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Self-Indicating Instant Radiation Alert Dosimeter (SIRAD) Test Results Final Report

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SELF-INDICATING INSTANT RADIATION ALERT DOSIMETER (SIRAD) TEST RESULTS

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1.0 COUNTERMEASURES TEST BEDS FINAL REPORT

1.1 Executive Summary

Problem statement

The Self-indicating Instant Radiation Alert Dosimeter (SIRAD) campaign investigated the suitability of a credit-card format, human-readable radiation dosimeter as a dose control tool for preparedness and response to a terrorist event involving radioactive material. The device could fill a technology gap for first responders since they do not routinely carry radiation dosimetry. The SIRAD is a passive, disposable dosimeter that changes color upon exposure to a medically significant radiation dose. Its convenient format and low cost ($10-20) would allow for pre-distribution and provide immediate indication of any significant radiation exposure. This would provide reduced responder anxiety and response delays when exposure is low, and support for tactical response decisions when exposure is high.

Deployed description

The SIRAD model tested has a color matching scale indicating doses from 5-200 rad. In the field test component of this campaign SIRADs were distributed to emergency responders in New Jersey, New York, and Illinois, along with a back-up thermoluminescent dosimeter (TLD) for dose verification and a 24-hour hotline for assistance in case of a color change. Regulations for human subjects research were followed. Other components of the campaign assessed the response of SIRAD to laboratory irradiations and physical stresses and investigated variations in visual interpretations of the color scale. Results were evaluated in terms of personnel dosimetry consensus standards, ANSI N13.11 and N322, which provide a general framework to quantify performance, though not written for SIRAD and not a pre-requisite for its use.

Key outcomes

The overall outcome is that the SIRAD demonstrated generally acceptable performance for homeland security mission needs. Incidence of loss or damage to the device during field deployment was low, false positive rates were less than one percent, and field conditions and physical stresses did not seem to compromise performance. The response to laboratory controlled irradiations was acceptable: SIRAD passed one out of three of the ANSI N13.11 accident categories (category IC, photons of low energy, 73 keV) and showed a 30 percent positive bias to 662 keV photons, thus tending to err on the side of caution. It responded to electrons but showed negligible neutron response. Visual interpretation of the color reference scale was variable but appears adequate for tactical applications in identifying high doses compared to a response worker guideline.

Decisions that can be made

Using these results, local responder decision makers can decide if SIRAD is a suitable dose control tool for their departments. U.S. Department of Homeland Security (DHS) policy makers can decide on inclusion of SIRAD in new standards and other DHS resources, such as the System Assessment and Validation for Emergency Responders (SAVER) program.

Next steps

The results will be disseminated at meetings and in publications that reach many types of local emergency preparedness planners and submitted for publication in a peer-reviewed technical journal. The next generation SIRAD, with a wider sensitivity range, will undergo laboratory tests. Plans are underway to include SIRAD in future top officials (TOPOFF) exercises.

1.2 Statement of the Problem

This campaign investigated a technology that could fill a capability gap in emergency response to a radiological terrorist event [1]. With the exception of hazardous materials (HAZMAT) teams, most emergency responders do not routinely carry radiation dosimeters. HAZMAT dosimetry is not typically appropriate for routine, non-radiation operations since alarming radiation monitors are expensive ($200-$400), and rad-worker badges are not field readable (requiring laboratory processing to determine the dose).

This campaign investigated a radiation dosimeter that is disposable and field readable. The Self-indicating Instant Radiation Alert Dosimeter (SIRAD) is the size of a credit card, with a radiation sensitive strip that turns shades of blue when it is exposed to medically significant levels of ionizing radiation (5-200 rad*). See Figure 1. If routinely carried by emergency responders, it could provide early indication of a significant radiation component after a terrorist event and measure individual responder dose for planning lifesaving operations. It could also reassure first responders of a lack of radiation, which could avoid response delays due to fear of radiation. Pre-distributed SIRADs could provide early data on the ground to assess the scope of a radiation event. This data could assist identifying those in the public that potentially received a significant radiation dose as well as help to reassure the worried well in order to appropriately allocate response resources. The SIRAD could also be issued after a radiation event has been identified as emergency back-up dosimetry.

SIRAD dosimeters are not as sensitive as those used for routine occupational monitoring, which measure lower doses (for example, from 30 millirem† - 500 rad). The lowest dose on the SIRAD scale is closer to an annual occupational dose limit. While the SIRAD is not appropriate for occupational dose of record, for homeland security applications the SIRAD could be carried as a precaution by those not normally occupationally exposed to radiation but who could be at the scene of an event.

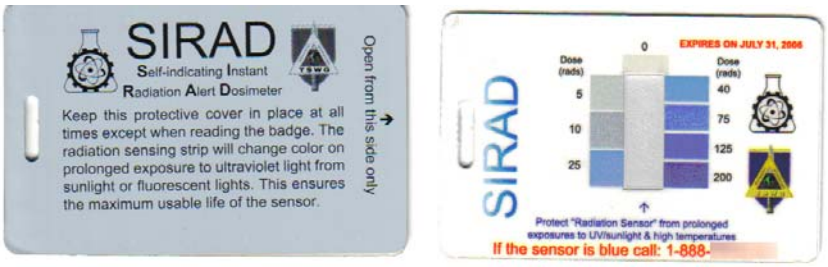

Figure 1. Front of SIRAD card. The image on the left shows a protective cover flap, and the one on the right shows the underlying SIRAD card with its radiation sensitive strip and color-matching scale. It was developed by Dr. Gordhan Patel, JPLabs (www.jplabs.com) with support in 2003-2005 from the Technical Support Working Group (U.S. Departments of Homeland Security, Defense, Justice, and State). Its early development (1995-1997) was supported by the U.S. Navy.

* "rad" is a unit of measure of the amount of energy absorbed or released in a material by radiation

† "rem" is a unit of measure of the biological effects of radiation. A prefix is used to indicate multiples or fractions of the units. The prefix "milli" means 1/1000th of a rem and may also be written "mrem"

1.3 Test Objectives and Hypotheses

The overall objective of this campaign was to determine the applicability of the SIRAD for emergency responders in an urban environment. The campaign consisted of four components, listed here with their objectives.

A. ***Field deployment*** – investigate distribution and operational parameters, including the probability for false positives, loss, and misuse.

B. ***Laboratory irradiation*** – assess dosimetric response to photons, neutrons, and beta radiation in the context of existing standards for emergency dosimetry.

C. ***Visual readout*** – assess variations in visual interpretation of the color-dose scale using laboratory irradiated dosimeters.

D. ***Environmental tests*** – verify the manufacturer's specifications and test performance under potential end-user external stresses.

Each section of this report is organized into subsections A, B, C, and D for the four components of the campaign. Interim reports with preliminary results and additional details about each component have been posted at the CounterMeasures Test Beds (CMTB) Web site at https://eml.st.dhs.gov/CMTB/main.cfm.

The four components of the test were designed to provide overlapping information to test the following hypotheses:

- Is the SIRAD format usable by emergency responders without significant damage, loss, or interference with operations?
- In routine field deployment, does the SIRAD have a false positive probability of less than 1 percent?
- Are the SIRAD radiation response and calibration acceptable in the context of existing standards for other types of emergency dosimeters?
- Can the color scale on the SIRAD card be accurately interpreted visually?
- Are the manufacturer's specifications accurate?
- Does the card function under potential end-user environmental stresses?
- Is the SIRAD card appropriate for use by first responders for preparedness for potential radiological terrorist events?

1.4 Results and Data Needed to Test Hypotheses

1.4 A. Field Deployment Test

In the original field deployment plan, SIRAD cards were to be distributed to up to 1,000 potential end users to carry for nine months. The targeted participants were among those who would be involved in emergency response to a radiological terrorist event. Data to be gathered from the field test are the frequencies of: false positives, damage, loss, and misuse as well as operational parameters such as how the cards were carried in emergency responder environments and any unforeseen issues that may develop during deployment. A subset of 10 field dosimeters was irradiated after collection from participants at the end of the field test to verify that the dosimeters remained functional.

We established Points of Contact (POCs) at 15 participating agencies (listed in Table 3, section 1.6 A.). Field dosimeters were hand delivered by Environmental Measurements Laboratory (EML) scientists who provided detailed instructions for the POCs on the distribution and follow-up tasks. The POCs recruited from 14-100 participants within their organizations and distributed

the dosimeters. At the midpoint and end of the field test, the POCs were asked to check on the status of their dosimeters and report how many were unchanged ("ok"), lost, damaged, or showed a color change. The POCs provided results in summary form; we did not track or record names of the participants. At the end of the field test, POCs collected and returned the dosimeters to us for examination.

Changes to the data collection plan
Situations within the participating agencies and beyond our control resulted in fewer than the planned 1,000 SIRADs being deployed. One group was not able to resolve internal approval requirements, and the 116 dosimeters originally allocated for it went undelivered. Some groups found they did not need as many dosimeters as planned: of the 884 dosimeters we delivered, 823 (93 percent) were deployed. These changes resulted in less data but did not affect the campaign objectives since the data quantity and quality were sufficient to evaluate the hypotheses.

1.4 B. Laboratory Radiation Response Tests

Since it is likely that most, if not all, of the field test dosimeters would receive no measurable radiation dose, other SIRAD cards were irradiated under controlled laboratory conditions. The irradiated cards were sent to the manufacturer for machine reading so as not to confound the SIRAD radiation response with potentially subjective visual interpretations. To assess the dose, the manufacturer uses an optical densitometer for comparison to a calibration curve of optical density versus air kerma*.

The irradiation procedures we used followed the American National Standards Institute (ANSI) standard N13.11-2001, "Personnel Dosimetry Performance – Criteria for Testing" [2]. Dosimeters were exposed to one of two photon sources: cesium-137 (^{137}Cs), with energy of 662 keV† and an M150 x-ray beam, with average energy 73 keV, by Pacific Northwest National Laboratory (PNNL). The dosimeters were irradiated on a 15 centimeter thick polymethyl methacrylate (PMMA) slab phantom, which approximates the backscatter properties of the human body, and the delivered dose is reported in the quantity personal dose equivalent $H_p(10)$. The ANSI N13.11 Accident Categories IA, IB, and IC were selected in which 15 dosimeters each were irradiated to doses randomly selected between 10-500 rad. In subcategory IC, all 15 are irradiated using the M150 photon beam; in subcategory IB, all 15 are irradiated with the radioisotope cesium-137; and in subcategory IA, dosimeters may be irradiated with either source, chosen at random by the testing laboratory.

Photon response is of primary interest for homeland security mission needs, but neutron and beta irradiations were also performed on a smaller number of dosimeters as a spot test since the SIRAD is described as responding to those as well. Neutron irradiations were performed at PNNL using both bare and moderated californium-252 (^{252}Cf) sources. The bare ^{252}Cf source provides a neutron spectrum with a peak at about 2 MeV and fewer photons than the moderated source. The D_20 moderated ^{252}Cf source has neutrons of lower average energy (0.5 MeV) and a higher percentage dose from photons. (The ratio of photon to neutron personal dose equivalent is 0.18 for moderated and 0.05 for un-moderated). Beta irradiations were performed by PNNL

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* The quantity "air kerma" is the kinetic energy released per mass of air by radiation. It can be expressed in units of "rad".

† "eV" is an abbreviation for the unit "electron-volt", a measure of energy. A prefix is used to indicate multiples of the unit, here "keV" stands for 1,000 electron volts.

using a sealed strontium-90 /yttrium-90 source. For both sources, dosimeters were irradiated using the PMMA slab phantom described above.

Changes to the data collection plan
In the original plan, SIRADs were to be tested in N13.11 categories IA and IB only. Since the results for IA showed that SIRAD performed better with M150 x-rays, category IC was added. This resulted in a more complete characterization of the SIRAD dosimetric performance.

1.4 C. Visual Readout Test

The visual readout component obtained a set of visual dose estimates that could be compared to the results of the optical densitometer readings and the laboratory delivered dose values. Twelve individuals volunteered to be subjects for this study, which was performed in compliance with regulations for the use of human subjects. All subjects were given Ishihara Tests for Color Deficiency prior to reading the SIRAD cards, and three of them demonstrated color deficiencies.

The visual test used 35 SIRADs, which had been pre-irradiated to doses ranging from 0-481 rad as described in section 1.4 B. They were placed in random order, and then numbered sequentially and linked together so that each subject viewed them in the same sequence. The complete instructions given were: “Estimate the dose value for each card. The dose may be any value that is zero or more, including values between those on the reference color scale or even off the scale.” The subjects wrote their estimates in a table listing the cards by number. No time limit or further instructions were given.

1.4 D. Environmental Test

For each environmental test, the SIRAD protective cover was left in place and subgroups of cards were irradiated prior to and after the environmental stresses. Irradiations were performed at Brookhaven National Laboratory. The tests checked the effects of the following conditions:

- storage in an automobile in warm weather for 5 days (maximum temperature 160 °F)
- one laundry cycle, washing and drying (maximum temperature 180 °F)
- high temperature storage 137 °F for 7 days
- low temperature storage 32 °F for 7 days
- direct sunlight for 6 hours
- fluorescent light for 2 months

The automobile test was performed as an example of a likely end-user situation. The other tests were designed to verify the manufacturer’s specifications. For tests involving temperature effects, a digital temperature logger that recorded the temperature every 10 minutes and/or a handheld infra-red (IR) thermometer was used to track the temperature during the test. In the automobile test, the cards remained in the automobile for 5 days, during which the outdoor temperature varied from 53 °F to 86 °F, while the temperature in the car ranged from 70 °F to 160 °F. All cards were compared visually before and after the environmental stress and again after the post-stress irradiation. Periodic observations were also recorded during the stress test, where possible. Later, all the irradiated cards were sent to the manufacturer for optical densitometer reading.

1.5 Operational Envelope

1.5 A. Field Deployment Test

The SIRAD met expectations for the field deployment. The test protocol underwent a full board review by the Human Subjects Institutional Review Board (IRB) at the Lawrence Livermore National Laboratory. The IRB required that we develop a consent form for each participant to sign, which clearly explained the risks and benefits of the study, before being issued the dosimeters. Participants were instructed to carry the cards for nine months, such that they would not interfere with routine duties, for example, along with ID cards already in use on existing badge clips, on lanyards, or in ID cases. We provided optional safety lanyards and badge clips.

The participants carried the SIRAD during duty hours with the option to also carry them while off duty. Most of the targeted participants are not routinely occupationally exposed to radiation and were not expected to receive an occupational radiation dose measurable by the SIRAD cards during the field test. Therefore, thermoluminescent dosimeters (TLD) were attached to the field-deployed SIRADs to confirm any SIRAD positive readings. The POC was given pre-addressed mailers to send the TLDs for emergency processing, if needed. The backup TLD would be read only in the case of a SIRAD color change to verify a radiation dose or identify a false positive; the campaign was not looking for false negatives in the field test. Participants were instructed to call a toll-free number printed on the front of the SIRAD if there was a color change. The number connected to a Reachback program maintained specifically for the SIRAD project with EML staff scientists available 24/7 to provide guidance to participants on sending the backup dosimeter for processing and appropriate actions to take until the TLD results are received.

Changes to operational envelope
For two groups, the field deployment time was six months rather than nine months. In one case, this was because the group was recruited late to partially compensate for another group; in the other case, it was because of the POC's workload. A few participants mistakenly called the SIRAD Reachback hotline at the midpoint check-in to report no color change, and at the end of the study, two sets of back-up TLDs were inadvertently sent by the POC for emergency processing. The changes did not affect the results; rather they provided quality assurance for contingency plans since no Reachback calls were missed and TLDs were processed as planned.

1.5 B. Laboratory Tests

As the SIRAD is a new device, there are no standards that were written specifically for it. Tests and performance measures from two relevant existing standards, ANSI N13.11 and ANSI N322 [3] were adapted to provide a framework to quantify the SIRAD performance.

ANSI N13.11-2001 standard "Personnel Dosimetry Performance – Criteria for Testing" covers dosimetry systems used for occupational and accident conditions. This standard was first published in 1983 after 10 years of development and pilot testing and has undergone two revisions. It is the basis for the National Voluntary Laboratory Accreditation Program (NVLAP), required for worker dosimetry at Nuclear Regulatory Commission licensed facilities [4]. As a widely used and recognized standard that provides well defined radiation test conditions and performance criteria, it is an appropriate benchmarking reference for this campaign, even though accreditation may not be required for dosimeters used by local emergency responders.

ANSI N13.11 includes six categories of tests, further divided into various subcategories, covering a wide range of radiation types and dose levels. The standard is designed so that tests are to be selected as appropriate for a particular dosimetry system. The only ANSI N13.11 test category appropriate to the SIRAD is the Accident Category I, since the others, including neutron and beta tests, span occupational dose ranges too low to register on the SIRAD card (e.g., 30 mrem – 10 rem). The relevant ANSI N13.11 performance tests are summarized in Table 1, and the performance measures are defined in section 1.6 B. These tests are used to accredit dosimetry of record and, therefore, may be considered a high bar for the SIRAD performance.

Table 1. Summary of relevant ANSI N13.11 Performance Test

I. Accident Test Category	Irradiation sources	Dose range*	Number of dosimeters	Requirement**
I.A.	M150 x-ray and ^{137}Cs	10 – 500 rad	15	$\|B\| + S \leq 0.3$
I.B.	^{137}Cs			
I.C.	M150 x-ray			

* N13.11 test range (500 rad) exceeds the SIRAD maximum (200 rad): the analysis was adapted (see section 1.6 B)

**B (bias) and S (standard deviation) are defined in section 1.6 B.

The other relevant standard is ANSI N322-1997 “Inspection, Construction, and Performance Requirements for Direct Reading Electrostatic/Electroscope Type Dosimeters.” The dosimeters covered by N322 use a different technology than SIRAD; therefore, the construction and inspection requirements are not applicable. (The devices covered by N322 are commonly referred by various names, including “pocket ion chambers” and “pencil dosimeters” and were distributed to states in the civil defense procurement during the 1960’s). However, some of the N322 radiological requirements are applicable because the pocket electroscope dosimeters are intended to be used for the same type of high-dose application as SIRAD, they are field-readable by eye, and they are excluded from the NVLAP requirement. The relevant N322 performance tests are summarized in Table 2. N322 uses a different approach than N13.11. For example, the N322 accuracy test requires that *each* dosimeter meet the requirement rather than taking an average result as N13.11 does.

Table 2. Summary of relevant ANSI N322 Performance Tests

Test	Source*	Dose	Number of dosimeters	Requirement
Accuracy	^{137}Cs	50% of full scale	10	Each dosimeter ± 10%
Energy Dependence	Photon sources with energy in range of response	20% - 80% of full scale	3	± 20% of calibration source

*ANSI N322 includes only photons sources.

1.5 C. Visual Readout Test

This visual readout component of the campaign was limited in scope in that it did not attempt to cover a wide demographic or to address a broad range of psycho-physical factors. The 12 subjects were employees of the U.S. Department of Homeland Security or the U.S. Department of Energy. Ten of the subjects had seen the SIRAD card before and were familiar with its

purpose as well as technical concepts of radiation dosimetry. One of these 10 had prior experience reading irradiated SIRADs in previously performed laboratory tests. Two of the subjects had not seen the SIRAD before and were unfamiliar with radiation dosimetry concepts.

Changes to the plan
In the original plan, the subjects for the visual readout test were to be drawn from the POCs in the field test. However, these contacts had heavy workloads and were not readily available. Since the SIRAD is designed to be read by anyone, other individuals provided the sufficient quantity and quality of data needed for the analyses.

1.5 D. Environmental Tests

The SIRAD met expectations for the environmental tests operational envelope. This component of the campaign served to spot test the manufacturer's specifications and performance under potential end-user external stresses. Consistent with the campaign scope it was not designed to be a full characterization of performance with environmental variables.

1.6 Data Analysis Framework

1.6 A. Field Test

The status of the SIRAD field dosimeters was analyzed at the midpoint and at the end of the field test according to the following categories: ok, lost, damaged, color change, and unknown/not collected. At the midpoint, we relied on the POCs' reports, while at the endpoint—in addition to the POCs' summaries—we also examined each dosimeter that was returned to us. Upon examination we noted some dosimeters that were "slightly damaged" but still considered "ok." For example, the protective cover was bent but intact, or the card was creased or cracked. The pie charts shown in Figure 2 summarize this analysis, and Table 3 shows the results for each participating group. Results were reported at the midpoint check-in for 573 dosimeters (70 percent): no color changes were reported, five dosimeters were reported lost, and seven had damage to the protective cover flap.

At the endpoint, 63 dosimeters were reported as confirmed lost (e.g., sent through a paper shredder, melted at dry cleaner), and 152 were uncollectable for various reasons such as participant unavailability or workload. Of the 608 dosimeters that were collected, 604 showed no color change and are categorized as "ok"; on inspection a subset of these (78) showed evidence of slight damage. Four other dosimeters were heavily damaged, such that the UV protection was compromised, as shown in the photo in Figure 3. These damaged dosimeters also showed a light blue color change. Their corresponding back-up dosimeters were sent for processing, and the TLD results verified that the SIRAD color change was ***not*** the result of radiation exposure.

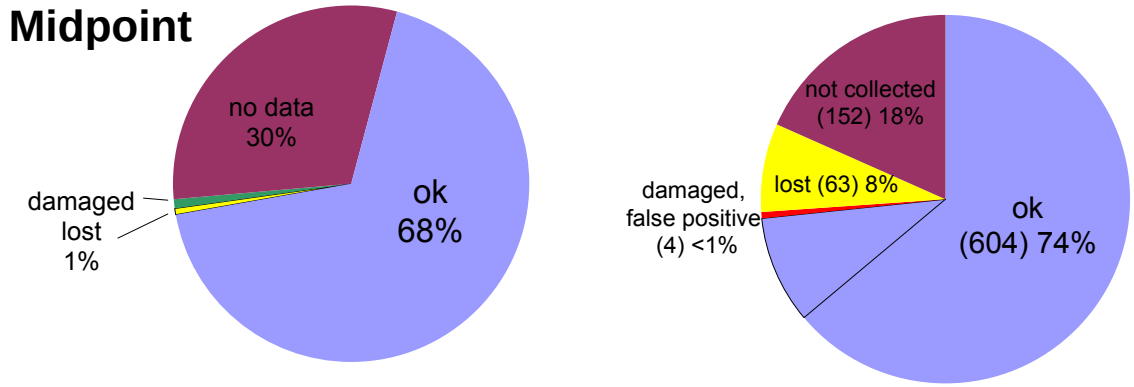

Figure 2. Midpoint and final status of the field dosimeters. "Ok" means no color change, loss, or significant damage. "No data" are those that were not reported on in the midpoint check. The 604 found to be "ok" at the field test endpoint included 78 with slight damage such as a creased cover flap. (This represents 9 percent of the total and is the unlabelled, outlined section of the "ok" area above). The four dosimeters represented by the small red section showed a positive color change at the endpoint and also suffered significant physical damage as shown below. The TLD results showed that the color change was not due to radiation and is attributed to the loss of UV protection resulting from the physical damage.

Figure 3. Photo of damaged SIRADs returned at the end of field deployment. For one of the dosimeters, the protective cover was entirely missing, and for the others, the cover was not held flat, leaving the sensitive strip unprotected from light.

Ten of the "ok" or "slightly damaged" dosimeters returned from the field were subsequently irradiated with ^{137}Cs by Brookhaven National Laboratory (BNL), and the dose was assessed by the manufacturer using optical densitometer readout. The difference between delivered dose and densitometer result ranged from -6 percent to + 56 percent, and the average was 19 percent. This is comparable to the range of results found for dosimeters that were not field deployed (see section 1.6) and indicates that the field dosimeters remained functional.

Table 3. Field test: Participating Agencies

Participating Agency	Number of SIRADs delivered	Number of SIRADs deployed	Midpoint status ok, lost, damage, color change, unknown	Endpoint status ok, lost, (ok -slight damage), color change, not collected
NJ Dept. of Fire Safety	24	24	24, 0, 0, 0, 0	20, 4, (0), 0, 0
NJ National Guard	20	20	20, 0, 0, 0, 0	19, 1, (3), 0, 0
NJ Division of Criminal Justice	40	40	40, 0, 0, 0, 0	36, 4, (7), 0, 0
NJ Department of Agriculture – State Emergency Response	31	27	24, 0, 0, 0, 2	26, 0, (8), 0,1
NJ Emergency Response and Environmental Radiation	14	14	14, 0, 0, 0, 0	14, 0, (10), 0, 0
NJ Department of Veterinary and Food Science	55	55	0, 0, 0, 0, 55	29, 19, (0), 0, 7
NJ Dept. of Transportation	50	50	50, 0, 0, 0, 0	49, 1, (20), 0, 0
NJ University of Medicine and Dentistry – Emergency Medical Services staff	100	100	86, 3, 7, 0, 4	73, 12, (22), 4*, 11
NJ State Police	75	65	65, 0, 0, 0, 0	62, 3, (0), 0, 0
Port Authority of NY and NJ	100	93	0, 0, 0, 0, 75	38, 0, (0), 0, 55
US Park Police of Statue of Liberty National Monument and Ellis Island	65	65	65, 0, 0, 0, 0	62, 3, (0), 0, 0
IL State Police	100	95	95, 0, 0, 0, 0	89, 6, (8), 0, 0
Chicago Police Dept.	100	65	0, 0, 0, 0, 65	55, 10, (0), 0, 0
Chicago Fire Dept.	100	100	72, 0, 0, 0, 28	22, 0, (0), 0, 78
US Dept. of Energy Radiological Assistance Program – Region 5	10	10	10, 0, 0, 0, 0	10, 0, (0), 0, 0
Totals	**884**	**823**	**561, 5, 7, 0, 250**	**604, 63, (78), 4*, 151**

* Significantly damaged, see photo in Figure 3.

1.6 B. Laboratory Tests Analyses – N322 and N13.11

For the laboratory tests analyses, the manufacturer reported the optical densitometer readout results, and we analyzed them according to performance measures adapted from relevant ANSI standards described in section 1.5 B.

ANSI N322

For ANSI N322, the performance requirement for the accuracy test is that the measured result be within 10 percent of the delivered dose for 10 dosimeters irradiated at the midpoint of their range. The laboratory results in context of ANSI standard N322 are shown in Figure 4. The photon irradiated dosimeters are shown on the left side, and neutron and beta results are on the right side in the same format, though ANSI N322 does not cover neutron and beta sources.

The photon results in Figure 4 show that most SIRAD results are found to be beyond 10 percent of the delivered dose. The ^{137}Cs results show a higher, positive percent difference compared to the results for M150 x-rays. The N322 performance requirement for energy dependence is that the response to different energy photons should be within 20 percent of the response to the calibration energy photons. This is measured in ANSI N322 by averaging the results of three

dosimeters exposed to each energy and then taking their ratio. Using this measure, the SIRAD ^{137}Cs response differs from the M150 x-ray response by 45 percent.

Figure 4 shows that the SIRAD does respond to electrons, but we find a limited response to neutrons. Since the bare and moderated neutron sources have a photon dose component of 5 percent and 18 percent respectively, we cannot not rule out the possibility that the SIRAD may be responding to photons only.

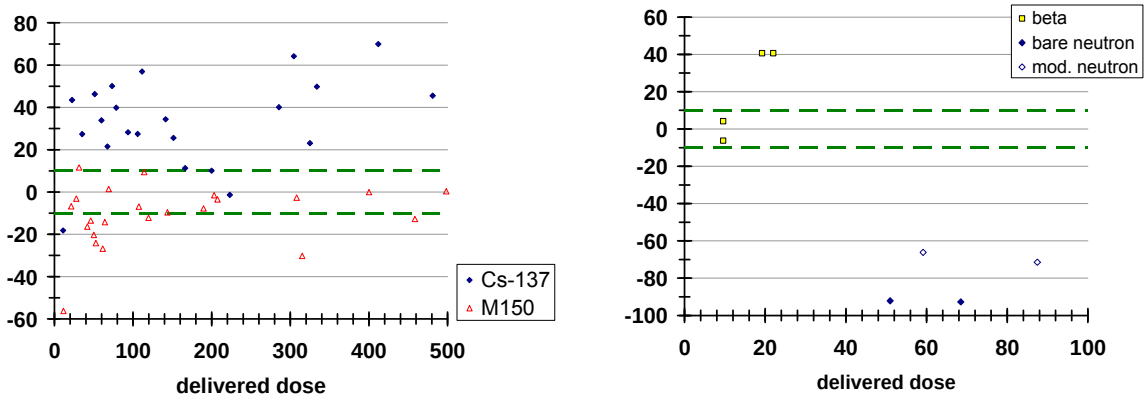

Figure 4. ANSI N322 laboratory performance for SIRAD read by optical densitometer. For each delivered dose on the x-axis, the percent difference of the optical densitometer result is plotted on the y-axis. Exact agreement between measured and delivered dose would be 0 percent difference. Points within the green dashed lines would meet the N322 accuracy test performance measure of 10 percent.

ANSI N13.11

In ANSI standard N13.11, the bias (B) and standard deviation (S) are dimensionless quantities which are calculated as follows:

$$Bias \equiv 1/n \sum_{i=1}^{n} P_i \quad \text{with} \quad P_i \equiv [H'_i - H_i]/H_i$$

where H_i is the personal dose equivalent delivered by the irradiation laboratory and H'_i is that reported upon readout of the dosimeter. P_i is the relative error for each dosimeter *"i,"* and is called the performance quotient. The bias is the mean performance quotient (averaged over the 15 dosimeters).

Standard Deviation of P: $S \equiv \sqrt{\dfrac{\sum_{i=1}^{n} (P_i - \overline{P})^2}{n-1}}$.

Performance criterion: $|B| + S \leq 0.3$ (tolerance level)

The analysis results for the N13.11 SIRAD performance measures are shown in Table 4 and Figure 5.

Table 4. ANSI N13.11 results for optical densitometer readings

Accident Photon Category	Bias (B)	Standard Deviation (S)	Performance Measure (|B| + S)	Tolerance Level
I.A. General ^{137}Cs & M150 x-ray	0.105	0.276	0.38	≤ 0.3
I.B. ^{137}Cs	0.320	0.236	0.56	≤ 0.3
I.C. M150 x-ray	-0.102	0.161	0.26	≤ 0.3

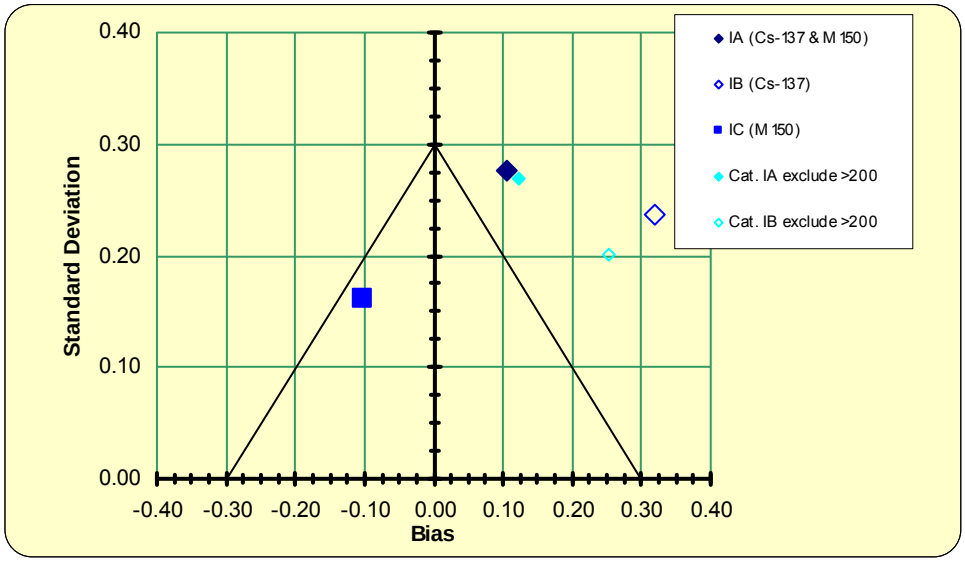

Figure 5. ANSI N13.11 performance for SIRADs read by optical densitometer. The bias (mean relative error) is plotted on the x-axis and the relative standard deviation is plotted on the y-axis for each category. Points within the triangle would pass the N13.11 performance criteria for the Accident categories.

Table 4 and Figure 5 show that the SIRAD's performance measure was within the tolerance level for N13.11 category IC only. Further analyses were performed to see if the performance in categories IA and IB would meet the tolerance level if delivered doses greater than 200 rad, the maximum of the SIRAD reference scale, were excluded from the analysis. (The delivered doses, randomly selected by the testing lab, ranged from 11-481 rad for Categories IA and IB and from 11-498 rad for Category IC). These further analysis results are shown in Table 5 and with the smaller symbols in Figure 5. While the IB results show a 5 percent improvement, they are not within the tolerance level.

The ANSI N13.11 results quantify the SIRAD radiation response in the framework used for occupational dosimetry of record, a higher standard than that likely to apply in the conditions of its intended use. In this context, the SIRAD performed reasonably well in that it passed in the N13.11 low energy photon category and the average bias was close to 30 percent or better in the other two categories tested.

Table 5. ANSI N13.11 densitometer results with doses > 200 rad omitted

Irradiation source (n=number of dosimeters)	Bias (B)	Standard Deviation (S)	Performance Measure (|B| + S)	Tolerance Level*
I.A. General ^{137}Cs & M150 x-ray Doses ≤ 200 rad (n=12)	0.123	0.269	0.392	≤ 0.3
I.B. ^{137}Cs Doses ≤ 200 rad (n=8)	0.254	0.202	0.456	≤ 0.3

* The tolerance level is defined for 15 dosimeters. These analyses used less than 15 dosimeters.

We also looked into how the SIRAD performance relates to the proper use of quantities and units in personnel dosimetry calibration. Quantities and units used in radiation measurement may be a significant source of confusion and require careful consideration. ANSI N13.11 uses the operational quantity Personal Dose Equivalent*. It is determined from the physical (measurable) calibration quantity air kerma using conversion factors appropriate for the radiation source. Conversion factors are specified in N13.11 to convert air kerma to personal dose equivalent; those that are applicable here are 1.21 rem/rad for ^{137}Cs and 1.78 rem/rad for M150. The manufacturer reported that they use a 100 keV x-ray calibration source with no irradiation phantom. The manufacturer's source is calibrated in air kerma in units of rad; no conversion factor was applied to convert to personal dose equivalent. We checked if the application of the ANSI conversion factors would have improved the SIRAD performance and found that this was not the case since they would have served to increase the reported dose for ^{137}Cs and M150 by 20 percent and 80 percent, respectively†.

1.6 C. Visual Tests

The visually determined dose results were compared across participants, compared to the delivered dose, and compared to the manufacturer's reported dose derived from optical densitometer readings. The comparisons were made using graphical exploratory data analysis techniques, statistical summaries, and ANSI performance measures N13.11 and N322. The results were also examined for the potential impact on tactical decisions.

Figure 6 compares the visual results with the delivered dose for each of the 12 participants. It shows that the doses determined visually by individual participants ranged from an

* The internationally accepted *radiation protection* quantity is "*Effective Dose*" (units of rem or Sievert, Sv). This is an un-measurable quantity based on a risk-weighted sum of approximate human tissue or organ dose multiplied by a radiation weighting factor for neutrons or gamma. The *operational* quantity is a conservative approximation to the protection quantity; it is defined at a particular depth (d) in a phantom and is called "*Personal Dose Equivalent*" $H_p(d)$. *See International Commission on Radiological Protection (ICRP) Report 60, 1991*

† An additional point of confusion with radiation quantities and their associated units may result from conventions used at high doses. The radiation weighting factors used in the definition of the protection quantity "Effective Dose", and quality factors used in calculation of the operational quantity "Personal Dose Equivalent" are based on *stochastic* radiation effects, but at high doses *acute* effects are of concern. At high doses the protection and operational definitions are therefore not meant to apply *(see ICRP Report 26, 1977)*. To reflect this, accident level doses are conventionally reported as "absorbed dose" in units of "rad", rather than "rem", although by convention *the same rad-to-rem conversion factors are applied*. However, since the rad-to-rem conversion factors would not improve the SIRAD results, it appears that this potential source of confusion has no bearing on the SIRAD performance in this study.

underestimate of two-thirds to overestimates by more than a factor of two. It also shows that these variations were not as great at higher doses. To meet the N322 requirement used for electroscope dosimeters the results should be within 10 percent.

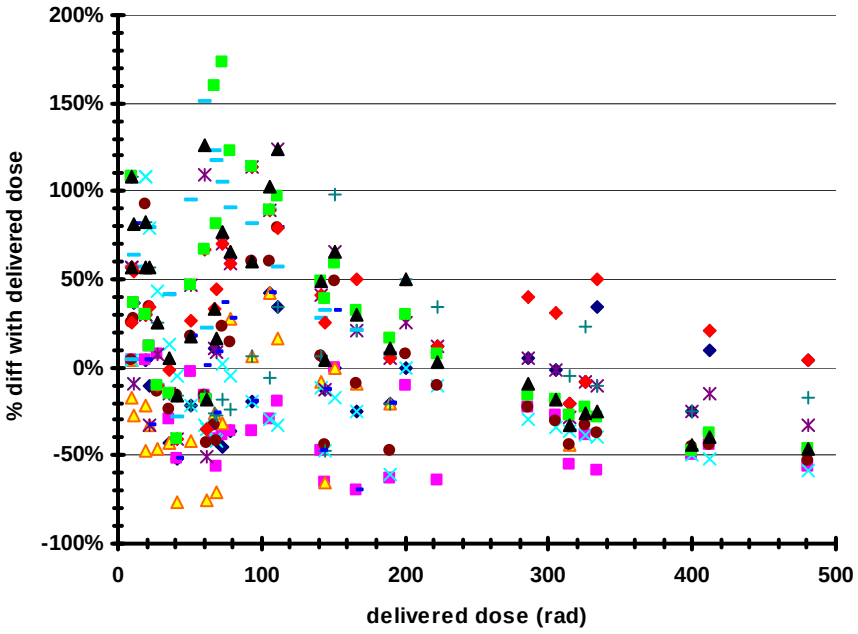

Figure 6. Percent difference between visual interpretation and delivered dose. For each delivered dose on the x-axis, the percent difference of the visual reading is plotted on the y-axis for each of the participants. Those in exact agreement with the delivered dose would show a 0 percent difference. For most dose values on the x-axis there are 12 points corresponding to the 12 subjects, but for some of the doses beyond the SIRAD maximum, there are less because some participants wrote ">200" rather than a numerical value.

The visual results analyzed according to the ANSI N13.11 performance criterion are shown in Figure 7. It shows results for N13.11 Category IA (^{137}Cs and M150 x-ray) and IB (^{137}Cs only), along with the densitometer performance results for comparison. Dosimeters irradiated in category IC were not available for the visual readout. The subjects are denoted by letters A through L; with upper and lower case used to indicate N13.11 categories IA and IB, respectively. This shows that, in most cases, visual readout of SIRAD does not pass the ANSI N13.11; however, two of the participants ("a" and "g") did pass N13.11 category IB, tests which the densitometer results failed. The color deficient subjects (I, J, and K) tended to show a positive bias.

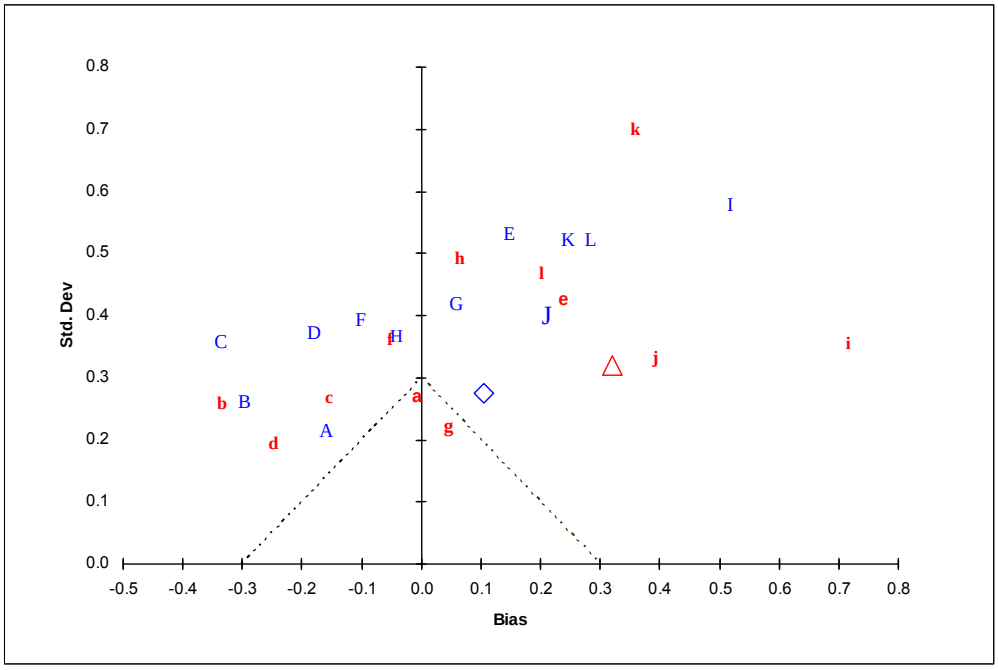

Figure 7. Results of visual readout in terms of the ANSI N13.11 performance measure. The bias (mean relative error) is plotted on the x-axis and the relative standard deviation is plotted on the y-axis for each of the 12 participants, who are denoted by the letters A through L. The upper case letters (blue) correspond to the results for dosimeters irradiated in ANSI category IA, and those in lower case (red) are results for the same participants' evaluation of the dosimeters irradiated for category IB. The small blue diamond and small red triangle symbols show the results for optical densitometer readings in IA and IB respectively. Points within the large dashed triangle would pass the N13.11 performance criteria for the Accident category. Observer A was very experienced in reading SIRADs. Observers K and L were unfamiliar with radiation dosimetry. Observers I, J, and K showed color vision deficiencies.

The results were further analyzed to see if the performance would improve if doses greater than 200 rad were omitted or if only M150 dosimeters were included. However, this did not improve the ANSI N13.11 defined performance for the visual readout results. These additional analyses are not shown here but were included in the interim report.

We also considered how the variations in visual interpretation of the color scale might affect tactical decisions if the SIRAD is used as a dose control tool. For example, in such applications, an incident commander might compare the SIRAD indicated dose with a reference value in order to direct lifesaving operations. The dose used for such operations may vary between localities. Several national and international guidance documents [5, 6, 7] use different terminology and recommend different dose values, such the Environmental Protection Agency's (EPA) "protective action guides" and "response worker guidelines" (25 rem), the National Council on Radiation Protection and Measurements' (NCRP) "decision dose" (50 rad), and the International Atomic Energy Agency (IAEA) "dose guidance" (100 rem). For this analysis, we used a reference decision level of 25 rad.

Because of the observed range in visual interpretations of SIRAD dose, there is potential for error where some dosimeters with doses below the reference level, and others with doses above the reference level, would be mistakenly placed in the wrong groups. Figure 8 shows the

percentage of the 12 subjects' reported results for each delivered dose value (≤ 200 rad) that would correspond to each type of error. Type 1 errors are cases where the delivered dose was <25 rad, but subjects interpreted it as > 25 rad. For doses near 10 rad, there were no such errors, but for doses close to 25 rad, 65-75 percent of the values were estimated as greater. Type 2 errors are cases where the delivered dose was >25 rad, but subjects interpreted it as less than 25 rad. For delivered doses of 73 rad or more, there were no such errors. For doses between 27 and 69 rad, the number of type 2 errors ranged from 8-33 percent. By counting all the data points and sorting the errors, we derived a cumulative estimate for the probability of type 1 errors at 29 percent and type 2 errors at 9 percent (shown in interim report).

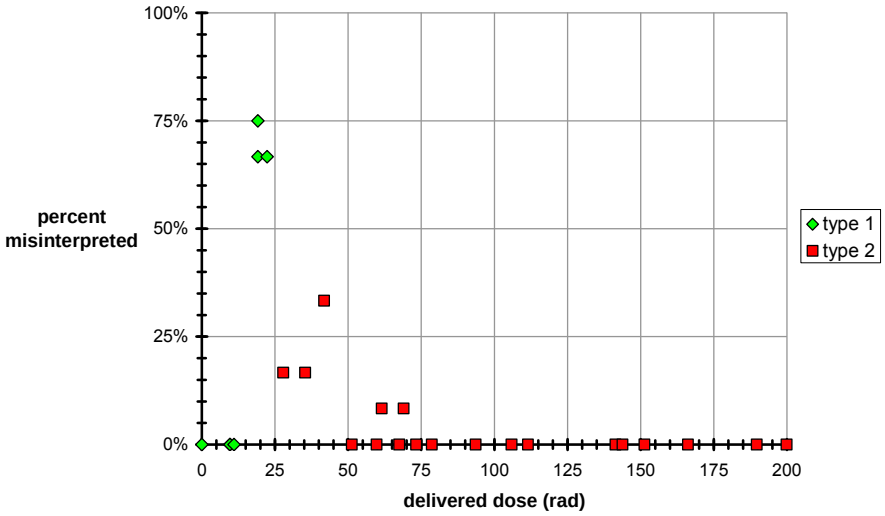

Figure 8. Analysis of potential for error in tactical applications. For each delivered dose on the x-axis, the y-axis shows the percentage of subjects who would misinterpret doses relative to a reference decision level of 25 rad. Those corresponding to lower doses mistakenly assigned values greater than the decision level (type 1 errors) are shown in green diamonds. Those corresponding to higher doses mistakenly assigned values below the decision level (type 2 errors) are shown as red squares. Below 11 rad and above 73 rad no decision errors are found.

This analysis represents a first attempt to consider the application of SIRAD to tactical/triage decisions. The data available are not ideal for this purpose because they were numerical estimates collected for comparison to delivered dose and densitometer values. A more thorough analysis in this vein should include additional delivered doses in the range of 0-10 rad, and might use alternate instructions wherein the subjects would sort dosimeters according to different decision levels rather than report numerical values. Nonetheless, this analysis illustrates that visual readout of the SIRAD is applicable to tactical decisions, particularly for identifying high doses, e.g. ≥ 3 times the reference level.

1.6. D. Environmental Tests

In the original plan for the environmental tests analyses, optical densitometer results for dosimeters irradiated pre- and post-stress were to be compared to identify potential effects from the stress condition. However, similar variations in densitometer results were observed for

laboratory irradiations without stress conditions, so we found that this comparison was inconclusive. Instead, we relied on visual observations to look for large effects.

There were no significant visually observable color changes in the SIRAD cards' color after the laundry cycle, though both cards were physically damaged with a crack in the middle. Similarly, for cards in the temperature and light tests, no significant changes were observed.

Changes in the SIRADs were observed for the automobile test, where they reached a temperature of 160 °F. An air bubble was observed between the clear protective overlay of the SIRAD cards and the sensing strips. After the cards were removed from the car, the air bubble gradually collapsed over several hours. Apparently, the air between the radiation sensitive strip and the plastic overlay of the SIRAD card expanded in the heat, stretching the plastic overlay and separating it from the sensor. While the bubble was present, the pre-irradiated cards appeared slightly lighter compared to the controls to three visual observers. After the bubble disappeared the sensor strip was perceived as less uniform to the same observers, but not different enough that it corresponded to a significantly different dose level. This effect also appeared to be observable during optical densitometer readout. The manufacturer reported that there was inconsistency within some of the cards where the densitometer reported spatially non-uniform results across the sensor area; this was alleviated by manually compressing the sensing strip during readout. Thus it appears that this effect should not be significant in the use of the SIRAD.

1.7 Evaluation Against the Criteria

The data analysis results can be used to evaluate the campaign hypotheses and determine the utility of the SIRAD. Each hypothesis and related results are discussed below.

- Is the SIRAD format usable by emergency responders without significant damage, loss, or interference with operations?

Yes. In the field deployment, 8 percent were lost, 10 percent were found to have slight damage (which did not affect their performance), and less than 1 percent were damaged severely enough to compromise performance. Feedback from participants was positive.

- In routine field deployment, does the SIRAD have a false positive probability of less than 1 percent?

Yes. The positive readings observed in the field deployment were for 4 dosimeters having obvious, severe damage to the protective cover, which identified them as suspect. These did not cause concern among the users: they were light blue and were interpreted by the POC as less than 5 rad. They represent less than 1 percent of those deployed.

- Are the SIRAD radiation response and calibration acceptable in the context of existing standards for other types of emergency dosimeters?

Yes. The SIRAD was tested against ANSI N13.11, though such a standard would likely be considered too high for a device that is not intended to be used for a legal dose of record. The SIRAD performed reasonably well, passing one of the three categories tested, even when doses beyond its upper scale range were included. The laboratory tests revealed a difference in response to photons of different energies (73 and 662 keV), which is common in many dosimeters (including TLDs, where it maybe corrected with filters or calibration adjustments). Since the SIRAD was shown to *over*-respond to higher energy photons, it would tend to err on the side of caution in this case.

- Can the color scale on the SIRAD card be accurately interpreted visually?

Not in all cases, but this should not be significant for the intended tactical applications. Color interpretation is subjective and corresponding numerical dose estimates vary between individuals, so the SIRAD should not be used for routine occupational dosimetry of record. However, doses significantly (factor of 3) above a reference decision level of 25 rad apparently can be easily identified for tactical decisions, despite the differences in assigning a corresponding numerical value. Future studies will investigate this topic in more depth.

- Are the manufacturer's specifications accurate?

Yes, in most cases. The specifications for functional temperature and light conditions, and photon, and beta response are accurate. However, the SIRAD did not demonstrate neutron sensitivity. Since neutrons are difficult to measure, this is common among other types of photon dosimeters and it is not crucial for the intended application since neutron sources are expected to have a significant gamma component.

- Does the card function under potential end-user environmental stresses?

Yes. Dosimeters returned from the field, left in a hot automobile, and put through the laundry continue to function.

- Is the SIRAD card appropriate for use by first responders for preparedness for potential radiological terrorist events?

Yes. It provides a color change that gives a field readable indication of a significant radiation exposure that could be valuable for tactical operations. Its low-cost and convenient format do not interfere with operations and would be useful for pre-distribution to emergency responders who would not otherwise use dosimetry but could be involved in the early response to a terrorist event.

1.8 Test Plan Completeness

The campaign was sufficiently complete to test the hypotheses. Another model of the SIRAD, with a wider dose range from 2-1000 rad and dual color test strips, was not ready in time to be included in the complete campaign. This missing element does not compromise the decision context for the completed campaign. Since the next generation model is ready now, at the end of the campaign, it will be possible to perform laboratory tests on it without the field deployment.

The analyses performed for the visual readout test indicate that additional research is warranted to quantify the potential for tactical decision errors. A more thorough analysis is planned to include additional pre-irradiated doses and to instruct the subjects to sort the dosimeters in relation to a reference decision level instead of assigning a numerical dose value. The reference decision values suggested in recent national and international guidance documents [5,6,7] could be used for comparison.

1.9 Lessons Learned

The most important lessons learned from this campaign are related to the field deployment tests. Since the field test involved distributing a device to people (rather than, for example, posting an instrument at a strategic location), it required a significant amount of preparation that is not typically involved in other types of field tests. Issues of risks and benefit, privacy, and health had to be thoroughly addressed. A Human Subjects Institutional Review Board (IRB)

usually reviews medical research. In some areas it was challenging to fit this campaign into the standard terminology used in the IRB-required application and consent forms. The IRB review process took several months to complete, but the extra effort involved was worthwhile. The campaign benefited from having an outside review of the protocol by experts from another field. Knowing that we were in compliance with standards and regulations and had passed review by medical researchers, we could be confident we were well prepared going into discussions with potential participants.

Obtaining participation of emergency responder groups also took several months. High-level contacts in New York, New Jersey, and Illinois identified the points of contact (POCs) for us to work with at agencies within their organizations. Initial contacts were enthusiastic about having their groups participate in the field deployment. However, achieving participation of each sub-group involved significant agency-specific interaction and follow-up—and in some cases, resulted in a 3-6 month delay in the field deployment. These interactions were most fruitful when one high-level contact was committed to having their agencies participate and helped follow through. In most agencies, several layers of review and approval were needed (e.g., legal, union) before the SIRAD could be distributed. Two groups also conducted their own Human Subjects IRB reviews. Ironically, our use of consent forms and human subjects' research standards may, in some cases, have invited greater legal scrutiny and delayed approvals.

Once the dosimeters were deployed, the data collection relied on the individual agency POCs who already had heavy workloads. For this element of the campaign, data collection was to a large extent outside of our control. At the end of the field test, we distributed Certificates of Appreciation to these POCs to acknowledge our reliance on their extensive efforts.

The field test also involved a significant amount of contingency planning for procedures to follow in case of a SIRAD color change. The main concern noted by the IRB was the potential for unnecessary angst that could be caused if there were a false positive indication on the SIRAD. The IRB endorsed the TLD back-up dosimeter and Reachback hotline to address this concern. This Reachback hotline was maintained solely for the SIRAD project, with 12 EML staff on call 24 hours. To provide appropriate advice for callers, a decision tree and related script was developed with input from the medical expertise of the U.S. Department of Energy Radiation Emergency Assistance Center/Training Site (REAC/TS). The Reachback component required practice and regular testing of the calling tree system. Contingency plans included allocations to cover emergency room costs and bio-dosimetry to resolve potential SIRAD and TLD discrepancies. The Department of Energy Radiological Assistance Program (RAP) teams in Regions 1 and 5 were told about the field test in case there would be any follow-up needed from a positive SIRAD reading, as were REAC/TS staff prepared for the potential for related calls from medical emergency rooms.

1.10 Next Steps

The results from this campaign will be disseminated in 2007 at meetings and in publications selected to reach many types of local emergency preparedness planners at the state and local levels including fire response, HAZMAT, law enforcement, and emergency medical. The study will also be submitted for publication in a peer-reviewed technical journal. The next generation SIRAD, with a wider sensitivity range (2-1000 rad), originally planned to be included in this campaign but not ready in time, will be subjected to laboratory irradiations and more investigations of tactical decision applications (as described in section 1.8); the results of any further tests will also be published.

Plans are underway to include SIRAD as part of the response protocol at one of the venues in the next Top Official (TOPOFF) exercise, drawing on the experience from this campaign. The writing group for a new homeland security standard being developed for emergency exposure control detectors is considering including colorimetric dosimeters since existing dosimetry standards were written for other technologies and purposes.

The SIRAD technology is commercially available and deployable. The current price is $10 each in quantities of 1,000 or more, or $20 for smaller quantities. (This can be compared to pocket electroscope and electronic dosimeters, which cost about $60 and $200 each respectively.) Responder organizations that chose to use this device will need to develop their own concept of operations (CONOPS) to reflect local policies for response actions and turn-back levels.

Acknowledgements

The field test deployment relied on the cooperation of the contacts at each participating agency. We are very grateful for the efforts of Ron Stryker, Paul Allen, Jeff Brownlee, Holly Chmil, Joe Buttich, Bill Csaszar, Dennis Dura, William Schaffer, Robert Sudol, John Grembowiec, Jim Rapp, Carl Bullock, Bonnie Mondelli, Anna Segura-Abernathy, David Beasley, Kevin Eack, Tom Seif, Myron Kovalevych, Joseph Serb, Lisha Harper, David Hanna, Brian Lacey, Charles Guddemi, Peter Culver, Christine Van Horn and Nick Contos. We are also grateful to Huban Gowadia, Matthew Barton, and Miles Dionisio (DHS) for direction and support; Subhash Sengupta (BNL) and Lyn Meyers (PNNL) for performing laboratory irradiations; Alysse Bak (Department of Energy) and John Klemic (California Institute of Technology) for performing some of the environmental tests; Todd Brethauer (Technical Support Working Group) and Albert Wiley (DOE REAC/TS) for consultations on reachback response planning; Jenny May and Penelope Sipll for photography; Ethel Davis (EML) for assistance with the human subjects regulations; and the Lawrence Livermore National Laboratory Institutional Review Board for assistance in developing the consent form.

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[6] National Council on Radiation Protection and Measurements, *Key Elements of Preparing Emergency Responders for Nuclear and Radiological Terrorism*, NCRP Commentary No. 19, December 31, 2005.

[7] International Atomic Energy Agency, *Manual for First Responders to a Radiological Emergency*, IAEA, October 2006. http://www-pub.iaea.org/MTCD/publications/PubDetails.asp?pubId=7606

Appendix

The relevant data files are retained at EML and are organized into six folders, each having numerous sub folders and files. The main folders are listed here, and the primary data analysis files contained within the folders are shown in parentheses.

1. Lab Tests & Visual Readout (n13.11readout_sept_2006.xls)
2. Field Test (TLD-SIRAD01_field_returns_2006_dec.xls)
3. Environmental Tests
4. Human Subjects
5. Response Plan
6. S&T CMTB administrative

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Acronym List

ANSI	American National Standards Institute
BNL	Brookhaven National Laboratory
CONOPS	Concept of Operations
DOE	Department of Energy
EML	Environmental Measurements Laboratory
EPA	Environmental Protection Agency
HAZMAT	Hazardous Materials
IAEA	International Atomic Energy Agency
IR	Infra-red
IRB	Institutional Review Board
LLNL	Lawrence Livermore National Laboratory
NCRP	National Council on Radiation Protection and Measurements
NVLAP	National Voluntary Laboratory Accreditation Program
RAP	Radiological Assistance Program
REAC/TS	Radiation Emergency Assistance Center/Training Site
SAVER	System Assessment and Validation for Emergency Responders
SIRAD	Self-indicating Instant Radiation Alert Dosimeter
TLD	Thermoluminescent Dosimeter
TOPOFF	Top Officials
TSWG	Technical Support Working Group
PMMA	Polymethyl Methacrylate
PNNL	Pacific Northwest National Laboratory
POC	Point of Contact