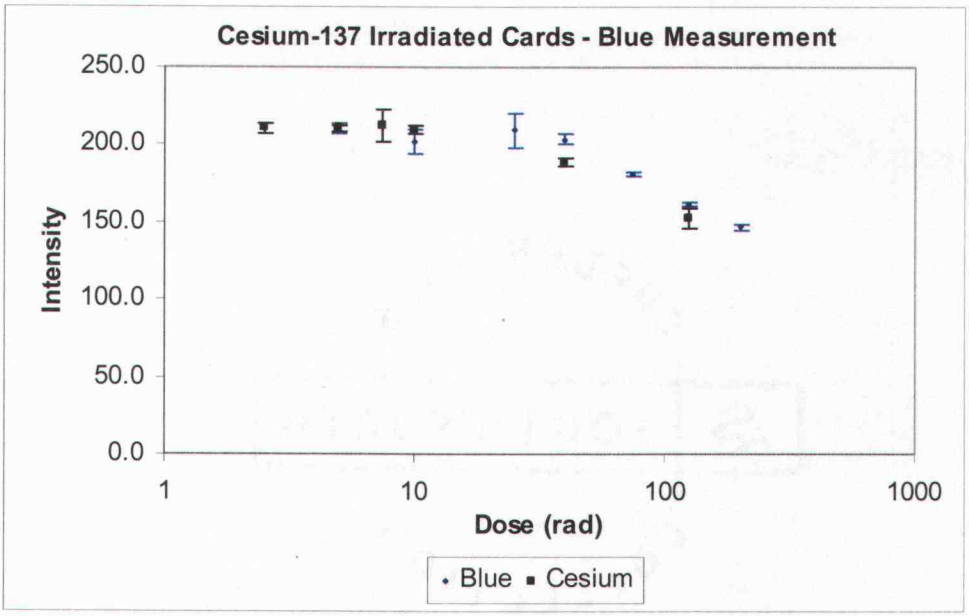


Figure 4.8. Cesium 137 Irradiated Cards versus Blue. The measured blue of the irradiated cards are plotted versus their total dose. The error bars are two standard deviations.

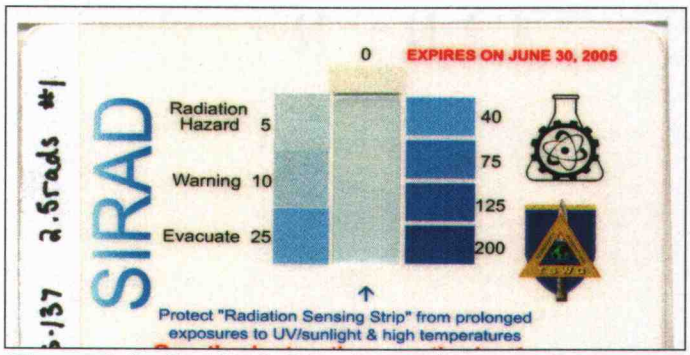


Figure 4.9: Cs-137 2.5 Rads Total Dose. A representative card after exposure to 2.5 Rads with chemical strip color change.

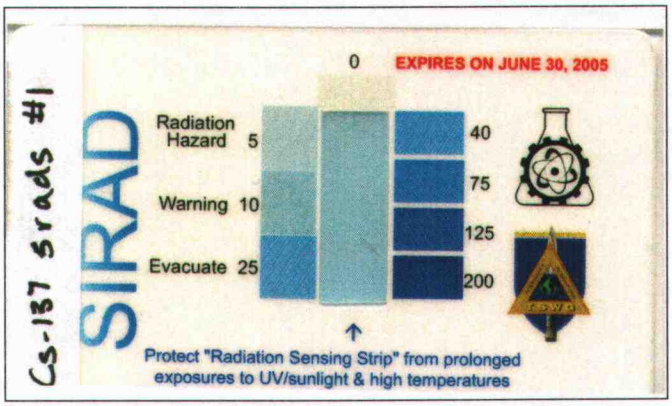


Figure 4.10: Cs-137 5 Rads Total Dose. A representative card after exposure to 5 Rads with chemical strip color change.

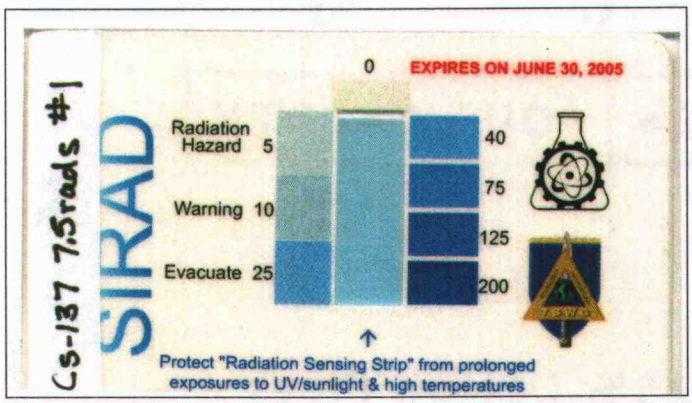


Figure 4.11: Cs-137 7.5 Rads Total Dose. A representative card after exposure to 7.5 Rads with chemical strip color change.

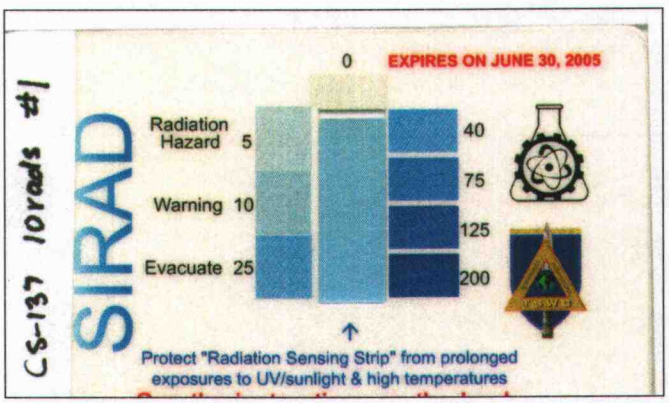


Figure 4.12:Cs-137 10 Rads Total Dose. A representative card after exposure to 10 Rads with chemical strip color change.

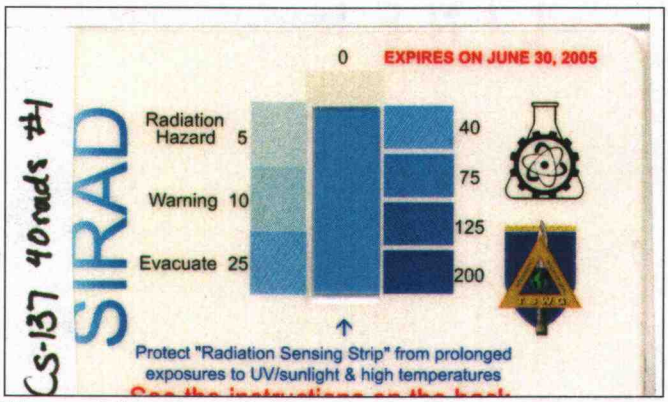


Figure 4.13: Cs-137 40 Rads Total Dose. A representative card after exposure to 40 Rads with chemical strip color change.

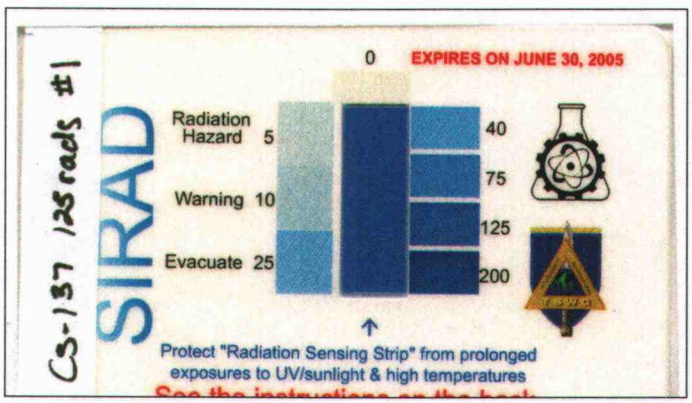


Figure 4.14: Cs-137 125 Rads Total Dose. A representative card after exposure to 125 Rads with chemical strip color change.

4.3 Neutron Sensitivity

4.3.1 Unmoderated Neutrons

A set of 10 cards were exposed to the PuBe source at a dose of 5 rads total neutron and gamma. For each of the intensities of the luminosity, the color red, the color green and the color blue were plotted against the control card plot (see Figs 4.15 through 4.18). A representative card is shown for visual comparison (see Fig 4.19). Based on the

manufacturer data, the neutron component was 4.6 rads and the gamma component was 0.4 rads. This test was only done for the 5 rad.

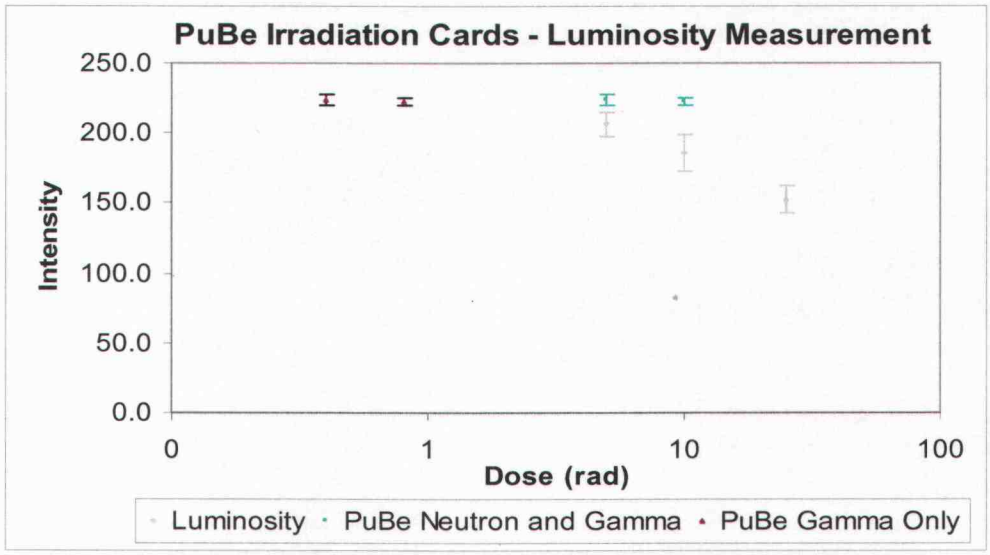


Figure 4.15. PuBe Irradiated Cards versus Luminosity. The measured luminosity of the irradiated cards are plotted versus their total dose. The PuBe is for total neutron and gamma component. The PuBe Gamma is for the gamma component only. The error bars are two standard deviations.

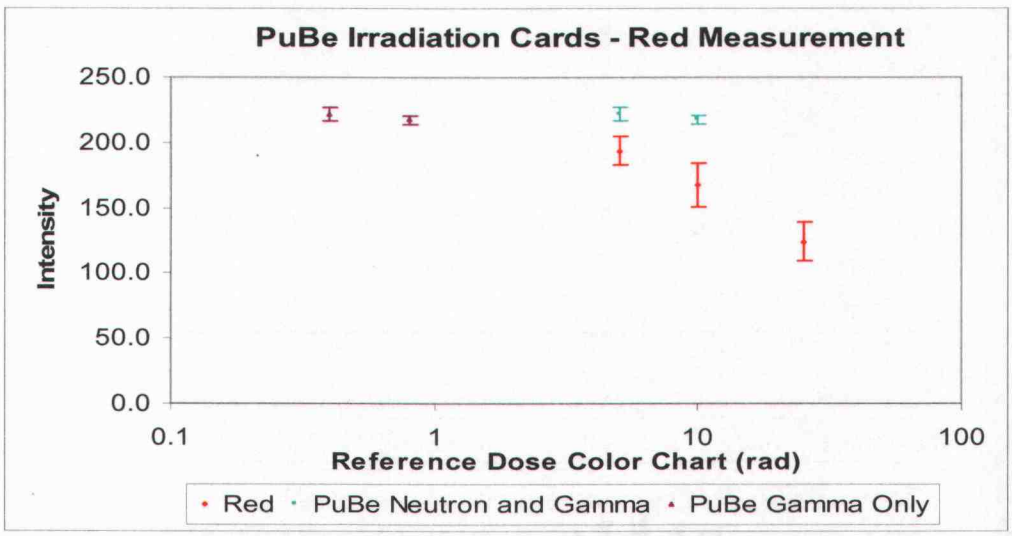


Figure 4.16. PuBe Irradiated Cards versus Red. The measured red of the irradiated cards are plotted versus their total dose. The PuBe is for total neutron and gamma component. The PuBe Gamma is for the gamma component only. The error bars are two standard deviations.

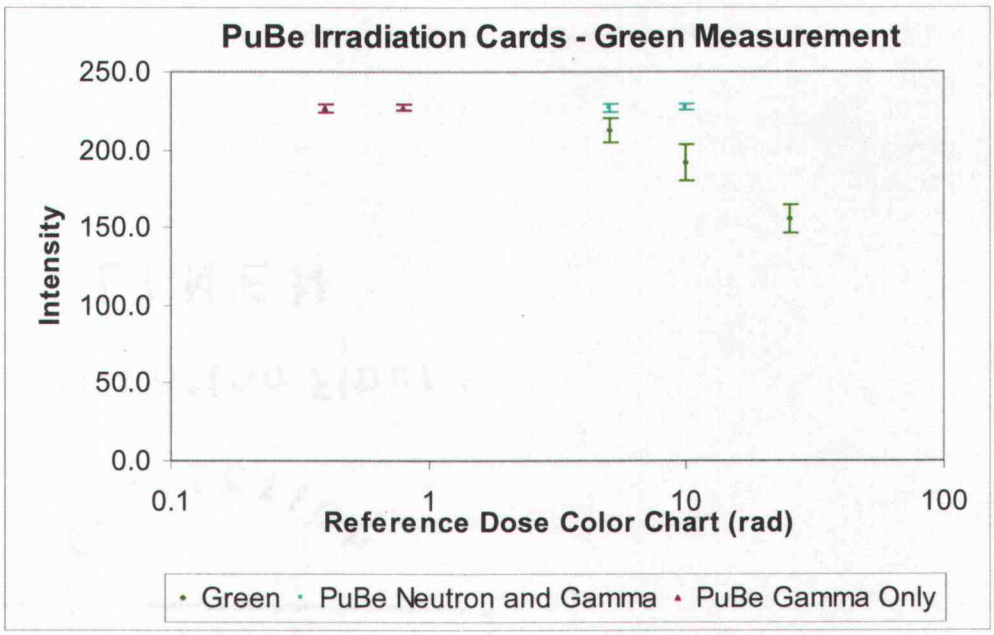


Figure 4.17. PuBe Irradiated Cards versus Green. The measured green of the irradiated cards are plotted versus their total dose. The PuBe is for total neutron and gamma component. The PuBe Gamma is for the gamma component only. The error bars are two standard deviations.

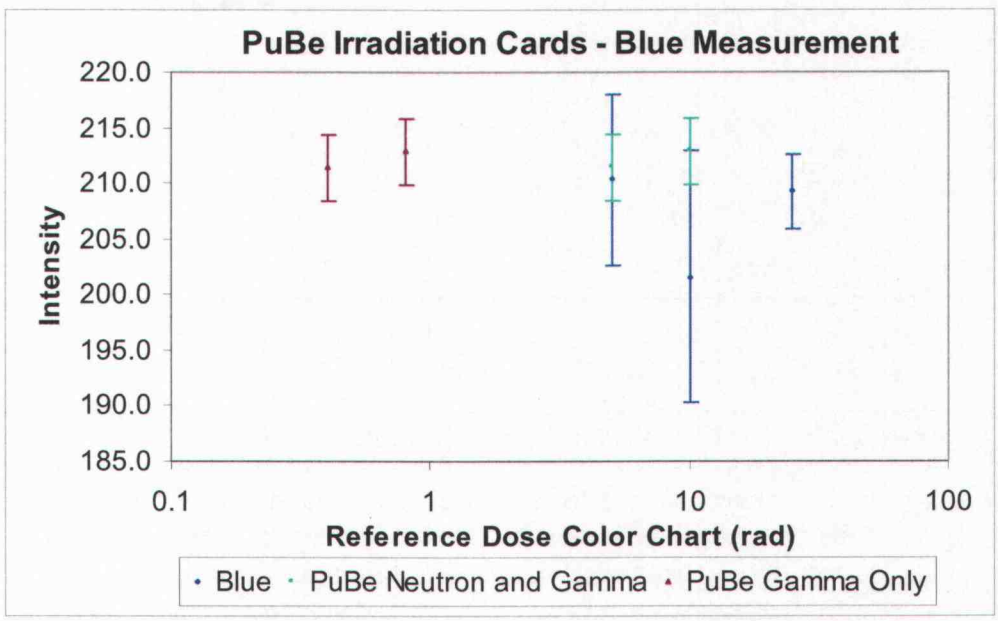


Figure 4.18. PuBe Irradiated Cards versus Blue. The measured blue of the irradiated cards are plotted versus their total dose. The PuBe is for total neutron and gamma component. The PuBe Gamma is for the gamma component only. The error bars are two standard deviations.

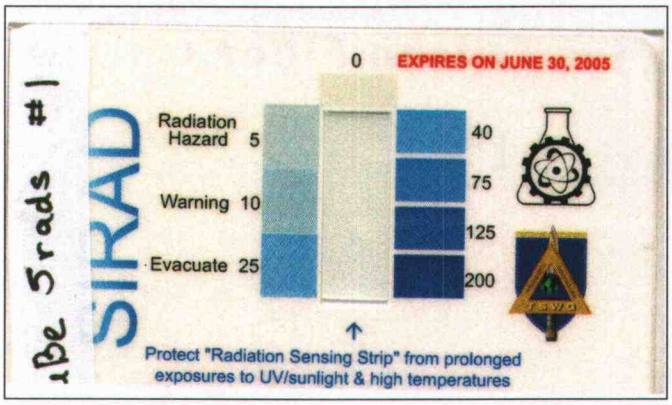


Figure 4.19: PuBe 5 Rads Total Dose. A representative card after exposure to 5 Rads with no apparent chemical strip color change.

4.3.2 Moderated Neutrons with Poly Block

A set of 10 cards were exposed to the PuBe source at a dose of 10 rads total neutron and gamma. The intensities of the recorded luminosity, colors red, green and blue were plotted against the dose (see Figs 4.15 through 4.18). A representative card is shown for visual comparison (see Fig 4.20). The neutron component was 9.2 rads and the gamma component was 0.8 rads. This test was only done for the 10 R range.

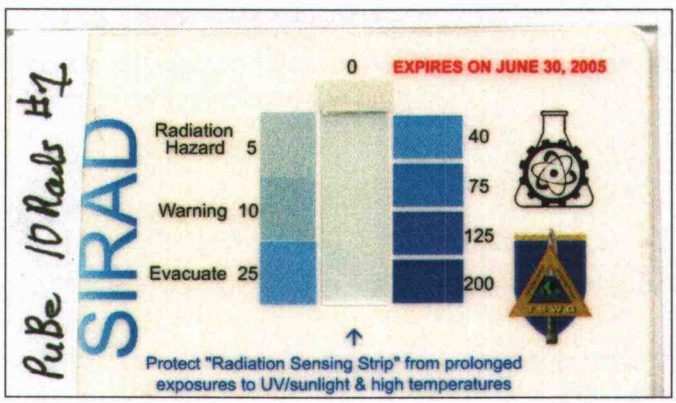


Figure 4.20: PuBe 10 Rads Total Dose. A representative card after exposure to 10 Rads with no apparent chemical strip color change.

4.3.3 Moderated Neutrons with Bonner Sphere

One card was exposed in a 10" bonner sphere to the PuBe source at a dose of 5 rads total neutron dose. The card is shown for visual comparison (see Fig 4.21). This test was only done for the 5 rad range. The results were similar to the unmoderated neutrons at 5 rad.

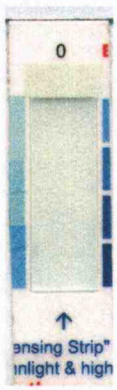


Figure 4.21: PuBe 5 Rads Total Dose Bonner Sphere Card. The card after exposure to 5 Rads with no apparent chemical strip color change.

4.3.4 Thermal Neutrons from TRIGA reactor

One card was placed into the thermal column of the Oregon State University's TRIGA Reactor. Each of the parameters; luminosity, red, green and blue were plotted against the control card plot (see Figs 4.22 through 4.25). The color reference key from the card is shown for comparison (see Fig 4.26). The gamma dose was measured at 26 rads. It was calculated that the thermal neutron dose is 5 rads in equation 3.1.

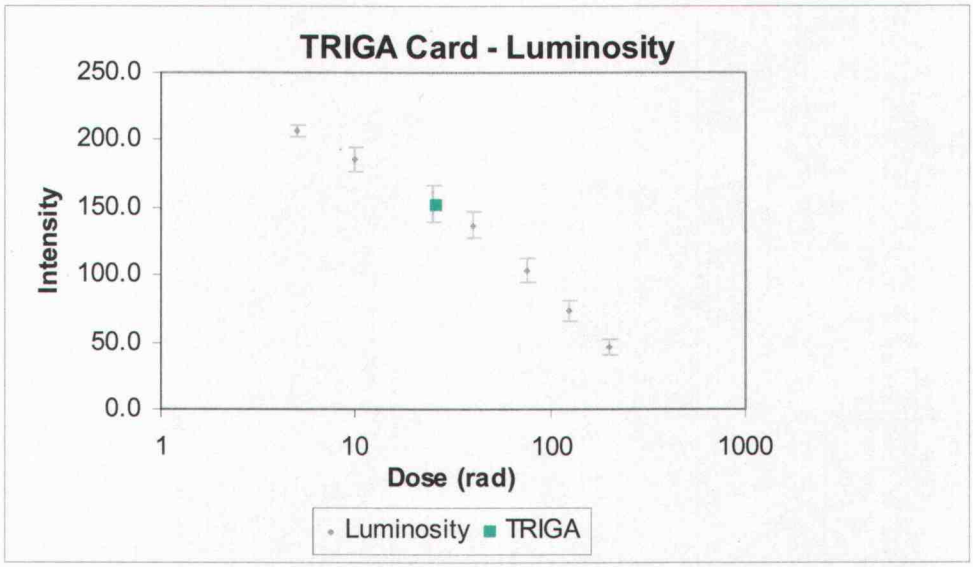


Figure 4.22. TRIGA Iradiation Card versus Luminosity. The measured luminosity of the irradiated card are plotted versus the total dose. The error bars are two standard deviations.

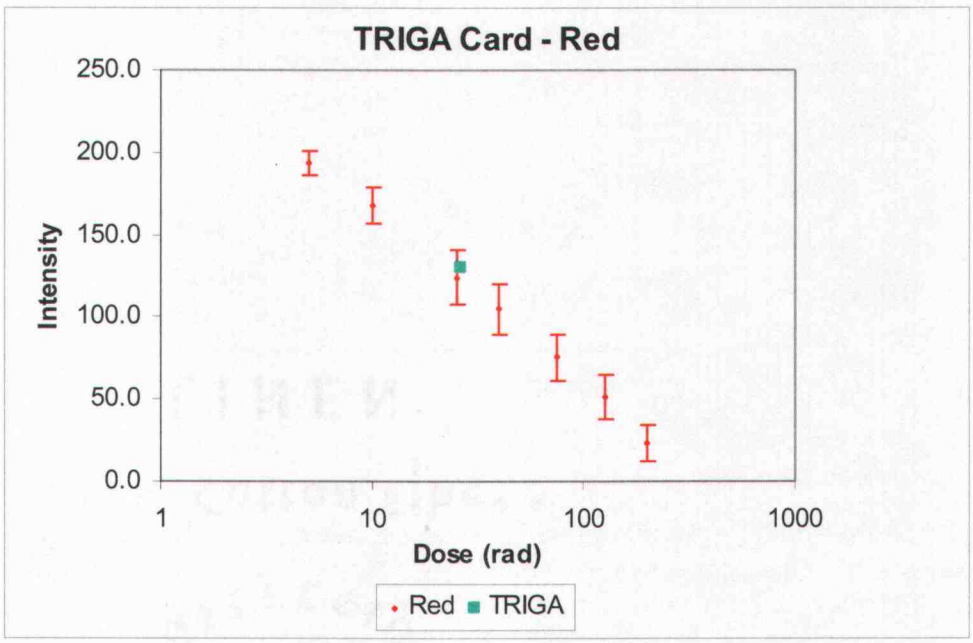


Figure 4.23. TRIGA Iradiation Card versus Red. The measured red of the irradiated card are plotted versus the total dose. The error bars are two standard deviations.

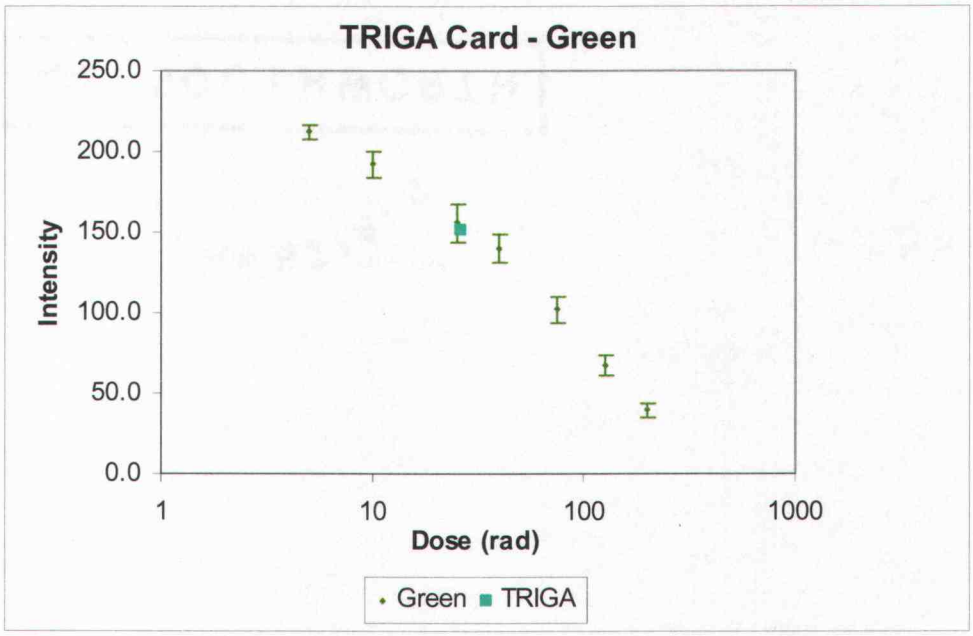


Figure 4.24. TRIGA Iradiation Card versus Green. The measured green of the irradiated card are plotted versus the total dose. The error bars are two standard deviations.

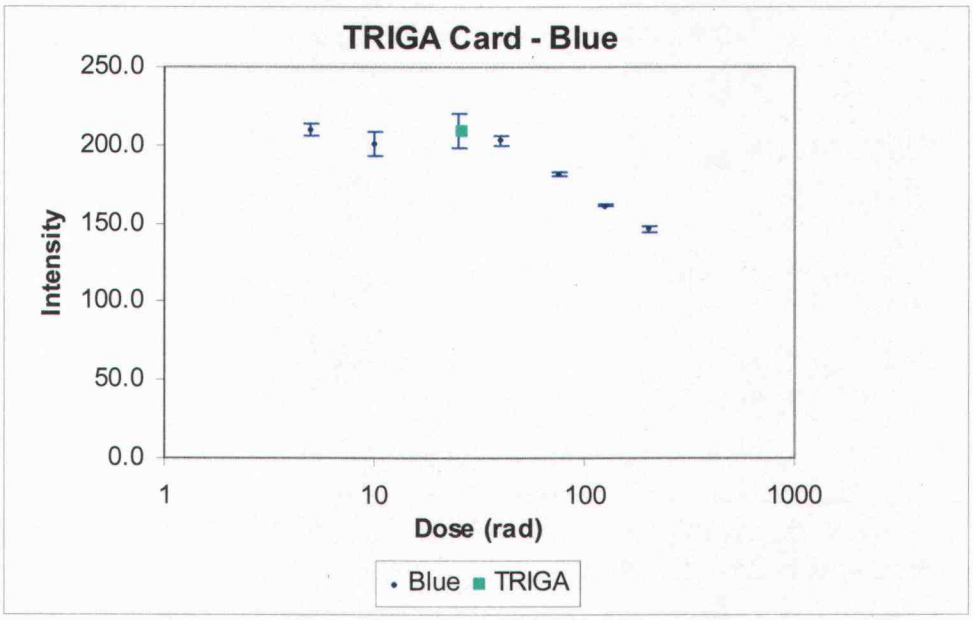


Figure 4.25. TRIGA Iradiation Card versus Blue. The measured blue of the irradiated card are plotted versus the total dose. The error bars are two standard deviations.

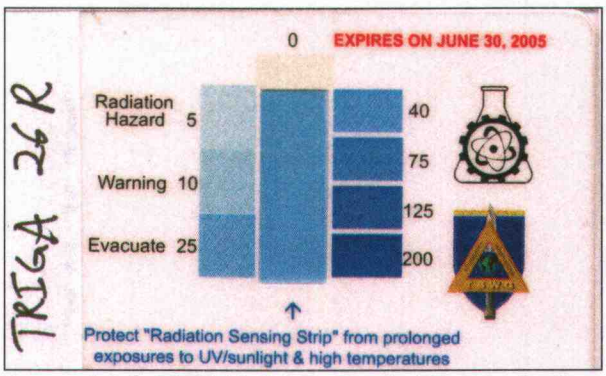


Figure 4.26: TRIGA 26 R Card. The card after exposure to 26 Rads in the TRIGA with chemical strip color change.

4.4 Scanner Characteristics

4.4.1 Scanner different areas

One card was scanned at seven different areas on the scanner bed. For the intensities of the luminosity, the color red, the color green and the color blue, the average and standard deviation of the seven areas were calculated (see Tables 4.6 through 4.9). The data was plotted on Figure 4.27. The abbreviations used on the tables are:

TCt.	Top Center
TRCo.	Top Right Corner
TLCo.	Top Left Corner
CtL	Center Left
CtCt	Center Center
CtR	Center Right
BCt.	Bottom Center

Table 4.6. SIRAD – Multiple Scanner Positions for Luminosity. The seven areas of the scanner were analyzed for each reference dose color provided by the manufacturer. The intensities were tabulated. The average and standard deviations were calculated.

SIRAD - Multiple Scanner Positions for Luminosity								
	Reference Dose Color Chart (rad)							
Position	0	5	10	25	40	75	125	200
TCt.	225.6	202.3	183.6	152.9	135.2	101.8	72.3	45.5
TRCo.	227.7	203.6	185.4	153.8	136.5	103.5	73.5	46.5
TLCo.	222.9	200.0	181.4	150.3	132.3	99.1	69.3	42.8
CtL.	226.9	204.6	186.5	155.2	136.2	102.6	73.9	48.1
CtCt.	227.0	204.8	186.2	155.7	137.5	104.4	75.4	48.2
CtR.	226.1	205.2	188.0	157.4	134.8	102.6	74.5	50.5
BCt.	229.3	206.3	187.9	156.9	139.3	106.7	77.8	50.9
Average	226.5	203.8	185.6	154.6	136.0	103.0	73.8	47.5
Std Dev	2.0	2.1	2.4	2.5	2.2	2.4	2.6	2.8

Table 4.7. SIRAD – Multiple Scanner Positions for Red. The seven areas of the scanner were analyzed for each reference dose color provided by the manufacturer. The intensities were tabulated. The average and standard deviations were calculated.

SIRAD - Multiple Scanner Positions for Red								
	Reference Dose Color Chart (rad)							
Position	0	5	10	25	40	75	125	200
TCt.	223.8	187.9	163.9	124.5	102.5	72.3	48.0	18.1
TRCo.	226.4	189.1	165.5	124.5	103.7	74.5	49.7	20.6
TLCo.	221.5	185.4	161.4	121.4	99.1	69.9	46.6	16.5
CtL.	226.1	190.7	167.3	126.6	103.2	73.3	50.3	22.5
CtCt.	228.1	192.9	168.9	129.1	106.6	76.6	52.9	23.3
CtR.	224.5	190.2	168.1	128.7	101.3	73.2	50.9	25.9
BCt.	231.0	194.7	170.7	130.3	109.2	80.0	56.3	27.4
Average	225.9	190.1	166.5	126.4	103.6	74.3	50.7	22.1
Std Dev	3.1	3.1	3.2	3.2	3.3	3.3	3.2	3.9

Table 4.8. SIRAD – Multiple Scanner Positions for Green. The seven areas of the scanner were analyzed for each reference dose color provided by the manufacturer. The intensities were tabulated. The average and standard deviations were calculated.

SIRAD - Multiple Scanner Positions for Green								
	Reference Dose Color Chart (rad)							
Position	0	5	10	25	40	75	125	200
TCt.	230.5	208.6	190.6	157.3	139.6	102.1	67.9	40.2
TRCo.	232.0	209.5	191.9	157.8	140.4	103.2	68.4	39.9
TLCo.	227.5	206.3	188.3	154.5	136.6	99.0	64.3	36.5
CtL.	231.4	210.9	193.3	159.3	140.5	102.7	69.0	41.8
CtCt.	230.8	210.4	192.3	159.3	141.4	104.2	70.5	41.8
CtR.	230.8	211.9	195.0	161.5	139.1	102.6	69.6	44.1
BCt.	232.8	211.8	193.9	160.6	142.8	106.2	72.6	44.2
Average	230.8	209.9	192.2	158.6	140.0	102.8	68.9	41.2
Std Dev	1.7	2.0	2.2	2.3	1.9	2.2	2.6	2.7

Table 4.9. SIRAD – Multiple Scanner Positions for Blue. The seven areas of the scanner were analyzed for each reference dose color provided by the manufacturer. The intensities were tabulated. The average and standard deviations were calculated.

SIRAD - Multiple Scanner Positions for Blue								
	Reference Dose Color Chart (rad)							
Position	0	5	10	25	40	75	125	200
TCt.	204.3	207.5	199.7	207.2	200.8	180.2	161.9	149.1
TRCo.	207.7	211.0	204.4	212.2	204.9	184.5	166.2	152.6
TLCo.	201.9	205.6	198.7	207.1	200.1	179.1	161.1	148.0
CtL.	205.2	209.1	202.7	211.0	203.6	182.7	164.4	151.5
CtCt.	203.5	207.1	200.5	208.5	201.1	180.9	163.2	149.9
CtR.	205.3	210.5	205.0	213.6	203.4	183.1	165.2	152.3
BCt.	206.1	208.8	202.0	209.6	202.5	182.6	164.2	150.6
Average	204.9	208.5	201.9	209.9	202.3	181.9	163.7	150.6
Std Dev	1.8	1.9	2.4	2.5	1.8	1.9	1.8	1.7

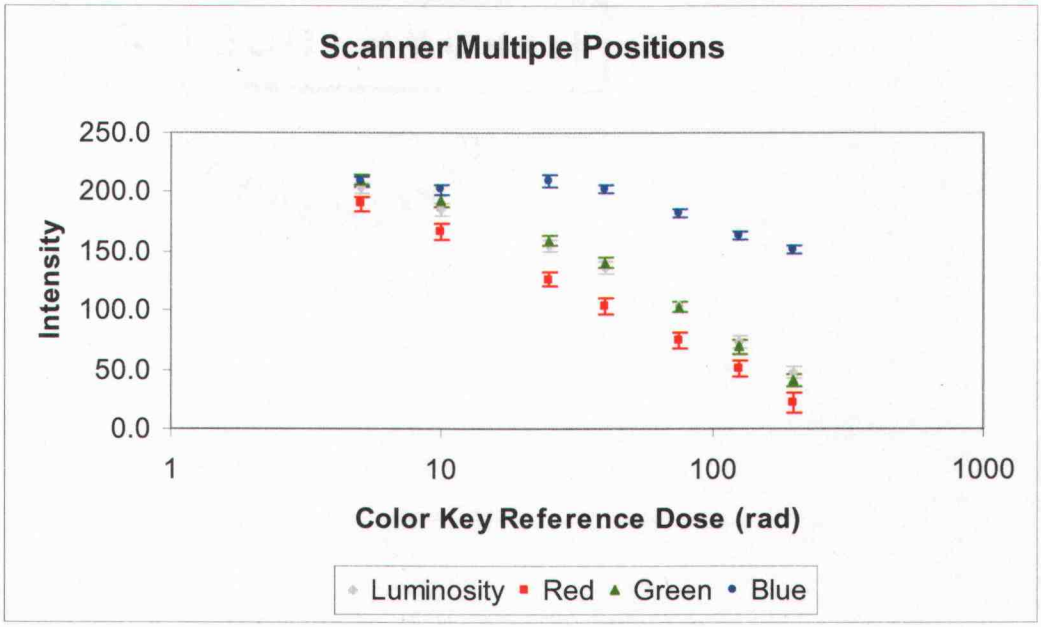


Figure 4.27. Scanner Multiple Positions of a single card. The intensities of the luminosity, the color red, the color green and the color blue are plotted. The error bars are two standard deviations.

4.4.2 Scanner Multiple Readings

A card was scanned multiple times to see if there was any effect of the scanner on the chemical strip. For the card, the intensity of the luminosity, the color red, the color green and the color blue were tabulated for every twentieth reading (see Table 4.10). The average and standard deviation of the chemical strip readings is also provided.

Table 4.10. Multiple Scan Readings of a Single Card. A card was read 100 times and the intensities of the luminosity, the color red, the color green and the color blue were tabulated for every twentieth reading. The average and the standard deviation were calculated and are shown.

Multiple Scan Readings of a Single Card								
	Number of Scans							Standard
Intensity	1	20	40	60	80	100	Average	Deviation
Luminosity	225.1	227.1	226.5	226.5	225.9	226.0	226.2	0.7
Red	223.3	226.9	226.5	226.6	225.8	226.0	225.8	1.3
Green	228.7	230.0	229.4	229.3	228.8	228.8	229.2	0.5
Blue	210.4	212.0	211.5	211.1	210.9	211.0	211.1	0.5

4.4.3 Scanner multiple types

A card was scanned on four additional different scanners to determine if the histogram would change from one scanner to another. For the intensities of the luminosity, the color red, the color green and the color blue, the average and standard deviation of the cards were calculated (see Tables 4.11 through 4.14). The data was plotted in Figures 4.28 through 4.31.

Table 4.11. SIRAD Multiple Scanners for Luminosity. The four additional scanners were analyzed for each reference dose color provided by the manufacturer. The intensities were tabulated. The average and standard deviations were calculated.

SIRAD Multiple Scanners for Luminosity								
	Reference Dose Color Chart (rad)							
Scanner	0	5	10	25	40	75	125	200
Epson	224.8	204.1	184.0	152.7	135.3	102.0	71.1	43.7
Cannon	223.8	216.4	200.2	174.7	157.5	129.3	101.0	72.2
HP 8250	233.3	214.7	199.3	171.8	154.6	128.2	102.5	75.1
HP 5200C	229.4	212.2	198.6	182.5	175.1	157.9	142.4	128.4
HP C7116	247.8	224.2	204.6	170.2	150.9	120.0	92.4	65.9
Average	231.8	214.3	197.3	170.3	154.7	127.5	101.9	77.1
Standard Deviation	9.7	7.3	7.8	11.0	14.3	20.2	25.9	31.3

Table 4.12. SIRAD Multiple Scanners for Red. The four additional scanners were analyzed for each reference dose color provided by the manufacturer. The intensities were tabulated. The average and standard deviations were calculated.

SIRAD Multiple Scanners for Red								
	Reference Dose Color Chart (rad)							
Scanner	0	5	10	25	40	75	125	200
Epson	223.7	190.7	165.0	124.9	102.1	72.1	46.9	17.2
Cannon	234.9	205.9	185.2	150.2	126.7	104.9	83.3	52.9
HP 8250	228.6	195.3	173.9	133.5	106.5	83.2	63.2	24.7
HP 5200C	225.6	200.8	183.7	164.1	154.7	142.5	131.5	118.7
HP C7116	246.9	208.4	183.1	139.1	112.3	87.1	68.3	39.2
Average	231.9	200.2	178.2	142.3	120.5	98.0	78.7	50.5
Standard Deviation	9.4	7.3	8.6	15.2	21.3	27.6	32.3	40.5

Table 4.13. SIRAD Multiple Scanners for Green. The four additional scanners were analyzed for each reference dose color provided by the manufacturer. The intensities were tabulated. The average and standard deviations were calculated.

SIRAD Multiple Scanners for Green								
	Reference Dose Color Chart (rad)							
Scanner	0	5	10	25	40	75	125	200
Epson	229.2	210.1	190.7	156.7	139.7	102.4	66.4	37.5
Cannon	236.9	221.1	205.6	180.1	164.0	131.1	98.0	67.5
HP 8250	237.7	222.7	208.8	182.3	168.0	138.5	108.3	83.7
HP 5200C	233.3	216.4	203.3	184.7	178.0	157.9	139.4	123.9
HP C7116	251.0	230.7	212.1	176.2	158.4	122.9	89.7	62.6
Average	237.6	220.2	204.1	176.0	161.6	130.6	100.3	75.0
Standard Deviation	8.2	7.6	8.2	11.2	14.2	20.4	26.7	32.0

Table 4.14. SIRAD Multiple Scanners for Blue. The four additional scanners were analyzed for each reference dose color provided by the manufacturer. The intensities were tabulated. The average and standard deviations were calculated.

SIRAD Multiple Scanners for Blue								
	Reference Dose Color Chart (rad)							
Scanner	0	5	10	25	40	75	125	200
Epson	204.1	208.7	199.7	206.7	201.9	181.3	162.2	149.4
Cannon	214.3	219.4	211.3	212.5	206.2	186.3	165.8	150.2
HP 8250	222.9	224.1	217.3	219.7	213.8	196.1	178.5	165.9
HP 5200C	233.3	216.4	203.3	184.7	178.0	157.9	139.4	123.9
HP C7116	233.0	232.6	223.4	223.1	216.1	193.5	172.4	156.1
Average	221.5	220.2	211.0	209.3	203.2	183.0	163.7	149.1
Standard Deviation	12.5	8.9	9.7	15.2	15.2	15.2	14.9	15.5

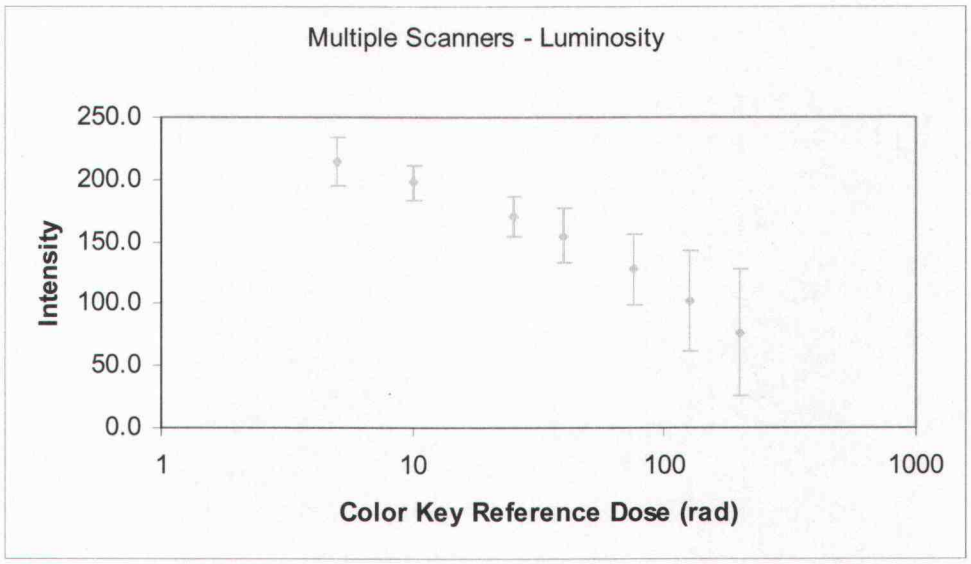


Figure 4.28. Multiple Scanners – Luminosity. The average intensities for the five scanners versus the reference dose color chart. The error bars are two standard deviations.

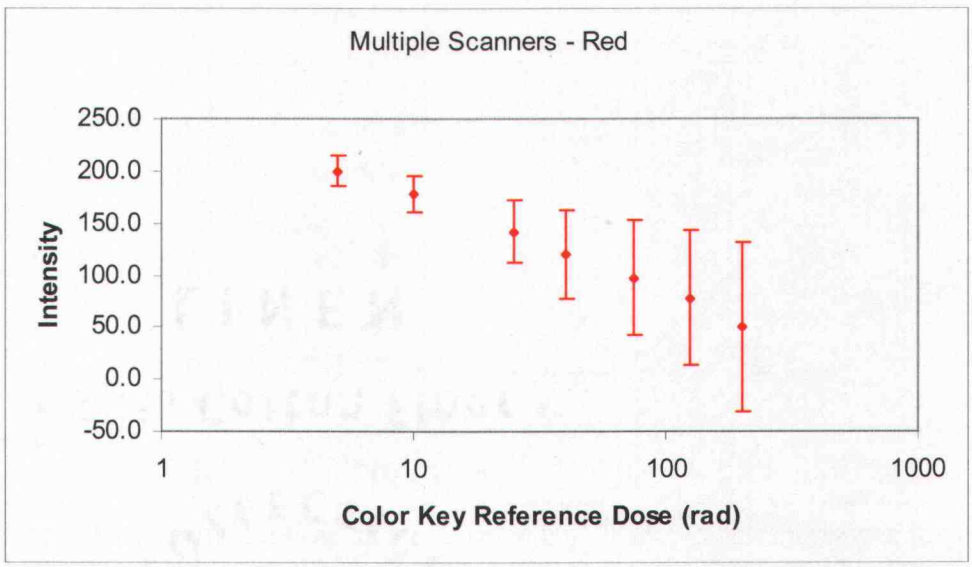


Figure 4.29. Multiple Scanners – Color Red. The average intensities for the five scanners versus the reference dose color chart. The error bars are two standard deviations.

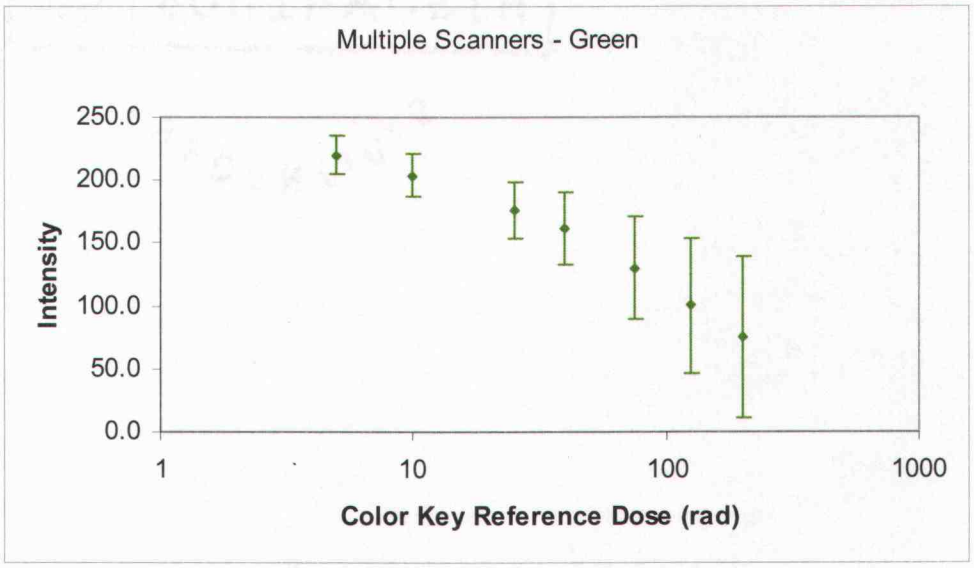


Figure 4.30. Multiple Scanners – Color Green. The average intensities for the five scanners versus the reference dose color chart. The error bars are two standard deviations.

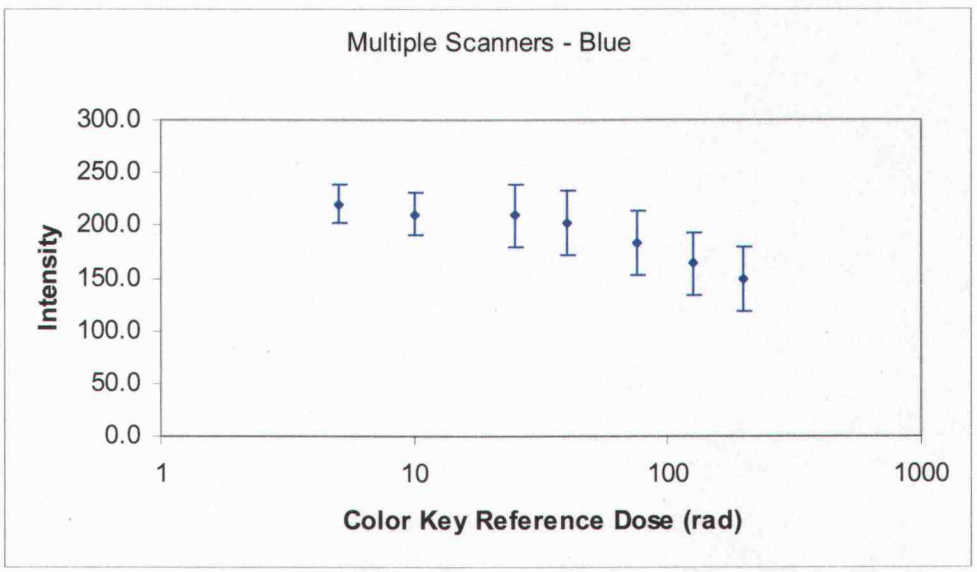


Figure 4.31. Multiple Scanners – Color Blue. The average intensities for the five scanners versus the reference dose color chart. The error bars are two standard deviations.

Chapter 5 – Discussion

5.1 SIRAD Dose Control Colors

The overall control card was compared to the control card from each of the cesium radiations. Tables 4.2 through 4.4 show the intensities of the luminosity, the color red, the color green and the color blue. The plotted graphs in Figures 4.1 through 4.4 show the calibration curve over the range of the card. This shows that the control cards from each set, can with reasonable accuracy, be used to determine the dose for that set.

5.2 Cs-137 SIRAD Cards

For the different levels of gamma dose applied to the SIRAD cards from the cesium source, the card readings were found to be consistent with what was expected based upon the color key reference dose. Figures 4.5 through 4.8 show that the luminosity, the color red, the color green and the color blue of the chemical strips for the set of cards fall within two standard deviations of the reference dose color code with the exception of 5 and 40 rads. For the 5 rads set, the luminosity, red and green are not within two standard deviations. For the 40 rads set, red is within two standard deviations but the luminosity, the color green and the color blue are not within two standard deviations. Overall, this shows that the SIRAD cards respond to gamma radiation of cesium as expected.

5.3 Unmoderated Neutrons

For unmoderated neutron response, the test dose was calculated to be 5 rads total neutron and gamma dose. Figures 4.15 through 4.18 show that the luminosity, the color

red and the color green of the chemical strips for the cards do not fall within the standard deviation of the color key reference dose for 5 rads. In comparing the scanned picture of a representative card (see fig 4.19) for unmoderated neutrons and a representative card (see fig 4.10) for Cs-137 at the same total dose, one can see that the color strips are not the same shade of blue. This suggests that the SIRAD card is not sensitive to unmoderated neutrons with an average energy of 4.5 MeV.

5.4 Moderated Neutrons with a Poly Block

For moderated neutron response with a poly block behind the SIRAD cards, the dose was calculated to be 10 rads total neutron and gamma dose. Figures 4.15 through 4.18 show that the luminosity, red and green of the chemical strips for the cards do not all fall within the standard deviation of the color reference key dose for 10 rads. In comparing the scanned picture of a representative card (see fig 4.20) for moderated neutrons with a poly block and a representative card (see fig 4.12) for Cs-137 at the same total dose, one can see that the color strips are not the same shade of blue. This suggests that the SIRAD card is not sensitive to neutrons moderated and reflected with a poly block.

5.5 Moderated Neutrons with Bonner Sphere

For moderated neutron response with one SIRAD card inside a 10" bonner sphere, the dose was calculated to be 5 rads neutron. The unmoderated gamma exposure is 0.4 rads. In comparing the scanned picture of the card (see fig 4.21) for moderated neutrons with a bonner sphere and a representative card for (see fig 4.10) for Cs-137 at the same total dose, one can see that the color strips are not the same shade of blue. This

suggests that the SIRAD card is not sensitive to neutrons moderated with a bonner sphere.

The reason for using a bonner sphere was to moderate the neutrons and see a specific reaction. The reaction is $H(n,\gamma)^2H$ and the gamma energy is 2.22 MeV from this reaction. This reaction was not detected with the SIRADs after moderating the neutrons.

5.6 Thermal Neutrons from TRIGA reactor

Since a reaction was not seen using fast neutrons from the PuBe source or from moderating the neutrons with polyethylene, one SIRAD card was exposed to a thermal beam of neutrons. The gamma dose was measured to be 26 rads using an ion chamber. Figures 4.22 through 4.25 show that the luminosity, red, green and blue of the chemical strip fall within the standard deviations of both 25 R and 40 R. Figure 4.26 is a picture of the SIRAD card and can be compared to a representative card from Cs-137 for 40 R (see Fig 4.13). It appears that the SIRAD card from the TRIGA is a slightly lighter shade than the Cs-137 at 40 R. This card did not appear to show sensitivity to thermal neutrons.

5.7 Scanner Different Areas

For all the readings prior, a jig was used to place the SIRAD card on the same area of the scanner for reproducibility. The data is tabulated in Tables 4.5 through 4.9 for the intensities of the different areas. As can be seen in Figure 4.27, the standard deviations are very small for the seven cards. This test showed that for seven different areas of the same scanner that the luminosity, the color red, the color green and the color blue are consistent from different placement areas.

5.8 Scanner Multiple Readings

The manufacturer mentions in the literature that the chemical strip may change due to direct light and should be read with only a fluorescent light source. This test is used to determine if multiple readings of the same chemical strip will change the intensity of the chemical strip. Table 4.9 shows that the luminosity, the color red, the color green and the color blue for all readings from 1 to 100 do not change significantly. This test suggests that the chemical strip is not affected by the light from a scanner and may be read multiple times if needed.

5.9 Scanner Multiple Types

This test was performed to determine if different scanners would be able to be reproducible with the chemical strips. As can be seen in Tables 4.11 through 4.14, the standard deviations of the five scanners is large. Figures 4.28 through 4.31 show a wide range of overlap for the reference dose color chart. For card readings to be meaningful to an user, a single type of scanner must be used consistently.

Chapter 6 – Conclusion

The SIRAD card is designed for first responders to be able to have a straight-forward way to determine if they have been exposed to elevated levels of ionizing radiation. The tests performed here were designed to determine whether the card was sensitive to gamma radiation and neutron fields. The test with gamma radiation supports the manufacturer claims. The tests with neutrons do not support the manufacturer claims that the SIRAD cards are "sensitive to neutrons (including thermal and epi-thermal)". There is no evidence from the four test conducted here that the chemical strip is directly or indirectly sensitive to fast or thermal neutrons. The one reaction not tested in this project is the N(n,p)C reaction with produces a proton of energy 0.626 MeV. This test may be what the manufacturer is basing their claim. Without further testing, the manufacturer may want to reword their claim of sensitivity to neutrons.

The use of a scanner for this project was chosen because most offices now have a scanner for various purposes. The scanner tests showed that the readings are consistent across the surface of the scanner and multiple readings will not affect the chemical strip. The third test showed that intensity numbers may vary from scanner to scanner and the same scanner should be used for all testing and documentation purposes.

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APPENDICES

Appendix A – Raw Data Histograms

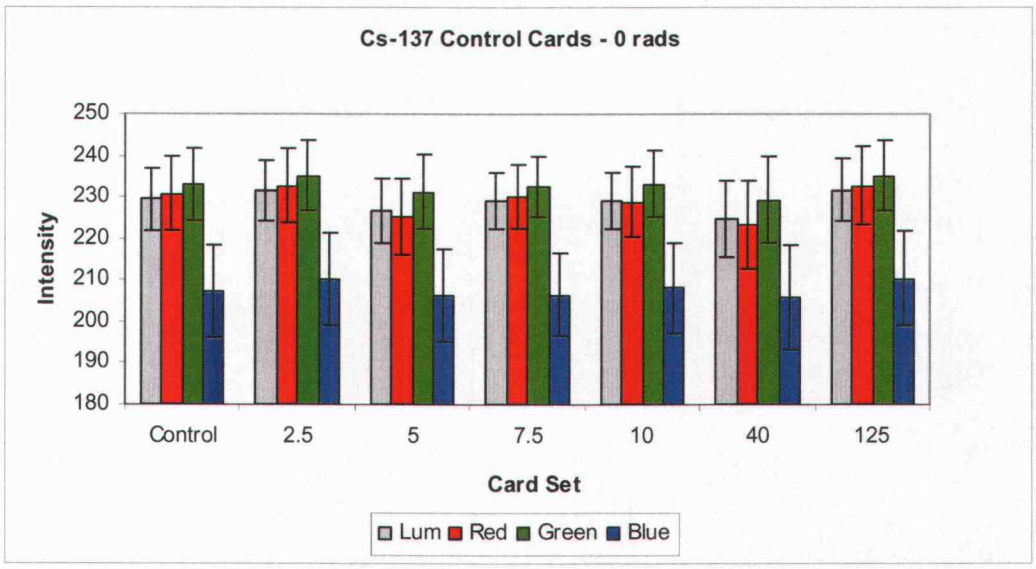


Figure A.1: Control Cards - 0 Rads. The x-axis is the control card from the listed exposure level of Cs-137. The intensity is from each card's reference dose color.

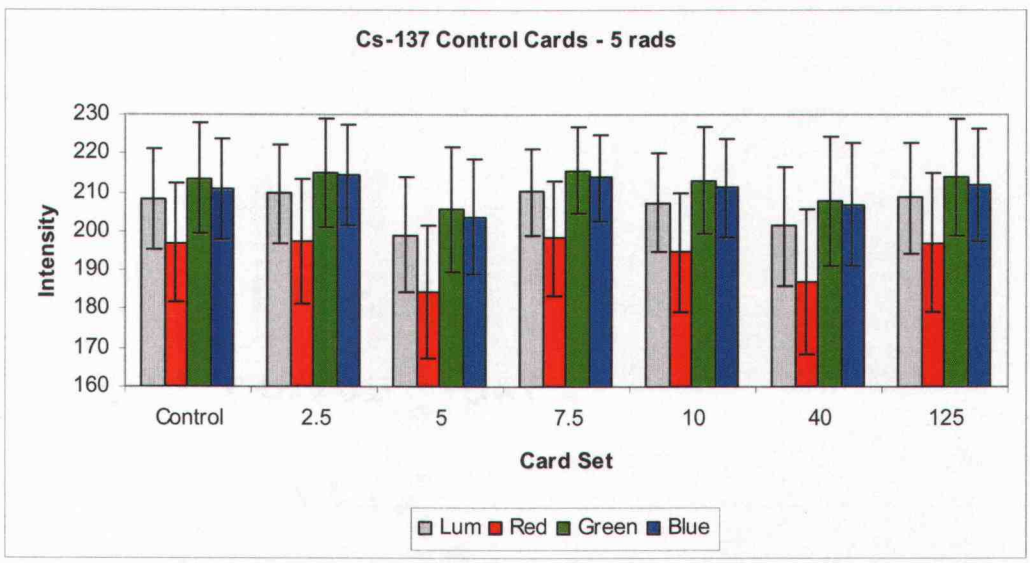


Figure A.2: Control Cards - 5 Rads. The x-axis is the control card from the listed exposure level of Cs-137. The intensity is from each card's reference dose color.

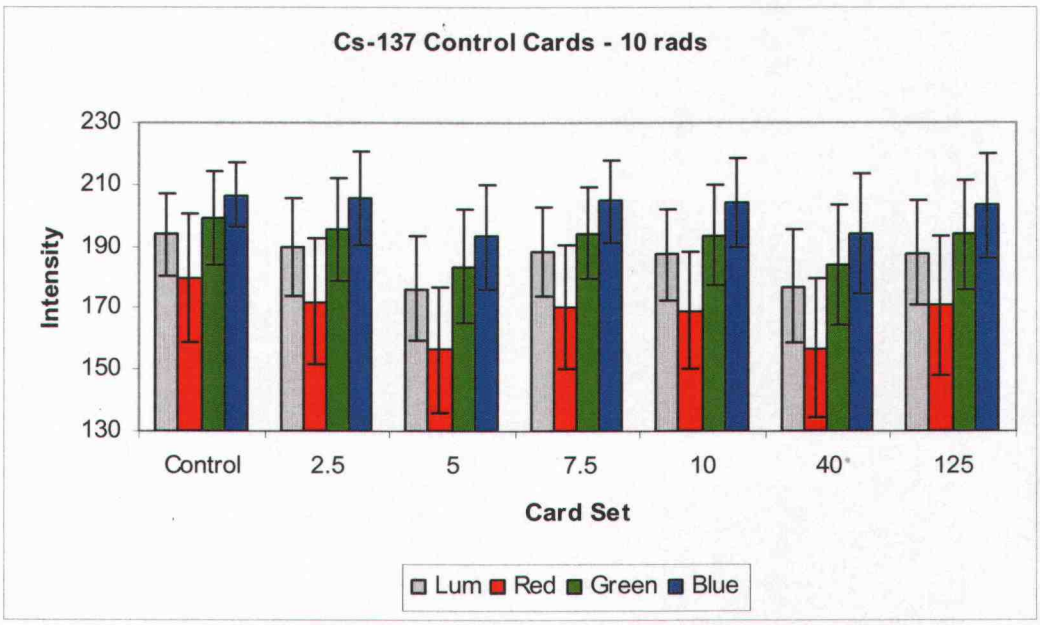


Figure A.3: Control Cards - 10 Rads. The x-axis is the control card from the listed exposure level of Cs-137. The intensity is from each card's reference dose color.

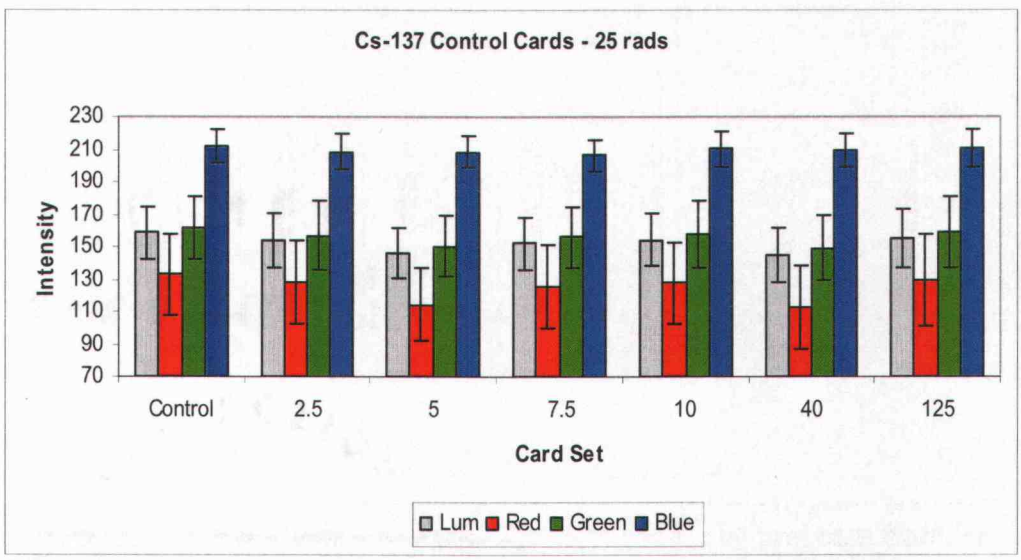


Figure A.4: Control Cards - 25 Rads. The x-axis is the control card from the listed exposure level of Cs-137. The intensity is from each card's reference dose color.

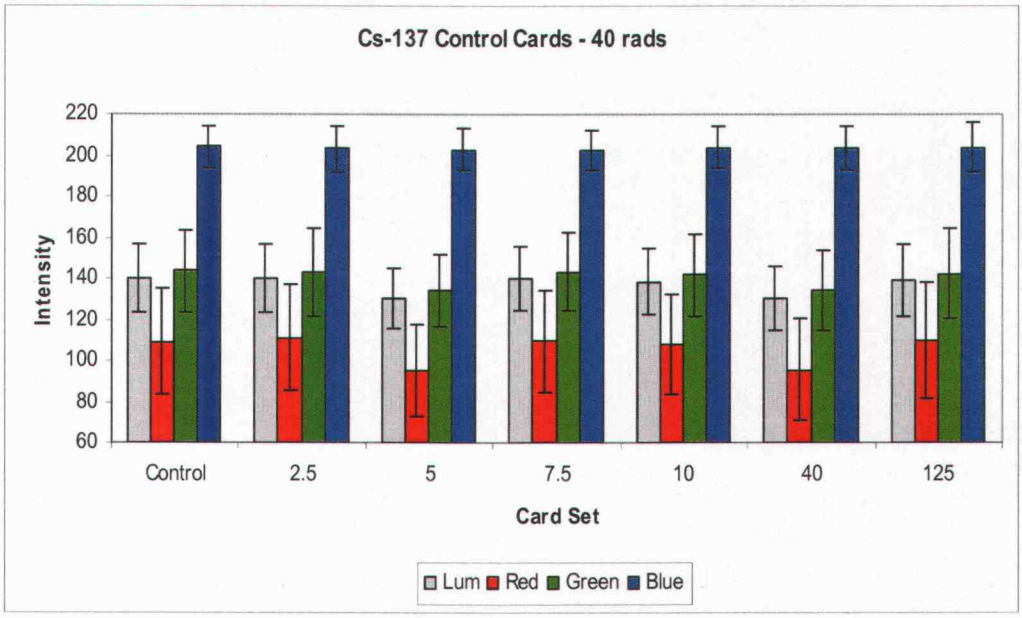


Figure A.5: Control Cards - 40 Rads. The x-axis is the control card from the listed exposure level of Cs-137. The intensity is from each card's reference dose color.

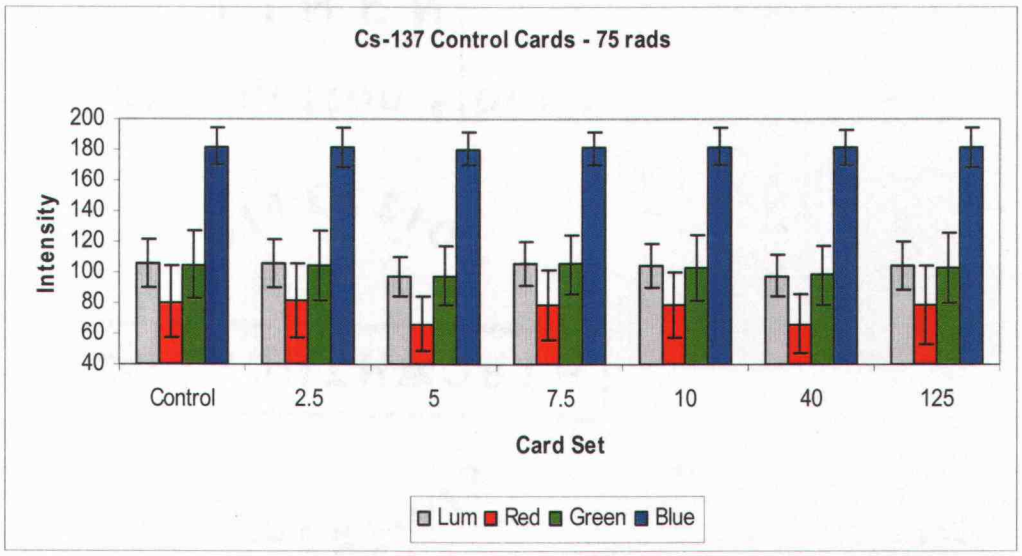


Figure A.6: Control Cards - 75 Rads. The x-axis is the control card from the listed exposure level of Cs-137. The intensity is from each card's reference dose color.

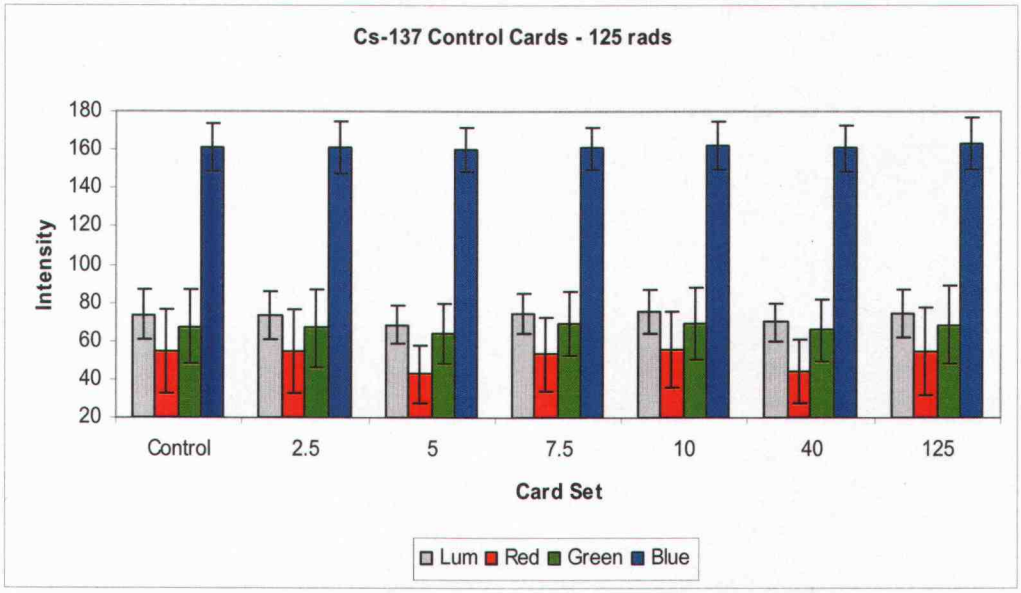


Figure A.7: Control Cards - 125 Rads. The x-axis is the control card from the listed exposure level of Cs-137. The intensity is from each card's reference dose color.

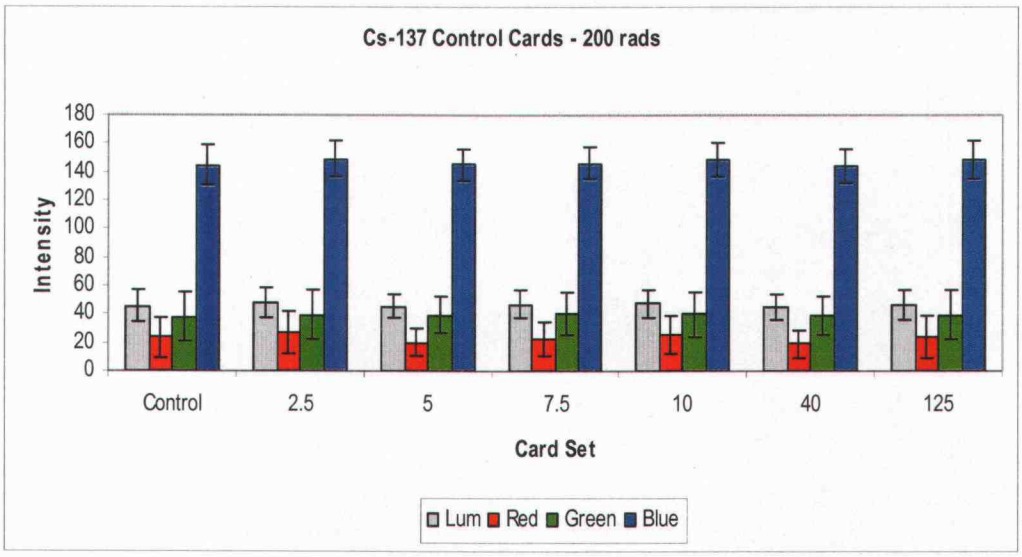


Figure A.8: Control Cards - 200 Rads. The x-axis is the control card from the listed exposure level of Cs-137. The intensity is from each card's reference dose color.

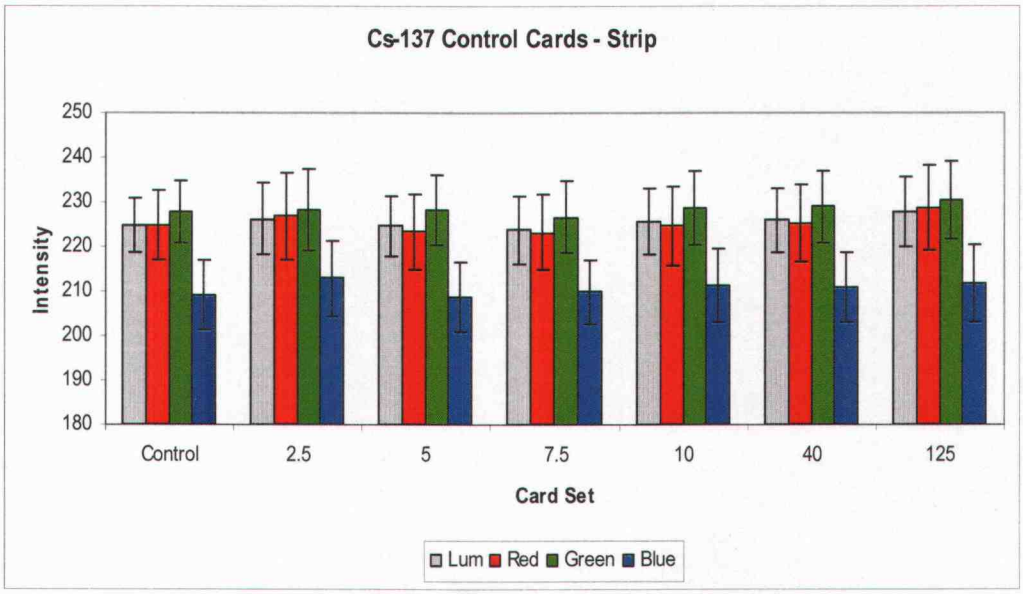


Figure A.9: Control Cards – Strip. The x-axis is the control card from the listed exposure level of Cs-137. The intensity is from each card's chemical strip.

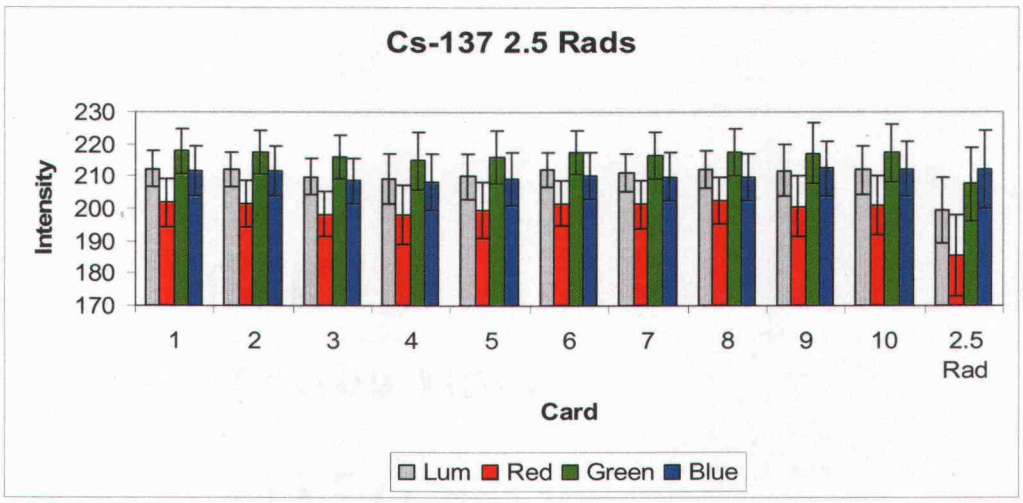


Figure A.10: Cs-137 2.5 Rads Histogram. The x-axis is the card number exposed this level of radiation. The intensity is from each card's chemical strip. The 2.5 Rad on the x – axis is the dose reference numbers for this exposure.

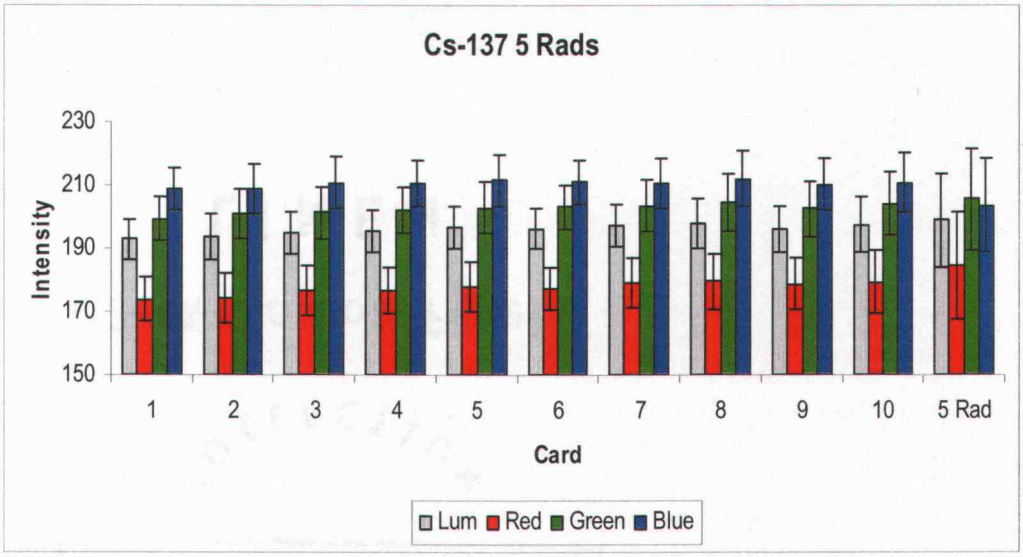


Figure A.11: Cs-137 5 Rads Histogram. The x-axis is the card number exposed this level of radiation. The intensity is from each card's chemical strip. The 5 Rad on the x – axis is the dose reference numbers for this exposure.

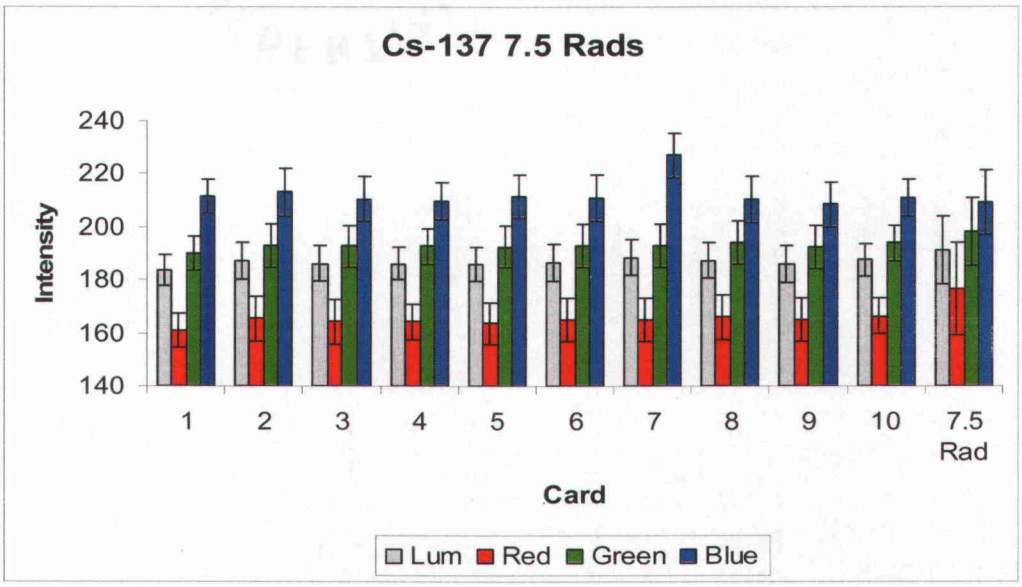


Figure A.12: Cs-137 7.5 Rads Histogram. The x-axis is the card number exposed this level of radiation. The intensity is from each card's chemical strip. The 7.5 Rad on the x – axis is the dose reference numbers for this exposure.

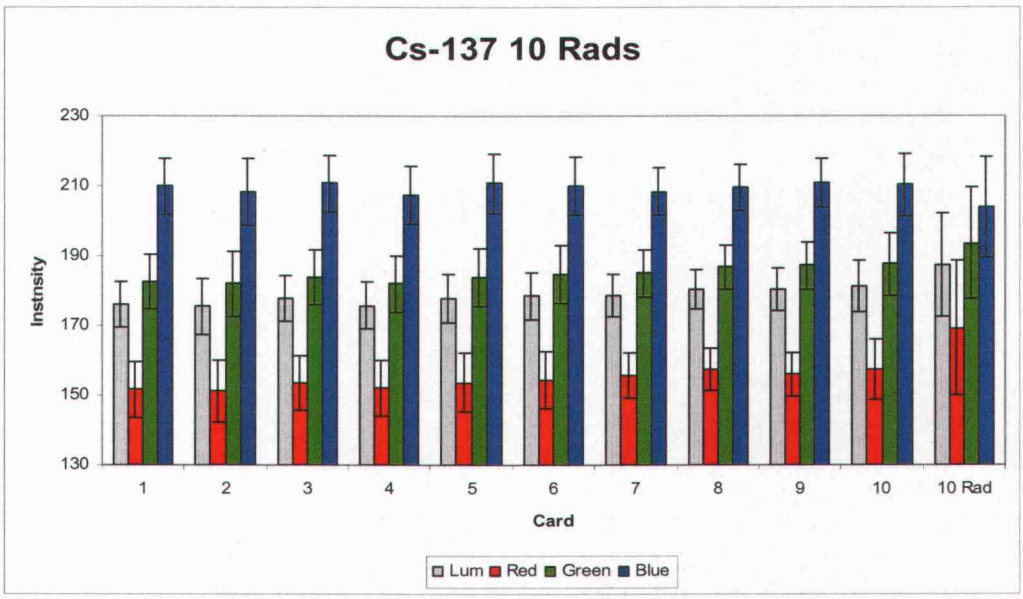


Figure A.13: Cs-137 10 Rads Histogram. The x-axis is the card number exposed this level of radiation. The intensity is from each card's chemical strip. The 10 Rad on the x – axis is the dose reference numbers for this exposure.

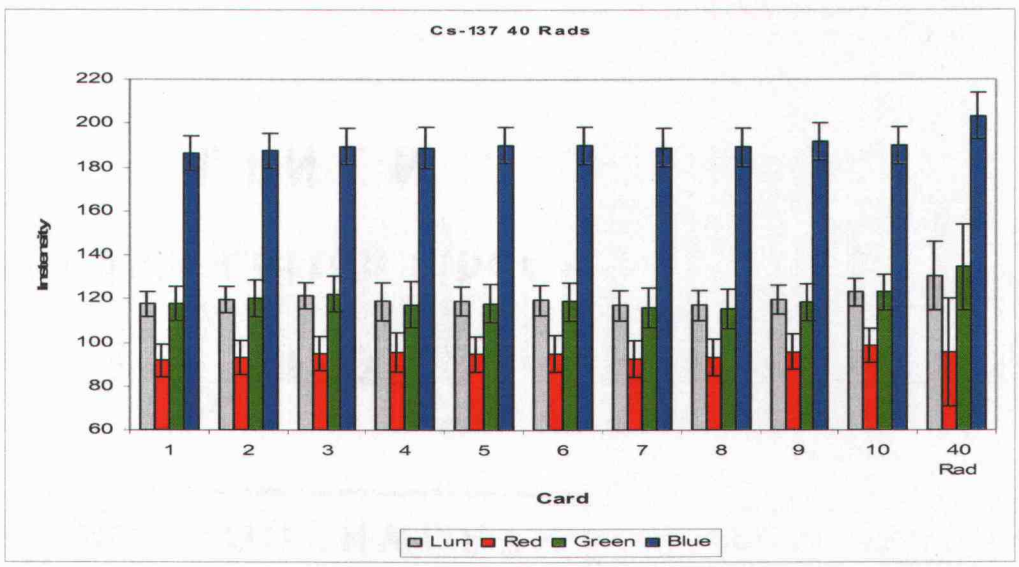


Figure A.14: Cs-137 40 Rads Histogram. The x-axis is the card number exposed this level of radiation. The intensity is from each card's chemical strip. The 40 Rad on the x – axis is the dose reference numbers for this exposure.

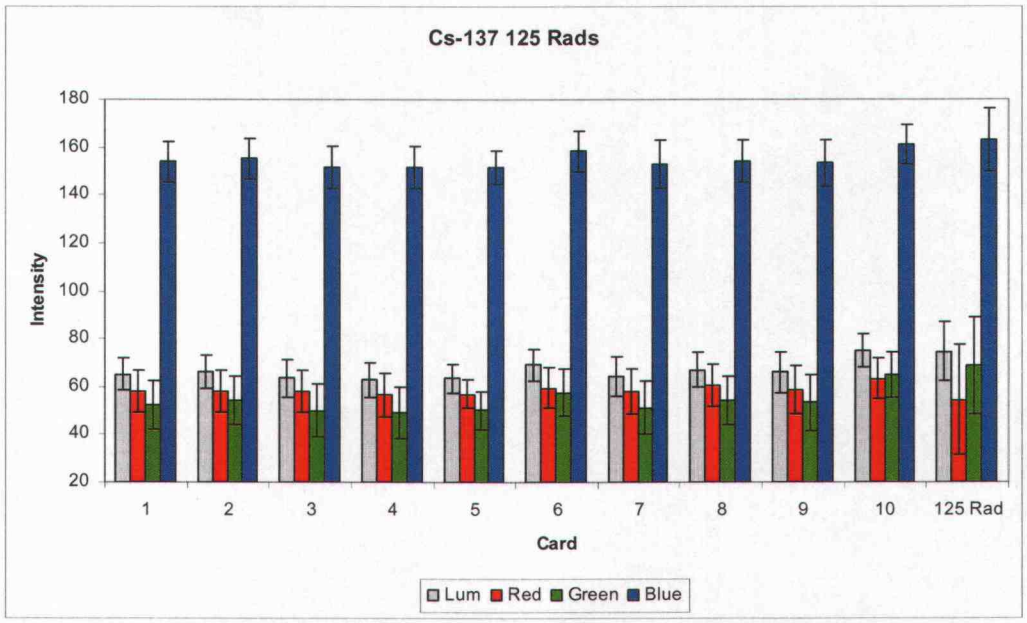


Figure A.15: Cs-137 125 Rads Histogram. The x-axis is the card number exposed this level of radiation. The intensity is from each card's chemical strip. The 125 Rads on the x – axis is the dose reference numbers for this exposure.

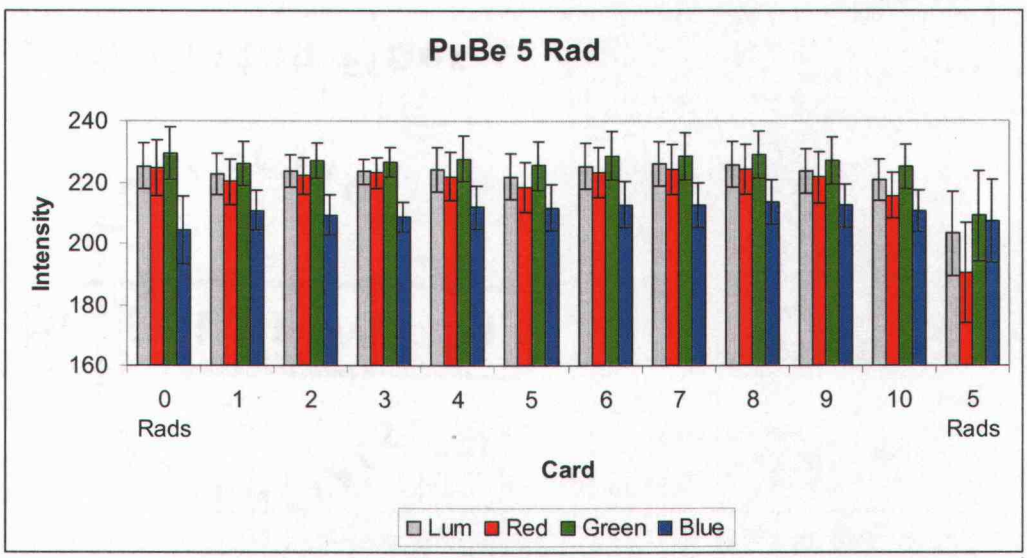


Figure A.16: PuBe 5 Rads Histogram. The x-axis is the card number exposed this level of radiation. The intensity is from each card's chemical strip. The 5 Rads on the x – axis is the dose reference numbers for this exposure.

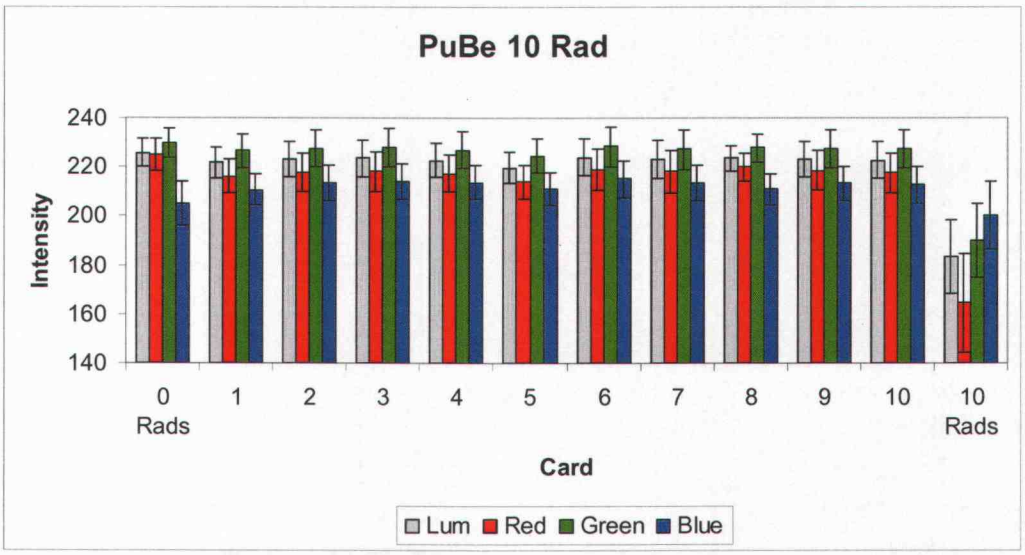


Figure A.17: PuBe 10 Rads Histogram. The x-axis is the card number exposed this level of radiation. The intensity is from each card's chemical strip. The 10 Rads on the x – axis is the dose reference numbers for this exposure.

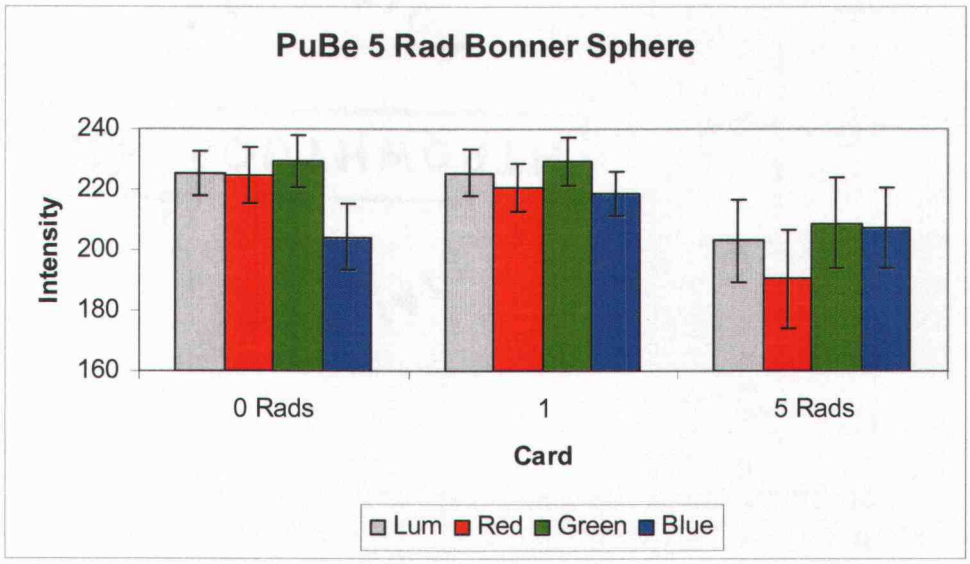


Figure A.18: PuBe 5 Rads Bonner Sphere Histogram. The x-axis is the card exposed to this level of radiation in the center and the two reference dose color points for 0 rads and 5 rads.

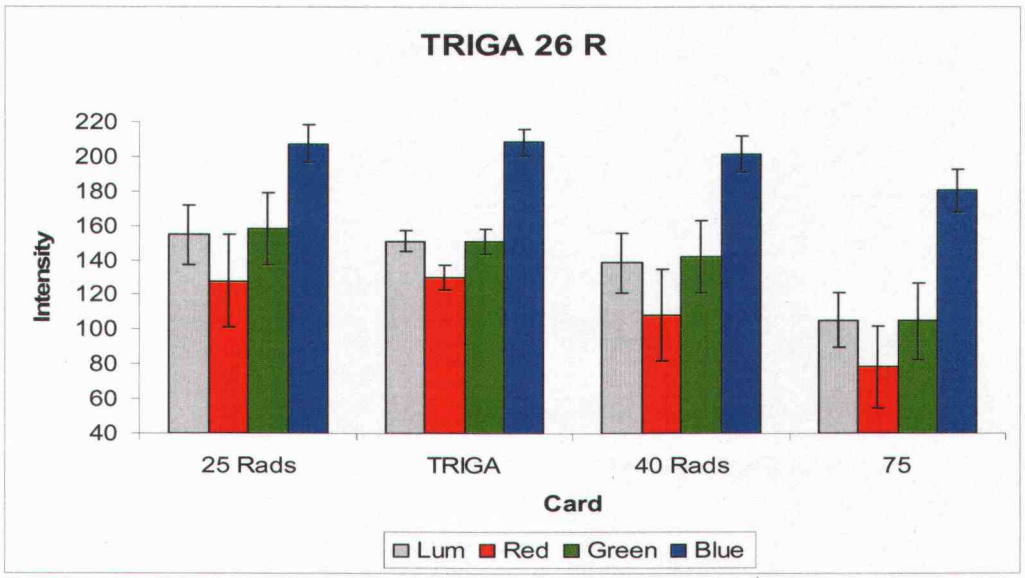


Figure A.19: TRIGA 26 Rads Histogram. The x-axis is the card exposed to this level of radiation in the TRIGA reactor and the three reference dose color points for 25 rads, 40 rads and 75 rads.

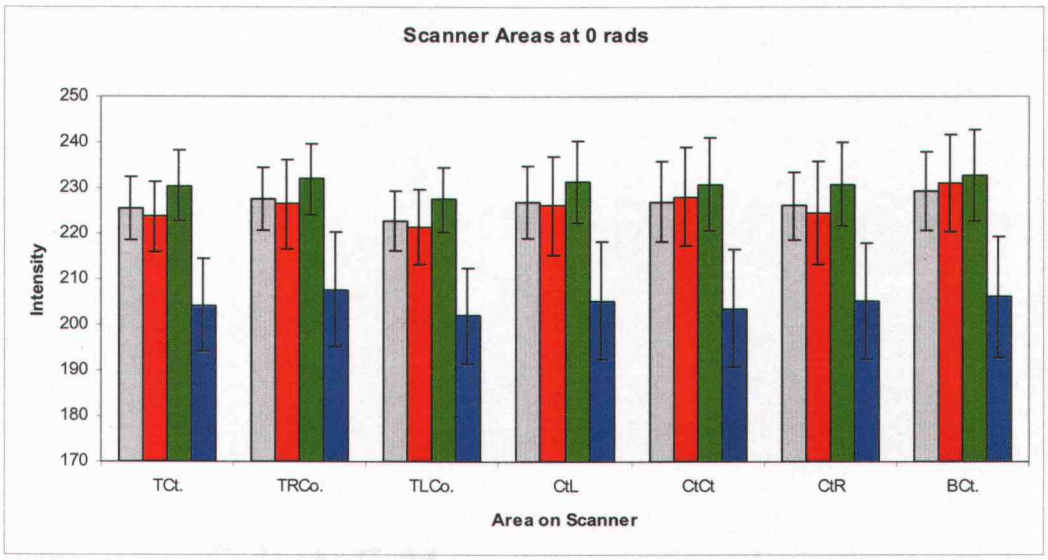


Figure A.20. Scanner Areas at 0 Rads. The x-axis is the card position on the scanner for this dose reference color. The intensity is for the luminosity, the color red, the color green and the color blue.

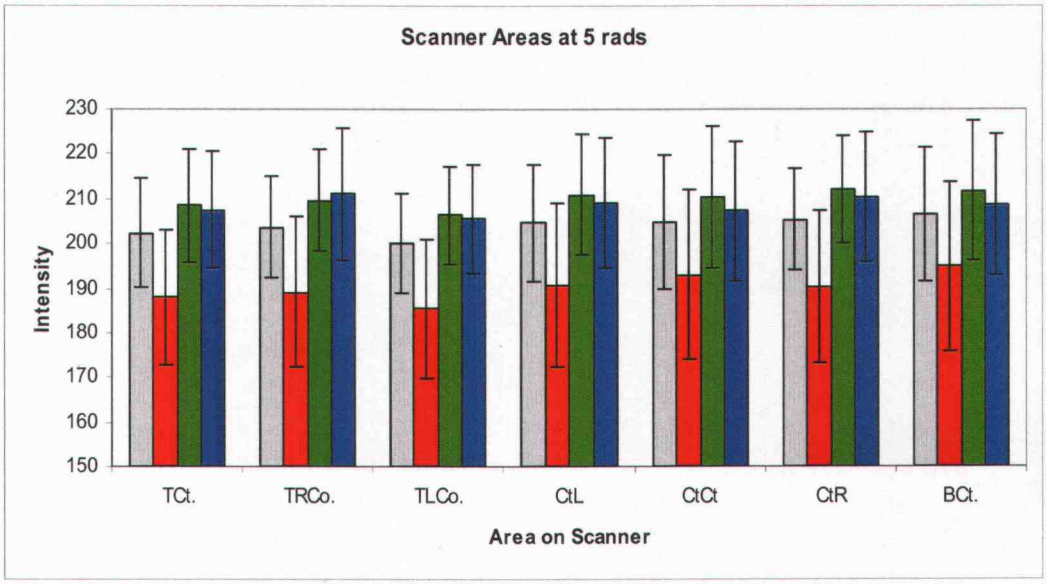


Figure A.21: Scanner Areas at 5 Rads. The x-axis is the card position on the scanner for this dose reference color. The intensity is for the luminosity, the color red, the color green and the color blue.

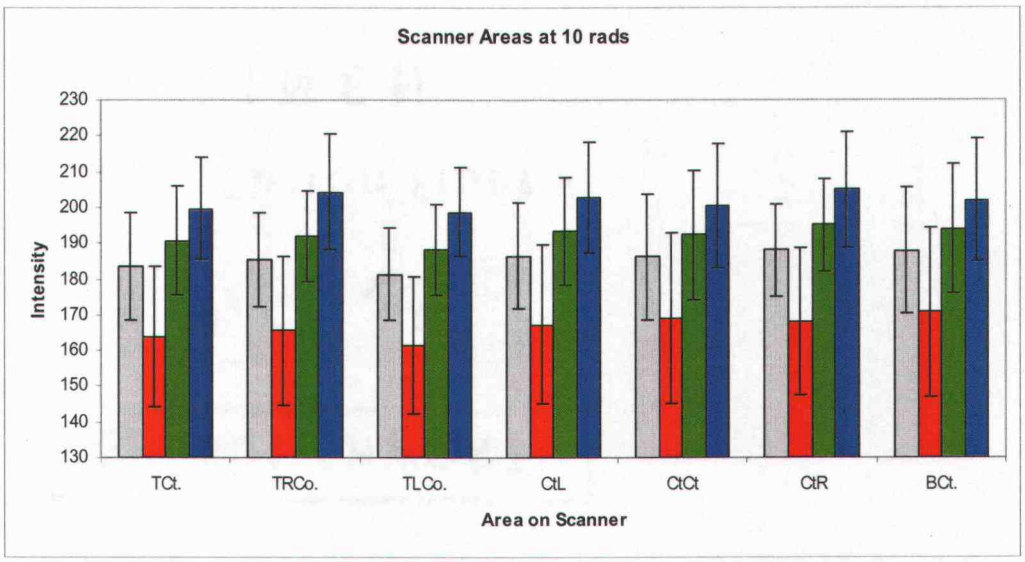


Figure A.22: Scanner Areas at 10 Rads. The x-axis is the card position on the scanner for this dose reference color. The intensity is for the luminosity, the color red, the color green and the color blue.

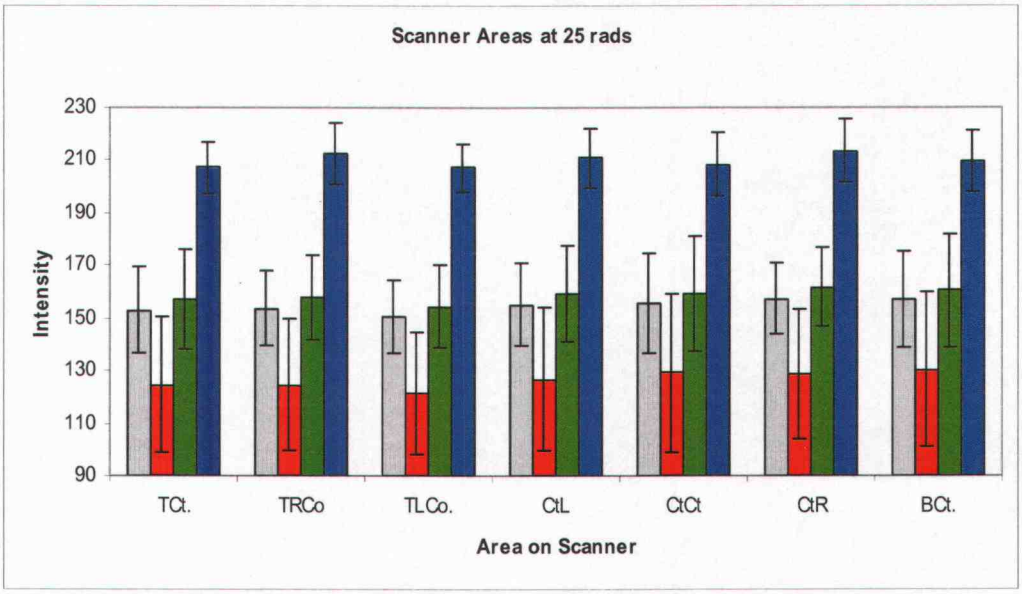


Figure A.23: Scanner Areas at 25 Rads. The x-axis is the card position on the scanner for this dose reference color. The intensity is for the luminosity, the color red, the color green and the color blue.

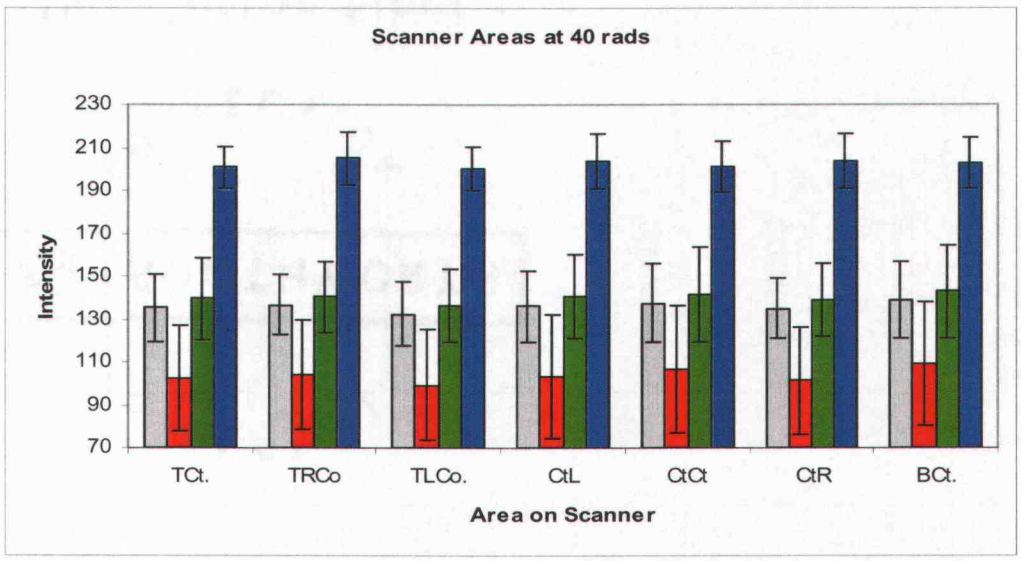


Figure A.24: Scanner Areas at 40 Rads. The x-axis is the card position on the scanner for this dose reference color. The intensity is for the luminosity, the color red, the color green and the color blue.

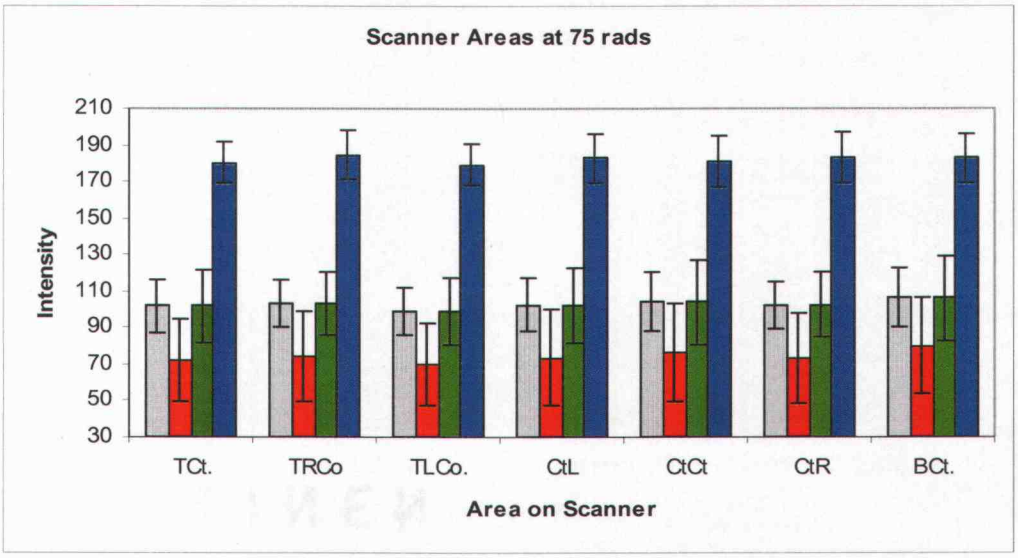


Figure A.25: Scanner Areas at 75 Rads. The x-axis is the card position on the scanner for this dose reference color. The intensity is for the luminosity, the color red, the color green and the color blue.

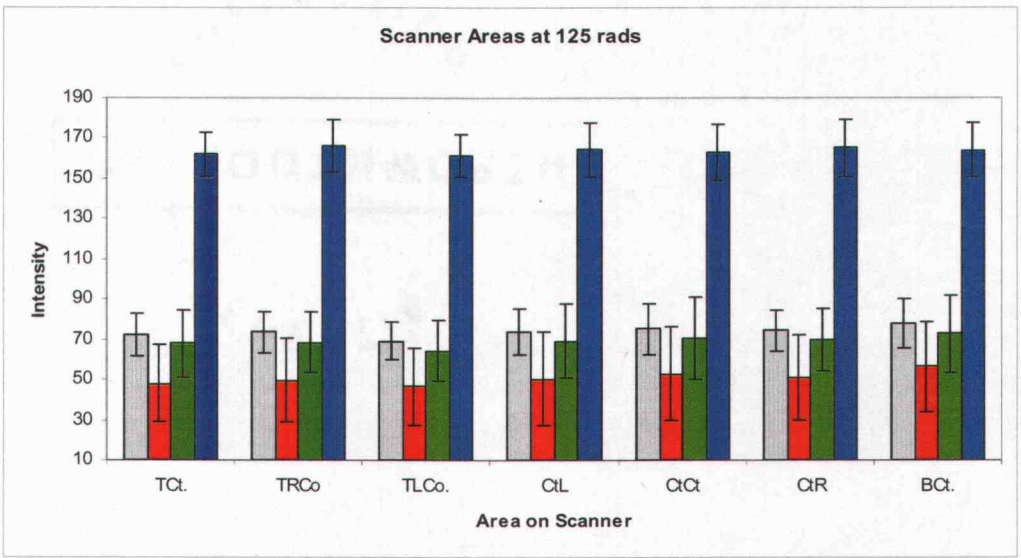


Figure A.26: Scanner Areas at 125 Rads. The x-axis is the card position on the scanner for this dose reference color. The intensity is for the luminosity, the color red, the color green and the color blue.

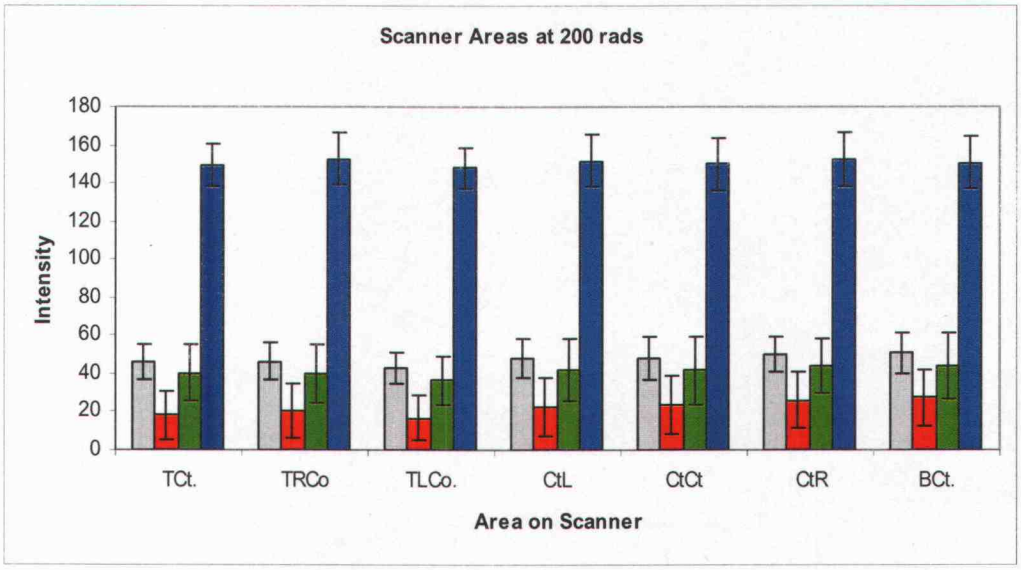


Figure A.27: Scanner Areas at 200 Rads. The x-axis is the card position on the scanner for this dose reference color. The intensity is for the luminosity, the color red, the color green and the color blue.

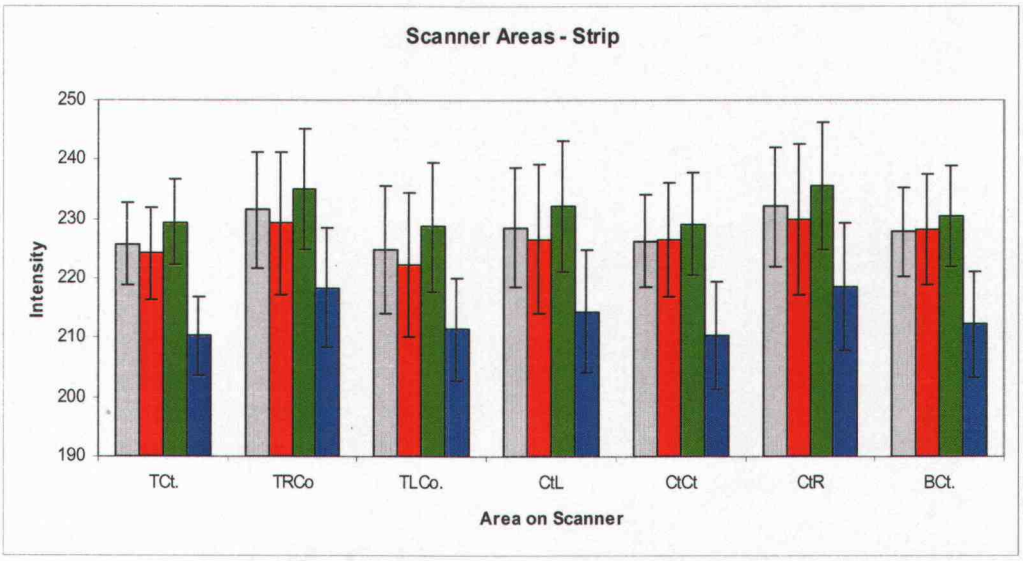


Figure A.28: Scanner Areas at Strip. The x-axis is the card position on the scanner for the chemical strip. The intensity is for the luminosity, the color red, the color green and the color blue.

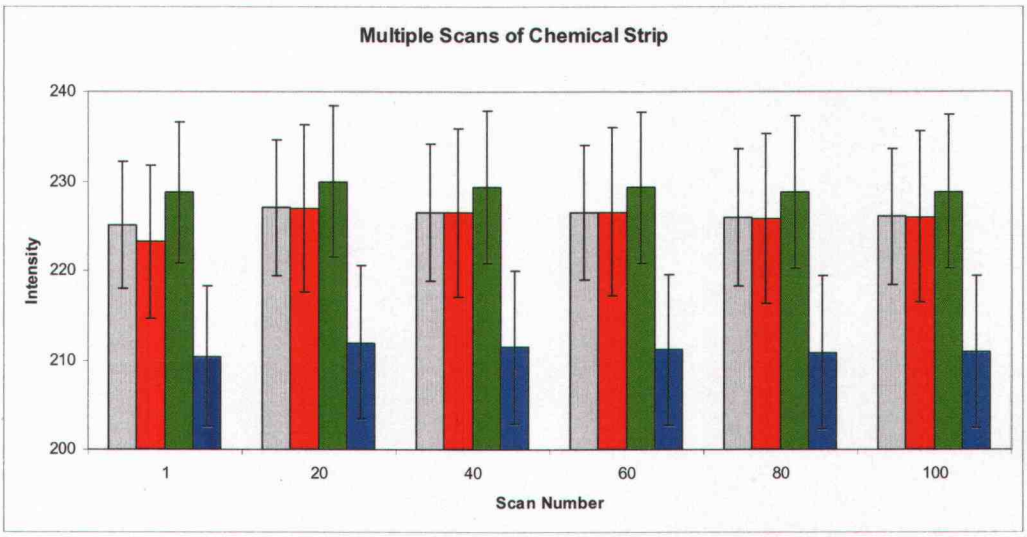


Figure A.29: Multiple Scans of Chemical Strip. The x-axis is number of times a single SIRAD card was scanned. The intensity is for the luminosity, the color red, the color green and the color blue.

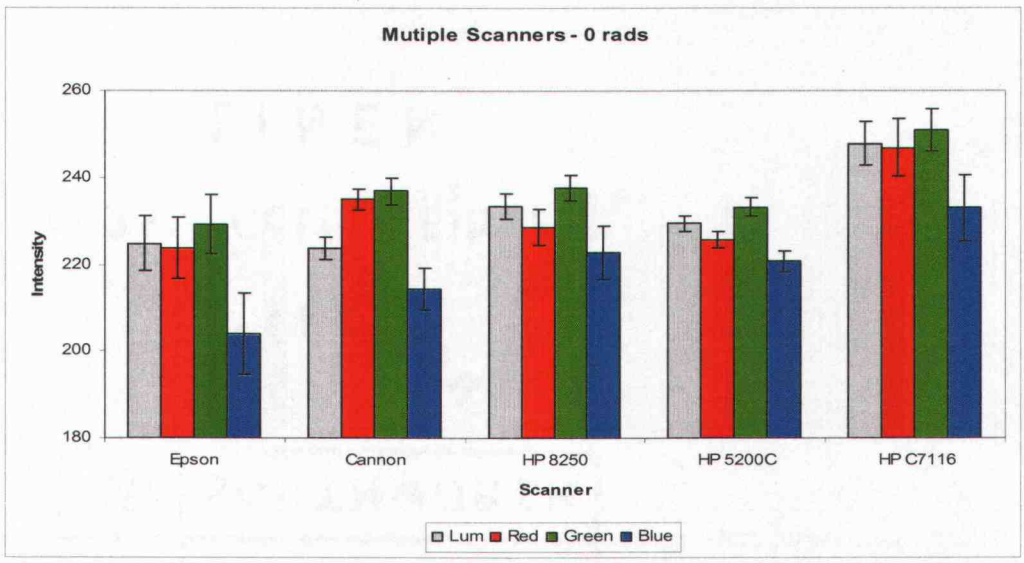


Figure A.30: Multiple Scanners - 0 Rads. The x-axis is the different scanners used to scan a single SIRAD card for the listed reference dose color. The intensity is for the luminosity, the color red, the color green and the color blue.

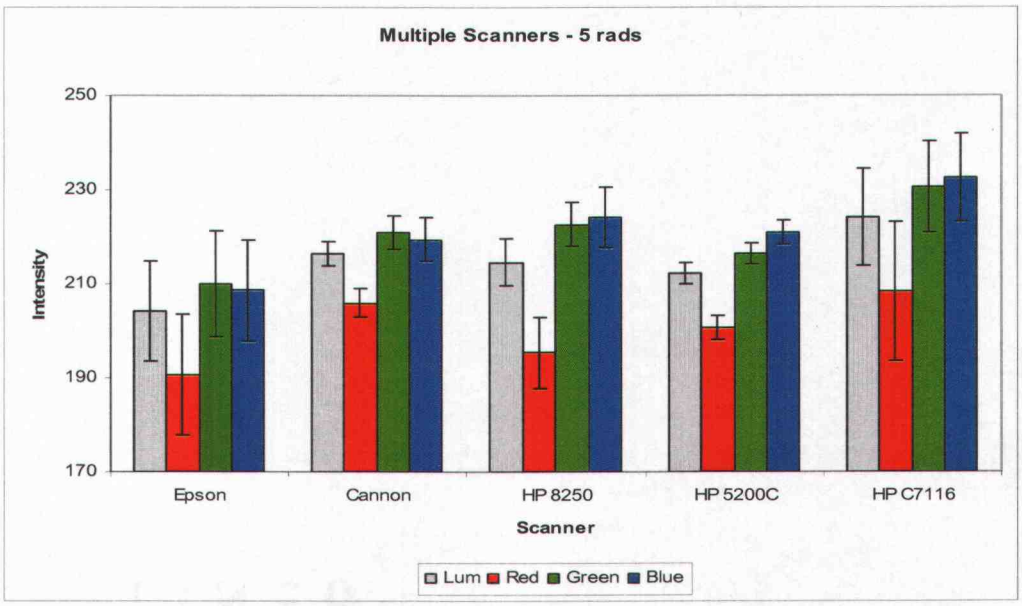


Figure A.31: Multiple Scanners - 5 Rads. The x-axis is the different scanners used to scan a single SIRAD card for the listed reference dose color. The intensity is for the luminosity, the color red, the color green and the color blue.

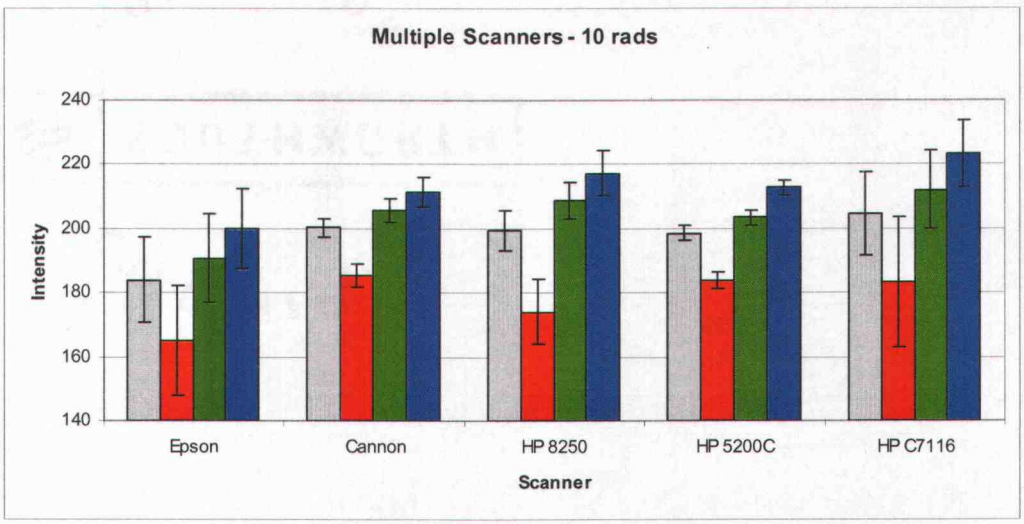


Figure A.32: Multiple Scanners - 10 Rads. The x-axis is the different scanners used to scan a single SIRAD card for the listed reference dose color. The intensity is for the luminosity, the color red, the color green and the color blue.

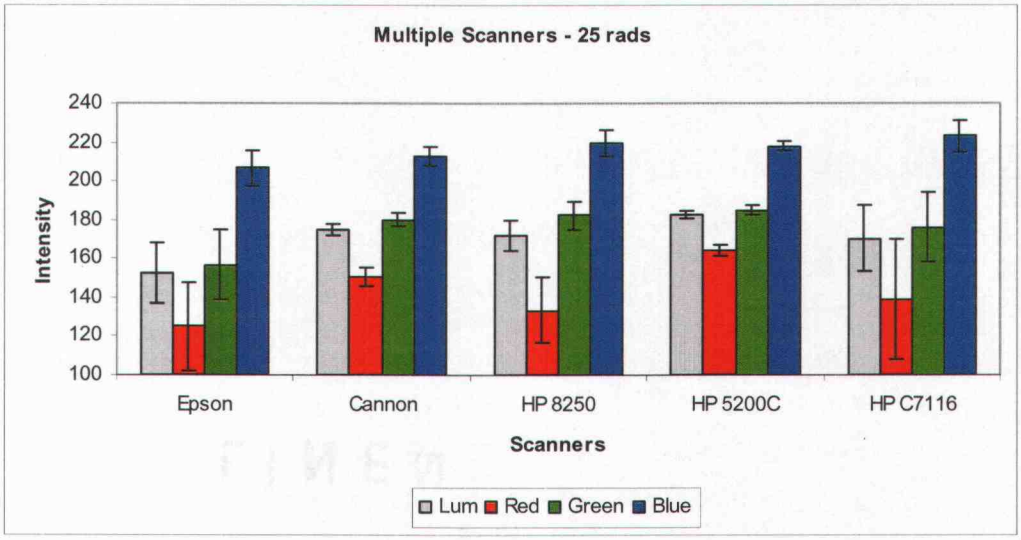


Figure A.33: Multiple Scanners - 25 Rads. The x-axis is the different scanners used to scan a single SIRAD card for the listed reference dose color. The intensity is for the luminosity, the color red, the color green and the color blue.

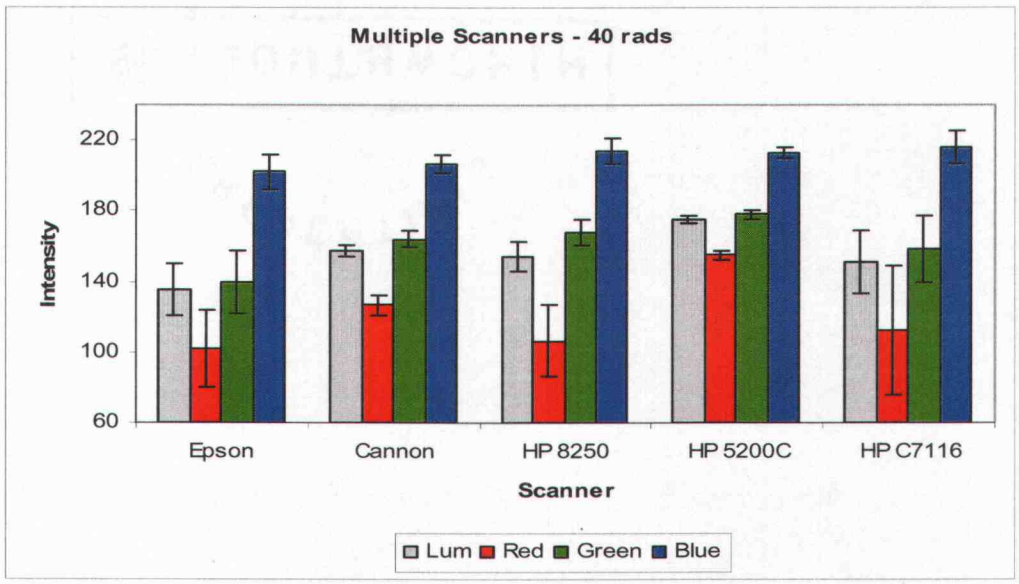


Figure A.34: Multiple Scanners - 40 Rads. The x-axis is the different scanners used to scan a single SIRAD card for the listed reference dose color. The intensity is for the luminosity, the color red, the color green and the color blue.

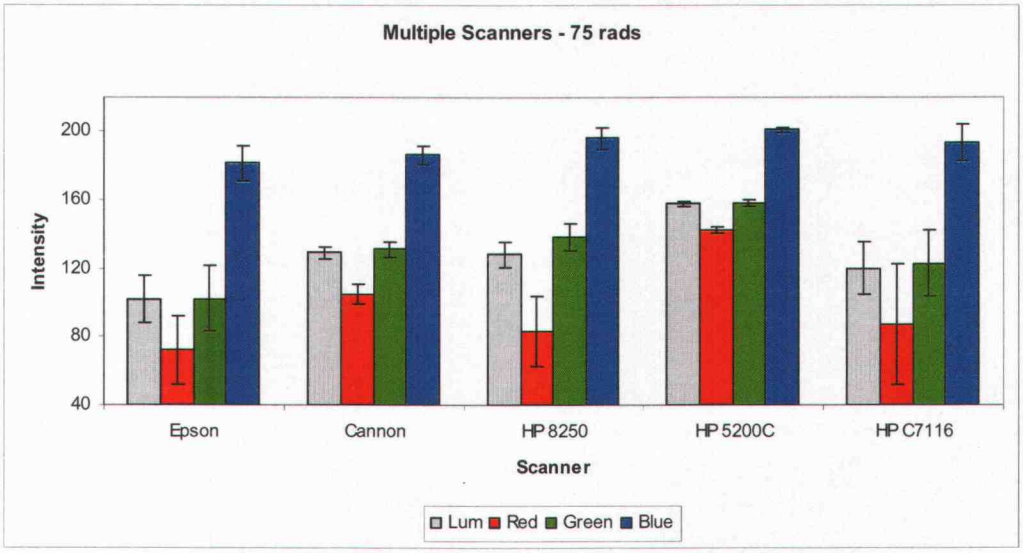


Figure A.35: Multiple Scanners - 75 Rads. The x-axis is the different scanners used to scan a single SIRAD card for the listed reference dose color. The intensity is for the luminosity, the color red, the color green and the color blue.

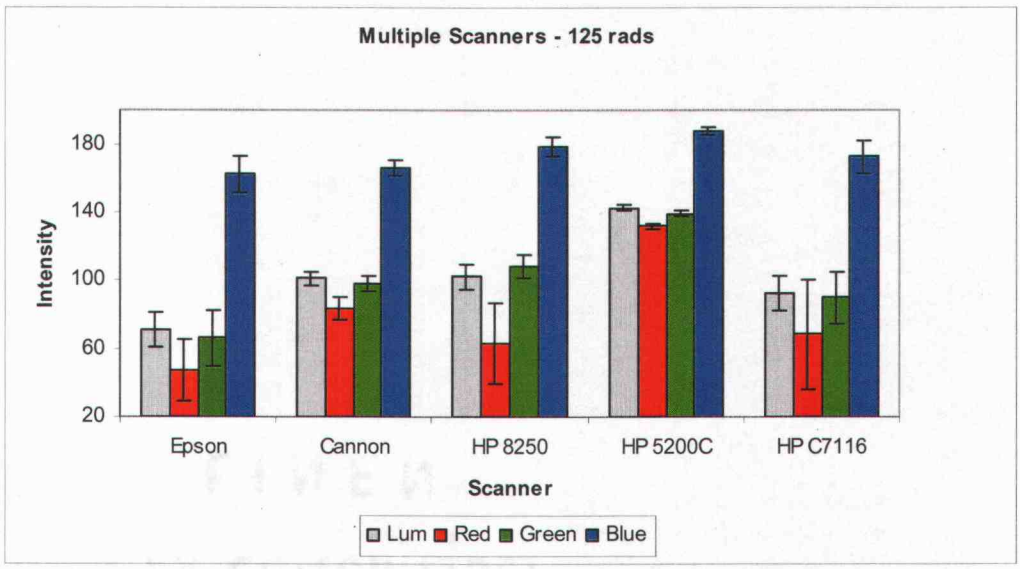


Figure A.36: Multiple Scanners - 125 Rads. The x-axis is the different scanners used to scan a single SIRAD card for the listed reference dose color. The intensity is for the luminosity, the color red, the color green and the color blue.

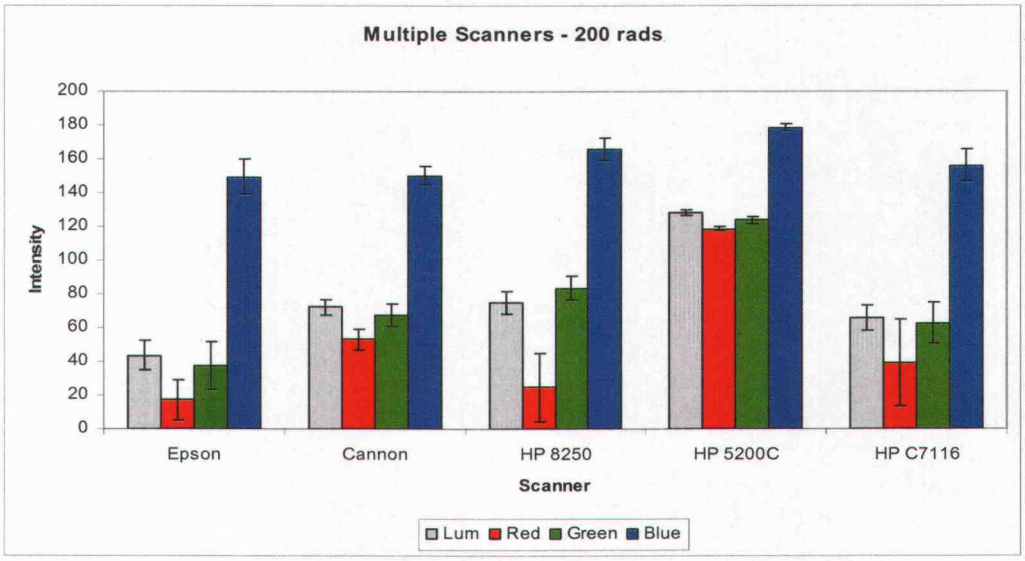


Figure A.37: Multiple Scanners - 200 Rads. The x-axis is the different scanners used to scan a single SIRAD card for the listed reference dose color. The intensity is for the luminosity, the color red, the color green and the color blue.

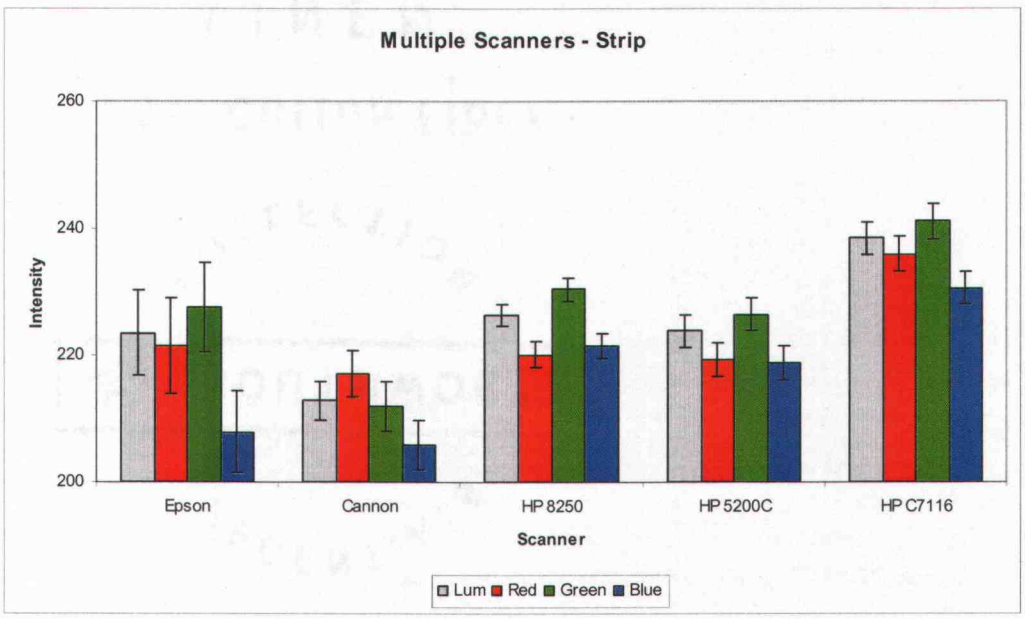


Figure A.38: Multiple Scanners – Strip. The x-axis is the different scanners used to scan a single SIRAD card for the chemical strip. The intensity is for the luminosity, the color red, the color green and the color blue.

APPENDIX B – PuBe Data Sheet

MONSANTO RESEARCH CORPORATION

SUBSIDIARY OF MONSANTO CHEMICAL COMPANY

NUCLEAR SOURCES DEPARTMENT
1515 NICHOLAS ROAD
DAYTON, OHIO

Address: Station B, Dayton 7, Ohio

Phone 268-5481
Area Code 513

SHIPPING DATA FORM

DATE OF CALIBRATION AND SHIPMENT: 16 September 1965

VIA: MOTOR FREIGHT | B/L NUMBER: 03176

OREGON STATE UNIVERSITY
BUSINESS OFFICE
CORVALLIS, OREGON

SHIPPING ADDRESS:

OREGON STATE UNIVERSITY
Dept. of Mech. & Ind. Eng.
RADIATION LABS, O.S.U.
35th & Jefferson
CORVALLIS, OREGON

Attn: Prof. Edward A. Daly
P.O. 13555

MONSANTO RESEARCH CORPORATION LICENSE NUMBER
SNM-567

Accountability data

License No. SNM-918 S. S. Allotment Quota No.

Remarks:

Monsanto Research Corporation
Nuclear Source No. MRC-N-SS-W-PuBe-329
Job No. MRC-N-SS-W-PuBe-359

2

Customer P. O. No. 13555

Type of source: Plutonium-beryllium Neutron Source

Amount and chemical form of isotope	MRC Source No.	Amt (Pu)	Amt (Be)	Emission (n/sec)
Weight and composition of target (in neutron sources)	PuBe-329	48.00g	24.00g	4.22×10^6
	PuBe-359	31.25g	16.00g	3.69×10^6

Emission rate: See above

Max. energy of emitted alpha or beta particles

Source container description

material: ~~304~~ 304-stainless steel

alpha or beta source cover material:

PuBe-329:
dimensions: 1.125" x 3.91"
PuBe-359:
cover thickness: 1.00" x 2.5"

Shipping container description:

15-gal paraffin filled drum No. N-231

Source PuBe-359--$ 765.00
Source PuBe-329-- 600.00
Value of shipping container $ 60.00(N-231)
Total price of source $1425.00

Remarks:

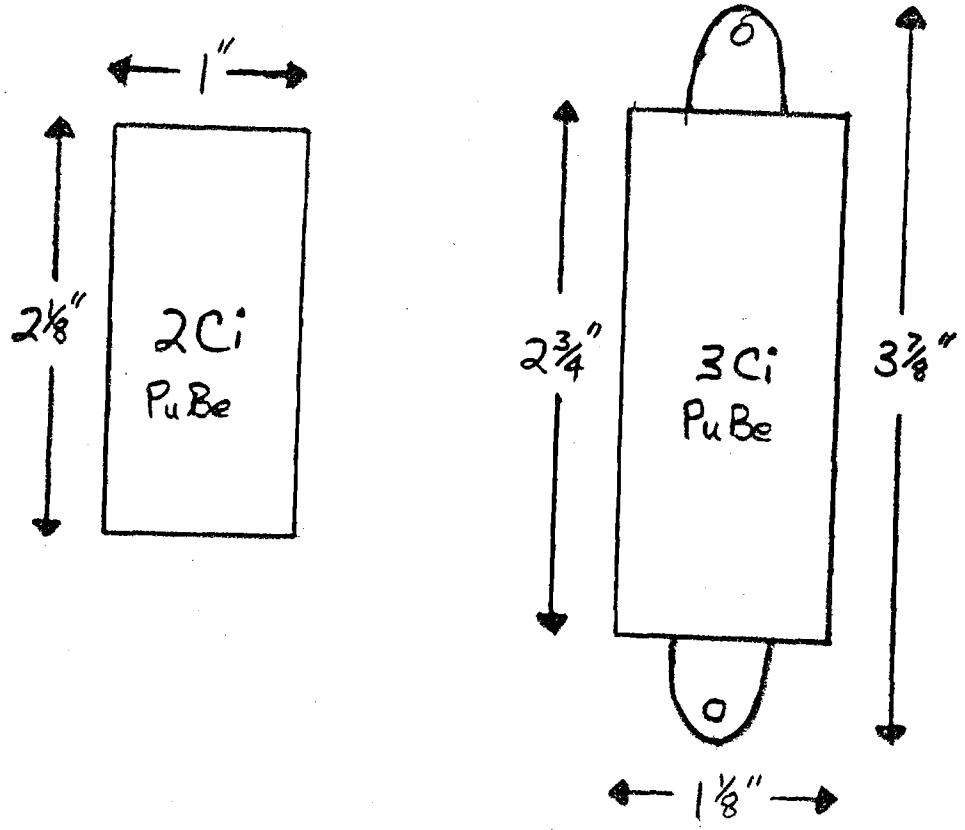
THE REYNOLDS & REYNOLDS CO., DAYTON, OHIO

MONSANTO RESEARCH CORPORATION

By M. R. Hertz

Title M. R. Hertz
Manager, Nuclear Product

Date 16 Sept 1965


1"
2⅛"
2Ci
PuBe
2¾"
3Ci
PuBe
3⅜"
1⅛"