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Heat capacity of thermoluminescent dosimeters using an INSB infrared detector

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**HEAT CAPACITY OF THERMOLUMINESCENT DOSIMETERS
USING AN INSB INFRARED DETECTOR**

A Thesis

Presented to

The Faculty of the Department of Nuclear Science

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Gregory Etcheber Jones

August 1998

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ABSTRACT

HEAT CAPACITY OF THERMOLUMINESCENT DOSIMETERS USING AN INSB INFRARED DETECTOR

by Gregory E. Jones

Heat capacity variations in thermoluminescent dosimeter (TLD) populations have been experimentally quantified for the first time using an infrared detector. Consistent heat is applied to each sample from a TLD reader, and infrared transmission is characterized by an indium antimonide (InSb) photodiode to determine the heat capacity. Using this method, variations as high as 30% were observed among TLDs manufactured over a period of about ten years. Nearly identical trends were observed among different phosphor types ($\text{Li}_2\text{B}_4\text{O}_7\text{:Cu}$, $\text{CaSO}_4\text{:Tm}$) and isotopically enriched phosphors (Li-6, Li-7, natural Li). Heat capacity differences are dominated by variations in the polyamide glue drop used for TLD construction. Observed shifts in TLD element correction factors (ECF) after heating alterations are strongly linked to heat capacity and can be predicted with $\pm 5\%$ accuracy using heat capacity measurements. Proper heating conditions can be applied to accommodate a wide range of TLDs when heat capacities are well characterized.

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CHAPTER 1

Introduction

Thermoluminescent dosimeters (TLDs) are passive devices routinely used to record radiological conditions in the workplace including occupational dose. The fundamental concepts of TLD dosimetry are reviewed for the reader in Chapter 2. In depth explanations of TLD solid-state physics and energy trapping are beyond the scope of this thesis but are available in several references¹. The emphasis of this thesis is an understanding of the heating necessary to release the TLD signal in a reproducible manner. After irradiation, the TLD signal is recovered by applying precise heating under laboratory conditions. Consistent heating is a critical prerequisite for a quality TLD processing program. Many laboratories have developed techniques to optimize the heat delivered to TLDs.^{2,3,4} However, only a few techniques have addressed the significance of heat capacity of the individual TLD elements^{5,6,7}.

Variation in TLD signal response is expected due to the amount of thermoluminescent material present and often normalized through calibration. TLDs that cannot be normalized in this manner are not optimally heated due to heat capacity differences. Historically, these heat capacity differences have never been quantified, forcing all processing laboratories to operate under broad assumptions about heat capacity variations. This work presents a powerful new tool to test these widely held assumptions. By adapting an infrared detector for use in a TLD reader, it is possible to directly measure TLD heat capacity differences for the first time. Understanding the source of heat capacity variations is necessary for improving manufacturing processes.

Additional applications of this new tool allow for enhancements in quality, productivity, and precision for a TLD processing laboratory.

Each TLD sample is heated using a consistent heating profile. The corresponding temperature change in the TLD is quantified from an infrared detector. Differences in the temperature profiles are directly linked to heat capacity variations. Over 40,000 TLD elements were evaluated to determine their heat capacity characteristics. TLDs were selected from different production batches as well as different phosphor composition. By correlating the heat capacity measurements to other calibration factors, it is possible to determine the underlying factors that dominate heat capacity variations. Surprisingly, the polyamide glue drop, not the phosphor, emerged as the dominant contributor responsible for heat capacity variations.

The basics of infrared and TLD fundamentals are reviewed in Chapter 2 followed by a detailed description of the research equipment and measurement methods in Chapter 3. To compare the heat capacities of different samples, a numerical factor is assigned to each element as described in Chapter 4. A detailed treatment of temperature calibration and error analysis is contained in Chapter 5. Most of the experimental data and analysis are summarized in Chapter 6. Chapter 7 outlines the major conclusions from this work. Supplemental information about equipment specifications and listings of software source code is contained in the appendices.

CHAPTER 2

Theory

Thermoluminescent Dosimeters

Fred Boyles was one of the first to describe the phenomena of thermoluminescence in the 1800's while examining mineral samples. Thermoluminescence simply describes the property of a material that emits light when heat is applied. Much to the surprise of Boyle, the mineral emitted light only during initial heating. Subsequent heating of the same mineral failed to produce the same effect. The light emitted was merely a release of energy that was stored in the mineral.

Modern understanding of solid state physics has revealed the trapping mechanism that is responsible for the thermoluminescent property. A crystal can be described as a highly ordered molecular structure or lattice. An occasional imperfection or defect in the crystalline structure creates a net charge in the surrounding area. This net charge serves as a trapping center for any free electrons. The number of trapping centers can be increased by *doping* the crystal by adding more impurity atoms.

When exposed to ionizing radiation, some crystals produce many free electrons that may be trapped by the crystalline imperfections. When stored at room temperature, many of the electrons remain trapped for long periods. When the crystal is heated, energy is transferred to the trapped electron. The trapped electron must receive enough energy to overcome the binding energy of the trap before it is released. Once released, the electron often returns to its ground state energy by combining with a positive ion and emits its stored energy as light.⁸

This thermoluminescent property is the basis of thermoluminescent dosimetry. Dosimetry is simply a method of measuring exposure to ionizing radiation. By carefully selecting crystals and doping agents it is possible to create a phosphor that is optimized for dosimetry methods. A *thermoluminescent dosimeter* (TLD) may be worn by a worker in a radiation environment and later heated in a laboratory. The amount of light emitted is recorded using a photomultiplier tube (PMT.) When plotted as a function of time, the light output is given the name *glow curve*. The integral of a glow curve is proportional to the dose received. A sample glow curve is shown in Figure 6.17 on page 57.

Once a TLD has been heated, almost all of the traps have been released. A TLD may be reused several hundred times provided the traps are efficiently released after each use. The term *anneal* describes the heating process of resetting or zeroing a TLD. A TLD is typically annealed immediately before field use.

Blackbody radiation

Since the early 1800's, it has been known that all objects emit infrared radiation. The wavelengths emitted are a function of the ambient temperature of the object. In 1900, Planck developed a mathematical formula that recognized the quantum nature of the photoemission spectra and correctly described the power emitted from a blackbody. Known as Planck's Radiation Law, the formula is given by:

Equation 2.1 Planck's Radiation Law⁹

$$M(\lambda) = \frac{C_1}{\lambda^5} \frac{1}{\exp(C_2 / \lambda T) - 1} \quad (W \, m^{-2} \, \mu m^{-1})$$

$M(\lambda)$ = Spectral radiation (spectral radiant exitance [areance]) from a blackbody

λ = wavelength, μm

$$C_1 = 2\pi h c^2 = 3.7418 \times 10^{-12} \quad W \, cm^2$$

$$C_2 = \frac{ch}{k} = 1.4387 \, cm \, K$$

T = absolute temperature, K

c = velocity of light = $3 \times 10^{10} \, cm \, s^{-1}$

h = Planck's constant = $6.626 \times 10^{-34} \, W \, s^2$

k = Boltzmann's constant = $1.3807 \times 10^{-23} \, W \, s \, K^{-1}$

The maximum power is emitted at a wavelength described by Wien's

Displacement Law:

Equation 2.2 Wein's Displacement Law

$$\lambda_{\max} T = \text{constant} = 2897 \, \mu m \, K$$

Planck's Radiation Law

Figure 2.1 Planck's Radiation Law & Wein's Law for various temperatures

Plots of Planck's radiation law and Wein's displacement law are shown in Figure 2.1. Planck's law further concludes that 25% of the power spectrum is found to the left of the peak wavelength leaving the remaining 75% of the power confined to the right of the peak wavelength.¹⁰

TLDs are typically heated to temperatures of approx. 300°C (600K). Although not a perfect blackbody, application of Wein's law and Planck's law may be used to estimate the infrared spectrum emitted by the TLD during its normal heating cycle. Shown in Figure 2.2 is the spectral radiant exitance of a blackbody at temperatures relevant for TLD readers. The spectral distribution of infrared power is important for proper selection of detectors and filters, which is covered in detail in Chapter 3.

Using the Panasonic heating lamp as an illuminator, each element is heated and begins radiating as a blackbody. By cold filtering the resulting spectrum with a silicon filter, only the infrared wavelengths in the shaded region of Figure 2.2 are recorded by the Indium Antimonide (InSb) infrared detector.

Planck's Radiation Law

Figure 2.2 InSb detector and Si Window are Well Matched to the Infrared Emission Spectra for Typical TLD Heating Temperatures

Variations in Heat Capacity

By definition, the heat capacity is the amount of heat required to raise a unit mass of material one unit of temperature. Heat capacity is typically measured in units of $\text{cal g}^{-1} \text{K}^{-1}$. For TLD elements, a more useful definition is found in chapter eight of the Panasonic manual:

The heat capacity of an element is its ability to transmit the infrared heat wave from the back of the black polyamide to the phosphor grains in the correct amount of time. If the heat capacity of an element is too high, the heat wave will be transmitted too slowly for the DOSE portion of the glow curve to be integrated properly. This will cause the same problems as weak heating conditions of the TLD If the heat capacity of an element is too low, the heat wave will be transmitted too rapidly for the DOSE portion of the glow curve to be integrated properly. This will cause the same problems as excessively strong heating conditions of the TLD reader. Thus it is important for the heating conditions of the TLD reader to be appropriate for the heat capacity of the elements to be processed.

Heat capacity is used by Panasonic in a relative way, not in an absolute way. For example, the heat capacities of two elements might be compared on a relative basis. The conclusion might be that the heat capacity of one element is larger than that of the other element. However, the absolute heat capacity of neither element is never [sic] measured. As used in the context of Panasonic elements, heat capacity has no units, and there is no method available to measure heat capacity.¹¹

Heat capacity is a strong indicator of manufacturing consistency among various production batches. A processor often owns dosimeters from several batches. If all the batches have essentially the same heat capacity, then the heating conditions of a TLD reader could be adjusted to integrate the DOSE or Main region (see Figure 6.17, page 57) of the glow curve accurately for all the dosimeters. However, if the heat capacities are very different from batch to batch, then the heating conditions of the TLD reader that are appropriate for one batch may not be appropriate for the other batches.

From the definition of heat capacity, it is possible to see where heat capacity variations for TLDs are possible. Chapter 8 of the Panasonic Manual also identifies several factors that affect TLD heat capacity including the polyamide backing, glue drop, phosphor grains, and teflon bubble. The full text of this section of the manual may be found in Appendix F. Figure 2.3 illustrates these different components.

Figure 2.3 Diagram identifying components affecting heat capacity of a TLD ¹²

The Panasonic Manual clearly defines six underlying assumptions relating to Heat Capacity. These assumptions are explicitly reprinted in Appendix F so that their validity can be determined from experimental results.

For a new processor, TLDs are often purchased in large quantities of several thousand TLDs. Often these TLDs are produced from a single production batch or several production batches from the same period. Minimal variation is expected within a single production batch. Subsequent procurements are often for smaller quantities and typically filled from a different production batch.

Occasionally, a subsequent order will exhibit a significantly different response when subjected to *Element Correction Factor* (ECF) qualification protocols (see Chapter 3.) If the signal yield is different due to the amount of phosphor, most processors will normalize the response using an ECF with a range of about 0.5 to 1.5. If an ECF falls outside of the acceptance range, the TLD is often rejected from use. ECF failures are typically attributed to variations in heat capacity. To understand variations in production batches, a direct measurement of heat capacity is necessary.

CHAPTER 3

Equipment

Panasonic TLDs

The powdered TL phosphor material is adhered to a black polyamide backing with a glue drop and covered with a transparent Teflon bubble. Four phosphors are mounted in a badge insert that is extracted from the badge holder for heating (see Figure 3.1.) The amount of phosphor can vary from sample to sample and hence yield a variable light output. The light output is normalized using an element correction factor ECF described below. The badge insert is housed in a badge holder that is used to identify the TLD serial ID# and badge type. Panasonic Industrial Company currently manufactures four different phosphor materials shown in Table 3.1.

Figure 3.1 Panasonic TLD Construction¹³

Table 3.1 Types of phosphors produced by Panasonic and their common uses

Phosphor Composition	Comments
$\text{CaSO}_4:\text{Tm}$	High sensitivity, β , highly γ energy dependent, neutron insensitive
$^7\text{Li}_2^6\text{B}_4\text{O}_7:\text{Cu}$	Tissue equivalent, β , γ , some albedo neutrons
$^7\text{Li}_2^{11}\text{B}_4\text{O}_7:\text{Cu}$	Depleted in ^6Li , neutron insensitive
$^6\text{Li}_2^{10}\text{B}_4\text{O}_7:\text{Cu}$	Enriched in ^6Li , increased neutron sensitivity

The position and filtration placed over these phosphors is used to determine badge types. Badge types are classifications given to TLDs so that they will be properly interpreted by the TLD reader. Several badge types are reserved by Panasonic for user defined configurations. Lawrence Berkeley National Laboratory (LBNL) uses three different badge types as shown in Table 3.2. Although the UD-802 is a standard TLD configuration, the UD-810 and UD-813 are user defined badge types that are specified by Berkeley Lab. These TLD types were used for heat capacity measurements. The isotopically separated Li species Li-7 and Li-6 must be read using the same lithium heating cycle used by the natural abundance $\text{Li}_2\text{B}_4\text{O}_7$.

Table 3.2 Dosimeter types in use at Lawrence Berkeley National Laboratory

Badge Type	Element 1	Element 2	Element 3	Element 4
UD-802	$^n\text{Li}_2^{\text{n}}\text{B}_4\text{O}_7\text{: Cu}$	$^n\text{Li}_2^{\text{n}}\text{B}_4\text{O}_7\text{: Cu}$	$\text{CaSO}_4\text{:Tm}$	$\text{CaSO}_4\text{:Tm}$
UD-810	$^7\text{Li}_2^{11}\text{B}_4\text{O}_7\text{: Cu}$	$^7\text{Li}_2^{11}\text{B}_4\text{O}_7\text{: Cu}$	$^6\text{Li}_2^{10}\text{B}_4\text{O}_7\text{: Cu}$	$\text{CaSO}_4\text{:Tm}$
UD-813	$^7\text{Li}_2^{11}\text{B}_4\text{O}_7\text{: Cu}$	$^7\text{Li}_2^{11}\text{B}_4\text{O}_7\text{: Cu}$	$^6\text{Li}_2^{10}\text{B}_4\text{O}_7\text{: Cu}$	$^6\text{Li}_2^{10}\text{B}_4\text{O}_7\text{: Cu}$

Element Correction Factors

Element correction factors (ECFs) are routinely used to normalize the light output of a TLD element. Although some Panasonic TLDs are encoded with an approximate calibration rank factor, the ECF is computed with this feature disabled. The process described here is the method used at LBNL and is similar to most other processing facilities.

A mean ECF is derived from the average of three measurements. TLDs are prepared for ECF generation by first annealing or resetting the TLD to low levels. Lithium elements must read less than 10 mR^* (Panasonic units) and calcium elements

must read less than 5 mR*. A group of 350 TLDs is loaded into seven magazines with 50 TLDs in each magazine. Slots 15 and 40 are reserved for a set of reference TLDs called a silver set. The magazines are then placed in a Lucite rack and irradiated to a dose of 3 mSv (300 mrem) using a ^{137}Cs irradiator. The TLDs are read after 24 hours to allow for short term fading of shallow traps. The light output of an individual TLD element is referenced to the light output of the reference TLDs as follows:

Equation 3.1 Calculation of Element Correction Factor (ECF)

$$\text{ECF}_i = \frac{(\text{Individual Element Response})_i}{\frac{\sum_{ref}^n (\text{silver reference})_i}{n}} \quad \text{where } i = 1..4 \text{ for each element position}$$

The process is repeated three times and a calculated mean ECF is used as a numerical divisor to correct all subsequent readings. An ECF is rejected from use if the ECF is less than 0.5 or greater than 1.5. The *percent coefficient of variation* (%CV) is computed for each mean ECF using the ratio of the standard deviation to the mean expressed as a percentage. A TLD is rejected from use if the %CV is greater than 5%.

TLD Reader and Modifications

The TLD reader used for heating the TLDs is a Panasonic UD-710A automatic TLD reader equipped with a UD-730 magazine changer. The TLD reader is supplied by a 120VAC filtered power source that is protected with an uninterruptible power supply to reliably deliver a stable power supply to the TLD reader. The TLD reader is housed in an environmentally controlled and monitored room to minimize temperature variations.

Exact positioning of the TLD is assured by a combination of pulse motors and position verification LEDs. The reader is capable of reading a variety of TLD badge

types composed of various TL phosphor combinations. The magazine changer is used to increase the total TLD capacity from 50 to 500. Operator control of the reader is provided by a keypad and status display panel. External computer control of the reader is available via an RS-232C communication port. A *number code reader* (NCR) is installed in the reader to identify the badge type and unique ID #. The output of the NCR is displayed on the front panel of the TLD reader as well as the printer and RS-232 data ports.

Heat is supplied by a 15-watt lamp mounted within the reader. The heat is focused on the TLD element using a convergence cone equipped with an infrared filter. The lamp is flashed three times in succession for each TLD element. A more complete description of the lamp timing may be found in Figure 3.2. There are two heating profiles available for use. Typically one heat cycle is allocated for the CaSO_4 elements and the other is used for the $\text{Li}_2\text{B}_4\text{O}_7$ elements.

Figure 3.2 TLD Heating Lamp Profile and Photomultiplier Tube Response¹⁴

Adjusting the heating cycle for the Panasonic TLDs is accomplished in two ways. Adjusting a potentiometer on the lamp power circuit board will alter the lamp's operating voltage. Typical lamp voltage settings are between 12 and 14 V. Minute voltage adjustments ($\Delta V = 0.1$ volt) are sufficient to significantly alter the heat profile. The other method to alter the heating profile is to change the length of time the lamp is on. Timing settings are altered by modifying the reader's heating parameters outlined in the Panasonic TLD operator manual. Between each of the three lamp flashes, the lamp is turned off for a specific time interval. Adjustment of any of these intervals by a few milliseconds will result in observed shifts in heat output.

To verify lamp power, each badge reading is preceded by a reference element flash during which the lamp is turned on for an extended time interval. This reference flash also eliminates heating errors due to initial lamp temperature by pre-heating the lamp. The stability of heat lamp output has been independently verified by several processing laboratories using Panasonic readers and thermocouple measurements.^{15,16} After repeatedly heating a sample monitored by a thermocouple, the output is examined to verify the reproducibility of the output of the lamp. While this measurement assures a stable lamp output, it does not describe the differences in the temperatures that each TLD attains. Variations between TLDs are linked to the heat capacity of each element

The amount of light emitted from a TLD during heating is directly proportional to the delivered dose. To measure the light output, the reader uses a *photomultiplier tube* (PMT). The photomultiplier tube is operated at 850V and has a peak efficiency that is well matched to the TLD light output in the UV and blue region of the visible spectrum.

To verify proper light measurements, the TLD reader is equipped with a ^{14}C *reference light source*. The reference light source is measured 10 times and the mean value is used to correct the light response of the PMT. This method results in a highly reproducible measurement of light output suitable for dose measurements.

The light output will vary as a function of heating time. A plot of light output as a function of time is used to determine the delivered dose. Such a plot is called a glow curve and may be integrated to determine delivered dose. Glow curves are automatically captured by a host computer during a TLD readout.

Several items must be modified for the reader to perform infrared measurements. The modifications can be performed easily by a trained technician using skills similar to those for routine cleaning of the TLD reader. The conversion can be performed in about 30 minutes and is easily reversed without compromising the quality of the TLD reader operations. The two overriding considerations in the following modifications are preventing damage to the photomultiplier tube and preserving the integrity of the normal heating cycle.

The photomultiplier is extremely vulnerable to damage by normal room light when the high-voltage (nominally 850 V) is applied. The TLD reader is equipped with a microswitch that will cutoff the high voltage when the sub housing plate is not mounted to the main housing plate. An auxiliary sub-housing plate will be mounted within the reader that will effectively bypass the function of this microswitch. A photomultiplier (PMT) plug (Microdesigns part #91ASY023G1) is used to protect the PMT from

damage. The PMT will remain in the reader with high-voltage applied, however, the PMT will be repositioned to permit introduction of the infrared detector.

After powering down the TLD reader, the PMT is removed following procedures for routine cleaning. With the PMT cable and grounding cable still connected, an auxiliary main housing plate is attached to the PMT and its sub housing plate using two auxiliary thumbscrews. To permit reader operation, a small amount of light is needed from a ^{14}C light source that is placed between the PMT and the PMT Plug. The PMT plug is mounted in the auxiliary main housing plate to block the transmission of any ambient light. The PMT assembly is placed on an elevated acrylic platform within the reader as shown in Figure 3.4.

Figure 3.3 Normal PMT mounting in TLD reader¹⁷

Figure 3.4 InSb detector mounting in TLD reader with PMT on support shelf¹⁸

An auxiliary sub housing plate (without a PMT) is equipped with a carrier inspection LED array (Panasonic Part# UD710A-014A) and a number code reader circuit board (Panasonic Part #UD710A-311B). About 0.5 cm must be cut off the lower edge of this board to permit the mounting of the detector shelf. A hinged aluminum shelf is attached to the base of the auxiliary sub housing plate to support the InSb detector. The auxiliary sub housing plate is installed in the reader in the normal manner and secured in place with two thumbscrews.

To permit mechanical operation of the TLD reader, several parameter changes are necessary before starting the reader. Listed in Table 3.3 are the necessary parameter changes. The original values of these parameters are recorded on a worksheet to permit restoration of normal reader operation. Parameter changes are entered via the TLD reader's keypad while in badge check mode.

Table 3.3 Parameter changes for InSb measurements.

Parameter	Description	Desired Value
P-53	Reference Element	3300
P-54	Dark Count Error (Photon)	3300
P-55	Dark Count Error (Frequency)	3300
P-56	Reference Element Error	3301
P-78H	Reference Light Source Error	99
P-0E	Dark Count Interval (T10)	0145
P-72H	Baud Rate	0E

Parameters 53 and 56 relax the constraints placed upon the reference element flash through the reference element hole. Parameters 54 and 55 relax the limits placed on the dark count. Parameter 78H enlarges the allowable error window for the reference light source. If reference light source errors persist, it may require adjustment of P-57 the Photon Calibration Factor. Parameter 0E shortens the dark count interval. Parameter 72H sets the RS-232 baud rate to 9600. A full parameter dump appears in Appendix A.

An RS-232 communication protocol is used by the TLD reader to control and capture data output. The reader is connected to the serial port of a PC using a null modem (full-duplex) cable with a male 25-pin D-sub connector on one end and a female 9-pin D-sub connector on the other. The reader and the PC are both configured with a data communication rate of 9600 baud.

InSb Infrared Detector Selection and Configuration

Indium Antimonide (InSb) was first introduced in the early 1950s as an infrared detector used for military applications. "Indium Antimonide (InSb) photodiodes have found numerous applications in the defense industry for more than 20 years. Perhaps the best known (and most successful) of these systems has been the Sidewinder air to air

antiaircraft missile.”¹⁹ InSb detectors are now used commercially for “precise radiometric measurements, spectroscopy, beam profiling and low resolution imaging.”²⁰

The following considerations were carefully evaluated: low-noise; sensitivity; physical dimensions, fast response; non-intrusive measurement capability. After careful consideration, an InSb photovoltaic detector was selected for this measurement. The detector is manufactured by Cincinnati Electronics Corp (Model SDD-7854-S1) and includes an integrated, low-noise TIA pre-amp in a small dewar operating at liquid nitrogen temperature (77K).

The single element InSb detector measures 1.0 mm in diameter. The InSb detector is a photovoltaic detector with a P-type mesa on an N-type monolithic substrate. The active element is mounted on a fixed cold shield sleeve thus maintaining the 77K operating temperature. The InSb detector is extremely susceptible to electrostatic discharge damage and special handling considerations are required.

The detector is equipped with a black-coated, knife edged aperture to limit the field of view (FOV) and minimize reflection (see Figure 3.5.) The aperture is ~0.26" in front of the detector with a 0.134" diameter circular opening. The resulting FOV is restricted to 30°. Directly behind the aperture, a silicon cold spectral filter is inserted to limit the wavelengths that strike the detector. The photodiode, filter, and aperture are secured within the dewar and covered by a thin sapphire window before pumping the dewar.

Figure 3.5 InSb Detector FOV²¹

Filter and aperture changes may only be done with a warm dewar at atmospheric pressures. The dewar should be pumped to 10^{-6} torr or better using a cold trap to prevent any organic impurities from coating the detector surface. A pressure of 3.8×10^{-7} torr was used for all measurements and allowed for a dewar hold time of approximately 12 hours.²² A 12-hour hold time is sufficient for a typical data collection for approximately 1500 badge samples. Liquid nitrogen is transferred to the dewar using a funnel inserted into the fill hole at the top of the dewar.

Spectral Response

The InSb photodiode detects radiation from absorption of a photon of energy greater than the bandgap of 0.22eV. An electron is excited from the valence band to the conduction band and leaves a hole in the valence band. The electron hole pairs are the charge carriers that alter the characteristic curve of the diode. Photons with energy less than the bandgap are not absorbed and simply pass through the InSb layer undetected.

The relationship between a photon energy and wavelength is given by the following relationship:

$$E = \frac{hc}{e\lambda} \cong \frac{1.24 \text{ eV} \cdot \mu\text{m}}{\lambda}$$

Equation 3.2 Energy and Wavelength Relationship²³

From this relationship, a cutoff wavelength can be determined. Since InSb has a bandgap of 0.22 eV, photons of wavelength 5.5 μm have just enough energy to excite a valence electron into the conduction band. Wavelengths longer than 5.5 μm do not have enough energy to overcome the bandgap and are not detected by the InSb detector. Wavelengths less than 5.5 μm (including visible light) are absorbed and detected by the InSb detector. To narrow the spectral response to the infrared region a cold filter is needed. A thin (0.021") silicon wafer is used as a filter because of its ability to block UV and visible light while allowing the IR signal to pass through to the detector. The filter was cut and shaped to a diameter of about 0.4" and placed within the FOV aperture described above. The infrared transmission characteristics of Si are favorable between 1.2 μm and 15 μm with an external transmittance greater than 10%.²⁴ Although the Si filter will pass wavelengths up to about 20 μm , the InSb response is self-limited to wavelengths less than 5.5 μm . At lower wavelengths, the Si filter will absorb photons less than 1.1 μm . Therefore, the effective spectral region that is measured by the InSb detector is 1.1 μm to 5.5 μm .

Sensitivity

The number of charge carriers produced for each photon is one measure of the detector's performance. Stated a different way, the number of charge carriers produced can be expressed as the probability that a single photon will generate a charge carrier. The term used to describe this probability is given the name quantum efficiency (η). The quantum efficiency will influence both the responsivity and noise limits for the detector.

Responsivity is the signal output divided by the radiant input and is given by the expression: $\mathfrak{R} = \frac{\eta e \lambda Z G}{hc}$ where e is the carrier charge, ($G=1$) is the gain and Z is the load impedance of the feedback resistor which is $94.3\text{k}\Omega$. The measured responsivity is 2.99A/W at $4.51\text{ }\mu\text{m}$ and 0.78 A/W at 600K .

The detector selected is a background-limited infrared photodetector (BLIP).²⁵ For such a detector, the noise from background (300K) is significantly greater than thermal or Johnson noise. Other sources of noise in a photovoltaic system can be identified as shot noise, generation-regeneration (gr) noise, and amplifier noise. Shot noise is due to the random arrival rate of charge carriers at the diode junction. For our case, shot noise can be quantified in the thermal limit as $I = I_s \left[e^{\left(\frac{eV}{kT} - 1\right)} \right]$ where I_s is the saturation current for the diode. Gr noise is a result of the random rate of carrier generation and the random lifetime of the carrier. The noise contribution from these sources is significantly smaller than the photon-generated background noise.

To characterize detector performance, the specific detectivity (D^*) is commonly used. It is defined as:

$$D^* = \frac{\text{responsivity} \times \sqrt{A_d}}{\text{noise} \times \sqrt{\Delta f}}$$

For BLIP detectors, the equation simplifies to:

$$D_{BLIP}^* = \frac{\lambda}{hc} \sqrt{\frac{\eta}{2\phi_B}}$$

The measured D^* for the InSb detector is given as

$$D_{4.51\mu m}^* = 1.961 \times 10^{11} \frac{cm\sqrt{Hz}}{W} \quad \text{and} \quad D_{Blackbody,600}^* = 5.13 \times 10^{10} \frac{cm\sqrt{Hz}}{W}$$

Detector Reproducibility

A stable detector response is essential to accurately measure sample variations. A straightforward test of detector reproducibility verified proper stability while measuring a variety of samples. With the detector fully assembled in its final configuration, 200 TLD elements were subjected to three replicate *Heat Capacity Factor* (HCF) measurements as described in Chapter 4. A percent coefficient of variation (%CV) technique was used to evaluate reproducibility. For the InSb detector measurements, the average %CV is about 2% for each element (see Table 3.4). Such a low %CV verifies the stability and reproducibility of the detector. Therefore, a single HCF measurement is sufficient to characterize a TLD element. Any observed variations in measured HCF for large TLD populations are truly due to physical differences in the TLD sample and not statistical fluctuations in the detector.

Table 3.4 InSb Detector Reproducibility

	Element 1	Element 2	Element 3	Element4
Average %CV	1.9%	1.8%	2.0%	2.1%

Amplifier and Power Supply

The AM-300 pre-amp is ideally located in close proximity to the detector to reduce stray capacitance from the diode leads. The low noise transimpedance preamplifier (TIA) uses a FET input operational amplifier. (See schematic in Appendix B). Sometimes called a current mode amplifier, the TIA produces a voltage output that is proportional to the current passing through the feedback resistor. The AM-300 is equipped with a $94.3\text{k}\Omega$ resistor. The signal to noise ratio is greatly enhanced by a large feedback resistor. However, the feedback resistor must remain much less than the detector impedance. The response time of the pre-amplifier is limited to the megahertz region and lower.

The power supply was built from a Power-One (Model HAD15-0.4-A) DC power supply to provide a stable $\pm 15\text{V}$ DC source to the detector. The signal output is referenced to ground as delivered by the AC line input ground. The power supply unit is enclosed in a grounded metallic case compact enough to fit within the reader.

InSb Data Capture

The InSb pre-amp signal output is connected to a connection block (National Instruments Model #BNC-2080) using a coaxial cable with BNC connectors. The pre-amp analog signal can range between 0 and $+10\text{VDC}$ with a current of a few milliamperes. For TLD measurements, the typical signal is between 0 and $+2.5\text{VDC}$. Other than proper shielding, no further signal conditioning is necessary for the InSb signal before digitization.

The Lamp gate signal from the TLD reader is connected to another channel of the same connector block used by the InSb signal using another shielded BNC coaxial cable.

The lamp gate is a transistor-transistor logic (TTL) level signal that will serve as a data acquisition trigger. The TTL signal will change from 0 to +5VDC with a fast switching time where typical propagation delay times are about 10 nanoseconds.²⁶ The lamp gate signal is normally held low (0VDC) while the lamp is off. When the heating lamp flashes, the lamp gate signal is driven high (+5VDC) for the duration of the lamp flash.

The connector board is cabled to a data acquisition card that is mounted in a PC laptop using a two meter ribbon cable in a shielded enclosure. The shield is connected to the TLD reader's reference ground. Without the ground, the input signal can suffer from local radio-frequency interference from the PC's power supply or any other nearby source of electromagnetic fields.

The data acquisition card (National Instruments DAQCard™-700) is a 12 bit, successive approximation, analog to digital converter (ADC) that is fully software configurable and calibrated. The board is manufactured in a very compact Personal Computer Memory Card International Association (PCMCIA) Type II enclosure. The data acquisition card is capable of accepting 16 single-ended (SE) analog inputs or 8 differential-ended (DE) analog inputs. All signals were connected using DE analog inputs to minimize common mode signal noise. The maximum settling time for the DAQCard-700 is 25 μ sec ($\pm 0.024\%$ accuracy) when configured for ± 5 VDC. The settling time permits a maximum sampling rate of 40 kHz, which is more than adequate for the InSb sampling rate of typically only a few hundred samples/sec. The DAQCard-700 has a 12-bit resolution resulting in an accuracy of ± 2.44 mV when the card is configured for the range ± 5 VDC. Additional specifications are included in Appendix B.

The laptop PC (Toshiba Tecra™500CDT) used for data acquisition and data reduction is equipped with an Intel Pentium® processor and 16 Mbytes of RAM using the Microsoft® Windows95²⁷ operating system. The software application selected for controlling the data collection and a majority of data reduction is LabView®.²⁸ This application software proved to be powerful and easy to use. Its programming tools are based upon the G language that differs greatly from traditional text based programming code. The source code is developed using wiring diagrams and graphical symbols that represent functions and other subroutines containing *virtual instruments* abbreviated as *VI*. Shown in Figure 3.6 is a portion of the main data acquisition code. A complete source code listing of all programs may be found in Appendix E.

Figure 3.6 Sample of InSb programming using LabView®

A LabView program was written to continuously sample the lamp gate at 200 scans/sec for a trigger condition. When the lamp gate voltage exceeds the threshold of +1.5VDC, an acquisition cycle was initiated for a period of 18 seconds. During this time,

the lamp flashes 13 times (see Figure 3.1) to heat all four elements of a TLD. The InSb voltage is then sampled at the same rate of 200 scans/sec, displayed, and graphed for the operator during the acquisition cycle. The signal is also routed through a series of digital signal processing techniques for real-time processing and analysis. The TLD ID# is obtained via the RS-232 data line. The raw data is stored in an ASCII text file with a filename linked to the TLD identification for post acquisition processing and subsequent data reduction (see Appendix E).

Thermal Curve Adapter

The Thermal Curve Adapter (TCA) is manufactured by Microdesigns Inc. (TCA/1 - Part # 91ASY014Gx). This product is made for use in conjunction with a Panasonic TLD reader to measure the heat profile of the heating lamp. This device measures the output of the heating lamp using a fixed TLD target equipped with a type K thermocouple. It is used to monitor the stability of lamp output or compare the heat output from different heating lamps. The thermocouple measurements are internally converted to temperature ($^{\circ}\text{C}$) for display on the front panel of the device. Digital signal output is also available from a BNC connector mounted on the rear of the device.²⁹

When a thermal curve is captured by the host computer using a GCI/3 Glow curve interface, a temperature reading is determined using Equation 3.3 supplied by the manufacturer. The temperature may be calculated with an accuracy of $\pm 0.7^{\circ}\text{C}$ for temperatures between 0°C and 1370°C .

$$\text{Voltage} = \frac{\text{Counts per sample period}}{4.946 \times 10^7 \times \text{Sample period}} - 1.1 \times 10^{-5} \text{ V}$$

$$\text{Temperature} = a_8 V^8 + a_7 V^7 + a_6 V^6 + a_5 V^5 + a_4 V^4 + a_3 V^3 + a_2 V^2 + a_1 V + a_0$$

where polynomial coefficients a_n are as follows :

$$a_0 = +0.226584602 \quad a_3 = +2210340.682 \quad a_6 = -1.18452 \times 10^{12}$$

$$a_1 = +24152.10900 \quad a_4 = -860963914.9 \quad a_7 = +1.38690 \times 10^{13}$$

$$a_2 = +67233.4248 \quad a_5 = +4.83506 \times 10^{10} \quad a_8 = -6.33708 \times 10^{13}$$

Equation 3.3 Converting thermal curve counts to temperature³⁰

CHAPTER 4

Heat Capacity Factor

The Heat Capacity Factor (HCF) is merely an assessment of the infrared emission of a TLD based upon the integration of InSb measurements. The response of the InSb detector during a normal heating cycle is shown in Figure 4.1. Each element has three peaks corresponding to the three lamp flashes. The exact position of the triple peak must be determined for proper numeric integration of the InSb signal. A peak detection program (or VI) provided by LabView and configured to look for valleys analyzes the array of InSb values. The peak detection VI finds the location, amplitude, and second derivative of peaks or valleys in the input array using an algorithm that fits a quadratic polynomial to sequential groups of data points.³¹ The user specifies the number of data points used in the fit and a value of 250 scans (1.25 sec) works very well for the InSb curve. For each peak or valley, the quadratic fit is tested against the threshold level: peaks with heights lower than the threshold or valleys with troughs higher than the thresholds are ignored. A threshold value of six produced consistent results.

InSb Infrared Profile UD-802

Figure 4.1 InSb Infrared Response (not a glow curve) with Integration Region Shown for Element 3 Heat Capacity Factor (HCF) Calculation.

A numeric integration of the InSb curve is calculated for each element using a VI supplied by LabView. The trapezoidal rule is used in computing the integral using successive applications of a basic formula in order to perform partial evaluations, which depend on one adjacent point. The result is the summation of these successive partial evaluations.³²

Equation 4.1 InSb Integral

$$\text{InSb Integral} \equiv \int f(t)dt \approx \sum_{i=1}^{j-1} \frac{(x_i + x_{i+1})}{2} * \Delta t$$

where j = number of InSb data points for a TLD element

The InSb integral is used to determine a Heat Capacity Factor (HCF) by normalizing the integral to the mean of an arbitrary set of 350 UD-802 reference TLDs. Hence, the HCF is computed by the following formula:

Equation 4.2 HCF Calculation

$$HCF_i = \frac{(\text{InSb Integral})_i}{\frac{\sum (\text{InSb Integral})_j}{j}} \quad (i = 1..4; j = \text{number of TLDs in reference set})$$

The HCF is actually a comparison of the relative heating of an individual TLD element. A high HCF indicates a TLD element that is easily heated and thus has a low heat capacity. Similarly, a low HCF is typical of a TLD element that is more difficult to heat and therefore has a higher heat capacity. The HCF is closely related to the definition of specific heat described in Chapter 2 and inversely proportional to the heat capacity.

Equation 4.3 HCF is inversely proportional to Heat Capacity

$$HCF \propto \text{Specific Heat} \propto \left(\frac{1}{\text{Heat Capacity}} \right)$$

Unlike calibration factors (ECFs) the HCF is not used to correct or modify the light output of a TLD reading. The HCF is used to classify the heating characteristics of a TLD. TLDs with a similar HCF can be grouped together for heating evaluations.

CHAPTER 5

Calibration and Error Analysis

Temperature Profile

To better understand the InSb signal measurements, it is important to correlate the measurements with more familiar measurements such as temperature. A correlation is possible with simultaneous measurements of temperature and InSb signal over the range of temperatures used for heating a TLD. The ideal geometry for such a test should match that found in the TLD reader. The TLD element embedded in the TCA is an ideal calibration reference standard.

The InSb detector output was calibrated to temperature using the TCA with a slight modification. The rear cover-plate of the TCA was removed permitting access to the rear of the TLD target. The InSb detector was then mounted in the same geometry found in the TLD reader (see Figure 5.1.) When used in this manner, the output from both the thermocouple and InSb detector can be captured simultaneously.

Figure 5.1 InSb detector and thermocouple configuration

A calibration curve is easily developed (see Figure 5.2) by plotting the two variables using the curve fitting program Table Curve³³ ver 1.11 by Jandel Scientific. Equation 5.1 below can now be used to convert InSb voltages into temperature readings. An eighth order polynomial is sufficient to describe the curve between 100 °C and 300 °C while keeping the residual temperature within $\pm 7^\circ\text{C}$. The associated calibration error is less than 3%. For temperatures above 200 °C, the curve is surprisingly linear. By applying this curve to InSb heat profile measurements, it is now possible to measure the temperature of a TLD using a non-contact method. The InSb detector can now be used as an optical thermometer.

The temperature region used for dose measurements must be closely matched to the trap depths of the specific phosphor. From Figure 5.4 it is clear that CaSO_4 has several glow peaks corresponding to temperatures of approximately 80°C, 135 °C, and 220 °C. The first two peaks fade too rapidly at room temperature whereas the 220°C trap fades very slowly. The higher temperature trap at 220°C is more stable and used for dose measurements. Similarly, $\text{Li}_2\text{B}_4\text{O}_7\text{:Cu}$ has two glow peaks at approximately 120°C and 205°C (see Figure 5.3.) The 120°C peak fades quickly and hence dose measurements are determined from the 205°C peak.

Using the InSb detector as a thermometer, it is possible to determine if each of the TLDs in a given population is heated to a temperature that will release these higher temperature peaks. Shown in Figure 5.5 through Figure 5.8 is a histogram of the maximum temperature of a TLD obtained in the Main region of the glow curve.

Temperature vs. Voltage

Figure 5.2 Temperature Calibration Curve from Simultaneous Thermocouple (TCA) and Photodiode (InSb) Measurements

Equation 5.1 InSb Temperature conversion

$$\text{Temperature (}^{\circ}\text{C)} = a_8 V^8 + a_7 V^7 + a_6 V^6 + a_5 V^5 + a_4 V^4 + a_3 V^3 + a_2 V^2 + a_1 V + a_0$$

where V is InSb signal in Volts and polynomial coefficients a_n are as follows :

$$a_0 = -288.30284 \quad a_3 = 10889.49153 \quad a_6 = 7862.23018$$

$$a_1 = 3249.95499 \quad a_4 = -2447.99248 \quad a_7 = -3076.19621$$

$$a_2 = -8814.0771 \quad a_5 = -7505.24863 \quad a_8 = 438.272309$$

With a coefficient of determination $r^2 = 0.9990528$

Figure 5.3 Temperature of Lithium Borate Traps³⁴

Figure 5.4 Temperature of Calcium Sulfate Traps³⁵

Figure 5.5 Distribution of Maximum Temperature Derived from InSb Measurements of Element 1 UD-802 TLDs (n = 3503)

Figure 5.6 Distribution of Maximum Temperature Derived from InSb Measurements of Element 2 UD-802 TLDs (n = 3503)

Figure 5.7 Distribution of Maximum Temperature Derived from InSb Measurements of Element 3 UD-802 TLDs (n = 3503)

Figure 5.8 Distribution of Maximum Temperature Derived from InSb Measurements of Element 4 UD-802 TLDs (n = 3503)

InSb Error Analysis

For a quantity Q composed of measured quantities A and B with standard deviation a and b respectively, we can determine a standard deviation for Q as follows:³⁶

Equation 5.2 General Expression for Error Propagation

$$q^2 = \left(\frac{\partial Q}{\partial A}\right)^2 a^2 + \left(\frac{\partial Q}{\partial B}\right)^2 b^2$$

The InSb analog signal is digitized by an analog to digital converter with an accuracy of ± 2.44 mV limited by the 12-bit resolution commonly called the code length. The Heat Capacity Factor is determined by summing approximately 650 individual InSb measurements. For arithmetic operations, Equation 5.2 above reduces to:

$$\begin{aligned} Q \pm q &= A \pm a + B \pm b \quad \text{where } q^2 = a^2 + b^2 \\ &= A + B \pm \sqrt{a^2 + b^2} \end{aligned}$$

To determine the HCF, the individual error must be propagated as follows:

$$\text{Absolute HCF}_{\text{error}} = \sqrt{\sum_{i=1}^{n=650} (\text{InSb error})_i^2} = \sqrt{650 * (0.00244)^2} = 0.622$$

When expressed as a percentage of the absolute HCF which has a value of at least 300, then the $\text{HCF}_{\text{error}}$ is less than 0.2%.

CHAPTER 6

Data Analysis

More than 40,000 TLD elements were evaluated and assigned a heat capacity factor (HCF). These results were compared to more than 300,000 Element Correction Factors obtained at Lawrence Berkeley National Lab (LBNL). Several hundred heat profiles were collected using the Thermal Curve Adapter. Ratios of Post to Main were computed for more than 80,000 elements.

Heat Capacity Variations

Several processors in the United States have been using Panasonic TLDs since the early 1980's. During that time, several procurements were made to acquire additional TLDs. The resulting population is hence a composite of several production batches. San Onofre Nuclear Generation Station (SONGS) has been using Panasonic TLDs since about 1984. To measure variations in production lots, nearly 3,500 Panasonic UD-802s were evaluated using the HCF measurement technique described in Chapter 4. Although the oldest TLDs have been retired from service, about 250 of the original TLDs were included in the testing population.

The HCF measurements are shown in Figure 6.1 and Figure 6.2. TLDs with a serial number less than 24,500 were purchased in 1984 and no longer used. TLDs with a serial number larger than 24,500 were purchased after 1984 and most are still in use. The largest shifts in measured HCF response are observed near TLD# 24,500 and TLD# 40,000. Small shifts are also seen within these larger designations suggesting that several production batches may be represented within a single procurement order.

Lithium Elements - UD-802 Elements 1 & 2

Figure 6.1 HCF for Lithium Elements with discontinuities occurring at boundaries of production batches (n = 3437)

Calcium Elements - UD-802 Elements 3 & 4

Figure 6.2 HCF for Calcium Elements with discontinuities occurring at boundaries of production batches (n = 3437)

When comparing the data in Figure 6.1 and Figure 6.2, it is surprising to notice the similarities in measured HCF. Although the calcium and lithium elements are produced separately, and read using a different heating cycle, they exhibit remarkably similar trends in HCF. Contrary to the assumptions that are stated in chapter eight of the Panasonic TLD manual, differences in phosphor types are not a dominant contributor to heat capacity variation.

The heating cycle used for Lithium Borate ($\text{Li}_2\text{B}_4\text{O}_7$) is used for heating all three types of Lithium Borate elements ($^n\text{Li}_2^m\text{B}_4\text{O}_7$, $^6\text{Li}_2^{10}\text{B}_4\text{O}_7$, $^7\text{Li}_2^{11}\text{B}_4\text{O}_7$). The heat capacity of these three lithium species was evaluated using HCF measurements of TLDs in use at Lawrence Berkeley National Laboratory. Shown in Figure 6.4 are the results of the UD-810 badge containing ^7Li and ^6Li . As with the 802 data shown in Figure 6.3, there is a greater fluctuation seen within a single species than there is between different lithium species (see Figure 6.4.) Therefore, if a TLD reader can be correctly configured to accommodate the range of heat capacities found in the 802 population, the same heat settings will correctly accommodate the range of heat capacities found in the 810 population as well.

Figure 6.3 HCF for Natural Lithium (Elements 1&2) for LBNL UD-802s

Figure 6.4 HCF for Li-7, Li-6 (Elements 1,2&3) for LBNL UD-810's

At Lawrence Berkeley National Lab, TLD reader heating is established using methods similar to those outlined in chapter eight of the Panasonic user's manual. After attaining properly shaped glow curves, acceptance criteria are applied to thermal noise and short term fading. These tests attempt to find a balance between the extremes of overheating or underheating a TLD. A few hundred TLDs are used for these tests and given the name heating reference TLDs. Ideally these TLD should be representative of the heat capacities found in the much larger field population.

Most processors select a few TLDs from each range of serial Id#'s to create a collective sample.³⁷ This method is certainly valid for new systems where the TLDs were produced at roughly the same time and minimal variations in heat capacity are anticipated. A more scientific method for selecting heating reference TLDs is possible by first measuring the HCF for a large segment of the population and then intentionally selecting an even distribution sampling. At a minimum, the extreme points of high and low HCFs should be addressed.

It is conceivable that a heating cycle can be found to accommodate a wide range of heat capacities when the reference heating TLDs are selected in this manner. If unable to accommodate all heat capacities with a single heat profile, the heating can then be tailored to the heat capacity most common in the larger population thereby disqualifying the smaller population that is not well heated. As additional TLDs are later added to the system, a HCF measurement is useful to determine if the heating reference TLDs remain representative of the entire TLD population. TLDs that were previously owned by another processor may also be evaluated for compatibility with existing populations.

ECF vs. HCF

The direct correlation between ECF and HCF is very weak. A sampling of more than 2,400 UD-802 TLDs is shown in Figure 6.5 through Figure 6.8. It is immediately obvious that there is no direct correlation between the magnitude of the ECF and the heat capacity under normal heating conditions. The ECF is proportional to the amount of light and hence the amounts of phosphor present. The results shown in Figure 6.5 through Figure 6.8 conclude that the variation in heat capacity is not particularly sensitive to the amount of phosphor present.

Figure 6.5 Correlation of HCF and ECF for Element 1

Figure 6.6 Correlation of HCF and ECF for Element 2

Figure 6.7 Correlation of HCF and ECF for Element 3

Figure 6.8 Correlation of HCF and ECF for Element 4

ECF Shift vs. HCF

Element Correction Factors (ECFs) are determined only after proper heating conditions have been established. The method used to establish proper heating is similar to the guidelines provided in chapter eight of the user manual. The ECFs generated with this heating profile are only valid for this same heat profile. ECF shifts as large as 50% are not uncommon when ECFs are applied to a different heating profile. To reduce this error, the Thermal Curve Adapter (TCA) can be used to compare different heating lamp profiles and assist in restoring a given heating profile.

Following a significant change in heating conditions, all ECFs must be re-established. This process is not trivial and can be quite lengthy and costly. Significant heating changes can occur when a heating lamp is replaced or the voltage and timing

parameters are changed. Attempting to read a TLD on a reader other than the reader used for ECF generation, can also give rise to heating changes if the readers are not well matched. Failure to re-generate new ECFs under altered heating commonly results in an apparent ECF shift. These shifts are highly erratic and seemingly unpredictable. Some TLDs will show an increased response, while others will drop sharply. Some users have reported a weak correlation between the nature of the shift and different production lots leading them to the conclusion that differences in heat capacity are primarily responsible for the unpredictable ECF shift.

There is strong correlation between the HCF determined by the above method when compared to a measured ECF shift. This is shown more clearly in Figure 6.9 through Figure 6.12(a, b, c). The results are depicted for 350 UD-802 dosimeters where each element is treated separately. TLDs were chosen that represent a large range of represented heat capacities. The distribution of measured HCFs appears in Fig a). Under normal heating conditions, an ECF was measured using the method described in Chapter 3. The ECFs show a typical distribution around 1.000 shown in Fig b). To produce an observed ECF shift, the lamp was replaced with one that is known to underheat the dosimeters. Results of measuring the ECFs a second time with the altered heating are shown in Fig c). By comparing the distribution of ECFs under different heating, it is obvious that both the mean and standard deviation of the ECF set have shifted.

To compare this shift to the measured HCF it is first necessary to define the ECF shift as follows:

$$\text{ECF Shift (\%)} = \frac{(\text{ECF}_{\text{altered heating}} - \text{ECF}_{\text{normal heating}})}{\text{ECF}_{\text{normal heating}}} \times 100$$

For this test, ECF shifts of $\pm 20\%$ were typical. A comparison of ECF Shift as a function of HCF is shown in Figure 6.13 through Figure 6.16. The nearly linear relationship between ECF shift and HCF confirms that variation in heat capacity is indeed the primary contribution to apparent ECF shifts following a heating change.

By grouping TLDs together into bins with similar heat capacity as measured by the HCF, it is possible to predict a new ECF with reasonable accuracy ($\pm 5\%$). TLDs with a similar HCF can use a common multiplier to modify their previously measured ECF. This new ECF could be used as an interim ECF until the normal re-ECF interval expires. Using this method, only a small population with a broad sampling of heat capacities is needed to generate new ECFs for large populations of TLDs. This technique is quite valuable when TLDs must be processed on another reader in case of an emergency or equipment failure. Application of this technique is recommended for emergency use only based upon the scatter observed in this limited data set.

Figure 6.9 Comparison of Heat Capacity Factor (Fig a), Element Correction Factor (Fig b) and New Element Correction Factor after heating change (Fig c) for UD-802 Element 1 $\text{Li}_2\text{B}_4\text{O}_7$ ($n=350$)

Figure 6.10 Comparison of Heat Capacity Factor (Fig a), Element Correction Factor (Fig b) and New Element Correction Factor after heating change (Fig c) for UD-802 Element 2 $\text{Li}_2\text{B}_4\text{O}_7$ ($n=350$)

Figure 6.11 Comparison of Heat Capacity Factor (Fig a), Element Correction Factor (Fig b) and New Element Correction Factor after heating change (Fig c) for UD-802 Element 3 CaSO_4 (n= 350)

Figure a) Measured Heat Capacity Factor (HCF) **Figure b) Element Correction Factor (ECF) for Normal Heating Conditions** **Figure c) Element Correction Factor (ECF) for Underheating Conditions**

Figure 6.12 Comparison of Heat Capacity Factor (Fig a), Element Correction Factor (Fig b) and New Element Correction Factor after heating change (Fig c) for UD-802 Element 4 CaSO₄ (n= 350)

ECF SHIFT vs HCF Element 1

Figure 6.13 Prediction of ECF Shift Based upon HCF for Element 1 ($\text{Li}_2\text{B}_4\text{O}_7$)

ECF SHIFT vs HCF Element 2

Figure 6.14 Prediction of ECF Shift Based upon HCF for Element 2 ($\text{Li}_2\text{B}_4\text{O}_7$)

ECF SHIFT vs HCF Element 3

Figure 6.15 Prediction of ECF Shift Based upon HCF for Element 3 (CaSO₄)

ECF SHIFT vs HCF Element 4

Figure 6.16 Prediction of ECF Shift Based upon HCF for Element 4 (CaSO₄)

Post/Main Ratio

When a TLD is read, the light output (glow curve) is integrated over three regions named Pre, Main, and Post as shown in Figure 6.17. The interval Pre is measured first while the TLD is just above room temperature. The Main region is used for primary dose interpretation. The Post region records the light output during the annealing step. For TLDs that are underheated, the full signal is not captured in the main interval and a small fraction is recorded in the Post region. By computing the ratio of post to main, it may be possible to infer which TLDs are being underheated. The Post/Main ratio is fundamentally a measure of the efficiency of emptying electron traps in the Main region. A high Post/Main ratio is attributed to low heating in the main peak and hence a good portion of the signal is left for the POST region. A low Post/Main ratio is representative of strong heating in the main peak leaving very little signal for the Post region. Since the supplied heat remains unchanged, the symptoms of over or under heating must be representative of heat capacity variations. This technique is more difficult to apply to TLDs with very deep traps from a high dose exposure. Although many TLD processing laboratories use the Post/Main ratio to select heating reference TLDs, the ratio is not a very reliable method to infer the heat capacity of a TLD.

To test the effectiveness of this method, a series of heat capacity measurements were performed and a HCF determined as described above. A Post/Main ratio was computed for the same set of TLDs from an ECF generation at a dose level of 300 mrem. For exposures at this dose level, nearly all traps are eligible for release in the main dose region. A comparison of the Post/Main ratio to the HCF is shown in Figure 6.18 through

Figure 6.21. A strong correlation would indicate that the Post/Main method is a suitable alternative method for inferring a TLD's heat capacity rather than a direct infrared measurement. Although, this alternative measurement technique can be performed more easily, the correlation in Figure 6.18 through Figure 6.21 show that the correlation is rather weak and a poor substitute for HCF measurements. The small amount of light recorded in the POST region does suffer from low signal problems and numerical rounding errors. The technique is more effective for those TLDs that are underheated and hence result in a higher Post/Main ratio. Perhaps this technique could be used more effectively if the TLD reader heating was lowered.

Typical Glow Curve

Figure 6.17 Glow curve showing the three PRE, MAIN, and POST peaks and integration region of MAIN peak.

HCF vs Post/Main (802s) E1

Figure 6.18 Correlation of HCF and Post/Main for Element 1

HCF vs Post/Main (802s) E2

Figure 6.19 Correlation of HCF and Post/Main for Element 2

HCF vs Post/Main (802s) E3

Figure 6.20 Correlation of HCF and Post/Main for Element 3

HCF vs Post/Main (802s) E4

Figure 6.21 Correlation of HCF and Post/Main for Element 4

CHAPTER 7

Conclusions

Historically, heat capacities of TLDs have only been understood qualitatively. To further understand the importance and significance of heat capacity variations, a quantitative method was needed. By installing an infrared detector in a TLD reader, it is now possible to directly quantify the heat capacity for a large number of TLD elements in a fully automated manner.

The application of this new tool has enormous implications for improving the quality of radiation measurements obtained from TLDs. Manufacturers of TLD materials can use this technique to assess product quality and consistency. Processors using TLDs may now selectively screen existing or newly purchased TLD populations to minimize heat capacity variations. TLDs previously owned by another processor may be evaluated for compatibility with an existing TLD population.

Heating adjustments for the TLD reader are greatly simplified. Sensible selection of a TLD heating reference set can be made easily and truly representative of the range of TLD heat capacities present in the larger population. By comparing the heat capacity of different lithium species, it may be possible to use a single TLD reader to accommodate many badge types. The temperature of any TLD can be determined by direct optical measurement under the TLD reader's true heating conditions.

Direct measurement of heat capacity can result in a cost saving in many ways. Following a change in heating parameters, it is common for a processor to reestablish

element correction factors (ECF) for an entire TLD population due to previously unpredictable ECF shifts of approx. $\pm 30\%$. This process can consume many months and is often quite expensive. The fundamental basis for the ECF shift is differences in heat capacity. It is possible to predict the new ECF shift using heat capacity measurements to determine the new ECF within $\pm 5\%$. Hence, the need for reestablishing an ECF can await the normal calibration schedule.

Heat capacity measurements also support academic research of TLD properties and heating techniques. The principal variations in heat capacity can now be directly linked to the polyamide glue drop variations. Given the poor correlation of ECF and HCF, it is clear that the amount of phosphor present in a TLD element is not a dominant contributor to heat capacity variations. Furthermore, heat capacity variations resulting from the type of phosphor are masked by the larger variations from glue drop contributions.

An important area of further study is now possible based upon this work. By reducing the size of the detector, it is conceivable that heat capacity measurements may be preformed simultaneously with glow curve measurements. With an electrical feedback circuit, the heating profile could be controlled dynamically to deliver the optimum heat tailored for each individual TLD element's heat capacity.

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Appendix A TLD Reader Parameter Dump and Diagram

[illegible]

PANASONIC UD-710A

- #1 PM TUBE ASSEMBLY
- #2 LAMP HOUSING ASSEMBLY
- #3 CIRCUIT BREAKER
- #4 INTERFACE PANEL

(Adapted from TLD Cleaning Procedure used at Pennsylvania Power & Light)

Appendix B InSb Detector Specifications

(Taken from Cincinnati Electronics)

**CINCINNATI ELECTRONICS CORP
STANDARD DETECTOR DEWAR SERIES**

DEWAR MODEL:	SDD-7854-S1	SERIAL #:	93-4100
TESTED BY:	T.S.SPAULDING	DATE:	09/21/93
DETECTOR ACTIVE AREA:	7.854E-3 CM2	FEEDBACK RESISTOR:	94.3 KOHMS

RESPONSIVITY (4.51 MICRONS):	2.99 A/W
D-STAR (4.51 MICRONS):	1.96E+11 cm(Hz)^0.5/W
RESPONSIVITY (BLACKBODY, 600K):	0.78 A/W
D-STAR (BLACKBODY, 600K):	5.13E+10 cm(Hz)^0.5/W
Q.E.:	0.82

Vsbb:	3.92E-01 V	Vs(4.51)	1.31E-02 V
Vn:	1.27E-05 V	Ad:	7.85E-03 cm^2
E(BB):	6.78E-06 W/cm^2	E(4.51):	5.91E-08 W/cm^2
GAIN:	100	Rf:	9.43E+04 OHMS
BW:	1 Hz	Wafer #:	5604
Tbb:	600 K	Td:	77 K

(Taken from Cincinnati Electronics)

(Taken from Cincinnati Electronics)

Appendix C Pre Amplifier Specifications

DETECTOR & MICROCIRCUIT DEVICES LABORATORIES

APPLICATION OF THE AM-300 LOW-NOISE PREAMPLIFIER

Applications Note

The AM-300 is a low-noise FET input operational amplifier particularly suited as a preamplifier for photovoltaic detectors (photodiode). It is ideally suited to small signal current, low-noise applications found in high performance photodetection systems. It is also versatile. Constructed of discrete components, feedback components may be changed by the user; this simplifies experimental work. The AM-300 is ideal as a laboratory tool for infrared detector (PV) evaluation.

soldered to the appropriate feed-thru pins. The output is via a standard BNC coax connector. The input leads should be as short as feasible. Shielding the input leads or using a shielded wire with the shield providing the C (+) connection has the disadvantage of increasing the total input capacitance which, in turn degrades noise performance and amplifier stability. Microphonics may also be observed with shielded cables. If a shielded cable must be used because of environmental field, it should be kept mechanically rigid as possible. Movement causes capacitance changes that induce spurious input currents. "Low-noise" cable such as HABIA CABLE'S SML50 also helps. The best input connection is a short one.

A block diagram of the AM-300 is shown in figure 1. The power supplies (± 15 volt @ < 4 millamp) and inputs are

Figure 1
AM-300 configuration

(Taken from Cincinnati Electronics)

Several features distinguish the AM-300. It is very low-noise. Both the input equivalent voltage noise ($\bar{e}_n \approx 7 \times 10^{-9}$ volts / $\sqrt{\text{Hz}}$) and the input equivalent current noise ($\bar{i}_n \approx 1.5 \times 10^{-15}$ AMP / $\sqrt{\text{Hz}}$) are extremely low. Photodiodes are capacitive transducers, thus both $\bar{e}_n$ and $\bar{i}_n$ contribute to the total system noise. The self-biasing input is internally adjusted to -3 millivolts (± 3 mv). This is optimum operating point for the Indium Antimonide photodiodes. The bias trim pot should not require adjustment unless the customer changes the R_f to a value that exceeds the detector resistance.

For proper operation, the + input of the amp must be connected to ground (see figure 1). For flexibility, such as use with special input networks, the AM-300's noninverting + input is provided separate from ground. Ground externally or to the ground tap located beside the board's + input. The input is grounded in SDD units.

The feedback network (Z_f) indicated in figure 1 is a customer provided option. Internal component standoffs have been provided for simplified modification of this network. The system response and noise levels are a complex tradeoff between detector characteristics, amplifier characteristics and the feedback network. If the user is not familiar with these considerations, CE Corp. will provide advice or suggestions.

Figure 2

The standard feedback network

The standard feedback component is a large valued resistor as shown in figure 2. Component Cf may either be stray or intentionally added to reduce frequency response.

Provisions have been made to implement the special T-feedback network of figure 3. The basic idea of this network is outlined as follows:

1. Use $R_s \ll R_f$ so that the d.c. value is still about R_f and the feedback noise is due to R_f .
2. If necessary, add a discrete Cf to make the total predictable and controllable.

Figure 3

The special T-feedback network

3. Use Cf to cancel R_f Cf rolloff.

4. Use Cs to control bandwidth.

In general, any T-feedback arrangement should be viewed with caution. The more standard (well-known) configuration shown in figure 4 replaces a large feedback resistor by a 3-terminal network proportioned to have the same effect with lower impedance levels and thus less susceptibility to strays. Figure 4 is unsuitable because of the increased "noise gain" and increased contribution of feedback component noise.

Figure 4

An unacceptable method of simulating $R_f = 10^6$ ohm with a three terminal network

Regardless of the selected feedback network, a good a.c. circuit analysis computer program is a help; it is especially useful once the nominal components have been selected. The applicable model of the AM-300 open loop gain is a r.f.c. value of 1.6 million with a gain bandwidth product of 7 megahertz. The rolloff is 20 dB/decade.

Note from figure 1 that the low impedance amplifier output is isolated from the output line with a series 51 ohm resistor. This resistor was included contemplating that users would monitor the output via a long coaxial cable. As with any other operational amplifier, the system may oscillate under capacitive loading. This is caused by effecting an addition pole in the open loop response with the interaction of the amplifier's open loop output resistance and the capacitance of the driven cable (≈ 30 pF/ft). The 50 ohm resistor isolates the output from the cable and gives a margin of stability with capacitive loads.

(Taken from Cincinnati Electronics)

Appendix D TLD Reader Heating Cycle

(Taken from Bio Data Systems)

Appendix E LabView source code listings

Appendix F Excerpts from Panasonic Reader Manual Chapter Eight.

Polyamide Backing. Each element is mounted on a layer of black polyamide substrate, which is the component of an element that is first struck by the Infrared heat wave. The polyamide must transmit a constant fraction of the heat wave toward the phosphor in a constant amount of time. If the polyamide were manufactured with the wrong thickness or with the wrong density, then the heat capacity of the element will be different than [from] the expected value. Any foreign material that settles on the polyamide when the dosimeter is being used will act as a diffuser or absorber of infrared heat. This will have the effect of creating an element with a high heat capacity, perhaps only until the foreign material is burned away. A common example of this condition is the presence of moisture on the outside of the polyamide due to humidity in the air or sweat from the worker.

Glue Drop. During the manufacture of each element, a drop of glue is placed on the black polyamide substrate, and the grains of phosphor are then dropped onto the glue. The glue is actually the polyamide compound in a liquid state. The glue drop must transmit a constant fraction of the heat wave toward the phosphor in a constant amount of time. If the glue drop were manufactured with the wrong thickness, with the wrong density, or with the wrong shape, then the heat capacity of the element will be different than [from] the expected value. There is some evidence that the shape of the glue drop is the most likely cause of heat capacity differences among elements from different production batches. There is little, if any, abuse by the user that could affect the glue drop.

Phosphor Grains. During the manufacture of each element, approximately 500 grains of the phosphor are placed on the glue drop while it is still wet. These grains have been carefully sieved to insure consistency among the elements. It is considered unlikely that slight variations in these grains among the elements will affect the heat capacity of the elements, although the number of grains will certainly affect the total light output of the element. However, light output is normalized by the proper use of ECFs.

Teflon Bubble. At the end of the manufacture of each element, a clear Teflon bubble is placed over the element to provide protection against environmental stresses. It is considered unlikely that the Teflon bubble will affect the heat capacity of the elements, although fogging of

the bubble will certainly affect the total light output of the element. However, light output is normalized by the proper use of ECFs.

Assumption 1. There are no significant differences in the heat capacities of the elements within the same production batch of dosimeters. A batch of dosimeters is assumed to be a production run made within a short period of time. The quality control in force during a production run seems to be good enough to result in essentially the same heat capacities for all of the LIBO elements and for all of the CaSO elements made during that batch process,

Assumption 2. There are small differences in the heat capacities of the elements from one production batch of elements to another. The batches are made at different times that are months, or even years, apart. The quality control procedures can allow for some differences in the heat capacities from batch to batch.

Assumption 3. If the heating conditions of a TLD reader are slightly strong, the reader will mask the small heat capacity differences among various production batches of dosimeters. Thus, weak heating conditions of a TLD reader will result in noticeable differences among dosimeters from different batches, but strong heating conditions will mask these differences. Excessively strong heating conditions of a TLD reader will cause additional problems (thermal noise, fogging of the Teflon bubble, burning of an element, etc.). Therefore, a good heating adjustment procedure for a TLD reader must avoid weak heating conditions and heating conditions that are excessively strong. This idea will become the basis for the heating adjustment procedure.

Assumption 4. The heat capacity of one production batch of dosimeters may, occasionally, be very different from the heat capacities of the other batches manufactured. Although this occurs very infrequently, it is to the user's advantage to check the heat capacity of each new batch of dosimeters purchased [sic] to determine if the heat capacity of the new batch is reasonably the same as those of the other batches purchased previously.

Assumption 5. The heat capacities of one type of Panasonic dosimeter may not be the same as the heat capacity of another type of dosimeter. For example, a processor that uses UD-802 whole body dosimeters and UD-809 neutron dosimeters may require two different heating adjustments of the TLD reader in order to integrate these two different types of dosimeters correctly. This difference in heat capacity

among the various types of dosimeters appears to be especially noticeable when comparing dosimeters with phosphors enriched in Li-6, Li-7, B-10, and B-11 to phosphors with natural LiBO.

Assumption 6. Regardless of how consistent the heat capacities are among new elements, the stresses of field use can affect the heat capacities of old elements. Anything that gets on the outside of the black polyamide substrate will increase the heat capacity of an element. These environmental stresses include humidity, sweat, dust, oil, and virtually anything else from the work place that can get to the elements and act as a diffuser or absorber of infrared heat.

IMAGE EVALUATION TEST TARGET (QA-3)

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