Characterization of a Thermal Reservoir for Consistent and Accurate Annealing of High Sensitivity Thermoluminescence Dosimeters in Brachytherapy Dosimetry

William Patrick Donahue
University of Connecticut - Storrs, willdonahue@snet.net

Follow this and additional works at: https://opencommons.uconn.edu/srhonors_theses

Recommended Citation
https://opencommons.uconn.edu/srhonors_theses/234
William Patrick Donahue  
Title: Characterization of a Thermal Reservoir for Consistent and Accurate Annealing of High Sensitivity Thermoluminescent Dosimeters  

Abstract:  

Unlike regular TLD, an accurate and consistent annealing of the high-sensitivity TLD at 240 °C for 15 minutes is challenging using conventional annealing ovens because the temperature in the oven chamber varies drastically over the 15-minute period after the opening (to put the TLD tray in) and closing of oven door. The temperature in the oven drops dramatically after the door is opened and ramps up gradually after the door is closed, often accompanied with significant temperature overshoot. Because an overshoot by more than 5 °C can significantly reduce the sensitivity of the TLD and the ramp-up profile varies with the duration of door opening, the goal of this project was to build a heat reservoir in the oven chamber to provide more stable annealing temperature to the TLDs. A heat reservoir was designed and manufactured. A LabView interface was written for accurate and efficient monitoring of the temperature in the oven chamber, the heat reservoir, and the TLD annealing tray. The temperature profile in the oven chamber was fully characterized for various conditions. Complete temperature profiles of the TLD annealing tray over the entire annealing process were measured and used to optimize the oven temperature settings. A successful and consistent annealing of high-sensitivity TLDs was carried out, which enabled the experimental tests of high-sensitivity TLDs for dosimetric characterization of low-energy brachytherapy sources. This thesis will review the theory of TLD dosimetry and summarize the experimental characterizations of thermal annealing of the high-sensitivity TLDs using a novel custom-built thermal reservoir.
Characterization of a Thermal Reservoir for Consistent and Accurate Annealing of High Sensitivity Thermoluminescence Dosimeters in Brachytherapy Dosimetry

William Patrick Donahue

A paper submitted in the partial fulfillment of the requirements for the University of Connecticut Honors Program in Physics

May 2012
Contents

Introduction: ........................................................................................................................................... 1

A. Thermoluminescent Dosimeters ......................................................................................... 1
B. Application of TLDs ............................................................................................................... 1
C. TLD usage .......................................................................................................................... 2
D. Chip Factor ......................................................................................................................... 4

I. Materials .................................................................................................................................... 5

A. Ovens .......................................................................................................................................... 5
B. New Annealing Parameters .................................................................................................. 5
C. Collecting temperature data ................................................................................................. 6
D. Annealing Trays .................................................................................................................... 7
E. Thermal Reservoir ................................................................................................................ 7

II. Methods ..................................................................................................................................... 8

A. Open Air data collection ........................................................................................................ 8
B. Heat reservoir experiments .................................................................................................. 8
C. Measuring the full annealing process ................................................................................ 9
D. Tray Comparison Readings .................................................................................................. 9
E. TLD Calibration ................................................................................................................... 9

III. Data .......................................................................................................................................... 10

A. Open Air Measurements ....................................................................................................... 10
B. Thermal Reservoir Measurements ...................................................................................... 11
C. Full Annealing cycle ............................................................................................................ 12
D. Tray Comparison ................................................................................................................ 13
E. Chip Factor Calibration ........................................................................................................ 15

IV. Discussion and Analysis ....................................................................................................... 15

A. Open Air Data ....................................................................................................................... 15
B. Reservoir data ...................................................................................................................... 16
C. Comparison of the Reservoir and Open Air .................................................................... 17
D. Full Annealing Temperature Profile .................................................................................. 18
E. Tray Comparison .................................................................................................................. 18
F. TLD Chip Factor Calibration ............................................................................................... 20

Conclusion ....................................................................................................................................... 22

References ....................................................................................................................................... 23
Appendix A .............................................................................................................................................. 24
Appendix B .............................................................................................................................................. 26
Appendix C .............................................................................................................................................. 29
Acknowledgements ................................................................................................................................. 31
Introduction:

A. Thermoluminescent Dosimeters

A thermoluminescent dosimeter (TLD) is a crystal structure that, when heated, releases light proportional to the amount of radiation incident on it. These devices allow users to quantize the amount of radiation given to a particular region and analyze dose distributions in target materials. TLDs come in varying sizes and forms, each type providing different properties. In this paper we will focus on micocube TLDs, which are approximately 1mm cubes.

TLDs are constructed from a dielectric material and doped with different elements to create the thermoluminescent properties. Doping the dielectric creates two types of impurities. The first impurity creates deep potential wells known as traps. These traps are what allow the dose measurements to be captured. The traps are able to hold either an electron or a “hole” left by an excited electron. The traps are deep enough to hold the electron or hole for a long period of time. The other impurity is a luminescence center. This is a location in the crystal lattice that emits light when an electron and hole combine. These are normally located at either electron and hole traps. The composition and number of traps in a particular type of TLD are dependent on the amount and types of doping agents used.

When radiation is incident on the TLD it excites an electron into an electron trap. The electron leaves behind a hole which moves into a hole trap. Useful traps are presumably deep enough to contain the electrons for a long enough time without room temperature thermal vibrations removing them from the trapped state. To release the trapped electron, the TLDs are deliberately heated. Depending on which is shallower a hole or electron might be released first or at the same time as each other. If the hole and electron recombine in a luminescence center a light pulse is released. Counting the number of light pulses and the temperature of release we are able to determine the dose provided to the TLD.

The traps described above are considered ideal traps. Two important real consequences are that not all traps are the same depth and some materials allow traps to move at room temperature. Some traps are shallow, allowing room temperature to excite the electrons into the conduction band, and allowing them to recombine with traps. This means that the dose measured from the TLD will vary in time. There has been some work on the topic (Fowler et. al, 1965) that has studied the long term decay of TLDs. The standard way to handle this issue is to take measurements in the first 24 hours following the irradiation (Attix, 1986). This causes a loss of stability. In many cases, such as the Li:F (TLD-100 & TLD-100H), special treatment is needed to lock these traps into place. This is called annealing, which was the primary focus of the research to follow.

B. Application of TLDs

In the field of Medical Physics, TLDs are used for many things. The primary use is for monitoring the radiation exposure of individuals who work constantly with radionuclides or other radiation sources. These are commonly seen as dosimetry badges. In radiation therapy there are two different areas of study to which TLDs are fundamental, external radiation beam therapy and brachytherapy. External Beam Therapy uses microwave waveguides to accelerate electrons and photons for treatment. TLDs provide the ability to directly monitor dose to a patient. This is accomplished by placing a TLD directly on the skin. Normally this is used to monitor the dose to a critical structure such as an eye. Also Treatment
accelerators undergo constant Quality Assurance (QA) tests, many small checks occurring daily. During initial commissioning and the larger yearly QA testing, the American Association of Physicists in Medicine (AAPM) requires independent confirmation of machine output (Nath, et al. 1994). TLDs are used to collect the data on the beam and then are mailed to an independent reading facility.

The other field in radiation therapy is brachytherapy. This is the use of radioactive “seeds” or other sources to treat the tumor directly. Seeds can be planted internally, for treating a prostate, or they can be used externally, such as a seeded plaque for treating eye disease. With the development of technology, treatments have become more complex requiring computer modeling software for planning. This software uses Monte Carlo techniques to show the dose distribution of the treatment whether it is a brachytherapy or external beam treatment. To be able to model this certain parameters must be known about the source. In brachytherapy TLDs are used as the standard for finding these parameters. The primary parameter is the dose rate, which is the amount of dose given to a prescribed distance in a certain unit of time. The other two functions are the radial dose function and the anisotropy dose function. The radial function is only along the axis perpendicular to the seed’s long axis. This measures the radial dose distribution. The anisotropy dose function takes this one step further and not only depends on the radius but also the angle from the central seed axis.

C. TLD usage

No matter how a TLD is being used it goes through the same primary stages during a normal use: annealing, irradiation, and reading. Irradiation is when the TLD collects its information. This step of course depends on the application of the TLD.

Reading the TLD is done with a specialized piece of equipment. The device, whose schematic is depicted below in figure 1, heats the TLDs and uses a photomultiplier tube to collect the output.

![Diagram of TLD reader](image.png)

Figure 1: (Rennhack, 2007) This figure is a basic diagram of a standard TLD reader. The photomultiplier tube does all the work collecting the data.
Due to the use of a photomultiplier tube that is tuned to the visible light spectrum, all other sources of light must be avoided. In the Harshaw 5500 used at Yale, the tray is not heated to raise the temperature of the TLDs. Instead the TLDs are heated using nitrogen gas. Nitrogen is inert so it will not react with the material or any other particulate that might have been collected, that could cause extraneous light emissions. This means that there are no opportunities for things like small combustion reactions that would produce light and cause a dose to be reported too high. Also its non-reactive nature prevents TLD degradation through other reactions. The reader controls the temperature of the TLD and records data in what is called a glow curve, figure 2.

![Glow Curve](image1.png)

Figure 2: (Rennhack, 2007) This is a sample Glow Curve. Normally peaks 1, 2, and 6 are ignored. 1 and 2 are unstable and are normally pre-annealed away either at room temperature or during the pre-anneal step on the reader.

The glow curve is the Intensity of light vs. the temperature. The collection program integrates this curve and outputs a measurement in charge. Prior to the use of a particular batch of TLDs, the TLDs are irradiated with different dose levels. This is used to construct what is called a dose response curve, figure 3.

![Dose Response Curve](image2.png)

Figure 3: In his textbook Attix has this chart as a representation of the dose response curve for different TLDs. TLD-100& TLD-100H dosimeters are most similar to the Li:F curve (Attix, 1986).
This has two portions, the linear lower region and the supralinear part. Depending on the type of TLD dopants and base material different linear ranges exist. The Li:F material of a TLD-100 has a very large linear range which allows for simpler calculations of dose. This curve also has a dependence on the energy of the radiation. When calibrating the dose dependence curve it is important to use an energy similar to the same as the energy to be studied with the TLDs. This energy dependence is due to the fact that the TLD sensitivity is affected by the linear energy transfer of the beam. To convert future readings of the TLD the output intensities are compared to the dose response curve. However for this curve to be accurate the TLDs must be handled carefully and the most important factor is consistent annealing.

Before each time a TLD is used it must be annealed to help set the trap system up as described earlier. The most common way to do this is to use the built-in annealing set-up that is built into many TLD readers. Cameron referred to TLD-100’s when he talked about special annealing procedures. In his paper he mentions a two-step annealing process that consisted of 1 hour at 400˚C, a cooling phase, and a 100˚C anneal for 24 hours (Cameron, 1964).

The annealing process must be very consistent to allow the TLDs to have reproducible results, because the annealing is responsible for emptying the remaining trapped electrons. Also in Li:F based TLDs annealing is responsible for resetting the trap locations and crystal structure. If the annealing process is not entirely reproducible, the TLD batch will not follow the same dose curve. If the dose response curve changes greatly between readings it is almost impossible to recover correct numbers from the TLDs.

D. Chip Factor

The TLDs used in this lab are microcubes. Their small size makes it difficult for the manufacturers to create perfect cubes. This means that the TLDs have the possibility to be rounded, chipped, or even have an odd geometric shape. While it is very hard to account for the shape, this can be ignored because of the small size of the TLDs. These shapes do create a different problem. As the shape changes and deviates from the perfect cube, the TLDs can become more or less massive. This means that the number of trap and recombination centers is different, for each TLD. This creates reading errors in the TLD, because if a TLD has more centers then the luminescence will be higher for a particular dose.

To correct for this deviation, chip factors are calculated. Chip factors are used to normalize the TLD output. These factors are calculated across an entire set and each individual TLD is assigned its own factor. That is why it is important to keep track of where TLDs go. These factors are calculated using, equation 1,

\[ CF_i = N \cdot \frac{R_i - BKG}{\sum_{j=1}^{N}(R_i - BKG)} \]

(1)

Where \( R_i \) is the reading of the individual TLD, \( BKG \) is the average background radiation, and \( N \) is the number of TLDs in the set (DeWerd, 2005). These factors can only be used when there is a reproducible annealing process and the TLDs are not misplaced or damaged. Placing the TLDs in the oven created a temperature change in the oven chamber, causing the oven to compensate by overshooting the desired temperature by more than 5˚C which could destroy the TLDs. The research in this thesis starts from this
point and proceeds by accurately characterizing the open air temperature of the oven. This is followed by the design and characterization of a thermal reservoir to control temperature variation.

I. Materials

A. Ovens

During research the most time was spent on the characterization of the high temperature oven (HTO). The HTO was a Barnstead International F62735. The chamber was 30 cm x 30 cm x 19 cm. This is a large cavity for annealing the TLD tray that will be discussed later. The heating elements in the oven were in the side, top and rear walls of the chamber. They were controlled by a temperature controller with feedback from a single probe near the top of the chamber. This oven is shown below in figure 4.

Figure 4: This is a general picture of the Oven, from the manufacturer documentation (Barnstead International F62735).

The low temperature oven used in the new annealing process was the same one used as the low temperature oven in the TLD-100 annealing process. Therefore we knew the stability of the oven was consistent. It was only necessary for the characterization of the entire temperature profile of the annealing process.

B. New Annealing Parameters

Due to the materials in TLD-100H and previous research it was determined that we anneal should the TLDs in the HTO for 15 minutes at 240°C (Davis, 2003). This was shown in the paper to produce good results. We then cooled the annealing tray for approximately 45 minutes on lead blocks to quickly remove heat. This was then followed by a low temperature anneal at 100°C for 2 hours. This came from the previous procedure, where we adjusted the time from 24 hours down to 2. The low temperature anneal was motivated by the lessened high temperature annealing cycle. Following the low temperature anneal the TLDs were allowed to cool for approximately 24 hours so they come back to room temperature.

The above described procedure was the goal process. Due to the fact that the time was shortened in the high temperature oven the fluctuations were more important. This was the reason for the creation of the aluminum thermal reservoir. Table 1, below, will shows the parameters for the entire annealing process for both types of TLDs.
Table 1: This Table shows a comparison of TLD annealing procedures. The TLD-100 Column represents the older procedure while the TLD-100H is the new procedure.

<table>
<thead>
<tr>
<th>Annealing Step</th>
<th>Parameter</th>
<th>TLD-100</th>
<th>TLD-100H</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Temperature Oven (HTO)</td>
<td>Temperature</td>
<td>400°C</td>
<td>240°C</td>
</tr>
<tr>
<td></td>
<td>Duration</td>
<td>60 minutes</td>
<td>15 minutes</td>
</tr>
<tr>
<td>Cooling Step 1</td>
<td>Duration</td>
<td>45 minutes</td>
<td>45 minutes</td>
</tr>
<tr>
<td>Low Temperature Oven (LTO)</td>
<td>Temperature</td>
<td>80°C</td>
<td>100°C</td>
</tr>
<tr>
<td></td>
<td>Duration</td>
<td>24 hours</td>
<td>2 Hours</td>
</tr>
<tr>
<td>Cooling Step 2</td>
<td>Duration</td>
<td>&gt;45 minutes</td>
<td>&gt;120 minutes</td>
</tr>
</tbody>
</table>

C. Collecting temperature data

To collect the temperature data one to two thermocouples were used depending on what was being studied. These thermocouples were exposed probe K-type thermocouples purchased from Omega Engineering Inc. Exposed probe varieties were used for the needed flexibility and for the small diameter of the probe.

To interface the thermocouples with the computer system two National Instrument TC01-USB Thermocouple interfaces were purchased. These interfaces came with built-in coding for use with the Labview system.

Labview was used to collect the temperature data. The graphical coding screen can be seen in appendix A. The program was designed based on knowledge from preliminary small scale trials with the oven. To reduce the number of data points collected, the program was written with three collection modes. The time intervals of collected data points can be seen in table 2. The third mode not displayed in the chart is a custom interval that can be set for any interval to be run for the entire interval.

<table>
<thead>
<tr>
<th>Long Cycle</th>
<th>Short Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>Measurement interval</td>
</tr>
<tr>
<td>0-2 hours</td>
<td>30 seconds</td>
</tr>
<tr>
<td>2-8 hours</td>
<td>60 seconds</td>
</tr>
<tr>
<td>8+ hours</td>
<td>15 minute</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: This table shows the timings for the different preprogramed modes. The left one was used during warm-up. The right one was used during door cycling.

The long cycle was designed to analyze the warm up profile of the oven. The short cycle was created for experiments involving disturbing the oven system. These will be discussed more in depth later but it includes opening and closing the door, as well as adding the tray to the thermal reservoir. All the data points collected were exported to a proprietary format that was then converted to a Microsoft Excel table for graphing and analysis. A free conversion tool provided by National Instruments was used to convert the file.
For later experiments the same program was used with an added thermocouple input. This allowed us to measure three temperatures at once allowing for more accurate readings when comparing the tray fluctuations in the open air and the reservoir. This is the diagram shown in Appendix A.

The user interface for the Labview application can also be seen in Appendix A. The UI included a real-time graph and temperature outputs when the program was running. It also included file save location dialogues, timers, and start and stop buttons. The length of data collection could be set through the user interface.

D. Annealing Trays

The trays used to anneal the TLDs are made from pure aluminum and have a copper removable lid. Because LiF TLDs are possibly reactive to copper, the lid should never touch the TLDs. The aluminum portion of the trays had 100 small chambers drilled in the top. These chambers were placed in a 10 by 10 grid that was labeled 1-10 on the top and A-J on the side. This labeling scheme is used to keep track of each TLD so that the correct Chip Factor is applied when calculating dose. Each tray had a small hole in the side to fit a thermocouple. There were two varieties of trays used. The first was an original from the TLD-100 process. These are thicker trays with the dimensions 12.6cm x 12.6cm x 1.3 cm. These were later replaced by thinner trays that were approximately half of the thickness of the thick trays. This was done to improve thermal heat transfer in the system as a whole.

E. Thermal Reservoir

The thermal reservoir was designed to reduce variations in the temperature during the high temperature annealing process. It is depicted in figure 5, resting in the oven and the original design specifications are shown in Appendix B.

![Figure 5](image)

*Figure 5: This is the Thermal reservoir resting in the oven. It is resting on aluminum blocks to raise it off the bottom of the oven and increase heat transfer. The slot is where the Annealing tray is placed.*

The tray slot was originally too narrow to accommodate the thick trays so it was machine milled to increase the thickness by 4 mm. This reservoir is made from the aluminum alloy 6061, which was chosen for its thermal properties. It was made in two parts to keep manufacturing costs down. The overall weight of the block was 25 pounds and the dimensions were 20 cm x 20 cm x 8 cm.
When the reservoir was placed in the oven it rested on 5 one-inch tall aluminum blocks to keep it off the floor and better center the block in the heating element regions. Also a small thermocouple hole was drilled in the bottom block. The hole was deep enough that a probe would rest under the tray near the back wall of the chamber. This thermocouple was used to denote the heat block and later showed how the block reacted to inserting a room temperature tray.

II. Methods

A. Open Air data collection

The data collected from the open air experimentation was done to prove that the oven was operating consistently and producing predictable results. These results also showed how the temperature varied during door cycling.

The first step was the characterization of how the oven warmed up. This was done using a single thermocouple. It was suspended in the center of the oven cavity using a custom holder that was suspended in the gas exhaust port on the oven. This holder allowed us to prevent motion of the probe, which would have caused fluctuations in the temperature being read. For these experiments the oven door started in the closed position. For collecting the data the computer was set for the long cycle. The Oven was allowed to cool overnight between each warm-up assuring that the oven was around the same starting temperature. Each trial was run for 4 hours, which made sure that the oven was stable before continuing to the next step. This step was run 4 times to collect statistical data.

The second set of data was the door cycling. This experiment showed how the oven temperature varied when the door was opened and closed. Once again the probe was suspended using the holder. In this experiment trials were run for three hours starting from the point when the door was opened. For this experiment the door was opened for 5, 10, or 15 seconds. Each of these times received three trials each. While the primary focus is on the first 15 minutes, the extra time was to see how the oven stabilized and reacted in the long run. The computer was set on the short cycle setting to allow for a better analysis of the data.

B. Heat reservoir experiments

Following the completion of the open air experiments, the aluminum block was inserted into the oven. This was done in a completely cooled state. The block was put on risers as described above. We inserted the rear thermocouple and made sure the oven probe was not touching the top of the block. For all experiments involving the reservoir two thermocouples were used. One was placed in the slot in the back; the other was either in the tray or the air chamber.

For the warm up cycles we used a custom milled aluminum block to hold the thermocouple in the center of the chamber. In this fashion we were able to monitor the air temperature in the chamber so that we could see how the air in the chamber reacted. Using the same collection method as above, we collected data on the warming up of the oven. Due to time constraints this was only performed once.

Once again using the Aluminum holder, data was collected for door cycling, using the short cycle method. To push the limits of the system a fourth time was added, 20 seconds.
C. Measuring the full annealing process

The next step was to completely measure the temperature profile for the entire 4 step annealing process. This process was long and involved. It began by making sure both ovens were up to temperature. The next step was to connect the two HTO thermocouples to the interface devices. The tray was inserted into the HTO for 15 minutes, sliding the chamber thermocouple into the tray slot. When the tray was removed and placed on the lead cooling block, one of the thermocouples attached to the computer was swapped for one that was now in the annealing tray. The other HTO thermocouple was swapped with one that was inserted in the LTO. After the 45 minute cooling period the tray was placed in the LTO and that thermocouple was inserted into the tray. The tray stayed in the LTO for two hours. Finally the tray was transferred back to the cooling blocks. For more clarity an outlined version of the procedure is attached, in Appendix C.

D. Tray Comparison Readings

This set of experiments was to see the differences in tray temperature when using the thermal reservoir and when the reservoir is not present. To test this the three thermocouple setup was used, so we could track the chamber temperature, the tray temperature, and the reservoir temperature at the same time. The door was kept open for 10, 15, and 20 seconds while the tray was being inserted. We tested these times both with and without the reservoir in the system. To reduce errors due to tray height in the oven, risers were inserted when the reservoir was not in the oven.

E. TLD Calibration

The TLD Calibration process for the TLD-100Hs consisted of the following steps. The first step was an anneal with the new annealing process. This is described in Section I-B. We then irradiated the TLDs using a Cs-137 irradiator, to a dose of approximately 50 cGy. They were allowed to sit for 24-hours and then were read using a Harshaw 5500 Reader. This process was repeated 3-times to create the chip factors discussed earlier.

At this time we chose not to perform any break-in process on the TLDs, which would have normally exposed the TLDs to the annealing process and irradiation, without reading, multiple times. This is because of concerns about the life of TLD-100H’s and not wanting them to degrade as quickly.
III. Data

A. Open Air Measurements

The open air measurements described in Section III-A, were taken in two parts. The first portion was the characterization of the oven warming up. The data collected is shown in figure 6. This data was captured using the long reading cycle, because the changes were fairly slow.

![Figure 6: This is a chart of the oven warming up. It has a very stable tail which means it reaches equilibrium and is very good at keeping it.](image)

Next we collected the door opening and closing cycles. This is displayed in figure 7 below. Only the first 15 minutes are shown in the chart because those are the only portions we were concerned with. The TLDs wouldn’t be in the oven for longer than 15 minutes.

![Figure 7: This Chart displays the temperature when the door of the oven is opened and closed while it is running. The time was started when the door was opened.](image)
B. Thermal Reservoir Measurements

The Thermal Reservoir was added to the Oven System. We set a new set point on the oven and then used the auto-tune setting on the oven. This allowed the oven controller to compensate for the load placed in it.

The first set of data of data collected was the warm up profile of the reservoir system. This has two sets of data, the first being the chamber temperature and the other is the temperature of the Aluminum reservoir itself. This data is displayed in figure 8.

Figure 8: This Chart shows the single trial of the heating of the Aluminum block. This took about 24 hours.

Next using the aluminum holder we collected data on the door cycles. This data is shown in figure 9, which displays the chamber temperature. It is important to note that the temperature scale is only a few degrees.

Figure 9: This shows the door cycling in the reservoir chamber. The error on each data point was ±0.29% of the value.
Another important feature to know is that the error bars are never greater than 1°C with an average of about 0.5°C. While this appears to cancel out in the data collected we will look at the data later using a different format. Our next graph with similar properties, figure 10, displays the temperature of the reservoir block.

![Temperature graph](image1)

**Figure 10:** This figure shows the temperature of the Thermal reservoir during the door cycling. The error on each data point was ±0.29% of the value.

### C. Full Annealing cycle

The Full temperature annealing cycle was the most difficult data to collect. Due to limited resources, thermocouples need to be swapped. Figure 11 shows the data for the time temperature profile for the annealing tray.

![Annealing profile graph](image2)

**Figure 11** This is the Annealing profile for the High Sensitivity TLDs. Only one trial was run.
The blank spots are the points where the thermocouples were being swapped into and out of the tray. During this time the thermocouples had not adjusted to the proper temperature and did not accurately represent the data.

D. Tray Comparison

The first data collected was on the tray temperature when it was inserted into the reservoir. Figure 12 shows the temperature of the tray from the time it was inserted up to 15 minutes, for varying door opening times.

![Figure 12: This is the graph showing the Reservoir tray warmup.](image)

Figure 13 shows the average reservoir and chamber temperature during these cycles.

![Figure 13: This chart shows the Reservoir and oven, lower and upper respectively, during the reservoir tests.](image)
Next we took the same data but without the reservoir. The tray temperatures are shown in figure 14 while the oven temperature and temperature near the tray, called top, are in figure 15.

**Figure 14:** This figure shows the tray heating up during the open air experiments.

**Figure 15:** This shows the oven and air temperature near the tray, top and bottom respectively.
E. Chip Factor Calibration

The chip factors were calculated using the outlined method. Table 3 contains the average TLD output for all three trials and table 4 contains the standard deviation of the output for each TLD.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>11207.749</td>
<td>10954.681</td>
<td>9738.816</td>
<td>10250.614</td>
<td>10427.759</td>
<td>10266.468</td>
<td>10213.024</td>
<td>10931.242</td>
<td>10276.034</td>
<td>10780.611</td>
</tr>
<tr>
<td>B</td>
<td>10559.312</td>
<td>10965.355</td>
<td>10381.637</td>
<td>11024.992</td>
<td>11166.453</td>
<td>10773.781</td>
<td>10313.935</td>
<td>10762.197</td>
<td>11253.940</td>
<td>10733.986</td>
</tr>
<tr>
<td>C</td>
<td>10715.762</td>
<td>11039.562</td>
<td>10517.486</td>
<td>9963.551</td>
<td>10196.474</td>
<td>10800.490</td>
<td>10047.766</td>
<td>11526.199</td>
<td>10125.740</td>
<td>10981.820</td>
</tr>
<tr>
<td>D</td>
<td>10926.020</td>
<td>11048.537</td>
<td>10603.546</td>
<td>11413.766</td>
<td>9504.040</td>
<td>9918.543</td>
<td>10952.687</td>
<td>9779.725</td>
<td>10665.327</td>
<td>11065.882</td>
</tr>
<tr>
<td>E</td>
<td>10975.204</td>
<td>10678.412</td>
<td>11124.096</td>
<td>10155.048</td>
<td>10568.666</td>
<td>10637.578</td>
<td>9451.449</td>
<td>10600.140</td>
<td>10519.716</td>
<td>11234.381</td>
</tr>
<tr>
<td>F</td>
<td>11081.210</td>
<td>10751.060</td>
<td>10894.474</td>
<td>10994.868</td>
<td>10810.163</td>
<td>10438.713</td>
<td>11100.532</td>
<td>9803.471</td>
<td>10923.660</td>
<td>10253.966</td>
</tr>
<tr>
<td>G</td>
<td>10492.196</td>
<td>10351.711</td>
<td>10656.496</td>
<td>10360.936</td>
<td>10988.992</td>
<td>10517.569</td>
<td>10631.895</td>
<td>10214.116</td>
<td>9461.831</td>
<td>10185.768</td>
</tr>
<tr>
<td>H</td>
<td>10959.684</td>
<td>10775.422</td>
<td>10281.304</td>
<td>10078.875</td>
<td>10618.804</td>
<td>9869.000</td>
<td>10791.293</td>
<td>10416.925</td>
<td>10622.237</td>
<td>9823.713</td>
</tr>
<tr>
<td>I</td>
<td>10888.453</td>
<td>10865.304</td>
<td>9976.850</td>
<td>11238.049</td>
<td>9922.610</td>
<td>10708.840</td>
<td>10235.040</td>
<td>10734.983</td>
<td>10729.334</td>
<td>10471.422</td>
</tr>
<tr>
<td>J</td>
<td>10955.720</td>
<td>10856.454</td>
<td>10903.662</td>
<td>10108.196</td>
<td>10346.658</td>
<td>10175.453</td>
<td>9740.724</td>
<td>10612.780</td>
<td>10681.709</td>
<td>10229.291</td>
</tr>
</tbody>
</table>

Table 3: This table shows the average thermoluminescent output of the TLDs from the three trials, in nC. This was done for the entire 100 TLD set. Table 4 contains the standard deviations for each chip.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>147.359</td>
<td>137.133</td>
<td>45.581</td>
<td>222.996</td>
<td>209.737</td>
<td>47.719</td>
<td>216.187</td>
<td>225.463</td>
<td>12.678</td>
<td>228.924</td>
</tr>
<tr>
<td>C</td>
<td>222.242</td>
<td>118.933</td>
<td>397.570</td>
<td>151.805</td>
<td>340.939</td>
<td>371.473</td>
<td>285.217</td>
<td>281.773</td>
<td>149.415</td>
<td>437.159</td>
</tr>
<tr>
<td>D</td>
<td>214.706</td>
<td>183.627</td>
<td>428.708</td>
<td>182.283</td>
<td>316.463</td>
<td>345.586</td>
<td>209.894</td>
<td>334.846</td>
<td>154.358</td>
<td>342.183</td>
</tr>
<tr>
<td>G</td>
<td>278.014</td>
<td>105.478</td>
<td>218.458</td>
<td>306.940</td>
<td>263.660</td>
<td>113.674</td>
<td>215.585</td>
<td>179.480</td>
<td>325.251</td>
<td>344.095</td>
</tr>
<tr>
<td>I</td>
<td>124.133</td>
<td>355.592</td>
<td>244.758</td>
<td>90.182</td>
<td>271.152</td>
<td>292.978</td>
<td>300.965</td>
<td>378.807</td>
<td>63.625</td>
<td>304.791</td>
</tr>
<tr>
<td>J</td>
<td>168.238</td>
<td>239.115</td>
<td>57.819</td>
<td>88.765</td>
<td>244.546</td>
<td>297.343</td>
<td>382.534</td>
<td>225.651</td>
<td>322.715</td>
<td>127.826</td>
</tr>
</tbody>
</table>

Table 4: This table is the standard deviation of the light output by each TLD for the three trial runs. This entire table has units of nC.

IV. Discussion and Analysis

A. Open Air Data

The open air data showed good results where the data was smooth and created a nice data set to compare to. In figure 8 we see the oven is very stable after its warm-up. This stability provides us with a firm foundation to add the thermal reservoir.

When cycling the door we noticed the exact issue we were worried about. The temperature dropped low and then went very high above our starting temperature. This overshoot is built into the oven to allow the oven to quickly return to the original state, when disturbed. However this temperature increase went to approximately 245°C at its minimum and at larger door openings to about
255°C. This large temperature variance would lead to the TLD losing some of its usable lifetime and changing the set of the traps. It could also completely destroy the TLDs at the upper limit. This would continue to change the results of the TLDs meaning they would not be reproducible.

There is also an important trend depicted: the fact that as the time was increased the temperature had a greater range of motion. This is a logical conclusion due to the fact that when the door is open for longer the air in the oven drops to a lower temperature. This means that the thermal probe on the oven is at a lower temperature and would cause the oven to begin heating. Because the oven has been auto tuned to its load, it over shoots the temperature by more to raise the temperature faster in the load. This is where the overshoot becomes dangerous.

B. Reservoir data

The use of the thermal reservoir created some of its own issues. The first one occurred in the warm up cycle. While the oven proved to be stable with the reservoir, it took approximately 24 hours to get up to temperature. This however meant that the aluminum reservoir would perform the task of holding the temperature closer to our desired temperature. This is seen in the fact that the response of the block to applied heat was much slower than the air temperature. This was why the aluminum was chosen as the material for the reservoir. During warm-up the block temperature slightly lagged behind the oven temperature due to the fact that the chamber was directly exposed to the air while the reservoir probe was near the center of the block. This delay in thermal propagation is what will prevent the temperature of the tray from exceeding the desired 240°C.

Next we looked at the effects of the temperature when the door was cycled. Once again it is important to notice that the scale of these graphs is not the same as that of the open air variation. The error on these charts was 0.29% which is very good but still produced a very large error when multiplied by the point value. When collecting this data 3 hours was left in between the trial runs of the oven. It is believed that this was not enough time for the oven and reservoir to come to full equilibrium. So as experiments were performed the starting temperature was reduced. Also due to the delay in propagation of heat a warmer outer temperature might have taken time to propagate to the core, where the thermocouple is. This would raise the temperature during the experiment.

However even with the large errors it is possible to see the same trend as the open air. When the door is open for longer it makes the temperature drop more. However the temperature in these trials failed to rise back up to the original temperature, the cause of the errors.
C. **Comparison of the Reservoir and Open Air**

With the two sets of door cycling data available it is time to compare them directly. To do this the data was converted to a percent difference so that the data could be easily compared. The open air data is displayed in figure 16, while the reservoir data is shown in the figure 17.

**Figure 16:** This graph shows the door cycling for the open air trials. All the data was normalized to the starting temperature of each trial run.

**Figure 17:** This graph shows the door cycling for the thermal reservoir trials. All the data was normalized to the starting temperature of each trial run.

Once again it is important to look at the scales. The reservoir percent change was about 100 times less than that of the oven without the block. This shows that the reservoir is performing as expected.
On the Reservoir graph there are two important things to notice. The first is the jaggedness of the graph. This is due to the noise in the signal on the collection equipment. This was present in all of the data but on the larger scales of most of the experiments it is not visible.

The second important point is the fact that the 10 and 15 second trials went higher than the 5 second trial in the testing. This is because of the oven response to the door opening. Looking at figure 7 we can see how the oven keeps the temperature higher for longer on those time scales. This same profile applied to the heating of the air outside of the reservoir, which is why the heating profile has higher temperatures at the end of the 15 minutes. When looking at figure 7 we can also see why the 10 second one dominates. The temperature drop is much less on the 10 second runs than it is on the 15 second runs, but the high temperature portion is just about the same duration for both. So the final temperature is higher.

**D. Full Annealing Temperature Profile**

The full annealing cycle with the thin tray allowed us to see the temperature of the tray through the process. During this single trial run the high temperature oven set up allowed us to reach 233°C in the 15 minute time window. The rest of the cycle met the expectations of the old annealing procedure. This allowed us to proceed with measurements using TLDs.

**E. Tray Comparison**

The first set of data seen in figures 12 and 13 allow us to draw some very interesting conclusions. The first one is that when the tray is heating it will come within a few degrees of the same value each time. The standard deviation of all the endpoints involving the reservoir was 0.488°C. This definitely falls within a consistency guideline of 2°C. What is more impressive is that this is independent of how long the door is open. This means that if you take a little longer or a little less time inserting the tray you will get the same results. Looking at figure 13 the lower line is the reservoir. It is nice to see a smooth drop that occurs due to the tray drawing heat and then have it rise slowly until the end of the time period. It was never able to fully return to proper temperature but this is to be expected as can be seen by the warm up profile in figure 8. The Oven temperature probe was placed next to the oven’s control thermocouple. This allowed us to look at the oven’s air temperature according to how the oven saw it. The oven’s temperature gradient required a high set point to create the temperatures we wanted near the tray.

In figures 14 and 15, the open air readings showed some similar results to those with the reservoir. The first one is once again that the tray reaches approximately the same temperature. This time the standard deviation is 0.480°C which is very similar. This is still independent of time the door is open, which is important for consistency of annealing as discussed above. In figure 15, the oven temperature probe was set at a lower temperature because the air around the tray needed less heat to be warmed to the starting temperature. This discrepancy is because the reservoir took up more volume and reflected heat energy as well as it absorbed it. Finally it is important to look at the “top” data. This data was taken with a probe just above the tray cover. This was done to replicate the data of the reservoir. We see a large dip in the beginning and then a rapid warm-toward the original temperature.

Figure 18 shows the temperature of the tray displayed on the same graph. This clearly shows how the reservoir differed from the open air annealing.
Figure 18: This shows both the data for the reservoir and open air systems. Error bars would be the same in those seen in figures 12 and 14 respectively.

In the beginning of the graphs it is possible to see the very quick rise in temperature from the reservoir set. Compared to the slow rising open air experiment this allows for quick trap clearing and then a long term peak later that will clear low level traps better. It is clear that the open air experiments will never reach this higher temperature and will always have some upper level traps still filled.

Figure 19 contains a comparison of the temperatures of the reservoir and the “top.”

Figure 19: This shows the temperature from the region near the tray. Error bars would be the same in those seen in figures 13 and 15 respectively.

This figure shows why there is the sharp early incline in the temperature of the tray when placed in the reservoir. Conduction is a much faster way to transfer heat to an object when compared to convection. The fact that the reservoir loses less heat than the air does means that the there is a better heat transfer
to the small tray. As we can see the air loses approximately 20°C for every additional 5 seconds it is open. While this doesn’t have an effect on the final tray temperature it does change where that flat peak occurs. The flat peak is created at the point where the oven finishes its overshoot and begins its first major descent. This is created by the time delay of heat propagation to the tray region and the fact that the oven has stopped actively providing heat. Later we can see that while the reservoir temperature continues to increase smoothly, the air temperature increases at varying rates. This is because of the oscillations that are suppressed in using the reservoir.

From this we are able to see that the TLDs are much closer to the goal of 240°C using the reservoir. It is important to notice that the TLDs are resting in small pockets in their aluminum tray with a copper lid covering it. This means that the TLD temperature is somewhere in between these two temperatures. This means there is always some uncertainty when determining the temperature of the TLDs; however it is possible to see that the tray and the reservoir quickly come to within two degrees of each other before the end of the test, whereas the air is about 50°C different.

### F. TLD Chip Factor Calibration

When working with TLDs it is important to realize that many things can affect their readings. Not all TLDs are perfectly shaped or have the same number of traps. To account for this the chip factors were calculated. In general a TLD which has a standard deviation of less than 5 percent is considered very good. Table 5 shows the percent standard deviation from the High Sensitivity TLDs.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.72</td>
<td>3.81</td>
<td>3.97</td>
<td>1.28</td>
<td>2.70</td>
<td>4.68</td>
<td>1.55</td>
<td>1.69</td>
<td>0.31</td>
<td>3.55</td>
</tr>
<tr>
<td>B</td>
<td>1.69</td>
<td>1.55</td>
<td>0.54</td>
<td>2.50</td>
<td>2.29</td>
<td>0.54</td>
<td>2.57</td>
<td>2.53</td>
<td>0.14</td>
<td>2.58</td>
</tr>
<tr>
<td>C</td>
<td>2.57</td>
<td>1.32</td>
<td>4.67</td>
<td>1.85</td>
<td>4.06</td>
<td>4.22</td>
<td>3.47</td>
<td>2.96</td>
<td>1.80</td>
<td>4.78</td>
</tr>
<tr>
<td>D</td>
<td>2.44</td>
<td>2.02</td>
<td>4.87</td>
<td>1.98</td>
<td>3.98</td>
<td>4.23</td>
<td>2.35</td>
<td>4.14</td>
<td>1.77</td>
<td>3.76</td>
</tr>
<tr>
<td>E</td>
<td>3.86</td>
<td>4.35</td>
<td>3.14</td>
<td>3.24</td>
<td>1.18</td>
<td>1.79</td>
<td>3.59</td>
<td>2.47</td>
<td>1.35</td>
<td>3.28</td>
</tr>
<tr>
<td>F</td>
<td>2.10</td>
<td>0.65</td>
<td>4.67</td>
<td>1.40</td>
<td>1.77</td>
<td>0.80</td>
<td>1.13</td>
<td>3.59</td>
<td>4.66</td>
<td>3.56</td>
</tr>
<tr>
<td>G</td>
<td>3.22</td>
<td>1.24</td>
<td>2.53</td>
<td>3.61</td>
<td>2.93</td>
<td>1.32</td>
<td>2.45</td>
<td>2.13</td>
<td>4.11</td>
<td>4.06</td>
</tr>
<tr>
<td>H</td>
<td>1.52</td>
<td>1.18</td>
<td>1.96</td>
<td>3.41</td>
<td>4.40</td>
<td>4.60</td>
<td>4.10</td>
<td>2.36</td>
<td>3.44</td>
<td>4.29</td>
</tr>
<tr>
<td>I</td>
<td>1.39</td>
<td>4.02</td>
<td>2.99</td>
<td>0.98</td>
<td>3.31</td>
<td>3.37</td>
<td>3.55</td>
<td>4.37</td>
<td>0.73</td>
<td>3.52</td>
</tr>
<tr>
<td>J</td>
<td>1.86</td>
<td>2.68</td>
<td>0.65</td>
<td>1.07</td>
<td>2.90</td>
<td>3.52</td>
<td>4.69</td>
<td>2.57</td>
<td>3.66</td>
<td>1.53</td>
</tr>
</tbody>
</table>

Table 5: This table shows the calculated percent standard deviation for each TLD. This was done by taking the standard deviation for each TLD and then dividing by its average output.

The Standard Deviations for this set are all below the 5% limit, so the TLDs can be used for purposes of source characterization and patient dose measurements. An important factor in the standard deviation is the consistency of the annealing process. The fact that these all are below 5% shows that the process is reproducible, although the annealing process is not the only factor that can change readings.

Table 6 shows the chip factors that were calculated using equation 1. These correction factors allow us to correct the thermoluminescent output to a normalized value. This allows us to compare the TLDs, and not just use the raw output.
This table shows many different things about the sets. It is important to remember that because each TLD is different, if we picked a different 100 TLDs at random from a set of 1000 it would not necessarily produce the results above. The average chip factor is 1 for both sets, this means that statistically the sets have a normal distribution of thermoluminescent output. The standard deviation of the chip factors is used to show the width of the Gaussian. They are on the same order of magnitude and for these sets the TLD-100H’s have a smaller distribution. The output standard deviations are also within an order of magnitude so the TLDs are comparable, however the TLD-100H in this case has a smaller distribution again. The average of the individual chip percent standard deviation is a small difference. This statistic shows that the sets of TLDs can be used with the same overall reliability.

The last parameter was the average output. Notice that the average output of the TLD-100H’s is approximately 10 times higher than that of the TLD-100. This is an impressive increase in output. This difference is made greater by the fact that the TLD-100H’s were irradiated with half the dose of the original ones. There is a 17.9% difference in their thermoluminescent output. This means that the TLD-100H dosimeters need less time to collect the same charge so lower dose can be measured more
accurately. The impact of the characterization experiments is these new TLDs will allow for a smaller dose to be measured, so that the time is significantly shorter. It might also provide the ability for seeds that have two different sources in them to be characterized. This was limited in the past because normally one of the sources had a very short half-life, meaning that many of the characterization experiments would not reach completion before the source degraded past useful levels.

**Conclusion**

The addition of a thermal reservoir to the High Temperature Oven provides a stable environment for TLD Annealing. This stability brings consistency and accuracy to the annealing process. The open air tray temperatures were short of the 240°C goal by about 60 degrees whereas the reservoir brought it to about 7 degrees difference. This is a large step toward the accurate annealing of TLDs, where the only difficult step is tuning the reservoir system to output the temperatures required. All the data from the tray experiments had results similar to those not involving the tray showing that the oven system is consistent and the tray has little effect on the 25 pound reservoir.

One ongoing experiment that is currently being carried out is using the TLD-100H’s to find the radial dose function, dose rate, and anisotropy dose function. This creates a profile for the seed that can be used in treatment planning. This test was to compare the two types of TLDs when it came to measurements using a source that has already been characterized, a Theragenics Model AgX100 125I brachytherapy source. Besides a time reduction from 38 to 3 days, for the calculation of the radial dose function, the TLD-100Hs have agreed within 6% of the value of the old TLDs. More data is needed to investigate the comparability of the results.

Another direction to investigate is different annealing parameters and seeing the effect on the sensitivity of the TLD-100H. Also more data should be collected on the full annealing process. A better tray could be built for testing the air temperature of the small chambers on the TLDs. All of this would create a better way to test other annealing procedures used by researchers. This would lead to more accurate and consistent results from everyone.
References


Appendix A

Three thermo.vi

C:UsersWillDropboxYale Summer ResearchApp Development3 thermo device\Three thermo.vi

Last modified on 4/6/2012 at 2:22 PM
Printed on 4/7/2012 at 8:39 PM
Appendix C

Characterization of Temperature Profile for Annealing

1) Things to check before beginning
   a) Thermocouple connections
      i) In Yale USB connector thermocouple 3 should be plugged in
      ii) In UConn USB Connector Thermocouple 1 should be plugged in
   b) Computer application settings
      i) Experiment Type: Custom time
      ii) Custom Interval: 2 sec
      iii) Length of Collection: 5 hours 30 minutes or more
      iv) File location: anywhere in the dropbox
   c) Use Hand held reader to confirm Block is greater than 240°C

2) 15 minute high temperature Annealing portion
   a) Start computer program at same time as opening the door
   b) Insert thermocouple into tray hole
   c) Insert tray into slot
   d) Close door (make sure thermocouple is not going to be caught)
   e) Start timer when door closes
   f) When 15 minutes completed
      i) Open door
      ii) Remove thermocouple
      iii) Remove tray
      iv) Close door

3) Cool Down 1 (45 minutes) (Continued from before)
   a) Place tray on lead block
   b) Start timer
   c) Insert thermocouple
   d) Swap thermocouple 1 for thermocouple 4
   e) Swap Thermocouple 3 for thermocouple 2
   f) Once 45 minutes completed remove thermocouple from tray

4) 2 hour Low Temperature Annealing (Continued from Before)
   a) Open Door
   b) Insert thermocouple into hole
   c) Place tray in center of chamber
   d) Close Door
   e) Start Timer
   f) When time is complete
      i) Open Door
      ii) Remove thermocouple
      iii) Remove tray
      iv) Close door
5) Cool Down 2 (2 Hours)
   a) Place tray on lead block
   b) Start timer
   c) Insert thermocouple
6) Cycle is now complete

**Important Notes:**
- Clear chart after thermocouple swap
- A standardized note sheet was used to document important times during experiments
- Follow annealing procedure for oven on time cyclings
- HTO should be ready after 48 hours
- LTO only takes 2 hours to warm up
Acknowledgements

First I would like to thank Dr. Ravinder Nath for allowing me to perform research in the Department of Therapeutic Radiology at Yale University. As my advisor, I would like thank Dr. Zhe Chen for providing me with an excellent project and any support I needed throughout the time at Yale. I would also like to thank Dr. Paul Bongiorni for teaching me everything I needed to know about the annealing process and provided materials on TLDs.

I would like to thank Dr. Cynthia Peterson for being my Thesis Advisor at UConn. She has been very supportive in all aspects of the writing and planning process for my report. I highly doubt I would have completed it without her help and motivation. For helping with my academic planning in the honors program, I would like to thank Dr. Philip Gould. His support throughout the project was greatly appreciated.