RADNeutron (SIRAD sensor with boric acid) evaluated in this report is not offered for sale as there is very little market

ASSESSMENT OF SIRAD NEUTRON SENSITIVITY

A REPORT TO

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Executive Summary

OSU was tasked with irradiating and determining the neutron sensitivity displayed by Self-indicating Instant Radiation Alert Dosimeter (SIRAD) sensing strips provided by JP Laboratories. This document lays out the procedures followed during the irradiations and an analysis of the results.

The method employed to determine neutron sensitivity was exposing one set of strips to known doses of gamma and neutron radiation, and another set to equal gamma doses, but no neutron dose. In every case the strips receiving neutrons as well as gamma radiation were significantly darker than those receiving only the gamma dose. The conclusion of this report is that this difference in color change can only be attributed to neutrons, though the response does not appear to be linear. Details of the irradiations and analyses are presented in the body of this report. All of the data gathered supports the assertion that the blue sensors of new SIRAD called RADTriage provided to OSU change color in response to neutrons.

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1.0 Introduction

This work was undertaken at Oregon State University during the summer of 2006. Previous work at OSU with SIRAD dosimeters indicated SIRAD response was independent of gamma energy, but that SIRADs were insensitive to neutrons. JP Laboratories has since altered the SIRAD strips by adding a boron compound. OSU has been contracted to determine the neutron sensitivity of the new formulation that is used in the blue sensors of the new RADTriage SIRAD.

Under the direction of TSWG, JP Laboratories provided a large number of sample strips and requested that they be exposed to different dosages, with suggested values of 2, 5, 10, 25, 50 rad of moderated (thermal) and unmoderated neutrons.

Seventy strips were exposed to a combination of gamma and neutron radiation utilizing three different sources. Strips were exposed to gamma radiation and either a thermal or a mixed source of neutrons. Table 1 lists the number of strips irradiated at each dose for a given type of exposure. The pure gamma exposures were done to gather benchmark data on color change. Neutron sensitivity was determined by the extent of induced color change in the exposed strips.

Table 1 Irradiations by Particle Type and Dose Delivered

Target Neutron Dose (rad)	Mixed Neutrons[a]	Thermal Neutrons[a]	Gamma Radiation[a]
2	3	5	6 (3/3)[c]
5	3	5	6 (3/3)[c]
10	3	5	6 (3/3)[c]
25	3	5	6 (3/3)[c]
50	3	5	6 (3/3)[c]
Total strips[b]	15	25	30

[a]Number indicates the total amount of strips irradiated with a particular dose/particle
[b]Unused strips were retained as controls with essentially zero (background) exposure;
[c] A range of pure gamma exposures were delivered to 30 strips. These include exposures equal to the expected gamma dose that is delivered to a strip irradiated with fast neutrons to the dose shown in the first column; and equal to the concomitant gamma dose delivered to a strip being irradiated with thermal neutrons to the neutron dose shown in the first column of Table 1. Additional information can be found in Tables 5 and 6 on the nature and extent of these irradiations.

A preliminary plan for these irradiations was submitted to and approved by TSWG and JP Laboratories. There were two areas in which there were deviations from the initial plan. The '"fast" exposure initially contemplated was discarded for failing to offer additional information. The irradiation times listed in the preliminary procedures were also changed as better dosimetry data became available. This change is discussed at greater length in section 4.0.

2. Sources

Two neutron sources were used for these experiments. These are: a 3-Ci PuBe source of fast neutrons, and thermal neutrons from the tangential beam port of the OSU TRIGA Reactor (OSTR). A gamma source was used to quantify color change from gamma-only contributions.

2.1 PuBe Source

The OSU RC has a PuBe source of 3 Ci. This source emits neutrons as a consequence of an (α,n) reaction with an average energy of 4.5 MeV. It was used earlier in this project for two sets of initial samples. The PuBe source was ideal for these irradiations because it has a small gamma component, relative to the neutron component (less than 50%). The PuBe source was used for the mixed neutron (fast down to thermal) exposures.

All exposures were carried out at 8 cm from the source. The mixed neutron dose rate (the dose rate of the strip receiving a range of neutrons with a polyethylene block behind it) is 67.1 mrad/hr with a gamma dose rate of 23.75 mrad/hr. The polyethylene block was provided to increase the neutron dose rate through reflection and to most closely simulate the SIRAD's operating environment. These dose rates were initially estimated using a model built in MCNP5; post irradiation more accurate values were determined through TLD dosimetry data provided by Global Dosimetry Solutions.

Figure 1. The polyethylene block used for the mixed irradiation and the Bonner Sphere used in earlier experiments.

2.2 The OSU TRIGA Reactor (OSTR)

The OSTR is a water-cooled, Mark III research reactor with graphite shielded core, designed to provide intense radiation fluxes for research and isotope production. The reactor is licensed by the U.S. Nuclear Regulatory Commission to operate at maximum steady state power of 1.1 MW, generating a peak in-core thermal neutron flux of 10^{13} n-cm^{-2}-s^{-1} and a peak fast neutron flux 5.0 x 10^{12} n $cm^{-2}s^{-1}$ (E > 1 MeV).

We used an out of core neutron radiography facility to irradiate the strips with thermal neutrons. This facility was chosen because it is designed to provide a neutron beam with no fast component, additionally, as an out of core facility; high temperatures were not an issue. Recent work done at OSU has determined neutron and gamma dose rates inside this facility to a high degree of precision and mitigated difficulties in separating neutron vs. gamma related color change.

All exposures were carried out at 1 MW operating power level, in the beam line 6 feet from the shutter. In a successful attempt to reduce the gamma dose relative to the neutron dose, a bismuth brick was used to attenuate the gamma component of the beam. The resultant thermal neutron dose rate is 2.68 rad/hr and the gamma dose rate 1.254 rad/hr. This dose rate is calculated from TLD dosimetry data provided by Global Dosimetry Solutions.

Figure 2. The shutter of the neutron radiography facility, the bismuth brick, and the concrete sample stand where sensing strips were held or irradiation.

2.3 Cs-137 Gamma Source

The Radiation Center has both an 8-Ci ^{137}Cs well source (Fig 3.a) and a 1000 Ci ^{60}Co source in a gamma cell irradiation facility (Fig 3.b). For irradiation of the SIRAD strips, the ^{137}Cs source was chosen because of its more moderate dose rates. Previous work at OSU has indicated that there is no significant difference in SIRAD response as a function of gamma energy. The gamma dose rate at the position used in the ^{137}Cs irradiator was 11.6 R/hr.

Figure 3.1a Cs-137 Irradiator

Figure 3.b Co-60 Irradiator

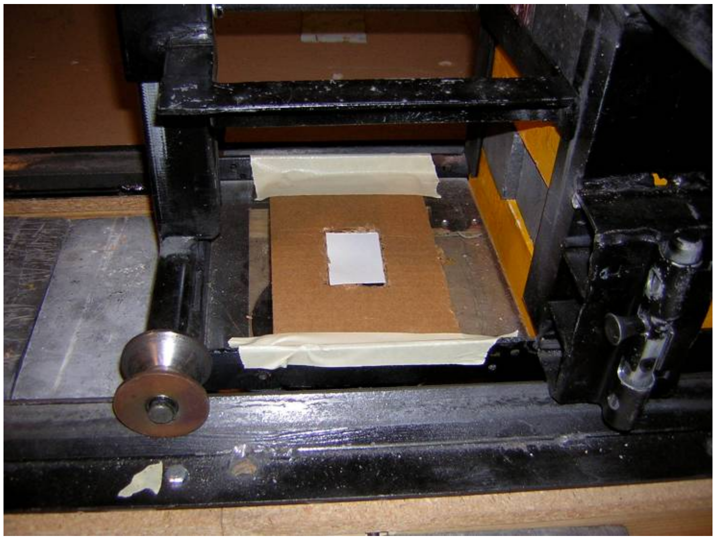


Figure 4. Close-up of the Cs-137 Irradiator and jig constructed to ensure all exposures occurred in the same area of the beam

3.0 Methods

The following is a concise outline of the procedures followed during the irradiations. TSWG and JP Laboratories requested the use of neutrons of varying energies as sources of radiation. The mixed irradiation was designed to most closely model the SIRAD's working environment, with the poly block representing the tissue mass of the wearer. All data capture scans were done at as high a resolution as was reasonable, and all images created were preserved. Relevant images are appended to this report.

3.1 Sample Preparation

1. Seventy strips were affixed to small paper cards, three or five strips to a card (see example Fig 5).
2. Strips were mounted using the adhesive backing with the UV blocking top coat facing out.
3. Each small paper card was labeled with the type of dose to be received (mixed, thermal, or gamma), and the dose to be delivered. Some of the dose labels were based on preliminary dosimetry data, more accurate doses are recorded in this report.
4. Each card was scanned with zero exposure for later comparison, taking care to scan in a consistent manner.

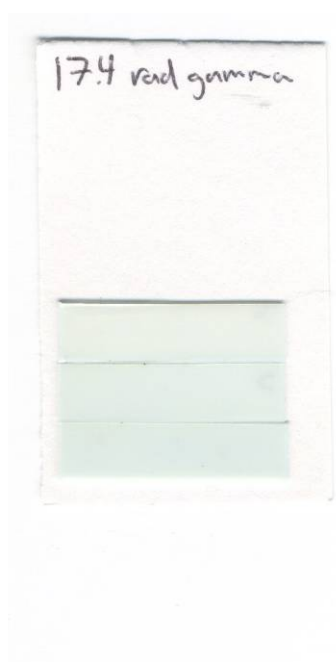


Figure 5. An example of sensing strips mounted on a paper card.

3.2 Mixed Neutron Irradiation Procedures (Using a PuBe source)

1. Five paper cards, one for each dose, were placed facing the PuBe source approx. 8 cm away.
2. Flush behind the cards a poly block was placed. This polyblock serves as a reflector/moderator for neutrons and is meant to be representative of the dose that would be received by a badge affixed to the lapel of a wearer
3. Cards were removed as they received their assigned dose (Table 3).

Table 3 Mixed Neutron Irradiation Times and Doses

SIRAD Card	Irradiation Time (hours)	Neutron Absorbed Dose (rad)	Gamma Absorbed Dose (rad)
Mixed Set 1/5	24	1.61	.57
Mixed Set 2/5	65	4.36	1.54
Mixed Set 3/5	138	9.26	3.28
Mixed Set 4/5	305	20.47	7.24
Mixed Set 5/5	641	43.01	15.22

3.3 Thermal Neutron Irradiation Procedures (Using the OSTR NRF)

1. Five paper cards, one for each dose, were placed in the neutron radiography facility. The were placed directly in the beam line behind a bismuth brick.

2. When a card reached its assigned dose, the beam was temporarily blocked while the card was removed before the next shot was begun.

Table 4 Thermal Neutron Irradiation Times and Doses

SIRAD Card	Irradiation Time (hours)	Neutron Absorbed Dose (rad)	Gamma Absorbed Dose (rad)
Thermal Set 1/5	1	2.68	1.25
Thermal Set 2/5	1.75	4.70	2.19
Thermal Set 3/5	3	8.05	2.76
Thermal Set 4/5	8	21.47	10.03
Thermal Set 5/5	14.1	37.83	17.68

3.4 Gamma Irradiation Procedures

1. Ten different paper cards, each with three strips per card, were exposed to ten different total doses of gamma radiation, matching the gamma doses in the third column of tables 3 and 4. That is also the reason behind the naming convention. “Gamma Set M 3/5” receives a gamma dose equal to the gamma dose received by the 3rd card in the mixed exposure set.
2. The irradiation format shown in Fig 4 was utilized to expose the strips. The cardboard jig was designed to ensure all the gamma irradiations were conducted under the same conditions.
3. When a strip reached its assigned dose it was removed.

Table 5 Gamma Irradiation Times and Doses

SIRAD Card	Irradiation time (minutes)	Absorbed Gamma Dose (rad)
Gamma Set M 1/5	2.9	.57
Gamma Set M 2/5	8.0	1.54
Gamma Set M 3/5	17.0	3.28
Gamma Set M 4/5	37.5	7.24
Gamma Set M 5/5	78.7	15.22
Gamma Set T 1/5	6.5	1.25
Gamma Set T 2/5	11.4	2.19
Gamma Set T 3/5	19.5	2.76
Gamma Set T 4/5	51.9	10.03
Gamma Set T 5/5	91.5	17.68

3.5 Control Procedure

Extra strips will be retained as controls. They were stored and not mounted. A sample was scanned at the end of the irradiations to determine the significance of “background” color change due to age, temperature, or other factors.

3.6 SIRAD Readout

An Epson Perfection 2480 PHOTO scanner was used to capture images of the exposed and control strips. This scanner was previously used in the work of Bak and Stewart testing the response of earlier versions of the SIRAD. It is a flatbed color image scanner with a Color Epson MatrixCDTM line sensor. It reaches an optical resolution of 2400 dpi and a hardware resolution of 2400 x 4800 dpi with Micro Step DriveTM technology. It can achieve a maximum resolution of 12,800 x 12,800 dpi with software interpolation. The dimensions of its effective pixels are 24,000 x 28,080 (2400 dpi). The scanner has a color hardware bit depth of 48-bits per pixel internal, 48-bits per pixel external. Depending on the image editing software used, external bit depth is selectable to 48 bits. Its grayscale hardware bit depth is 16-bits per pixel internal, 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, pg. 1) SIRADS will also be retained and returned to JP Laboratories for colorimeter analysis.

Fig. 6 Epson Scanner

4.0 Determining Absorbed Dose

Before proceeding on to the analysis of the results, a few words on determining absorbed dose in neutrons are in order. The determination of absorbed dose from neutrons is not a simple task. OSU has used three methods to determine neutron dose rates, but each has some uncertainty associated with it.

The first two methods were employed to arrive at rough dose rate estimates that were used to choose exposure durations, these were also the times in the irradiation procedures approved by JP Laboratories. These exposures were assigned more accurate doses when the dosimetry data from method three arrived.

1. Based on the known neutron spectra, the absorbed dose was calculated using fluence to dose conversion factors. This required an accurate knowledge of the neutron spectra in order to start the calculation. There are published values of spectra for PuBe sources, and recent measurements in the OSU Radiography Facility have provided considerable detail on the neutron energies there as well. Hand calculations, however, by necessity, may be overly simplistic.
2. Based on the known neutron spectra, the dose distribution was modeled using the Monte Carlo Neutral Particle (MCNP) code. As in approach 1, the user must determine the appropriate spectra for the source. Then an accurate model of the source geometry as well as the target must be built in MCNP in order to determine the absorbed dose.
3. Directly measure dose using an appropriately calibrated detector. OSU obtained neutron sensitive thermoluminescent dosimeters (TLDs) from Global Dosimetry Solutions that are calibrated for neutrons of different energies. The difficulty here is that the results provided by Global Dosimetry readout in mrem (i.e., dose equivalent, with an implied quality factor). Backing out the absorbed dose requires knowledge of the quality factor (Q) or the radiation weighting factor (w_r) used in the calibration. This is relatively simple for the thermal exposures, the neutrons in the NRF should be entirely thermal. The PuBe exposures are slightly more complicated because the PuBe source has a spectrum of neutrons from fast down to thermal. The Q value used to back out the absorbed dose was taken from the average neutron energy of 4.5 MeV. Unfortunately, various quality factors for neutrons have been published over the years. For this work the neutron quality factors published in 10CFR20.1004 will be used, as it is the current standard used by the United States Government. A further discussion of this difficulty appears in the following section.

5.0 Results

A visual inspection of cards receiving equal gamma doses, with one receiving neutrons clearly shows the card which also received neutrons universally experienced more color change than cards exposed to an equal gamma dose. This section will quantify the observed color change, which corresponds to neutron sensitivity.

The tool used to evaluate color change is Adobe Photoshop. Photoshop has a number of methods of color analysis. There is channel information available for Red Green Blue, Cyan Yellow Magenta, as well as other color models. For the purposes of this analysis, the most useful tool was a simple grayscale value, which provided a value for the increasing color density of the SIRAD strips as absorbed dose increased. Data on several other color channels was recorded, and is available on request, but was deemed to offer little in the way of new information to this analysis and so was not included in this report.

The basic method of analysis was to subtract the color change seen on the pure gamma exposure from the color change seen on the gamma and neutron strips, attributing excess color change to the neutrons. There are two methods of doing this, neither of which is obviously superior to the other, both of which are presented below.

Table 6 presents the initial grayscale readings of all the cards, irradiated and unirradiated as well as their difference, the color change associated with irradiation. These are the values used in subsequent tables to determine neutron sensitivity.

In the following tables 7, 8, and 9 the card names are abbreviated. “Thermal Set 3/5” is abbreviated T 3. Likewise “Gamma Set T 1/5” is G T 1.

Table 6 Grayscale Values

SIRAD	Unirradiated	Irradiated	Irradiated – Unirrad.
Thermal Set 1/5	8.2	17.5	9.3
Thermal Set 2/5	8.1	22.1	14
Thermal Set 3/5	10.9	30.4	19.5
Thermal Set 4/5	9.6	44.8	35.2
Thermal Set 5/5	8.1	53.1	45
Mixed Set 1/5	7.33	12.5	5.17
Mixed Set 2/5	7.5	20.66	13.16
Mixed Set 3/5	8.33	31.66	23.33
Mixed Set 4/5	9	44.16	35.16
Mixed Set 5/5	6.16	54	47.84
Gamma Set T 1/5	7.83	13.66	5.83
Gamma Set T 2/5	11	19.5	8.5
Gamma Set T 3/5	12	25	13
Gamma Set T 4/5	11.33	36.5	25.17
Gamma Set T 5/5	9.83	45	35.17
Gamma Set M 1/5	8.5	11	2.5
Gamma Set M 2/5	9.16	15.5	6.34
Gamma Set M 3/5	10.16	22.33	12.17
Gamma Set M 4/5	11.33	32.33	21
Gamma Set M 5/5	7.5	43	35.5

5.1 Neutron Sensitivity Assessment Method 1

This method is the simplest and takes the grayscale value of the gamma and neutron irradiated card minus the grayscale value of the appropriate gamma only card, attributing the excess color change to neutron sensitivity.

As mentioned above, the differences between absorbed and equivalent dose are a matter for some concern. For that reason the change in color due to neutrons was calculated both on a per rad and a per rem basis to determine if there was a significant impact on the results due to our choice of quality factors.

Table 7 Neutron Sensitivity Method 1

SIRAD	Change in Grayscale	Change in Grayscale per rad neutron	Change in Grayscale per rem neutron
(T 1) - (G T 1)	3.84	1.43	0.57
(T 2) - (G T 2)	2.6	0.55	0.22
(T 3) - (G T 3)	5.4	0.67	0.27
(T 4) - (G T 4)	8.3	0.39	0.15
(T 5) - (G T 5)	8.1	0.21	0.09
(M 1) - (G M 1)	1.5	0.93	0.12
(M 2) - (G M 2)	5.16	1.18	0.15
(M 3) - (G M 3)	9.33	1.01	0.13
(M 4) - (G M 4)	11.83	0.58	0.07
(M 5) - (G M 5)	11	0.26	0.03
Average		**0.72**	**0.18**

5.2 Neutron Sensitivity Assessment Method 2

This method is only slightly more complicated. It takes the grayscale value of the gamma and neutron irradiated card minus the grayscale value of the gamma and neutron card while unirradiated. Then that value is subtracted by the grayscale value of the appropriate iraddiated gamma card minus the same card's value unirradiated. Again the excess color change is attributed to neutron sensitivity. The difference between the two methods is that the first method assumes the gamma only and the gamma plus neutron cards have the same unirradiated value, the absolute difference. The second method focuses on the relative changes observed, and is perhaps slightly more trustworthy.

Table 8 Neutron Sensitivity Method 2

SIRAD	Change in Grayscale	Change in Grayscale per rad neutron	Change in Grayscale per rem neutron
(T 1) - (G T 1)	3.47	1.29	0.52
(T 2) - (G T 2)	5.5	1.17	0.47
(T 3) - (G T 3)	6.5	0.81	0.32
(T 4) - (G T 4)	10.03	0.47	0.19
(T 5) - (G T 5)	9.83	0.26	0.10
(M 1) - (G M 1)	2.67	1.66	0.21
(M 2) - (G M 2)	6.82	1.56	0.20
(M 3) - (G M 3)	11.16	1.21	0.15
(M 4) - (G M 4)	14.16	0.69	0.09
(M 5) - (G M 5)	12.34	0.29	0.04
Average		0.94	0.23

5.3 Gamma Sensitivity Assessment Method

This table was constructed so that the relative sensitivity of neutrons and gammas can be compared. The values in table 9 are all from the pure gamma exposures. Since the quality factor for gammas is 1, there is no need for a separate “change in grayscale per rem gamma” column.

Table 9 Gamma Sensitivity

SIRAD	Change in Grayscale	Change in Grayscale per rad/rem gamma
Gamma Set T 1/5	5.83	4.65
Gamma Set T 2/5	8.5	3.87
Gamma Set T 3/5	13	4.71
Gamma Set T 4/5	25.17	2.51
Gamma Set T 5/5	35.17	1.99
Gamma Set M 1/5	2.5	4.39
Gamma Set M 2/5	6.34	4.11
Gamma Set M 3/5	12.17	3.71
Gamma Set M 4/5	21	2.90
Gamma Set M 5/5	35.5	2.33
Average		3.52

5.4 Graphical Presentation of Data

This section presents two graphs of the data in tables 7 and 8.

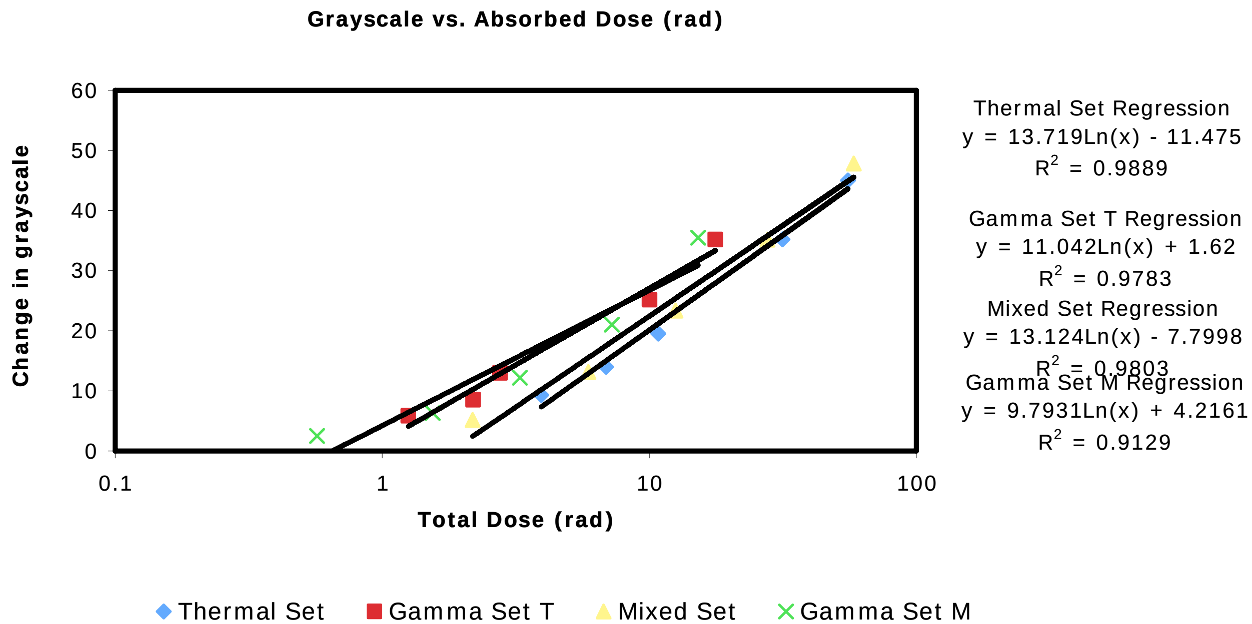


Figure 7 Changes in grayscale vs. total dose in rads

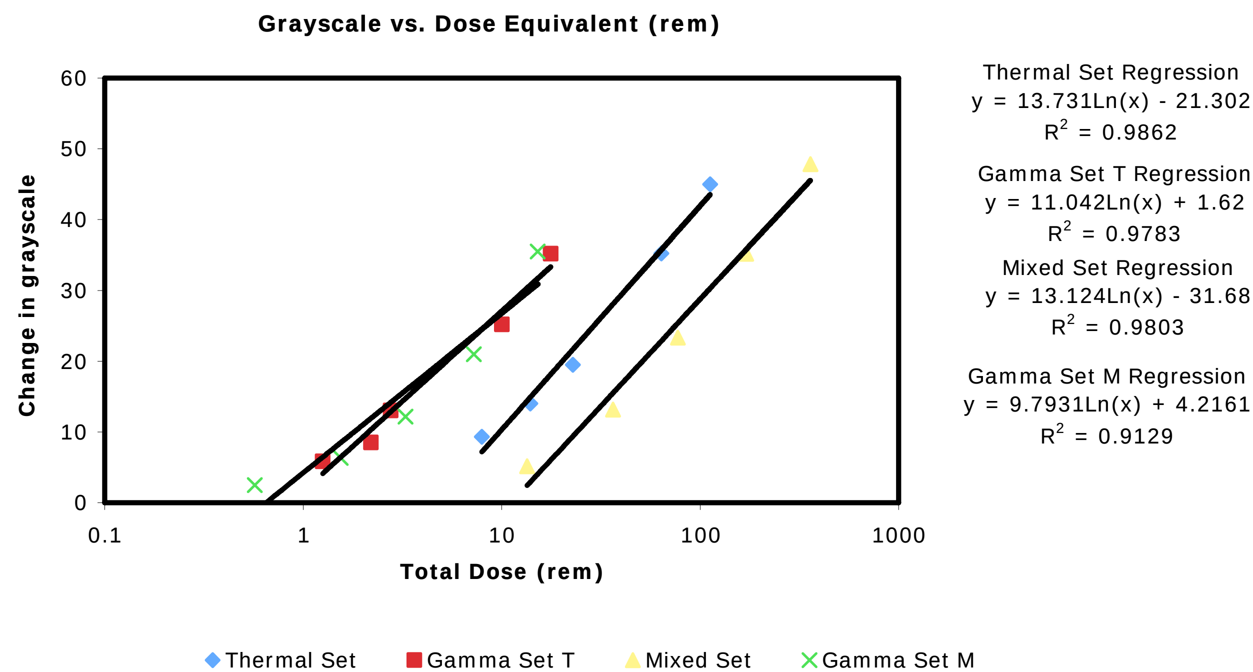


Figure 8 Changes in grayscale vs. total dose in rem

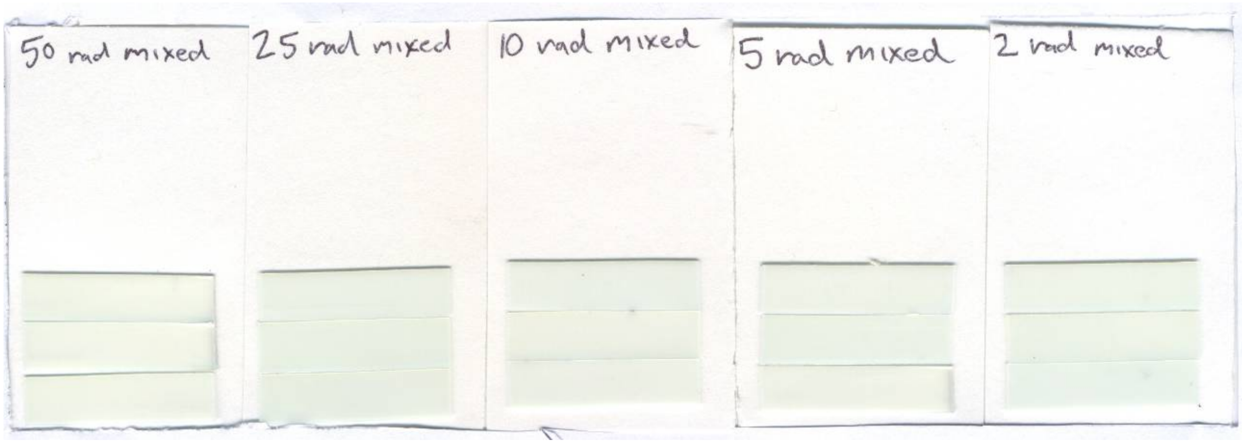
6.0 Conclusion

An examination of the results of the analysis clearly supports the initial conclusion that the tested SIRAD strips are sensitive to neutrons. In every case there was more color change shown by the neutron and gamma exposures than in the pure gamma exposures.

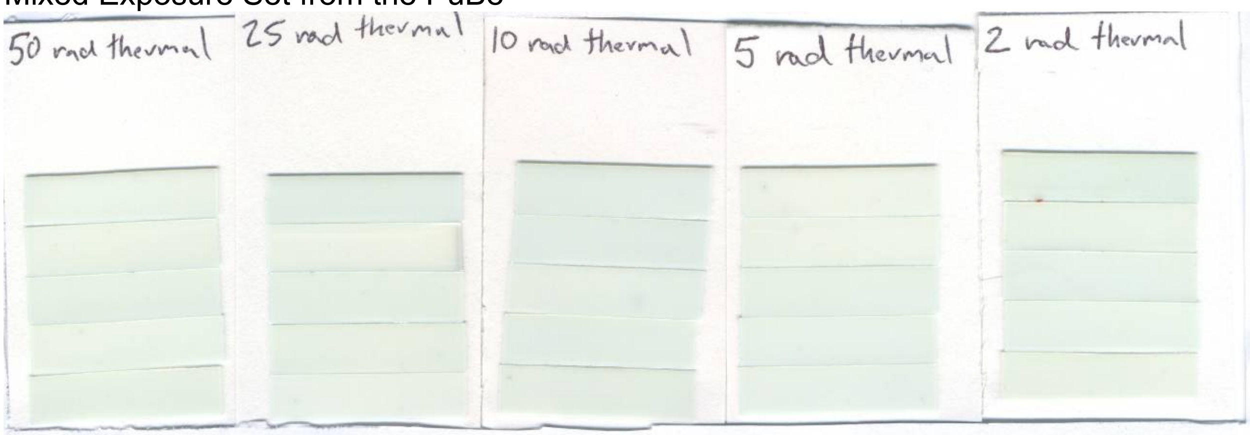
The chances that other factors that could explain this color change aside from neutron sensitivity are negligible. Previous work at Oregon State has established that SIRADS are relatively insensitive to gamma energy, and the dosimetry data is equally solid, vouched for by Global Dosimetry.

Based on the values of tables 7, 8, and 9, SIRAD strips were about 4 times more sensitive to gammas than neutrons in terms of induced color change per rad, and about 18 times more sensitive to gammas than neutrons per rem. Averaging values for the dose – response relationship is of questionable utility because the response shown by the SIRADs did not appear to be linear. In table 8, the change in color per rad declines with every increase in absorbed dose. In table 7 the relationship is less pronounced, but there is still a general decline in sensitivity with dose. This does not in any way invalidate the primary finding of this report, which is that the new blue sensors in the RADTriage SIRAD are capable of detecting neutrons.

Appendix A: Unirradiated Images

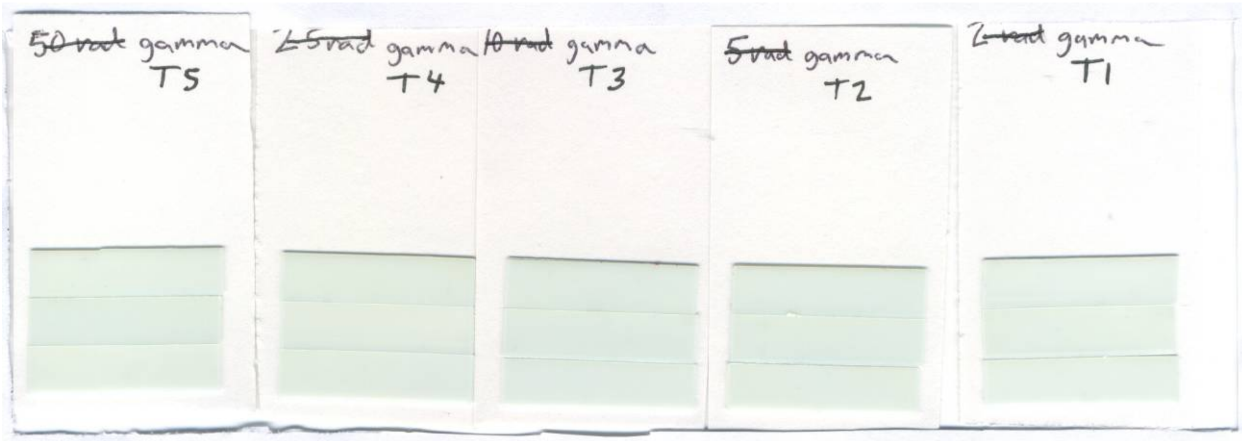


Mixed Exposure Set from the PuBe



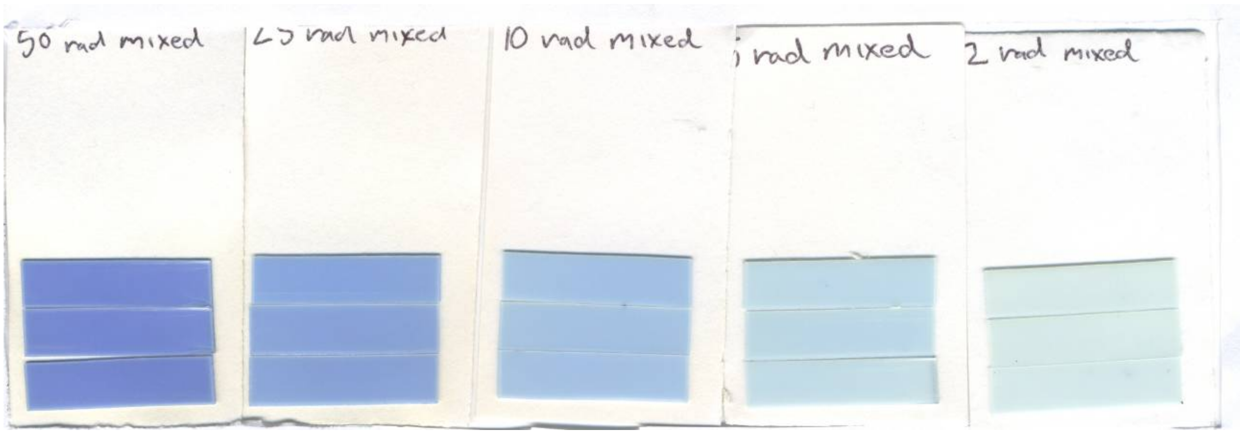
Thermal Exposure Set from the NRF

Gamma exposures equal to the gamma components of the mixed exposure set

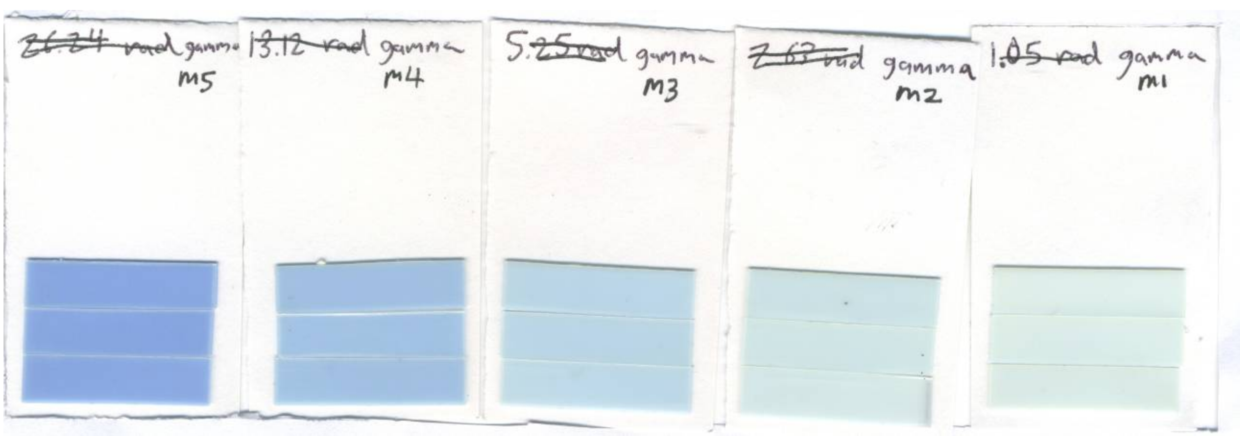


Gamma exposures equal to the gamma components of the thermal exposure set

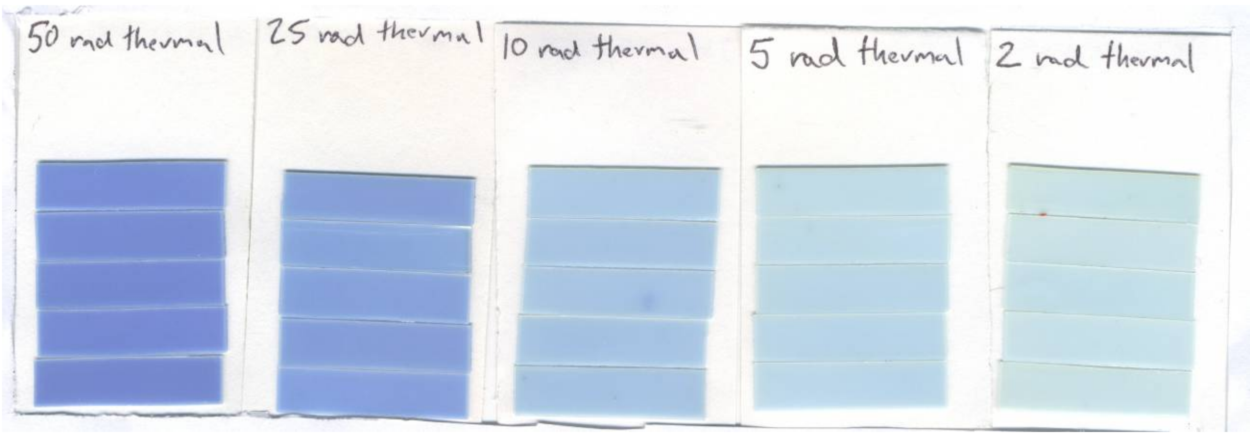
Appendix B: Irradiated Images



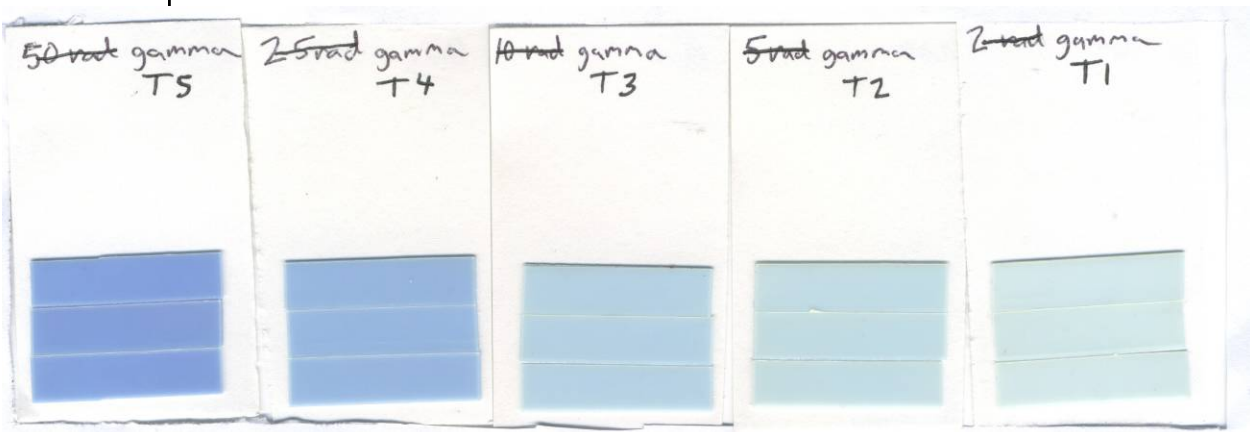
Mixed Exposure Set from the PuBe



Gamma exposures equal to the gamma components of the mixed exposure set



Thermal Exposure Set from the NRF



Gamma exposures equal to the gamma components of the thermal exposure set