Assessing and Evaluating the Self-indicating Instant Radiation Alert Dosimeter (SIRAD)

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Abstract – **The Self-indicating Instant Radiation Alert Dosimeter, SIRAD, manufactured by JP Labs*, is a user-friendly, disposable casualty radiation dosimeter for monitoring high doses (5-200 rads) of ionizing radiation. The dosimeter has been distributed to first-responders for the purpose of dose tracking. When exposed to radiation, the sensing strip of the SIRAD badge will instantly develop a permanent color change which is cumulative and proportional to dose. As part of a research project, Oregon State University's Department of Nuclear Engineering and Radiation Health Physics conducted a series of evaluations of the SIRAD. The SIRAD badges were assessed to see if they met the manufacturer's claims of a color change independent of radiation type and if the strips monitors x-rays (>10ev), electrons, photons, alpha particles and neutrons. Evaluations of the SIRAD's response to gamma and neutron radiation were done using three gamma sources; ^{137}Cs, ^{226}Ra, and ^{60}Co, and a mixed gamma-neutron source, plutonium-beryllium (PuBe). These evaluations included the cards response to gamma exposures totaling between 2.5 to 125 rads. The color-changing strip was read using a commercially available, cost-effective, flatbed scanner and Adobe Photoshop 7.0® software to provide quantitative results and to remove subjectivity in the process. Under normal conditions of use, the SIRAD can be read by personnel using the color reference chart incorporated into the device. As a result of this evaluation, it was determined that the SIRAD card responds to the gamma radiation of cesium and cobalt with possible dependence to radium. Tests show that there is no evidence that the chemical strip is responsive directly or indirectly to neutrons.**

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INTRODUCTION

The Self-indicating Instant Radiation Alert Dosimeter, SIRAD, is a dosimeter that is targeted for use by emergency response personnel. It is used for the determination of personnel exposure from radiation sources a first responder may encounter during a possible nuclear conflict or radiological accident, e.g. “dirty bomb”. This dosimeter allows the individual to immediately self-assess the dose they may be subjected to. This will provide the wearer and medical personnel instantaneous, easy to read, and accurate information about the radiation exposure to the victim. In turn this will help them assess the health risks and guide in treatment. The use of the SIRAD card will allow the user to have a limited radiation dosimetry program without the need to process dosimeters.

The device has many desirable characteristics. It is user-friendly, inexpensive, and disposable. SIRAD is approximately the size and thickness of a credit card and can be worn around the neck like an identification (ID) badge or clipped to a shirt pocket. It monitors high doses, 5-200 rads, of ionizing radiation and is designed to be read under fluorescent light. A chemical sensing strip made up of proprietary diacetylenes ($R-C\equiv C-C\equiv -R$, where R is a substituent group) in the center of the card is tissue equivalent. This strip will change a shade of blue which corresponds to a dose on the adjacent color reference chart. A black UV film is placed on top of the card to protect it from ultra-violet light and excess exposures to fluorescent and ambient light. SIRAD badges have a shelf-life of approximately one year.

Evaluations of this card were performed at Oregon State University and based on manufacturer claims. The cards were exposed to known gamma and neutron radiation fields and their responses were measured. For the gamma sources, the cards were exposed to radiation fields from 2.5 to 125 rads and 5 to 35 rads from the neutron source. Test for angular dependence were conducted to observe the cards efficiency of detecting a dose from exposure from any angle. Self-shielding or other factors may contribute to erroneous readings.

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 charts. 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. These measurements were taken for the chemical strips and then compared to the color reference chart on the card. By using the scanner and the software, the human element of uncertainty in determining the color was removed.

Optical scanners are a common workplace tool and are fairly inexpensive. They were able to provide a logical means to capturing and recording the SIRAD cards. However, consistency in performance is essential if they are to be used for these tasks. As a side issue, two testes were done to evaluate their use. The first test looked at different areas of a single scanner to determine if the readings would vary. The second test looked 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.

MATERIALS AND METHODS

Self-indicating Instant Radiation Alert Dosimeter

The card has been discussed in some detail already. However, it is important to emphasize that it is dosimeter that is designed to be used by emergency response personnel and that it is user-friendly, inexpensive, and disposable. Figure 1 shows the SIRAD badge prior to exposure to radiation and the black UV protective film which covers the badge.

Epson® model 2480 Scanner

The Epson® model 2480 Scanner[†] was used to read the cards prior to and after radiation exposures.. The photoelectric device is a Color Epson MatrixCCD™ line sensor which is a white cold cathode fluorescent lamp. A jig was used to ensure a consistent reading area.

Tests were done to determine if there were any effects from the scanner. The first test evaluated the scanners ability to yield consistent results in reading the cards at seven different locations on the scanner. The second test involved multiple readings of an unexposed card to determine if the chemical strip reading would change with multiple scans under its florescent light source. The card was scanned 100 times and a reading of the chemical strip using Adobe Photoshop 7.0® was done every 20 scans.

Adobe® Photoshop 7.0

The software program used to analyze the SIRAD cards was Adobe® Photoshop 7.0[‡]. This program provided a distribution of color intensities (luminosity, red, green, and blue) for an area of interest selected by the user. The software also provided an average intensity response, a standard deviation, and the brightness for each of the three colors.

[†] Epson® Model 2480. Website www.epson.com/cgi-bin/Store/consumer on February 28, 2005.
[‡] Adobe® Photoshop 7.0. Website www.adobe.com on March 9, 2005.

The control card for each set of cards was read for all of the color bars on the color reference charts of respective dose and the unexposed chemical strip. Only the chemical strip was read on all the exposed cards and then compared with the respective color reference chart. The data from Adobe Photoshop 7.0® was used to ensure reproducibility.

Radiation Dose Application using Gamma Sources

The gamma sources used were a secondary National Institute of Standards and Technology, NIST, traceable ^{137}Cs source; a pedigreed, traceable ^{226}Ra needle; and a Gammacell 220 ^{60}Co Irradiation Unit used for calibrations[§]. The cards were exposed to radiation fields ranging from 2.5 to 125 rads.

As a reference, a single SIRAD card was chosen to be an overall control card. This control card was not exposed to any radiation. It was kept with all the other experimental cards to ensure that any unknown factors would be the same for all cards. This card was scanned into a file and the reference color charts and the chemical strip were analyzed using Adobe Photoshop 7.0®. The cards color reference chart values were then tabulated. The data recorded included a histogram of each reference dose color and the chemical strip. All cards were read and evaluated in this manner.

Several SIRAD card sets were exposed to a ^{137}Cs source. The dose rate of the ^{137}Cs source utilized from the Oregon State University Radiation Center is 5780 mR hr^{-1} at the position 192.2 of the well counter.[**] Doses of 2.5, 5, 7.5, 10, 40 and 125 rads were delivered to the cards.

[§] 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.

[**] 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.

A set of cards consisted of 11 for each dose of radiation exposure of interest. One of these cards was used as a control. This card was not exposed, but was kept with the other ten to determine if any other changes occurred within the set. The tenth or top card of each set was raised to a 15° angle to test for angular dependence.

Using a ^{226}Ra needle, more badges were exposed. The dose rate of the ^{226}Ra needle utilized from the Oregon State University Radiation Center was 94.1 mR hr^{-1} at one foot as of February 1, 2005.[††] The cards were exposed to doses of 2.5, 5, 7.5, and 10 rads. A set of cards consisted of 11 for each level of radiation exposure. One card was used as a control and was not exposed. It was kept with the other ten to determine if any other changes occur with the set. One card, (#10), was set against a peg at a 45° angle to test for angular dependence.

A third set of SIRAD cards was exposed to a ^{60}Co source. The exposure rate[‡‡] of the ^{60}Co utilized from the Oregon State University Radiation Center was 8.38E+4 mR hr^{-1} in the center of the sample chamber. A dose of 125 rads was delivered to the cards. A set of cards consisted of 11 for each level of radiation exposure. One card was used as a control and was not exposed. It was used to determine if any other changes occur with the set. Two Victoreen Condenser R-Meters were used to check for traveling dose. The cards were not present in the chamber during traveling dose runs. The traveling dose was tested a total of six times, three for each R-Meter used. Figure # shows the observed results for the gamma exposures of the SIRAD cards.

Radiation Dose Application using Neutron Sources

[††] 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.

[‡‡] Radiation Center health Physics Procedure 21, Revision #5, Feb. 2000

To determine if the interaction of the chemical strip shows any dependence upon the type of incident radiation, a neutron source was used to expose the badges. The neutron sources were a PuBe source and the Oregon State University TRIGA Mark II reactor system (Anderson 1986). The cards were exposed to radiation fields ranging from 5 to 35 rads.

The first neutron evaluation involved three tests using the PuBe source. The neutron source used had an activity of 3 Ci. Based upon information provided about the PuBe source, it had 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) was found to be 18 mrad/hr.

The first test performed involved unmoderated neutrons to obtain a dose of 5 rad. The second test consisted of placing a polyethylene block behind the cards to thermalize the neutrons with an "expected and calculated" exposure of 10 rad. The final test involved only the chemical strip of a SIRAD badge being placed within a 10 inch Bonner Sphere. This test was performed for a period of 25 hours to obtain a dose of 5 rad resulting from just the neutron exposure rate.

The second neutron evaluation involved determining 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 used. 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 the thermal column with an ionization chamber (Victoreen CDV-715R Serial Number 140679). The ionization chamber was used to determine the gamma readings within the thermal column. The reading from the ionization chamber (which is insensitive to neutrons) is plotted in figure 8. 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 calculated.

The neutron flux in the thermal column is 8×10^{10} $n\ cm^{-2}\ s^{-1}$ *at 1 MW*[§§]. *The flux is scalable with power and with the reactor at 100 W the flux is* 8×10^{6} $n\ cm^{-2}\ s^{-1}$. *The dose rate for thermal neutrons based upon the flux is* 980×10^{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:*

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

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 badge 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.

RESULTS AND DISCUSSION

Control Cards

All of the set control cards as well as the overall control card were blank cards not subjected to any radiation. Each dose on the color reference chart was read, charted, and

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[§§] Oregon State University TRIGA Specification Thermal Column http://n3.oregonstate.edu/facilities/radiation_center/spec4.html on March 3, 2005 graphed. Histograms were created and compared. The graphs showed that there was little or no variation among the cards and that they were statistically similar.

Gamma Exposures

For all three sources, the values for each card were charted and graphed. They were then compared to other cards as well as the control cards within their respective groups. Intensity values for cards one through ten in each set were averaged for each dose and plotted on a calibration curve for comparison (figure?). The error bars were calculated to two standard deviations. For the tenth card in the ^{137}Cs and ^{226}Ra exposures, angular dependence was tested at 15° and 45° angles respectively.

The ^{137}Cs exposures (2.5, 5, 7.5, 10, 40, and 125 rads) showed all but one of the cards within the standard deviations of the color reference charts calculated by Adobe Photoshop 7.0®. There was slight inconsistency with the 40 rad readings for luminosity, green, and blue. Intensity values for each dose were averaged and compared to the calibration curve. An assumption was made that there was no appreciable attenuation or shielding taking place. Card number ten, which was test for angular dependence at 15°, kept the same pattern as the rest of the cards in the set. This showed that there was no angular dependence expressed in this evaluation between 0° and 15°.

For the ^{226}Ra exposures (2.5, 5, 7.5, and 10 rads), intensity values for cards one through ten in each set was averaged for each dose and plotted on the calibration curve for comparison. Error bars were calculated to two standard deviations. Card number ten, which was tested for angular dependence at 45°, kept similar patterns to the rest of the cards in the set and therefore there was no angular dependence observed on the card between a 0° and 45 ° angles.

Radium exposures were not as clear as those in the cesium and cobalt groups. According to standard deviation values computed by Adobe Photoshop 7.0®, the 2.5 rad and 7.5 rad card sets were found to be within the error bounds of the set control. The 5 rads card set and the 10 rads card set showed inconsistent values on several readings amongst the cards. Due to this inconsistency, gamma attenuation calculations were done. Using the mass attenuation coefficient, $\frac{\mu}{\rho}$, for Tissue-Equivalent Plastic***, which was used to represent the UV film, attenuation was calculated. A value of .9998 was calculated for the .01 cm film concluding that there was no attenuation occurring. Attenuation was also calculated for the total thickness (.11cm) of the card and the UV film combined, and resulted in a value of .9982. Attenuation for the UV film was calculated using ^{226}Ra gamma emitting progeny. Calculations were done for the gamma energies most probable per decay.

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

Only 125 rads was tested using the Gammacell ^{60}Co irradiation unit. In order to receive a dose of 125 rads, traveling dose was determined by using Victoreen Condenser R-Meters. Out of six trials between two R-Meters, an average traveling dose of 77 rads was calculated. After this determination, the proper calculations were done to yield the irradiation time needed. The

*** Value was taken from the Handbook of Health Physics and Radiological Health, 3rd ed, edited by Bernard Shleien, Lester A. Slaback, Jr. and Brian Kent Birky. Baltimore, Williams & Wilkins , 1998, 5-24 closes possible dose to 125 rads was 124 rads. All ten cards in the set were compared to each other as well as the set control. Intensity values for cards one through ten were averaged and plotted on the calibration curve for comparison with the color reference chart values. The error bars were calculated to two standard deviations. Similarity was found amongst the cards and the control.

Neutron Exposures

The first test involving unmoderated neutrons consisted of a set of ten cards exposed to the PuBe source at a dose of 5 rads total neutron and gamma. The cards intensities were red and plotted against the control card. Based on the manufacturer data, the neutron component was 4.6 rads and the gamma component was 0.4 rads. Card readings showed that the luminosity, red, and green components of the chemical strips for the cards do not fall within the standard deviation of the color reference dose for 5 rads. When compared to a card of 5 rads from the ^{137}Cs group, the color strips were not of 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.

The second test involving the PuBe source subjected the cards to a total neutron and gamma dose of 10 rads (neutron component of 9.2 rads and a gamma component of 0.8 rads). A moderated neutron response was created by placing a polyethylene block behind the SIRAD cards. When the cards were read, luminosity, red, and green values of the chemical strip did not all fall within the standard deviation of the color reference chart dose for 10 rads. When the cards were compared to a 10 rad card from the ^{137}Cs group, the color strips were not the same shade of blue. This suggests that the SIRAD card is not sensitive to neutrons moderated and reflected with a polyethylene block.

The final test involving the PuBe source included the use of a 10 inch Bonner sphere. The chemical strip was cut, placed inside the Bonner sphere, and then subjected to a dose of 5 rads (5 rads neutron, unmoderated gamma exposure is 0.4 rads). The results were similar to the unmoderated neutrons at 5 rads and therefore the SIRAD card is not sensitive to neutrons moderated with a Bonner sphere.

The second evaluation of the dosimeter involving neutrons took place in the thermal column of the Oregon State University's TRIGA Reactor. The gamma dose in the column was measured to be 26 rads using an ion chamber. The thermal neutron dose is 5 rads as shown in equation 1. The intensity readings for the card in the thermal column fall within the standard deviations of both 25 R and 40 R. This card was compared to a ^{137}Cs card at 40 R. It appeared that the SIRAD card from the TRIGA Reactor is a slightly lighter shade than the ^{137}Cs at 40 R. This card did not appear to show any sensitivity to thermal neutrons.

Scanner Tests

The scanner test for consistency showed that the luminosity, red, green, and blue intensity readings for the SIRAD card were consistent when the card was placed at seven different areas of the scanner. The scanner test for multiple readings effect on the chemical strip shows no significant changes in intensity readings for a total of 100 scans. This test suggests that the chemical strip is not affected by the light of the scanner and may be read multiple times if needed.

CONCLUSION

The SIRAD card is designed for first responders to be able to have a quick and easy 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 met manufacture claims of sensitivity towards gamma radiation and neutron fields.

The test with gamma radiation largely supports the manufacturer claims. The SIRAD card was found to have no or slight energy dependence among the isotopes ^{137}Cs and ^{60}Co. It is possible that the card has dependence with radium. The evaluation displayed no angular dependence between 0° and 45°. Based on the findings of this evaluation, it is recommended that JP Labs examine the cards energy dependence to sources of similar strengths and characteristics of ^{226}Ra. It is also recommended to test more angles and other isotopes. A human evaluation for visually reading the dosimeters should be conducted as well.

The tests with neutrons do not support manufacturer claims of neutron sensitivity. 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 which 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 dosimeter is an easy, cheap, and beneficial device for first responders to utilize in their line of work. It will give them an indication of whether or not they were exposed to gamma radiation. Using this device, first responders have the potential to better monitor themselves and take any appropriate actions to reduce any further exposure.

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Fig. 2 Adobe® Photoshop 7.0 histograms

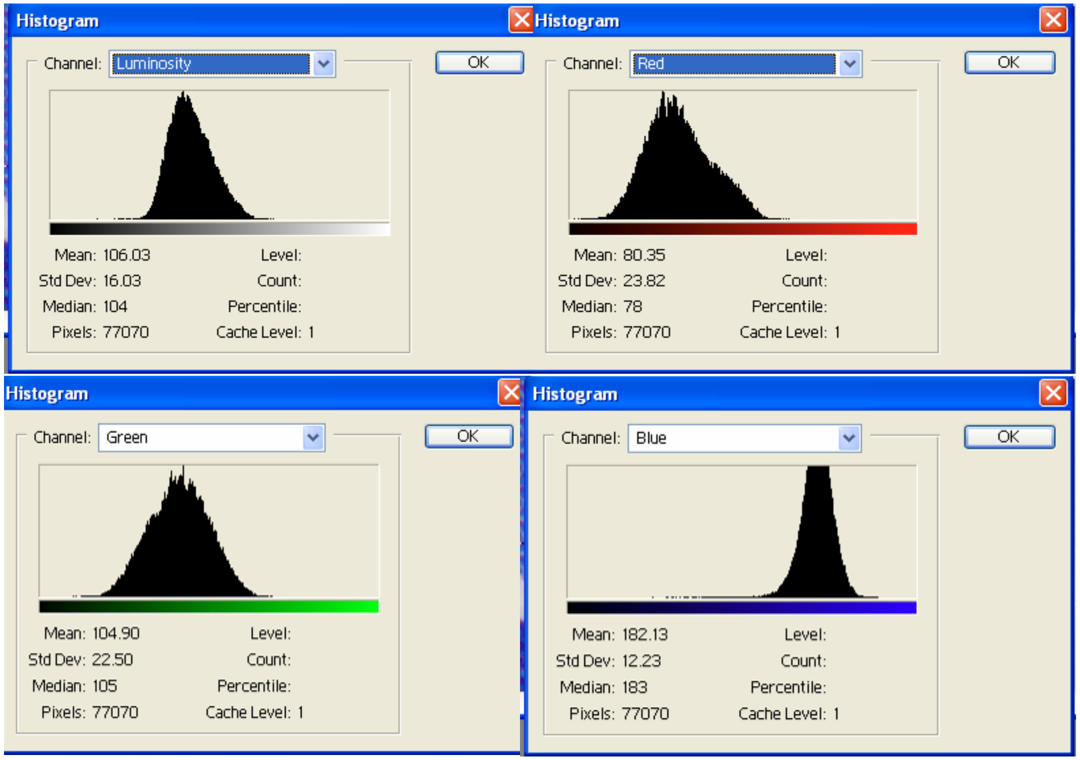


Fig. 3 Observed Results: Measured Luminosity of Color Key and Chemical Strips

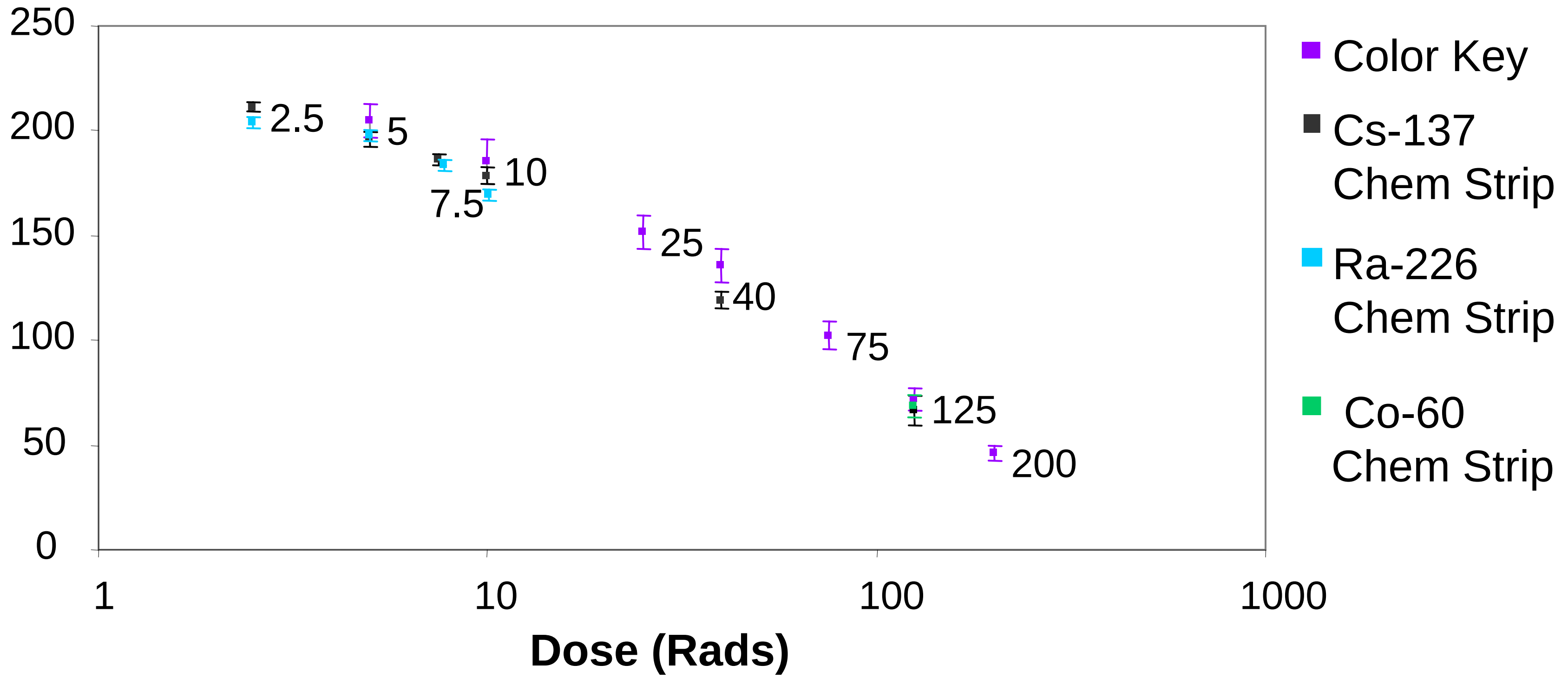
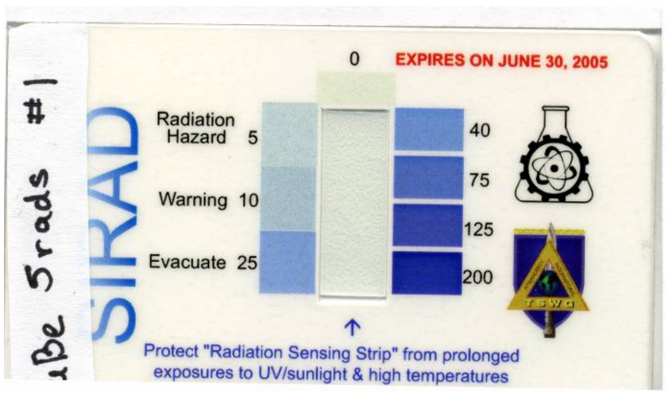
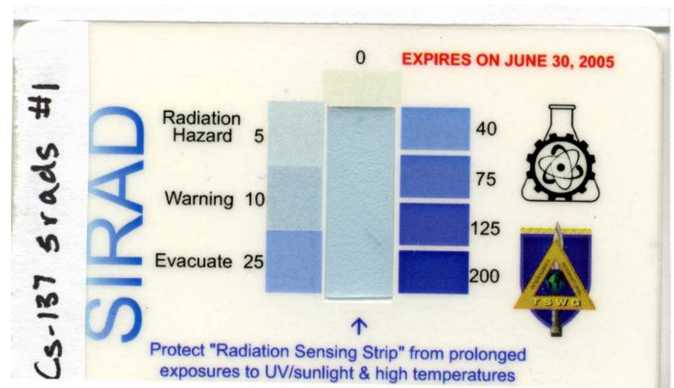


Fig. 4 Observed Results: PuBe Neutrons

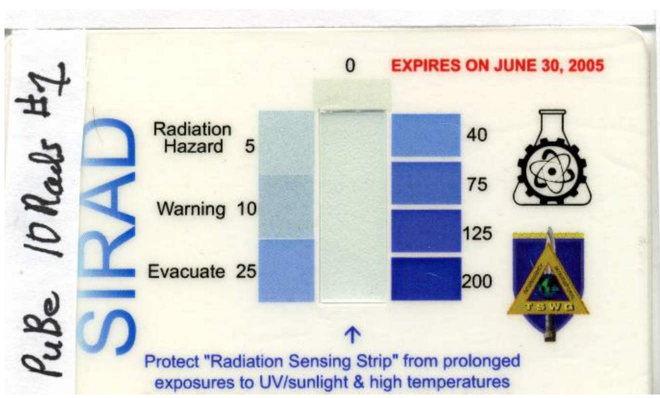
5 rads
neutron
un-
moderated

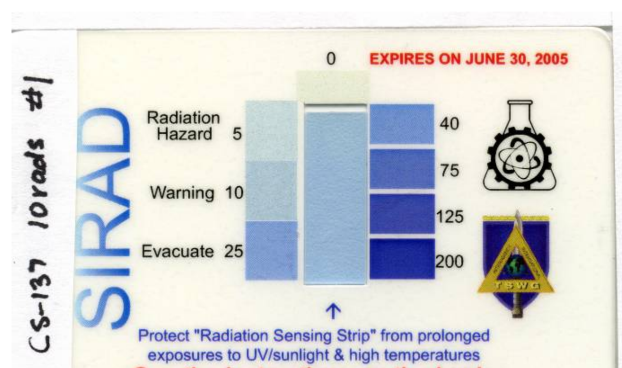




5 rads
gamm
a

10 rads
neutron
reflected
/moderated

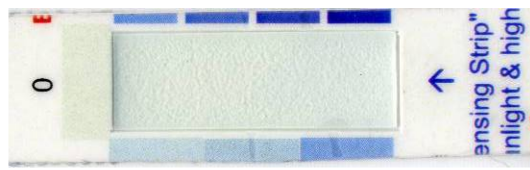




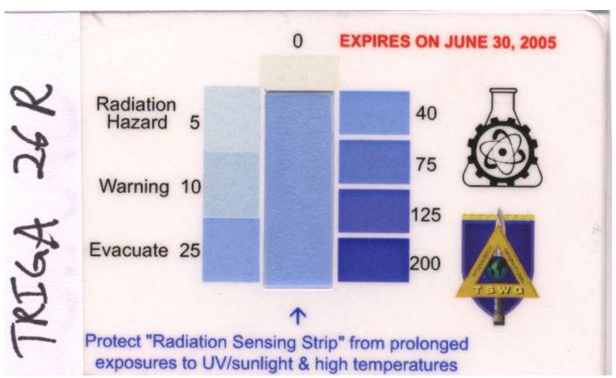
10
rads
gamm
a

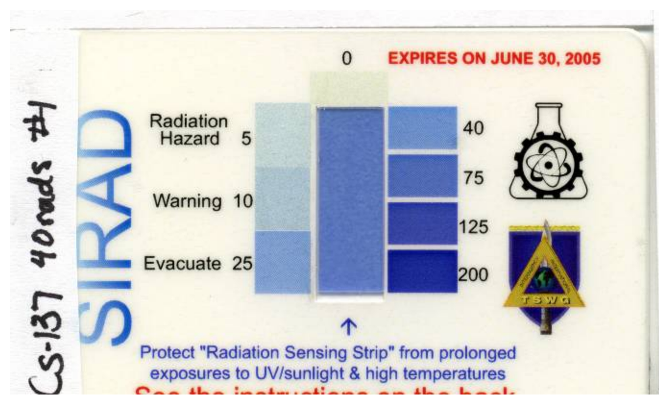
Fig. 5 Other Neutron Exposures – Bonner Sphere & TRIGA Reactor

PuBe 5 Rads through Bonner sphere



26 rads gamma + 5 rads neutron via TRIGA





40 rads gamm a