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Optical Calibration of TLD Readers

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13. ABSTRACT: The Navy uses thermoluminescent dosimeters (TLDs) on all of its nuclear warships. TLDs measure the amount of radiation a person receives through the use of a small internal crystal. Electrons in the crystal are excited to a higher energy state when they absorb radiation. If the crystal is later taken out of the TLD and heated to a high temperature, the electrons drop back to the lower energy state, emitting light. A TLD reader determines the radiation exposure by measuring the emitted optical energy. Presently, TLD readers need to be calibrated frequently to ensure the measurements are accurate. A reference light source is used to calibrate the output of the reader. However, the power emitted by this light source is not stable over time, resulting in poor calibration. For this project, four light sources were compared as possible alternatives. The sources are a commercial light emitting diode, a commercial laser diode, a scintillating C-14 doped radioactive source, and a tritium source. The first part of this project was to determine the cause of the instability in the output of the TLD reader. This included understanding the effects of environmental temperature variations on both the reader components and light sources. Consequently a temperature data acquisition system (DAQ) was developed to record the time variation of these temperatures. A second DAQ was then implemented to measure the optical power stability of each light source. After the power stability of each source was measured, the stability of the photomultiplier tube output in the reader was verified. Finally, since the Navy prefers to eliminate the use of unnecessary radioactive sources, various methods of guiding the light from the diode sources to the TLD reader using optical fiber were considered. The research determined that the Ocean Optics LED and the C-14 source are relatively temperature independent.

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Abstract

The Navy uses thermoluminescent dosimeters (TLDs) on all of its nuclear warships. TLDs measure the amount of radiation a person receives through the use of a small internal crystal. Electrons in the crystal are excited to a higher energy state when they absorb radiation. If the crystal is later taken out of the TLD and heated to a high temperature, the electrons drop back to the lower energy state, emitting light. A TLD reader determines the radiation exposure by measuring the emitted optical energy.

Presently, TLD readers need to be calibrated frequently to ensure the measurements are accurate. A reference light source is used to calibrate the output of the reader. However, the power emitted by this light source is not stable over time, resulting in poor calibration. For this project, four light sources were compared as possible alternatives. The sources are a commercial light emitting diode, a commercial laser diode, a scintillating C-14 doped radioactive source, and a tritium source.

The first part of this project was to determine the cause of the instability in the output of the TLD reader. This included understanding the effects of environmental temperature variations on both the reader components and light sources. Consequently a temperature data acquisition system (DAQ) was developed to record the time variation of these temperatures. A second DAQ was then implemented to measure the optical power stability of each light source. After the power stability of each source was measured, the stability of the photomultiplier tube output in the reader was verified. Finally, since the Navy prefers to eliminate the use of unnecessary radioactive sources, various methods of guiding the light from the diode sources to the TLD reader using optical fiber were considered.

The research determined that the Ocean Optics LED and the C-14 source are relatively temperature independent. The C-14 operates within the ± 1% power stability criterion defined by the Naval Dosimetry Center.

Keywords: thermoluminescent dosimeters, TLD reader, temperature compensation, laser diodes, light emitting diodes, scintillation

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List of Symbols and Acronyms

α	radioactivity, disintegrations/sec
Ω	fractional solid angle, dimensionless
θ	angle from vertical to side of PMT, radians
λ	wavelength of light, nm
μCi	microCurie (3.7 x 10^4 disintegrations/sec)
c	speed of light, m/sec
E	Energy of a single photon, eV
E_{avg}	average energy, keV
E_{max}	maximum energy, keV
E_{rate}	energy per time, keV/sec
h	Planck's constant, eV-sec
I_{th}	threshold current, A
l	light output of source
l_o	initial light output of source
l_{Opmt}	light output into PMT, photons/sec
l_{os}	light output from source, photons/sec
NDC	Naval Dosimetry Center
P	Power, watts
PMT	Photomultiplier Tube
$t_{1/2}$	source half-life, years
T	temperature, °C
T_o	temperature coefficient, K
TEC	Thermoelectric cooler
TLD	Thermoluminescent Dosimeter

Chapter 1: Background

Since the development of nuclear power there has been the need to monitor human exposure to radiation. Personnel radiation dosimetry is the science currently being used to monitor radiation exposure. It is used in a variety of environments ranging from the operation of a nuclear reactor on a ship to radiation research in a laboratory. In today's Navy all submarines are nuclear powered, and the majority of aircraft carriers are nuclear powered. With this in mind it is clear why the Navy is very interested in continuing research and development in the area of radiation dosimetry.

A thermoluminescent dosimeter (TLD) is the device that is used by the Navy to measure personal radiation dose. After exposure, the TLD stores the measured dose for a long period of time. There are many different types of dosimeters that are used throughout the nuclear industry. These include bubble dosimeters, film badges, track etch detectors and pocket dosimeters. Each of these is designed for different uses, but they all perform the same basic function.

Thermoluminescence occurs when a device is thermally stimulated. This results in the emission of light due to the removal of excitation. Excitation is the process of adding energy to the material, whereas stimulation is the action needed to release the energy added during excitation. There are many different forms of excitation that lead to luminescence in certain materials. These include mechanical excitation, chemical excitation, optical excitation and radiation excitation. The TLDs used by the Navy are sensitive to radiation excitation, and this type of thermoluminescence is of the highest concern for monitoring safety.[1]

The thermoluminescent process can be explained by a simple model. In an inorganic crystal lattice the outer atomic energy levels are divided into continuous allowed energy bands

[1] Horowitz, Yigal S. *Thermoluminescence and Thermoluminescent Dosimetry*. CRC Press. Pp. 3. Boca Raton FL, 1984.

separated by forbidden energy bands. The outermost filled band is referred to as the valence band. This is separated from the conduction band by several electron volts (the energy of an electron falling through a potential of one volt). The radiation excites an electron giving it enough energy to move from the valence band to the conduction band. The movement of this electron leaves a hole in the valence band. Impurities in the crystal lattice can result in other discrete energy levels in the forbidden energy region between the valence and conduction band. An electron that moved into the conduction band is able to "fall" into one of these defect regions, becoming trapped. These trapped electrons can return to the valence shell with subsequent heating, leading to thermoluminesence.[2]

The compound used in the Navy's TLD is Lithium Fluoride (LiF). The LiF is doped with copper, manganese, and phosphorous impurities in its crystalline structure. The impurities cause the defects that allow holes to form, and these "holes" can capture electrons when they are excited. The radiation given off by a source, such as a nuclear reactor, provides the energy to excite the electrons. These electrons then jump into higher energy levels from which the above process involving thermoluminesence occurs.

The light that is given off is measured and recorded by a TLD reader. The emitted optical energy is small, so it is directed into a photomultiplier tube (PMT) that converts the light into a charge pulse that is amplified on the order of 10^6.[3] The phenomenon of amplification in the PMT is based on secondary electron emission. Optically excited electrons are accelerated and caused to strike the surface of an electrode, called a dynode. This material is chosen so that the incident electron results in the emission of more than one electron from the same source.

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[2] Horowitz, Yigal S. *Thermoluminescence and Thermoluminescent Dosimetry*. CRC Press. Pp. 3. Boca Raton FL, 1984.

[3] Hammamatsu Application Notes. Photomultiplier Tubes R6094, R6095.

Multiple stages in the PMT must be used to reach the appropriate levels of amplification necessary for dosimetry. Each stage of the PMT consists of another dynode that emits increasingly more electrons as the signal propagates through the tube. The output signal from the PMT is measured and is then converted into a dose. This dose corresponds to the radiation exposure received by an individual and is used to determine the safety of people working in a nuclear environment.

The Navy is especially concerned with accurate dosimetry, because it must ensure the safety of sailors who work in close proximity to nuclear reactors and other nuclear material, as well as remaining an accredited reader of TLDs. The Navy is accredited to read TLDs by the National Voluntary Laboratory Accreditation Program (NAVLAP). The Navy developed the Naval Dosimetry Center (NDC) in Bethesda, MD to act as the authority for the dosimetric needs of the Navy. The NDC controls the Navy's DT648 Whole Body Dosimetry System which includes the dosimeters, the calibration machines and the readers. The NDC is able to read over 30,000 dosimeters per month from shore bases and vessels deployed across the world. One of NDC's primary responsibilities is to maintain an extensive database of all records for both health and legal reasons. The Navy has established a regulation limiting the amount of radiation an individual is able to receive quarterly, yearly, and for their lifetime. These limits can be found in the Rad-10 manual and are in compliance with the national standards set by the Nuclear Regulatory Commission.[4]

The instrument that measures the radiation dosages recorded by TLD cards is called a TLD reader. The TLD readers the Navy uses are made by Harshaw/Bicron Corporation, which was recently bought by Thermoelectron. Harshaw manufactures a variety of readers, all of

[4] United States, Naval Sea Systems Command, *Radiological Affairs Support Program Manual, NAVSEA so420-AA-RAD-010* (1991) II-2.

which measure radiation, though each is used for different applications. The Model 3500 TLD reader is the smallest reader Harshaw manufactures. Figure 1 shows the block diagram for the functioning components of the 3500 reader. It can only measure one TLD at a time, and the measurement must be manually initiated by the technician taking the readings. This is appropriate for users that only need to measure a small number of TLDs. The other models include the 4500, 5500, 6500, and the 8800 models. The 8800 is the most sophisticated model and is automated throughout most of the process. It can have 1400 TLD cards placed in it at a time. It automatically cycles through all of these cards and measures the radiation levels recorded on each card. Additionally, the reader scans a barcode on each card, so that the NDC can determine the individuals that may have been exposed to excessive levels of radiation.

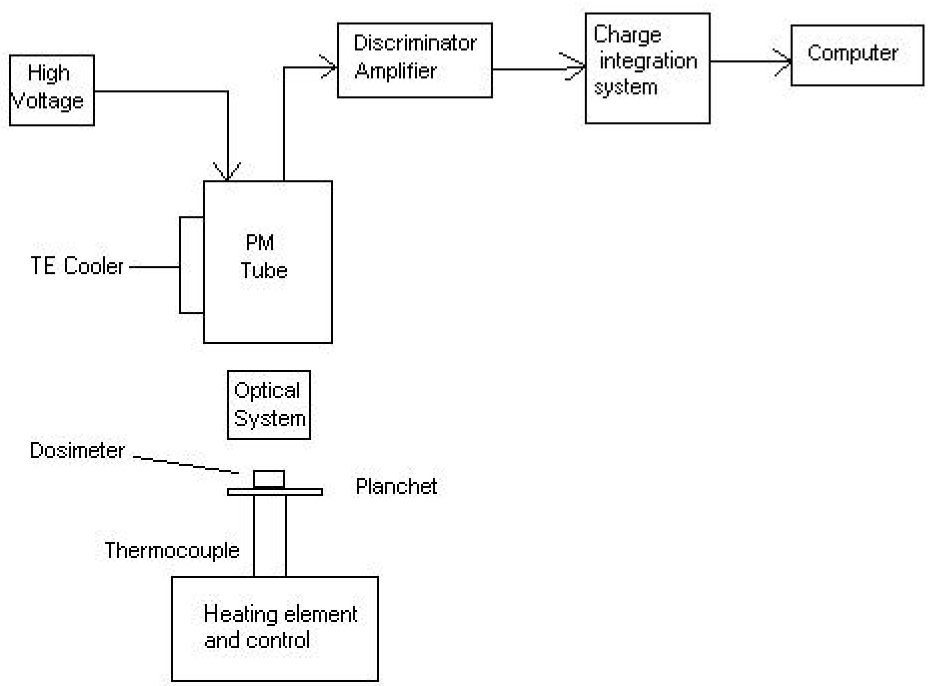

Figure 1.1: Block diagram of the 3500 TLD reader.[5]

[5] Horowitz, Yigal S. *Thermoluminescence and Thermoluminescent Dosimetry*. CRC Press. Pp. 10. Boca Raton FL, 1984.

The Navy is most interested in the 3500 and the 8800 models. The Navy has an interest in the 3500 model because it is the simplest version. Modifications and changes are most easily tested on this reader. Naval shore commands such as the NDC and shipyards have many 8800 model readers and use them to do the vast majority of the measurements that are recorded each year. The 8800 is faster than the 3500 because it can read the light from four thermoluminescent dosimeters simultaneously, while the 3500 can only read one chip at a time. In a TLD card there are 4 chips that must be read in order to determine the total dose. However, since the 3500 could be used in a shipboard application, it could provide immediate feedback to the users.

The current TLD readers used by the Navy experience various problems. This project focuses on calibration problems. The 3500 model reader is used because of its availability and the ease with which tests can be performed. The concepts learned on the 3500 can then be used in the 8800 model. The development of a reliable calibration system in the 3500 model is especially important to the Navy. The 3500 is small enough to be placed on a submarine. If the reader is poorly calibrated, the confidence in the readings drops immensely, limiting its effectiveness for dosimetry. [6]

[6] Naval Reactors. Personal Interview. January 03.

Chapter 2. Problem/Objectives

The 3500 and 8800 readers must be calibrated periodically to ensure accuracy in the measured dose. The TLD is not a self-calibrating system, so there is a need to calibrate them using a stable source. If such a source is not available then significant error can be introduced. A reference light source is currently used to produce a stable output for calibration of the TLD reader. The reference light shines into the PMT, simulating the light produced during a normal measurement procedure. Ideally the optical power emitted by the reference light would be constant and could be used to calibrate the TLD reader, thereby ensuring accurate readings. The current calibration method is unreliable in both models because the PMT output often varies by more than 1% over a 24-hour period.

The 3500 and the 8800 models each use a different type of source as a reference light. The 3500 uses a light emitting diode (LED) to calibrate the reader. The LED is located on the underside of a drawer. When that drawer is opened it places the LED directly under the PMT. This LED is constantly on, and when initiated by the technician, the PMT measures the light emitted by the diode and records the reference light reading.

The 8800 model uses a radioactive material that luminesces at an appropriate wavelength as the reference light. The radioactive material is Calcium Flouride (CaF_2) doped with Carbon – 14 (C-14), which emits ultraviolet light as the C-14 decays. The use of radioactive material in the reader complicates the shipping and transport of the 8800 model and results in a large administrative burden on the Navy.

Both the 3500 and the 8800 models experience similar problems with instability, even though the reference light is emitted by different sources. The ability to ensure proper operation of the TLD reader is greatly inhibited by the lack of stability in calibration. The Navy and

Harshaw both suspect the reference light is the cause of the instability. This project verified if the reference light was the problem and then considered a solution. Four different light sources are considered as possible solutions in the 3500 reader. These include a commercially available LED from Ocean Optics and a commercially available laser diode from Micro Laser Systems. Both sources are temperature compensated to provide constant power. In addition, a tritium radioactive source and a C-14 doped radioactive source were tested. The activity of the radioactive sources are below the exempt quantities determined by the U.S. Nuclear Regulatory Commission, indicating that the sources do not need to be licensed.[7]

Initially the research project focused on determining the cause of the instability in the PMT output in the 3500 model. While the LED in the current system was the suspected source of the problem, no tests had been done before to verify this assumption. Determining this was essential to solving the problem.

The reference light source must meet a variety of specifications to be practical. Table 2.1 shows the design specifications that must be met for a successful reference light. The ambient temperature of the reader can vary between 10 °C and 40 °C.[8] Humidity is not expected to be a problem for this reader, though it was varied in the tests to ensure that humidity had no negative impact on the performance of the reader. Stability in the optical output is the most important specification. The Navy's goal is to achieve no more than a ± 1% variation in optical output power over a one-month period. Ultimately, it is preferable if the light source varies by less than this amount. The wavelength of the laser or LED must be confined between 400 nm and 430 nm (blue to green light). This is the optimum operating wavelength of the PMT in the reader.

[7] "U.S. Nuclear Regulatory Commission." Available at www.nrc.gov
[8] Taken from "Specification: Temperature Compensated Stabilized Reference Light for Bicron TLD Readers." Available from Bicron.

Parameter	Range
Temperature Range	10 °C to 40 °C (50 °F to 104 °F)
Humidity	90% relative @ 40 °C
Stability	< 1% per month
Wavelength	Blue region (400 to 430 nm)

Table 2.1: Design parameters for the reference light in the TLD reader.

To test the stability of the alternative light sources a data acquisition system (DAQ) was developed using LabView[9] software and a Newport[10] optical power meter to record the output power of the optical sources. Additionally, a DAQ was implemented to record the temperatures of the reader during all the tests.

The next part of the research was to integrate alternative light sources into the 3500 reader. The radioactive sources easily fit into the current design of the reader. For the temperature compensated sources, fiber optic cable was used to provide flexibility given the mechanical constraints of the reader. A fiber optic splitter and a power meter were incorporated to simultaneously monitor the power stability of these sources as the TLD reader takes measurements.

Finally, the reference light sources were tested to ensure that they meet the Navy's standards for its TLD readers. The temperature must be varied over the specified ranges in order to simulate operation in a shipboard environment.

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[9] LabView Software, Version 6.1. Austin, Texas.
[10] Newport Multi-Function Optical Power Meter. Model 1835 C. Irvine, CA.

Chapter 3: Internship – Bicron and NDC

During July, 2002, two weeks were spent in Solon, Ohio with engineers at Bicron and one week was spent at the Naval Dosimetry Center in Maryland as part of an internship sponsored by the Naval Dosimetry Center. The internship provided opportunities to become familiar with the readers used in this research and to provide a focus for the research.

One week was spent learning about the basic concepts of dosimetry, specifically, how energy given off by the radiation is captured and then released in the form of light. The next part of the internship was to become familiar with the two readers that are used in this research. The 3500 was simpler and easier to learn than the 8800. A DOS program is used to control the readings in the 3500 reader. The output of this DOS program is shown in Figure 3.1. The program was also used extensively at the USNA to collect data for the project. The dose is represented by the integrated charge measured by the PMT and is displayed in nano-coulombs in the upper right-hand corner at the conclusion of each read (i.e. 314.1 nC). The program records the dosage from each read, which can be exported to an Excel spreadsheet. In the 8800 model the program is Windows based and more user friendly. However, the output contains the same information. The similarities in the output of each reader made it easy to become familiar with both readers over the course of the internship.

During the last week at NDC, trends in data that had already been recorded with actual TLDs were studied. The NDC had a large file of reference light readings that had been recorded during the previous weeks by two readers, each taking readings in the same room. Since the readers were in close proximity, environmental causes of problems in the readers could be correlated.

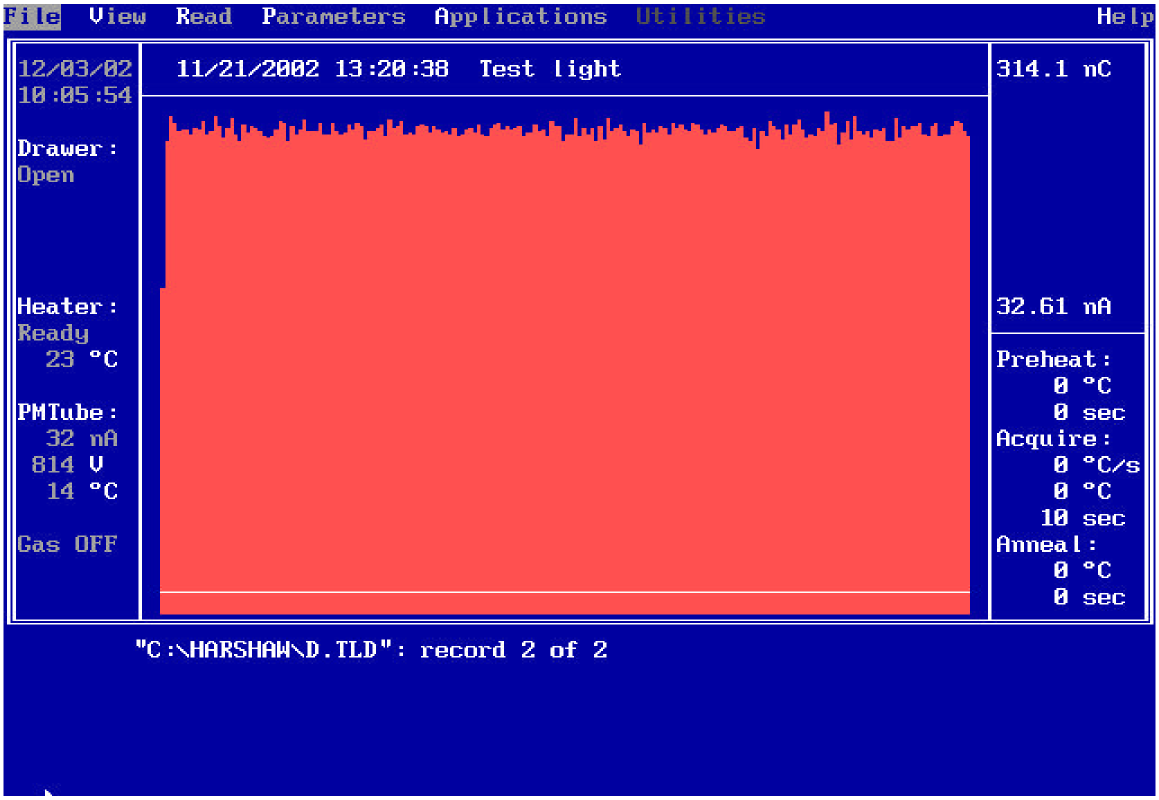

Figure 3.1: Screen capture of TLD shell program used in measurements

The first step in analyzing this data was to organize all the readings in order of time and date. This allowed measurements from one reader to be compared to those of the other reader within the room. The standard deviation of all the readings were compared to find any correlation between the readers. The data indicated that the readings varied as much as ± 6%, and both readers in the room had similar results. When one reader output varied the other would almost exactly mimic this change in output. This close correlation seemed to indicate that the cause of the instability was an environmental issue. Unfortunately, this data has been lost due to a theft of the laptop computer on which it was stored.

Chapter 4: Problem Identification

As testing began in the 3500 reader, shown in figure 4.1, four possible causes of the instability were identified. They were changes in temperature in the electronics on the reader, stray light entering the PMT, varying voltages in the wall socket, or instability in the optical output power of the LED reference light.

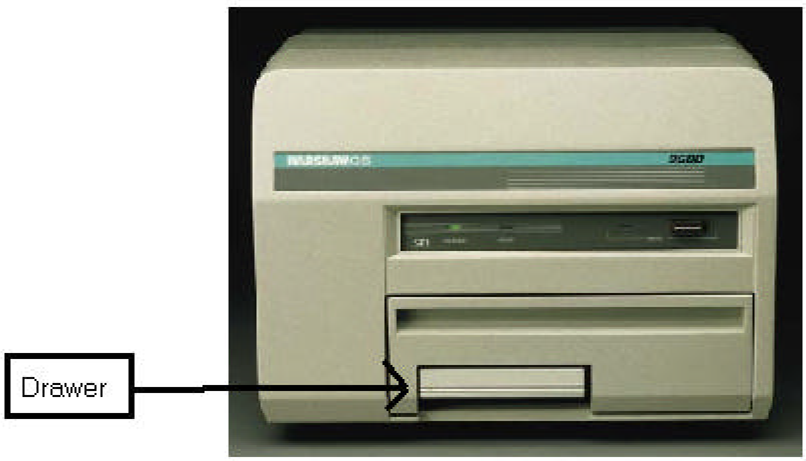

Figure 4.1: The 3500 TLD reader. The drawer is the center rectangle that is identified by the arrow.

First the stability of the reader was tested as the temperature of the PMT output electronics was varied. To test this, an extender board was obtained from Bicron. This allowed the electronics to be moved outside of the machine so that direct heat could be applied to the board. This board, shown in figure 4.2, processes the output signal from the PMT.[11] A temperature change in these electronics could affect the properties of the components, leading to variation in the output charge in Figure 3.1. With the extender board in place, a blow dryer was used to heat the board to a very high temperature. As the board was heated, reference light

[11] Mode 3500 Manual TKD Reader Technical Service Manual. Publication No. 3500-0-S-1099-001. October 5, 1999.

readings were continually taken to see if there was any variation in the output. The temperature on the board was raised from 68° F to 120° F, but no variation was observed in the output charge.

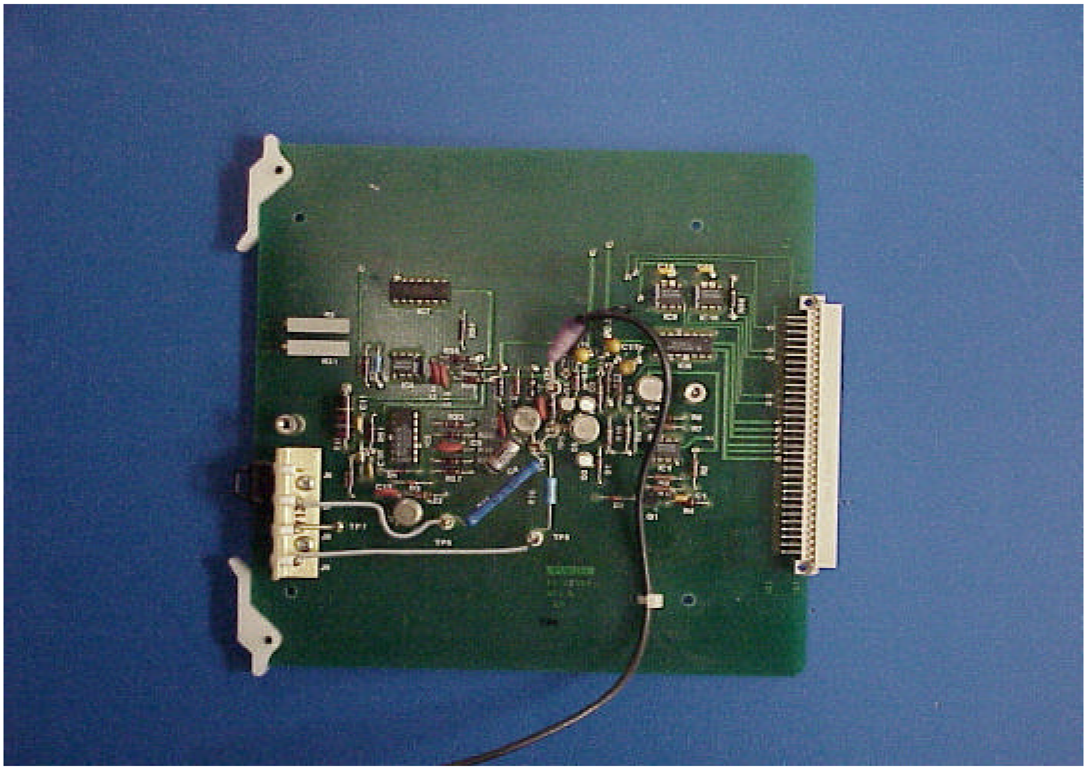

Figure 4.2: Bicron photronics board for the 3500 TLD reader.

The second possibility investigated was whether stray light could be a source of inaccuracy. To assess this, reads were first taken with all the lights on within the room. Later in the evening all the room lights were turned off and the same set of tests were conducted. Again, no change in the output was observed.

Another possible source of error was the varying voltage in the building wall socket. During a series of tests it was noted that the voltage in the wall socket varied from less than 120

V to 126 V. A variac was used to vary the voltage into the reader from 100 V to 125 V in 5 V increments. No variations were noted in the PMT output for any of the readings.

The last possible source of error was temperature variations of the LED circuitry. The LED is attached to a small board that provides the current to run the LED, as shown in Figure 4.3. The drawer in the reader, pictured in Figure 4.1, was left open to take readings as the LED was heated using the blow dryer. There were immediate changes in the output of the TLD reader as the temperature varied. Figure 4.4 shows the temperature dependence in the output charge in nC.

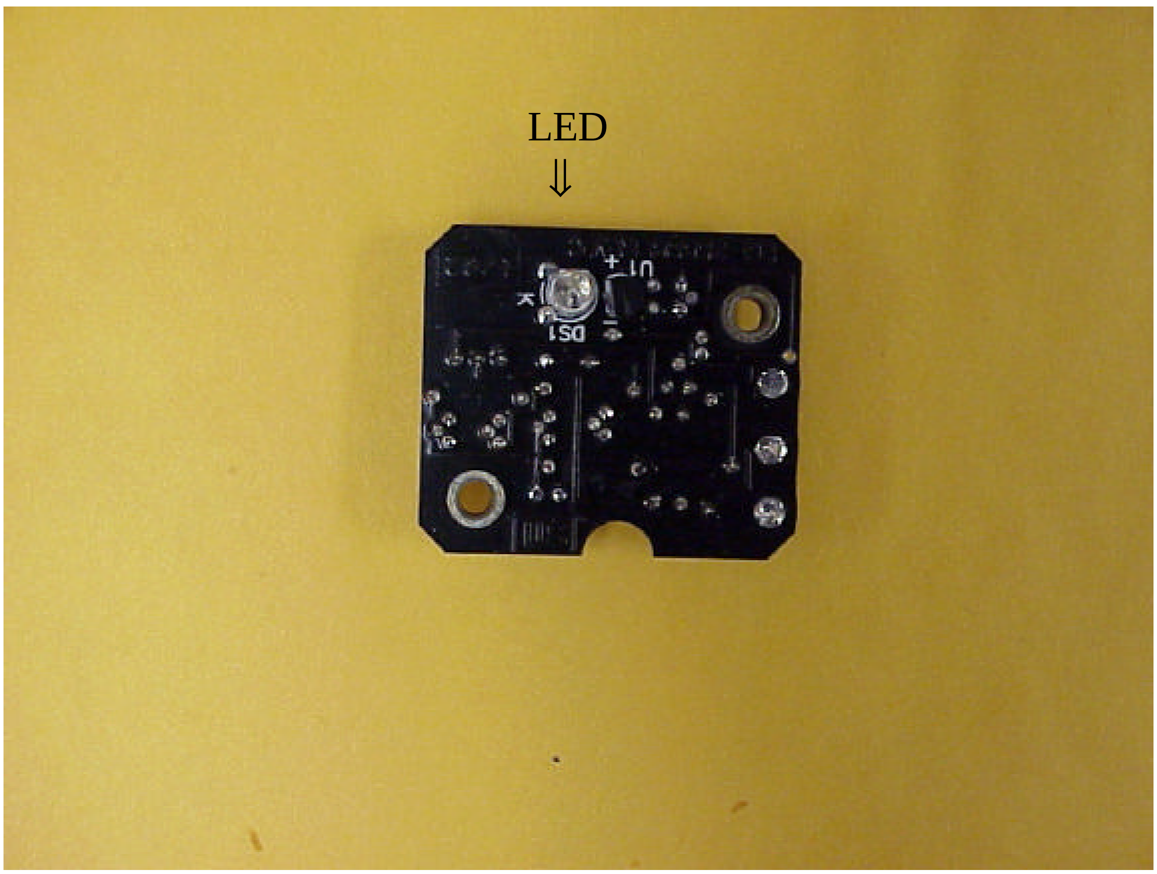

Figure 4.3: LED board from the Bicron 3500 TLD reader.

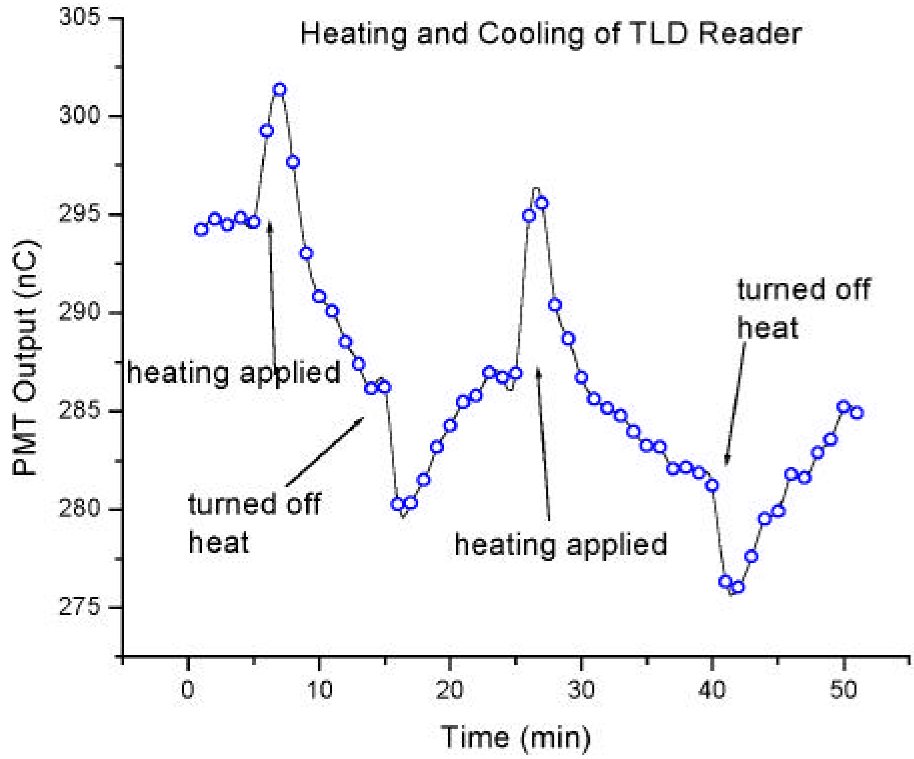

Figure 4.4: Model 3500 Output while heating and cooling the Bicron LED board with a blow dryer.

This experiment confirmed that the problem must be related to the reference light source. Thus, during the course of a day, changes in the room temperature also result in a varying output in the TLD reader. This experiment (results shown in Figure 4.4), however, was not conducted according to the specifications defined by Bicron and shown in Table 2.1. The temperature at the LED was raised to nearly 120° F, well above the 104° F maximum operating temperature.

One other concern was whether the problem was confined to the LED and totally unrelated to the PMT. The PMT in the TLD reader is in direct contact with a thermo-electric cooler that maintains its temperature. The thermometer is located in that region, and the output of that temperature is displayed when a reading is being conducted (see Figure 3.1). The temperature in the PMT was observed to fluctuate between 14 and 15 °C. This is within the parameters defined in the manuals for operating the TLD reader. Throughout the heating of the LED, the temperature at the PMT remained constant, further ensuring that the problem was with the LED in the current reader.

Based on the properties of an LED some variation in the output was expected, but it must be tested within the instrument's design parameters. Three different temperatures were selected. These temperatures were 80°, 85°, and 92° F (26.6°, 29.4° and 33.3 °C respectively). It was expected, based on previous results, that the charge output of the LED and PMT assembly would be the lowest when it was exposed to the highest ambient temperature. The temperature coefficient of most LEDs is negative (in dB/°C) with respect to power, so that the optical power drops as temperature increases.[12] In these experiments the initial ambient temperature was between 68-70° F before heat was applied. Figure 4.5 clearly shows that the output was lower at higher temperatures. These experiments were difficult to conduct with the blow dryer since the temperatures were hard to control. A better test method was required for further experiments. This is discussed in the next chapter.

[12] Mynbaev, Djafa K. and Lowell L. Scheinev. *Fiber-Optic Communication Theory*. Prentice Hall, 2001, pg 325 – 329

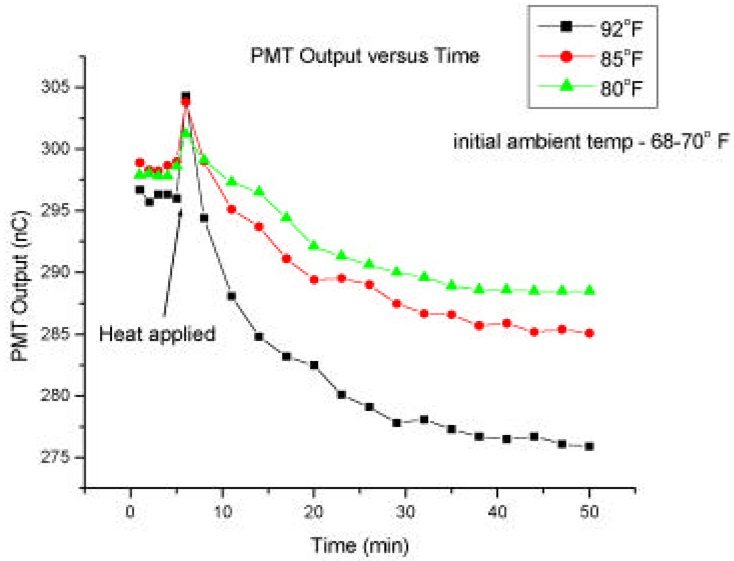

Figure 4.5: Initial tests comparing the output at the ambient temperatures of 92°, 85°, and 80° F.

Chapter 5: Test Setup

To better monitor the operating environment of the TLD reader, an environmental chamber was obtained and modified to control both temperature and humidity. A heat gun was included in the chamber and attached to a temperature regulator to accelerate the heating of the environmental chamber. The heat gun also helped to maintain a constant temperature in the chamber. In addition to the heat gun, a humidifier was used to control the humidity. Lastly, the TLD reader was placed in the environmental chamber, as shown in Figure 5.1.

Figure 5.1: Environmental chamber with 3500 model reader.

Another problem encountered with the TLD reader was that it had to be manually operated to take reference light readings by pushing a button on the front of the reader. This posed two problems. First, long term readings were impossible to take regularly without constant monitoring. Second, it was not possible to initiate a reading with the TLD reader in the environmental chamber. To solve this problem, the electrical circuit controlled by the button was modified.[13] A computer external to the chamber was used to drive the electrical signal

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[13] Mode 3500 Manual TKD Reader Technical Service Manual. Publication No. 3500-0-S-1099-001. Drawing No. D-24575. October 5, 1999.

initiating each read. The reader was driven from the printer port of the computer, and a computer program was written to set the time interval between each read.

The ability to conduct long term readings meant that the output of a reference light source could be monitored for temperature changes similar to those that occur over long periods of time. The environmental chamber actually simulated the temperature variation of a room fairly well. Its temperature would fluctuate in a similar manner to the way a room may change temperatures with an influx of people.

To record the temperatures throughout the readings, a temperature DAQ was developed. The program Omega Personal DAQ[14] was acquired and used for taking these recordings. The setup for the temperature DAQ was fairly simple. The computer was connected to the DAQ through the USB port which supplied it with both power and a means of communication. A temperature probe was attached to the DAQ and was placed next to the equipment that needed to be monitored. The rate at which the recordings were taken was controlled, so that readings were correlated with the measurements of optical power with the power meter. Figure 5.2 shows the user interface for the temperature data acquisition system.

To record the power output of a laser or LED, a second DAQ had to be used. LabView is a program that uses icons to graphically represent various programming functions rather than having to write an entire function in a programming language. A user interface must be constructed by using a set of tools and objects. Then, using the dataflow programming logic, the functions are created in order to make a program that will control different devices. Figure 5.3 shows what a typical screen looks like when using the dataflow programming in LabView.

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[14] Omega Personal Daqview. Omega Engineering, Inc. Stamford, CT.

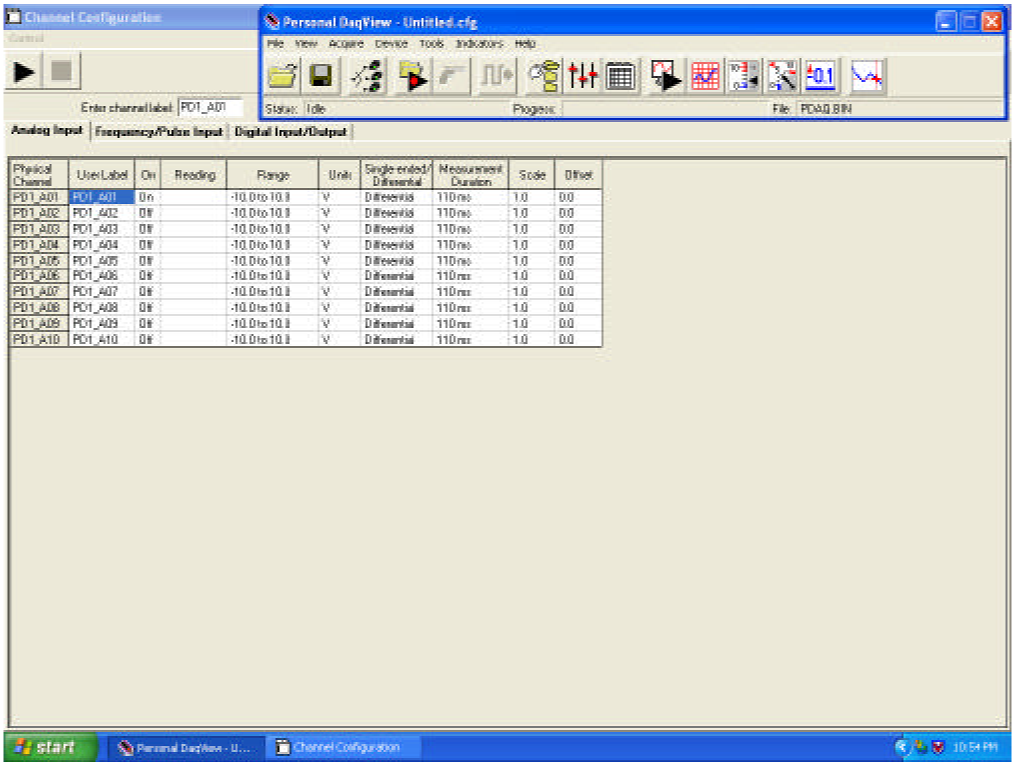

Figure 5.2: Temperature DAQ user interface.

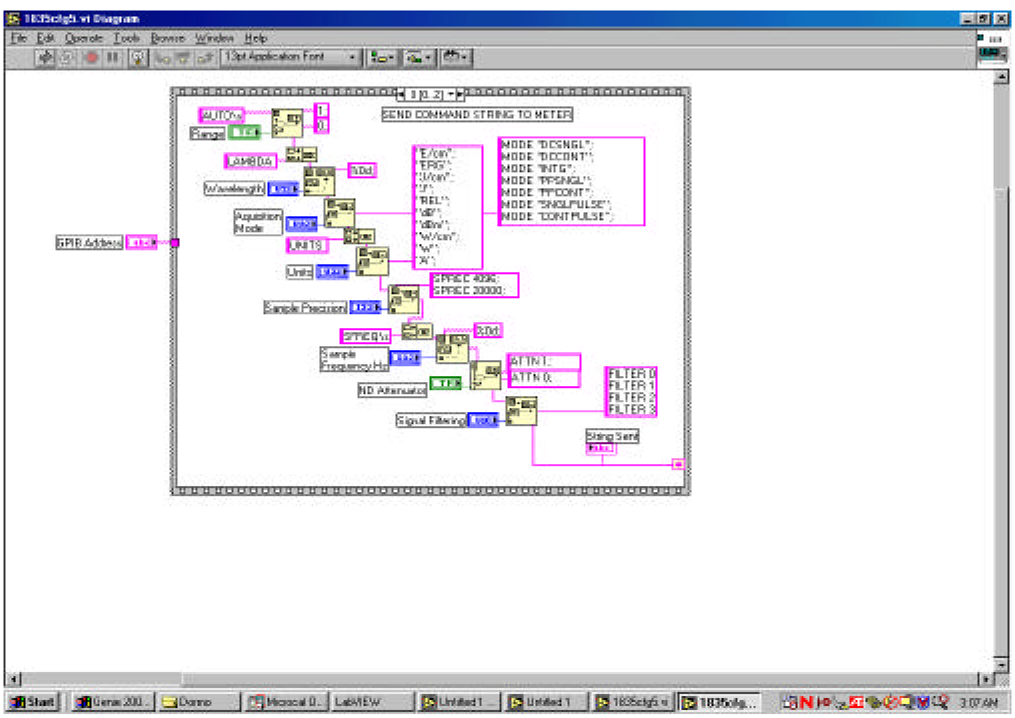

Figure 5.3: LabView dataflow programming.

For this research the Newport optical power meter already had a LabView driver that was designed to record readings from the power meter. This driver, however, was not able to accomplish all of the desired tasks, so the driver had to be significantly modified to perform the appropriate tasks. The driver interface is shown in Figure 5.4. The driver designed by Newport was able to take readings, but it was not able to write them to a spreadsheet. The program was altered so that the reading from the final output was then entered into an array. Upon completion of the readings the array was automatically written to an Excel spreadsheet in scientific format.

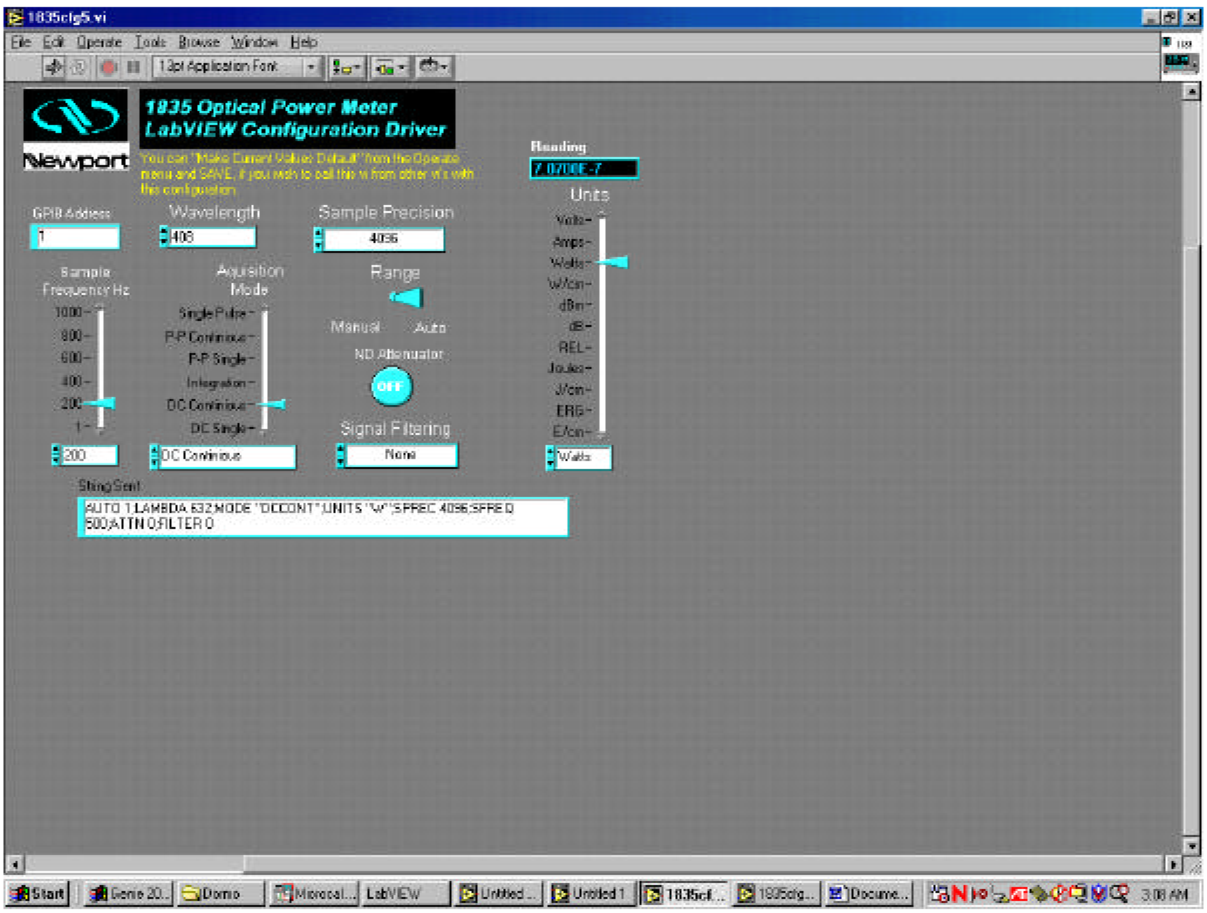

Figure 5.4: Driver interface for Newport Optical Power Meter.

The Newport power meter also had to be slightly altered to make it compatible with the LabView software. Initially the GPIB address was not defined. The GPIB address had to be adjusted (i.e. set to 1) so that the Lab View driver could communicate with the Newport power meter. The block diagram in Figure 5.5 shows the information flow in this setup.

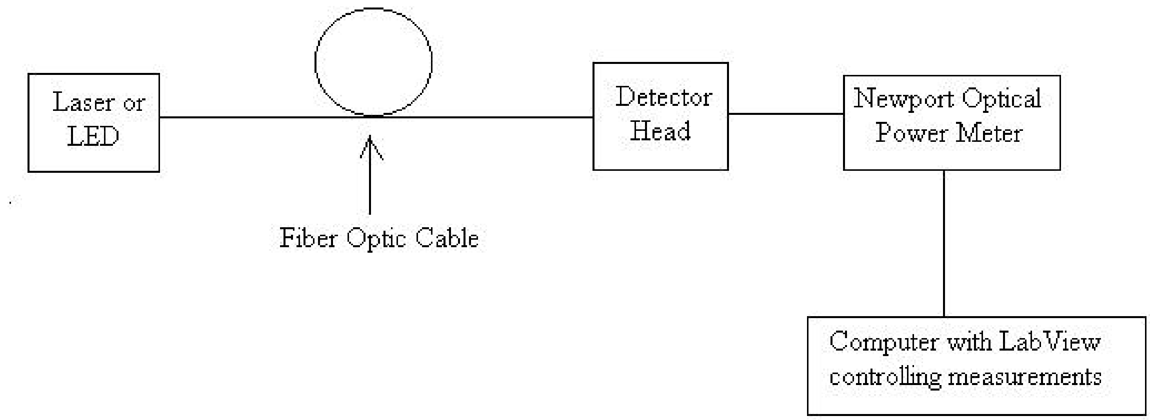

Figure 5.5: Setup for laser and LED into the Optical Power Meter.

The final part of the test setup was to design a system that would integrate the laser and LED sources with the TLD reader. The Bicron LED in the current reader is small enough that it is easily attached to the bottom side of the drawer. This drawer is opened and closed to allow access to the heating tray of the TLD reader, but it is difficult to temperature compensate this LED in the limited space this requires. A fiber optic cable is the most effective way to get the light from the laser and the Ocean Optics LED to the TLD reader. Additionally, a fiber optic splitter can be used to provide an independent monitor of the calibration process. In order to mount the fiber optics on the TLD reader so that it illuminates the PMT, a special device was designed that would hold the fiber optics in place. A standard fiber optic FC connector was attached to an aluminum plate that was then screwed into the bottom of the drawer, as shown in figure 5.6. This plate served the function of holding the fiber optics in place, as well as shielding the PMT from any stray light.

The 3500 TLD reader did not have adequate space to allow a fiber optic cable to be attached to the bottom of the drawer. A slit in the bottom plate of the TLD reader was milled to provide an adequate opening directly below the center of the drawer. The fiber optic cable is attached to the connector plate, which then extends through the bottom of the reader directed toward the PMT. Figure 5.7 is a another picture of the bottom of the TLD reader.

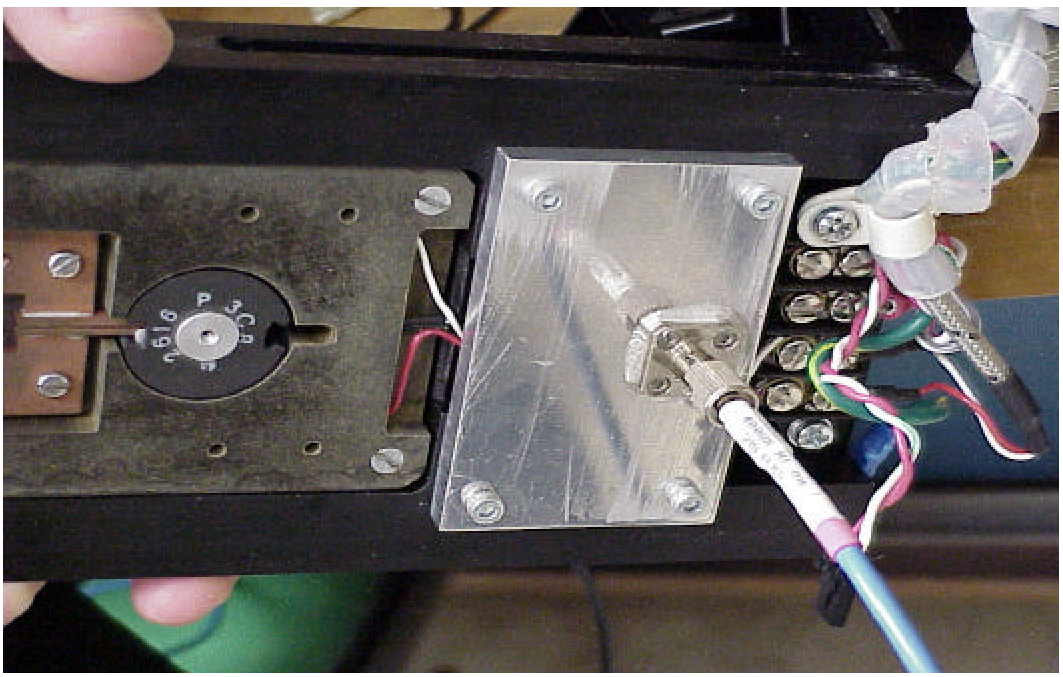

Figure 5.6: Bottom view of fiber optic connection to the TLD reader with the drawer removed.

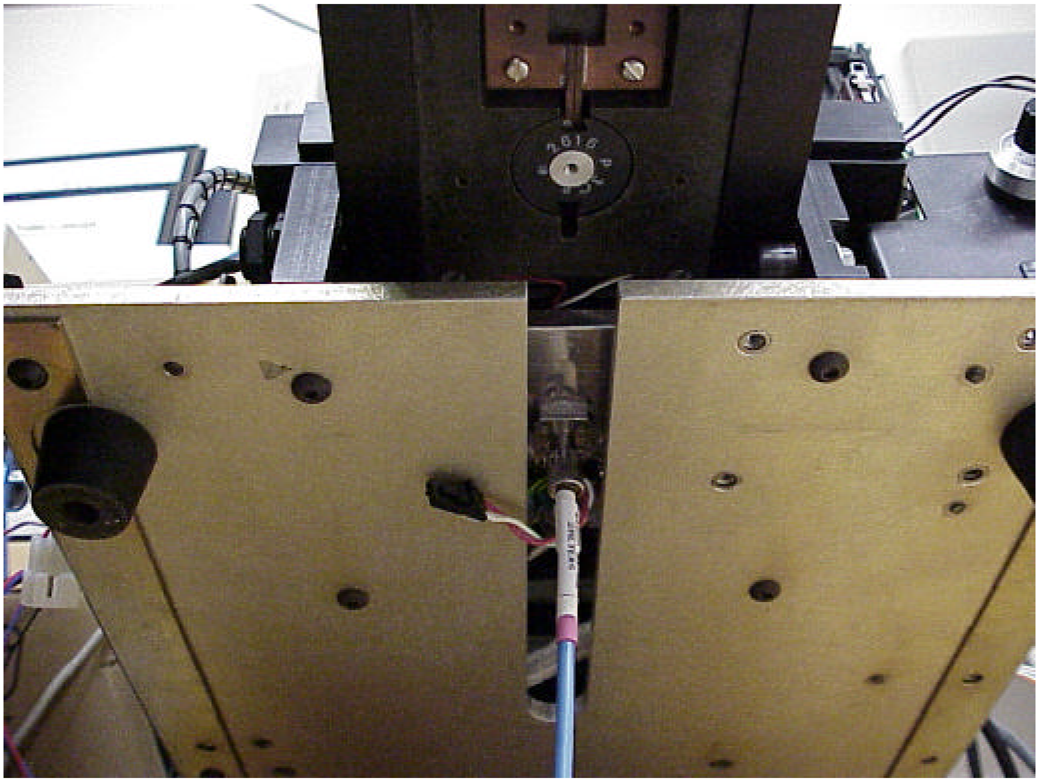

Figure 5.7: Bottom view of fiber optic connection to the TLD reader with the drawer in place for readings.

Chapter 6: Analysis and Test Results: Diode Sources

6.1 Bicron LED

Once the readings were automated, extended tests were conducted over a longer period of time with the various sources. Figure 6.1 shows reference light readings taken on two consecutive days using the Bicron LED in the TLD reader. The tests give a better understanding of the stability problem, and show consistent behavior over time. When the temperature changes as the environmental chamber is heating up, there is a drop in the output of the TLD reader. Once the temperature has stabilized the reader output is close to the ± 1% range.

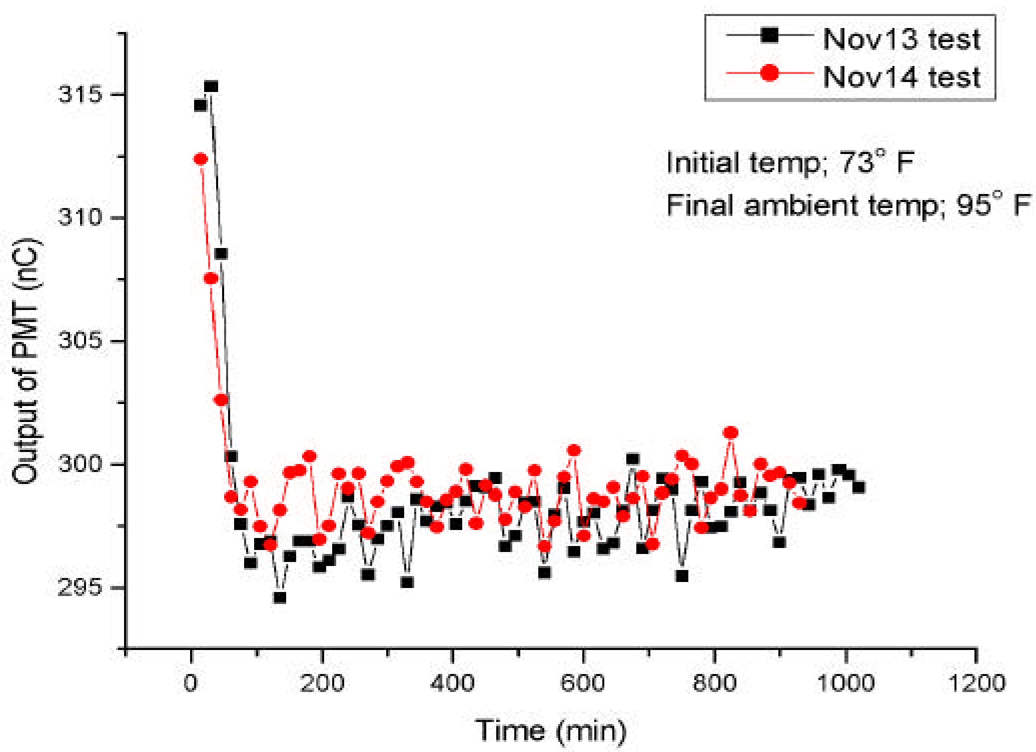

Figure 6.1: Bicron 3500 model long term reads compared on two different days in the same environmental conditions.

For both readings there was a total charge difference of approximately 20 nC in the output of these readings (315 to 295 nC). This is a variation of 6.5% over a temperature range of 22° F (i.e. 73-95° F). Figure 6.2 shows that the variation in the reader output slightly exceeds ± 1% after a stable temperature is reached. During this period, a variation of 6 nC (295 – 301 nC) was observed although the temperature is nearly constant. However, Figure 4.4 shows that the reader output is not stable when the temperature varies.

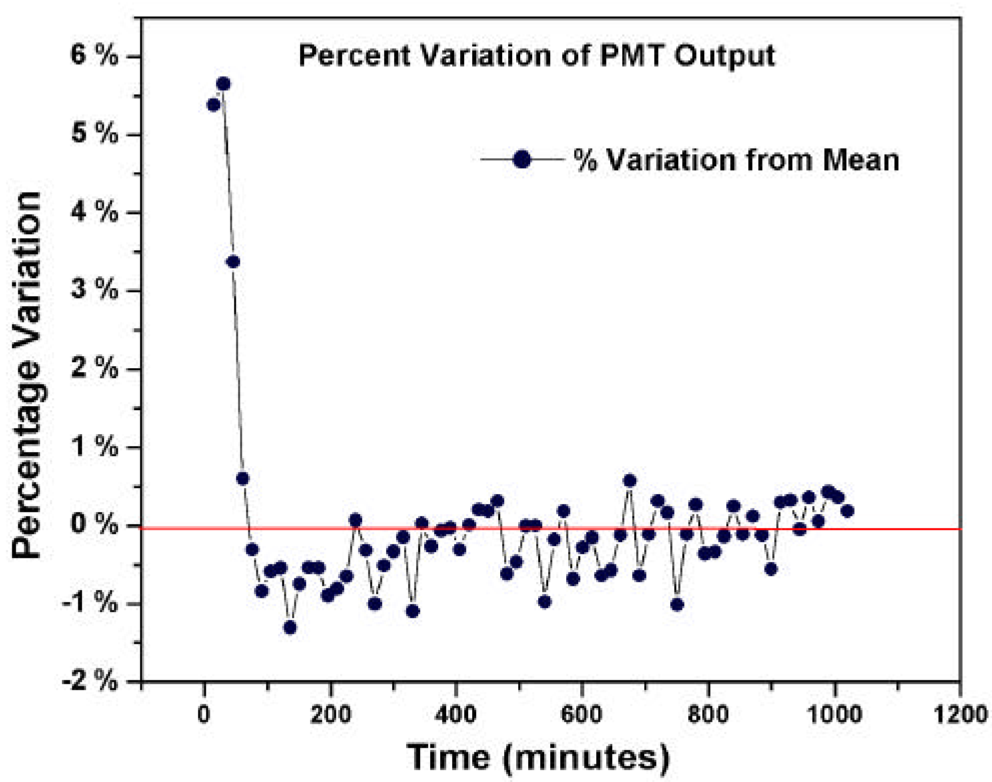

Figure 6.2: Percent variation of PMT output of 3500 model from Nov. 13 test.

6.2 Micro Laser Systems Laser Diode

The laser was the second diode source that was tested. This laser was purchased from Micro Laser Systems in California. The laser is rated to emit 3 mW of optical power at a wavelength of 408 nm. It has a fiber optic connector at its output.

A laser diode emits light when a specified threshold current I_{th} is reached. The threshold current of a laser diode is temperature sensitive and this affects the power of the laser. The threshold current varies according to the following equation:

$$I_{th}\ (T)= I_{th}(0\ °C)e^{T/To}, \qquad (6.1)$$

where T is the temperature of the laser diode in °C and T_o is a temperature coefficient. Figure 6.3 depicts how a changing temperature will cause the power to vary. As the temperature increases, the optical power will drop if a constant current is maintained.

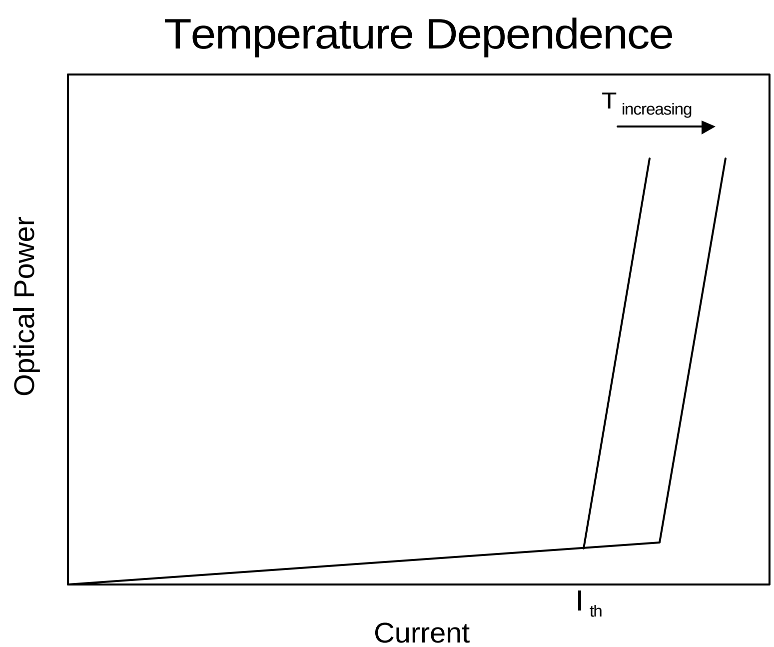

Figure 6.3: Temperature dependence of a laser diode as a function of current and power.

In order to ensure that the laser maintains a constant output, the laser diode uses a thermoelectric cooler that is attached to the rear of the laser. The diode can be operated in two modes: constant current mode and constant power mode. In constant current mode the current supplied to the diode is kept constant. In constant power mode, the power is kept constant. The output of the laser is rated to have an optical power stability of < 0.02% over a 24-hour period in constant power mode.[15] Unfortunately the laser diode did not meet this specification during experimentation. The suspected cause of this instability was that the thermoelectric cooler was not working properly. While the laser was more stable in the constant power mode its behavior was still inconsistent from one run to the next.

For the first tests with the laser diode, it was connected only to the Newport optical power meter. The optical power output and the temperature were recorded over the course of a weekend to test the stability of the laser diode. The results are shown in Figure 6.4.

[15] Micro Laser Systems Specifications. "Diode Drivers," pg 2.

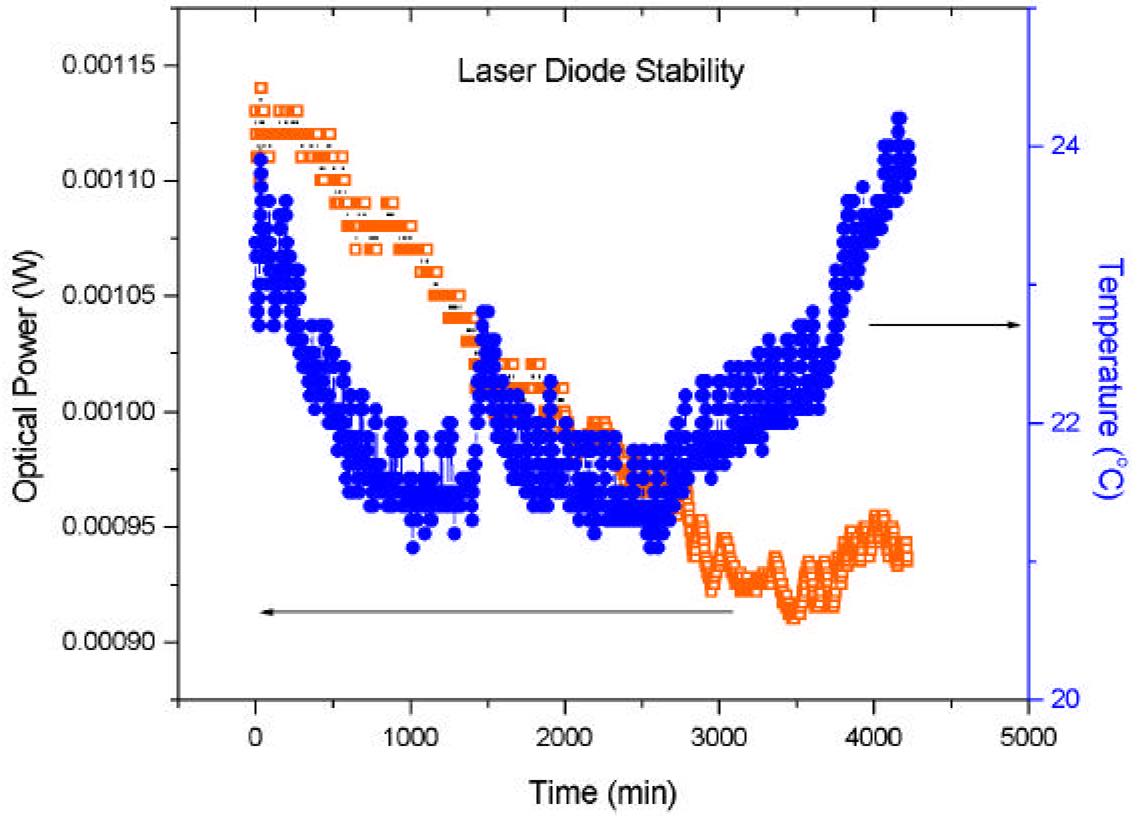

Figure 6.4: Laser diode optical power stability versus ambient temperature.

From this data it was clear that the laser diode did not meet the 1% stability criterion specified in Table 2.1. The temperature variations in the room were relatively minor, but with only 3 °C variation the temperature, there was over a 15% variation in the optical power. If the temperature controller or the driver were not working properly, the change in the output power could be due to internal heating in the laser diode. There was some indication that the TEC was, in fact, not working. There seemed to be insufficient heat removal from the heat sink attached to the temperature controller. In addition, the electric current to the TEC was insufficient. After a power supply with greater current capability was used, the stability improved, though not consistently.

There was also some concern as to whether the optical power meter detector head was sensitive to temperature. This device was not temperature compensated, which added the possibility of some small variations in the responsivity of the detector head to optical power. In order to ensure this was not a problem, another temperature-controlled chamber, an incubator, was used that maintained the temperature to within ± 1°C. The test was repeated, and the laser diode still did not meet the stability requirements. The laser diode consistently had an instability of ±7.5%.

To further test the laser, the environmental chamber was set up so that its temperature would continually oscillate. The laser diode was placed inside the environmental chamber, and the temperature was allowed to vary between 36°C and 44°C. Figure 6.5 shows the measurements recorded by the optical power meter. Immediately following is Figure 6.6, which shows the corresponding variation in the temperature. Though the test ran for 1200 minutes, only the first 600 minutes are shown in the plots (the last 600 minutes are consistent with this data).

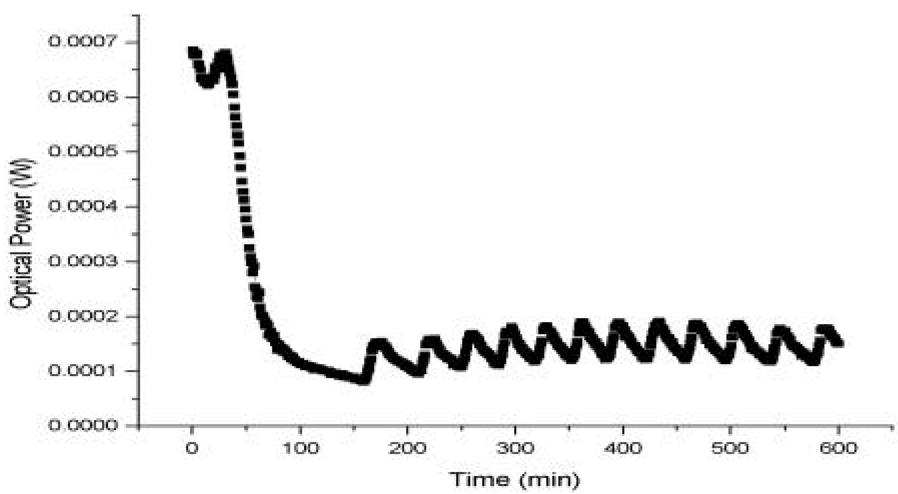

Figure 6.5: Optical power output of the laser diode with varying ambient temperature versus time.

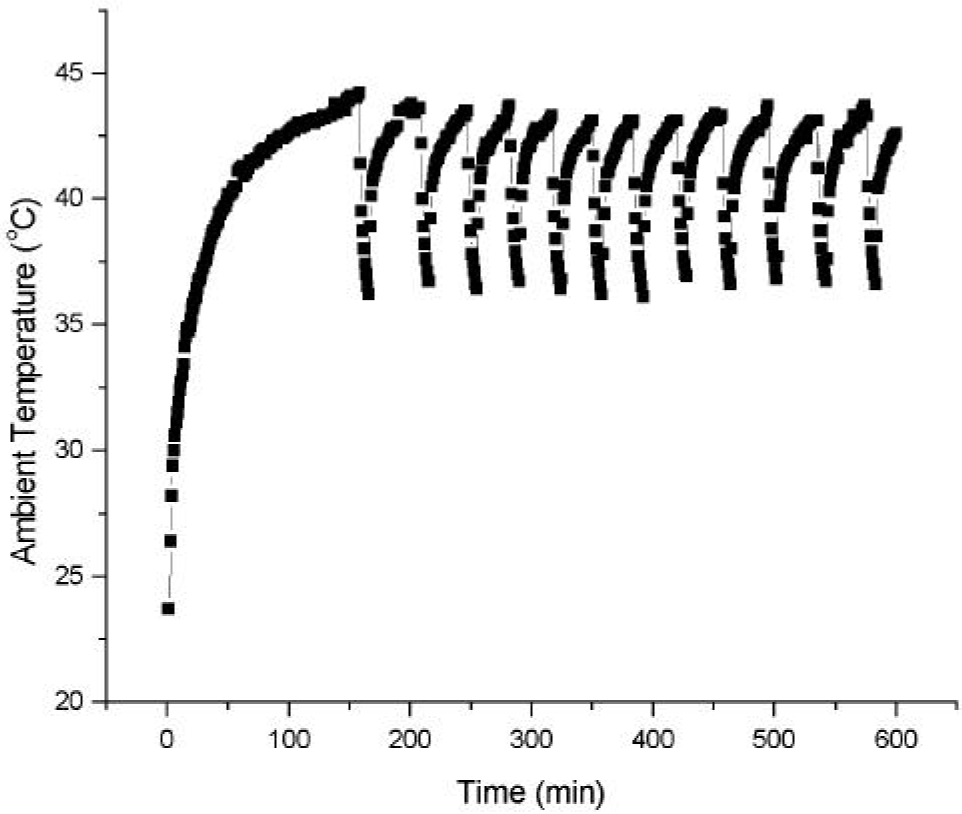

Figure 6.6: Temperature recordings for the laser diode at the same time when optical power measurements were made in Figure 6.5.

Figure 6.5 and 6.6 clearly show the correlation between the optical power and the temperature. The optical power of the laser is inversely proportional to the ambient temperature. With a properly operating thermoelectric cooler, the laser manufacturer specifications of < 1% stability in the power output over ranges of 30 °C would clearly meet the requirement in Table 2.1.[16]

It was also important to test the laser diode in the TLD reader. One concern with testing the laser diode in the TLD reader was that its power was so high. High optical power could

[16] Adachi, Norma. "Information on the Micro Laser Systems Laser." E-mail to applications specialist. 28 Jan 03.

damage the PMT. To test the stability in the reader a fiber splitter was used to split the power of the light output in half. Prior to the splitter, a fiber optical attenuator was used to reduce the power of the light to an acceptably low intensity that would not saturate the PMT. Figure 6.7 is a diagram of the laser diode connected to the optical power meter and the PMT.

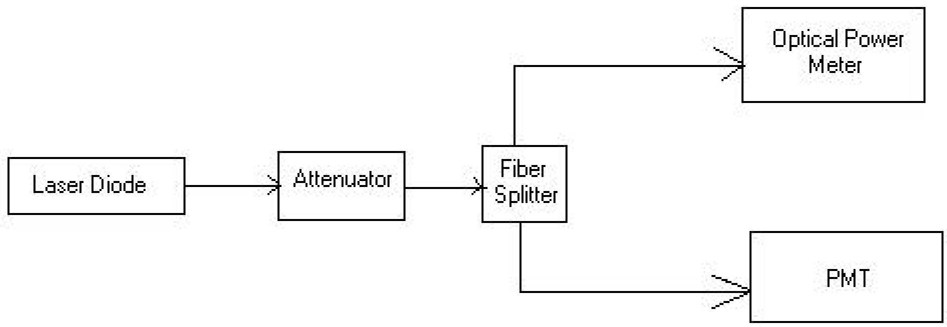

Figure 6.7: Diagram for setup of the laser diode connected to the optical power meter and the PMT.

The following procedure was used to determine the proper power level. First, the laser was turned on with the attenuator set to its maximum attenuation of 40 dB (or 10^4). At this setting the reader output was observed to be 80 nC. The attenuation was then gradually decreased, until the reader output charge was close to 150 nC. This amount of charge is sufficient to ensure that the laser operates above threshold, and that the PMT operates above the background noise (i.e. 1 nC). This is sufficiently below the optical power that saturates the PMT (i.e. 1000 nC). Figure 6.8 shows the measurements of optical power meter and the output of the TLD reader.

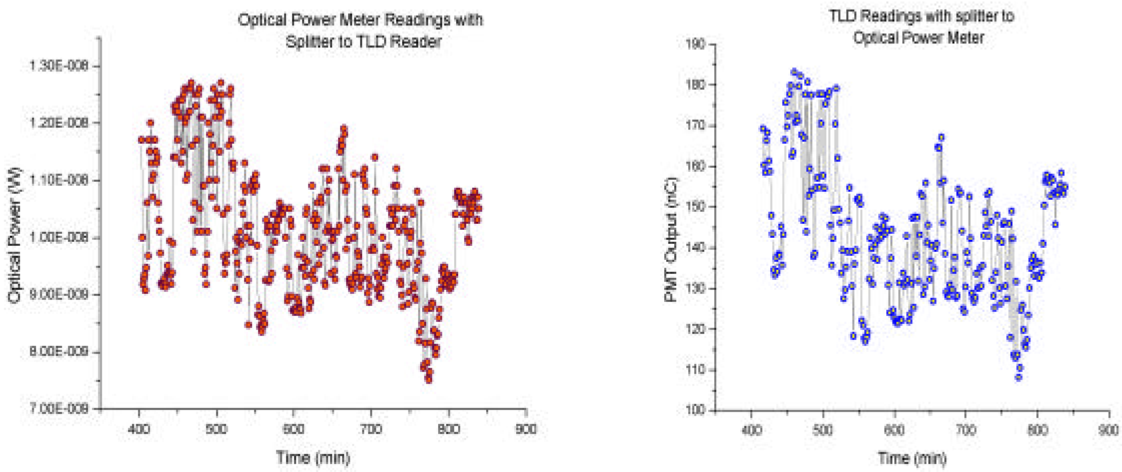

Figure 6.8: Optical power meter measurements and TLD readings of the laser diode. The laser was connected to both the power meter and the TLD reader for these measurements.

The readings for this run were taken at 1-minute intervals over the course of 800 minutes (13.3 hours). Only the last 400 minutes are plotted to improve the visibility of the graph. Note that an optical power output of 13 nW corresponds to 180 nC of charge in the TLD. The minimum optical power was 7.5 nW, which corresponded to a TLD reading of 110 nC. The close correlation between the results indicates that the power meter could provide an independent method of calibrating the reader.

It is fairly straightforward to verify the accuracy of these results. Note that one reading from the TLD reader recorded 138.0 nC. The corresponding optical power meter measurement recorded 7.81 nW. Since the test light reading is conducted over 10 seconds, and since current is charge per time, the output current from the PMT is 13.8 nA. For a gain of 42.6 A/mW in the PMT the power that entered the PMT is estimated to be around 0.324 pW.[17] Since there is an additional filter in the optical system before the PMT in Figure 1.1 that reduces the light by a factor of 10^4, the optical power that actually enters the reader would be around 3.24 nW. This is

[17] Hamamatsu Photomultiplier Tubes R6094 and R6095 spec sheets.

on the same order of magnitude as the power meter reading of 7.81 nW. This difference is not significant. The end of the optical fiber is around 1 inch from the PMT, and the light diverges as it exits the fiber, so some difference is expected. Thus it was concluded that the TLD reader output was consistent with the optical power meter reading.

6.3 Ocean Optics Light Emitting Diode

The third diode source that was tested was the Ocean Optics LED. This LED is temperature compensated and is designed to be used to calibrate other sources. The LED has been traced to a standard light source provided by the National Institute of Standards and Technology, which provides the user with a known absolute intensity/wavelength.
The Ocean Optics LED utilizes a tungsten halogen light source that emits light in the range from 350 nm to 1050 nm. Since the responsivity of the PMT is optimized in the 410 nm range, the output from the LED was filtered to obtain the proper wavelength. This posed some problems.

First, the LED emits light over a broad spectral range, but the intensity is lowest at its shortest wavelengths. Figure 6.9 shows the spectral density of the output of the Ocean Optics LED. The graph clearly shows that the output power at the lower wavelengths is significantly lower than in other areas of its spectrum. Therefore only a small amount of the actual power emitted by the LED is measured during a TLD reading. The filter used to select the proper wavelength reduced the power as well, so that only 0.9 μW of power was emitted from the terminating end of the fiber. While this power is larger than that emitted by the laser diode in Figure 6.8, the LED output is much more divergent, so that only a small fraction of this power is incident on the PMT.

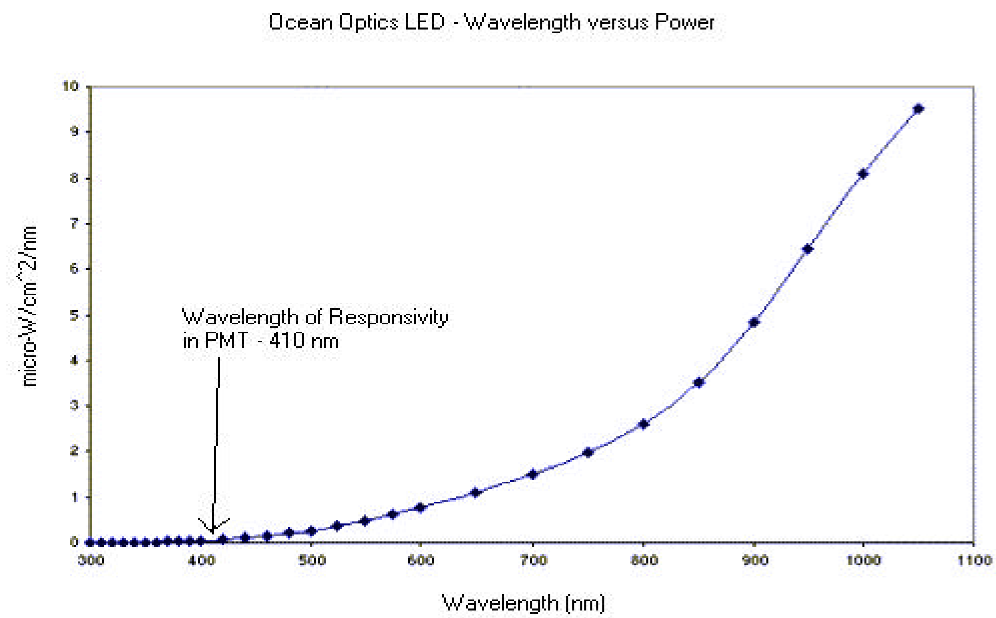

Figure 6.9: Output intensity of the Ocean Optics LED as a function of wavelength.

The initial tests with the Ocean Optics LED in a 12-hour read showed an optical power stability that was close to the specifications required by the NDC. As seen in Figure 6.10, the variation in the power was slightly greater than 1 %. Figure 6.10 is plotted with a time scale beginning at –100 minutes in order to more clearly show this variation. As shown in Figure 6.10 the initial surge in power is related to the warm-up period of the LED. An explanation for this initial change in output is that the Ocean Optics LED must reach a stabilized temperature before its power will also stabilize.

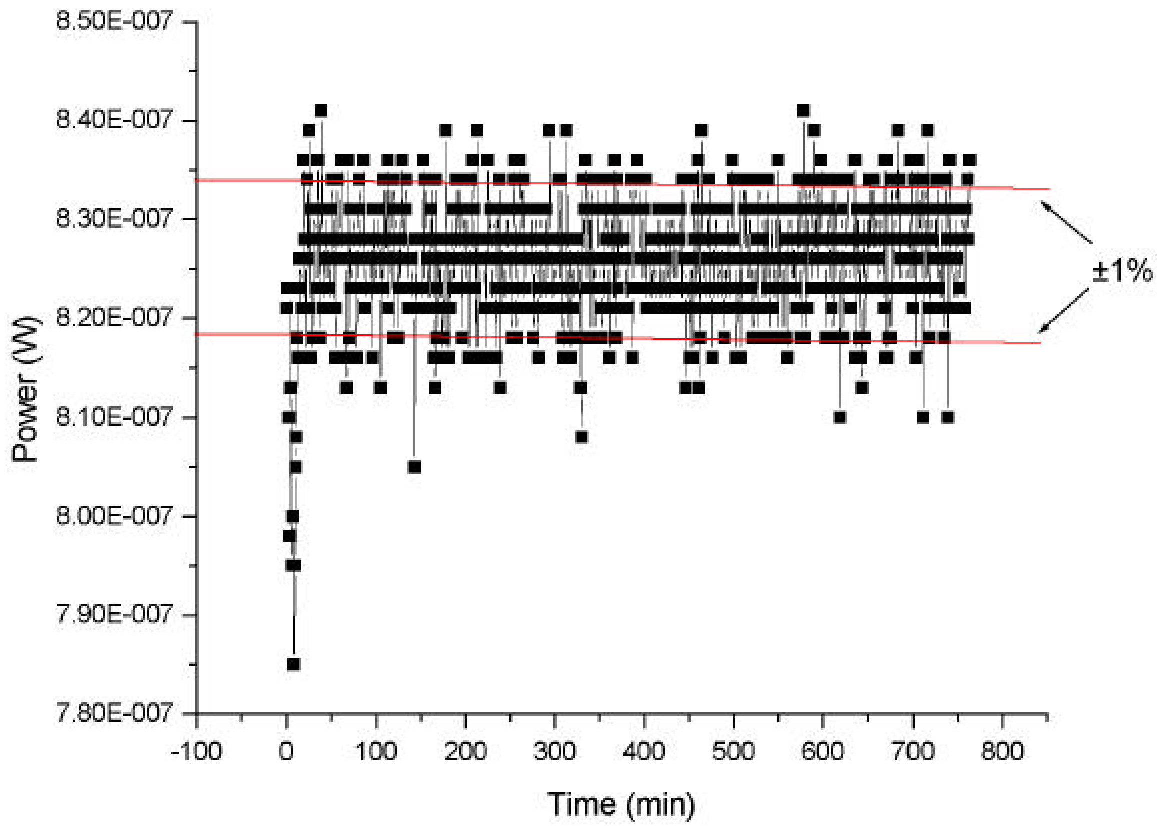

Figure 6.10: Ocean Optics LED power output over time.

The main disadvantage of using the LED is that it has a limited lifetime in comparison to other sources. It may require recalibration every 50 hours, which may be impractical, since TLD readers are generally left on for extended periods of time. Additionally, the bulb must be replaced after 900 hours of use, also shorter than desired. The tests done in these experiments were all conducted past the 50-hour time limit without any recalibration. However, the results still remained stable.

The Ocean Optics LED was also tested with the TLD reader. A fiber optic connection was used, as shown in Figure 6.11. The power output of the LED was so low that it was tested without the fiber splitter. Adding the fiber splitter would have further attenuated the signal going into the TLD reader. Since the fiber splitter was not used, the readings from the TLD reader could not be compared to readings taken by the optical power meter.

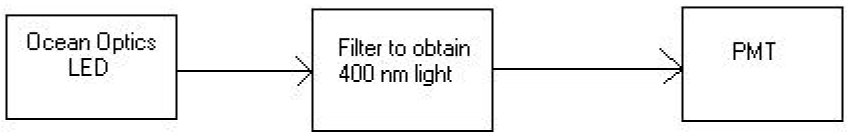

Figure 6.11: Configuration for the Ocean Optics LED connected to the PMT.

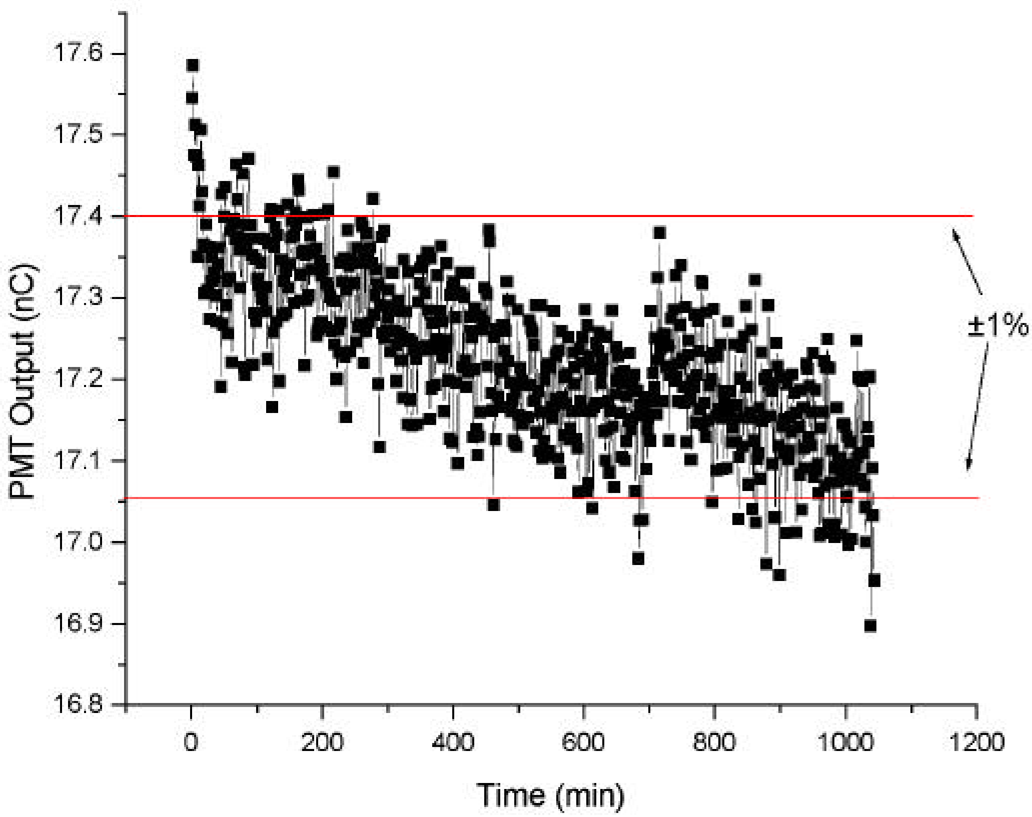

Figure 6.12: Output of Ocean Optics LED connected to the TLD reader.

Figure 6.12 shows the output of the TLD reader with the Ocean Optics LED acting as the reference light. While the output of the LED was not stable to within the ± 1% limit, it was close over a 1050 minute run. The power stability of the Ocean Optics LED is an improvement over the Bicron LED.

To test the ability of the LED to handle temperature variations, it was also tested in the environmental chamber. The environmental chamber provided a controlled environment where the temperature was a changing variable. Figure 6.13 shows the PMT output for a varying temperature. The reading was conducted over a period of 1000 minutes. The data from 400 to 600 minutes was plotted to show more detail. The remaining data points are consistent with those shown in the plot. Again, while the output variation is not within the 1% standard, it is close. Figure 6.14 shows the corresponding temperature recordings. The output of the Ocean Optics LED is less sensitive to temperature variations, in contrast to the Bicron LED and the laser diode. This demonstrates that the LED is a viable non-radioactive source, as its output is considerably more stable than the Bicron LED when the temperature is varying.

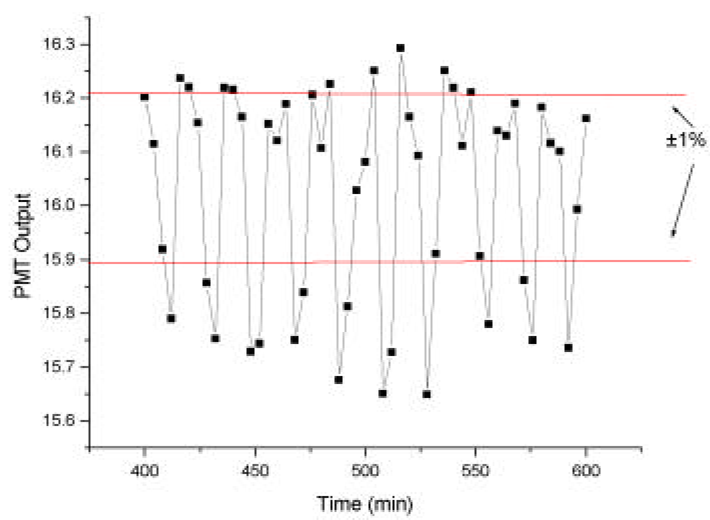

Figure 6.13: PMT Output of the Ocean Optics LED with a varying ambient temperature versus time.

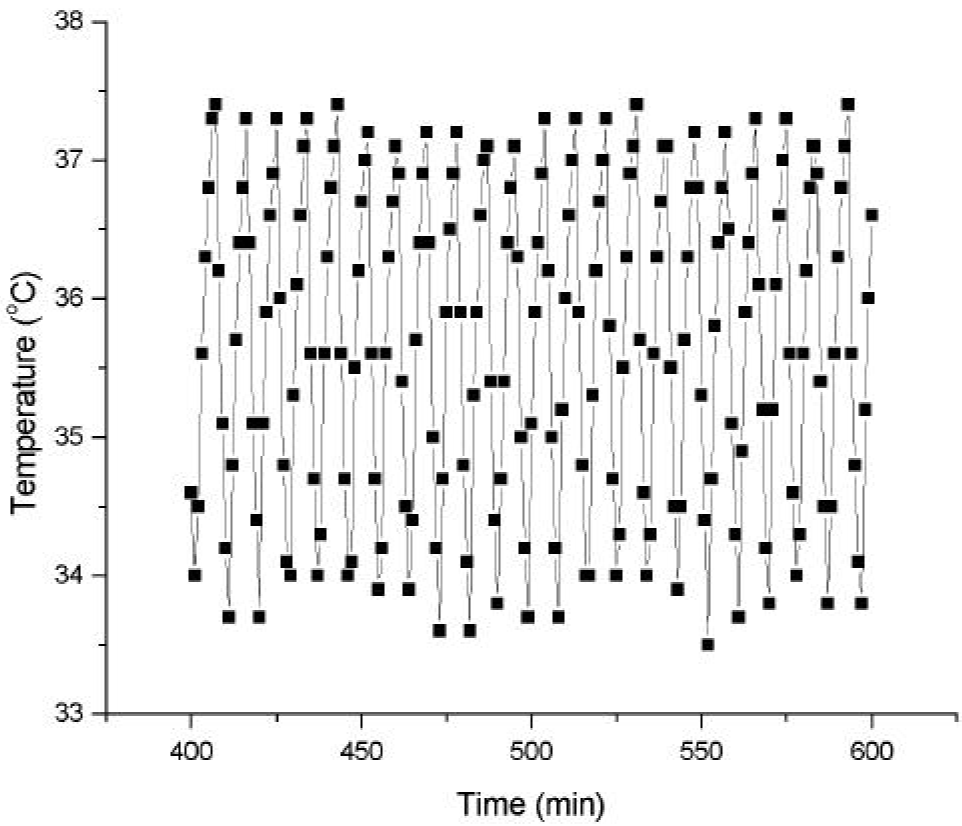

Figure 6.14: Ambient temperature recordings for the LED versus time for PMT output readings shown in Fig 6.13.

Chapter 7: Analysis and Test Results: Radioactive Sources

7.1 C-14 Scintillating Source

The first radioactive source that was tested was a C-14 scintillating source. The 8800 model TLD reader made by Bicron uses a source that contains 5 μCi of C-14 radioactive material. The 8800 reader does have some stability problems. However, these problems are on a much smaller scale than those present in the 3500 reader, which has shown a 10% variation in its output. Testing the C-14 source served two vital functions. First, it helped determine the capability of the C-14 source to be used as a reference light for the 3500 reader. Second, it helped determine if temperature changes around the C-14 source cause the instability in the 8800 model.

Isotope Product laboratories in California was contacted to construct a source that contained 5 μCi of C-14 in an organic scintillator.[18] An organic scintillator is defined as a material that contains carbon and hydrogen atoms. It converts the energy of the radiation into light. The Bicron BC-490 scintillator was chosen because of its availability.[19] BC-490 was designed to be used for general-purpose applications as is needed in the 3500 reader. The source also needed to fit in the small planchet tray in the 3500 reader, shown in Figure 1.1, so that the drawer can easily be closed, allowing the light to be projected into the PMT. The source obtained from Isotope Product Laboratories had a diameter of 5 mm and a thickness of 2 mm.

When tested, the C-14 source was placed on the planchet tray, and the drawer was closed to conduct these tests. Under normal operation, when the drawer is closed, the planchet tray will proceed through a heating phase in order to acquire and anneal a TLD reading in a LiF crystal.

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[18] Isotope Product Laboratories. Valencia, CA 91355.
[19] Knoll, Glenn F. *Radiation Detection and Measurement*. John Wiley & Sons, Inc. New York, NY. 2000.

This heating would destroy the BC-490 scintillator. A method was devised to override the TLD reader, so that the 3500 will perform a 10 second test light reading with the drawer closed.

The C-14 source was only tested in the TLD reader. Its optical output was below the noise floor of the optical power meter, so it could not be tested with that device. The PMT output and temperature variation for the C-14 source are shown in figures 7.1 and 7.2, respectively.

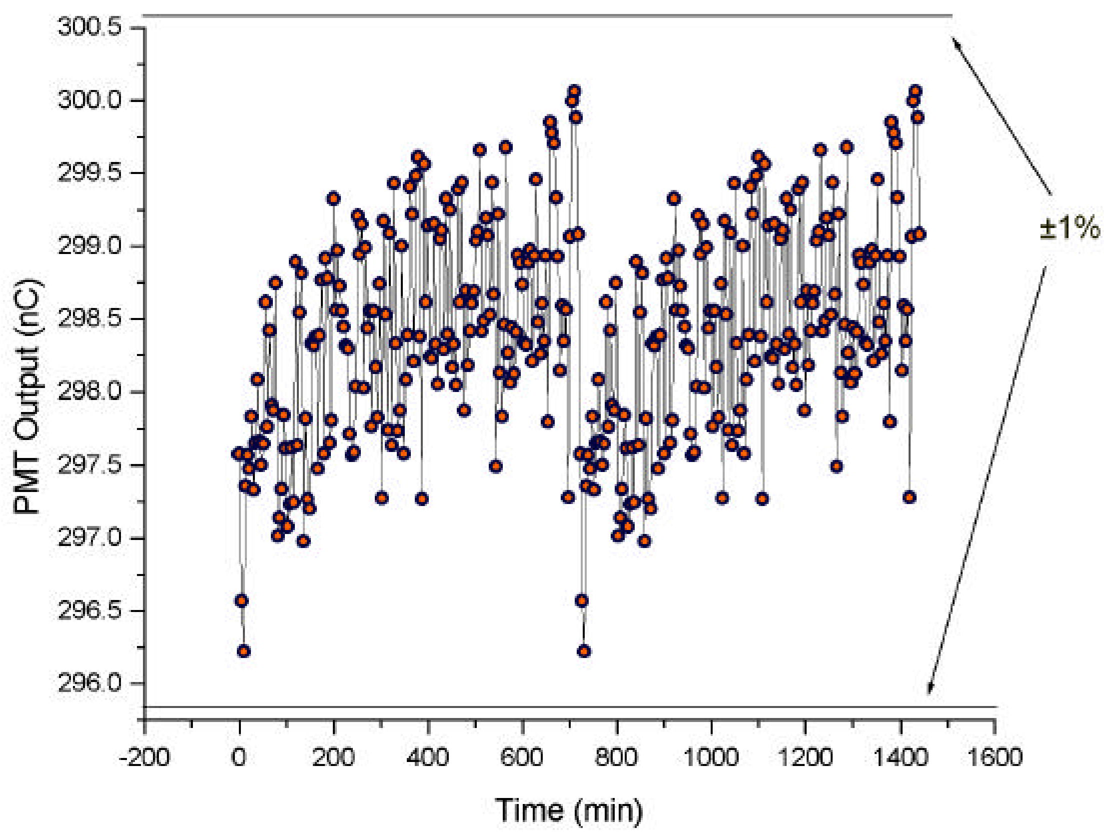

Figure 7.1: Output of the C-14 radioactive source into the PMT versus time.

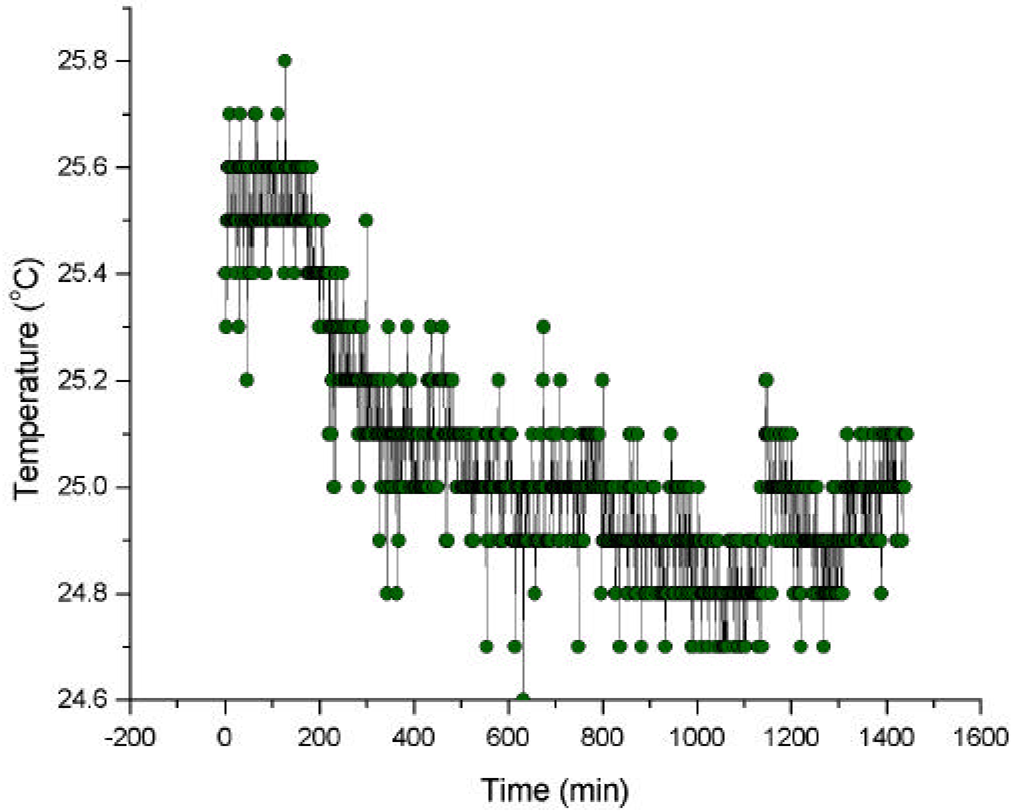

Figure 7.2: Ambient temperature of measurements versus time corresponding to PMT readings shown in Figure 7.1.

It is clear that the C-14 source does meet the stability standards defined by the NDC. The slight temperature variation has no effect on the output of the source. Figure 7.1 shows the average output of the C-14 source to be near 298 nC. This value is close to the value that is normally recorded by the TLD reader during normal operation with the Bicron LED. The Isotope Product's C-14 source is therefore, already operating at an output level conducive to accurate calibration.

Based on a few simple known facts about C-14 and the BC-490 scintillating source, the output of the source can be predicted theoretically. The first step was to calculate the average energy of the C-14 source. C-14 emits a β^- with a maximum energy, E_{max}, of 156 keV, and an average energy, E_{avg}, of 46.8 keV. E_{avg} is the average energy and η is the efficiency of the BC-490 scintillator. Hence the average rate of the energy emission from the source can be calculated, which is done using the equation:

$$E_{rate} = (E_{avg})(\alpha) = 8.658\text{x}10^6 \text{ keV/sec} \qquad (7.1)$$

where α is equal to the source reactivity in disintegrations per second. In the case of the tested C-14 there were 185,000 β^- disintegrations per second. The final value of E_{rate} is found to be $8.658\text{x}10^6$ keV/sec, which is the rate at which the C-14 source emits its energy into the BC-490 scintillator. This rate was converted into a light emission rate l_{os}. A plastic fiber scintillator, similar to the one being used, is known to have an emission of 8 – 10 photons/keV.[20] If a rate of 9 photons/keV is used, then l_{os} can be found by equation (7.2) as:

$$l_{os} = (E_{rate})(9) = 7.792\text{x}10^7 \text{ photons/sec} \qquad (7.2)$$

Equation 7.2 calculates the total light emission rate from the source in photons per second. This emission rate is for light emitted in all directions. The fraction of the light that enters the PMT is determined by knowing the fractional solid angle Ω, that the source makes with the PMT. The fractional solid angle can be found from the equation:

$$\Omega = \frac{1}{2}(1 - \cos q\ ) = 0.528 \qquad . \qquad (7.3)$$

Ω is the fraction of the light that is reaching the PMT. θ in this equation is determined trigonometrically based on Figure 7.3. The height in Figure 7.3 was found to be 1.125 inches, and the radius was found to be 0.5625 inches. Since $\cos\theta = 1.125/\sqrt{0.5625^2 + 1.125^2}$ the efficiency of light reaching the PMT is $\Omega = 0.0528$.

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[20] Knoll, Glenn F. *Radiation Detection and Measurement.* John Wiley & Sons, Inc. pp. 256. New York, 2000.

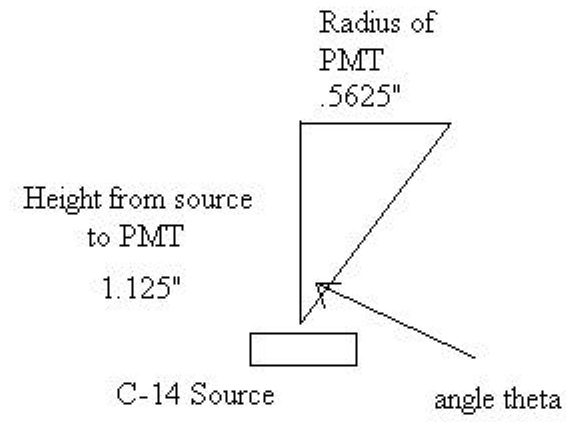

Figure 7.3: Picture of dimensions from the radioactive source to the PMT

Combining the results of Equations (7.1) – (7.3), the rate in photons/sec that enters the PMT was determined using the following equation:

$$l_{Opmt} = (\Omega)(l_{os}) = 4.11\text{x}10^{6} \text{ photons/sec} \qquad (7.4)$$

The gain of the PMT was known to be $4.84\text{x}10^5$ when a voltage of 812 volts is applied to the PMT. This gain was multiplied by the anode sensitivity of the PMT, which was given in the PMT specs as 88 mA/W, to find the total sensitivity of the PMT assembly, or 42,592 A/W.[21] The energy of each photon was then calculated. The wavelength of light emitted by the C-14 source was 420 nm, so that

$$E = \frac{hc}{l} = 4.74 \text{ x}10^{-19} \text{ Joules/photon.} \qquad (7.5)$$

In Equation (7.5) h is Planck's constant, c is the speed of light and λ is the wavelength of the emitted light. Combining equations (7.4) and (7.5), the photon power entering the PMT as calculated using equation (7.6).

[21] Hamamatsu Photomultiplier Tubes R6094 and R 6095 spec sheets.

$$P = (I_{Opmt})(E) = (4.11x10^{6})(4.74x10^{-19}) = 1.95\ pW \qquad (7.6)$$

The power is then converted into a current using the gain of 42,592 A/W. This current is then integrated over a time of 10 seconds to find the equivalent charge that was produced. The final value of the charge was determined to be Q = 831 nC. Ideally this calculation would come out to be identical to that measured by the TLD reader. While the value is off by a factor of 2.77, it is close enough to ensure confidence in the readings. The approximately factor of three difference could be caused by the following factors. One source of error was that these calculations were performed assuming an ideal point source. Second, the shape of the C-14 source was not uniform, causing different emission rates at different locations on the source. Some variance from the theoretical value would be expected because of these reasons.

Although the C-14 source proved to have less than a ± 1% variation under conditions with a stable temperature, it could not be considered a viable solution until it was tested under varying conditions. The C-14 source was placed in the TLD reader, and the entire reader was placed inside the environmental chamber. Figure 7.4 shows the results from the C-14 source with a varying ambient temperature. The temperature variation with time is shown in Figure 7.5.

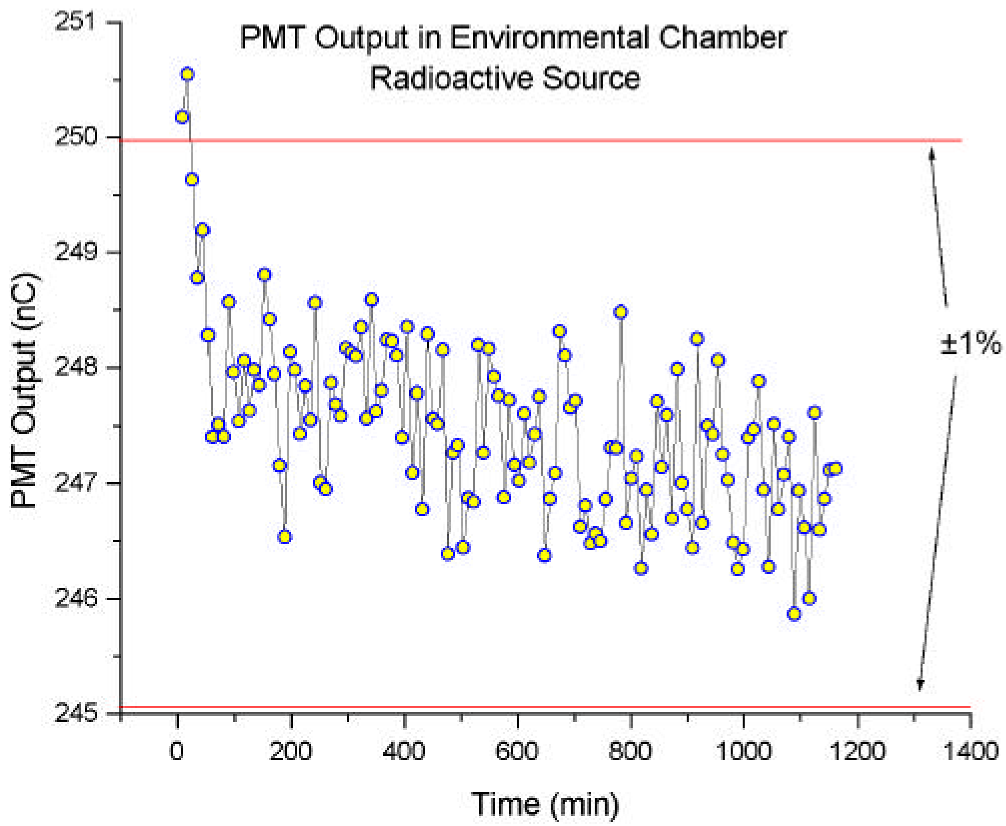

Figure 7.4: PMT output of the C-14 source with a varying temperature versus time.

Figure 7.4 clearly shows that the C-14 source does operate with in the ± 1% standards. The first two readings correspond to a warm up period in the TLD reader, and are not indicative of the general trend. Note that the output in Figure 7.4 is much less than the output shown in Figure 7.1. This difference is due to the location of the C-14 source. As the drawer is moved into place the C-14 source is moved slightly by the jolt of closing the drawer. Since this is not a point source, different angles of the source emit more light than others, and this may be responsible for the PMT output difference between Figures (7.1) and (7.4). This problem can be fixed by permanently mounting the C-14 source, ensuring the same amount of light is directed to the PMT for every reading. Figure 7.4 is also a clear example that the C-14 source is relatively independent of temperature. Figure 7.5 shows the temperature that was recorded simultaneously with the power readings in Figure 7.4.

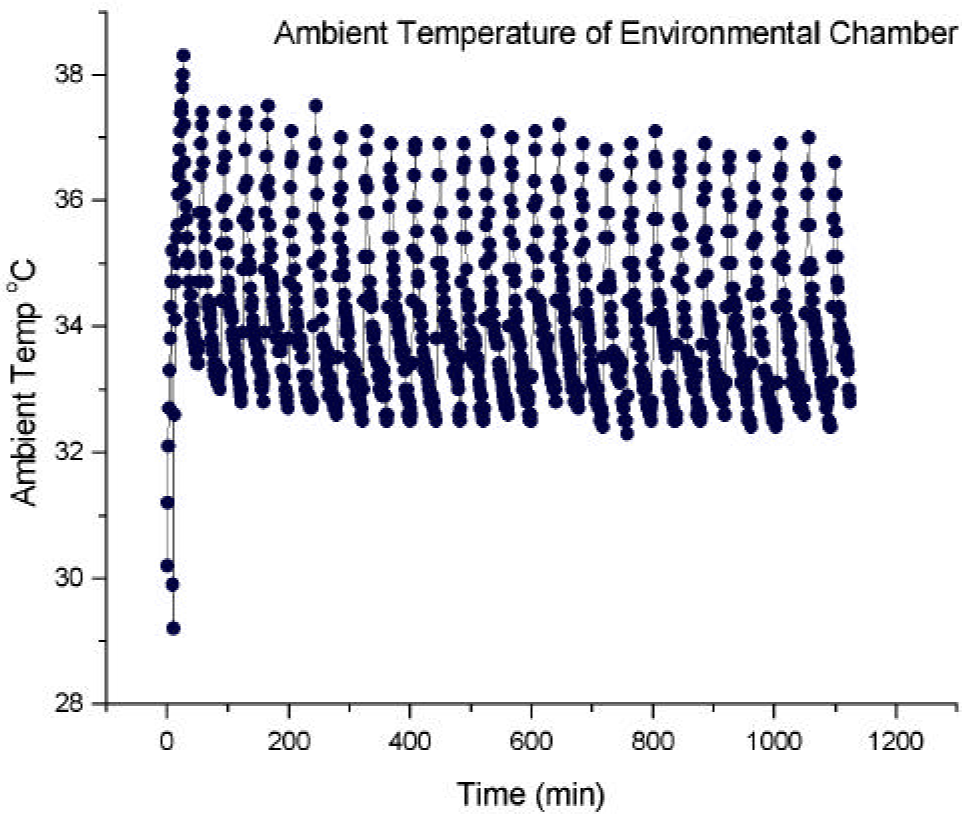

Figure 7.5: Temperature recordings for the C-14 source at the same time for PMT readings shown in Fig. 7.4.

As the temperature oscillated, the output of the TLD reader remained stable. There are no obvious instances where the output of the reader can be directly correlated to the change in the temperature.

The NDC is concerned about the use of a radioactive source in the TLD reader. For the experiments conducted with the TLD reader, the C-14 source was below the exempt quantities defined by the U.S. Nuclear Regulatory Commission.[22] Since the source contained below the exempt quantities, it is not necessary to license the source. Therefore it should pose no problems with shipping and movement throughout the world.

C-14 is a very appealing solution because it has a half-life that is 5730 years. Over this length of time there is little concern about the need to compensate for the decrease in intensity as the source slowly decays away. The life of the reader is too short to make this a necessary consideration.

Since the C-14 source performed well, other radioactive sources were considered. An inexpensive and readily available source was desired, so that it could quickly be integrated into the TLD reader. The tritium source met this criteria, so it was purchased and used as a second radioactive source.

7.2 Tritium Source, H-3

The tritium radioactive source is in gaseous form and is enclosed in a small transparent capsule. In its typical application, the source is mounted inside of the sight for a bow and arrow and is designed for use in low light situations for hunting. In this case, a special plate, shown in Figure 7.6, was designed that allowed the tritium source to be mounted in place of the Bicron LED where it could illuminate the PMT. It can be easily interchanged with other tritium sources of the same brand. This tritium source was purchased from Cabela's.[23]

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[22] "U.S. Nuclear Regulatory Commission." Available at www.nrc.gov
[23] Cabela's Outfitter. Online store, available at www.cabelas.com on April 9, 2003.

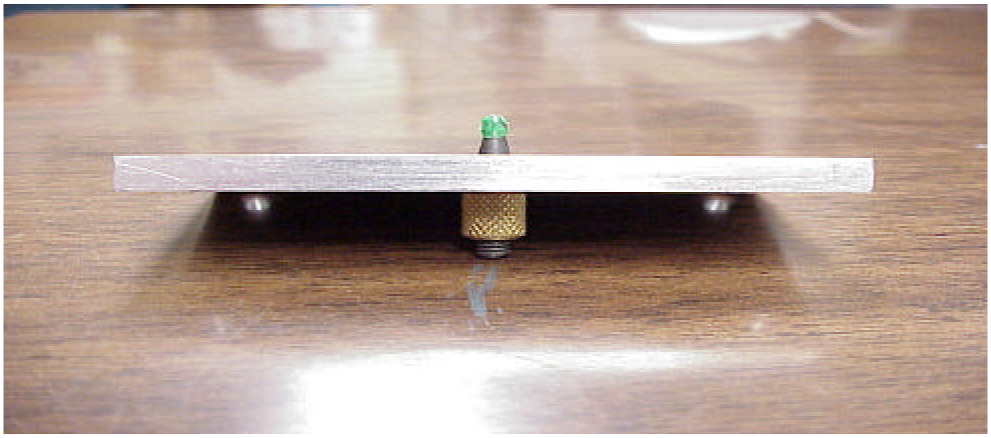

Figure 7.6: Side view of plate holding the tritium source in the TLD reader.

The readings taken using the tritium source showed some promise. There was some doubt at first because the light output was very small. Furthermore, it did not emit much light in the blue region. The results are shown in Figure 7.7 where the two parallel lines on the graph show $\pm 1\%$ variation about the mean output of the source, with a constant ambient temperature. Over the course of the 1700-minute run, the tritium source operated just outside of the 1% range. This result indicates that the tritium source is a possible candidate for use in the actual TLD reader. The PMT output is low because the tritium source was mounted beneath the optical filter. If the tritium source is to be used in the 3500 reader, the attenuation of the filter would need to be reduced.

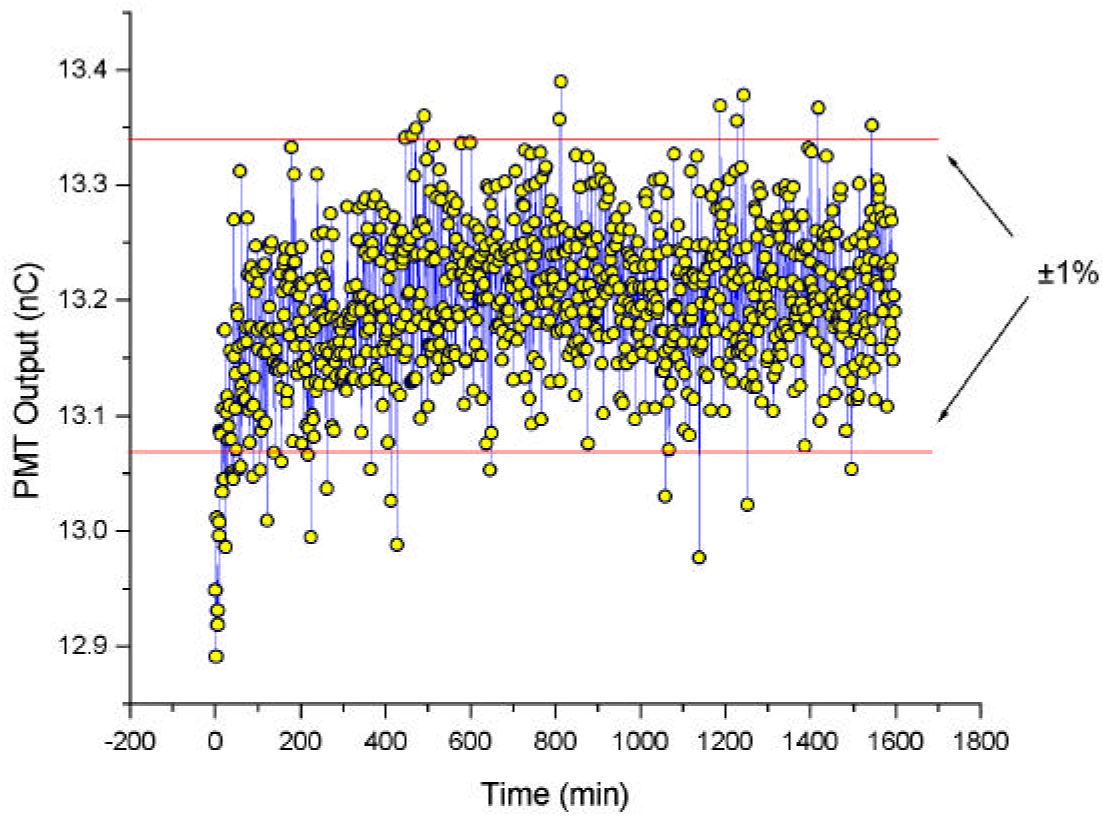

Figure 7.7: Tritium source tested in the TLD reader versus time.

As done with the other sources, the tritium source was also tested in an environment with a varying temperature. Based on the results of the C-14 radioactive source, the tritium radioactive source was expected to maintain a similar stability. However, Figure 7.8 shows that the results differ when the tritium source was used as its reference light.

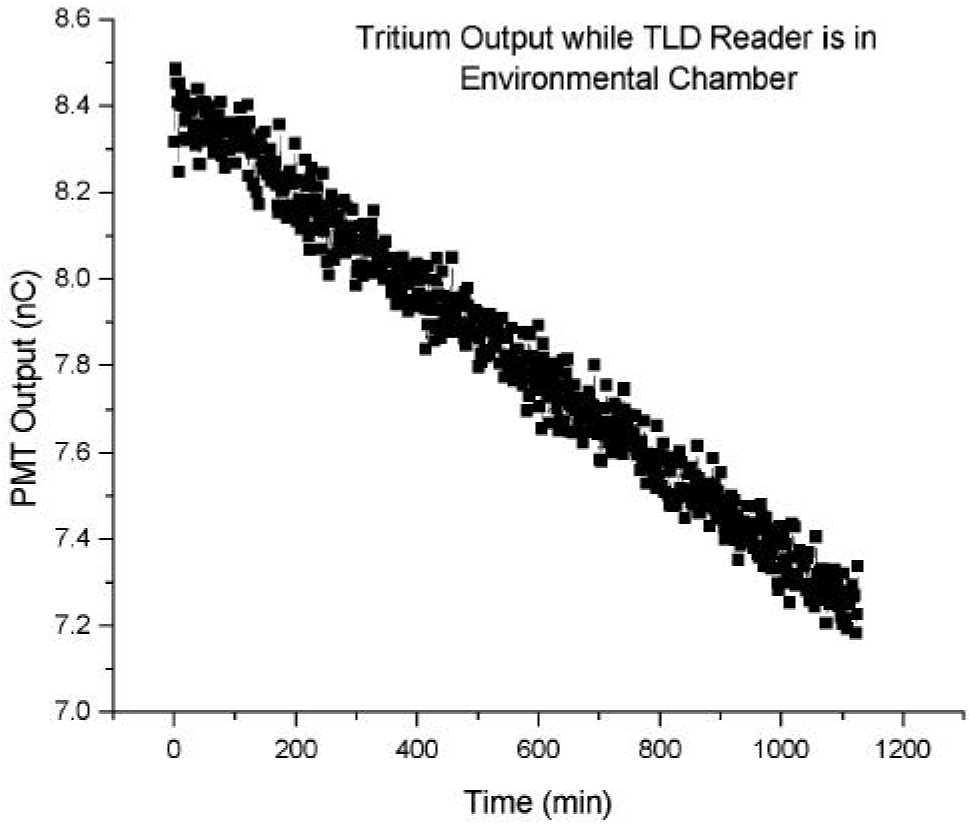

Figure 7.8: PMT output of the tritium source with a varying ambient temperature versus time.

In an environment with varying temperature, the tritium source did not operate with the stability it demonstrated in the first experiments. The decay in the power is too fast to be caused by the radioactive decay. Also, the temperature does not seem to be the cause of this instability. Figure 7.9 shows that there is no correlation between the recorded temperature and the PMT output over the course of these readings. Rather, Figure 7.8 demonstrates that there was a constant decrease in the PMT output. While the tritium source appears to be insensitive to temperature it did not meet the required stability criteria.

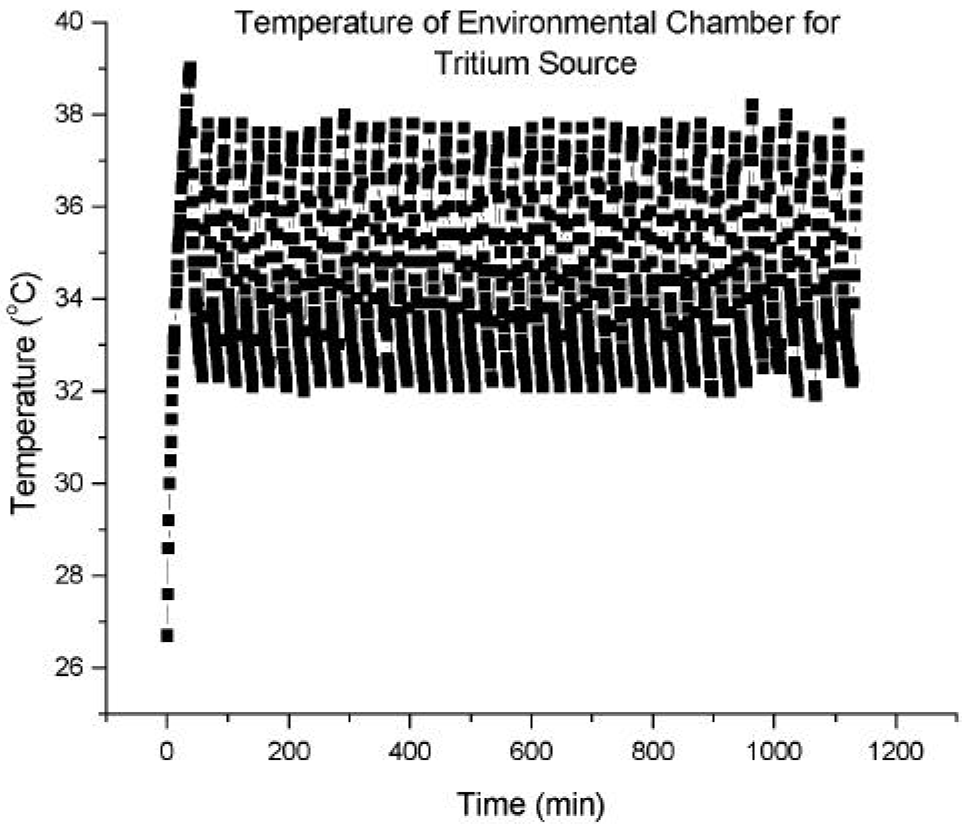

Figure 7.9: Ambient temperature recordings for the tritium source at the same time for PMT output readings shown in Figure 7.8.

The tritium source has one other disadvantage compared to C-14. Its half-life is only 12.43 years. A half-life of this magnitude would require the TLD reader to apply a correction factor to its output to account for the decay time of the source. Such decay correction processes are very common in the nuclear field. The decay curve for this source can be easily obtained, as shown in figure 7.10.

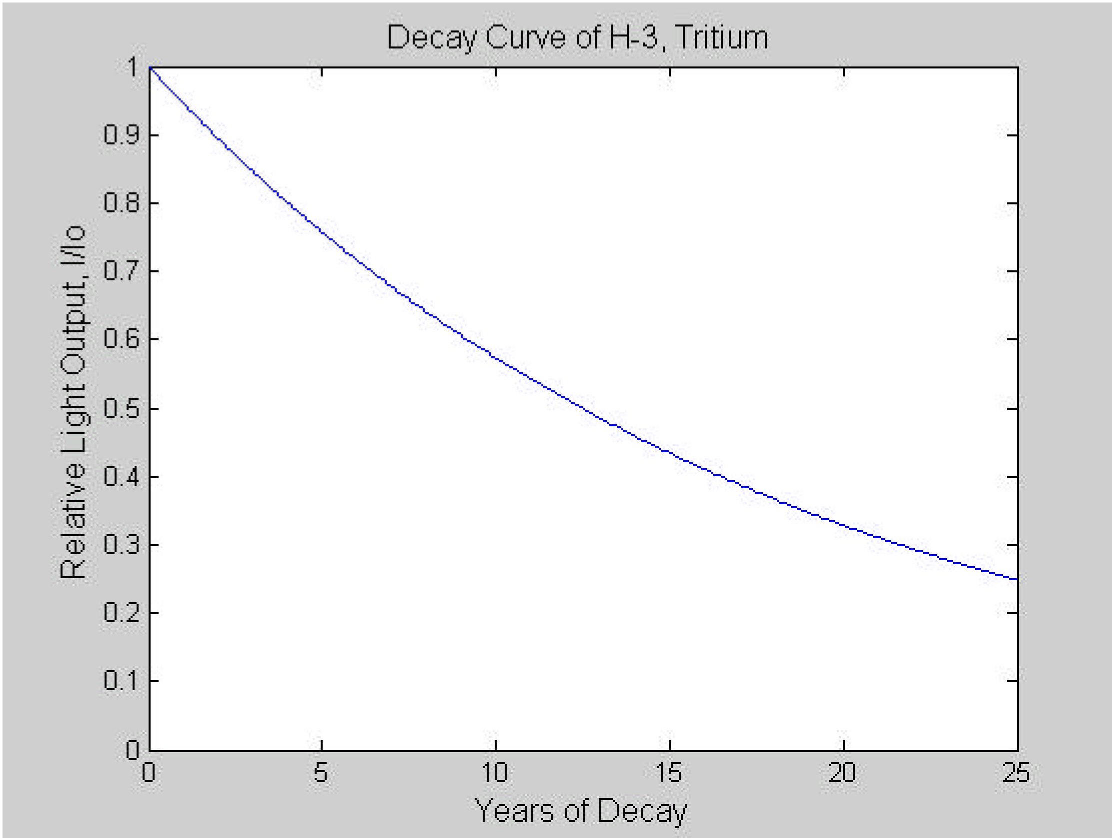

Figure 7.10: Decay correction curve of tritium, H-3.

Figure 7.10 was generated by evaluating equations 7.8 and 7.9.

$$l / l_o = e^{-\lambda t} \qquad (7.8)$$

$$\lambda = \ln(2) / t_{1/2} \qquad (7.9)$$

where l/l_o is the relative light output, and $t_{1/2}$ is the half life of tritium. Figure 7.10 gives a relative light output that is normalized to unity at time equals 0. It is seen from Figure 7.10 that when the reader is initially calibrated the light output will be 25% of its initial value after 25 years. This is acceptable if the reader is calibrated accordingly.

The bigger concern with this decay is that the output of the tritium is already very low. If the light intensity is reduced by 75%, the output into the PMT would only be 4.3 nC. This is above the noise floor of 1 nC, but it is small compared to the typical readings from TLD cards. It is preferable to have the reference light output close to that recorded during a standard thermoluminescent reading. Consequently, a stronger tritium source might be required, or a filter with less attenuation could be used.

Chapter 8: Conclusions

Overall, this research has been successful in finding a source that is relatively temperature independent, meeting the specifications defined by the Naval Dosimetry Center. Five different sources were thoroughly tested for stability. These were the original Bicron LED used in the 3500 model TLD reader, the Micro Laser Systems Laser, the Ocean Optics LED, a C-14 scintillating source, and a tritium scintillating source. Each light source was first tested at an ambient temperature that was relatively constant. The five sources were then tested in an environment with temperatures that varied so as to test each source's temperature dependence. Table 8.1 summarizes the measurement configuration for the various sources.

Summary of Measurement Devices used throughout Tests

Light Source	Vendor	TLD Reader	Optical Power Meter
LED	Bicron	yes	no
Laser Diode	Micro Laser Systems	yes	yes
LED	Ocean Optics	yes	yes
C-14	Isotope Products	yes	no
Tritium (H-3)	Cabellas	yes	no

Table 8.1: Summary of measurements taken for the five different sources in an environment with a stable temperature and a varying temperature.

A method to integrate the Micro Laser systems laser diode and the Ocean Optics LED into the current TLD reader was also developed. This used a fiber optic splitter to enable the comparison of the optical power meter measurements to those of the TLD reader.

Table 8.2 shows a summary of the results that were obtained during the testing. The C-14 source was found to be the most stable, and it meets the specifications of the NDC.

Summary of Results obtained from Tests	
Source	Response within 1% Variation
Bicron LED	No
Micro Laser Systems Laser	No
Tritium	No
Ocean Optics LED	No, but close
C-14	Yes

Table 8.2: Results from the testing of each source.

The research also showed conclusively that the current Bicron LED cannot meet the power stability requirements. The Bicron LED experiences large swings in its output with variations in the temperature. A new light source is necessary to have reference light readings that can be used reliably for calibration.

The Micro Laser Systems laser was the least stable source in these tests. The laser, however, was not meeting the specifications that were determined by the manufacturer. The manufacturer rated the laser diode with a stability of < 0.02% over the course of 24 hours. The inability to meet the manufacturer's specifications is an indication that there was a user problem in operating the laser. The most likely cause of this problem was that the thermoelectric cooler was not working. If fixed, the laser would likely meet the specifications.

Although the laser did not meet the specifications of the NDC or the specifications of Micro Laser Systems, it does have other important characteristics that would make it a very desirable source if its stability can be improved. The laser has the longest life of all the sources, with the exception of the radioactive sources. Its lifetime is 10,000 hours, ten times the length of the LED sources. Though the initial price of the laser was around $5,000, the price is expected to drop as blue laser diodes become more common. This laser also has an output that is within the optimum region for the PMT.

The most important result found with the Micro Laser Systems laser was that an outside light source can be connected to the reader. Fiber optic cabling provides a reasonable method to get light into the TLD reader. Additionally, a method of comparing the measurements of an optical power meter to the measurements of the TLD reader was demonstrated using a fiber optic splitter. Hence, two independent sources can be used to determine the output measurements. Comparing the TLD readings to the optical power meter measurements eliminates the need for a reference light with less than ± 1% power stability. The optical power meter verifies the measurements of the TLD reader are correct, ensuring proper reader operation and calibration. Figure 6.8 proves the TLD reader is taking accurate measurements, even though the TLD readings are not within the ± 1% standard. This is an important step towards higher accuracy dosimetry.

The tritium radioactive source did not meet the specifications of the NDC. Its initial tests showed that its output power stability was very close to 1%. Upon subsequent testing, its output steadily declined on each test that was performed. The decline in the output of the Tritium source was not explained by any information regarding its half-life. The tritium should be a stable source over the course of many years.

The tritium source was the least expensive source. It cost $20 and is immediately available, but its output was only 11 nC during the first tests. Ideally the output would be between 200 and 300 nC. This problem could be solved by utilizing a stronger tritium source, or by using a different attenuating filter in the TLD reader. The high decay rate of the tritium source would necessitate a decay correction factor be applied, but otherwise would not pose any major problems.

The Ocean Optics LED is very close to meeting the stability standards of the NDC, as its output was relatively temperature independent. The stability remains within 2% of its mean value. This is an improvement over the current LED in the TLD reader.

The Ocean Optics LED is also a relatively inexpensive reference light after its initial purchase. The cost initially is approximately $800 for the LED. After this purchase the bulb within the LED is not very expensive to replace. The vendor quotes the life of a single bulb as 900-hours. This reference light is unique when compared to the current LED in the system, because the Ocean Optics LED can be turned on and off. The Bicron LED is wired so that it remains on whenever the TLD reader is turned on, and there is no way to independently turn it off without turning off the entire reader. The ability to turn the LED off could help extend its life beyond 900-hours if it was only turned on when calibrations were performed.

The C-14 scintillating source met the stability requirements defined by the NDC and is relatively easy to integrate into the model 3500 reader. The cost of the source is approximately $800. Although this source is radioactive, it is well below the exempt quantity defined by the U.S. Nuclear Regulatory Commission and RAD-10.[24] For this reason the C-14 source does not need to be a licensed source, and would impose no restrictions on its movement.

In order to use the C-14 source in the model 3500 reader, some changes would need to be made to the reader. A mount to hold the source would need to be designed. This source can easily fit in the location of the optical density filter for the Bicron LED. The same drawer can be used and only this adjustment would need to be made.

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[24] United States, Naval Sea Systems Command, *Radiological Affairs Support Program Manual, NAVSEA so420-AA-RAD-010* (1991) II-2.

In conclusion this research found two sources that are immediate solutions to the calibration problems in the model 3500 reader. These sources are the Ocean Optics LED and the C-14 scintillating source. Using either of these as the reference light source will allow TLD readers to be used more easily in shipboard environments, while increasing the confidence in the system's readings.

Chapter 9. Recommendations for Further Research

There are still many areas which could be studied further before changing the reference light source. First, a better design is needed to integrate the fiber optics for diode sources. The design must include minimal changes to the body of the current reader to keep costs low. The fiber optics must be located so that there is little possibility of damaging the optics when opening and closing the drawer for readings. Additionally, a program that automatically calculates the output of the TLD reader based on the measurement of the optical power meter could be integrated into the current program. This program could immediately indicate the quality of the readings being taken by the TLD reader. It would also eliminate the need to have an optical calibration source that had a power stability of 1%. The purpose of the reference light source is to ensure the TLD reading is accurate. Hence, if two data points can be compared to see if they are within an allowed tolerance, then a user will immediately know if the TLD reading is accurate.

Further research needs to be done to determine the stability of these sources over a longer period of time. Due to time constraints no tests longer than one weekend were conducted. These tests are necessary to ensure the stability of these sources over the lifetime of the TLD reader.

More research also needs to be performed to assess the instability of the laser diode source and the tritium source. In this project the laser diode was not functioning properly. The cause of the instability must still be found. This source should be a stable, temperature independent source when it is meeting the specifications defined by the vendor. Additionally, the tritium source should be more stable over time. Its initial tests showed it to operate just outside of the ± 1% range, but these tests were not repeatable. More in depth research with this source might uncover the problem and enable the tritium source to be used as a stable reference light.

Finally, further research needs to be invested to determine the cause of the instability of the 8800 model reader, as discussed in Chapter III. The C-14 source tested in these project experiments seems to produce stable PMT output readings, within the desired levels. Hence, the cause of the instability in the 8800 reader may be unrelated to the reference light source.

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11. United States, *Naval Sea Systems Command, Radiological Affairs Support Program Manual, NAVSEA SS420-AA-RAD-010*, 1991.

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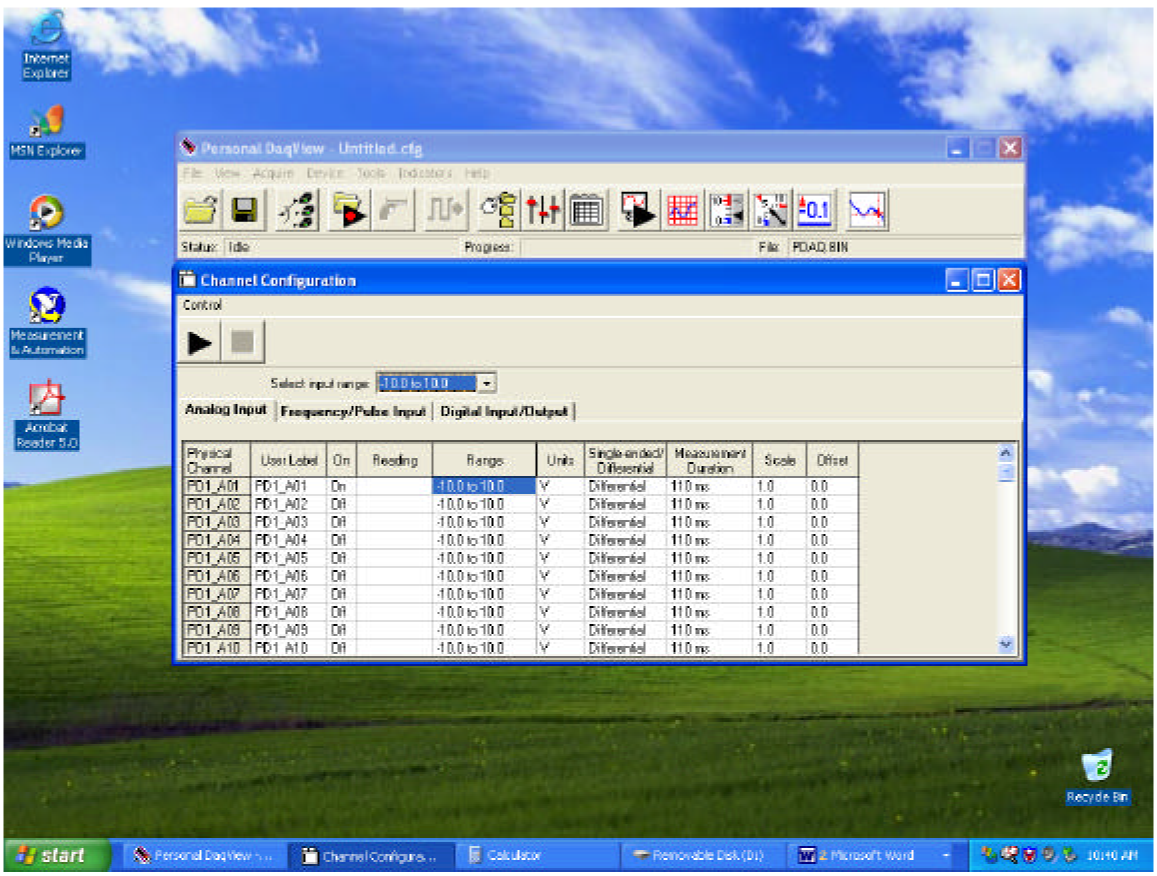
Appendix A

<u>Operating Instructions for Measurements for For Systems Used in this Project</u>

Bicron LED in TLD reader

1. Turn on TLD reader. There is a black switch on the back of the reader that turns it on. Let it run for 30 minutes to warm up before beginning any readings.
2. Turn on Computer.
3. Click on Start menu and go to programs.
4. Find Omega Personal DaqView and click on pDaqView 1.9.
5. A task bar should open after clicking on the program. Go to the ninth icon from the left. It is a gray and white graph, which is the channel configuration settings. Click on this. (There is a possibility that this will already be opened in conjunction with the initial opening of the program. If this is the case there will be a task bar and a channel configuration window already open and this step can be skipped.) At the end of this step the monitor should look as follows:



6. In the Channel Configuration Window click on the first block under range. Click the arrow next to select input range and scroll down to select Type J.
7. Click on the diagram with 3 folders on it. Change the folder to C:\Data. Change the file to TempDataMarXX.BIN. Click OK.
8. Click the icon in between the previous 2 icons. Go down to scan rate and enter .01667. The units should be in Hertz, which will result in one reading per minute.
9. Go to the laptop. Ensure cable goes from it to the TLD reader and other cable goes to the control panel of the reader. Connect the wires red to blue and green to green for the second cable. Ensure a good connection.
10. Turn on Laptop. Right click on screen and turn off the screen saver.
11. Open up the Harshaw folder on the desktop screen. In it click on the TLDshell.exe program. A screen will come up that asks you to press any key to continue. Do this and the TLD shell program will open up.
12. Go to File → Open → Response. For file name write the date (i.e. Mar4, etc.). For folder click on the 2 dots next to one another. A list will show up. Scroll down to TLData and select this folder. Then click OK.
13. The drawer on the TLD reader must be pulled out all the way. In the TLD shell program one should be able to see a place that says drawer: open on the left hand side. The drawer must be open to read the LED.
14. Press - alt tab. This will take one back to the main screen. Click on shortcut to PIO timer. A screen will come up asking that a time be entered. Type a number (usually 5) and then enter. This will result in one reading every 5 minutes.
15. Perform alt tab again to go back to the TLD shell program. Within a few minutes a reading should occur. Leave this program up on the screen for readings to occur.
16. Go back to other computer and press on the icon that is fourth from the left. It has a large triangle with a red dot in the middle of it. This will start the temperature readings.
17. Collect data for the desired amount of time.
18. At end of run press the same button as in step 15 to stop temperature readings. On the laptop press alt tab to get back to the main screen. Close the PIO timer program. A warning will come up, but just press OK.
19. Go back to the laptop and go back to the TLD Shell program. Go to file → export. This should export the data to the specified location.

*note – when closing the Temperature Daq program it will ask if you want to save current configurations. Click no and it will close.

C-14 in TLD reader

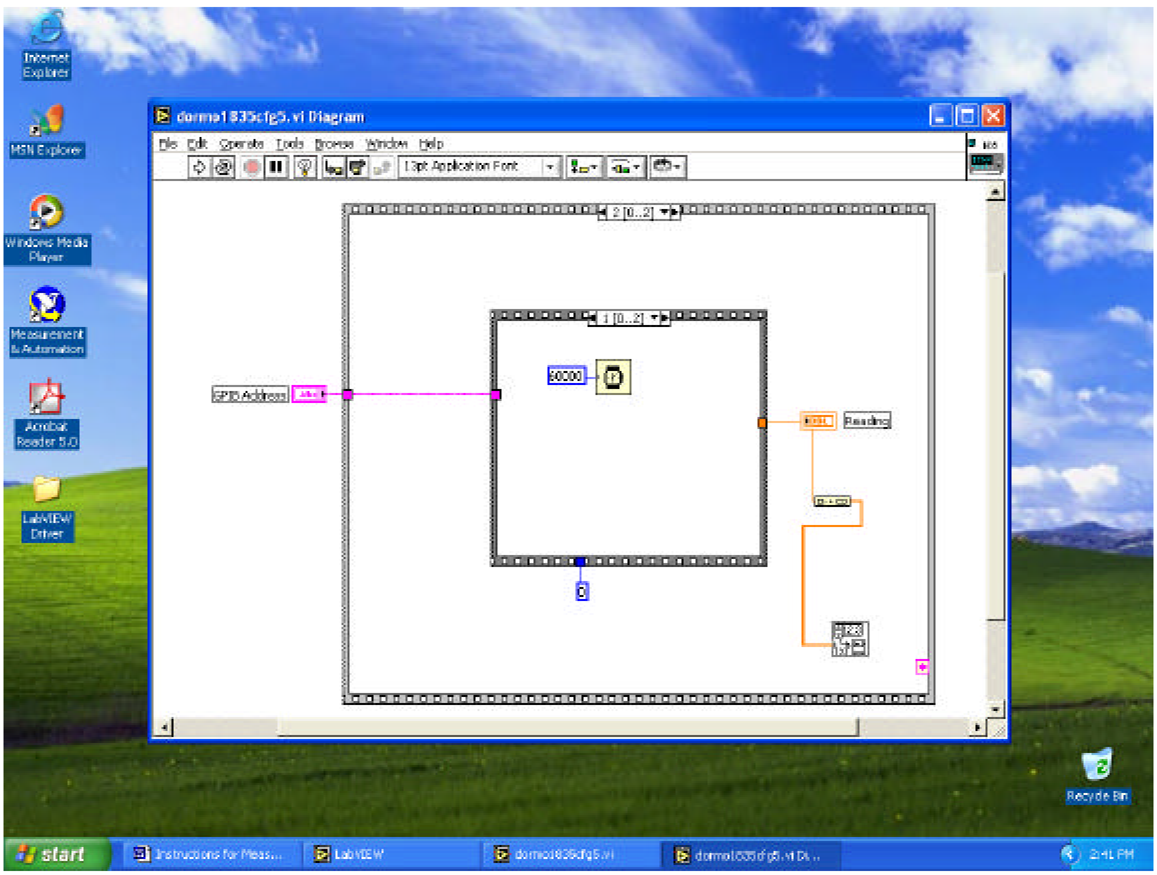
1. Perform steps 1 through 12 for the LED in the TLD reader.
2. On the TLD reader pull out the tray and gently place the C-14 source onto the holder. Very carefully slide the tray back into the TLD reader. Look back at the Laptop and check to see that on the left hand side on the places says drawer: closed.
3. Disconnect the 2 large wires that come out from the side of the reader next to the drawer. They are on the left side when one looks at the reader from the front.
4. Take the plexiglass piece that was built for the project and set it down next to the reader. Connect the wires to the TLD reader. Slide the magnet back and forth until it is under one of the wires and the program indicates that the drawer is open (The drawer is still

physically closed). This is a manual override so that the reader thinks it is doing a reference light reading.

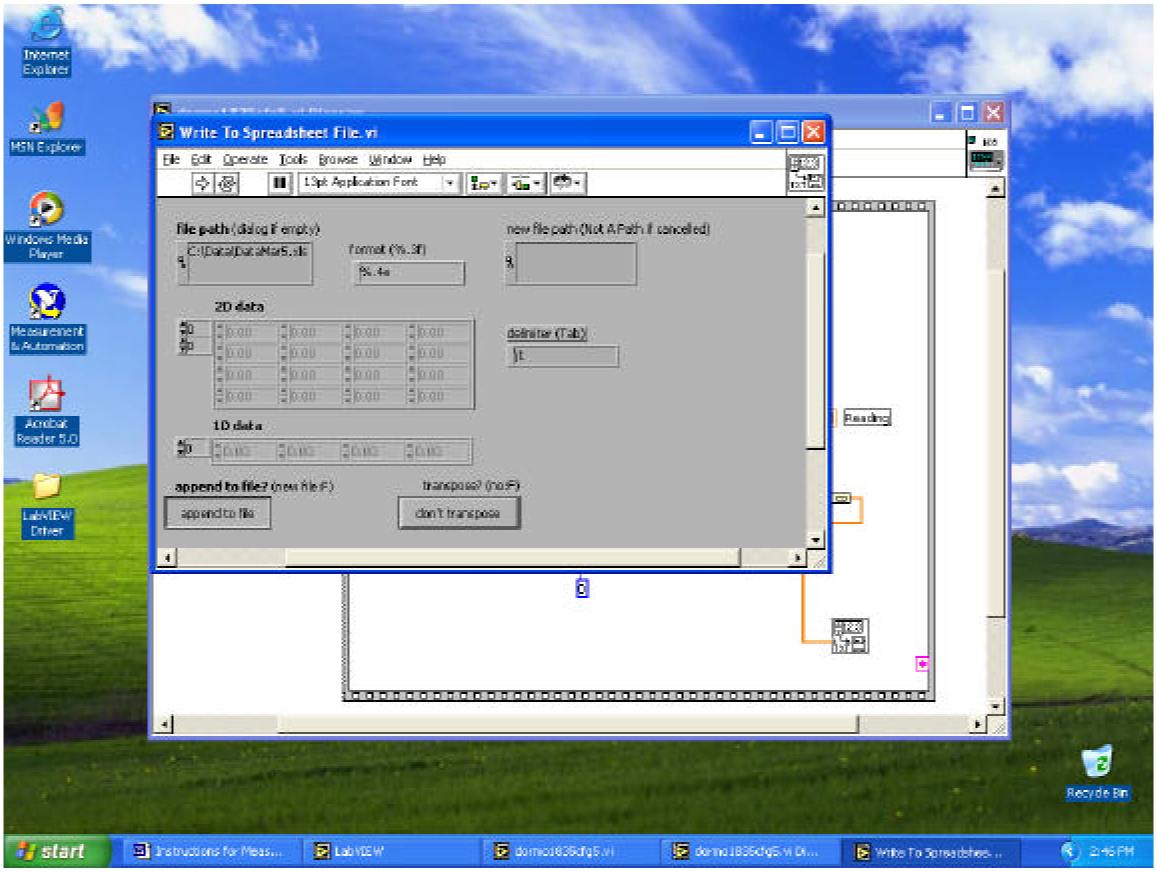
5. Resume with step 14 above and continue through the end of the instructions. Everything else remains the same.

Laser into the Optical Power Meter

1. Follow steps 2-8 of the LED into the TLD reader to set up the temperature DAQ. Only change is the date.
2. On the desktop, open the LabView drivers folder. There is only 1 driver in it. Open this. The file is dormo1835cfg5.vi.
3. Go to Window → Show Diagram. A picture like this will appear



4. Move the cursor over into white area of the LabView program. Press Tab until the cursor looks like a cross.
5. Move the cursor over the square in the bottom right hand corner. The square has 12.3 and TXT written in it. When the cursor is moved over this icon it will change into an arrow. Double click on the icon. A new window will appear that will look like the picture below.



6. Go to the box labeled file path. Click tab until the arrow turns into the normal cursor you see in Word. Click on the words and change the date to the appropriate date.
7. Go to Operate → Make Current Values Default.
8. Then go to File → save. Close this window. Then close the window that has the actual blocks drawn in it. There should be only 1 window left open, and it will be the interface between labView and the Optical Power meter.
9. Turn on the Optical Power Meter (press the red button). It should be reading out a number and then also have GPIB displayed below it.
10. Ensure fiber from the Laser is connected to the Optical Power meter.
11. Turn on the laser. Flip the switch on the Power supply up. The 2 displays should be showing 10.0 or 10.1 V. The power in the Optical Power meter should now be displaying a value in the mW range.
12. Place the detector head into the temperature controlled environment.
13. Turn on fan so that it is blowing across the temperature controlling circuitry.
14. Go back to LabView and on the icon that has two arrows completing a square. If the mouse is held over it, it should say run continuously. Click this button.
15. Start the Temperature DAQ by clicking on the Icon with a large triangle and a red dot in the middle of it. Both LabView and the DAQ should be working now. They are going to be taking one reading every minute so check back after a couple of minutes and look to make sure it seems as though some readings have occurred. The numbers should be changing slightly.

16. When ready to stop the data collection press the same button as used to start the Temperature DAQ to stop that device. To stop the LabView press on the red octagon that looks like a stop sign. Turn off the laser and then the Power meter.
17. That should have everything for the laser and power meter complete.

Ocean Optics LED into Optical Power Meter

1. Follow steps 1-9 of Laser into Optical Power Meter.
2. Ensure fiber from the LED is connected to the optical power meter.
3. Place the detector head into the temperature controlled environment.
4. Turn on the LED.
5. Follow steps 14-16 from above. Replace Laser with LED.

*note – when disconnecting a fiber be sure to place a dust cover over it before it is put down. Just switch one to the other fiber when ready to use the different devices.