RESPONSE COMPARISON OF AN OPTICALLY STIMULATED LUMINESCENT DOSIMETER, A DIRECT-ION STORAGE DOSIMETER, AND A THERMOLUMINESCENCE DOSIMETER

A Thesis

by

PETE JEVON HERNANDEZ

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2008

Major Subject: Health Physics

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Approved by:

Chair of Committee,	John W. Poston, Sr.
Committee Members,	John R. Ford, Jr.
	Michael A. Walker
Head of Department,	Raymond Juzaitis

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ABSTRACT

Response Comparison of an Optically Stimulated Luminescent Dosimeter, a Direct-ion
Storage Dosimeter, and a Thermoluminescence Dosimeter. (August 2008)
Pete Jevon Hernandez, B.S., Texas A&M University
Chair of Advisory Committee: Dr. John W. Poston, Sr.

This study was undertaken to compare the response of three dosimeters to different environments. Comanche Peak Nuclear Power Plant wants to replace the current badge of record. The RaDos DIS-1 direct-ion storage dosimeter (DIS-1) and the Landauer InLight optically stimulated luminescence dosimeter (OSL) are the two candidates for replacement of the Panasonic UD-802 thermoluminescence dosimeter (TLD). The dosimeters were compared in five categories: dose linearity, dose-rate linearity, fade response, humidity response, and the angular dependence of the dosimeters.

The major results include verified linear relationship evidence for dose and dose-rate and a better fade response for both the DIS-1 and OSL. The TLDs faded by 9.2% over a month and the DIS-1 and OSL faded by 4.2% and 1%, respectively. Following a dose of 557.5 mrem, the dosimeters were exposed to different relative humidites. The dose to the DIS-1 and OSL did not change drastically while the TLDs dose readout was reduced by 10%. Finally, the angular dependence of the dosimeters was compared and the worst responses were 66% at 90° in the horizontal orientation for the OSL and 1.7%

at 90° in the horizontal orientation for the DIS-1. Based on the results of these tests the OSL seems like a more viable candidate for the new badge or record.

DEDICATION

I would like to dedicate this work to Kim, my best friend, my confidant, my muse, and my wife to be. Without your constant support, understanding and love none of what I do would be possible. I look forward to sharing a front seat with you on the rollercoaster of life.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Poston, for letting me into graduate school and for providing the idea for the research project. I would also like to thank my committee members, Dr. Ford, for always lending an ear and being optimistic and encouraging, and Dr. Walker, for his support throughout the course of this research and for helping to provide basic understanding of how TLDs function.

I would like to thank Landauer and Mirion Technologies for the loan of the OSLs and DIS-1s, respectively. Also without their loan of the readers no data would have been retrievable. I would like to thank the staff and management at Luminant, Comanche Peak for providing the need for the research and resources as well as guidance and personnel for this project and at times even a place to sleep while I was conducting the experiments. Special thanks to Senovio for all the help provided even when it infringed on your other duties.

I would like to thank all of my friends and the Nuclear Engineering Department for making my time at Texas A&M University an unforgettable experience. I have truly made some lifelong friends. Thanks also go to the National Science Foundation that provided funding allowing me to continue my studies.

I would also like to thank my parents, Michael and Mildred Marks, for their understanding, patience and willingness to help with stress relief throughout my college career. I know at times I have been difficult to deal with but they were always there when I needed help.

Lastly, I have to thank my lovely bride to be, Kimberly Hamala, who has made sure that I did not die of starvation whenever I forgot to eat. She has always been there with a helping hand when I needed it and has been very understanding and patient throughout the long nights and many long semesters that I have been in school. Mostly, I want to thank her for the love she gives me.

NOMENCLATURE

CP	Comanche Peak Nuclear Power Plant
TLD	Thermoluminescence Dosimeter
OSL	Optically Stimulated Luminescent Dosimeter
DIS-1	Direct-ion Storage Dosimter

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1. INTRODUCTION

1.1 Comanche Peak Nuclear Power Plant

Comanche Peak Nuclear Power Plant (CP), located near Dallas, Texas, produces 2300 MW of electricity for Luminant Power, which supplies energy to power over 110,000 customers across Texas. With 1300 employees, a number of contractors and members of the public, there are as many as 2000 people who have access to the plant site each day where there is opportunity to be exposed to radiation. Of constant concern at CP is the safety and protection of its staff and the public against unnecessary and excess radiation exposure. To maintain the levels of exposure to as low as reasonably achievable (ALARA) levels, personal radiation monitoring devices are carried by everyone onsite and they are placed throughout the plant and in surrounding areas.

The Health Physics/Radiation Protection (HP/RP) office is in charge of measuring, recording and controlling radiation doses at CP. The devices carried by the individual used to determine the dose are called dosimeters. The HP/RP office has an onsite calibration lab complete with a 5-kCi Cs-137 well source and a 2-Ci Cs-137 self-contained panoramic irradiator source to keep all plant detectors and dosimeters accurate and within specifications. At CP the Panasonic UD-802[*] thermoluminescence dosimeter is the current badge of record. In addition to the TLDs, CP uses two electronic personal

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This thesis follows the style of Health Physics.

[*] Panasonic Industrial Company, 2 Panasonic Way, Panazip: 7E-6, Secaucus, NJ 07094

dosimeters for active readout and a complex dosimetry records system to keep track of the doses for the entire staff and visitors.

CP has been using the TLDs for the badge of record since opening its doors in the 1990. Weekly and monthly standard tests are run on the TLDs using the onsite sources to maintain confidence in their reliability as the badges of record. Still, almost two decades have passed, new technology has emerged and the HP/RP office at CP believes that it is time to switch to a new dosimeter for their badge of record. The transition to new technology can have some obstacles. TLDs are the most widely used dosimeter in the industry today (McKeever, 2003). Their predecessors were film badges, which are still used even though they are considered an old technology. TLDs have been used for decades and are the industry standard (Frame 2005); so in order to supplant them at Comanche Peak, the new badges must pass all the same tests routinely performed on the TLDs and preferably perform better where the TLDs are lacking (Charlton 1995).

1.2 Dosimeters

The performance of two new personal dosimeters were compared to the performance of TLDs during these trials in order to determine if one of them will be a candidate to replace the TLD as the badge of record at CP. TLDs have many attractive features that make them so widely used and hard to replace. These include their reliability, easy maintenance, reusability, and durability as well as low cost (Carinou et al. 2001; d'Errico 2004). Ambrosi states "performance requirements for dosemeters are based on the assumption that the dosemeter is suitable for the workplace conditions under which it is used (Ambrosi 2001)." Based on this, it was decided to perform some tests on the new dosimeters that are routinely performed on the TLDs and some that were requested. All three types of dosimeters will be tested in accordance with the standards in the procedure manual at CP which was written to satisfy ANSI N13.11-2001 in relation to dosimetry (ANSI 2001). The two other dosimeters that will be explored are the optically stimulated luminescent dosimeter or OSL made by Landauer[†], and the direct-ion storage dosimeter called the DIS-1 made by Rados a subsidiary of Synodys and provided by Mirion Technologies[‡]. For the new dosimeters to be of maximum effectiveness and a representation of actual dose to the person, it is necessary that the individuals understand how and when to use them (Collison 2005).

Thermoluminescence dosimeters are the best understood of the three dosimeters which is why even the governing bodies speak specifically to them about requirements for processing and accreditation (Poston 2005; Veinot and Hertel 2001; Kumar et al. 2007). There have been literally hundreds of papers published since the 1960's that attest to the capabilities of the TLDs (Poston 2005). On the other hand the practice of using optically stimulated luminescence and direct-ion storage dosimeters is relatively young and is still being tested and proved so there is less industry-wide accepted data on these (Frame 2005).

This project compared the response of the three dosimeters in five categories. The first category was to verify that the dosimeters were working correctly. This is done

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[†] Landauer Regional Office, 17779 Sunset Strip, Flint, Tx 75762
[‡] Mirion Technologies, 5000 Highlands Pkwy, Suite 150, Smyrna, Ga, 30082

by showing a linear relationship between the actual dose and the measured dose of the dosimeter. Each dosimeter was placed in the irradiator at a fixed distance and exposed at a constant dose rate for varying time periods. The second category was the comparison of the dose-rate dependence of the dosimeters. The third category compared the fade response of the dosimeters, which evaluated how much the stored dose faded after a long and short period of time. The fourth category compared the angular dependence of the two new dosimeters to previously published results of TLD angular dependence (Charlton 1995). The final category determined the response of the dosimeters to changes in relative humidity ranging from 40% to 95% after being irradiated.

2. BACKGROUND

2.1 Thermoluminescence Dosimeter

TLDs are made from crystalline materials with impurities. This crystal creates electron-hole pairs once exposed to radiation. The radiation excites electrons to higher energy levels and the impurities form traps, which capture the electrons. When the TLD is heated, the electrons will recombine with the hole-pairs and return to the ground state. A photon in the visible light spectrum is emitted as the recombination takes place. Figure 1 illustrates the thermoluminescence process.

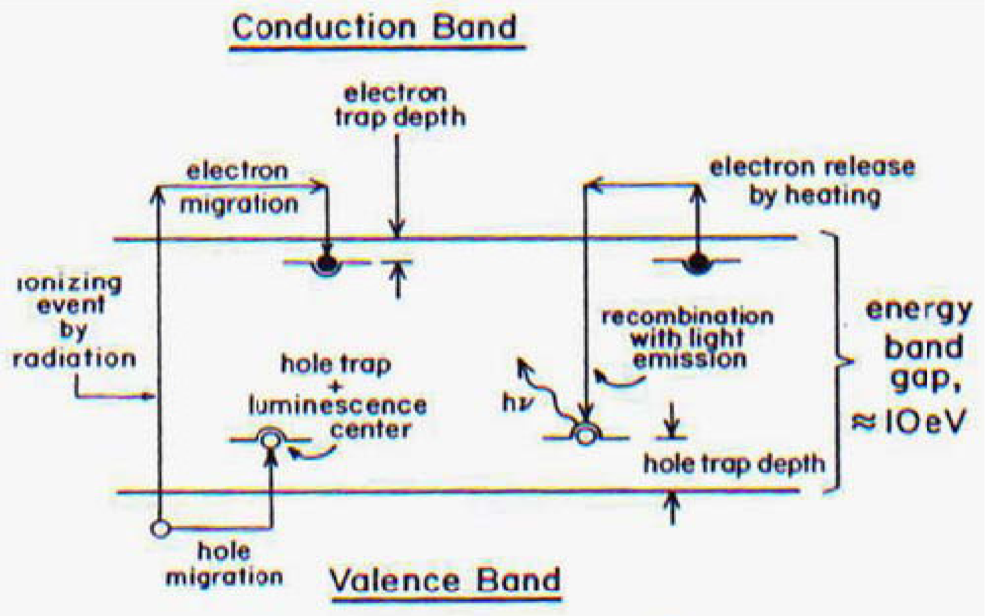


Fig. 1 Simple band model for thermoluminescence. The ionizing radiation causes the electron and the hole to migrate and get trapped on the left and on the right the addition of heat releases the electron to recombine and a photon is released (Attix).

The TLDs used in this trial were the conventional four-filter Panasonic UD-802 TLDs (see Figure 2), which have 2 $Li_2B_4O_7$:Cu phosphor elements and 2 $CaSO_4$:Tm elements. One $Li_2B_4O_7$:Cu element is under a total filtration of 17 mg cm^{-2} and the other is under 320 mg cm^{-2} and these elements are used to determine skin and whole body dose. The $CaSO_4$ elements are under filters of 320 mg cm^{-2} and 1020 mg cm^{-2} and are used to indicate the presence of low-energy photons and determine the whole body dose, respectively (Charlton 1995). The elements are contained on a plastic slide that is housed in the dosimeter case. The TLDs are placed in a plastic badge holder with rectangular transmission windows cut out to allow radiation to enter the dosimeter directly in front of each element (Veinot and Hertel 2001; Collison 2005).

Fig. 2 TLD with exposed slide

In order to gather exposure data stored in TLDs, the dosimeters must be heated, hence the term thermoluminescence. The TLDs are placed in the reader and, using a tungsten pulsing light source, the temperature is increased through a method called optical-heating. This heating releases the trapped electron-hole pairs to recombine and the resulting fluorescence is detected by a photomultiplier tube. The intensity of the total emitted light is proportional to the number of trapped charges, which is proportional to the accumulated radiation dose over the period of exposure (Knoll 2000; Frame 2005; Kumar et al. 2007).

2.2 Optically Stimulated Luminescent Dosimeter

Optically stimulated luminescent dosimeters are very similar to TLDs with the main difference being that a laser or LED instead of heat is used to add energy to the trapped charges to cause their de-excitation through luminescence states (Knoll 2000). In fact, many of the same materials that exhibit optically stimulated luminescence are also thermoluminescent (Frame 2005).

OSLs are made from crystalline materials with impurities. This crystal creates electron-hole pairs once exposed to radiation. The radiation excites electrons to higher energy levels and the impurities form traps in which the electrons are captured. When the OSL is exposed to strong light from a laser or light emitting diode, LED, the electrons will recombine with the hole-pairs and return to the ground state. A photon in the visible light spectrum is emitted as the recombination takes place. Thus, Figure 1 also illustrates the path of the electrons in the OSL. Unlike the TLD not all of the trapped charge is released because the laser only heats a specific area of the material. For this reason, the OSL can be read out many times.

The OSLs used in this trial are designed for whole body monitoring. They are part of the InLight badge system by Landauer loaned to CP along with a reader for the purposes of this experiment. The badges are so similar in appearance to the TLDs that a mistake could easily be made if they are not kept separate. These OSLs use aluminum oxide, Al_2O_3:C which is currently the only material being used for OSL dosimetry (Frame 2005). The aluminum oxide powder doped with carbon is made into a film roll and small discs are cut to fit into the dosimeter badges as illustrated in Figure 3.

There are four elements in this dosimeter that are contained on a slide which is housed in a case with metal and plastic filters. Each element is a small disc of Al_2O_3:C placed between two polyester layers. The filters are plastic, aluminum and copper and an open window with no filter is in the last spot. The thicknesses of the filters can be found in Table 1.

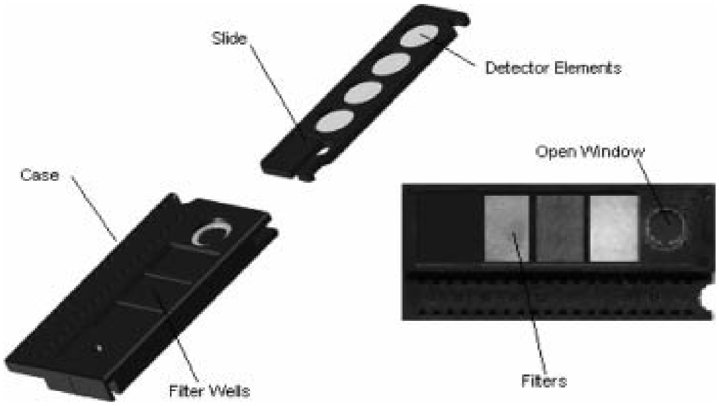


Fig. 3 Exploded view of the OSL dosimeter
(Perks et al. 2007)

Table 1. Filter thicknesses for the InLight badge (Perks et al. 2007)

	Thickness (mg cm^{-2})			
	Open window	Plastic	Aluminum	Copper
Front	29	275	375	545
Back	134	283	383	553

As previously stated for this trial a manual reader was used that allowed reading the OSLs individually. There are also available 200- and 500- capacity readers that read the OSLs automatically. To gather exposure data stored in the OSLs, they have to be exposed to light. The reader consists of 38 LEDs that illuminate the dosimeters either individually for the manual reader or the whole magazine for the automatic readers. This light releases the trapped electron-hole pairs to recombine and the resulting fluorescence is measured with a photomultiplier tube. A dose algorithm controlled by a dedicated computer converts the photon counts to dose. The computer outputs a deep, lens and shallow dose (Perks et al 2007).

2.3 Direct-Ion Storage Dosimeter

The third dosimeter being compared is a direct-ion storage dosimeter called the DIS-1 made by Rados a subsidiary of Synodys and it is vastly different. The DIS-1 combines air-filled ion chambers, non-volatile memory cells (EEPROM) and metal oxide semiconductor field effect transistors (MOSFET) (Wernli and Kahilainen 2001). The standard MOSFET is pictured in Figure 4. Electron-hole pairs are formed in the silicon dioxide layer when exposed to radiation. In the presence of a positive charge, electrons will move toward the gate and the holes will move to the silicon oxide/silicon interface. This causes a fixed positive charge and a reduction of gate voltage which is a linear measure of the integrated dose (Knoll 2000).

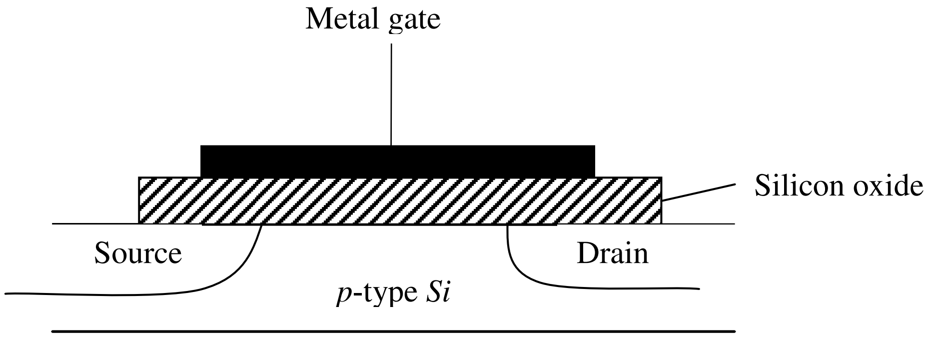


Fig. 4 Configuration of a metal oxide semiconductor field effect Transistor (MOSFET) (Knoll 2000)

The EEPROM was originally used for voice recording devices and has the capability of storing a variable analog voltage for indefinite periods of time. For application in the DIS-1, modifications to the typical EEPROM were necessary.

The DIS-1 ion chamber is created between the floating gate of the modified EEPROM and the conducting wall with air or gas in the chamber seen in Figure 5 (Wernli and Kahilainen 2001). The floating gate is set to a predetermined charge usually less than 30 volts to prevent ion recombination. Ionizations that take place in the air chamber partially discharge the gate and the resulting drain in conduction can be read out electronically (D'Errico and Bos 2004; Fuchs et al. 2007). The change in voltage is proportional to the number of ionizations and, thus, the dose. The walls of the chamber are made of either Teflon or graphite in order to provide a suitable representation of dose to the body (Boschung et al. 2002; Wernli and Kahilainen 2001). The dosimeter can be used to measure deep and shallow dose to the individual.

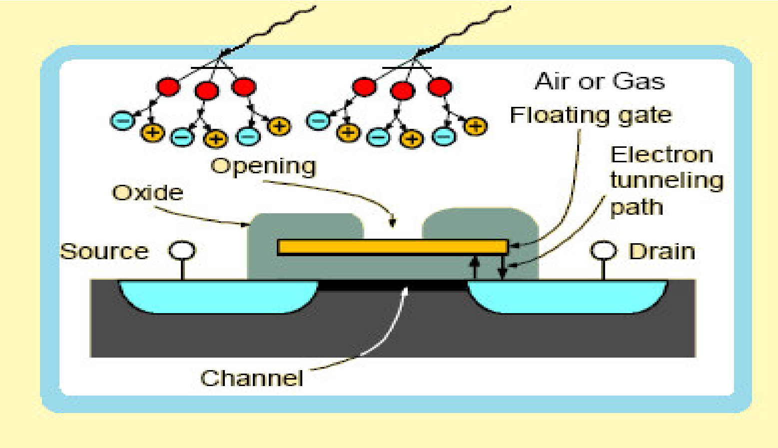


Fig. 5 DIS memory cell surrounded by a conductive wall (Wernli and Kahilainen 2001)

As can be seen in Figure 6, the DIS-1 is housed in a plastic case which is placed into an aluminum badge to attach to clothing. The readout of the dosimeter is performed with a table-top unit called the DIS badge reader, DBR-1 (Fiechtner et al. 2004). It can be used as a standalone reader and the information downloaded to a computer at a later time; or it can be directly connected to a computer for immediate archiving.

Fig. 6 The DIS-1 dosimeter and DBR-1 reader (Collison 2005)

2.4 Dosimetry Testing Criteria

Dosimeters should be tested according to American National Standards Institute, Inc. specified testing criteria. The most update standard is ANSI N13.11-2001 Personnel Dosimetry Performance: Criteria for Testing. The purpose of this standard is to establish the test conditions and performance criteria for evaluating personnel dosimetry systems (ANSI 2001). Meeting these standards satisfactorily means estimating the dose equivalent, H, for the nine specified performance categories and tolerance levels. The dosimeters in this project needed to only be tested for the category in which they were going to be used. The ANSI standard requires the use of a specific type of phantom. However, this phantom was not used in this comparison because it was not used routinely at CP. Instead the radiation protection technician provided a polyethylene ring which is used at CP for TLD exposures. This ring was used for all dosimeter comparison trials. Table 2 lists the test categories, irradiation ranges, and associated tolerance levels required to analyze the performance of the dosimeters. The performance quotient, or performance index, P_i, for the i^{th} dosimeter is

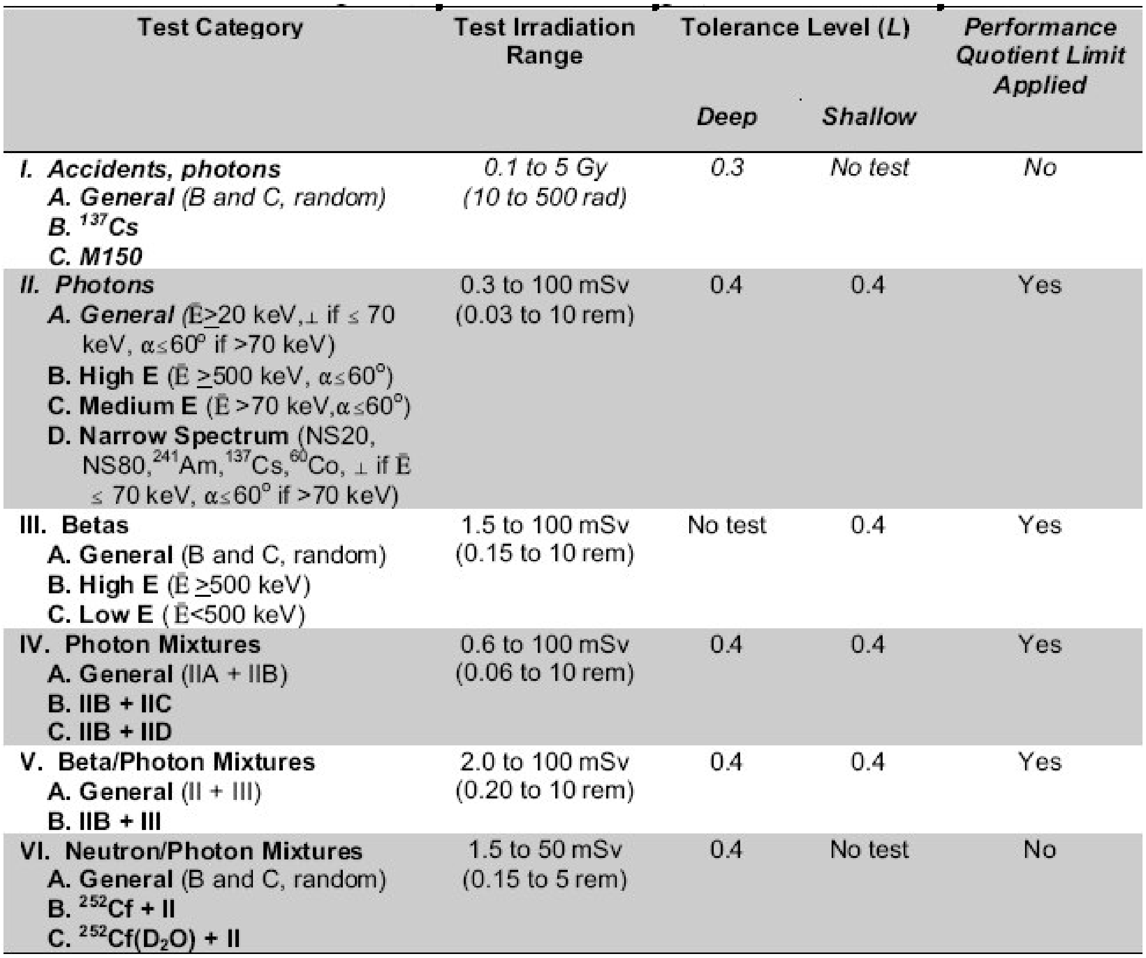
$$P_i = \frac{\left(H_i^{'} - H_i\right)}{H_i} \qquad \text{(Eq. 1)}$$

where H'_i is the true dose or dose equivalent for dosimeter *i*, and H_i is the measured dose. One of the quantities calculated from the performance indices is the bias, B, which is the average of the quotients. This is defined as

$$B = \overline{P} = \left(\frac{1}{n}\right)\sum_{i=1}^{n} P_i \qquad \text{(Eq. 2)}$$

where n is the number of dosimeters (Soares 2007; van Dijk 2006). The tolerance level is the acceptable value for all test irradiation categories.

Table 2. Test Categories, Test Irradiation Ranges, and Tolerance Levels (ANSI 2001)



Test Category	Test Irradiation Range	Tolerance Level (L)		*Performance Quotient Limit Applied*
		Deep	*Shallow*	
I. Accidents, photons ***A. General*** *(B and C, random)* ***B.*** ^{137}***Cs*** ***C. M150***	*0.1 to 5 Gy* *(10 to 500 rad)*	*0.3*	*No test*	*No*
II. Photons ***A. General*** ($\bar{E} \geq 20$ keV, ⊥ if ≤ 70 keV, α≤60° if >70 keV) **B. High E** ($\bar{E} \geq 500$ keV, α≤60°) **C. Medium E** ($\bar{E}$ >70 keV, α≤60°) **D. Narrow Spectrum** (NS20, NS80, ^{241}Am, ^{137}Cs, ^{60}Co, ⊥ if $\bar{E}$ ≤ 70 keV, α≤60° if >70 keV)	0.3 to 100 mSv (0.03 to 10 rem)	0.4	0.4	Yes
III. Betas **A. General** (B and C, random) **B. High E** ($\bar{E} \geq 500$ keV) **C. Low E** ($\bar{E}$<500 keV)	1.5 to 100 mSv (0.15 to 10 rem)	No test	0.4	Yes
IV. Photon Mixtures **A. General** (IIA + IIB) **B. IIB + IIC** **C. IIB + IID**	0.6 to 100 mSv (0.06 to 10 rem)	0.4	0.4	Yes
V. Beta/Photon Mixtures **A. General** (II + III) **B. IIB + III**	2.0 to 100 mSv (0.20 to 10 rem)	0.4	0.4	Yes
VI. Neutron/Photon Mixtures **A. General** (B and C, random) **B.** ^{252}**Cf + II** **C.** ^{252}**Cf(D_2O) + II**	1.5 to 50 mSv (0.15 to 5 rem)	0.4	No test	No

3. PROBLEM

The Panasonic UD-802 TLD, although an industry standard, has two major flaws that CP wants to alleviate with the new device that replaces it. First, evaluation of the dosimeters can be a time consuming process, averaging 30 sec, to read each TLD. This is due in part to the requirement of heating the TLD and then reading the dose. It takes time to heat up and then before the new magazine can be run the temperature has to be brought back down. The age of the software and hardware used for processing also plays a role as it is almost two decades old. The reading process is automatic; so could be set to read overnight, but it still takes a significant amount of time especially if needed the same day. When this time is multiplied by the large number of TLDs used, it adds up quickly. The second major flaw of the TLD is once it has been read it cannot be reread in case of an error or as a check. This is because once heat is added to read the TLD all the electrons vacate the holes and fall back to their ground state. In essence the radiation exposure information is expunged (Abraham et al. 2007). This leaves nothing to read a second time. According to CP, the TLDs have, on occasion, also been susceptible to humidity after being exposed. The new badge of record must not have these flaws and must perform at least as well as the TLD in all the areas in which it will be used at CP.

It is sufficient that the dosimeters meet the operating capabilities of the location that they will be used (Ambrossi 2001). With this assumption, it was decided that the two new dosimeters should be put through the same CP-specific standards testing that the TLDs are routinely put through to have a valid comparison of relevant data. These standards are listed in the Comanche Peak Radiation Protection Instruction Manual.

The two other dosimeters that will be explored are the optically stimulated luminescent dosimeter or OSL made by Landauer, and the direct-ion storage dosimeter called the DIS-1 made by Rados a subsidiary of Synodys. Both of these dosimeters are quickly read and have reproducible dose readouts which address both of the main issues of concern with the TLD.

4. MATERIALS AND METHODS

This project consisted of comparing the dosimeter performance in five tests and evaluating the indicated doses compared to the delivered dose. The performance was compared to the standard for personnel dosimeters, ANSI N13.11-2001. The categories for irradiation are dose linearity, dose-rate linearity, fade, angular response, and humidity effect. The procedure for each dosimeter in each test is the same. Cesium-137 sources were be used for all experiments.

Two passive dosimeters were chosen to be compared to the TLDs in this project. The first was an optically stimulated luminescent dosimeter made by Landauer. Several dosimeters were provided by Landauer so new dosimeters were used for each trial due to the fact that they cannot be reset. The second device is a direct-ion storage dosimeter called the DIS-1 made by Rados a subsidiary of Synodys. Only eighteen DIS-1 dosimeters were provided by Rados so some had to be zeroed and reused. The main idea is to compare the responses of the OSL and DIS-1 to the badge of record at CP, the Panasonic UD-802 TLD.

4.1 Dose Linearity

The first test was to determine the relation between the actual and indicated doses as a function of the total dose delivered to the dosimeter. To determine if a dosimeter is operating correctly and detecting radiation can be done by finding the relationship between the incident dose and the dose output by the dosimeter. This was done by placing the dosimeters in the panoramic irradiator with a constant dose rate of 111.5 mrem min^{-1} and varying the exposure times. It was anticipated that a linear relationship should be the result. At the time of this experiment, the source in the panoramic irradiator was calibrated and recorded to be 1.33-Ci Cs-137. It was used to irradiate all the dosimeters in the dose linearity comparison. The source is housed in a lead-lined drum placed on the ground while not in use and elevated to the panoramic deck during exposures. The dosimeters were placed in this panoramic irradiator at 111.5 mrem min^{-1} for exposure times of 0.5, 1.5, 2.5, 5, 10, 30, and 60 min. The dose for each dosimeter was read and recorded after each exposure. Where it was possible, the dosimeters were reset to a zero reading to minimize error. The results can be found in the results section.

4.2 Dose-Rate Linearity

The next category for irradiation is dose-rate linearity. This test should result in a linear relationship between the incident dose rate and the output dose on the dosimeters. For this experiment the dosimeters were placed above a collimated Cs-137 well source. At the time of this trial, the well source was calibrated and recorded to be 2.84 kCi. Unlike in the dose linearity comparison, where the time of irradiation was varied, for the dose-rate linearity comparison the time will be constant and the radiation field will be varied. The exposure rates that the dosimeters will be exposed to were 991, 2496, 4018 9985, 25023, 40001 and 599508 mrem h^{-1} or 16.5, 41.6, 67.0, 166.4, 417.1, 667.0, and 9991.8 mrem/min.

The badges will be read and the dose recorded after each exposure and the dosimeters reset where applicable. Five of each dosimeter was irradiated at each dose rate to determine the dose-rate dependence. The dose rates were adjusted by raising and lowering the source in the well and placing varying thicknesses of lead between the dosimeters and the source. The dose-rate linearity data and response curve are found in the results section.

4.3 Fade Response

Thermoluminescent dosimeters have been known to fade up to 3% within 24 hours and more after longer periods of time. To conduct the comparison and determine the fade response of the dosimeters, the OSLs, DIS-1s and TLDs will be irradiated for a dose of 557.5 mrem. Only 6 TLDs were used because of the well established fade record of the TLDs at CP, also due to their inability to be reread a different dosimeter will have to be used for each reading whereas with the other two dosimeters readings can be retaken.

The dosimeters were placed in the panoramic irradiator on the polyethylene ring and given a dose of 557.5 mrem. One third of the TLDs were read immediately after irradiation along with the DIS-1s and OSLs. After two weeks, another third of the TLDs will be read and the DIS-1s and OSLs will be reread. And after a month, the last third of the TLDs will be read with rereading of the DIS-1s and OSLs. Ideally, the two potentially new dosimeters will not exhibit a significant fade either in the short-term fade test or the long term-fade test. The design of this test was congruent with the procedure for a fade test in the CP operating manual. While waiting the two-week time, and month-long time periods, the dosimeters will be stored. The fade response data can be found in the results section.

4.4 Humidity Response

The humidity response test measures the performance of the dosimeters when exposed to various relative humidities at a constant temperature after being irradiated. This was requested by the HP/RP office as one of the tests because it seems that once the TLDs have received a dose, and then are exposed to humidity, the dose changes. The idea is that having a badge of record that does not react poorly to humidity changes would result in fewer errors in dose records for employees.

All of the dosimeters were given a dose of the CP standard 557.5 mrem and all the OSLs and DIS-1s were read immediately after the irradiation. The dosimeters were then taken to the Environmental and Meteorology lab and placed in the environmental chamber at the set temperature of 90° F and humidities ranging from 40% to 95%. They were allowed to sit in each environment for 4 hours to acclimate and were then read again. After each reading the dosimeters were reset and irradiated again to a dose of 557.5 mrem where applicable. The steps are the same for each relative humidity setting. Using a climate controlled chamber allowed the temperature to be set at 90^{o} F and the use of a variable relative humidity. The first relative humidity was 57.7% and was used as the reference humidity. The dosimeters were also tested at relative humidities of 40%, 80% and 95%. Ideally, a dosimeter would show little or no change no matter the relative humidity of the environment. The data for the humidity response test can be found in the results section.

4.5 Angular Dependence of Dosimeters

Finally, the effects of badge orientation will be tested by irradiating the badges at different angles of irradiation incidence and reading them. This will be done in both the horizontal and vertical orientation to encompass a hemispherical region. ANSI N13.11-2001 requires that at least 0°, ± 40°, ± 60° in both the horizontal and vertical orientations be evaluated for personnel dosimetry. The ± 90° angles were not specified. This angle was included in this experiment for completeness and to determine if the newer dosimeters have a wider range of sensitivity than the TLDs. Also, since the DIS-1 had a differently shaped badge holder, including more angles will show what if any effect this has.

In both the horizontal and vertical planes, irradiations were conducted at angles of 0°, ± 15°, ± 30°, 45°, ± 60°, ± 75°, and ± 90° using five of each dosimeter types. The exposures were made with the 1.33-Ci Cs-137 source in the panoramic irradiator. The dosimeters were administered a dose of 334.5 mrem at each angle and were placed against the polyethylene ring for each exposure. Angles were measured using a handheld protractor with one-degree divisions. For the horizontal angles the dosimeters stood on their own and for the vertical angles the dosimeters were placed in a rotating grasper whose effect on dose was considered negligible due to the low density.

The procedure for the angular dependence test was as follows:

1. Turn on power to the air compressor 2 minutes prior to operation to ensure ample pressure.
2. Verify that all visible interlocks and limit switches are not physically damaged and are in place.
3. Turn the POWER key switch to the left to power-up the unit. The power light and the source OFF light should be illuminated.
4. Set the digital preset timer which controls the exposure to the desired exposure time.
5. Set the turntable to the OFF position
6. Set the attenuator to the ON position
7. Raise the chamber access cover.
8. Place the absorbed dose irradiator ring on the panoramic irradiator turntable.
9. Place the dosimeter on the turntable against the polyethylene ring.
10. Adjust the angle of the dosimeter to the appropriate angle with the handheld protractor.
11. Lower the chamber access cover
12. Set the attenuator to the OFF position
13. Set the turntable to the ON position
14. Activate the source ON switch. Within two seconds the source should move to the ON position and the indicator lights on the control panel will show where the source is located. This will start the preset timer and irradiate the dosimeter for the desired time and to the desired dose
15. When the source returns to the OFF position an alarm will sound, indicating the end of the irradiation cycle.
16. Set the turntable to the OFF position.
17. Set the attenuator to the ON position
18. Raise the chamber access cover.
19. Remove the dosimeter and put in the next dosimeter to be irradiated.

20. Repeat from step 9 for each dosimeter and each angle.

The TLDs were not evaluated since there is an exhaustive body of data to compare to and to save time. Efficiency data from Charlton (1995) are presented in the results for completeness. In that study, data are available for TLDs evaluated at 0°, ± 30°, ± 60°, 75°, ± 90° in the vertical and horizontal orientations. Including these data will allow comparison between all three dosimeters.

5. RESULTS

5.1 Dose Linearity

This test served as the baseline test to ensure proper function and calibration. The raw data can be found in the Appendix. Five readings were recorded for each dose per dosimeter. Table 3 shows the average values of the dosimeter readings for each dose delivered and the percent difference between the two for the UD-802 TLD. The average deep dose, average shallow dose, and the percent differences between these and the dose delivered are shown in Table 4 for the Landauer OSL. The average deep dose output, average shallow dose output values and percent difference between them and the dose delivered are shown in Table 5 for the Rados DIS-1. Table 6 compares the dose delivered with the measured doses for all the dosimeters. This comparison is illustrated in Figure 7. As the figure shows all 3 dosimeters exhibited a linear relationship with the incident dose. No shallow dose data were provided by CP for the TLDs for any experiment.

Table 3. Dose linearity for Panasonic UD-802 TLD

Dose Delivered	Avg. Dose Output	Standard Deviation	Percent Difference
(mrem)	(mrem)	(mrem)	
55.75	56	2.44948974	0.45%
167.25	163	2.82842712	2.61%
278.75	277.75	5.05799697	0.36%
557.5	543.66667	19.7315314	2.54%
1282.5	1193.5	27.5771645	7.46%
3345	3395	33.9411255	1.47%
6690	7137	65.0538239	6.26%

Table 4. Dose linearity for Landauer OSL

Dose Delivered	Avg. Deep Dose Output	Standard Deviation	Percent Difference	Avg. Shallow Dose Ouput	Standard Deviation	Percent Difference
(mrem)	(mrem)	(mrem)				
55.75	58.330	4.573	4.424%	59.83	2.630	6.819%
167.25	176.750	14.796	5.375%	166.75	18.626	0.300%
278.75	286.750	15.521	2.790%	286.25	43.370	2.620%
557.5	562.749	54.615	0.933%	569.749	63.478	2.150%
1282.5	1125.749	40.657	13.924%	1226.999	178.406	4.523%
3345	3314.250	259.368	0.928%	3454.75	799.545	3.177%
6690	6355.484	394.455	5.263%	6854.734	776.911	2.403%

Table 5. Dose linearity for Rados DIS-1

Dose Delivered	Avg. Deep Dose Output	Standard Deviation	Percent Difference	Avg. Shallow Dose Ouput	Standard Deviation	Percent Difference
(mrem)	(mrem)	(mrem)				
55.75	65.267	0.2081666	14.581%	57.733333	0.569	3.435%
167.25	184.933	1.5011107	9.562%	170.2	2.042	1.733%
278.75	0.000	0	0.000%	0	0	0.000%
557.5	623.167	3.555746523	10.538%	573.86667	5.522	2.852%
1282.5	1232.567	3.666515148	4.051%	1151.6333	10.707	11.364%
3345	3625.433	8.799052979	7.735%	3443.1333	17.215	2.850%
6690	7386.867	32.89473109	9.434%	7044.5333	46.340	5.033%

Table 6. Comparison of dose linearity for UD-802 TLD, OSL, and DIS-1

Dose Delivered	Average TLD (mrem)		Average OSL (mrem)		Average DIS-1 (mrem)	
(mrem)	Deep	Shallow	Deep	Shallow	Deep	Shallow
55.75	56	N/A	58.330	59.83	65.267	57.73333
167.25	163	N/A	176.750	166.75	184.933	170.2
278.75	277.75	N/A	286.750	286.25	N/A	N/A
557.5	543.667	N/A	562.749	569.749	623.167	573.8667
1282.5	1193.5	N/A	1125.749	1226.999	1232.567	1151.633
3345	3395	N/A	3314.250	3454.75	3625.433	3443.133
6690	7137	N/A	6355.484	6854.734	7386.867	7044.533

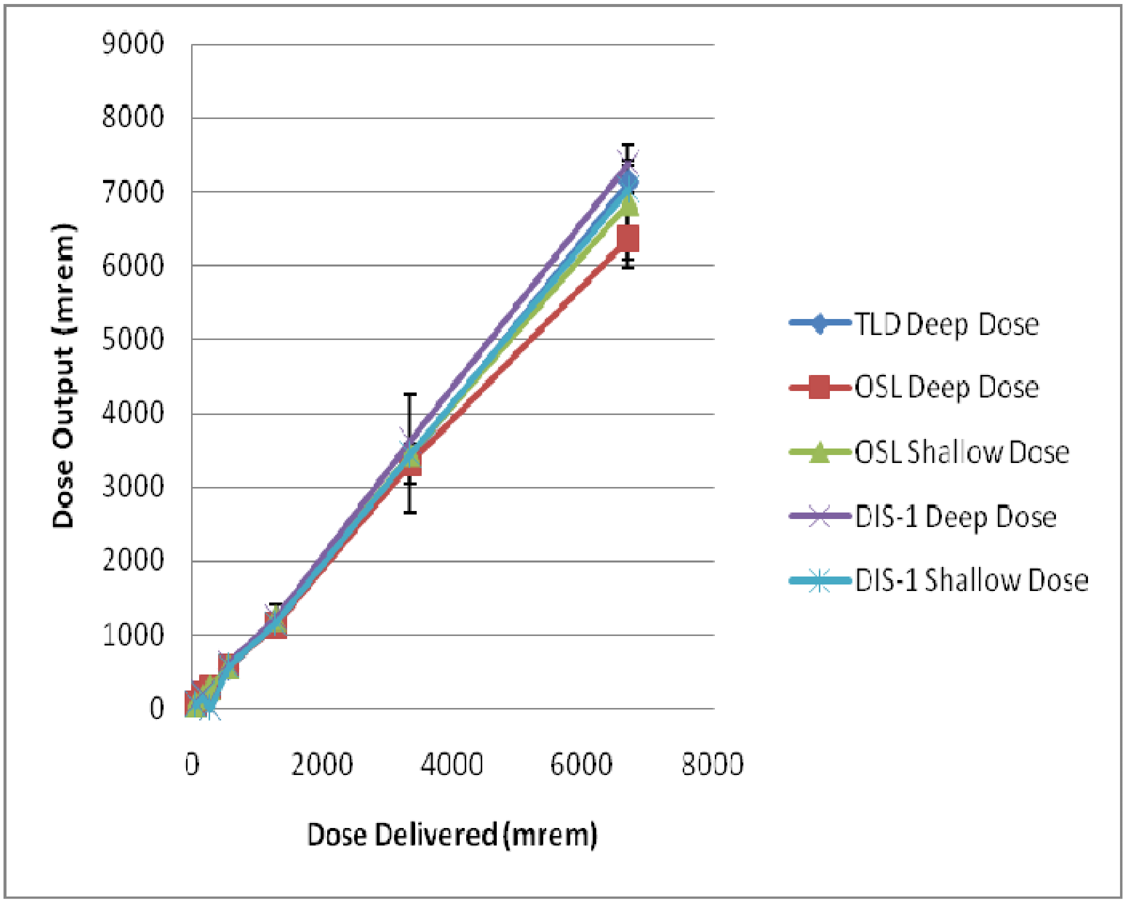


Fig. 7 Dose linearity comparison for the UD-802 TLD, OSL, and DIS-1 dosimeters.

5.2 Dose-Rate Linearity

The data in Table 7 compares the dose rates measured by the UD-802 TLD, OSL and the DIS-1 to the delivered dose. Effective dose rate was calculated by dividing the measured reading of the dosimeter by the exposure time, in this case 1 minute. A 2.84-kCi well source was used for this test and the graphic results are shown in Figure 8.

Table 7 Comparison of UD-802 TLD, OSL, and DIS-1 dose-rate linearity.

Dose Rate Delivered	TLD	OSL		DIS-1	
(mrem h^{-1})	(mrem h^{-1})	(mrem h^{-1})		(mrem h^{-1})	
		Deep	Shallow	Deep	Shallow
991	998	934.830	1264.8303	881.99	905.2785
2496	2502	2789.993	2939.9927	2172.768	2151.552
4018	4009	4289.982	3389.989	3405.255	4104.387
9985	9862	9870.000	9359.9927	8656.995	8841.7175
25023	24678	25710.000	28440	21982.71	25298.253
40001	39029	40739.883	44909.883	39640.99	33940.849
599508	615205	906562.500	971571.56	602205.8	572230.39

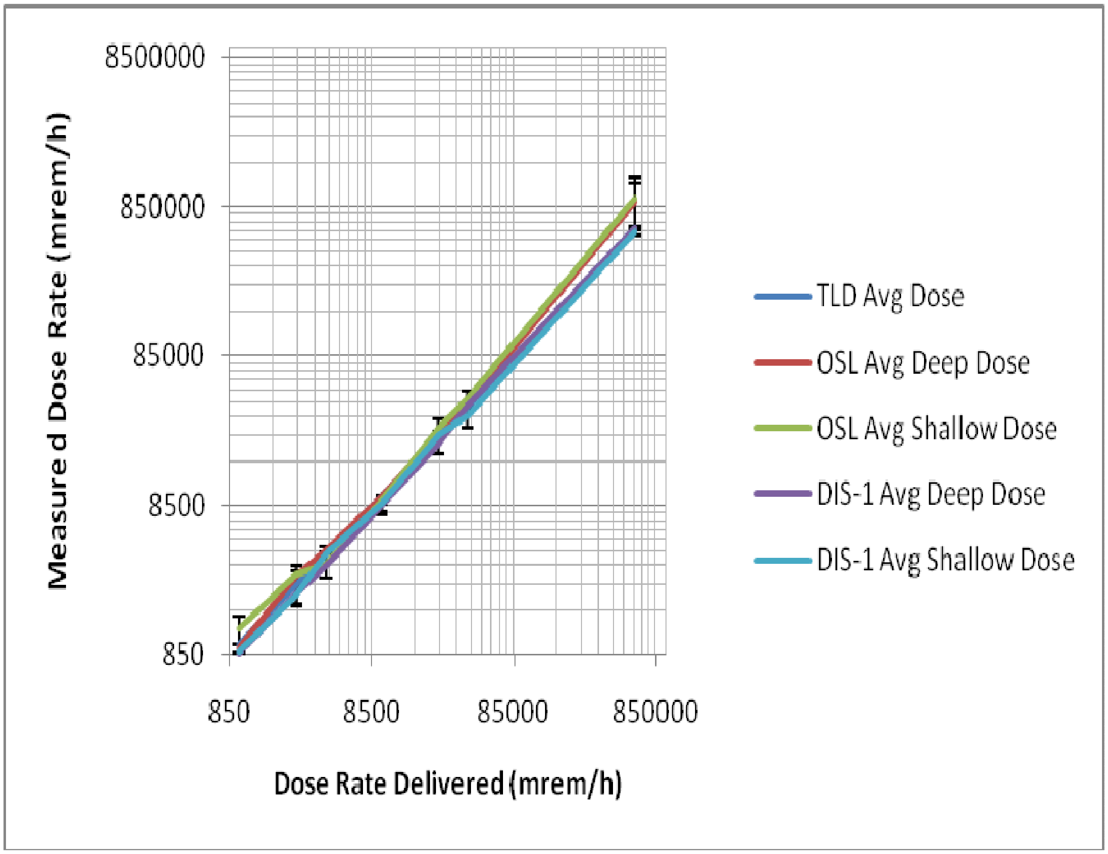


Fig. 8 Comparison of UD-802 TLD, OSL, and DIS-1 dose-rate linearity.

5.3 Fade Response

Table 8 shows the comparison of fade response in the three dosimeters tested. Only two TLDs were irradiated per reading because of the well-established fade response recorded at CP and to keep the number of occupied TLDs to a minimum. For the DIS-1 and OSL, five dosimeters were used for the readings and an average was taken to get the values in the table. The fade is represented by the % difference columns. It is the percent difference between the measured dose and the dose administered.

Table 8 Comparison of fade response in TLD, OSL, and DIS-1 from delivered dose of 557.5 mrem

Dose Delivered	24hours	% difference	2 weeks	% difference	1 month	% difference
557.5	(mrem)		(mrem)		(mrem)	
TLD	572.746	0.027	544.92	0.023	517.3	0.078
OSL	563.413	0.010	552.413	-0.009	557.913	0.001
DIS-1	582.05	0.042	568.15	0.019	573.2	0.027

5.4 Humidity Response

In Table 9 the comparison values of responses for the TLDs, OSLs and DIS-1s investigated in this project are shown. The dosimeters were given doses of 557.5 mrem before being immersed in relative humidities ranging from 40% to 95% all at 32°C. For the humidity response test, TLD deep dose values, and deep and shallow dose values for the OSLs and DIS-1s were all taken at a 57.7% relative humidity as a reference. All dosimeters were read after 4 hours in each environment.

Table 9 Response to different relative humidity environment after being dosed for TLD, OSL and DIS-1

Dosimeter	Deliver Dose (mrem)	57.7 RH DD	57.7 RH SD	40 RH DD	40 RH SD	80 RH DD	80 RH SD	95 RH DD	95 RH SD
TLD	557.5	532	N/A	551	N/A	528	N/A	516	N/A
OSL	557.5	575	555	599	568	572	561	556	530
DIS-1	557.5	600	555	609	571	624	584	632	594

5.5 Angular Dependence of Dosimeters

An atypical handheld protractor was used to measure the angles in both the horizontal and vertical directions. Figure 9 shows the protractor angles. The angular dependence for the Landauer OSLs and the Rados DIS-1s in both the vertical and horizontal directions was performed with the Cs-137 source in the panoramic irradiator. For the -90° horizontal irradiation, both the OSL and DIS-1 were placed in the standard operating orientation with the sensitive window facing the source or perpendicular to the incident radiation. Figures 10 and 11 show this orientation for the OSL and DIS-1. The 0° position for the horizontal placed the dosimeters parallel to the source of incident radiation with the sensitive window facing to the right. This is applicable for both the OSL and DIS-1. The 90° horizontal position had the dosimeter facing backward again at a perpendicular position with respect to the incident radiation. Figures 10 and 11 also show the orientation for the 90° position.

Figure 12 shows the vertical orientation at ±90° for the Rados DIS-1. The -90° position had the sensitive window facing downward with the metal top of the dosimeter closest to the source. The +90° position had the dosimeter placed on its back with the sensitive window facing up and the plastic bottom of the badge closest to the source.

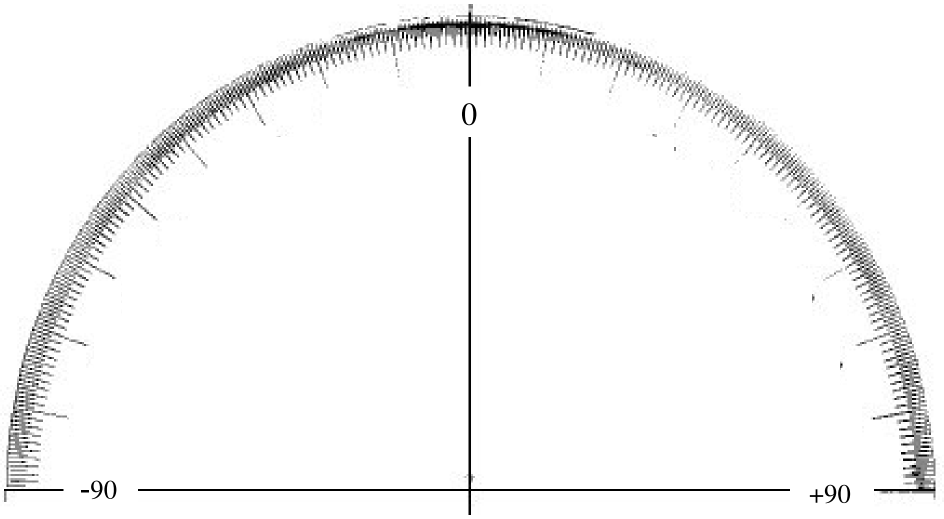


Fig. 9 Handheld protractor

The 0° position placed the dosimeter straight up in the standard operating orientation with the sensitive window facing the source or perpendicular to the incident radiation. The OSL was positioned the same way for all vertical angles but no figure is provided as both ±90° look the same.

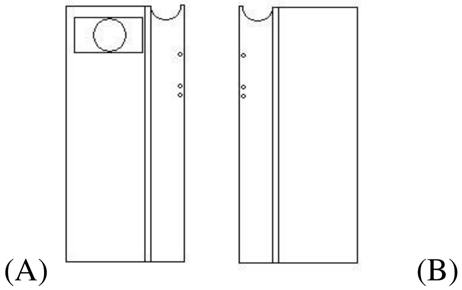


Fig. 10 OSL positioning A) -90° orientation for the OSL in the horizontal irradiation and B) +90° orientation for the OSL in the horizontal irradiation both are from the viewpoint of the source

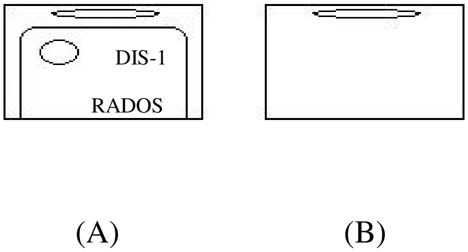


Fig. 11 DIS-1 positioning A) -90° orientation for the DIS-1 in the horizontal irradiation and B) +90° orientation for the DIS-1 in the horizontal irradiation both are from the viewpoint of the source

Table 10 shows the horizontal angular dependence for the OSL. The ratio column in each table represents the efficiency of the detector for the angle of incidence. It is the average measured dose divided by the known incident dose. Table 11 shows the horizontal angular dependence for the DIS-1. Tables 12 and 13 show the vertical angular dependence values for the OSL and DIS-1, respectively. All tables contain standard deviation and bias data as well. Only the deep dose is recorded in these tables.

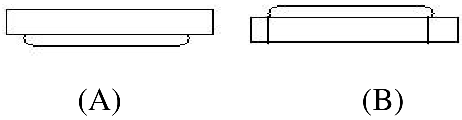


Fig. 12 DIS-1 positioning A) -90° orientation for the DIS-1 in the vertical irradiation and B) +90° orientation for the DIS-1 in the vertical irradiation both are from the viewpoint of the source

Table 10 Horizontal angular dependence for the OSL

Angle	Incident dose (mrem)	Avg. measured dose (mrem)	St. Dev	Ratio	Bias
-90	334.5	334.41	41.32	1.00	0.00
-75	334.5	303.00	49.24	0.91	-0.09
-60	334.5	395.83	37.07	1.18	0.18
-45	334.5	275.33	37.07	0.82	-0.18
-30	334.5	272.17	15.01	0.81	-0.19
-15	334.5	380.67	82.87	1.14	0.14
0	334.5	370.00	57.09	1.11	0.11
15	334.5	237.00	109.74	0.71	-0.29
30	334.5	400.67	81.22	1.20	0.20
45	334.5	205.83	176.14	0.62	-0.38
60	334.5	356.00	102.27	1.06	0.06
75	334.5	326.17	70.87	0.98	-0.02
90	334.5	447.00	209.63	1.34	0.34

Table 11 Horizontal angular dependence for the DIS-1

Angle	Incident dose (mrem)	Avg. measured dose (mrem)	St. Dev	Ratio	Bias
-90	334.5	5.823	17.44	0.017	-0.98
-75	334.5	9.58	18.17	0.029	-0.97
-60	334.5	381.98	7.71	1.14	0.14
-45	334.5	375.28	9.48	1.12	0.12
-30	334.5	369.18	8.55	1.10	0.10
-15	334.5	338.23	8.170	1.01	0.01
0	334.5	328.52	10.61	0.98	-0.02
15	334.5	340.18	12.87	1.01	0.02
30	334.5	361.83	10.53	1.08	0.08
45	334.5	357.78	15.62	1.07	0.07
60	334.5	356.93	20.59	1.06	0.07
75	334.5	343.5	28.75	1.03	0.03
90	334.5	329.53	29.53	0.99	-0.01

Table 12 Vertical angular dependence for the OSL

Angle	Incident dose (mrem)	Avg. measured dose (mrem)	St. Dev	Ratio	Bias
-90	334.5	360.58	26.26	1.08	0.08
-75	334.5	308.75	64.35	0.92	-0.08
-60	334.5	311.00	5.66	0.93	-0.07
-45	334.5	305.00	0.71	0.91	-0.09
-30	334.5	391.75	83.44	1.17	0.17
-15	334.5	316.50	95.46	0.95	-0.05
0	334.5	325.75	32.53	0.97	-0.03
15	334.5	518.00	31.82	1.55	0.55
30	334.5	491.00	74.25	1.47	0.47
45	334.5	194.25	83.16	0.58	-0.42
60	334.5	396.00	169.71	1.18	0.18
75	334.5	489.75	77.07	1.46	0.46
90	334.5	480.00	248.90	1.43	0.43

Table 13 Vertical angular dependence for the DIS-1

Angle	Incident dose (mrem)	Avg. measured dose (mrem)	St. Dev	Ratio	Bias
-90	334.5	307.88	35.40	0.92	-0.08
-75	334.5	341.15	43.92	1.02	0.02
-60	334.5	349.90	36.49	1.05	0.05
-45	334.5	372.03	28.40	1.11	0.11
-30	334.5	378.58	35.55	1.13	0.13
-15	334.5	376.18	29.29	1.12	0.12
0	334.5	374.65	27.65	1.12	0.12
15	334.5	392.60	25.17	1.17	0.17
30	334.5	394.55	9.93	1.18	0.18
45	334.5	389.75	11.78	1.17	0.17
60	334.5	418.03	13.43	1.25	0.25
75	334.5	388.08	7.58	1.16	0.16
90	334.5	83.65	9.48	0.25	-0.75

Table 14 compares the efficiencies of the OSL, and DIS-1 obtained from the experiment with efficiency data for the TLDs from Charlton (1995). The TLD was only examined at seven different angles of radiation incidence where the OSL and DIS-1 both underwent testing at thirteen different angles.

Table 14 Efficiency comparison for angular dependence test

Angle	Horizontal orientation			Vertical Orientation		
	TLD	OSL	DIS-1	TLD	OSL	DIS-1
-90	0.76	1.00	0.02	0.86	1.08	0.92
-75	N/A	0.91	0.03	N/A	0.92	1.02
-60	0.96	1.18	1.14	0.95	0.93	1.05
-45	N/A	0.82	1.12	N/A	0.91	1.11
-30	0.98	0.81	1.10	0.99	1.17	1.13
-15	N/A	1.14	1.01	N/A	0.95	1.12
0	1.00	1.11	0.98	1.00	0.97	1.12
15	N/A	0.71	1.02	N/A	1.55	1.17
30	0.96	1.20	1.08	0.99	1.47	1.18
45	N/A	0.62	1.07	N/A	0.58	1.17
60	0.97	1.06	1.07	0.96	1.18	1.25
75	N/A	0.98	1.03	N/A	1.46	1.16
90	0.86	1.34	0.99	0.88	1.43	0.25

6. CONCLUSIONS

This project was undertaken at the request of the HP/RP office at CP, which is seeking to replace the Panasonic UD-802 thermoluminescence dosimeter as the badge of record. Two dosimeters being used in industry around the world, the Landauer optically stimulated luminescent dosimeter and the RaDos direct-ion storage dosimeter, were compared in five irradiation categories with the thermoluminescence dosimeter. CP meets all requirements set forth by the American National Standards Institute in its standard on personal dosimeters. The design of the experiment was geared to satisfy the requests of the CP staff and their direction was followed over the ANSI standard in some instances trusting to their judgment and to satisfy their need. The five irradiation setups consisted of a dose linearity comparison, a dose-rate linearity comparison, a fade response test, a humidity response test and a comparison of the angular dependence for the dosimeters. Most of these exposures used the Cs-137 source in the panoramic irradiator. The irradiator had a functioning dose rate of 111.5 mrem min^{-1}. Although there is error involved with this calibration dose rate, none was reported. The error associated with the irradiator is a likely source of most error in this report.

6.1 Dose Linearity

The dosimeters all performed well as evidenced in Figure 7. There is truly a linear trend through all the data points. For the irradiation range from 55.75 mrem to 6690 mrem, the TLD performed the best with a maximum 7% difference. The shallow doses for both the OSL and DIS-1 were more accurate with ranges of 0.3% to 6.8% and 1.73% to 11.36%, respectively. The deep doses, though still within the tolerance of ±40% ranged from 0.93% to 13.92% and 4.05% to 14.58% for the OSL and DIS-1, respectively. There is some inaccuracy for the DIS-1 because for the dose of 278.75 mrem a timer malfunction resulted in a shorter exposure time so that data point was discarded. Other sources of error include the accuracy of the timer and because the source is on a pressurized lift, some lag might have occurred. Hot spots in the irradiator were limited due to the operating turntable.

6.2 Dose-Rate Linearity

For this test the dosimeters were subjected to dose rates ranging from 991 to 599,508 mrem h^{-1}. All the dosimeters performed relatively well within the ±40% tolerance except the OSL, which failed at the highest dose rate by over 50%. This may be due to the fact that the OSLs are not resettable, or they cannot be zeroed so saturation probably occurred. New OSLs were used for each category of experiment to avoid this error. In this case, the deep doses were more accurate. For the OSL, the shallow doses ranged from 6% to 27% and the deep dose ranged from 1% to 11%, except for the highest dose rate. For the DIS-1, the shallow doses ranged from 1.1% to 15% and the deep dose ranged from 0.5% to 15%.

The well source was used for these one-minute irradiations at each dose rate. The dose rate was varied using both distance and shielding. The well is 30-feet deep and the source is connected to a crane that hoists it up at thousandths of an inch increments.

It is unknown how often the accuracy of the hoist measurements is tested so any variation in this distance to the source would cause some error. Unlike the irradiator which is on an automatic timer, which controls the source, a handheld timer was used for this test. This opened the door to many sources of error. The timer, though calibrated the day before use, has some error associated with it. But the major source of error was the time associated with placing all the shields in place between the dosimeters and the source to stop the exposure. This time varied as the five lead shields are on heavy manual slides. These were not always pushed in instantaneously but never took an exceedingly long time. This is responsible for much of the over exposure.

6.3 Fade Response

The panoramic irradiator was used to expose these dosimeters as well. The same sources of error as in the dose linearity test are present. Though only two TLDs were used for this comparison their tendency to fade is documented at CP. The TLDs showed their characteristic fade within the first day with a 2.7% fade but this would undoubtedly have been different with more TLDs to average as is demonstrated by the two TLDs read at 2 weeks which showed less fade, 2.3%, than the first two. The OSLs registered differences from 0.1% to 1% with the lowest difference being at the 1 month read time. So either OSLs do not fade or the time period in which they fade is longer than a month. Either one is optimal for CP as they read the dosimeters on a monthly basis. The DIS-1s registered differences from 1.9% to 4.2% with the highest difference being within the first 24 hours. Again there does not seem to be an apparent fade over the month time period. The fade of the OSLs and DIS-1s all fell within 5% of the delivered dose with the TLDs fading 9.2% after 1-month.

6.4 Humidity Response

The panoramic irradiator was used for these exposures. The delivered dose was 557.5 mrem. Each time the dosimeters were placed in the irradiator for five minutes with a 111.5 mrem min^{-1} source. For the DIS-1, all of the deep-dose values were higher than the incident dose was supposed to be and this might have been due to residual dose left on the dosimeter though the zeroing process took place between each irradiation. All but one of the shallow dose readings was higher than expected. This led to the belief that the DIS-1s were exposed for slightly longer times, which might be because of timer malfunction in the irradiator or the source not falling back quickly to stop the exposure. At the 95% relative humidity the dosimeters over-estimated the dose by the largest margin, which could lead to a conservative dose caused by the humidity.

The OSLs performed with the smallest deviation from the recorded delivered dose. Again, many of the readings were above the expected delivered dose, which strengthens the idea of irradiator error. This is a problem that should be addressed by the calibration lab. The only relevant difference between the readings at the 80% or 95% relative humidity levels and the 40% and standard 57.7% relative humidity levels is that, in the presence of higher humidity, the dose readout was less than the administered dose. This might lead to a slight underestimate of dose in these areas.

The TLDs underestimated the dose in all the environments with more inaccurate dose readouts as the relative humidity increased. This can be due to a number of things. First the TLD is known to give inaccurate dose accounts at high humidity, which was evidenced here. The irradiator could still be causing an error in the administered dose. Also, in the case of the TLDs, readings were not taken immediately so the fade effect could have been partially responsible for the under-response.

6.5 Angular Dependence of Dosimeters

Many contributors to error exist in this test, including the previously mentioned irradiator problems and the manual positioning of the dosimeters in the irradiator against the polyethylene ring. At all the angles listed in ANSI N13.11-2001 the measured dose was within the 40% tolerances. Eight more angles were tested in addition to the ones listed in the standard.

The TLDs were not irradiated in this experiment due to the well known responses at different angles thanks to Charlton (1995) and Plato et al. (1988). The data for the efficiency comparison in Table 14 were taken from Charlton (1995). Unfortunately, only seven angles were examined in that paper whereas thirteen angles were examined for the DIS-1 and OSL. Only the deep doses were reported here since only these were reported by Charlton. In Tables 10-14, the data for the OSLs and DIS-1s in the horizontal and vertical rotations are listed. The standard deviation for the incident dose is listed as well as the ratio and bias between the recorded dose and incident dose. The ratio is the efficiency of the detector in measuring the radiation at the particular angle of incidence.

The OSL dosimeter responded well in the horizontal rotation angles with the lowest response of 34% at 90°, which has the dosimeter facing 180° from standard operating orientation or backwards. The OSL dosimeter operated differently in the vertical rotation angles. From -90° or facedown to standing straight up at 0°, it responded very well but, from 0° to 90°, all of the data points were above the ±40° tolerance. This could be due to the fact that most of these have the dosimeter reversed from normal use or shielding from the positioning device.

The DIS-1 dosimeter responded well in the horizontal rotation angles except at -75° and -90° where the dosimeter only recorded 2.9% and 1.7% of the incident dose, respectively. Besides those two angles the lowest response was 84%. It operated well in the vertical rotation angles also except for the 90° angle where it showed a response of 25%. This position has the dosimeter on its back with the sensitive ion chamber furthest from the source. It was surprising that more self-shielding was not evident due to the thickness of the dosimeter and metal and plastic coverings.

Additional error in this test was from the positioning of the dosimeters, as stated earlier, and possible shielding of the positioning device; in this case a low density clasp was used. Although the distance was kept uniform throughout the exposures, the rectangular prism shapes of the dosimeters caused the sensitive window to be at different distances from the source in different orientations. The distance was kept constant with the polyethylene ring, which was kept in place at all times and the same position marked for each dosimeter.

Based on the results the DIS-1 and OSL both performed as well if not better than the TLD in most of the tests. Beside the few anomalous instances where the candidate dosimeters performed worse than the TLD such as in the horizontal angular dependence at 90° and 75° and 90° for the OSL and DIS-1, respectively, the performances were inside the parameters set forth in the ANSI standards. The humidity and fade response tests both showed positive results for the OSL and DIS-1 in that the dose readings were maintained.

Though the DIS-1 and OSL performed equally well, some other factors should be taken into account before making the final decision. For the dosimeter to be of optimum effect, it must be easy to use and easy for the user to understand. In the case of the OSL, it looks exactly like the current badge so transition should be smooth. The users would not have to do anything different than what they do now so additional training would be unnecessary unless they were involved in the reading. In addition, the grid system where the badges are stored would not have to be modified for the OSLs as they would be to house the DIS-1s. In terms of usability the OSL lends itself less to tampering as the case is more difficult to open. The DIS-1 just slides in and out of the badge holder so might get lost easily.

Based on the test categories in this project, the OSL is the recommended dosimeter to replace the TLD as the badge or record at CP. The tests in this study should be rerun to assure accurate results and additional tests as discussed in the future work section should be performed. The prices of the OSL and DIS-1 systems are comparable so that should not be a factor. The DIS-1 and OSL dosimeters performed closely in these categories but a drawback of the DIS-1 is that there is not a reader that can process many DIS-1s at once. The OSLs have 200 and 500 dosimeter readers available and with the InLight system Landauer can handle all the reading and data collecting for CP off site. The specific needs of CP as well as the performance data make the OSL the best dosimeter to replace the TLD.

6.6 Future Work

The time constraints and inability to perform some tasks leaves a good deal of future work to be performed. First, the tests must be completed with an approved phantom to more accurately model the response on a tissue equivalent surface. Were this in common practice or readily available at CP it would have been used. Tests for neutron sensitivity and response should be performed as well due to the possibility of neutron exposure in certain areas of the plant. Beta tests are another viable option for completeness.

To reduce the error in all cases, more dosimeters of each type should examined. Because only a few dosimeters were loaned to CP, the minimum amount of dosimeters was run. The error would be reduced by providing a larger sample and by running the same tests at different times; irradiator error could also be reduced.

The ANSI N13.11-2001 standards list different categories that tests should fall under and to better fulfill the requirements different radiation sources should be used.

As mentioned above a neutron source and a beta source should be used as well as an alternate photon source. Finally, better communication avenues and an understanding of mutual needs should be addressed early on with the CP staff to assure prompt availability of data. Relevant training to use all the sources, irradiators, and readers should also be addressed.

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APPENDIX A

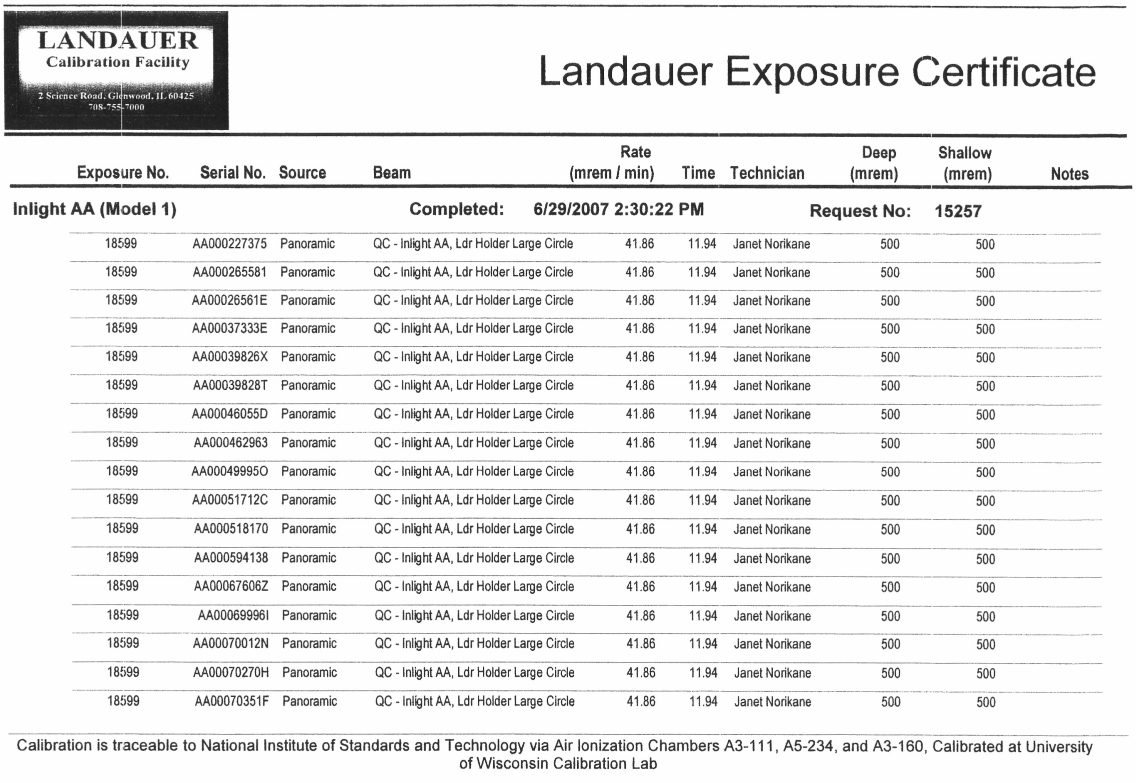
Dose Linearity Data for the Thermoluminescent Dosimeter			
Dose Delivered (mrem)	Dosimeter Output (mrem)	Avg. Output	St. Dev.
55.75	58	56	2.1
	58		
	53		
	55		
	56		
167.25	161	163	2.3
	160		
	165		
	164		
	165		
278.75	271	277.8	4.7
	277		
	278		
	284		
	279		
557.5	554	543.6	13
	552		
	540		
	523		
	549		
1282.5	1212	1193.4	31
	1174		
	1238		
	1160		
	1183		
3345	3346	3395	76
	3324		
	3515		
	3371		
	3419		
6690	7239	7137	469
	7381		
	6454		
	6928		
	7683		

Dose Linearity Data for the Optically Stimulated Luminescence Dosimeter						
Dose Delivered (mrem)	Dosimeter Output (mrem)	Avg. Deep Dose Output	St. Dev.	Dosimeter Output (mrem)	Avg. Shallow Dose Output	St. Dev.
55.75	57	58	4.5734231	62	59.83	2.63
	64			60		
	59			56		
	53			61		
	58			55		
167.25	185	177	14.795877	179	166.75	18.626
	193			183		
	168			163		
	161			142		
	168			157		
278.75	295	286	15.52149	269	286.25	43.37
	304			350		
	270			253		
	278			273		
	286			278		
557.5	595	563	54.614982	585	569.749	63.478
	623			652		
	516			534		
	517			508		
	562			572		
1282.5	1168	1126	40.656742	1236	1226.999	178.406
	1125			1257		
	1139			1424		
	1071			991		
	1115			1193		
3345	3556	3314	259.36766	3267	3454.75	799.545
	3521			4630		
	3085			2878		
	3095			3044		
	3419			3533		
6690	5956	6355	394.45532	6895	6854.734	776.911
	6659			7321		
	6078			5746		
	6727			7456		
	66294			6690		

Dose Linearity Data for the Direct Ion Storage Dosimeter						
Dose Delivered (mrem)	Dosimeter Output (mrem)	Avg. Deep Dose Output	St. Dev.	Dosimeter Output (mrem)	Avg. Shallow Dose Output	St. Dev.
55.75	65	65	0.2	57	57	0.6
	65			57		
	65			58		
	64			56		
	67			55		
167.25	185	185	1.5	169	170	2.1
	193			172		
	168			170		
	161			173		
	168			168		
278.75	N/A	N/A	N/A	N/A	N/A	N/A
	N/A			N/A		
	N/A			N/A		
	N/A			N/A		
	N/A			N/A		
557.5	595	623	3.6	575	574	5.5
	623			567		
	516			579		
	517			577		
	562			572		
1282.5	1168	1233	3.7	1139	1152	11
	1125			1159		
	1139			1156		
	1071			1140		
	1115			1169		
3345	3556	3625	8.8	3440	3443	17
	3521			3462		
	3085			3428		
	3095			3454		
	3419			3431		
6690	5956	7387	33	7051	7045	46
	6659			7087		
	6078			6995		
	6727			7069		
	66294			7026		

APPENDIX B

Irradiator Exposure Rate Chart (mrem/min)					
Month	2004	2005	2006	2007	2008
JAN	119.2	116.9	114.7	112.5	110.4
FEB	119	116.7	114.5	112.4	110.2
MAR	118.8	116.6	114.4	112.2	110
APR	118.6	116.4	114.2	112	109.9
MAY	118.5	116.2	114	111.8	109.7
JUNE	118.3	116	113.8	111.7	109.5
JULY	118.1	115.8	113.6	111.5	109.4
AUG	117.9	115.6	113.4	111.3	109.2
SEPT	117.7	115.5	113.3	111.1	109
OCT	117.5	115.3	113.1	110.9	108.8
NOV	117.3	115.1	112.9	110.8	108.7
DEC	117.1	114.9	112.7	110.6	108.5



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Landauer Exposure Certificate

Inlight AA (Model 1) **Completed:** **6/29/2007 2:30:22 PM** **Request No:** **15257**

Exposure No.	Serial No.	Source	Beam	Rate (mrem / min)	Time	Technician	Deep (mrem)	Shallow (mrem)	Notes
18599	AA000227375	Panoramic	QC - Inlight AA, Ldr Holder Large Circle	41.86	11.94	Janet Norikane	500	500	
18599	AA000265581	Panoramic	QC - Inlight AA, Ldr Holder Large Circle	41.86	11.94	Janet Norikane	500	500	
18599	AA00026561E	Panoramic	QC - Inlight AA, Ldr Holder Large Circle	41.86	11.94	Janet Norikane	500	500	
18599	AA00037333E	Panoramic	QC - Inlight AA, Ldr Holder Large Circle	41.86	11.94	Janet Norikane	500	500	
18599	AA00039826X	Panoramic	QC - Inlight AA, Ldr Holder Large Circle	41.86	11.94	Janet Norikane	500	500	
18599	AA00039828T	Panoramic	QC - Inlight AA, Ldr Holder Large Circle	41.86	11.94	Janet Norikane	500	500	
18599	AA00046055D	Panoramic	QC - Inlight AA, Ldr Holder Large Circle	41.86	11.94	Janet Norikane	500	500	
18599	AA000462963	Panoramic	QC - Inlight AA, Ldr Holder Large Circle	41.86	11.94	Janet Norikane	500	500	
18599	AA00049995O	Panoramic	QC - Inlight AA, Ldr Holder Large Circle	41.86	11.94	Janet Norikane	500	500	
18599	AA00051712C	Panoramic	QC - Inlight AA, Ldr Holder Large Circle	41.86	11.94	Janet Norikane	500	500	
18599	AA000518170	Panoramic	QC - Inlight AA, Ldr Holder Large Circle	41.86	11.94	Janet Norikane	500	500	
18599	AA000594138	Panoramic	QC - Inlight AA, Ldr Holder Large Circle	41.86	11.94	Janet Norikane	500	500	
18599	AA00067606Z	Panoramic	QC - Inlight AA, Ldr Holder Large Circle	41.86	11.94	Janet Norikane	500	500	
18599	AA00069996I	Panoramic	QC - Inlight AA, Ldr Holder Large Circle	41.86	11.94	Janet Norikane	500	500	
18599	AA00070012N	Panoramic	QC - Inlight AA, Ldr Holder Large Circle	41.86	11.94	Janet Norikane	500	500	
18599	AA00070270H	Panoramic	QC - Inlight AA, Ldr Holder Large Circle	41.86	11.94	Janet Norikane	500	500	
18599	AA00070351F	Panoramic	QC - Inlight AA, Ldr Holder Large Circle	41.86	11.94	Janet Norikane	500	500	

Calibration is traceable to National Institute of Standards and Technology via Air Ionization Chambers A3-111, A5-234, and A3-160, Calibrated at University of Wisconsin Calibration Lab

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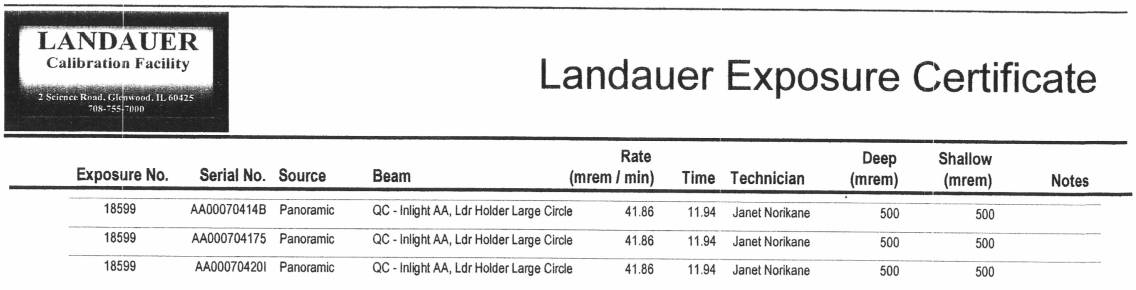

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Exposure No.	Serial No.	Source	Beam	Rate (mrem / min)	Time	Technician	Deep (mrem)	Shallow (mrem)	Notes
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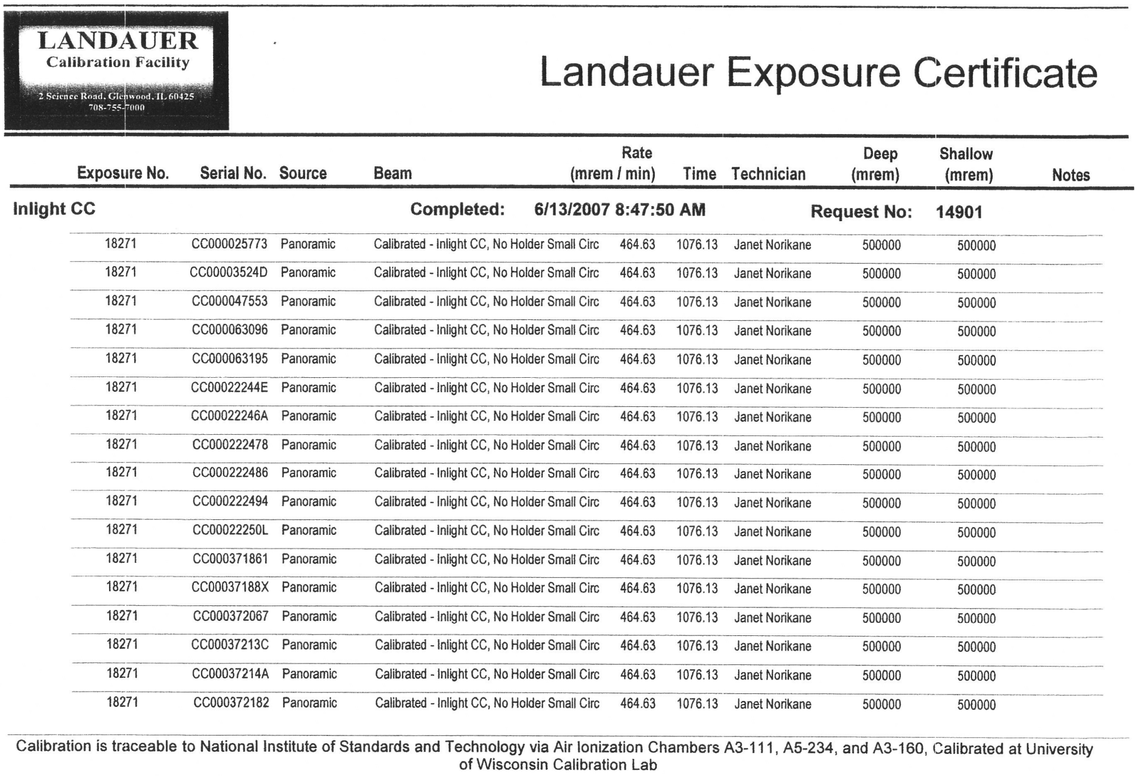
18599	AA000704175	Panoramic	QC - Inlight AA, Ldr Holder Large Circle	41.86	11.94	Janet Norikane	500	500	
18599	AA00070420I	Panoramic	QC - Inlight AA, Ldr Holder Large Circle	41.86	11.94	Janet Norikane	500	500	



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Inlight CC **Completed: 6/13/2007 8:47:50 AM** **Request No: 14901**

Exposure No.	Serial No.	Source	Beam	Rate (mrem / min)	Time	Technician	Deep (mrem)	Shallow (mrem)	Notes
18271	CC000025773	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.63	1076.13	Janet Norikane	500000	500000	
18271	CC00003524D	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.63	1076.13	Janet Norikane	500000	500000	
18271	CC000047553	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.63	1076.13	Janet Norikane	500000	500000	
18271	CC000063096	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.63	1076.13	Janet Norikane	500000	500000	
18271	CC000063195	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.63	1076.13	Janet Norikane	500000	500000	
18271	CC00022244E	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.63	1076.13	Janet Norikane	500000	500000	
18271	CC00022246A	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.63	1076.13	Janet Norikane	500000	500000	
18271	CC000222478	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.63	1076.13	Janet Norikane	500000	500000	
18271	CC000222486	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.63	1076.13	Janet Norikane	500000	500000	
18271	CC000222494	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.63	1076.13	Janet Norikane	500000	500000	
18271	CC00022250L	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.63	1076.13	Janet Norikane	500000	500000	
18271	CC000371861	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.63	1076.13	Janet Norikane	500000	500000	
18271	CC00037188X	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.63	1076.13	Janet Norikane	500000	500000	
18271	CC000372067	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.63	1076.13	Janet Norikane	500000	500000	
18271	CC00037213C	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.63	1076.13	Janet Norikane	500000	500000	
18271	CC00037214A	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.63	1076.13	Janet Norikane	500000	500000	
18271	CC000372182	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.63	1076.13	Janet Norikane	500000	500000	

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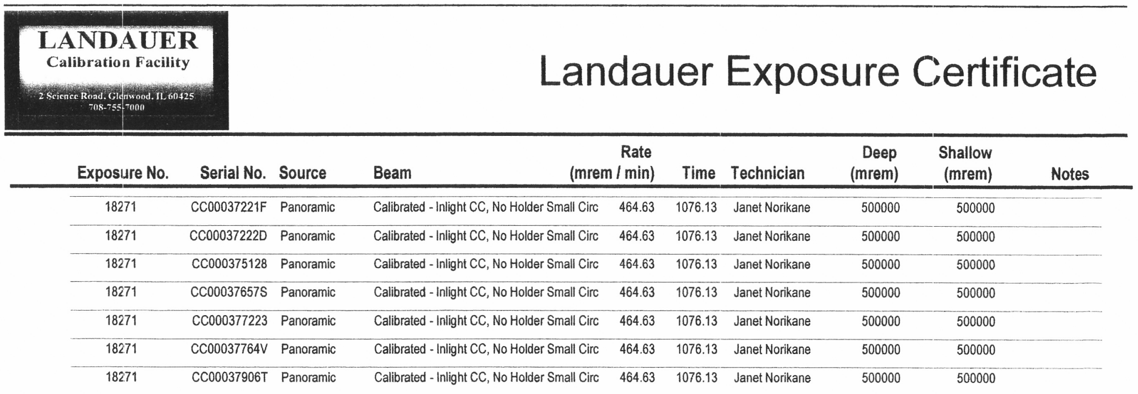

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Exposure No.	Serial No.	Source	Beam	Rate (mrem / min)	Time	Technician	Deep (mrem)	Shallow (mrem)	Notes
18271	CC00037221F	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.63	1076.13	Janet Norikane	500000	500000	
18271	CC00037222D	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.63	1076.13	Janet Norikane	500000	500000	
18271	CC000375128	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.63	1076.13	Janet Norikane	500000	500000	
18271	CC00037657S	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.63	1076.13	Janet Norikane	500000	500000	
18271	CC000377223	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.63	1076.13	Janet Norikane	500000	500000	
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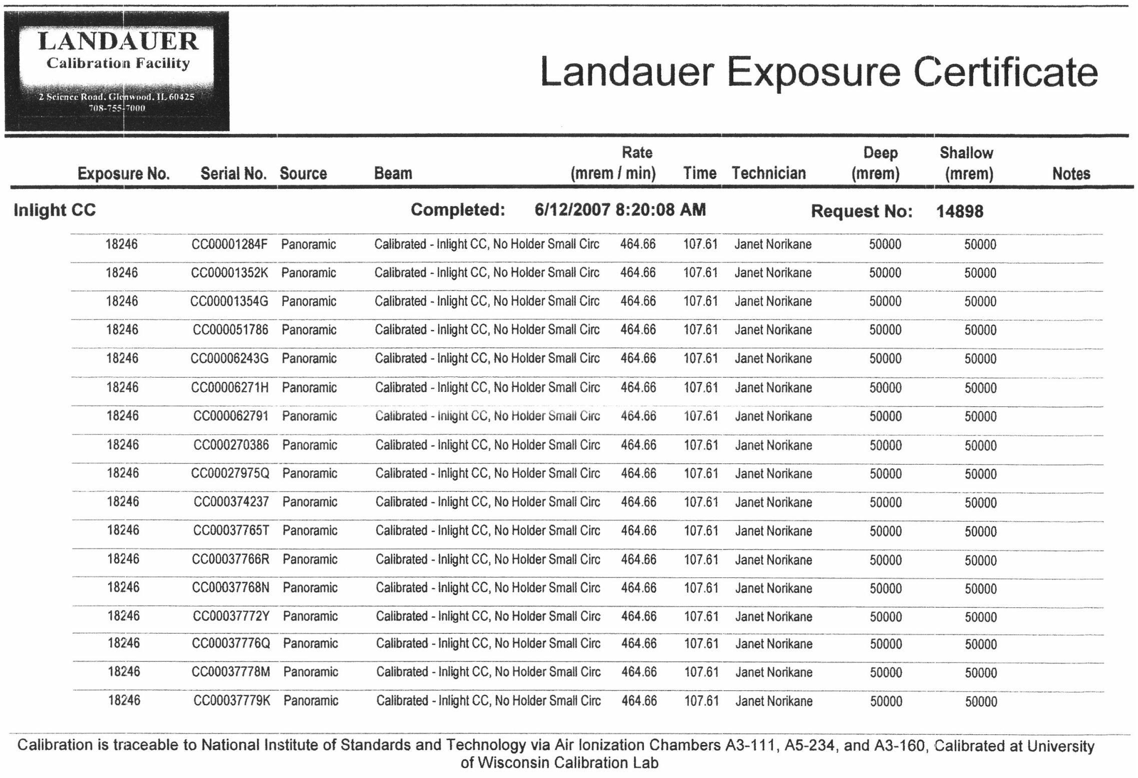

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Landauer Exposure Certificate

Inlight CC **Completed:** **6/12/2007 8:20:08 AM** **Request No:** **14898**

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18246	CC00001284F	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.66	107.61	Janet Norikane	50000	50000	
18246	CC00001352K	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.66	107.61	Janet Norikane	50000	50000	
18246	CC00001354G	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.66	107.61	Janet Norikane	50000	50000	
18246	CC000051786	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.66	107.61	Janet Norikane	50000	50000	
18246	CC00006243G	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.66	107.61	Janet Norikane	50000	50000	
18246	CC00006271H	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.66	107.61	Janet Norikane	50000	50000	
18246	CC000062791	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.66	107.61	Janet Norikane	50000	50000	
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18246	CC00027975Q	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.66	107.61	Janet Norikane	50000	50000	
18246	CC000374237	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.66	107.61	Janet Norikane	50000	50000	
18246	CC00037765T	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.66	107.61	Janet Norikane	50000	50000	
18246	CC00037766R	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.66	107.61	Janet Norikane	50000	50000	
18246	CC00037768N	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.66	107.61	Janet Norikane	50000	50000	
18246	CC00037772Y	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.66	107.61	Janet Norikane	50000	50000	
18246	CC00037776Q	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.66	107.61	Janet Norikane	50000	50000	
18246	CC00037778M	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.66	107.61	Janet Norikane	50000	50000	
18246	CC00037779K	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.66	107.61	Janet Norikane	50000	50000	

Calibration is traceable to National Institute of Standards and Technology via Air Ionization Chambers A3-111, A5-234, and A3-160, Calibrated at University of Wisconsin Calibration Lab

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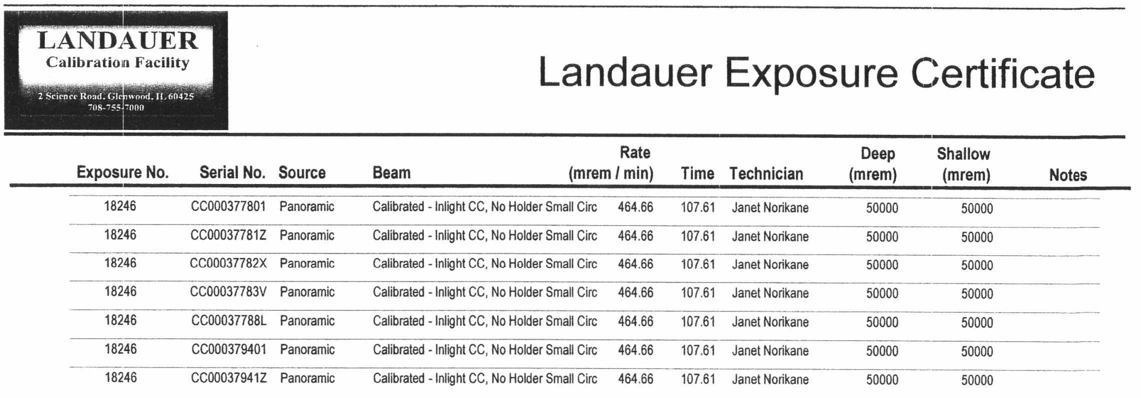
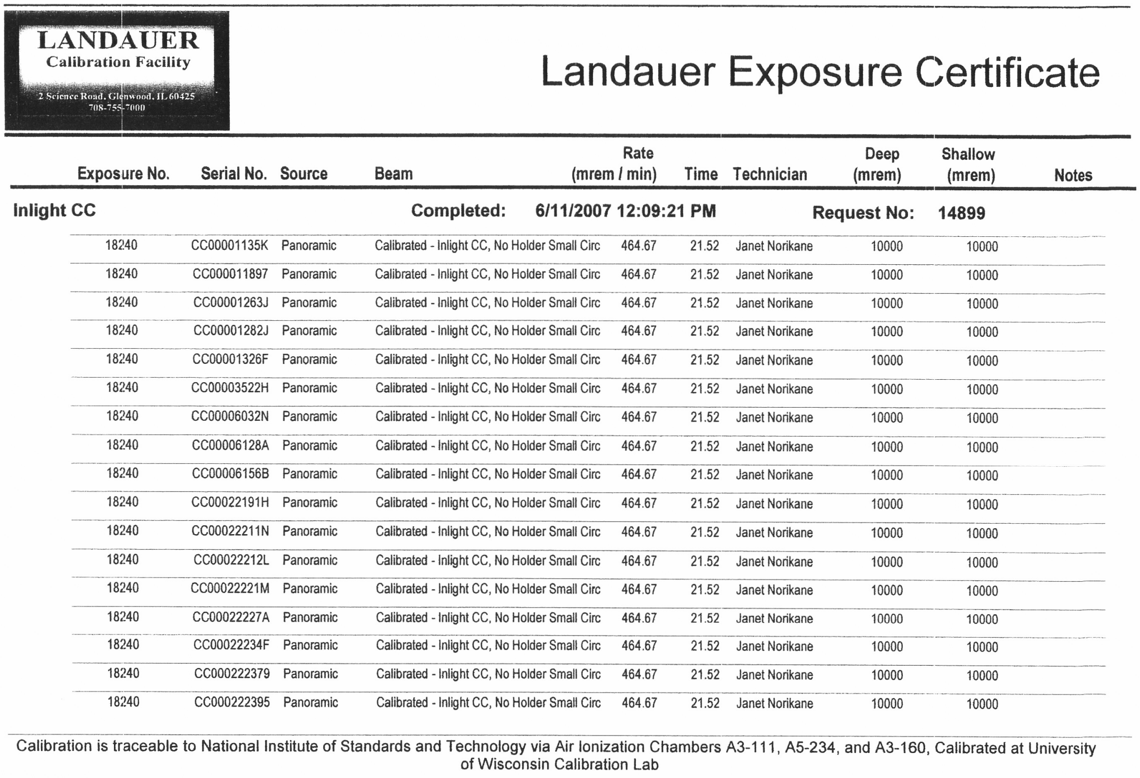


LANDAUER
Calibration Facility
2 Science Road, Glenwood, IL 60425
708-755-7000

Landauer Exposure Certificate

Exposure No.	Serial No.	Source	Beam	Rate (mrem / min)	Time	Technician	Deep (mrem)	Shallow (mrem)	Notes
18246	CC000377801	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.66	107.61	Janet Norikane	50000	50000	
18246	CC00037781Z	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.66	107.61	Janet Norikane	50000	50000	
18246	CC00037782X	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.66	107.61	Janet Norikane	50000	50000	
18246	CC00037783V	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.66	107.61	Janet Norikane	50000	50000	
18246	CC00037788L	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.66	107.61	Janet Norikane	50000	50000	
18246	CC000379401	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.66	107.61	Janet Norikane	50000	50000	
18246	CC00037941Z	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.66	107.61	Janet Norikane	50000	50000	



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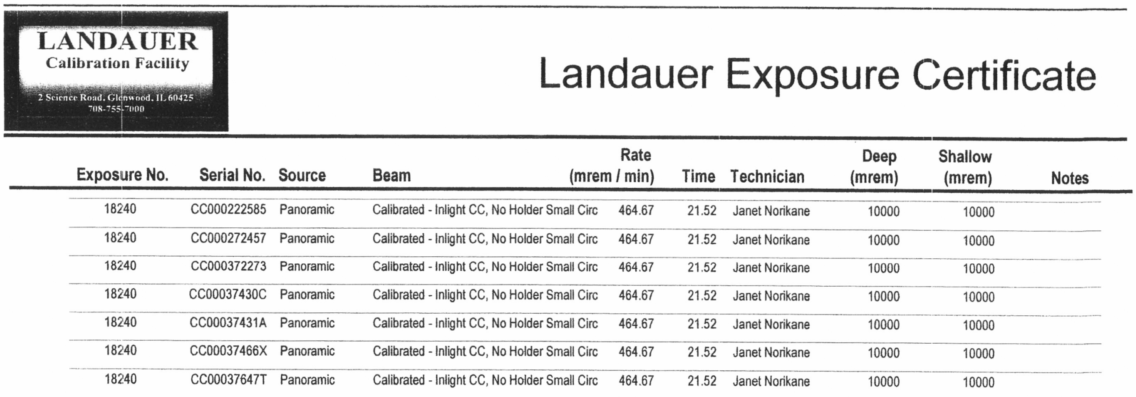
Landauer Exposure Certificate

Exposure No.	Serial No.	Source	Beam	Rate (mrem / min)	Time	Technician	Deep (mrem)	Shallow (mrem)	Notes
Inlight CC			**Completed:**	**6/11/2007 12:09:21 PM**		**Request No:**	**14899**		
18240	CC00001135K	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.67	21.52	Janet Norikane	10000	10000	
18240	CC000011897	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.67	21.52	Janet Norikane	10000	10000	
18240	CC00001263J	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.67	21.52	Janet Norikane	10000	10000	
18240	CC00001282J	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.67	21.52	Janet Norikane	10000	10000	
18240	CC00001326F	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.67	21.52	Janet Norikane	10000	10000	
18240	CC00003522H	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.67	21.52	Janet Norikane	10000	10000	
18240	CC00006032N	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.67	21.52	Janet Norikane	10000	10000	
18240	CC00006128A	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.67	21.52	Janet Norikane	10000	10000	
18240	CC00006156B	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.67	21.52	Janet Norikane	10000	10000	
18240	CC00022191H	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.67	21.52	Janet Norikane	10000	10000	
18240	CC00022211N	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.67	21.52	Janet Norikane	10000	10000	
18240	CC00022212L	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.67	21.52	Janet Norikane	10000	10000	
18240	CC00022221M	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.67	21.52	Janet Norikane	10000	10000	
18240	CC00022227A	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.67	21.52	Janet Norikane	10000	10000	
18240	CC00022234F	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.67	21.52	Janet Norikane	10000	10000	
18240	CC000222379	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.67	21.52	Janet Norikane	10000	10000	
18240	CC000222395	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.67	21.52	Janet Norikane	10000	10000	

Calibration is traceable to National Institute of Standards and Technology via Air Ionization Chambers A3-111, A5-234, and A3-160, Calibrated at University of Wisconsin Calibration Lab



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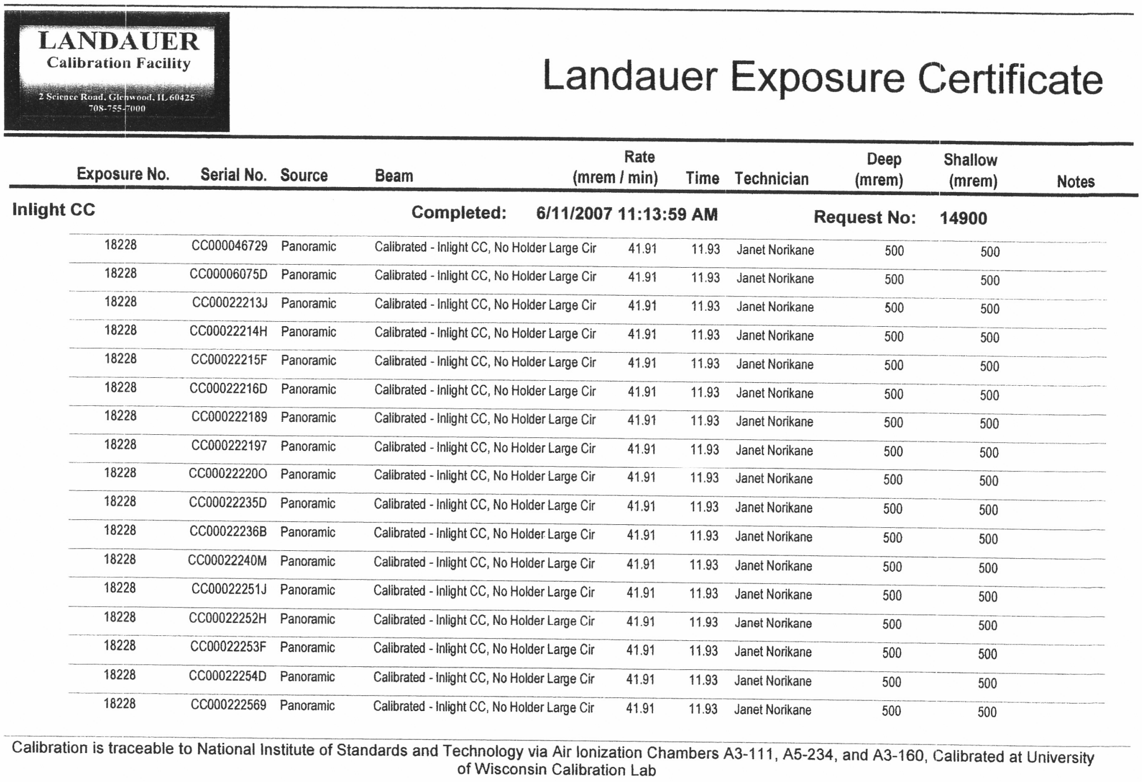
Landauer Exposure Certificate

Exposure No.	Serial No.	Source	Beam	Rate (mrem / min)	Time	Technician	Deep (mrem)	Shallow (mrem)	Notes
18240	CC000222585	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.67	21.52	Janet Norikane	10000	10000	
18240	CC000272457	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.67	21.52	Janet Norikane	10000	10000	
18240	CC000372273	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.67	21.52	Janet Norikane	10000	10000	
18240	CC00037430C	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.67	21.52	Janet Norikane	10000	10000	
18240	CC00037431A	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.67	21.52	Janet Norikane	10000	10000	
18240	CC00037466X	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.67	21.52	Janet Norikane	10000	10000	
18240	CC00037647T	Panoramic	Calibrated - Inlight CC, No Holder Small Circ	464.67	21.52	Janet Norikane	10000	10000	



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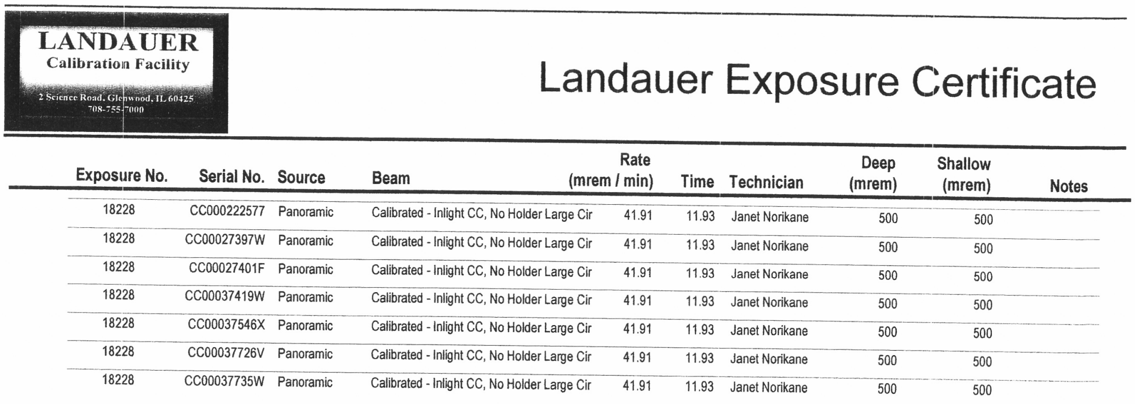
Landauer Exposure Certificate

Inlight CC **Completed: 6/11/2007 11:13:59 AM** **Request No: 14900**

Exposure No.	Serial No.	Source	Beam	Rate (mrem / min)	Time	Technician	Deep (mrem)	Shallow (mrem)	Notes
18228	CC000046729	Panoramic	Calibrated - Inlight CC, No Holder Large Cir	41.91	11.93	Janet Norikane	500	500	
18228	CC00006075D	Panoramic	Calibrated - Inlight CC, No Holder Large Cir	41.91	11.93	Janet Norikane	500	500	
18228	CC00022213J	Panoramic	Calibrated - Inlight CC, No Holder Large Cir	41.91	11.93	Janet Norikane	500	500	
18228	CC00022214H	Panoramic	Calibrated - Inlight CC, No Holder Large Cir	41.91	11.93	Janet Norikane	500	500	
18228	CC00022215F	Panoramic	Calibrated - Inlight CC, No Holder Large Cir	41.91	11.93	Janet Norikane	500	500	
18228	CC00022216D	Panoramic	Calibrated - Inlight CC, No Holder Large Cir	41.91	11.93	Janet Norikane	500	500	
18228	CC000222189	Panoramic	Calibrated - Inlight CC, No Holder Large Cir	41.91	11.93	Janet Norikane	500	500	
18228	CC000222197	Panoramic	Calibrated - Inlight CC, No Holder Large Cir	41.91	11.93	Janet Norikane	500	500	
18228	CC00022220O	Panoramic	Calibrated - Inlight CC, No Holder Large Cir	41.91	11.93	Janet Norikane	500	500	
18228	CC00022235D	Panoramic	Calibrated - Inlight CC, No Holder Large Cir	41.91	11.93	Janet Norikane	500	500	
18228	CC00022236B	Panoramic	Calibrated - Inlight CC, No Holder Large Cir	41.91	11.93	Janet Norikane	500	500	
18228	CC00022240M	Panoramic	Calibrated - Inlight CC, No Holder Large Cir	41.91	11.93	Janet Norikane	500	500	
18228	CC00022251J	Panoramic	Calibrated - Inlight CC, No Holder Large Cir	41.91	11.93	Janet Norikane	500	500	
18228	CC00022252H	Panoramic	Calibrated - Inlight CC, No Holder Large Cir	41.91	11.93	Janet Norikane	500	500	
18228	CC00022253F	Panoramic	Calibrated - Inlight CC, No Holder Large Cir	41.91	11.93	Janet Norikane	500	500	
18228	CC00022254D	Panoramic	Calibrated - Inlight CC, No Holder Large Cir	41.91	11.93	Janet Norikane	500	500	
18228	CC000222569	Panoramic	Calibrated - Inlight CC, No Holder Large Cir	41.91	11.93	Janet Norikane	500	500	

Calibration is traceable to National Institute of Standards and Technology via Air Ionization Chambers A3-111, A5-234, and A3-160, Calibrated at University of Wisconsin Calibration Lab



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708-755-7000

Landauer Exposure Certificate

Exposure No.	Serial No.	Source	Beam	Rate (mrem / min)	Time	Technician	Deep (mrem)	Shallow (mrem)	Notes
18228	CC000222577	Panoramic	Calibrated - Inlight CC, No Holder Large Cir	41.91	11.93	Janet Norikane	500	500	
18228	CC00027397W	Panoramic	Calibrated - Inlight CC, No Holder Large Cir	41.91	11.93	Janet Norikane	500	500	
18228	CC00027401F	Panoramic	Calibrated - Inlight CC, No Holder Large Cir	41.91	11.93	Janet Norikane	500	500	
18228	CC00037419W	Panoramic	Calibrated - Inlight CC, No Holder Large Cir	41.91	11.93	Janet Norikane	500	500	
18228	CC00037546X	Panoramic	Calibrated - Inlight CC, No Holder Large Cir	41.91	11.93	Janet Norikane	500	500	
18228	CC00037726V	Panoramic	Calibrated - Inlight CC, No Holder Large Cir	41.91	11.93	Janet Norikane	500	500	
18228	CC00037735W	Panoramic	Calibrated - Inlight CC, No Holder Large Cir	41.91	11.93	Janet Norikane	500	500	

APPENDIX C

Raw Vertical Angular Dependence Data			
Read ID	First Name	Deep Dose	Shallow Dose
155	Vertical	335	344
156	Vertical	370	393
157	Vertical	600	647
158	Vertical	656	774
159	Vertical	994	1013
160	Vertical	946	968
161	Vertical	1274	1210
162	Vertical	1225	1432
163	Vertical	1618	1930
164	Vertical	1549	1611
165	Vertical	1915	2023
166	Vertical	1981	2055
167	Vertical	2352	2283
168	Vertical	2332	2310
169	Vertical	2671	3487
170	Vertical	2606	2585
171	Vertical	3082	3225
172	Vertical	3122	3360
173	Vertical	3093	3301
174	Vertical	3050	3265
175	Vertical	3318	3151
176	Vertical	3357	3432
177	Vertical	3649	4622
178	Vertical	3370	3201
179	Vertical	3911	3815
180	Vertical	4081	4250
181	Vertical	4190	4579
182	Vertical	4372	4836
201	Vertical	4632	5091
202	Vertical	4433	4211
203	Vertical	4752	5122
204	Vertical	4713	5370
210	Vertical	5201	5002
211	Vertical	4940	5582
212	Vertical	4604	4540
213	Vertical	4805	4817

228	Vertical	5469	5195
229	Vertical	5470	5454
230	Vertical	5257	5149
231	Vertical	5164	6057
232	Vertical	5291	5496
233	Vertical	5084	5739
234	Vertical	5022	5043
235	Vertical	5183	5177
263	Vertical	4960	5219
264	Vertical	5185	6455
279	Vertical	5264	6510
280	Vertical	5302	6146
281	Vertical	5186	4957
282	Vertical	5128	6590
283	Vertical	4745	5807
284	Vertical	5293	5027
295	Vertical	5633	5735
296	Vertical	5627	5746
297	Vertical	5573	6521
298	Vertical	5578	6370
299	Vertical	5660	5959
300	Vertical	5373	5225
311	Vertical	5761	5473
312	Vertical	5492	6127
313	Vertical	5486	5211
314	Vertical	5861	6769
315	Vertical	6030	7169
316	Vertical	5685	6134
328	Vertical	5841	5924
329	Vertical	6040	7439
342	Vertical	6146	7225
343	Vertical	6065	6941
344	Vertical	6707	7179
345	Vertical	6170	7041
346	Vertical	6131	6474
347	Vertical	6170	6422
348	Vertical	6085	7152
349	Vertical	6305	7080
361	Vertical	6476	7559

362	Vertical	6421	8136
363	Vertical	7075	6981
364	Vertical	6583	6253
365	Vertical	6634	6749
366	Vertical	6479	7165
378	Vertical	6530	7264
379	Vertical	6461	7098
380	Vertical	6492	6167
381	Vertical	6670	8244
382	Vertical	6792	8132
383	Vertical	7151	6793
384	Vertical	7227	8013
385	Vertical	6798	7748
386	Vertical	7303	7237
387	Vertical	7071	8659
388	Vertical	7247	7583
389	Vertical	7154	6796
390	Vertical	6893	6590
391	Vertical	6607	7860
392	Vertical	6954	7364
393	Vertical	6732	6866
427	Vertical	0	0
428	Vertical	-264	-284
429	Vertical	3429	3023
430	Vertical	6565	5593
431	Vertical	10565	8846
432	Vertical	14267	12207
433	Vertical	18214	15614
434	Vertical	22021	19089
435	Vertical	25845	22499
436	Vertical	29830	26383
437	Vertical	34005	30454
438	Vertical	37957	34446
439	Vertical	41896	38465
440	Vertical	46181	42750
441	Vertical	50095	46599
442	Vertical	50849	47375
443	Vertical	50765	47283
444	Vertical	0	0

445	Vertical	-340	-348
446	Vertical	3797	3374
447	Vertical	7179	6601
448	Vertical	10615	9558
449	Vertical	14492	12614
450	Vertical	18466	16167
451	Vertical	22743	19751
452	Vertical	26859	23448
453	Vertical	30621	26803
454	Vertical	34474	30410
455	Vertical	38507	34215
456	Vertical	42400	37954
457	Vertical	46547	41958
458	Vertical	50340	45925
459	Vertical	51304	46777
460	Vertical	51249	46729

Raw Horizontal Angular Dependence Data			
Read ID	First Name	Deep Dose	Shallow Dose
107	Horizontal	299	366
108	Horizontal	383	365
110	Horizontal	598	607
112	Horizontal	752	740
114	Horizontal	877	1006
115	Horizontal	1102	1420
116	Horizontal	1483	1547
118	Horizontal	1200	1309
119	Horizontal	1775	1969
121	Horizontal	1492	1417
122	Horizontal	2159	2312
124	Horizontal	1711	1999
125	Horizontal	2123	2076
127	Horizontal	2552	2513
128	Horizontal	2865	2721
130	Horizontal	2219	2519
132	Horizontal	3144	3709
133	Horizontal	2630	2535
134	Horizontal	2788	3047
136	Horizontal	3557	3714
137	Horizontal	3714	3528
138	Horizontal	3118	3227
141	Horizontal	3423	3385
142	Horizontal	4156	4216
144	Horizontal	3589	3997
145	Horizontal	4313	4266
147	Horizontal	4051	4106
148	Horizontal	4845	4895
195	Horizontal	4166	4062
196	Horizontal	4160	3951
197	Horizontal	5098	5181
198	Horizontal	4899	5645
199	Horizontal	4177	4210
200	Horizontal	4006	3805
205	Horizontal	4441	4837
206	Horizontal	4402	4181

207	Horizontal	5343	5261
208	Horizontal	5429	5281
209	Horizontal	4410	4797
214	Horizontal	4619	4832
215	Horizontal	5718	5681
216	Horizontal	4757	4519
217	Horizontal	4736	4498
218	Horizontal	4562	4424
219	Horizontal	4529	4302
220	Horizontal	4653	4420
221	Horizontal	4765	5056
222	Horizontal	4596	4417
223	Horizontal	4795	4766
224	Horizontal	5948	6142
225	Horizontal	5495	6019
226	Horizontal	5540	5262
227	Horizontal	5452	5707
265	Horizontal	4637	4965
266	Horizontal	4487	4765
267	Horizontal	5520	5896
268	Horizontal	4957	5247
269	Horizontal	4582	5469
270	Horizontal	4591	4434
271	Horizontal	4569	4953
272	Horizontal	5647	5939
273	Horizontal	5538	7163
274	Horizontal	5923	5626
275	Horizontal	5738	5862
276	Horizontal	4604	4485
277	Horizontal	4599	5997
278	Horizontal	4587	5271
285	Horizontal	4990	4909
286	Horizontal	4739	4973
287	Horizontal	4959	5627
288	Horizontal	4879	5039
289	Horizontal	6000	6686
290	Horizontal	6125	7484
291	Horizontal	6046	5844
292	Horizontal	4990	5598

293	Horizontal	4720	4760
294	Horizontal	4787	4826
301	Horizontal	5365	5165
302	Horizontal	5063	5431
303	Horizontal	4951	5503
304	Horizontal	5012	5193
305	Horizontal	6080	7414
306	Horizontal	6025	6306
307	Horizontal	6209	7311
308	Horizontal	5125	5694
309	Horizontal	4977	5239
310	Horizontal	4920	4673
317	Horizontal	5341	6498
318	Horizontal	5528	5830
319	Horizontal	5035	4783
320	Horizontal	5231	5067
321	Horizontal	6481	7364
322	Horizontal	6343	7205
323	Horizontal	6240	7361
324	Horizontal	5264	5618
325	Horizontal	5284	5232
326	Horizontal	5328	6201
327	Horizontal	5074	6202
330	Horizontal	6788	6448
331	Horizontal	5397	6670
332	Horizontal	5404	6495
333	Horizontal	5513	5550
334	Horizontal	5703	6958
335	Horizontal	6995	8320
336	Horizontal	6862	7185
337	Horizontal	5387	6070
338	Horizontal	5444	6575
339	Horizontal	5438	5966
340	Horizontal	5256	6201
341	Horizontal	6329	7009
350	Horizontal	5772	5820
351	Horizontal	5619	5338
352	Horizontal	5589	5309
353	Horizontal	6747	8135

354	Horizontal	7154	7973
355	Horizontal	6873	6528
356	Horizontal	6975	7152
357	Horizontal	5838	6157
358	Horizontal	5938	5641
359	Horizontal	5746	5866
360	Horizontal	5439	5904
367	Horizontal	7202	7565
368	Horizontal	7366	8430
369	Horizontal	7070	8123
370	Horizontal	6820	7020
371	Horizontal	5948	5650
372	Horizontal	5910	6358
373	Horizontal	5796	5704
374	Horizontal	5582	5656
375	Horizontal	6231	5919
376	Horizontal	6169	5907
377	Horizontal	5553	5850
394	Horizontal	3414	4062
395	Horizontal	3420	3954
396	Horizontal	3610	3817
397	Horizontal	3634	4022
398	Horizontal	3710	4081
399	Horizontal	3733	4108
400	Horizontal	3594	3790
401	Horizontal	3620	3830
402	Horizontal	7571	8006
403	Horizontal	7591	8044
404	Horizontal	7365	7540
405	Horizontal	7420	7603
406	Horizontal	11262	11700
407	Horizontal	11268	11724
408	Horizontal	11269	11370
409	Horizontal	11319	11426
410	Horizontal	15015	15500
411	Horizontal	14973	15016
412	Horizontal	18397	18796
413	Horizontal	18465	18375
414	Horizontal	21766	22032

415	Horizontal	21842	21534
416	Horizontal	25263	25408
417	Horizontal	25346	24764
418	Horizontal	29069	28345
419	Horizontal	28944	28896
420	Horizontal	32747	31696
421	Horizontal	32628	32494
422	Horizontal	36310	35841
423	Horizontal	36543	35148
424	Horizontal	40275	38298
425	Horizontal	39937	39072
426	Horizontal	43827	41266
427	Horizontal	43475	42195

VITA

Pete Jevon Hernandez received his Bachelor of Science degree in Nuclear Engineering from Texas A&M University at College Station in May 2006. He entered the Health Physics program at Texas A&M University in August 2006 and will receive his Master of Science degree in August 2008. His research interests include direct energy conversion, black box identification, border safety, power plant safety, external dosimetry, space radiation and the benefits of radiation in the medical field. He plans to work for the Nuclear Regulatory Commission where he will be able to pursue these interests further.

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