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Title of Thesis: "Evaluation of the Sensitivity and Signal Response of the DT-702 LiF:Mg,Cu,P TLD"

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ABSTRACT


Title of Thesis/Dissertation: **Evaluation of the Sensitivity and Signal Response of the DT-702 LiF:Mg,Cu,P TLD**

Name, degree, year: LT J. Robert Hawley, BS, MSC, USN, MSPH, 2007

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The reliability and accuracy of a radiation dosimetry program is dependent on the intimate knowledge of the characteristics of the dosimetry material. In this study, the effects of pre-exposure (sensitivity) and post-exposure (signal) time on the Navy's DT-702/PD (Harshaw Thermoluminescent Dosimeter 8840/41) are evaluated. The results of this study show that the DT-702 TLD has no statistically significant loss of sensitivity or loss of signal with up to 29 weeks of pre-exposure or post-exposure time. Therefore, the DT-702 could be in use for at least 29 weeks producing accurate results without any additional fade correction required.

**Evaluation of the Sensitivity and Signal Response of the DT-702 LiF:Mg,Cu,P TLD**

by

J. Robert Hawley

Thesis/dissertation submitted to the Faculty of the Department of Preventative Medicine and Biometrics Graduate Program of the Uniformed Services University of the Health Sciences in partial fulfillment of the requirements for the degree of Master of Science of Public Health 2007

## Dedication

To my beautiful wife Ashlee.
Whose loving support and continuous sacrifice, strengthens and encourages me. The successes in my life are only great because of having you by my side. You give me purpose and celebration in life.

And to God,
For blessing me with this opportunity. My strengths and abilities are gifts from you Lord, and I will live my life to honor You.

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# 1.0. Introduction

## 1.1. Purpose

This study evaluated the operating characteristics of a thermoluminescent material: lithium fluoride (LiF) manufactured with manganese (Mg), copper (Cu), and phosphor (P) impurities. This material is used in the U.S. Navy's (Navy) newest thermoluminescent dosimeter (TLD), a device used for personnel and environmental radiation monitoring. The purpose of this study was to provide a detailed evaluation of the sensitivity and signal response of the LiF:Mg,Cu,P material used in the Navy's DT-702/PD (DT-702). The material was studied over a 29-week period to determine if time has an effect on its ability to detect and accurately record exposure to ionizing radiation. The effects of time were evaluated for: time before irradiation (pre-exposure), time following irradiation (post-exposure), and combinations of both. This study tested the null hypothesis that the DT-702 does not have any significant loss of sensitivity or signal response when stored for varying lengths of time before and after exposure to ionizing radiation. If the data validate the hypothesis, the results of this study will demonstrate that longer periods of issue may be feasible. A longer issue period will enhance the Navy's dosimetry program, reducing the need for both domestic and international shipping, as well as reducing the amount of handling required to process the TLDs each year. Additionally, the results of this study will improve the capabilities of personnel and environmental monitoring in the Navy by providing a detailed knowledge of the characteristics of the dosimeter.

## 2.0. Background

### 2.1. Radiation Detection

Accurate and reliable monitoring methods are required to minimize the potential negative health effects caused by exposure to ionizing radiation. Ionizing radiation exposure has been shown to cause both stochastic and deterministic health effects.[1] Stochastic effects do not have a minimum amount (threshold) of exposure to cause the effect, but the probability of the effect occurring increases with the radiation dose. The severity of the effect is also independent of the dose. An example of a stochastic effect of ionizing radiation exposure is the induction of cancer. Deterministic effects have a threshold dose, which is required to cause the effect, and the severity of the effect depends on the amount of radiation exposure. Radiation induced cataracts are an example of a deterministic effect of ionizing radiation exposure. Accurate monitoring of personnel for exposure to radiation is essential to minimize the potential of these harmful effects.

The Navy has been monitoring personnel radiation exposure since at least 1946.[2] Until the mid-1950's, monitoring was performed exclusively using dosimetric film badges.[3] In 1953 Schulman et al. introduced a solid-state dosemeter made of silver-activated phosphate glass.[4] This dosemeter (Navy designation DT-60) had a minimum range of 10 rem, and was designed for measuring exposure from large, acute exposures such as those that would occur in nuclear warfare.[4] A new method of radiation detection using thermoluminescence was adopted by the Navy in 1973.[2] Thermoluminescence was first discussed in regard to radiation monitoring in the 1940's by Daniels et al. at the University of Wisconsin-Madison.[5] Thermoluminescent

dosemeters (TLDs) provide a visual (light) response that is proportional to the amount of radiation delivered to the material. This light response can be captured, measured, and a radiation dose can be determined. The enhancement of this process continues today as we search for more accurate methods to measure and document personnel radiation exposure.

### 2.2. Theory of Thermoluminescence

Bohr's atomic model states that all materials are made of atoms consisting of protons and neutrons bound in a nucleus, surrounded by orbital electrons.[6] The electrons are held in discrete orbits whose radii are determined by the energies of the electrons. While this model is useful in explaining the characteristics of simple atoms (ex. hydrogen), it is insufficient to describe more complex interactions that occur within molecules and solids. Quantum mechanics was introduced in the mid-1920's to expand on Bohr's principles and create a more accurate method of explaining atomic and molecular phenomenon.[7] Similar to Bohr's model, quantum mechanics also describes electrons orbiting a nuclear structure. Instead of specific circular orbits, electrons move about the nucleus in a much less classically-defined electron probability cloud. Quantum mechanics theorizes that the mean energy, the primary quantum number($n$) is the same for all electrons of a given energy "shell", but each electron is also characterized by three additional quantum values: the orbital angular-momentum quantum number ($l$), the magnetic quantum number ($m$), and the spin quantum number ($s$).[7] The Pauli Exclusion Principle states that no two electrons in an atom can have the same set of

quantum numbers (*n, l, m, s*).[7] The use of quantum mechanical principles and the Pauli Exclusion Principle can be used to organize elements in the Periodic Table.

The molecular structure is different for different states of matter, such as gases, liquids, or solids. In a gas, atoms are relatively distant from each other compared to their size. They are allowed to move freely and do not have a defined shape or volume. The molecules in a liquid are closer than in a gas and are limited to the volume of their container, but still do not have a definite shape. For solids, the atoms are bound much closer together in a more defined structure, forming a crystalline lattice. This lattice can take on numerous configurations, such as cubic, orthorhombic, or hexagonal for example (see Figure 1). The atomic cores of the solid are located at each lattice point in the crystal.

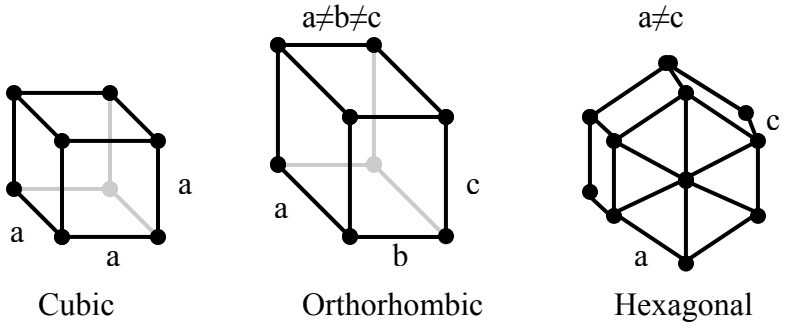


Figure 1
Examples of solid material atomic lattice structures.

Electrons orbit the atomic core as described by quantum mechanics. The free-electron theory states that metals have some electrons that are allowed to move freely within the volume of the material.[8] This is how energy transfer, such as electrical conductivity occurs in solids. To better understand this, we must identify the energy arrangement of electrons in the material. In analogous fashion to individual atoms,

electrons in a crystalline solid are arranged into allowed energy ranges (bands), based on the energy levels of the electrons in the solid. The highest energy band that is filled with electrons at zero absolute temperature (Kelvin scale) is called the valence band. A higher energy band, called the conduction band, exists above the valence band, but is empty at zero absolute temperature.[8] At room temperature (~300K) some electrons can populate the conduction band because of the additional internal energy that can be absorbed.[8] In the case of semi-conductors and dielectrics, a band gap exists between the valence band and the conduction band. This band gap is a range of energy states that electrons are not allowed to occupy. In order for an electron to migrate into the conduction band, it must absorb energy equal to at least the width of the band gap. The presence of this gap and its energy width determine if a solid is a conductor, semi-conductor, or an insulator. If the material is a conductor, the valence and conduction bands may be separated by a relatively small band gap, or may actually overlap, having no gap at all. This allows electrons to move easily within the material with no requirement to absorb additional energy. Insulators have large band gaps that prevent this migration of electrons. Semi-conductors have a smaller band gap (~1eV) that allows electrons to migrate into the conduction band if energy is available.[9] Figure 2 illustrates this electron energy band structure for a semi-conductor at room temperature. The physical properties of semi-conductors make them good candidates for use as dosimeters using the properties of thermoluminescence.

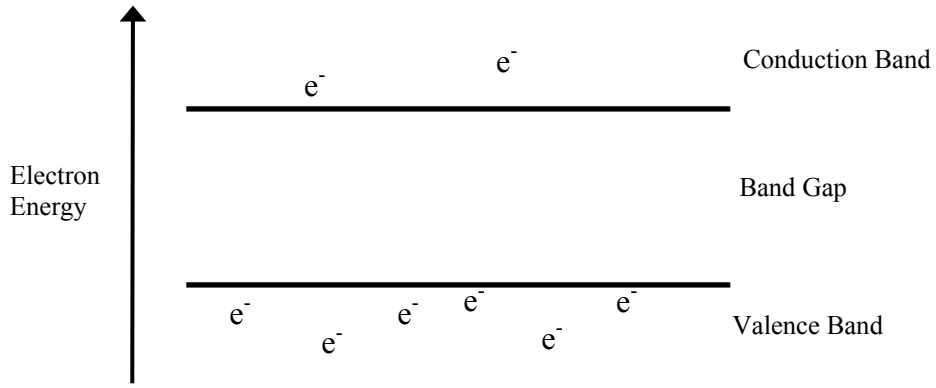


Figure 2
Illustration of the energy band structure in a semi-conductor at room temperature.

If an electron absorbs enough energy and migrates into the conduction band, it leaves behind a vacant state, termed a hole, in its place. The absence of the electron (hole) is just as important as the presence of the electron for current flow in semi-conductor materials. Just as an electron is a negative charge carrier, the hole can be considered a positive charge carrier. When energy is transferred within a semi-conductor, the motion of the electrons is opposite to the motion of the holes.[8] As an example, if a magnetic polarity is applied to a semi-conductor, the negatively charged electrons will be drawn to the positive side of the field. As each electron moves into an available hole, the hole has the appearance of moving in the opposite direction, toward the negative side of the field. While each transition of an electron to the conduction band creates a hole, the remaining discussions will consider processes involving the electron for reasons of simplicity.[8]

As radiation interacts with a solid material, it makes energy available to the electrons. If enough energy is absorbed, the electron can migrate from the valence band

into the conduction band (Figure 3, Step 1). In a pure, defect-free material, the electron tends to recombine with the hole quickly, not retaining any of the energy from the radiation interaction (Figure 3, Step 2a).[10] This process occurs almost immediately, precluding the ability to capture any of the radiation exposure information from the material.

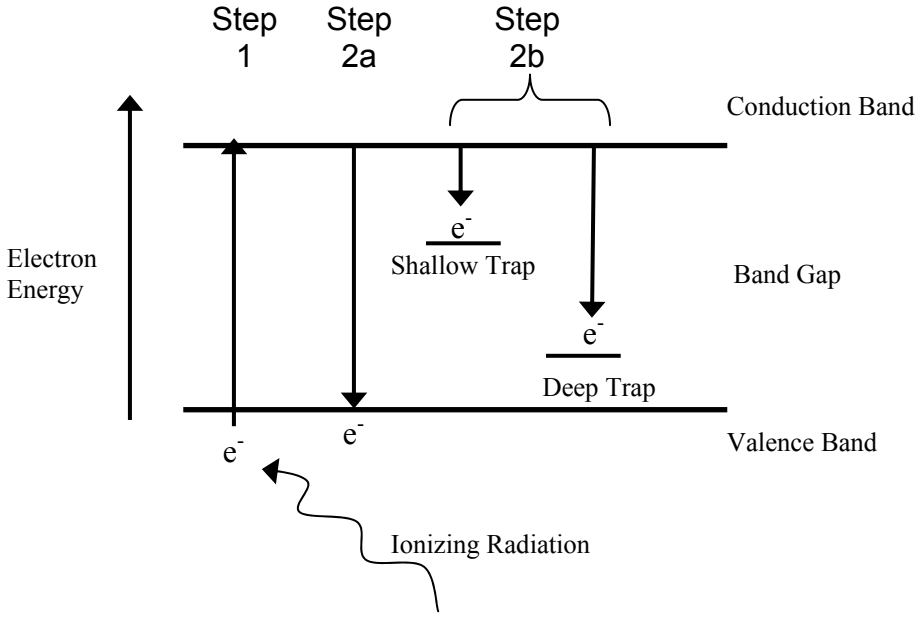


Figure 3
Illustration of electron excitation in a semi-conductor

In a non-pure semi-conductor material, the electron may not immediately recombine with a hole in the valence band. Instead it may be caught in higher energy state (trap) located between the valence and conduction band (Figure 3, Step 2b). Traps are created by the presence of impurities in the pure material or by lattice defects in the crystalline structure of the material.[8] In a pure semi-conductor material, there is a hole in the valence band for every electron in the conduction band.[8] The presence of the impurities causes the addition of an electron (or hole) from the impurity molecule that

exists at energy levels not normally allowed by the pure material (in the band gap).[8] This creates a distortion in the conduction or valence band, allowing the electron to be held in an energy state above the valence band energies and below the conduction band energy states. This state is relatively stable over time and effectively stores some energy of the radiation interaction in the crystal. The presence of these impurities can be naturally occurring or may be designed into the manufacturing process of the material (doping). Doping is used to increase the thermoluminescent efficiency of a semi-conductor material.

If the impurity or defect creates a trap close to the conduction band, it is considered a shallow trap (Figure 3). An electron caught in a shallow trap may be able to absorb enough energy at room temperature (~300K) to migrate back to the conduction band, possibly recombining with a hole in the valence band or being caught again in a trap closer to the valence band. This process does not occur in a controlled manner, inhibiting the capture any of the radiation exposure information from the material. If the trap is located closer to the valence band, it is termed a deep trap. Electrons caught in deep traps require more energy to be migrated back into the conduction band. This is a useful property for thermoluminescent materials, since the process of adding the additional energy can be controlled to allow measurement of the radiation exposure information retained by the material. For thermoluminescent materials, the material must be heated to cause the electron to absorb enough additional energy to potentially release it from the trap (Figure 4, Step 3). The electron can then recombine with a hole in the valence band, or be caught in a deeper trap, as illustrated by Figure 4, Step 4.

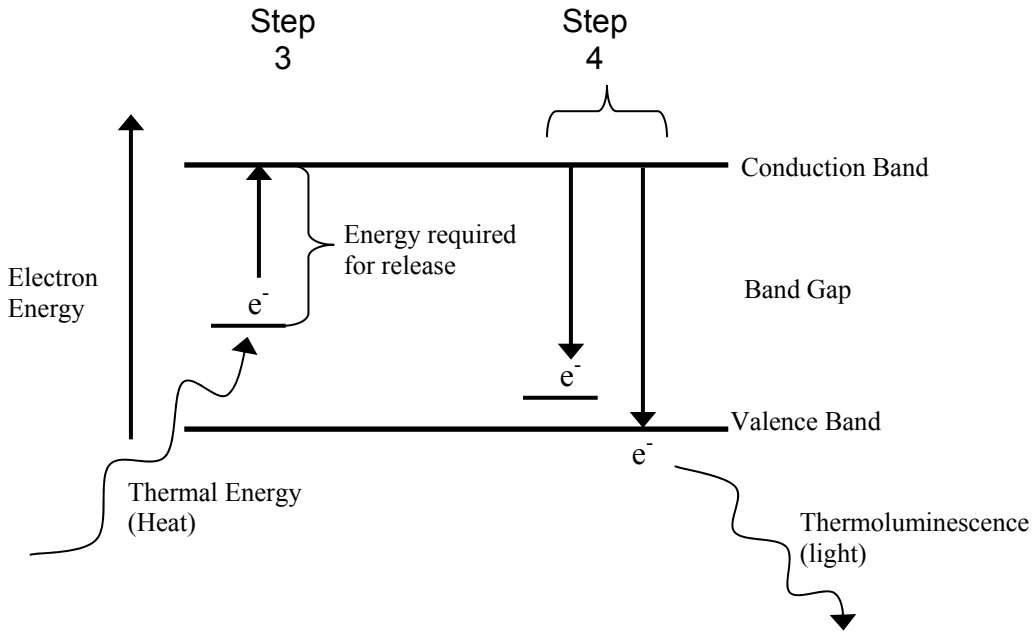


Figure 4
Illustration of electron de-excitation in a semi-conductor

Not all electrons will be initially released from their traps when thermoluminescent material is heated. The release of the electron is a probabilistic event, based on the energy level (depth) of the trap, and the internal energy available to the electron.[11] This internal energy is directly proportional to the temperature of the material. Electrons caught in deeper traps require more energy than those caught in shallow traps to be released back into the conduction band. The probability (per second) that the amount of radiation energy absorbed is enough to release the trapped electron is calculated via Equation 1; where *s(T)* is a temperature dependent term related to the thermal conductivity of the material , *E* is the energy barrier (depth) between the trap and the valence band, and *kT* is the intrinsic energy of the electron.[11]

$$p(T) = s(T) \exp(-E/kT) \qquad (1)$$

This equation determines the probability of electron release based on how much energy is required, and how likely the electron will absorb that energy.

If the electron is released from the trap and recombines with a hole in the valence band or a lower energy trap, the difference in energy from the initial trap to the electrons final location is released in the form of light. For thermoluminescent materials, as the material's temperature is increased during processing, electrons will be released from increasingly deeper traps.[11] This ultimately provides a total light output from the material that is proportional to the amount of radiation that was absorbed. The amount of light emitted is proportional to the number of electrons that are released, which in turn is proportional to the amount of energy deposited by the ionizing radiation.[11]

A glow curve is a plot displaying the luminous emission of the material versus the heating temperature. An example of a generic glow curve is shown in Figure 5. The (glow) peaks in a glow curve are specific to the type of thermoluminescent material used. These peaks indicate temperatures where more electrons are released from traps, and correlate to energy levels where more traps are located in the material.[11] Lower temperatures indicate higher energy trap sites (shallow traps), whereas higher temperatures indicate lower energy trap sites (deep traps).

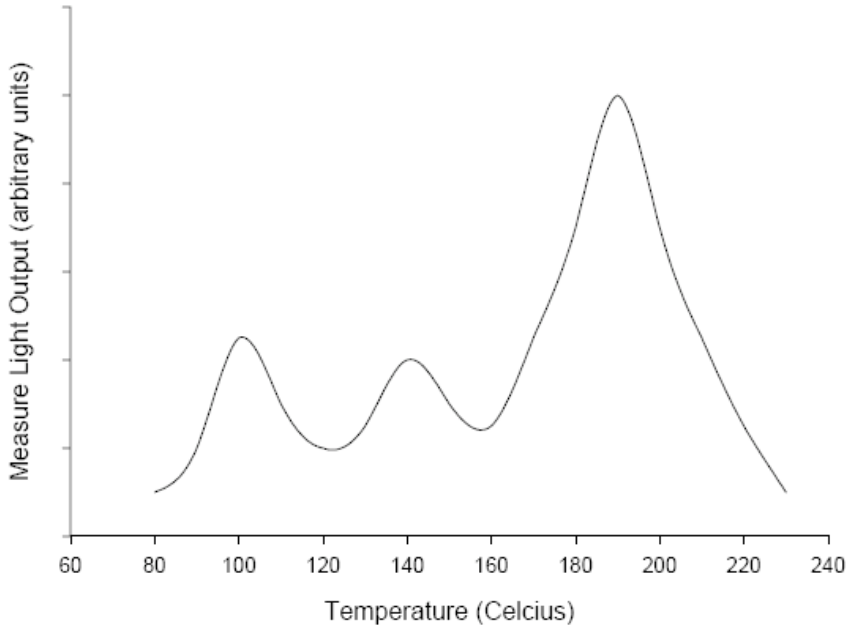


Figure 5
Example of a Generic TLD Glow Curve

A calibration of the material can be performed to determine how much light is emitted when the material is exposed to a specific dose of radiation.[10, 11] This value is normally calculated as the total area under the curve, but may also be determined by the maximum height of the main peak created by the material. Control of the heating process and the timing of light collection can be adjusted to collect a specific range of thermoluminescent information. The luminescent information captured from the material can then be used to calculate the radiation dose.

## 3.0. Thermoluminescent Materials

Several materials have properties that make them suitable for use as thermoluminescent dosimetry. For example; calcium fluoride ($CaF_2$), lithium fluoride (LiF), oxides of aluminum (Al), beryllium (Be), or magnesium (Mg), and various sulphates and borates are used in thermoluminescent dosimeters. Table 1 lists the most common materials used and their designations, given by the manufacturer, Harshaw Chemical Company (Harshaw).[12] One of the leading manufacturers of radiation dosimetry products, Thermo Fisher Scientific (Thermo) owns Harshaw, and has become the Navy's prime vendor for radiation dosimetry products and support. This study focuses on the LiF:Mg,Cu,P being used by the Navy, and the older materials that it has replaced ($CaF_2$:Mn and LiF:Mg,Ti).

| TYPE | MATERIALS |
|---|---|
| TLD-100 | Lithium Fluoride (Li natural) LiF:Mg,Ti |
| TLD-100H | Lithium Fluoride (Li natural) LiF:Mg,Cu,P |
| TLD-200 | Calcium Fluoride Dysprosium, $CaF_2$:Dy |
| TLD-400 | Calcium Fluoride Manganese, $CaF_2$:Mg |
| TLD-500 | Aluminum Oxide, $Al_2O_3$:C |
| TLD-600 | Lithium Fluoride ($^6$Li Isotope) LiF:Mg,Ti |
| TLD-600H | Lithium Fluoride ($^6$Li Isotope) LiF:Mg,Cu,P |
| TLD-700 | Lithium Fluoride ($^7$Li Isotope) LiF:Mg,Ti |
| TLD-700H | Lithium Fluoride ($^7$Li Isotope) LiF:Mg,Cu,P |
| TLD-800 | Lithium Borate Manganese, $Li_2B_4O_7$:Mg |
| TLD-900 | Calcium Sulfate Dysprosium, $CaSO_4$:Dy |

Table 1
TLD Material Designations from Harshaw (Manufacturer)

### 3.1. General Characteristics of Thermoluminescent Materials

Several classifications are used to describe the operating characteristics of thermoluminescent materials, such as sensitivity, signal response, and energy response. The sensitivity of a material is defined as the thermoluminescent signal strength per unit of absorbed dose, or basically how receptive the material is to absorbing the radiation to which it is exposed.[11] Equally important is the material's signal response, which is the variation in detected thermoluminescent output for a known absorbed dose.[11] Simply, this is the energy released by the material when it is processed relative to the energy which it absorbed during exposure.

Any loss of thermoluminescent sensitivity or signal response from an exposed material is termed fade. A decrease in the sensitivity of the material can occur before being exposed to radiation and is known as pre-irradiation fade. Pre-irradiation fade is a loss in the material's efficiency for absorbing energy from ionizing radiation interactions. The loss of sensitivity results from electrons gaining additional energy from sources

(thermal, vibration, ect.) prior to being exposed to radiation. Electrons are then caught in traps, reducing the number of traps available to capture electrons when the material is exposed to ionizing radiation.

A decrease in the signal response can occur after the material is exposed to ionizing radiation and is known as post-irradiation fade. This is a release of the energy stored from the radiation interactions that occurs prior to the TLD being read. Electrons can absorb additional energy from sources other than heating of the material, freeing them from their traps. This releases some of the stored energy from the radiation interactions and results in a decreased output when the TLD is read.

The most prevalent cause of TLD fading is heat.[11] Just as the process of thermoluminescence is designed, exposure to heat can impart additional energy to the electrons. Even with slight increases in ambient temperature, electrons caught in shallow traps can absorb enough additional energy to be released back into the conduction band, causing a loss of signal. Additionally, electrons in the valence band can absorb enough energy to migrate into deeper traps, reducing the sensitivity of the material.

Changes in signal can also occur if the material is light sensitive. Similar to thermal fading, optical stimulation can cause electron release and a resulting loss of signal if the material is exposed to light. Light stimulation can also have the opposite effect, where the light energy is absorbed by the material causing an increase in signal. Even with environmental controls in place to control temperature and light exposure, anomalous unexplained fading can still occur.[11]

Another important material characteristic is its energy response. The energy response is the variation of the thermoluminescence, for a set exposure, as a function of

the energy of the absorbed radiation.[11] As radiation interacts with a material it can impart its energy in different ways. The method of energy deposition is not only determined by the energy of the radiation, but also the material's effective atomic number ($Z_{eff}$). The $Z_{eff}$ is determined by the atomic number of the atoms that make up the material, and the fractional portion that each atom contributes to the molecule. The main purpose of personnel monitoring is to determine a radiation dose absorbed by the human body, so it is desirable to use a material with $Z_{eff}$ similar to that of human tissue ($Z_{eff}$ = 7.4).[11] This ensures that the radiation interactions will be similar to those that take place in human tissue.

### 3.2. $CaF_2$:Mn

The first thermoluminescent material used by the Navy for personnel monitoring was $CaF_2$,Mn.[2] It has a $Z_{eff}$ = 16.3 and has a useful range of 0.01 mrem - 10,000 rem (TLD-400).[11, 12] The $CaF_2$:Mn material is approximately 10 times more sensitive to gamma radiation exposure compared to LiF:Mg,Ti.[11, 12] The material has been shown to significantly over-respond (~1,200%) to low energy gammas (about 40 keV) which is considered to be a significant limitation for its use.[11] Additionally, the relatively higher $Z_{eff}$ results in a different response of the material when exposed to beta radiation versus gamma radiation. Studies have shown $CaF_2$:Mn to respond by a factor of 10 times higher to gamma than to beta, which may lead to an over-estimation of beta dose.[11] McKeever et al. reported signal losses for $CaF_2$:Mn to be 5% during the first 24 hours, stabilizing at approximately 8% after two days.[11] The material does exhibit some non-universality between batches based on the varying reports of measured fading and

sensitivity values.[11] The $CaF_2$:Mn material has also been shown to develop an intrinsic background signal over time. Natural potassium in the encasement materials and traces of other naturally occurring radioactive material in the base material are believed to be the greatest contributing factors.[11]

### 3.3. LiF:Mg,Ti

Lithium Fluoride was first successfully used as radiation dosimetry by Farrington Daniels during atomic bomb testing in the early 1950's.[11] He used a very similar material to the TLD-100 (Table 1), patented by the Harshaw Chemical Company in 1963.[11] Still commercially available today, the TLD-100 is made with LiF in its natural isotopic abundance (7.5% $^6$Li and 92.5% $^7$Li) and is doped with approximately 180 parts per million (ppm) magnesium ($Mg^{2+}$) and 10 ppm titanium ($Ti^{4+}$).[11] The LiF:Mg,Ti material is also available in two other forms. The TLD-600 material is enriched with 95.6% $^6$Li and 4.4% $^7$Li, creating a material that is sensitive to both neutron and gamma radiation.[11] The TLD-700 material is comprised of 0.07% $^6$Li and 99.93% $^7$Li and is sensitive to gamma and beta radiation.[11]

Lithium Fluoride has a $Z_{eff} = 8.2$. This is much closer to tissue-equivalent, only 11% higher, compared to $CaF_2$:Mn, which is 120% higher.[11, 12] Therefore the radiation interactions that will occur in LiF will be similar to the interactions in human tissue. This provides a more representative record of the energy absorbed (dose) by the individual, and makes LiF a desirable material to use for personnel monitoring.

Numerous studies have been performed on LiF:Mg,Ti to classify its thermoluminescent properties. It has a useful range of 0.001 – 1,000 rem, although the

response of the material has been shown to become supra-linear above $10^2$-$10^3$ rem.[11-13] Study results have varied for the LiF:Mg,Ti material, including the range of linear response, and its sensitivity to light.[11-16] The basis for these variations is largely believed to be caused by inconsistencies between batches being tested.[3, 15] It has also been shown that the LiF:Mg,Ti has a large susceptibility to anomalous fading.[11, 14, 16] Studies have reported varied amounts of signal loss from test to test. [11-16] Thermo claims only a 5% decrease per year, while Doremus et al. reported (photon) signal losses of 40% over 40 weeks in a study with a similar design to the methods used in this study.[12, 14] Thermo recommends using a fade correction algorithm which they developed based on a 14 week fade evaluation.[14] Doremus et al. was able to achieve an additional 5-10% improvement in accuracy by using simple and multiple regression models based on the specific operating environment and procedures used by the Navy.[14] The LiF:Mg,Ti material has also been shown to be sensitive to light, reporting signal increases equivalent to approximately 4 mrem, with eight hours of exposure to general office lighting.[17]

### 3.4. LiF:Mg,Cu,P

In the mid-1970's, Japanese physicist Nakajima and colleagues began experimenting with manganese (Mg), copper (Cu), and phosphorus (P) impurities in LiF.[18] The material produced was found to be about 23-25 times more sensitive than TLD-600 (LiF:Mg,Ti).[18] The sensitivity of the material was greatly reduced after its first use, unless it was thermally pre-treated.[18] Experiments with thermal treatments were performed on the material for 10 minutes at 250$^{o}$C and also at 240$^{o}$C.[18] The

initial treatments at 250°C showed significant changes in both the shape and the temperature at which the glow curve peaks were seen.[18] Treating at only 240°C however showed no considerable change in response.[18-20] It was later discovered that heating of the material above 240˚C caused a change in the valence of the copper ion from $Cu^{+}$ to $Cu^{2+}$.[21] This change is believed to be a major cause of the degradation in sensitivity of the material.[21]

In 1983, Wu et al. produced a LiF:Mg,Cu,P material that retained its high sensitivity following several uses (<5% after eight uses).[22] Moscovitch reported an approximate 10% loss of sensitivity after 1,003 read cycles of the TLD-700H material.[23] The resultant LiF:Mg,Cu,P material was shown to still be about 23 times more sensitive to photons and betas compared to TLD-100.[3, 22] It was also reported to have negligible fading over 120 days and have a linear response up to at least 2,000 rem (bare material).[13, 22] The LiF:Mg,Cu,P has the same $Z_{eff}$ as LiF:Mg,Ti.[11]

The new LiF:Mg,Cu,P material is still susceptible to a loss of sensitivity when heated above approximately 240°C.[19, 20, 22, 24, 25] This decrease in sensitivity is seen when the chips are encapsulated as part of the TLD manufacturing process (280°C – 290°C). This reduces the sensitivity of the material to about 10 times that of LiF:Mg,Ti.[3, 23] Some studies have demonstrated that this process is at least partially reversible with annealing at 240 °C, although Moscovitch reported this loss to be permanent and irreversible.[20, 21, 23] The current commercially available copper doped material is limited to maximum temperatures of 240°C for bare material and 260°C for encapsulated chips.[13, 19, 20, 25] A summary comparison of $CaF_2$:Mn, LiF:Mg,Ti and LiF:Mg,Cu,P is available in Table 2.

| | CaF:Mn (TLD-400) | LiF:Mg,Ti (TLD-100) | Lif:Mg,Cu,P (TLD-100H) |
|---|---|---|---|
| **Effective Atomic Number** | 16.3 | 8.2 | 8.2 |
| **Useful Range** | 0.01 mrem - 10,000 rem (TLD-400) | 1 mrem – 1,000 rem (TLD-100, TLD-600, TLD-700) | 0.1 mrem – 1,000 rem (TLD-100H, TLD-600H, TLD-700H) |
| **Response[11, 26]** | linear to 500 mrem – supralinear >100mrem | linear to 10 rem - supralinear to 1,000 rem - sublinear >1,000 rem | linear to 10 rem - sublinear >10 rem |
| **Sensitivity to Co-60 (relative to TLD-100)** | 10 | 1 | 15 |
| **Sensitive to light?[11, 17]** | Yes | Yes | No |
| **Fade? (loss of signal response)** | 8% in first 24 hrs, 12% in 3 months | 5% per year (corrected) | negligible |

** All data provided by Thermo Fisher Scientific (manufacturer)[12], unless otherwise noted.

Table 2
A Comparison of Properties for $CaF_2$:Mn,
LiF:Mg,Ti, and LiF:Mg,Cu,P Materials.

### 3.5. History of TLDs in the Navy

The first TLD used by the Navy was introduced in 1973, and was made of $CaF_2$:Mn (Navy designation DT-526/PD (DT-526)).[2] The DT-526 (Figure 6) consisted of two $CaF_2$:Mn chips attached to a central wire, and encased in a glass bulb.[27] When worn by the user, the glass bulb is placed into a protective plastic housing. The housing incorporates thin lead shielding around the bulb to shield low energy gammas radiation.[27] Low-energy gammas cause the $CaF_2$:Mn to over-respond, producing an inaccurate reading. The bulb is enclosed with a plastic cap that screws into the end of the housing. The plastic cap also includes an emergency dosimeter, made of sulfur tablets and indium foil.[27] It is used to grossly estimate large acute exposures (>25 rem).[27] The DT-526 is read by the local issuing command, using a single TLD manual reader.[2] The reader applies a voltage to the wire, heating the chips to initiate the thermoluminescent response. Measurements are made similar to the process described in

Section 2.2., except that the radiation dose is based on the maximum height of the glow curve, vice the area under the curve.[3]

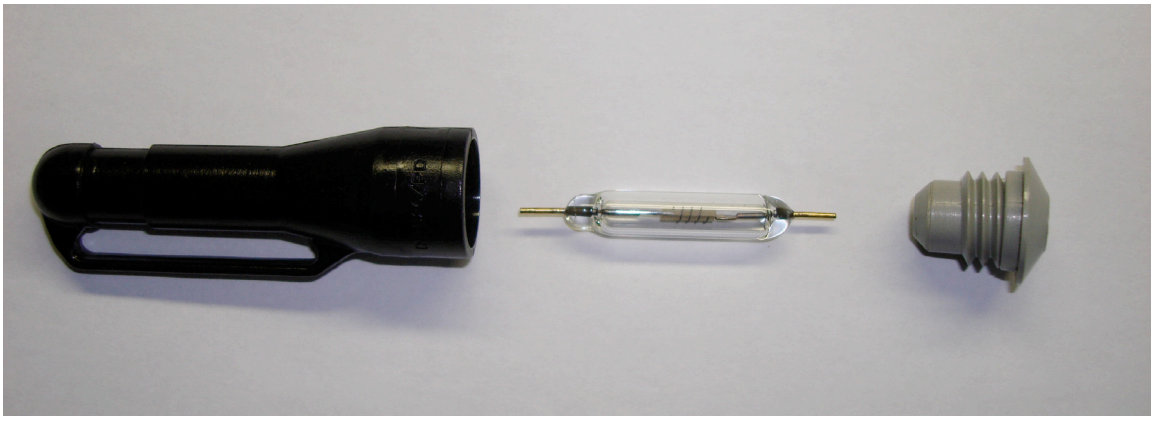

Figure 6
DT-526 ($CaF_2$:Mn) TLD

In addition to the DT-526, the Navy began using a two-chip LiF:Mg,Ti dosimeter in 1975 (Harshaw Model 2270/71, Navy designation DT-583/PD (DT-583)). The DT-583 was used for personnel and environmental monitoring primarily for neutron exposures.[2, 13, 28] It consisted of one TLD-600 and one TLD-700 chip, shielded by a small cadmium plate (Figure 7).[28] The cadmium plate shielded the chips from incoming thermal neutrons, allowing the measurement of fast neutrons that were reflected back out of the body as thermal neutrons.[29] This was the Navy's first use of an albedo neutron dosimeter. When worn simultaneously with the DT-526, it was possible to measure both high-energy gamma and albedo neutron dose.

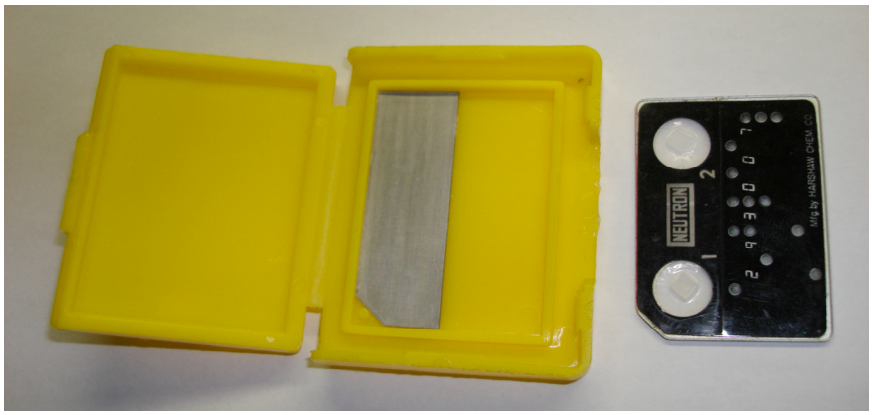


Figure 7
DT-583 (LiF:Mg,Ti) TLD

A need for more comprehensive radiation monitoring led to the development of the Harshaw Model 8801 TLD (Navy designation DT-648/PD (DT-648)). The DT-648 replaced the DT-583 in 1988.[2] It is a four-chip TLD that consists of three square TLD-700 chips and one square TLD-600 chip (Figure 8). Chips 1 and 2 are identically sized TLD-700 chips used to record gamma radiation exposure. Chip 3 is a thinner TLD-700 chip used to evaluate beta radiation exposures, and Chip 4 is the TLD-600 material used to evaluate neutron radiation exposures. When worn, the DT-648 card is housed in a plastic card holder that incorporates filter materials installed in front of the individual chips. Chip 1 is filtered behind a 600 $mg/cm^2$ plastic filter, and is used to measure deep dose gamma and beta radiation.[30] Chip 2 has 0.11 mg of copper and 242 $mg/cm^2$ of plastic filtration to allow energy discrimination of the gamma radiation dose.[30] Chip 3 lies behind a 0.006 cm thick aluminized Mylar film, and provides information for the calculation for a shallow (skin) dose (beta radiation).[30] Chip 4 is filtered by 600 $mg/cm^2$ plastic, and provides data for determining neutron exposures.[30] The advent of the DT-648 allowed discrimination and measurement of high and low energy gammas as well as beta and neutron radiation from a single dosimeter.

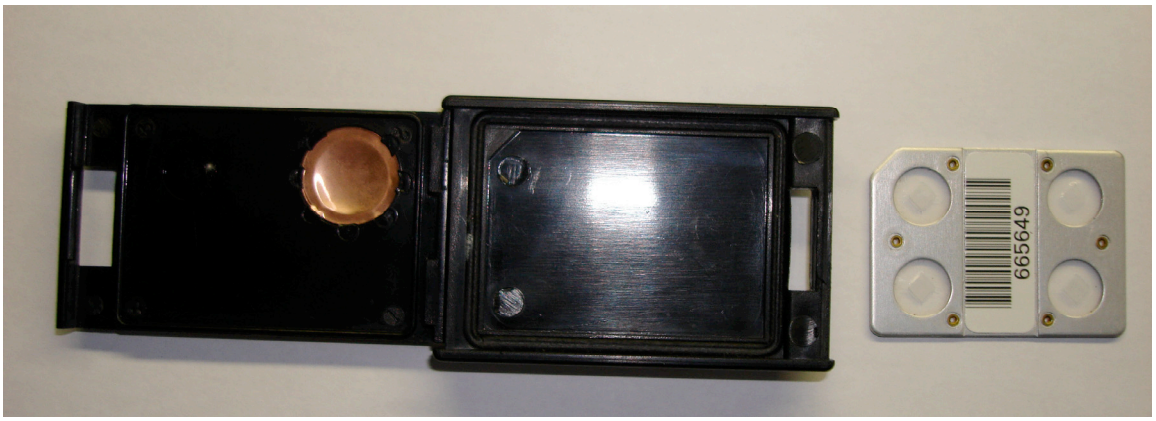


Figure 8
DT-648 (LiF:Mg,Cu,P) TLD

In the late 1990's, Thermo, in cooperation with the Navy, developed a LiF:Mg,Cu,P TLD, similar in design to the DT-648. The Harshaw Model 8840/41 TLD consists of four Teflon® encapsulated, circular LiF,Mg,Cu,P chips, each 0.4 cm in diameter.[13] The chips are encased in a thin, riveted aluminum frame, labeled with a unique, serialized barcode. The barcode is read by an automated scanner during processing, and is also visible through a clear, colored window located on the back of the TLD holder. Chips 1 and 2 are 0.0381 cm of LiF-700H, Chip 3 is a thinner 0.0254 cm of LiF-700H, and Chip 4 is 0.0381 cm of LiF-600H.[13] The TLD-100H, 600H, and 700H materials all have the same LiF composition as their respective LiF:Mg,Ti counterparts. The Harshaw Model 8840/41 TLD also utilizes filters installed in the TLD holder to allow detailed radiation dose discrimination and measurement. Chip 1 is filtered by 242 $mg/cm^2$ of plastic and 91 $mg/cm^2$ of copper and is used to discriminate gamma radiation energy levels.[23] Chip 2 is filtered by 1,000 $mg/cm^2$ of plastic and is also used for determining gamma, as well as beta radiation dose.[23] Chip 3 is covered only by a 17 $mg/cm^2$ aluminized Mylar window and provides beta radiation information, and Chip 4 is filtered by 242 $mg/cm^2$ plastic and 240 $mg/cm^2$ of Tin(Sn).[23] Chip 4 provides neutron

dose information, as well as medium energy gamma discrimination.[23] The advent of the Model 8840/41 TLD improves on the single dosimeter function of the DT-648 by providing a 10 fold increase in sensitivity for gamma radiation, as well as improved fading characteristics.[3] The Model 8840/41 TLD only responds with about 25% as much signal as the DT-648 for neutron radiation.[3] Because of the reduced need to monitor exposure of personnel to neutron sources, compared to gamma sources, the Model 8840/41 TLD was determined to be an improved substitution for the DT-648 and DT-526. This commercially available TLD was purchased by the Navy and designated the DT-702/PD (DT-702) (Figure 9). The DT-702 began replacing the DT-648 in 2002, and the DT-526 in 2005, becoming the primary dosimeter used for personnel and environmental monitoring in the Navy.[13]

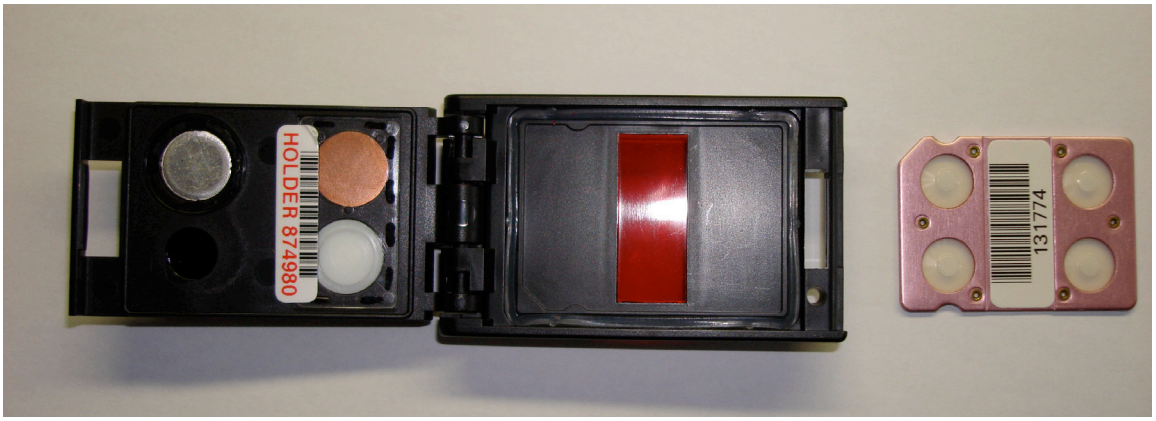


Figure 9
DT-702 (LiF:Mg,Cu,P) TLD

## 4.0. Processing Thermoluminescent Dosimeters

### 4.1. Harshaw Model 8800 TLD Reader[31]

The Harshaw Model 8800 TLD Reader (8800 Reader) is a fully automated TLD reader that is used to process up to 1,400 TLD cards of either LiF:Mg,Ti or LiF:Mg,Cu,P. The system's host computer is located within the TLD reader and is used for all mechanical and electrical operations that the machine performs. A second computer is physically separate from the reader (connected by serial cable), and runs the WinREMS® (Windows Radiation Evaluation and Management System) program that controls the overall operation of the reader and processes the results from the reader. The TLD reader consists of a TLD transport mechanism, a barcode reader, the TLD read station, and a Strontium-90/Yttrium-90 (Sr-90) irradiator. The TLDs are moved by the transport mechanism from a load carousel to the barcode reader where the card is identified.

While every DT-702 card is physically the same, some cards are used for different purposes. The four types of cards we will discuss here are: field cards, calibration cards, quality control (QC) cards, and Gold Standard cards. Field cards are the TLD cards that are issued for personnel and environmental radiation monitoring. Calibration cards, QC cards, and Gold Standard cards are used for establishing and verifying the calibration of the DT-702 TLD and 8800 Reader system. The use of these cards will be discussed in more detail later. The purpose of the card is identified by its serial number, and by the color of the card substrate. When the barcode is scanned, its number is located in a database which correlates to the purpose of the card.

After the 8800 Reader identifies the card, it is sent to the TLD read station to be read or annealed. For the purpose of thermoluminescent dosimetry, annealing is the

process used to clear any radiation exposure information from a TLD, preparing it for reuse. The process for reading or annealing of a TLD is operationally the same. The TLD is heated to release the stored energy as described in Section 2.2., except that for annealing, the luminous emission is not used to determine a radiation dose.

The TLD read station consists of a non-contact heating system and photomultiplier tube (PMT) assembly. The heating system is made of a resistive heating tube, which heats supplied nitrogen gas conductively to precisely control the temperature of the chip based on the time-temperature profile (TTP). The time-temperature profile is the specific method that the computer uses to control the reading of the TLD, based on the limiting characteristics of the material. It defines the heating rate, temperature, and time that the chip is held at that temperature. Physical integrity of the TLD is protected, since there is not any physical contact between the heating system and the TLD. Additionally, this ensures uniform heating of the TLD chip with no loss due to the conductivity properties of the heating elements used in previous contact type designs. In the 8800 Reader, all four chips of the TLD are heated and read at the same time.

The process of capturing the light emitted from the TLD starts in the PMT assembly. Dosimeter reading is performed by four separate detection channels, each with a separate PMT. The PMT consists of a photoelectric layer (photocathode) coupled to an electron multiplier structure. Figure 10 illustrates the photo-multiplication process.

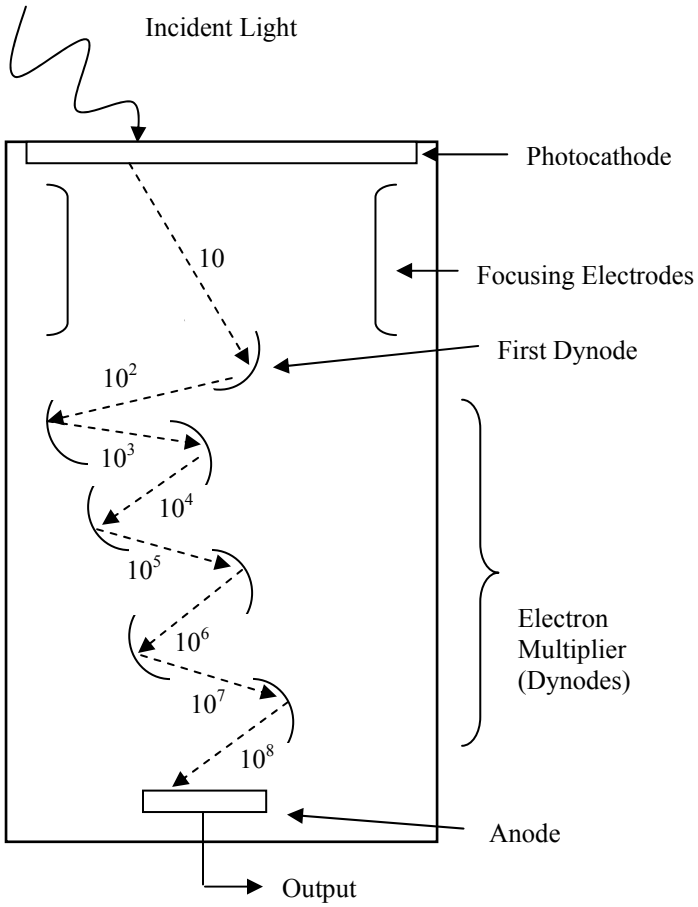


Figure 10
Photomultiplier Tube Assembly

The photocathode is used to convert the light photons emitted from the thermoluminescent material into photoelectrons. It does this by absorbing the photon energy, transferring it to electrons in the material, and then ejecting the electrons into the inner volume of the PMT.[9] The electrons are accelerated by electric fields (produced by the focusing electrodes) into the multiplier structure.[9]

The number of electrons produced is not typically enough to be used for an electric signal. Therefore the signal must be amplified and converted to digital logic pulses. Primary amplification of the signal occurs through the production of secondary

electrons within the PMT. Secondary electrons are produced from the impact of the initial electron on an electrode (dynode).[9] They are successively accelerated to a second dynode, and then a third, and a fourth, and so on. Multiple stages of dynodes are used to achieve gains on the order of $10^6$-$10^8$.[9] The electrons are finally gathered on a collector anode and an electric signal is generated.[9]

Additional processing must be performed on the signal before it is usable for quantitative analysis. This takes place in a micro-processor based data acquisition system that provides functions similar to the simplified schematic diagram shown in Figure 11. The signal is sent from the anode circuit to a pre-amplifier followed by a linear amplifier.[9] The pre-amplifier is used to reduce the extraneous electrical noise in the signal that is not related to the radiation signal.[9] The linear amplifier then amplifies the signal from the pre-amplifier, and shapes the signal into linear voltage pulses.[9] A pulse discriminator is then used to convert the linear voltage pulses into countable logic (digital) pulses.[9] The discriminator may also include a pulse-height analyzer. A pulse height analyzer is used set voltage limits. This device can be used as a pulse height "switch", to choose which pulses are converted to digital pulses and which are rejected as noise.[9]

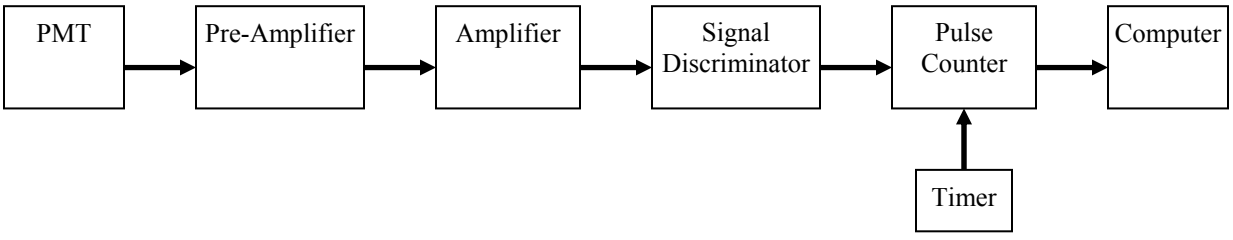


Figure 11
Typical elements of a signal processing system.

Finally the output pulses from the discriminator are sent to the counter, and accumulated over time. The results of the counter are sent to a computer for display, processing, and archiving. In the 8800 Reader, the results are displayed on both the host computer, and the WinREMS computer. When processing at the read station is complete, the transport mechanism moves the TLD to the unload carousel, and the process begins again for the next TLD.

### 4.2. TLD Reader Calibration

The 8800 Readers are semi-annually calibrated to a Cesium-137 (Cs-137), National Institute of Standards and Technology (NIST) standard. This calibration verifies the consistency of the Sr-90 source installed in the TLD reader. Sets of TLDs are taken to NIST and exposed to 500 mrem from a Cs-137 source. The cards are then brought back to NDC and read on the TLD reader. Results from the TLDs provide a quantitative assessment of the light output from the TLD for a 500 mrem exposure in nanocoulomb per mrem (nC/mrem). The cards are then subsequently irradiated using the installed Sr-90 source to approximately 500 mrem and read. Results of the second TLD read provide a quantitative assessment of the light output from the TLD when exposed to the Sr-90 source for a period of time in (nC/sec). The response from exposure to the Sr-90 source (nC/sec) is divided by response from exposure to the Cs-137 NIST source (nC/mrem) to determine the (mrem/sec) output of the installed Sr-90 source in the reader. Since the reader is calibrated to NIST's Cs-137 source, irradiations on subsequent TLDs

using the Sr-90 irradiator calibrated to the NIST standard are considered to be “Cs-137 equivalent”.

In addition to the biannual NIST calibration, a daily reader calibration factor (RCF) is calculated for each channel of the 8800 Reader. This procedure occurs at the beginning of each day before processing any TLDs, and involves irradiating a set of ten calibration TLDs to 100 mrem and reading them. Since the NIST calibration verifies the time required to irradiate the TLD to 100 mrem using the installed source, any variation in the response for that amount of exposure time must be corrected. Variations in the TLD reader are caused by environmental changes and are corrected by the RCF. The RCF is calculated using Equation 2; where L is the known irradiation value of the ten calibration TLDs (100 mrem), and <Q> is the average measurement of the ten calibration cards.[23].

$$RCF = \frac{< Q >}{L} \tag{2}$$

The RCF is applied in Equation 3 to determine the indicated value (Dose) from each chip; where TLR is the thermoluminescent response (measure light output) of the chip, and ecc is the element correction coefficient (defined in Section 4.3).[23]

$$Dose = \frac{(ecc * TLR)}{RCF} \tag{3}$$

### 4.3. TLD Card Calibration

Element correction coefficients (ecc) are used to compensate for material composition and manufacturing introduced variations between the chips. Each chip is assigned an ecc, correcting its sensitivity to a standard set by calibration TLDs.[23] An

ecc is generally determined by irradiating a card to a known dose and correcting the response to a reference population. [31] The reference population (Gold Standards) is a subset of cards from the entire population of TLDs.

The determination of the ecc correction for field cards begins with the calibration of the Gold Standards and the calibration of the TLD reader. The abbreviations of ECC and ecc are used to define the element correction coefficient for the Gold Standards and the field cards, respectively. The Gold Standards are irradiated at NIST to a specified dose, and then read. For the Gold Standard cards, the ECC is calculated by Equation 4; where <Q> is the average measurement of the Gold Standard cards, and Q is the measurement of the Gold Standard card being tested.[23, 31]

$$ECC = \frac{< Q >}{Q} \qquad (4)$$

Once the ECCs are assigned, the TLD reader is calibrated (Section 4.2) using the Gold Standard cards, and can then be used to generate additional calibration cards.[23, 31] These calibration cards are purple in color, and are used to perform the daily RCF calibrations, representing an operational surrogate for the Gold Standard TLDs. Assuming that the TLD reader's response did not change once established by the Gold Standards, and is verified using the calibration cards, the eccs generated for the remainder of the population will correct their response to the response of the Gold Standards. Calculating the ecc is performed using Equation 5; where <Q> is the average measurement of the calibration cards, and q is the measured charge of the field card being tested. This ensures that the entire population of DT-702 TLDs respond in a similar manner to the Gold Standard TLDs.[23, 31]

$$ecc = \frac{< Q >}{q} \tag{5}$$

This process is illustrated in Figure 12.[31] .

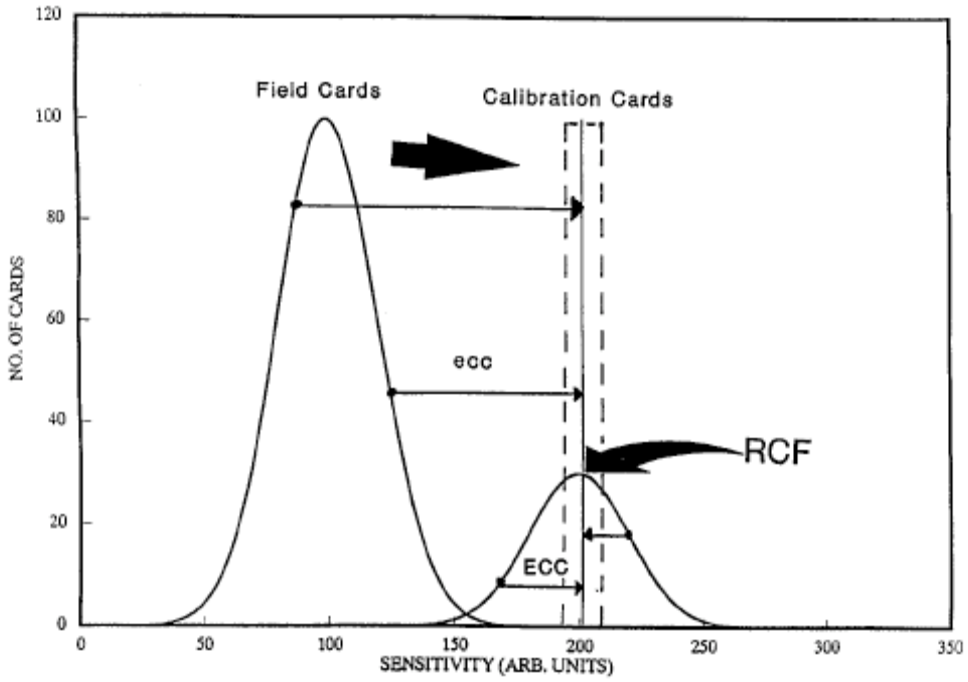


Figure 12
ECC Determination and Application

## 5.0. Previous Studies

### 5.1. Wu et al.[22]

In his study, Wu et al. performed tests to characterize properties of the LiF:Mg,Cu,P material. The material was prepared in powder form, and spread uniformly over a plate heating surface for annealing and reading. The material was initially annealed at 250$^{o}$C for 15 minutes followed by two hours at 100$^{o}$C. This was reported as their standard annealing process. The material was then encapsulated into two sizes of black plastic tubes: 22.7 mg and 5.1 mg. Irradiations for the various characterizations were performed using Cobalt-60 (Co-60), Radium-226 (Ra-226), and Americium-

241(Am-241) sources, as well as a deep therapy x-ray unit. To evaluate the effects of time after exposure (signal fade), the material was exposed to 10 rem of Co-60 gamma rays, and then stored at varying temperatures for varying lengths of time. The material was then read by again spreading the material uniformly over the heating plate and heating it to a maximum of about 230$^{o}$C, with a linear heating rate of 15$^{o}$C/sec. It was reported that the response of the material stored for one month at 40$^{o}$C and two months at room temperature were within experimental error. Additional explanation was not given in the report to define the experimental error, or to clarify if the 40 $^{o}$C and room temperature evaluations were separate groups or if the time/temperature was sequential. Material stored at 70$^{o}$C for one month responded at only 73% of the initial value. Evaluation was not performed for any effects of pre-exposure time, nor were any results reported beyond two months. Additionally, the report did not include the use of control TLDs to account for the accumulation of background radiation.

This study expands on the evaluation provided by Wu et al. by providing a detailed analysis of the potential loss of signal due to post-exposure time, evaluating the effects of pre-exposure time and combinations of pre and post-exposure time, and evaluating the material for a longer period of time while accounting for accumulation of background radiation. Additionally, this study provides pertinent data by evaluating the characteristics of the TLD-600H and TLD-700H material used in the DT-702 TLD.

### 5.2. Perry et al.[32]

Perry et al. performed a 90-day fade evaluation of the Harshaw Model 8854/55 TLD in 1999. The Model 8854/55 TLD is similar in design to the DT-702, except it does

not contain a TLD-600H chip. It is comprised of four 0.38mm thick LiF:Mg,Cu,P TLD-700H chips. The study evaluated the effects of equal amounts of pre and post-exposure time. This was accomplished by annealing the TLDs, waiting a predetermined amount of time, and dosing to 1 rem using a Co-60 source. The dosemeters were then stored again to provide equal amounts of pre-exposure and post-exposure time. A Harshaw Model 6600 TLD Reader (6600 Reader) was used to read the TLDs. The 6600 Reader is the predecessor of the 8800 Reader. It operates in a similar manner as described in Section 4.1, but is limited to only 200 cards at a time and does not utilize a separate WinREMS computer. Perry et al. reported less than 4% fading in 90 days (45 days pre-exposure, 45 days post-exposure), without pre-heating the TLD prior to readout. Pre-heating is recommended for LiF:Mg,Cu,P chips to eliminate low temperature traps that are confounding and short lived compared to the main dosimetric peak.[33-35] Perry et al. predicted that a pre-heat cycle would likely reduce the fading to near zero percent. The report stated additional testing that involved pre-heat cycles was in progress, but further results were not disclosed. The study did not specify if the irradiations for the fade evaluation were made on the bare TLDs or if they were encased in the TLD holders. Additionally, because the study did not evaluate the separate effects of pre-exposure and post-exposure time, the reported fade was not determined to be either a loss of sensitivity or a loss of signal. Similar to Wu et al., compensation for the accumulation of background radiation was not mentioned in the report.

This study expanded on the results provided by Perry et al. by providing a longer study of the TLD-700H material. Readings included a standard pre-heat cycle to eliminate the low temperature peaks, and an analysis was made to determine separately,

the changes in sensitivity and signal response over time. Also, control TLDs were used to account for any accumulation in background radiation.

### 5.3. Gilvin[36]

A recent (2006) study of a two-chip LiF:Mg,Cu,P TLD was performed by the National Radiological Protection Board (NRPB), United Kingdom Health Protection Agency, and was summarized by Gilvin. The TLD tested was manufactured by Thermo, and was made with two identical chips of LiF:Mg,Cu,P. The specific type of LiF:Mg,Cu,P material was not reported in the study. A total of 75 TLDs were sorted into three groups of 25: ageing (pre-exposure time), fading (post-exposure time), and controls. The TLDs were exposed to a specific dose (not disclosed in study) of radiation using the installed Sr-90 source in an 8800 Reader. Irradiations occurred immediately after TLD annealing for the fading group, and only just prior to reading for the ageing group. Control TLDs remained unexposed after annealing and were used to account for accumulation of background radiation. The TLDs were then read at 0, 45, 90, 135, and 180 days using the 8800 Reader. No loss of sensitivity or signal was reported for the LiF:Mg,Cu,P TLDs (within +/- 5%). Evaluation was not performed for the effects of both pre-exposure and post-exposure time.

This study enhances these results by providing a broader analysis of the effects of time on LiF:Mg,Cu,P. It also evaluated the potential compounding effects of pre and post-exposure time, as well as how the time specifically effects the TLD-700H and TLD-600H materials, since material type was not specified in Gilvin's study.

### 5.4. Jones et al.[37]

Jones et al. also performed a recent (2006) fade study on the Harshaw 8841 TLD, the same model TLD used in this study. Pre-exposure and post-exposure time were evaluated separately for both gamma and neutron radiation exposures. Dosemeters were irradiated inside of their Harshaw 8840 TLD holders on a 30x30x15 cm phantom, with no additional description of the phantom. All dosemeters were positioned within a central circle of 15 cm diameter on the front face of the phantom. The TLDs were exposed to a Americium-241(Am)-Beryllium(Be) source, delivering a neutron dose of 260 mrem and a photon dose of 83 mrem. The TLDs were irradiated after annealing for post-exposure time evaluation. Irradiation occurred just prior to being read for TLDs being evaluated for pre-exposure time effects. Control TLDs were also used to account for background radiation accumulation. Sets of five TLDs were read from each group on days 7, 14, 28, 56, 84, and 164. The study was performed at storage temperatures of $8^{o}$C(low temperature), $25^{o}$C(room temperature), and $50^{o}$C(high temperature). The TLDs were read using a Harshaw Model 8800 TLD Reader, using a 10 second pre-heat at $165^{o}$C, followed by a linear increase of $15^{o}$C/sec to $260^{o}$C. Light output measurement continued for 13 seconds at $260^{o}$C.

Chip 1 showed an initial increase in sensitivity of 8% after 14 days at room temperature (12% after 80 days at low temp, and only 4% after 7 days at high temp). By the end of the 164-day study, there was not any significant change in sensitivity for storage at room temperature. For low temperature storage, small increases in sensitivity (1-2%) were seen, and a 14% decrease was seen for storage at high temperatures. Initial increases in signal were also seen for Chip 1 at all temperatures. Maximum readings of

12%, 10%, and 8% were measured at 60 days for low, room, and high temperatures, respectively. After 164 days, no significant change in signal was seen for low and room temperature, with an 8% decrease for high temperature storage. Only the results for Chip 1 were shown in the report, although it was stated that all three TLD-700H chips responded in the same manner. Since irradiations were performed inside of the TLD holder (with varying filter materials over the chips), and Chip 3 is thinner than Chips 1 and 2, the additional information may have been beneficial.

Chip 4 (TLD-600H) was evaluated separately for gamma and neutron response. Pre-exposure time on Chip 4 showed a significant increase in sensitivity after 60 days at room temperature (~5%) with no increase seen at low or high temperature storage. Decreases in sensitivity (pre-exposure time) of 5% were seen after 164 days of storage at low and room temperatures, and a maximum decrease of 15% for high temperature storage. Post-exposure signal increases initially similar to the TLD-700H, with maximum increases of 6-8% seen for low and room temperature storage (20-30 days respectively). No significant change in signal was recorded after 164 days at low and room temperature, although a decrease of 8% was seen for high temperatures.

Neutron information was evaluated by subtracting the reading of Chip 2 (gamma) from the reading from Chip 4 (gamma and neutron). A correction factor was also determined and applied to account for the differences in the filter materials for each chip in the TLD holder. For the neutron evaluation, the gamma response of Chip 4 was assumed to be identical to the gamma response of the TLD-700H material (Chip 2). The neutron response of the TLD-600H chip did not show the initial increase in sensitivity for pre-exposure storage that was seen in the TLD-700H. One increase was noted in Chip 1

of ~4% after 60 days of storage at room temperature, although adjacent readings did not show an increase. No error bars were shown in the report to clarify the potential variation of the readings, which would have been beneficial in interpreting the data. Post-exposure neutron signal did initially increase, although not as much as the TLD-700H. Additionally, the neutron signal had larger decreases (~6-8%) after 164 days for all storage temperatures.

Jones et al. summarized that complex changes in sensitivity and signal response occurred that appear to depend on storage time, temperature, and the type of radiation measured. It is difficult to interpret the data presented with no error data and no statistical analysis to show if the variations are truly significant. Furthermore, no evaluation was made for combinations of pre and post-exposure time.

This study expanded on the results of Jones et al. by providing a statistical evaluation of the changes in sensitivity and signal response. Additionally, the potentially compounding effects of having both pre and post-exposure time were evaluated.

### 5.5. Summary of Topics Not Considered in Previous Studies

While each of these studies have provided good insight into the operating characteristics of the LiF:Mg,Cu,P material, a further analysis over a longer period of time is necessary. None of the previous studies provided data for combinations of pre- and post-exposure time, and while some studies provided data through 180 days, only a few data points were evaluated. Short-term studies have shown variation that merits further evaluation than what has been provided thus far.

Currently the Navy issues the DT-702 to personnel for 6-8 weeks, with maximum periods of 12 weeks only under special circumstances.[38] With deployment cycles of 24 weeks or more, it may be necessary to ship TLDs internationally four or more times. This increases the possibility for lost packages, excessive transport times where the status of the dosemeters may not be accountable, as well as longer wait periods before the dose can be reported to the individual or command. An evaluation of the effects of storage over a period of at least six-months will demonstrate the feasibility of extending the issue periods to six-months or more. This will potentially eliminate the need for international shipping, as well as reduce the amount of general handling required of the dosemeters. This research will contribute to the current scientific conversation and provide the Navy with data to evaluate extended issue periods.

## 6.0. Sensitivity and Signal Response Evaluation

### 6.1. Study Goals

The goal of this study was to provide an evaluation of the actual changes in sensitivity and signal response of the DT-702. This study was restricted to the response of the DT-702 TLD to 500 mrem of gamma radiation exposure. Five hundred mrem was chosen to provide a measurable dose greater than the average annual 360 mrem background radiation dose.[39] All irradiations were performed on the bare TLD card (not inside the TLD holder), using the 8800 Reader Sr-90 irradiator. This was done to reduce potentially confounding interactions of the filter materials installed over the chips. Also, a whole body phantom was not utilized during irradiations, as it was not germane to

the study. Additionally, in this study we considered a range of combinations of pre-exposure and post-exposure time to evaluate potential compounding effects.

### 6.2. Preparation

For this study, two thousand DT-702 four-chip TLDs were obtained from the Naval Dosimetry Center (NDC), Bethesda, MD. Each card was tested by Thermo prior to delivery to NDC to verify the correct placement of the chips. The cards were exposed to both gamma and neutron radiation to verify that Chips 1, 2, and 3 (TLD-700H) were sensitive to gamma radiation, but relatively insensitive to neutron radiation and that Chip 4 (TLD-600H) was sensitive to both gamma and neutron radiations.[2] When received by NDC, a quality control is performed, exposing the card to a Plutonium-Beryllium (Pu-Be) neutron source, verifying the placement of the neutron sensitive chip. The cards were then evaluated and assigned ECCs as described in Section 4.3. The TLDs were stored in an air-conditioned lab minimizing the potential for thermal fading. The TLD cards were stored in boxes (cardboard) to minimize the confounding effect of light exposure.

For this study, NDC also provided the service of their 8800 Readers. With the exception of the element correction coefficient (ecc) procedure, Reader #3 (Harshaw serial# 707004) was used exclusively for this study. Prior to the start of the study, a NIST calibration was performed as described in Section 4.2. A daily RCF calibration was also performed each day, prior to processing any TLDs. All procedures were performed using current operating instructions provided by NDC.[40]

### 6.3 Study Description and Data Acquisition

At the start of the study, all TLDs were annealed and then were segregated into several groups: controls, pre-exposure, post-exposure, and mixed pre-exposure and post-exposure. Approximately 200 TLDs were established as control TLDs and stored for later use. Control TLDs were used to correct for the accumulation of any background radiation. Approximately 200 of the remaining TLDs were then irradiated to 500 mrem. Following irradiation, these TLDs were then stored and evaluated for variations in signal response from post-exposure time only. Another 200 TLDs were separated and analyzed for variations in sensitivity caused by pre-exposure time only. These TLDs were stored after annealing and were irradiated to 500 mrem just prior to processing. The remaining TLDs were stored for varying periods of time (weeks) before being irradiated to 500 mrem. The TLDs were then stored for additional lengths of time (weeks) to evaluate the effects of various combinations of pre-exposure and post-exposure time. Table 3 presents these combinations of time as they were applied to the TLDs.

Prior to the full study, a five-day pilot study was performed to evaluate how variations in pre and post-exposure time would initially affect the TLDs. For the pilot study, TLDs were annealed and then sorted on Day 0. Three groups were created: control TLDs, pre-exposure TLDs, and post-exposure TLDs. Pure post-exposure TLDs were irradiated to 500 mrem on Day 0. For each of the next 4 days, five pre-exposure TLDs were irradiated to 500 mrem and read with five of the post-exposure TLDs exposed on Day 0, and five control TLDs. Results of the control TLDs were subtracted to eliminate any accumulation of background radiation.

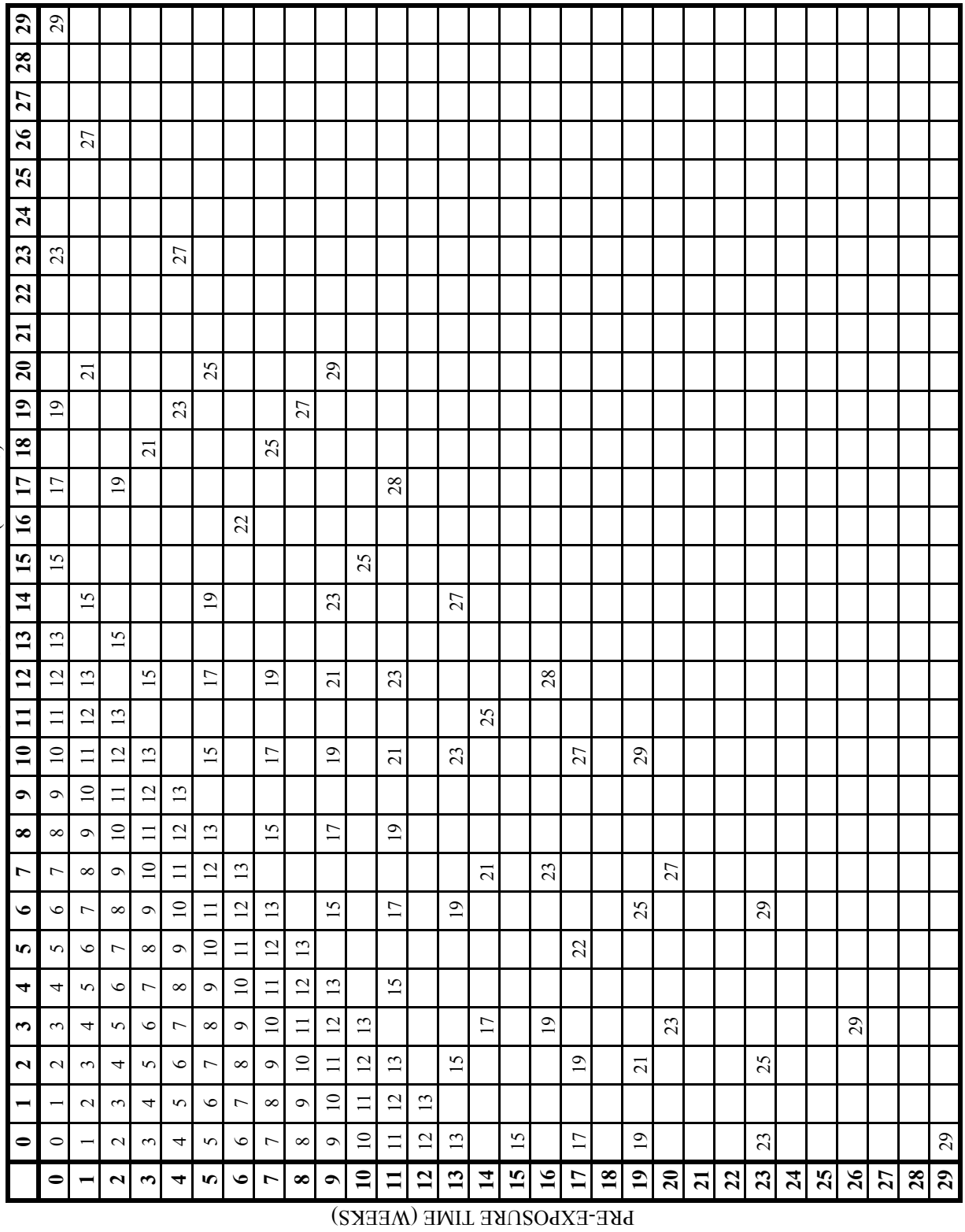


Table 3

List of Data Points (Number in block indicates the week TLDs were read)

All measured variations were within 2% of the zero storage time response. One-way ANOVA testing determined that there was no statistically significant change in sensitivity or signal response for TLDs that were annealed and irradiated within five days. The ANOVA testing procedure will be discussed in more detail in Section 6.5. This allowed all annealing and irradiation processes to be performed on Reader #3 for consistency, and prevented impacting NDC's TLD processing capabilities. For the full study, TLD annealing was performed on Thursday and Friday, and initial exposures were performed on Monday. The initial data points for the study were taken the following Thursday and were considered to have a one week time period of initial storage.

The TLDs were read using a time-temperature profile (TTP) that was designed to maximize the sensitivity and re-usability of the DT-702. The TTP used for the DT-702 began with an initial preheat of the TLD to 165$^{o}$C for 10 seconds to eliminate low temperature traps that are confounding and short lived compared to the main dosimetric peak.[33] This was followed by a 16.67 second acquisition time, where heat increased at a rate of 15$^{o}$C/sec to a maximum of 260$^{o}$C. Maximum temperatures were limited to 260$^{o}$C to prevent damage to the material from overheating. [13, 19, 20, 25] The TLD was then cooled to ambient temperature before being transferred out of the read station.

Previous studies on the older DT-648 TLD showed that the greatest change in response of the material occurred during the first ten weeks.[14] In order to more accurately quantify any early changes in the DT-702 dosemeter properties, semi-weekly data points were recorded for the first 12 weeks of the study. Additional data points (Table 3) were taken for combinations of pre-exposure and post-exposure fade to provide a complex spread of data over the course of the study.

### 6.4. Error Propagation and Data Discrimination

Each data point was determined by the mean of five DT-702 TLD cards ($\overline{Dose}_{raw}$). The associated standard deviation of each data point was used as the error calculated using Equation 6; where $\bar{x}$ is the sample mean, and *N* is the number of cards used for the data point.

$$\sigma_{raw} = \sqrt{\frac{\Sigma(x-\bar{x})^2}{N-1}} \tag{6}$$

After processing each set of five TLDs, the results of each chip were evaluated to identify and remove any statistically spurious data points using Chauvenet's Criterion. Chauvenet's Criterion allows removal of a data point from a data set if the probability of obtaining the particular deviation from the mean is less than $(2N)^{-1}$.[41] Since N=5 for each data point, if the probability of obtaining that value was less than 10%, then the point was eliminated. This was accomplished by determining the difference between the value and the mean of the values for that data point. If the difference was greater than 1.63 times the standard deviation of the group, the point was rejected. This process was performed once for each set of five TLDs giving a final mean value ($\overline{Dose}_{raw}$) and standard error ($\sigma_{raw}$) for each data point. Once each set of TLDs were evaluated for outliers, the mean of the control TLDs ($\overline{Dose}_{bkgd}$), was subtracted to give an accurate, background corrected reading, ($\overline{Dose}_{net}$), for each chip of the TLD using Equation 7.

$$\overline{Dose}_{net} = \overline{Dose}_{raw} - \overline{Dose}_{bkgd} \tag{7}$$

The error ($\sigma_{net}$) was propagated using Equation 8.[9]

$$\sigma_{net} = \sqrt{(\sigma_{raw}^2 + \sigma_{bgnd}^2)} \tag{8}$$

After correcting for background, each data point was then ratioed against the week 0 TLD data with no associated pre-exposure or post-exposure fade.

During the study, it was noted that the effect of the RCF variation calculated each day was compounding the variations seen in the study TLDs. As seen in Equation 3, each data point was calculated using the RCF for that day. If the RCF values are different, the relative response will then be different, even if the measured light output was the same (corrected by the ecc). To eliminate the effects of these RCF values, the results of the QC cards processed each day were used as surrogate cards for the Week 0 TLDs. Quality Control cards were inserted in the beginning, middle, and end of each batch of TLDs processed, and are normally used to verify reader operation during TLD processing. The QC card was recognized by the TLD reader by its barcode identification number. When identified, the card was annealed, irradiated to 100 mrem using the installed Sr-90 source, and then read. Since the QC cards are physically the same as the standard DT-702 TLD, the response should be identical to the response of a DT-702 with no storage time. From Equation 3, the indicated value or dose reported from the chip was calculated using Equation 9; where $RCF_{chnl-day(x)}$ wasthe RCF calculated for that day (*day(x)*), for the channel (chip) being read.

$$Dose_{raw} = \frac{(ecc_{raw} * TLR_{raw})}{RCF_{chnl-day(x)}} \tag{9}$$

The mean of the control TLDs was subtracted, which was calculated in the same manner to calculate the $Dose_{net}$ for the data point. This results in Equation 10:

$$Dose_{net} = \frac{(ecc_{raw} * TLR_{raw})}{RCF_{chnl-day(x)}} - \frac{(ecc_{bgnd} * TLR_{bgnd})}{RCF_{chnl-day(x)}} \tag{10}$$

Further refinement gives Equation 11:

$$Dose_{net} = \left(\frac{1}{RCF_{chnl-day(x)}}\right) * [(ecc_{raw} * TLR_{raw}) - (ecc_{bgnd} * TLR_{bgnd})] \quad (11)$$

The dose ratio ($R_{Dose}$) can then be calculated by dividing by $Dose_{raw(QC\ cards)}$ resulting in Equation 12:

$$R_{Dose} = \frac{\left(\frac{1}{RCF_{chnl-day(x)}}\right) * [(ecc_{raw} * TLR_{raw}) - (ecc_{bgnd} * TLR_{bgnd})]}{\frac{(ecc_{QC} * TLR_{QC})}{RCF_{chnl-day(x)}}} \quad (12)$$

The $RCF_{chnl-day(x)}$ values cancel, resulting in Equation 13:

$$R_{Dose} = \frac{[(ecc_{raw} * TLR_{raw}) - (ecc_{bgnd} * TLR_{bgnd})]}{(ecc_{QC} * TLR_{QC})} \quad (13)$$

This results in a relative response of each chip for each value of pre-exposure and post-exposure time, with no effects from the variations of RCF value. Since the TLD reader automatically applies the ECC and RCF values to each chip, this calculation was made using Equation 14:

$$R_{Dose} = \frac{\overline{Dose}_{net}}{\overline{Dose}_{raw(QCcards)}} \quad (14)$$

The error associated with the Dose Ratio was propagated using Equation 15:

$$\sigma_{Dose} = \left(\frac{\overline{Dose}_{net}}{\overline{Dose}_{raw(QCcards)}}\right) * \sqrt{\left(\frac{\sigma_{net}}{\overline{Dose}_{net}}\right)^2 + \left(\frac{\sigma_{QCcards}}{\overline{Dose}_{raw(QCcards)}}\right)} \quad (15)$$

The 100-mrem QC card exposure value was not changed for the remainder of the study for consistency. The mean $\overline{Dose}_{raw(QCcards)}$ and standard error ($\sigma_{QCcards}$) were scaled five fold to equal the 500 mrem dose to the experimental TLDs.

### 6.5. Data Display and Analysis

Statistical analysis was performed on all data to verify the significance of any variations measured over the course of the study. A one-way analysis of variance (ANOVA) test was initially used to test for significant variations in the data. The one-way ANOVA tests for variation by comparing the standard deviations of the TLDs used to create each data point (difference between the groups), to the standard deviations of the data points about the mean of the entire test population (difference within the groups). If a statistical difference was detected by the ANOVA, a multiple comparison test versus the control group, using the Holm-Sidak method, was performed .[42] The Holm-Sidak test is a more powerful test than a standard ANOVA, and attempts to identify which specific points are statistically different, compared to the control value (zero storage time baseline response).[42] Using the Holm-Sidak method, p-values are determined for each value as compared to the control value. Any data point with $p<0.002$ was considered significant (95% confidence level). All statistical analysis was performed using SigmaStat® for Windows, version 3.11.[42]

The coefficient of variation for a chip is defined as the variation in the response of that chip when read under the same conditions, multiple times in succession. Single chip variations in response reproducibility of 2-4% have been noted in the DT-702 in other studies.[23] In this study, a value of 3.5% was used for reproducibility.[38] Given a Gaussian (normal) statistical distribution for the entire population of TLDs, it is expected that 99% of the readings will fall within three standard deviations ($3\sigma$) of the average. Therefore, a $3\sigma$ experimental error of about 10.5% should be expected. While this was

not mathematically accounted for in this study, it can be assumed that differences of about 10.5% or less fall within this experimental error.

## 7.0. Data Evaluation

### 7.1. Background Radiation

Throughout the course of the study, the control TLDs were evaluated for the accumulation of background radiation (Figures 13-16). The slope of the line was indicative of the daily rate of background radiation, and was determined using linear regression analysis. The least-squares method of regression analysis was used for this study. The slopes for each chip were then compared using a one-way ANOVA test, and found to have no statistically significant differences. The average of the slopes as calculated using the least-squares method was 0.74 (+/- 0.19) mrem per day. The results of the linear regression analysis are shown for each chip on its respective graph. This accumulation of background radiation was mathematically subtracted from the TLDs being tested. All graphs were created using SigmaPlot® for Windows, version 10.0.[43]

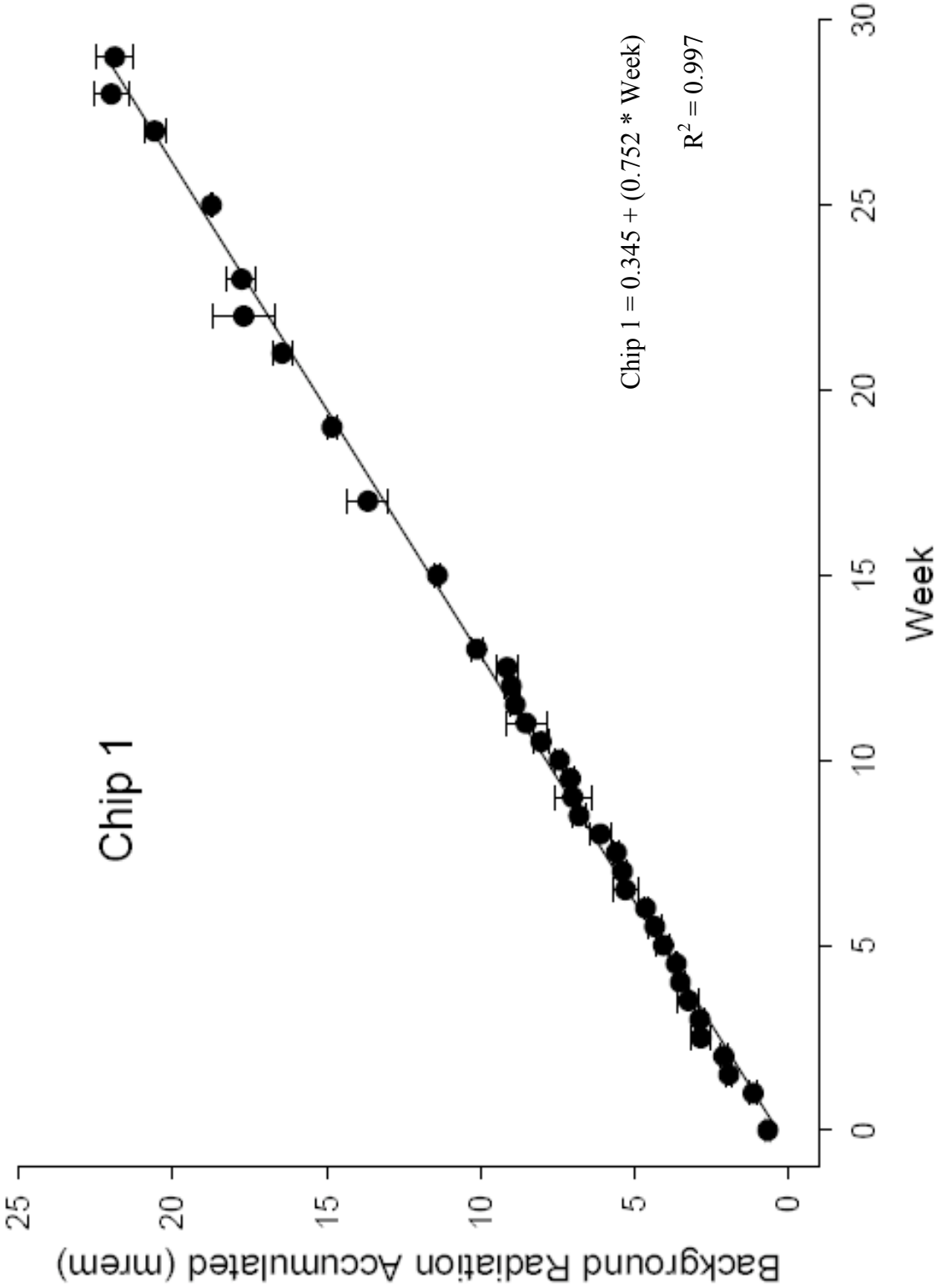


Figure 13
Background Radiation Accumulation for Chip 1.
Line through data determined by simple linear regression analysis. Error bars indicate propagated errors for each data point. Equation and $R^2$ values are listed.

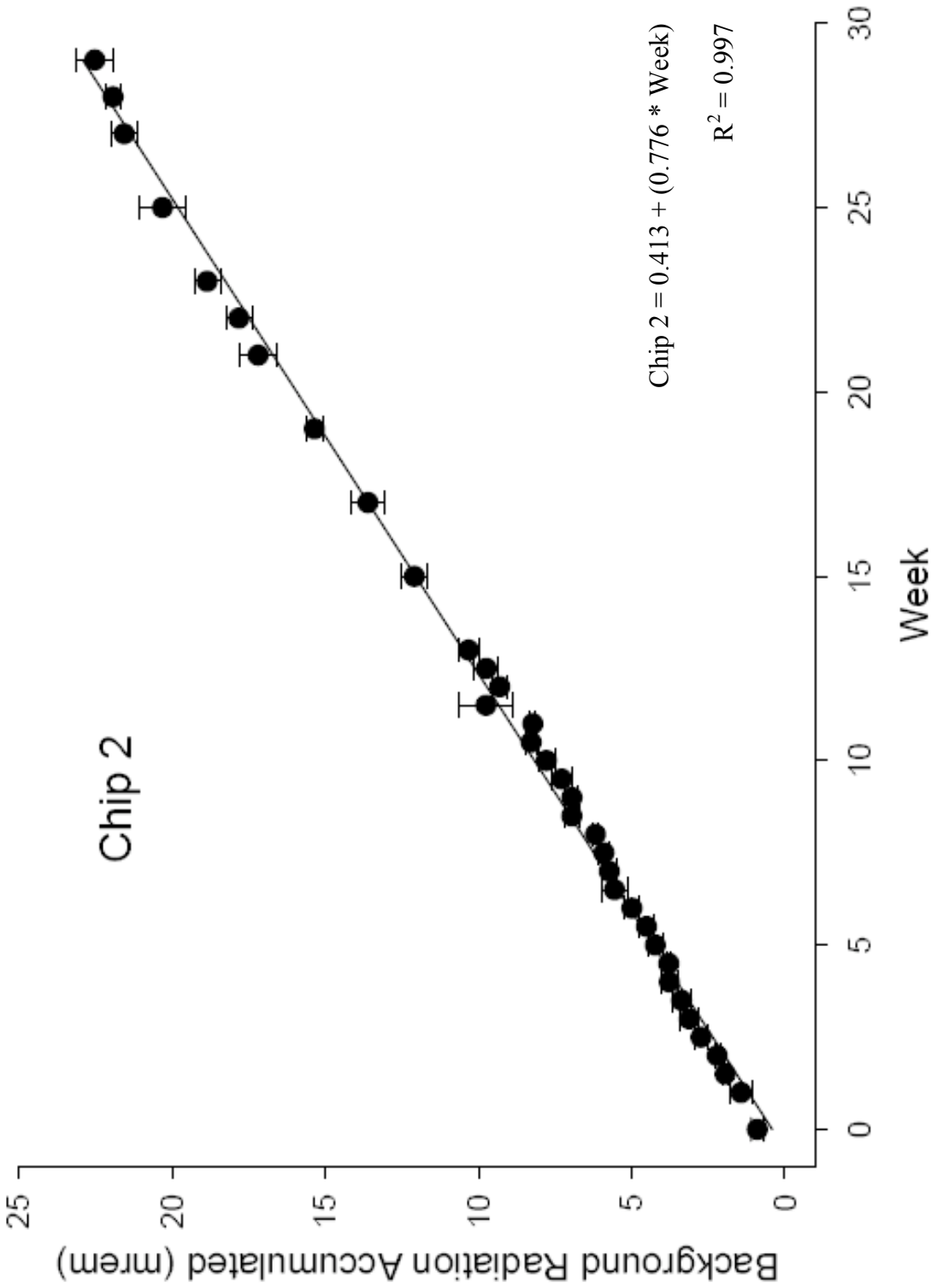


Figure 14
Background Radiation Accumulation for Chip 2.
Line through data determined by simple linear regression analysis. Error bars indicate propagated errors for each data point. Equation and $R^2$ values are listed.

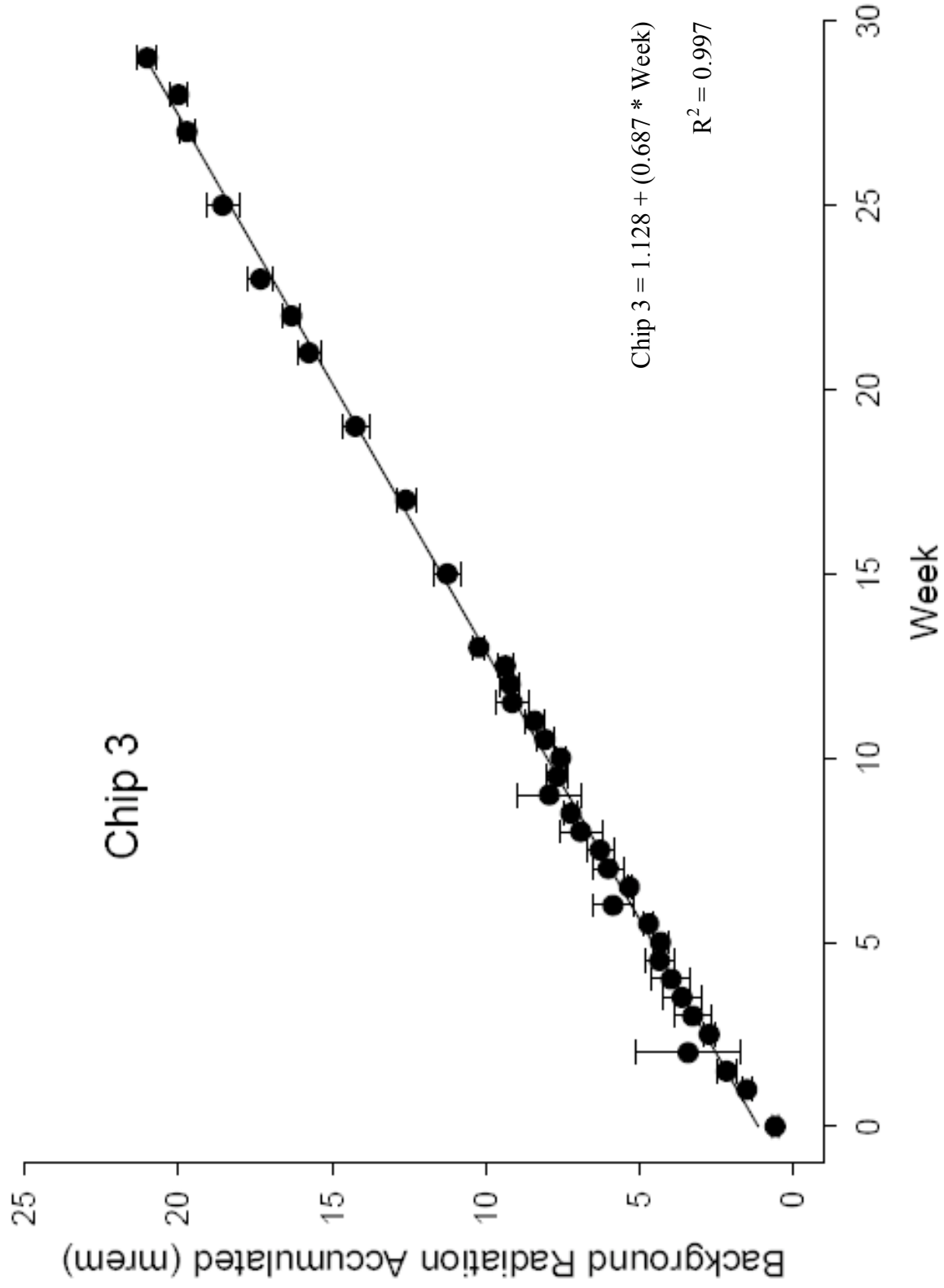


Figure 15
Background Radiation Accumulation for Chip 3.
Line through data determined by simple linear regression analysis. Error bars indicate propagated errors for each data point. Equation and $R^2$ values are listed.

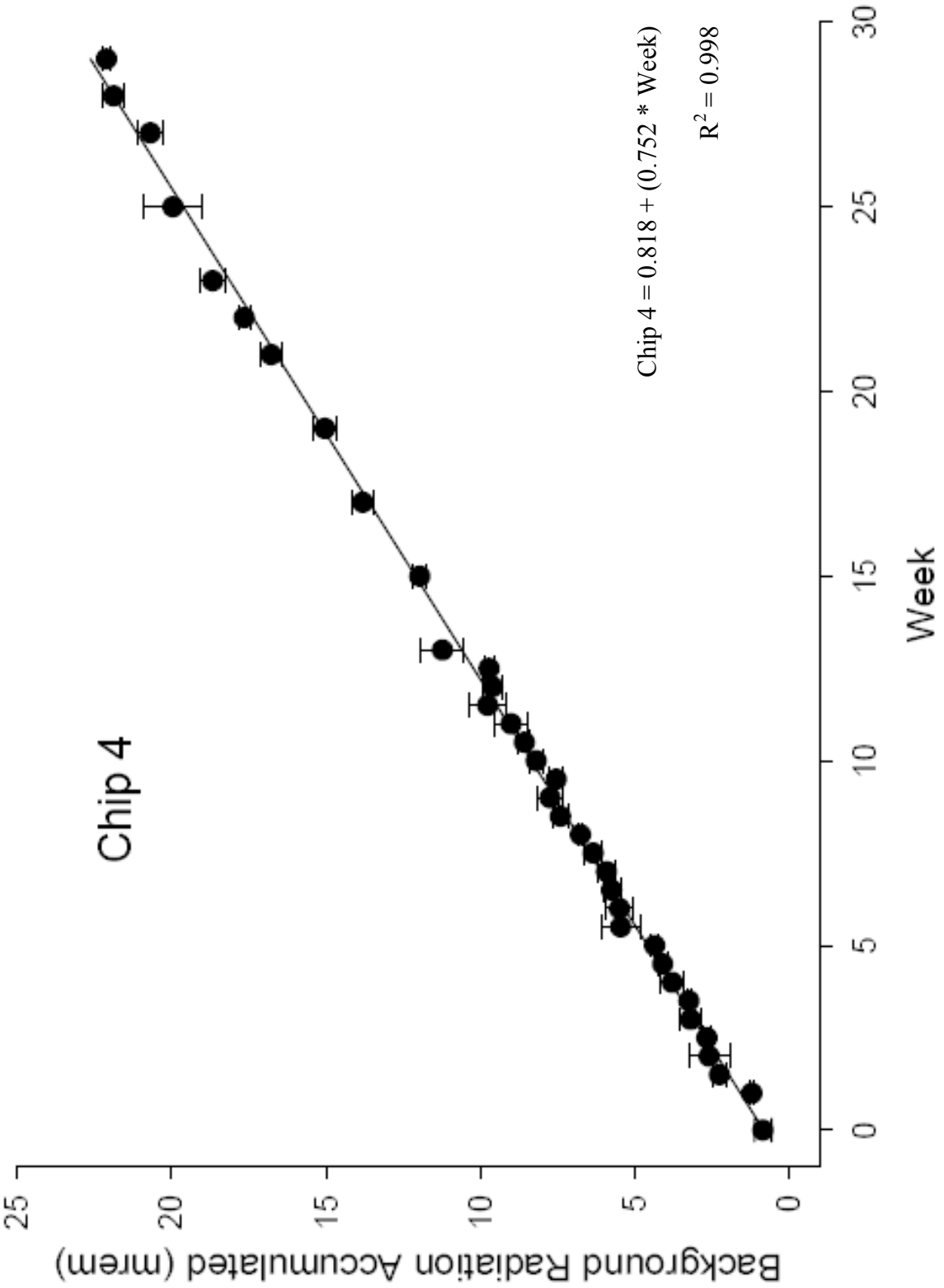


Figure 16
Background Radiation Accumulation for Chip 4.
Line through data determined by simple linear regression analysis. Error bars indicate propagated errors for each data point. Equation and $R^2$ values are listed.

### 7.2. Pre-Exposure Changes in Sensitivity

Given that Chips 1 and 2 are the same material composition and material thickness, their associated responses are expected to be similar. A one-way ANOVA test comparing the two chips demonstrated that there was no significant difference between the responses of the two chips ($p=0.888$). Increases in sensitivity were measured in both Chips 1 and 2 during the initial stages of the study. The maximum increases measured were 5% and 3%, respectively. The TLD response appeared relatively consistent for the remainder of the study, with maximum decreases measured at 5% for both chips. Changes in sensitivity for Chips 1 and 2 are displayed in Figures 17 and 18. All measurements of sensitivity for Chips 1 and 2 were within the 10.5% experimental error. One-way ANOVA tests on Chips 1 and 2 initially detected a significant change in sensitivity ($p=<0.001$); however, the Holm-Sidak test calculated that not any actual data points were statistically significant when compared to the zero pre-exposure time QC card response ($p=0.014$ and $p=0.004$, respectively).

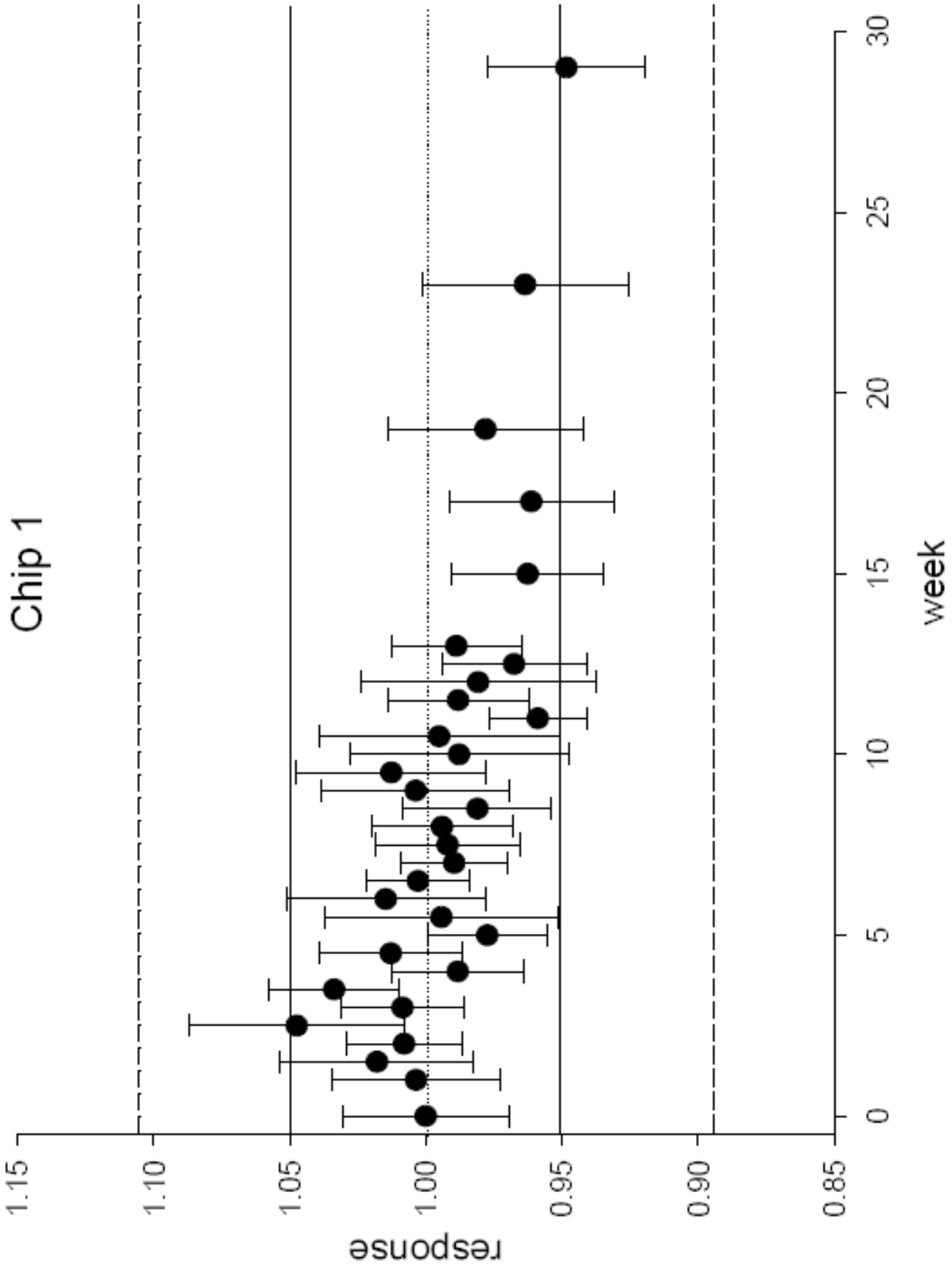


Figure 17
Effects of Pre-Exposure Storage on Sensitivity for Chip 1.
(···) Dotted line represents 1.00 reference data, (—) solid lines represent a +/- 5% variance, and the (----) dashed lines represents the +/- 10.5% experimental error. Error bars indicate propagated errors for each data point.

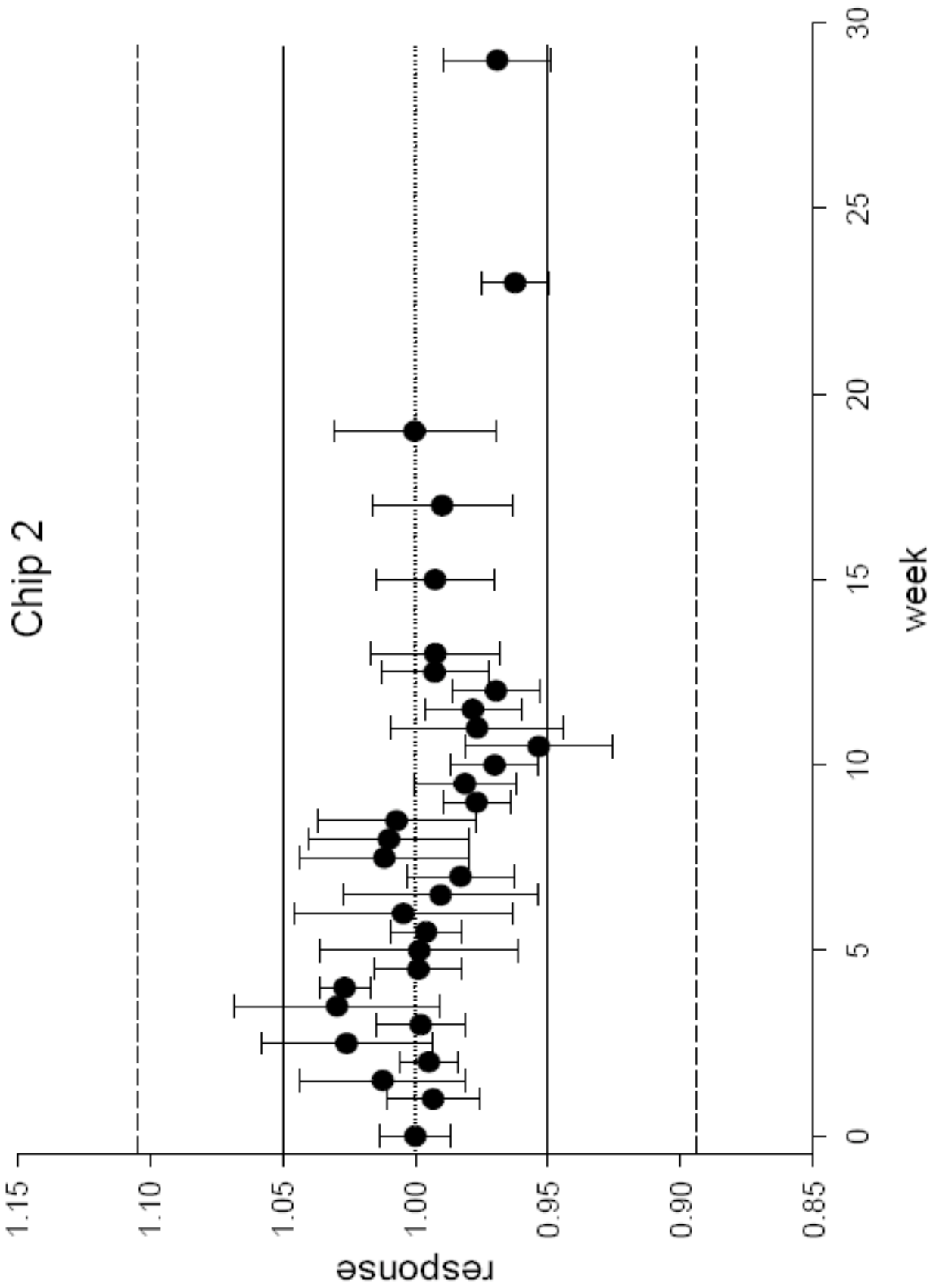


Figure 18
Effects of Pre-Exposure Storage on Sensitivity for Chip 2.
(⋯) Dotted line represents 1.00 reference data, (—) solid lines represent a +/- 5% variance, and the (----) dashed lines represents the +/- 10.5% experimental error. Error bars indicate propagated errors for each data point.

Chip 3 appeared to respond somewhat differently from the other chips (Figure 19). Chip 3 is a thinner chip made of the same LiF-700H material as Chips 1 and 2. A decrease in sensitivity of 4% was measured after the first week. Readings throughout the remaining 28 weeks seemed to vary only slightly and remained 2-6% lower than the zero storage time data. One-way ANOVA test of the response of Chip 3 indicated that there were no statistically significant differences for any amount of pre-exposure time through 29 weeks ($p=0.821$).

Similar to Chips 1 and 2, Chip 4 shows an initial increase in sensitivity (Figure 20). A maximum increase in response of 6% was seen, with maximum decreases of 4% also measured. The one-way ANOVA test of the response of Chip 4 detected a significant difference ($p=0.020$), but Holm-Sidak testing determined no points to actually be statistically significant ($p=0.036$). All Chip 4 responses were within the 10.5% experimental error.

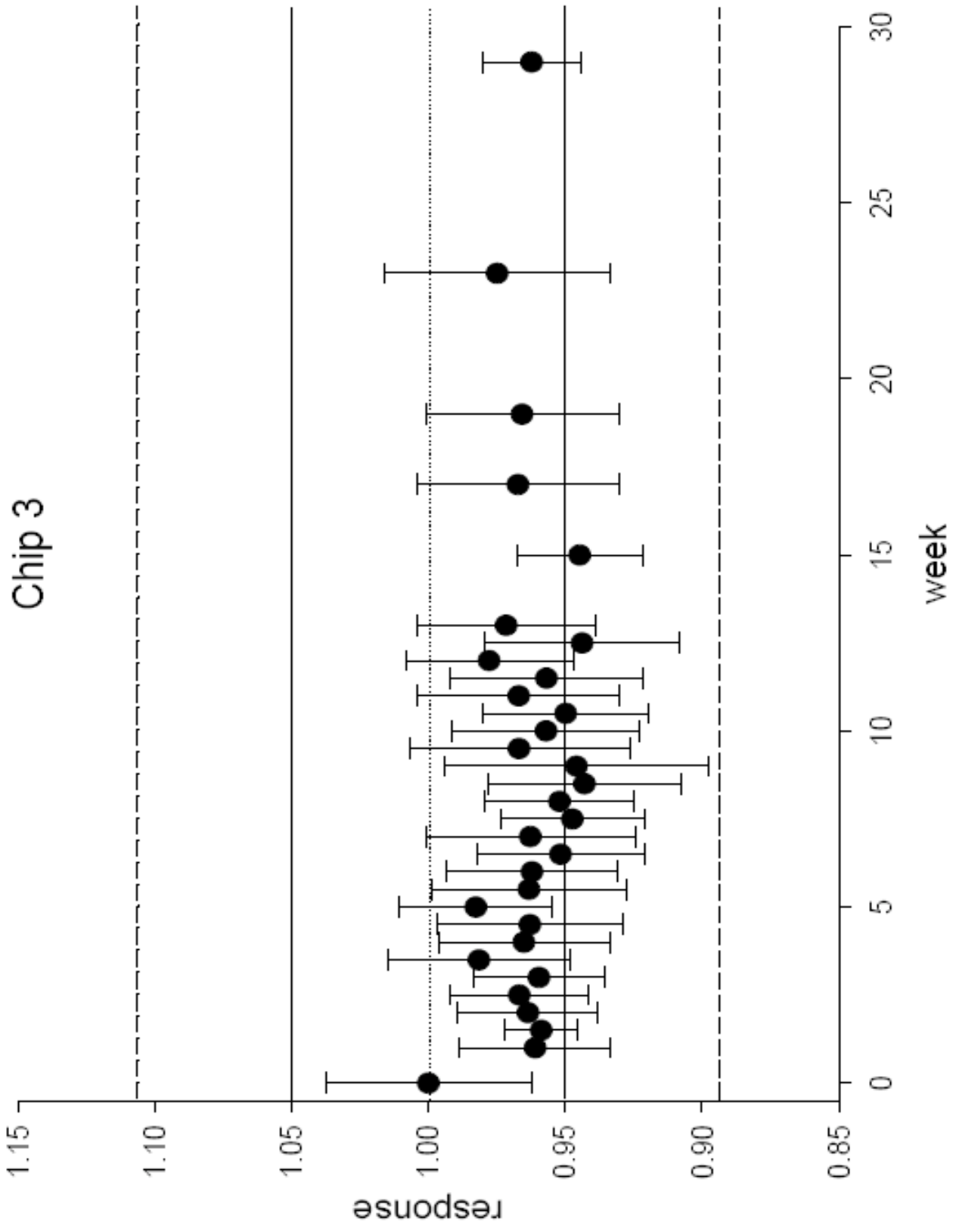


Figure 19
Effects of Pre-Exposure Storage on Sensitivity for Chip 3.
(···) Dotted line represents 1.00 reference data, (—) solid lines represent a +/- 5% variance, and the (----) dashed lines represents the +/- 10.5% experimental error. Error bars indicate propagated errors for each data point.

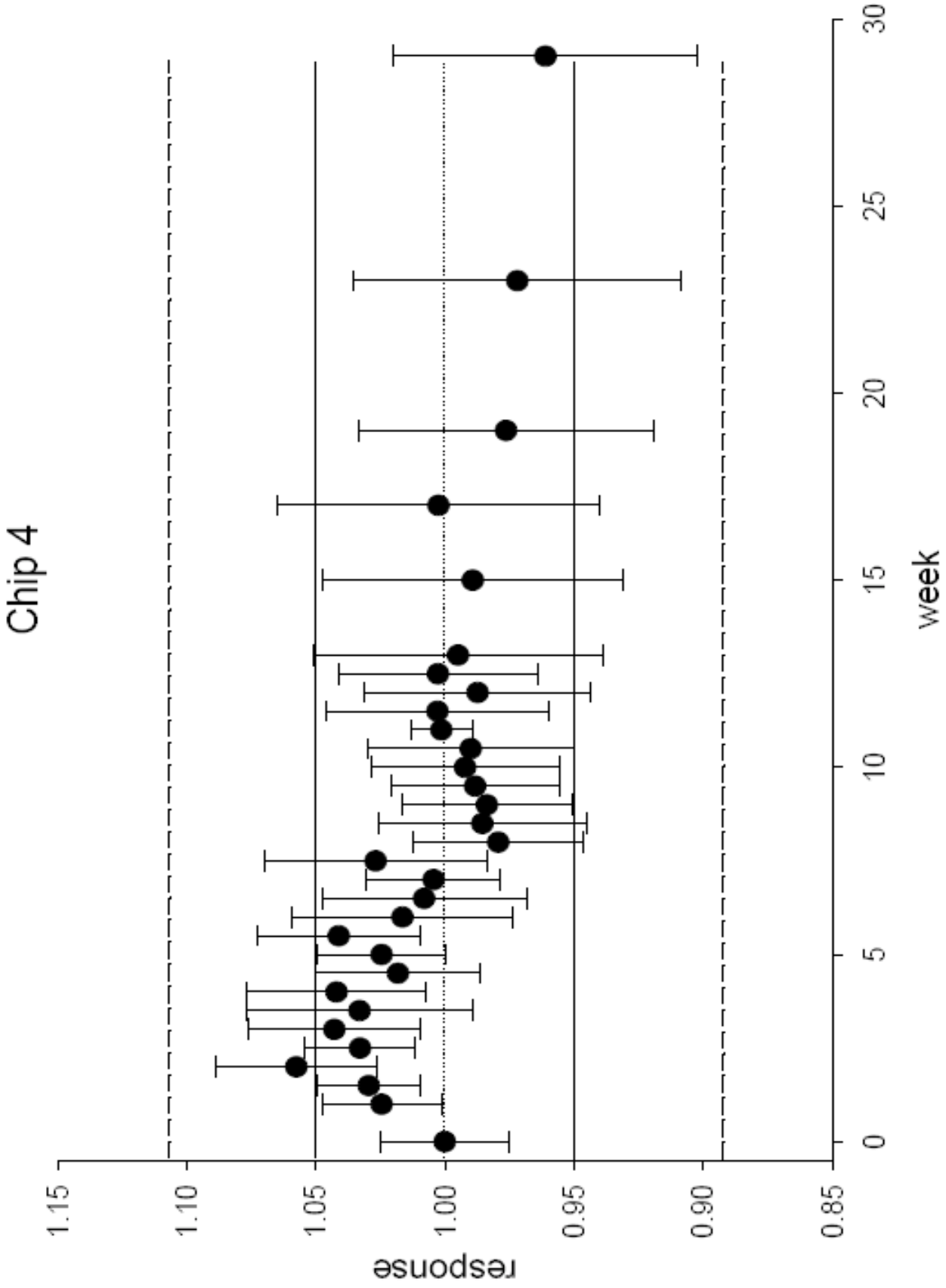


Figure 20
Effects of Pre-Exposure Storage on Sensitivity for Chip 4.
(⋯) Dotted line represents 1.00 reference data, (—) solid lines represent a +/- 5% variance, and the (----) dashed lines represents the +/- 10.5% experimental error. Error bars indicate propagated errors for each data point.

### 7.3. Post-Exposure Changes in Signal Response

The effects of post-exposure time on the signal response of the DT-702 are shown in Figures 21-24. Similar to the effects seen from pre-exposure time, an initial increase appeared to occur in Chips 1 and 2 (Figures 21-22). A maximum 5% increase in response was measured for Chips 1 and 2. Maximum decreases of only 2% were also measured for both chips. A one-way ANOVA test comparing the responses of the two chips showed that there was no statistically significant difference between the two chips. ($p=0.369$). Additionally, a one-way ANOVA test on the response of Chip 1 determined that there were no significant changes in signal response for any amount of post-exposure time up to 29 weeks ($p=0.146$). Chip 2 however produced one statistically significant change in signal response. A 5% increase in signal measured from Chip 2 at 2.5 weeks was determined to be significant based on Holm-Sidak testing ($p=0.0017$). Since one-way ANOVA testing determined that no significant difference existed between Chips 1 and 2, and no data points for Chip 1 were found to be statistically significant, the 5% increase in Chip 2 was most likely due to experimental variations, and does not represent an actual change in response of the material. All measurements of signal response for Chips 1 and 2 were within the 10.5% experimental error.

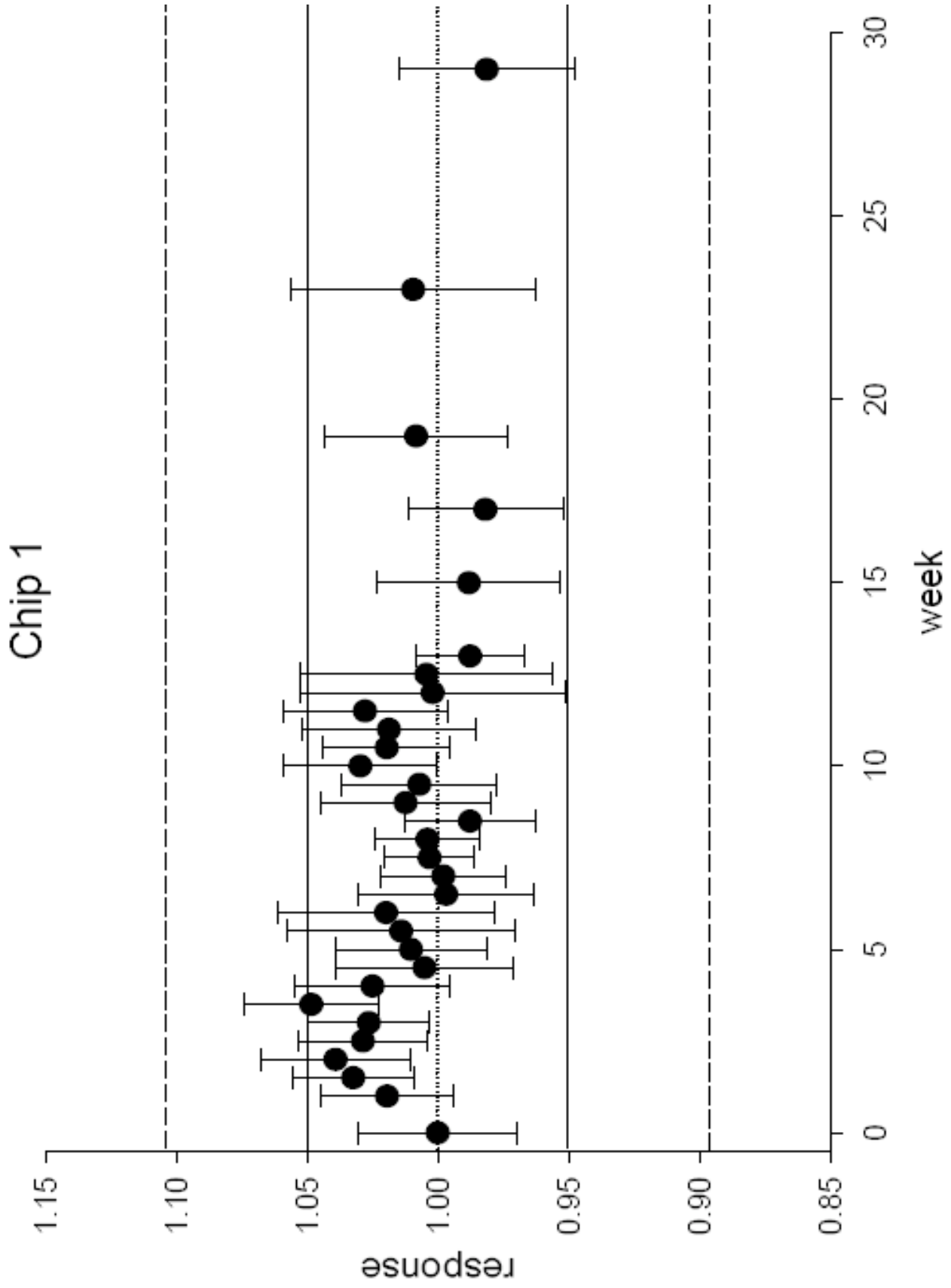


Figure 21
Effects of Post-Exposure Storage on Signal Response for Chip 1.
(⋯) Dotted line represents 1.00 reference data, (—) solid lines represent a +/- 5% variance, and the (----) dashed lines represents the +/- 10.5% experimental error. Error bars indicate propagated errors for each data point.

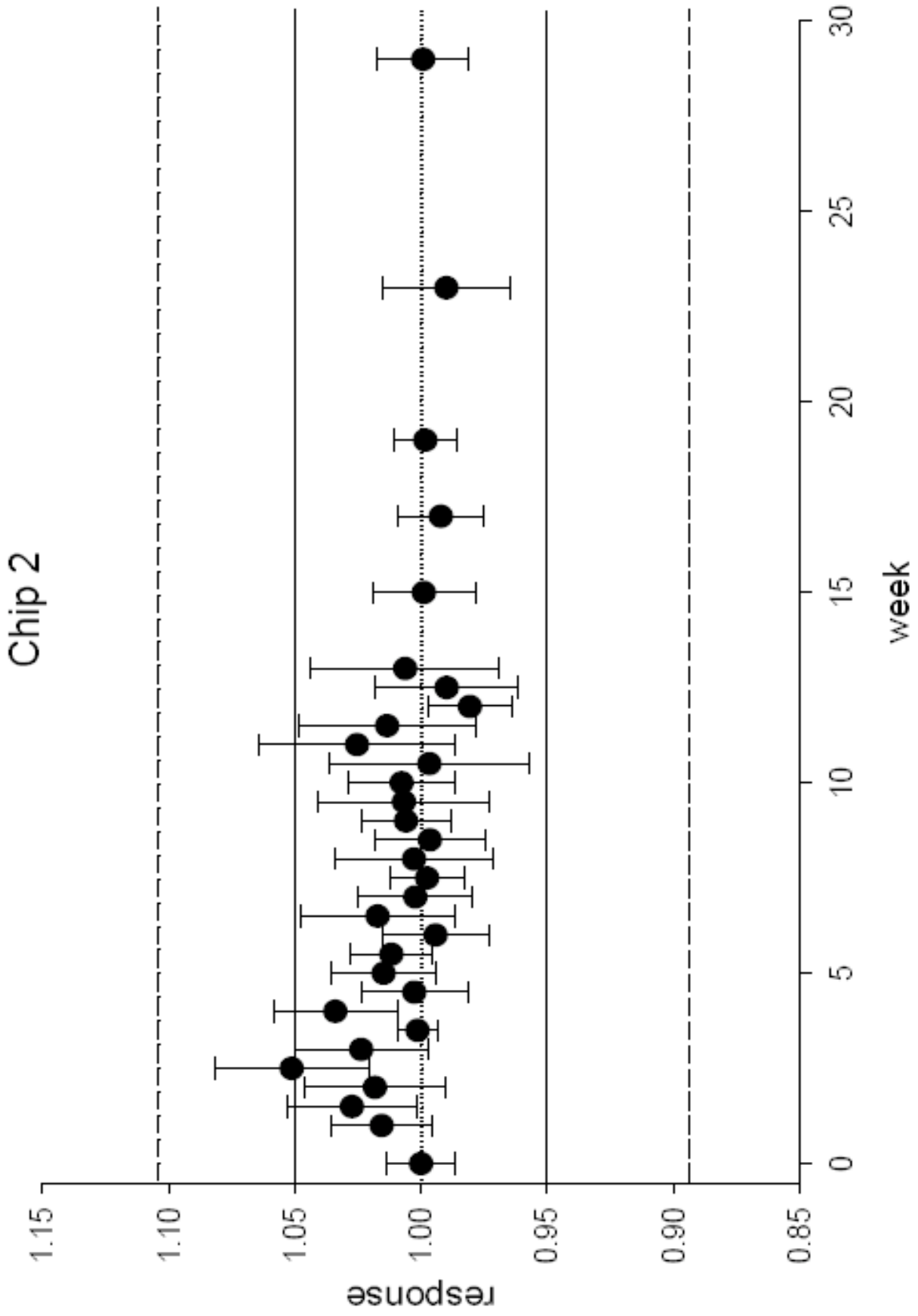


Figure 22
Effects of Post-Exposure Storage on Signal Response for Chip 2.
(⋯) Dotted line represents 1.00 reference data, (—) solid lines represent a +/- 5% variance, and the (----) dashed lines represents the +/- 10.5% experimental error. Error bars indicate propagated errors for each data point.

As seen for pre-exposure time, Chip 3 seemed to respond differently than the other chips (Figure 23). Maximum initial decreases of 4% were measured, with maximum increases of 2% measured over the course of the study. It was also noted that the errors measured for each point were larger than what was measured for Chips 1 and 2. Because Chip 3 is a thinner chip, there is less material and therefore fewer traps for the electrons to be captured. Since the dose reported is proportional to the number of electrons released, fluctuations in the number of electrons released will cause a greater effect on the deviation (error) in the reported dose for Chip 3. All measurements of signal response for Chip 3 were still within the 10.5% experimental error, and the one-way ANOVA test determined that there were not any statistically significant differences for any amount of post-exposure time through 29 weeks ($p=0.160$).

Similar to the pre-exposure effects for Chip 4, an apparent initial increase in post-exposure response was observed (Figure 24). Maximum increases of 7% and maximum decreases of 2% were measured. One-way ANOVA initially detected a significant difference in Chip 4 ($p=0.017$), but Holm-Sidak testing determined that no point was statistically significant ($p=0.016$). All measurements of signal response for Chip 4 were within the 10.5% experimental error.

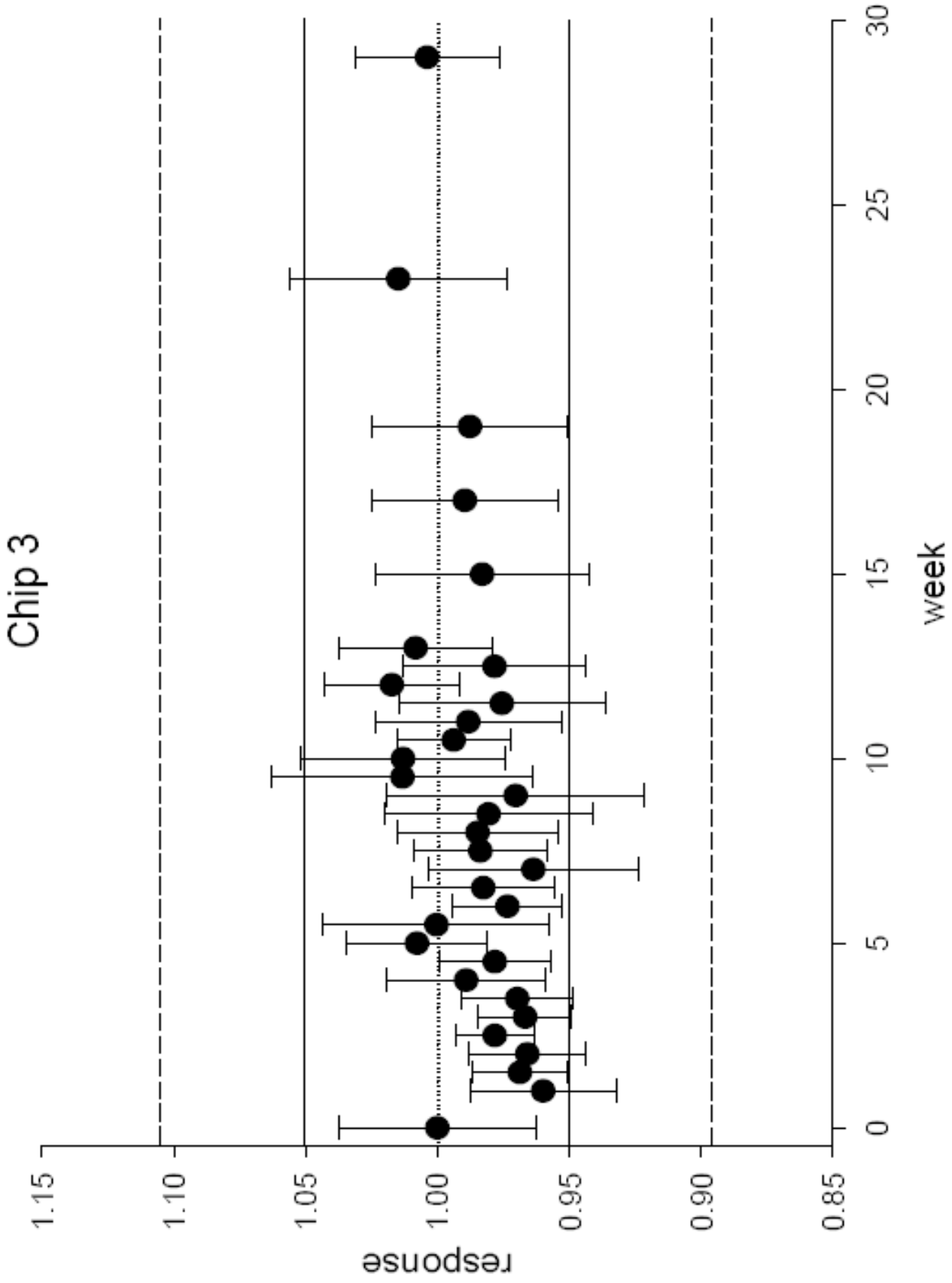


Figure 23
Effects of Post-Exposure Storage on Signal Response for Chip 3.
(⋯) Dotted line represents 1.00 reference data, (—) solid lines represent a +/- 5% variance, and the (----) dashed lines represents the +/- 10.5% experimental error. Error bars indicate propagated errors for each data point.

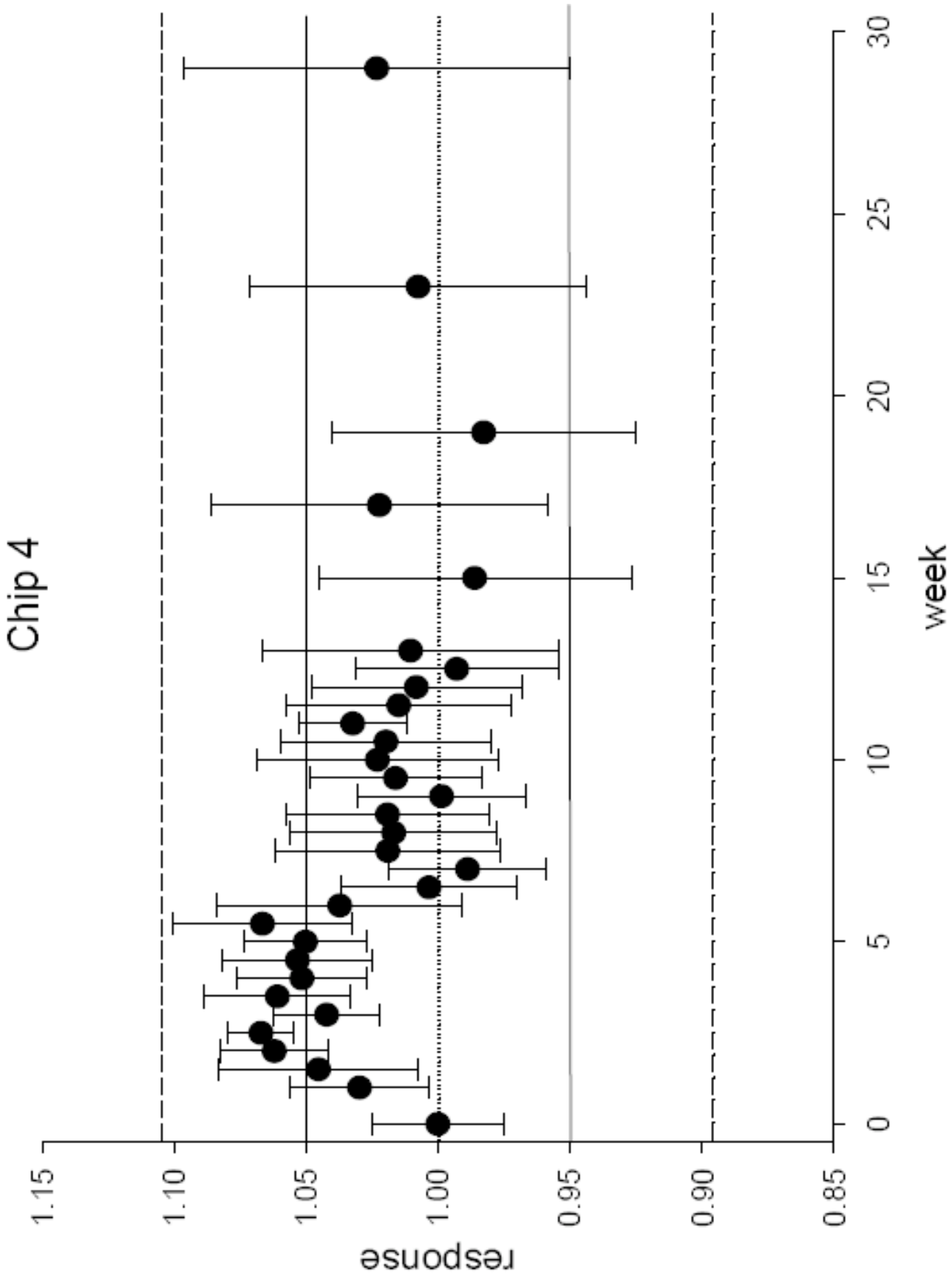


Figure 24
Effects of Post-Exposure Storage on Signal Response for Chip 4.
(⋯) Dotted line represents 1.00 reference data, (—) solid lines represent a +/- 5% variance, and the (----) dashed lines represents the +/- 10.5% experimental error. Error bars indicate propagated errors for each data point.

### 7.4. Combination Effects of Pre and Post-Exposure Storage

The effects of having both pre-exposure time and post-exposure time were also evaluated in this study. Analysis included results of the pure pre-exposure and pure post-exposure data to provide an all inclusive evaluation of the effects of time on the TLD. The measured response of each chip for the range of pre-exposure and post-exposure times evaluated are displayed in Tables 4-7. Additionally, the propagated errors for each chip are displayed in Tables 8-11, in Appendix A.

A maximum increase of 6% and maximum decrease of 8% was measured for the response of Chip 1. One-way ANOVA tests determined that a significant change in response existed for Chip 1 ($p=<0.001$). Holm-Sidak method testing found two statistically significant points: 13 weeks pre-exposure/14 weeks post-exposure time resulting in a decrease of about 8%, and 16 weeks pre-exposure/12 weeks post-exposure time resulting in a 7% decrease. Considering the total of 192 points measured for Chip 1, and that both significant points were still within the 10.5% experimental error, the occurrence of these two points did not indicate a significant change in response of the material, and did not require any additional action.

Chip 2 responded with a maximum increase of 5%. A maximum decrease in response of 5% was also measured. All data points were still within the 10.5% experimental error. One-way ANOVA tests found significant differences for Chip 2 ($p=<0.001$), although multiple-point (Holm-Sidak method) analysis showed that no statistically differences were measured for Chip 2.

Chips 1 and 2 were again compared using a one-way ANOVA and determined to not be statistical different ($p=0.126$). This supports the determination that the two

significant measurements for Chip 1 were most likely due to experimental variation, since no points were statistically significant for Chip 2. It was therefore determined that combining pre-exposure and post-exposure time has no compounding effects on the response of Chips 1 or 2.

Chip 3 continued to show the least variation about the mean of all the chips. A maximum increase in response of 3% was measured. Maximum decreases of 7% were also measured for Chip 3. All measured values were within the 10.5 % experimental error, and were similar to the results seen for the separate pre-exposure and post-exposure time evaluations. One-way ANOVA results detected a significant difference ($p=<0.001$), however the multiple-point (Holm-Sidak method) analysis concluded that there were no statistically significant measurements for Chip 3 with any combination of pre-exposure and post-exposure storage up to 29 weeks of total storage.

Chip 4 continued to demonstrate a similar response as compared to Chips 1 and 2. Post-exposure changes in signal appear to have more of an effect, although all measurements are within the 10.5% experimental error. A maximum increase of 8% and a maximum decrease of 8% were measured for Chip 4. One-way ANOVA testing initially found a statistically significant difference ($p=<0.001$), although the multiple-point (Holm-Sidak method) analysis determined that no points were actually statistically different. Therefore, having both pre-exposure and post-exposure time does not have any compounding effects on Chip 4.

**CHIP 1 RESULTS**

**POST-EXPOSURE TIME (WEEKS)**

| | 0 | 1 | 1.5 | 2 | 2.5 | 3 | 3.5 | 4 | 4.5 | 5 | 5.5 | 6 | 6.5 | 7 | 7.5 | 8 | 8.5 | 9 | 9.5 | 10 | 10.5 | 11 | 11.5 | 12 | 12.5 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 1.00 | 1.02 | 1.03 | 1.04 | 1.03 | 1.03 | 1.05 | 1.03 | 1.01 | 1.01 | 1.01 | 1.02 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 1.01 | 1.01 | 1.03 | 1.02 | 1.02 | 1.03 | 1.00 | 1.00 | 0.99 | | 0.99 | | 0.98 | | 1.01 | | | 1.01 | | | | | | 0.98 |
| **1** | 1.00 | 1.04 | | 1.04 | | 1.00 | | 1.01 | | 1.02 | | 1.03 | | 1.04 | | 1.02 | | 1.01 | | 1.02 | | 0.99 | | 1.01 | | | 0.99 | | | | | 1.01 | | | | | | 0.97 | | | |
| **1.5** | 1.02 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **2** | 1.01 | 1.03 | | 1.04 | | 1.01 | | 1.02 | | 0.99 | | 1.02 | | 1.01 | | 1.01 | | 1.01 | | 0.99 | | 0.98 | | | | 0.97 | | | | 0.98 | | | | | | | | | | |
| **2.5** | 1.05 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **3** | 1.01 | 1.04 | | 1.01 | | 1.02 | | 1.01 | | 1.01 | | 1.01 | | 0.98 | | 1.00 | | 0.98 | | 0.99 | | 0.98 | | | | | | | | | 0.99 | | | | | | | | | |
| **3.5** | 1.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.97 | | | | | | |
| **4** | 0.99 | 1.01 | | 0.98 | | 0.98 | | 1.01 | | 1.03 | | 0.99 | | 1.01 | | 0.99 | | 0.94 | | | | | | | | | | | | | | 0.96 | | | | | | | | | |
| **4.5** | 1.01 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **5** | 0.98 | 1.00 | | 1.02 | | 1.00 | | 1.00 | | 1.01 | | 1.00 | | 0.99 | | 1.00 | | | | 0.99 | | | | 0.98 | | | 0.97 | | | | | | 0.98 | | | | | | | | |
| **5.5** | 0.99 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **6** | 1.01 | 1.03 | | 1.04 | | 1.01 | | 1.04 | | 1.02 | | 0.99 | | 0.97 | | | | | | | | | | | | | | | 1.01 | | | | | | | | | | | | |
| **6.5** | 1.00 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **7** | 0.99 | 1.01 | | 1.01 | | 1.06 | | 1.02 | | 1.03 | | 1.01 | | | | 1.02 | | | | 0.99 | | | | 1.00 | | | | | | | 0.99 | | | | | | | | | |
| **7.5** | 0.99 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **8** | 0.99 | 1.02 | | 1.01 | | 0.98 | | 1.02 | | 0.97 | | | | | | | | | | | | | | | | | | | | | | 0.95 | | | | | | | | |
| **8.5** | 0.98 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **9** | 1.00 | 1.01 | | 0.97 | | 0.97 | | 0.98 | | | | 0.95 | | | | 0.98 | | | | 0.98 | | | | 0.98 | | | 0.97 | | | | | | 0.98 | | | | | | | | |
| **9.5** | 1.01 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **10** | 0.99 | 0.99 | | 0.99 | | 0.96 | | | | | | | | | | | | | | | | | | | | | | 0.96 | | | | | | | | | | | | |
| **10.5** | 1.00 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **11** | 0.96 | 0.99 | | 0.95 | | | | 0.97 | | | | 0.96 | | | | 0.96 | | | | 0.99 | | | | 0.98 | | | | | | 0.96 | | | | | | | | | | |
| **11.5** | 0.99 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **12** | 0.98 | 1.01 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **12.5** | 0.97 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **13** | 0.99 | | | 0.99 | | | | | | | | 0.94 | | | | | | | | 0.94 | | | | | | | 0.92 | | | | | | | | | | | | | |
| **14** | | | | | | | | | | | | | | 0.97 | | | | | | | | 0.96 | | | | | | | | | | | | | | | | | | | |
| **15** | 0.96 | | | | | 0.96 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **16** | | | | | | 0.97 | | | | | | | | 0.94 | | | | | | | | | | 0.93 | | | | | | | | | | | | | | | | | |
| **17** | 0.96 | | | 0.98 | | | | | | 0.98 | | | | | | | | | | 0.94 | | | | | | | | | | | | | | | | | | | | |
| **18** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **19** | 0.98 | | | 1.00 | | | | | | | | 0.98 | | | | | | | | 0.97 | | | | | | | | | | | | | | | | | | | | |
| **20** | | | | | | 1.00 | | | | | | | | 0.94 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **21** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **22** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **23** | 0.96 | | | 0.96 | | | | | | | | 0.94 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **24** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **25** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **26** | | | | | | 0.95 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **27** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **28** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **29** | 0.95 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

**PRE-EXPOSURE TIME (WEEKS)**

**Table 4**

**Summary of Chip 1 response with associated pre-exposure and post-exposure storage time.**

**CHIP 2 RESULTS**

**POST-EXPOSURE TIME (WEEKS)**

| | 0 | 1 | 1.5 | 2 | 2.5 | 3 | 3.5 | 4 | 4.5 | 5 | 5.5 | 6 | 6.5 | 7 | 7.5 | 8 | 8.5 | 9 | 9.5 | 10 | 10.5 | 11 | 11.5 | 12 | 12.5 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 1.00 | 1.02 | 1.03 | 1.02 | 1.05 | 1.02 | 1.00 | 1.03 | 1.00 | 1.01 | 1.01 | 0.99 | 1.02 | 1.00 | 1.00 | 1.00 | 1.00 | 1.01 | 1.01 | 1.01 | 1.00 | 1.03 | 1.01 | 0.98 | 0.99 | 1.01 | | 1.00 | | 0.99 | | 1.00 | | | 0.99 | | | | | | 1.00 |
| **1** | 0.99 | 1.03 | | 1.03 | | 1.03 | | 1.04 | | 1.01 | | 1.01 | | 1.02 | | 1.01 | | 0.99 | | 1.00 | | 1.01 | | 1.01 | | | 1.02 | | | | | 1.05 | | | | | | 0.99 | | | |
| **1.5** | 1.01 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **2** | 0.99 | 1.02 | | 1.03 | | 1.03 | | 1.00 | | 1.00 | | 1.01 | | 1.02 | | 0.98 | | 1.01 | | 0.97 | | 1.00 | | | | 1.02 | | | | 1.00 | | | | | | | | | | | |
| **2.5** | 1.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **3** | 1.00 | 1.03 | | 1.01 | | 1.02 | | 1.02 | | 1.00 | | 1.03 | | 0.99 | | 1.03 | | 0.97 | | 1.01 | | | | 1.02 | | | | | | | 1.01 | | | | | | | | | | |
| **3.5** | 1.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **4** | 1.03 | 1.01 | | 1.00 | | 0.99 | | 1.01 | | 1.00 | | 1.00 | | 1.02 | | 0.97 | | 1.00 | | | | | | | | | | | | | | 0.96 | | | 0.97 | | | | | | |
| **4.5** | 1.00 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **5** | 1.00 | 1.02 | | 1.01 | | 0.99 | | 1.01 | | 0.98 | | 1.00 | | 1.00 | | 0.99 | | | | 1.00 | | | | 1.02 | | | 0.98 | | | | | 0.99 | | | | | | | | | |
| **5.5** | 1.00 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **6** | 1.00 | 1.00 | | 0.99 | | 0.99 | | 1.00 | | 1.01 | | 0.97 | | 1.01 | | | | | | | | | | | | | | | 0.99 | | | | | | | | | | | | |
| **6.5** | 0.99 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **7** | 0.98 | 1.00 | | 0.98 | | 1.05 | | 1.03 | | 1.02 | | 1.02 | | | | 1.05 | | | | | | | | 1.03 | | | | | | 1.04 | | | | | | | | | | |
| **7.5** | 1.01 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **8** | 1.01 | 1.00 | | 0.98 | | 1.00 | | 0.99 | | 0.99 | | | | | | | | | | | | | | | | | | | | | | 1.00 | | | | | | | | |
| **8.5** | 1.01 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **9** | 0.98 | 1.00 | | 1.00 | | 0.98 | | 0.99 | | | | 1.01 | | | | 1.00 | | | | 1.00 | | | | 0.97 | | | 0.98 | | | | | 0.98 | | | | | | | | | |
| **9.5** | 0.98 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **10** | 0.97 | 1.00 | | 0.96 | | 0.99 | | | | | | | | | | | | | | | | | | | | | | 0.97 | | | | | | | | | | | | |
| **10.5** | 0.95 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **11** | 0.98 | 0.97 | | 0.96 | | | | 0.98 | | | | 1.00 | | | | 0.97 | | | | 1.00 | | | | 0.98 | | | | | | 0.97 | | | | | | | | | | |
| **11.5** | 0.98 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **12** | 0.97 | 1.04 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **12.5** | 0.99 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **13** | 0.99 | | | 0.98 | | | | | | | | 0.96 | | | | | | | | 0.95 | | | | | | | 0.97 | | | | | | | | | | | | | | |
| **14** | | | | | | 1.00 | | | | | | | | 0.99 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **15** | 0.99 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **16** | | | | | | 0.97 | | | | | | | | 0.97 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **17** | 0.99 | | | 1.00 | | | | | | 0.99 | | | | | | | | | | 0.96 | | | | | | | | | | | | | | | | | | | | | |
| **18** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **19** | 1.00 | | | 1.03 | | | | | | | | 1.02 | | | | | | | | 0.99 | | | | | | | | | | | | | | | | | | | | | |
| **20** | | | | | | 1.01 | | | | | | | | 0.95 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **21** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **22** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **23** | 0.96 | | | 0.98 | | | | | | | | 0.97 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **24** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **25** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **26** | | | | | | 0.96 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **27** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **28** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **29** | 0.97 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

**PRE-EXPOSURE TIME (WEEKS)**

**Table 5**

**Summary of Chip 2 response with associated pre-exposure and post-exposure storage time.**

**CHIP 3 RESULTS**

**POST-EXPOSURE TIME (WEEKS)**

| | 0 | 1 | 1.5 | 2 | 2.5 | 3 | 3.5 | 4 | 4.5 | 5 | 5.5 | 6 | 6.5 | 7 | 7.5 | 8 | 8.5 | 9 | 9.5 | 10 | 10.5 | 11 | 11.5 | 12 | 12.5 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 1.00 | 0.96 | 0.97 | 0.97 | 0.98 | 0.97 | 0.97 | 0.99 | 0.98 | 1.01 | 1.00 | 0.97 | 0.98 | 0.96 | 0.98 | 0.98 | 0.98 | 0.97 | 1.01 | 1.01 | 0.99 | 0.99 | 0.98 | 1.02 | 0.98 | 1.01 | | 0.98 | | 0.99 | | 0.99 | | | 1.01 | | | | | 1.00 |
| **1** | 0.96 | 0.99 | | 0.98 | | 0.99 | | 1.00 | | 0.99 | | 1.00 | | 0.97 | | 0.98 | | 1.00 | | 0.99 | | 1.02 | | 1.02 | | 1.00 | | | | | | 0.98 | | | | | | 0.99 | | |
| **1.5** | 0.96 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **2** | 0.96 | 0.96 | | 0.98 | | 1.00 | | 0.97 | | 0.98 | | 1.00 | | 0.97 | | 1.00 | | 0.97 | | 1.00 | | 1.00 | | | | 0.98 | | | | 0.99 | | | | | | | | | | |
| **2.5** | 0.97 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **3** | 0.96 | 0.98 | | 0.97 | | 0.99 | | 0.98 | | 0.96 | | 0.95 | | 0.98 | | 0.99 | | 1.00 | | 0.99 | | | | 0.98 | | | | | | | 0.98 | | | | | | | | | |
| **3.5** | 0.98 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **4** | 0.97 | 0.99 | | 0.95 | | 0.98 | | 0.96 | | 0.97 | | 0.97 | | 0.98 | | 0.99 | | 0.98 | | | | | | | | | | | | | | 0.98 | | | 0.96 | | | | | |
| **4.5** | 0.96 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **5** | 0.98 | 0.97 | | 0.97 | | 0.97 | | 0.95 | | 0.97 | | 0.96 | | 0.98 | | 0.98 | | | | 0.98 | | | | 0.98 | | | 0.99 | | | | | | 0.98 | | | | | | | | |
| **5.5** | 0.96 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **6** | 0.96 | 0.97 | | 0.95 | | 0.95 | | 0.99 | | 0.97 | | 0.98 | | 0.96 | | | | | | | | | | | | | | | 0.98 | | | | | | | | | | | |
| **6.5** | 0.95 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **7** | 0.96 | 0.97 | | 0.95 | | 0.99 | | 1.00 | | 1.00 | | 1.00 | | | | 1.00 | | | | 1.00 | | | | 0.99 | | | | | | | 0.98 | | | | | | | | | |
| **7.5** | 0.95 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **8** | 0.95 | 0.94 | | 0.96 | | 0.95 | | 0.97 | | 0.98 | | | | | | | | | | | | | | | | | | | | | | 0.96 | | | | | | | | |
| **8.5** | 0.94 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **9** | 0.95 | 0.97 | | 0.95 | | 0.98 | | 0.96 | | | | 0.98 | | | | 0.98 | | | | 0.97 | | | | 0.95 | | | 0.97 | | | | | 0.95 | | | | | | | | |
| **9.5** | 0.97 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **10** | 0.96 | 0.95 | | 0.95 | | 0.95 | | | | | | | | | | | | | | | | | | | | | | 0.95 | | | | | | | | | | | | |
| **10.5** | 0.95 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **11** | 0.97 | 0.98 | | 0.94 | | | | 0.96 | | | | 0.96 | | | | 0.97 | | | | 0.95 | | | | 0.96 | | | | | | 0.97 | | | | | | | | | | |
| **11.5** | 0.96 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **12** | 0.98 | 1.01 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **12.5** | 0.94 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **13** | 0.97 | | | 0.98 | | | | | | | | 0.95 | | | | | | | | 0.96 | | | | | | 0.91 | | | | | | | | | | | | | | |
| **14** | | | | | | 0.97 | | | | | | | | 0.94 | | | | | | | | 0.94 | | | | | | | | | | | | | | | | | | | |
| **15** | 0.94 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **16** | | | | | | 0.98 | | | | | | | | 0.96 | | | | | | | | | | 0.93 | | | | | | | | | | | | | | | | |
| **17** | 0.97 | | | 0.97 | | | | | | 0.94 | | | | | | | | | | 0.95 | | | | | | | | | | | | | | | | | | | |
| **18** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **19** | 0.97 | | | 0.98 | | | | | | | | 1.00 | | | | | | | | 0.98 | | | | | | | | | | | | | | | | | | | |
| **20** | | | | | | 1.00 | | | | | | | | 0.93 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **21** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **22** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **23** | 0.97 | | | 0.95 | | | | | | | | 0.96 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **24** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **25** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **26** | | | | | | 0.95 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **27** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **28** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **29** | 0.96 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

**PRE-EXPOSURE TIME (WEEKS)**

**Table 6**

**Summary of Chip 3 response with associated pre-exposure and post-exposure storage time.**

**CHIP 4 RESULTS**

**POST-EXPOSURE TIME (WEEKS)**

| | 0 | 1 | 1.5 | 2 | 2.5 | 3 | 3.5 | 4 | 4.5 | 5 | 5.5 | 6 | 6.5 | 7 | 7.5 | 8 | 8.5 | 9 | 9.5 | 10 | 10.5 | 11 | 11.5 | 12 | 12.5 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 1.00 | 1.03 | 1.05 | 1.06 | 1.07 | 1.04 | 1.06 | 1.05 | 1.05 | 1.05 | 1.07 | 1.04 | 1.00 | 1.00 | 1.02 | 1.02 | 1.02 | 1.00 | 1.02 | 1.02 | 1.02 | 1.03 | 1.01 | 1.01 | 0.99 | 1.01 | | 0.99 | | 1.02 | | 0.98 | | | | 1.01 | | | | | 1.02 |
| **1** | 1.02 | 1.08 | | 1.06 | | 1.04 | | 1.04 | | 1.03 | | 1.02 | | 1.03 | | 1.01 | | 1.02 | | 1.02 | | 1.03 | | 1.03 | | 1.03 | | | | | | 1.01 | | | | | | 0.99 | | | |
| **1.5** | 1.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **2** | 1.06 | 1.03 | | 1.04 | | 1.02 | | 1.00 | | 1.01 | | 0.99 | | 0.99 | | 1.01 | | 1.04 | | 1.00 | | 1.01 | | | | 1.02 | | | | 0.99 | | | | | | | | | | |
| **2.5** | 1.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **3** | 1.04 | 1.04 | | 1.03 | | 1.04 | | 1.01 | | 0.99 | | 0.97 | | 1.00 | | | | 1.00 | | 1.01 | | | | 1.00 | | | | | | | 0.98 | | | | | | | | | |
| **3.5** | 1.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **4** | 1.04 | 1.04 | | 0.99 | | 1.00 | | 0.98 | | 1.03 | | 1.00 | | 1.04 | | 0.96 | | 0.96 | | | | | | | | | | | | | | 0.98 | | | 0.94 | | | | | |
| **4.5** | 1.02 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **5** | 1.02 | 1.02 | | 0.98 | | 0.96 | | 1.00 | | 1.00 | | 1.01 | | 0.97 | | 1.00 | | | | 0.99 | | | | 0.98 | | | 0.98 | | | | | | 0.98 | | | | | | | | |
| **5.5** | 1.04 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **6** | 1.02 | 0.99 | | 1.01 | | 0.98 | | 0.99 | | 1.04 | | 0.98 | | 0.96 | | | | | | | | | | | | | | | 1.00 | | | | | | | | | | | | |
| **6.5** | 1.01 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **7** | 1.00 | 0.97 | | 1.00 | | 1.02 | | 1.04 | | 0.99 | | 1.02 | | | | 1.00 | | | | 1.01 | | | | 0.99 | | | | | | | 0.97 | | | | | | | | | |
| **7.5** | 1.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **8** | 0.98 | 0.99 | | 1.00 | | 1.02 | | 0.97 | | 0.98 | | | | | | | | | | 0.95 | | | | 0.98 | | | | | | | | 0.97 | | | | | | | | |
| **8.5** | 0.99 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **9** | 0.98 | 1.00 | | 1.01 | | 0.98 | | 0.98 | | | | 0.97 | | | | 1.00 | | | | 0.95 | | | | 0.98 | | | 0.98 | | | | | 0.96 | | | | | | | | |
| **9.5** | 0.99 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **10** | 0.99 | 1.00 | | 0.98 | | 0.97 | | | | | | | | | | | | | | | | | | | | | | 0.97 | | | | | | | | | | | | |
| **10.5** | 0.99 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **11** | 1.00 | 0.98 | | 0.96 | | | | 0.96 | | | | 0.98 | | | | 0.99 | | | | 0.99 | | | | 0.98 | | | | | | 0.97 | | | | | | | | | | |
| **11.5** | 1.00 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **12** | 0.99 | 1.02 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **12.5** | 1.00 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **13** | 0.99 | | | 0.99 | | | | | | | | 0.98 | | | | | | | | 0.95 | | | | | | | 0.92 | | | | | | | | | | | | | |
| **14** | | | | | | 0.99 | | | | | | | | 0.96 | | | | | | | | 0.96 | | | | | | | | | | | | | | | | | | | |
| **15** | 0.99 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **16** | | | | | | 0.97 | | | | | | | | 0.96 | | | | | | | | | | 0.95 | | | | | | | | | | | | | | | | | |
| **17** | 1.00 | | | 0.95 | | | | | | 0.96 | | | | | | | | | | 0.99 | | | | | | | | | | | | | | | | | | | | |
| **18** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **19** | 0.98 | | | 0.99 | | | | | | | | 0.99 | | | | | | | | 0.99 | | | | | | | | | | | | | | | | | | | | |
| **20** | | | | | | 1.00 | | | | | | | | 0.92 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **21** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **22** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **23** | 0.97 | | | 0.96 | | | | | | | | 0.94 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **24** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **25** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **26** | | | | | | 0.94 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **27** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **28** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **29** | 0.96 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

**PRE-EXPOSURE TIME (WEEKS)**

**Table 7**

**Summary of Chip 4 response with associated pre-exposure and post-exposure storage time.**

## 8.0. Conclusions

In conclusion, the DT-702 TLD has been shown to not have any statistically significant loss of sensitivity or loss of signal response with up to 29 weeks of pre-exposure, post-exposure, or combination of pre-exposure and post-exposure time.

Currently the DT-702 TLDs are normally issued for six-week periods, with a 12 week maximum for special circumstances.[44] The data presented in this study indicates that an evaluation of extended issue periods beyond current issue periods is warranted. Approximately 240 commands ship and receive TLDs every 6 weeks at approximately $5.00 a shipment (typical domestic shipping, international rates higher).[44] This results in the Navy spending on average $20,800.00 each year to send and receive TLDs. If six-month issue periods were permitted, this cost would drop to around $4,800, saving the Navy around $16,000 per year. The cost calculations also do not include any potential costs incurred from lost or damaged TLDs. A single DT-702 costs approximately $50.00.[44] Considering even the smallest commands receive at least 10-12 TLDs, losing a shipment would result in $500.00-$600.00 in replacement costs.

Additionally, the loss of a DT-702 represents the loss of radiation exposure history information. If a group of TLDs is lost in shipping, a dose investigation must be performed for each TLD. The investigation is performed to determine, as accurately as possible, the radiation dose received by the individual who was being monitored. This is a time consuming process that involves environmental radiation surveys and extensive documentation review. The investigation will ultimately result in a calculated estimation of the radiation dose received, which is less accurate than a measured dose from a

calibrated dosimeter. Additionally, this process must be repeated for each TLD lost, potentially resulting in numerous investigations.

The longevity of the DT-702 has been demonstrated out to 29 weeks of storage time, and consideration should be given to extending the issue periods of use for these TLDs. This will not only save money and time lost to shipping, but also reduce the chance for lost TLDs during mailing. Lost TLDs result in not only monetary losses, but a loss of irreplaceable records of radiation exposure history for personnel and environmental monitoring.

## 9.0. Recommended Future Studies

The response of the DT-702 through 29 weeks should be examined further. A longer study should be performed to determine more accurately how long the TLD can be in use before a statistically significant loss of sensitivity or signal response is measured. Care must be given however to ensure that the variations in reader operation (specifically the RCF calculation) are accounted for to provide an accurate evaluation of the TLD.

Additionally, the DT-702 should be evaluated under the same standards for neutron radiation exposures, as well as mixed radiation field effects. More extensive studies in these areas will provide an even more detailed characterization of the DT-702, increasing the accuracy of personnel occupational and environmental radiation monitoring in the Navy.

Evaluation of the raw data for Chips 1, 2, and 4 showed initial increases in response for both pre-exposure and post-exposure time. Conversely, Chip 3 showed initial decreases in response for both pre-exposure and post-exposure time. Although

determined to not be statistically significant in this study, these initial variations in response have also been seen in other concurrent studies of the DT-702 TLD.[45] Additional evaluation with increased sample sizes needs to be performed to determine if these increases are actually statistically significant. Increasing the sample size will reduce the standard deviation associated with the data points. Limitations regarding the time it takes to determine a data point by processing a larger sample however, can make the ability of testing with larger samples less practical. The standard deviation of a normally distributed sample varies by approximately $1/\sqrt{N}$. To decrease the deviation by half, the sample size must increase four fold. This could result in unrealistic processing times required to obtain deviations small enough to identify actual variations in response.

The ability to detect small increases in radiation exposure is important for personnel and environmental monitoring. The smallest quantity of dose that a material can detect is defined as the Lower Limit of Detection (LLD).[46] In order to increase issue periods, further studies are needed to determine if the current LLD (3 mrem for shallow dose, 3 mrem for deep dose, and 5 mrem for neutron dose) is still accurate with the increased background radiation associated with the longer issue period.[38] Longer issue periods will result in larger accumulations of background radiation exposure. Based on this study, an average of 150 mrem of background radiation could be expected after a 29-week issue period. With a larger background radiation exposure, the likelihood of being able to detect a small increase from an occupational source decreases. Further studies need to be performed to determine if the LLD of the DT-702 will force any limitations on extension of the current issue periods.

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# Appendix A

**CHIP 1 ERROR**

**POST-EXPOSURE TIME (WEEKS)**

| | 0 | 1 | 1.5 | 2 | 2.5 | 3 | 3.5 | 4 | 4.5 | 5 | 5.5 | 6 | 6.5 | 7 | 7.5 | 8 | 8.5 | 9 | 9.5 | 10 | 10.5 | 11 | 11.5 | 12 | 12.5 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 0.03 | 0.03 | 0.02 | 0.03 | 0.02 | 0.02 | 0.03 | 0.03 | 0.03 | 0.03 | 0.04 | 0.04 | 0.03 | 0.02 | 0.02 | 0.02 | 0.03 | 0.03 | 0.03 | 0.03 | 0.02 | 0.03 | 0.03 | 0.05 | 0.05 | 0.02 | | 0.04 | | 0.03 | | 0.03 | | | | 0.05 | | | | | | 0.03 |
| **1** | 0.03 | 0.03 | | 0.04 | | 0.03 | | 0.02 | | 0.03 | | 0.04 | | 0.05 | | 0.03 | | 0.04 | | 0.04 | | 0.03 | | 0.03 | | | 0.03 | | | | | 0.04 | | | | | | 0.02 | | | |
| **1.5** | 0.04 | | | | | | | | | | | | | | | | | | | | | 0.04 | | | | | | | | | | | | | | | | | | | |
| **2** | 0.02 | 0.03 | | 0.03 | | 0.04 | | 0.03 | | 0.02 | | 0.02 | | 0.03 | | 0.03 | | 0.03 | | 0.03 | | 0.02 | | | | 0.03 | | | | 0.03 | | | | | | | | | | | |
| **2.5** | 0.04 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **3** | 0.02 | 0.02 | | 0.03 | | 0.03 | | 0.05 | | 0.02 | | 0.04 | | 0.03 | | 0.01 | | 0.03 | | 0.04 | | | | 0.03 | | | | | | | 0.03 | | | | | | | | | | |
| **3.5** | 0.02 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **4** | 0.02 | 0.23 | | 0.02 | | 0.02 | | 0.03 | | 0.03 | | 0.03 | | 0.02 | | 0.04 | | 0.02 | | | | | | | | | | | | | | 0.03 | | | 0.04 | | | | | | |
| **4.5** | 0.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **5** | 0.02 | 0.02 | | 0.02 | | 0.03 | | 0.03 | | 0.04 | | 0.02 | | 0.02 | | 0.02 | | | | 0.03 | | | | 0.04 | | | 0.03 | | | | | | 0.03 | | | | | | | | |
| **5.5** | 0.04 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **6** | 0.04 | 0.03 | | 0.03 | | 0.03 | | 0.04 | | 0.01 | | 0.03 | | 0.02 | | | | | | | | | | | | | | | 0.03 | | | | | | | | | | | |
| **6.5** | 0.02 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **7** | 0.02 | 0.02 | | 0.03 | | 0.04 | | 0.02 | | 0.04 | | 0.04 | | | | 0.04 | | | | 0.03 | | | | 0.02 | | | | | | 0.03 | | | | | | | | | | |
| **7.5** | 0.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **8** | 0.03 | 0.03 | | 0.03 | | 0.01 | | 0.03 | | 0.02 | | | | | | | | | | | | | | | | | | | | | 0.02 | | | | | | | | | |
| **8.5** | 0.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **9** | 0.03 | 0.03 | | 0.01 | | 0.03 | | 0.03 | | | | 0.03 | | | | 0.04 | | | | 0.04 | | | | 0.03 | | | 0.03 | | | | | 0.05 | | | | | | | | |
| **9.5** | 0.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **10** | 0.04 | 0.01 | | 0.03 | | 0.02 | | | | | | | | | | | | | | | | | | | | | | 0.03 | | | | | | | | | | | | |
| **10.5** | 0.04 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **11** | 0.02 | 0.02 | | 0.02 | | | | 0.03 | | | | 0.03 | | | | 0.03 | | | | 0.03 | | | | 0.04 | | | | | | 0.04 | | | | | | | | | | |
| **11.5** | 0.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **12** | 0.04 | 0.04 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **12.5** | 0.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **13** | 0.02 | | | 0.04 | | | | | | | | 0.03 | | | | | | | | 0.03 | | | | | | | 0.02 | | | | | | | | | | | | | |
| **14** | | | | | | 0.03 | | | | | | | | 0.02 | | | | | | | | 0.04 | | | | | | | | | | | | | | | | | | | |
| **15** | 0.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **16** | | | | | | 0.03 | | | | | | | | 0.04 | | | | | | | | | | 0.02 | | | | | | | | | | | | | | | | | |
| **17** | 0.03 | | | 0.04 | | | | | | 0.04 | | | | | | | | | | 0.02 | | | | | | | | | | | | | | | | | | | | |
| **18** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **19** | 0.04 | | | 0.02 | | | | | | | | 0.03 | | | | | | | | 0.03 | | | | | | | | | | | | | | | | | | | | |
| **20** | | | | | | 0.04 | | | | | | | | 0.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **21** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **22** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **23** | 0.04 | | | 0.03 | | | | | | | | 0.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **24** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **25** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **26** | | | | | | 0.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **27** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **28** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **29** | 0.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

**PRE-EXPOSURE TIME (WEEKS)**

**Table 8**

**Summary of Chip 1 propogated errors with associated pre-exposure and post-exposure storage time.**

**CHIP 2 ERROR**

**POST-EXPOSURE TIME (WEEKS)**

| | 0 | 1 | 1.5 | 2 | 2.5 | 3 | 3.5 | 4 | 4.5 | 5 | 5.5 | 6 | 6.5 | 7 | 7.5 | 8 | 8.5 | 9 | 9.5 | 10 | 10.5 | 11 | 11.5 | 12 | 12.5 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 0.01 | 0.02 | 0.03 | 0.03 | 0.03 | 0.03 | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.03 | 0.02 | 0.02 | 0.03 | 0.02 | 0.02 | 0.03 | 0.02 | 0.04 | 0.04 | 0.04 | 0.02 | 0.03 | 0.04 | | 0.02 | | 0.02 | | 0.01 | | | 0.03 | | | | | | 0.02 |
| **1** | 0.02 | 0.02 | | 0.03 | | 0.02 | | 0.02 | | 0.02 | | 0.02 | | 0.04 | | 0.03 | | 0.02 | | 0.02 | | 0.04 | | 0.05 | | | 0.02 | | | | | 0.04 | | | | | | 0.01 | | | |
| **1.5** | 0.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **2** | 0.01 | 0.02 | | 0.01 | | 0.01 | | 0.02 | | 0.02 | | 0.03 | | 0.02 | | 0.02 | | 0.02 | | 0.02 | | 0.02 | | | | 0.03 | | | | 0.02 | | | | | | | | | | | |
| **2.5** | 0.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **3** | 0.02 | 0.01 | | 0.01 | | 0.03 | | 0.02 | | 0.02 | | 0.04 | | 0.03 | | 0.03 | | 0.01 | | 0.04 | | | | 0.04 | | | | | | | 0.04 | | | | | | | | | | |
| **3.5** | 0.04 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **4** | 0.01 | 0.02 | | 0.02 | | 0.02 | | 0.04 | | 0.01 | | 0.03 | | 0.03 | | 0.02 | | 0.02 | | | | | | | | | | | | | | 0.01 | | | | 0.01 | | | | | |
| **4.5** | 0.02 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **5** | 0.04 | 0.03 | | 0.03 | | 0.02 | | 0.01 | | 0.02 | | 0.02 | | 0.03 | | 0.02 | | | | 0.03 | | | | 0.02 | | | 0.02 | | | | | | 0.02 | | | | | | | | |
| **5.5** | 0.01 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **6** | 0.01 | 0.02 | | 0.02 | | 0.01 | | 0.03 | | 0.02 | | 0.03 | | 0.04 | | | | | | | | | | | | | | | 0.01 | | | | | | | | | | | | |
| **6.5** | 0.04 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **7** | 0.02 | 0.03 | | 0.01 | | 0.04 | | 0.04 | | 0.03 | | 0.03 | | | | 0.05 | | | | 0.03 | | | | 0.04 | | | | | | 0.04 | | | | | | | | | | |
| **7.5** | 0.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **8** | 0.03 | 0.02 | | 0.02 | | 0.04 | | 0.03 | | 0.03 | | | | | | | | | | | | | | | | | | | | | 0.02 | | | | | | | | | |
| **8.5** | 0.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **9** | 0.01 | 0.03 | | 0.02 | | 0.03 | | 0.02 | | | | 0.03 | | | | 0.03 | | | | 0.02 | | | | 0.01 | | | | | | | | 0.02 | | | | | | | | | |
| **9.5** | 0.02 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **10** | 0.02 | 0.04 | | 0.01 | | 0.04 | | | | | | | | | | | | | | | | | | | | | | 0.02 | | | | | | | | | | | | |
| **10.5** | 0.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **11** | 0.03 | 0.02 | | 0.03 | | | | 0.02 | | | | 0.03 | | | | 0.02 | | | | 0.02 | | | | 0.03 | | | | | | 0.03 | | | | | | | | | | |
| **11.5** | 0.02 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **12** | 0.02 | 0.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **12.5** | 0.02 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **13** | 0.02 | | | 0.02 | | | | | | | | 0.01 | | | | | | | | 0.02 | | | | | | | | | | | | | | | | | | | | | |
| **14** | | | | | | 0.03 | | | | | | | | 0.03 | | | | | | | | 0.04 | | | | | | | | | | | | | | | | | | | | |
| **15** | 0.02 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **16** | | | | | | 0.01 | | | | | | | | 0.02 | | | | | | | | | | 0.02 | | | | | | | | | | | | | | | | | | |
| **17** | 0.03 | | | 0.02 | | | | | | 0.03 | | | | | | | | | | 0.02 | | | | | | | | | | | | | | | | | | | | | |
| **18** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **19** | 0.03 | | | 0.01 | | | | | | | | 0.03 | | | | | | | | 0.02 | | | | | | | | | | | | | | | | | | | | | |
| **20** | | | | | | 0.04 | | | | | | | | 0.02 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **21** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **22** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **23** | 0.01 | | | 0.02 | | | | | | | | 0.02 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **24** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **25** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **26** | | | | | | 0.01 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **27** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **28** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **29** | 0.02 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

**PRE-EXPOSURE TIME (WEEKS)**

**Table 9**

**Summary of Chip 2 propogated errors with associated pre-exposure and post-exposure storage time.**

**CHIP 3 ERROR**

**POST-EXPOSURE TIME (WEEKS)**

| | 0 | 1 | 1.5 | 2 | 2.5 | 3 | 3.5 | 4 | 4.5 | 5 | 5.5 | 6 | 6.5 | 7 | 7.5 | 8 | 8.5 | 9 | 9.5 | 10 | 10.5 | 11 | 11.5 | 12 | 12.5 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 0.04 | 0.03 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.03 | 0.02 | 0.03 | 0.04 | 0.02 | 0.03 | 0.04 | 0.03 | 0.03 | 0.04 | 0.05 | 0.05 | 0.04 | 0.02 | 0.04 | 0.04 | 0.03 | 0.03 | 0.03 | | 0.04 | | 0.04 | | 0.04 | | | 0.04 | | | | | | 0.03 |
| **1** | 0.03 | 0.02 | | 0.02 | | 0.03 | | 0.02 | | 0.02 | | 0.04 | | 0.03 | | 0.05 | | 0.03 | | 0.03 | | 0.04 | | 0.04 | | | 0.03 | | | | | 0.04 | | | | | | | | | |
| **1.5** | 0.01 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **2** | 0.03 | 0.02 | | 0.03 | | 0.02 | | 0.02 | | 0.04 | | 0.03 | | 0.05 | | 0.03 | | 0.03 | | 0.03 | | 0.03 | | | | 0.03 | | | | 0.04 | | | | | | | | | | | |
| **2.5** | 0.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **3** | 0.02 | 0.03 | | 0.02 | | 0.03 | | 0.04 | | 0.03 | | 0.05 | | 0.03 | | 0.03 | | 0.03 | | 0.03 | | 0.03 | | 0.03 | | | | | | | 0.05 | | | | | | | | | | |
| **3.5** | 0.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **4** | 0.03 | 0.03 | | 0.03 | | 0.04 | | 0.03 | | 0.05 | | 0.03 | | 0.03 | | 0.02 | | 0.03 | | | | | | | | | | | | | | 0.04 | | | 0.04 | | | | | | |
| **4.5** | 0.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **5** | 0.03 | 0.03 | | 0.04 | | 0.03 | | 0.05 | | 0.03 | | 0.03 | | 0.03 | | 0.03 | | | | 0.03 | | | | 0.04 | | | 0.04 | | | | | | 0.04 | | | | | | | | |
| **5.5** | 0.04 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **6** | 0.03 | 0.04 | | 0.03 | | 0.05 | | 0.03 | | 0.03 | | 0.02 | | 0.02 | | | | | | | | | | | | | | | 0.06 | | | | | | | | | | | | |
| **6.5** | 0.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **7** | 0.04 | 0.03 | | 0.05 | | 0.03 | | 0.04 | | 0.03 | | 0.03 | | | | 0.02 | | | | 0.04 | | | | 0.04 | | | | | | | 0.04 | | | | | | | | | | |
| **7.5** | 0.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **8** | 0.03 | 0.05 | | 0.03 | | 0.03 | | 0.03 | | 0.04 | | | | | | | | | | 0.04 | | | | 0.04 | | | | | | | | 0.05 | | | | | | | | | |
| **8.5** | 0.04 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **9** | 0.05 | 0.03 | | 0.03 | | 0.02 | | 0.03 | | | | 0.04 | | | | 0.04 | | | | 0.04 | | | | 0.04 | | | 0.04 | | | | | 0.02 | | | | | | | | | |
| **9.5** | 0.04 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **10** | 0.03 | 0.03 | | 0.02 | | 0.03 | | | | | | | | | | | | | | | | | | | | | | 0.04 | | | | | | | | | | | | |
| **10.5** | 0.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **11** | 0.04 | 0.03 | | 0.03 | | | | 0.03 | | | | 0.04 | | | | 0.04 | | | | | | 0.05 | | | | | | | | 0.03 | | | | | | | | | | |
| **11.5** | 0.04 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **12** | 0.03 | 0.04 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **12.5** | 0.04 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **13** | 0.03 | | | 0.03 | | | | | | | | 0.04 | | | | | | | | 0.04 | | | | | | | 0.04 | | | | | | | | | | | | | |
| **14** | | | | | | 0.04 | | | | | | | | 0.04 | | | | | | | | 0.04 | | | | | | | | | | | | | | | | | | | |
| **15** | 0.02 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **16** | | | | | | 0.04 | | | | | | | | 0.04 | | | | | | | | | | 0.03 | | | | | | | | | | | | | | | | | |
| **17** | 0.04 | | | 0.04 | | | | | | 0.05 | | | | | | | | | | 0.04 | | | | | | | | | | | | | | | | | | | | | |
| **18** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **19** | 0.04 | | | 0.05 | | | | | | | | 0.04 | | | | | | | | 0.03 | | | | | | | | | | | | | | | | | | | | | |
| **20** | | | | | | 0.04 | | | | | | | | 0.04 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **21** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **22** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **23** | 0.04 | | | 0.05 | | | | | | | | 0.04 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **24** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **25** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **26** | | | | | | 0.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **27** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **28** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **29** | 0.02 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

**PRE-EXPOSURE TIME (WEEKS)**

**Table 10**

**Summary of Chip 3 propogated errors with associated pre-exposure and post-exposure storage time.**

**CHIP 4 ERROR**

**POST-EXPOSURE TIME (WEEKS)**

| | 0 | 1 | 1.5 | 2 | 2.5 | 3 | 3.5 | 4 | 4.5 | 5 | 5.5 | 6 | 6.5 | 7 | 7.5 | 8 | 8.5 | 9 | 9.5 | 10 | 10.5 | 11 | 11.5 | 12 | 12.5 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 0.02 | 0.03 | 0.04 | 0.02 | 0.01 | 0.02 | 0.03 | 0.02 | 0.03 | 0.02 | 0.03 | 0.05 | 0.03 | 0.03 | 0.04 | 0.04 | 0.04 | 0.03 | 0.03 | 0.05 | 0.04 | 0.02 | 0.04 | 0.04 | 0.04 | 0.06 | | 0.06 | | 0.06 | | 0.06 | | | 0.06 | | | | | | 0.07 |
| **1** | 0.02 | 0.03 | | 0.03 | | 0.03 | | 0.02 | | 0.05 | | 0.03 | | 0.04 | | 0.04 | | 0.04 | | 0.02 | | 0.04 | | 0.06 | | | 0.06 | | | | 0.05 | | | | | | 0.07 | | | |
| **1.5** | 0.02 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **2** | 0.03 | 0.02 | | 0.03 | | 0.02 | | 0.04 | | 0.03 | | 0.03 | | 0.04 | | 0.05 | | 0.03 | | 0.04 | | 0.05 | | | | 0.06 | | | | 0.07 | | | | | | | | | | |
| **2.5** | 0.02 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **3** | 0.03 | 0.04 | | 0.02 | | 0.04 | | 0.03 | | 0.03 | | 0.03 | | 0.04 | | 0.03 | | 0.04 | | 0.05 | | | | 0.06 | | | | | | | 0.05 | | | | | | | | | |
| **3.5** | 0.04 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **4** | 0.03 | 0.03 | | 0.04 | | 0.03 | | 0.04 | | 0.04 | | 0.04 | | 0.03 | | 0.04 | | 0.05 | | | | | | | | | | | | | | 0.06 | | | | 0.06 | | | | |
| **4.5** | 0.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **5** | 0.02 | 0.04 | | 0.03 | | 0.03 | | 0.03 | | 0.04 | | 0.01 | | 0.04 | | 0.05 | | 0.06 | | | | | | 0.06 | | | 0.05 | | | | | | 0.06 | | | | | | | | |
| **5.5** | 0.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **6** | 0.04 | 0.03 | | 0.03 | | 0.03 | | 0.04 | | 0.01 | | 0.05 | | 0.05 | | | | | | | | | | | | | | | 0.05 | | | | | | | | | | | | |
| **6.5** | 0.04 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **7** | 0.03 | 0.03 | | 0.04 | | 0.04 | | 0.02 | | 0.04 | | 0.05 | | | | 0.06 | | | | | | | | 0.06 | | | | | | | 0.06 | | | | | | | | | |
| **7.5** | 0.04 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **8** | 0.03 | 0.04 | | 0.04 | | 0.14 | | 0.04 | | 0.06 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **8.5** | 0.04 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **9** | 0.03 | 0.04 | | 0.02 | | 0.05 | | 0.05 | | | | 0.06 | | | | 0.06 | | | | | | | | 0.05 | | | 0.07 | | | | | | 0.06 | | | | | | | | |
| **9.5** | 0.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **10** | 0.04 | 0.02 | | 0.05 | | 0.05 | | | | | | | | | | | | | | | | | | | | | | 0.06 | | | | | | | | | | | | |
| **10.5** | 0.04 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **11** | 0.01 | 0.04 | | 0.05 | | | | 0.06 | | | | 0.06 | | | | 0.06 | | | | 0.05 | | | | 0.06 | | | | | | | 0.07 | | | | | | | | | |
| **11.5** | 0.04 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **12** | 0.04 | 0.05 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **12.5** | 0.04 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **13** | 0.06 | | | 0.07 | | | | | | | | 0.06 | | | | | | | | 0.07 | | | | | | | 0.06 | | | | | | | | | | | | | |
| **14** | | | | | | 0.06 | | | | | | | | 0.05 | | | | | | | | 0.06 | | | | | | | | | | | | | | | | | | | |
| **15** | 0.06 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **16** | | | | | | 0.06 | | | | | | | | 0.07 | | | | | | | | | | 0.06 | | | | | | | | | | | | | | | | | |
| **17** | 0.06 | | | 0.05 | | | | | | 0.06 | | | | | | | | | | 0.07 | | | | | | | | | | | | | | | | | | | | |
| **18** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **19** | 0.06 | | | 0.06 | | | | | | | | 0.06 | | | | | | | | 0.06 | | | | | | | | | | | | | | | | | | | | |
| **20** | | | | | | 0.06 | | | | | | | | 0.06 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **21** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **22** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **23** | 0.06 | | | 0.06 | | | | | | | | 0.06 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **24** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **25** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **26** | | | | | | 0.06 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **27** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **28** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **29** | 0.06 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

**PRE-EXPOSURE TIME (WEEKS)**

**Table 11**

**Summary of Chip 4 propogated errors with associated pre-exposure and post-exposure storage time.**